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EXPERIMENTAL ANALYSIS OF A DIESEL CYCLE ENGINE USING GASOLINE AS FUEL: HCCI TECHNOLOGY

Braga S.L.[a,]*, Milón J.J.[b], Aguilar J.A.[a]

*Author for correspondence
[a]Vehicle Engineering Laboratory, Pontifical Catholic University of Rio de Janeiro, PUC-Rio, Brazil
[b]Energy Institute, San Pablo Catholic University, UCSP, Peru
E-mail: slbraga@puc-rio.br

ABSTRACT

An experimental setup was designed and built to evaluate the performance of a Diesel cycle engine operating in HCCI mode, using gasoline as fuel. Different sensors and equipment were installed to monitor fuel and air flows, pressure in the air suction, torque, rotation and different temperatures (exhaust gas, air and engine case, among others). The results indicate that the admission charge temperature (air-fuel) and the amount of fuel injected affect the performance of the engine in HCCI mode. The start of the combustion is brought forward as the admission temperature increases, which in some circumstances can cause a detonation characterized by the presence of a loud noise, due to an unstable combustion. The fuel in this case is the commercial gasoline sold in Brazil that contains 22% in volume of anhydrous ethanol.

INTRODUCTION

About 80% of the total energy used each year is consumed by combustion in thermal machines like gasoline and diesel powered engines, jet planes and power electric plants. Worldwide, fossil fuels release more than twenty five billion tons of carbon dioxide into the atmosphere every year with large amounts of other pollutants [1]. Today, modest gains in the efficiency of combustion result in significant energy savings (fuel), reduced pollution and less dependence on foreign energy sources.

HCCI technology is considered a promising alternative combustion process compared to the traditional combustion systems SI (Spark Ignition) and CI (Compression Ignition). The homogeneous charge compression ignition (HCCI) combustion engine combines the best features of both SI and CI engines, guaranteeing the high efficiency of a diesel engine with low NO_X and particulate emissions using a homogeneous mixture as an Otto engine [2].

However, several problems are occurring in experimental studies for automotive applications such as extending the operating range of HCCI to high loads, controlling ignition timing and burning rate over a range of engine rotation and loads, cold starts and minimizing HC - CO emissions [2, 3].

HCCI is characterized by the fact that the fuel and air are mixed outside the combustion chamber to form a homogeneous mixture which reacts and burns volumetrically throughout the cylinder by the compression of the piston. HCCI combustion is initiated by a spontaneous ignition in many low places under high temperature and high pressure.

NOMENCLATURE

CO	Carbon monoxide
HC	Hydrocarbon
HCCI	Homogeneous charged compression ignition
MEP	Mean effective pressure
NO_X	Nitrogen oxides
PM	Particulate emissions
RPM	Revolutions per minute
SFC	Specific fuel comsumption
SI	Spark Ignition
TDC	Top dead center

Special characters

λ	Lambda factor

The critical problem of this technology is the control of start of the ignition and burning rate. From a control standpoint, the SI combustion is controlled by the start of sparks and the CI combustion is controlled by the injection time, but in the HCCI engine there isn't a mechanism of action that directly controls the combustion timing [4]. Therefore, the fuel physical and chemical properties, mixture components, environmental conditions including temperature and pressure, and engine operating conditions such as engine speed and load, play an important role on ignition timing and combustion duration [5].

Due to the combustion process, the diesel engines are less probable to achieve the required emission levels of PM and NO_X for future legislation. The same situation occurs with SI engines because they cannot achieve high efficiencies at partial loads because of the construction and operating principle of the engine. Facing these problems, the HCCI engine can be considered as a hybrid of both types of the engines mentioned, linking all the attractive properties and becoming the technology that will be used in vehicles in the future.

Despite the resulting problems from the complex combustion control system, HCCI provides enormous benefits for heavy duty and light passenger vehicles. It can also be applied outside the transportation sector such as those used for electrical power generation and pipeline pumping, but above all HCCI can be operated at high compression ratios and using fuels with high octane rating, resulting in higher efficiencies and cleaner exhaust gases [6].

Finally, today’s engines are required to be characterized by low fuel consumption, high efficiency, reliability, low cost and low maintenance costs. The HCCI combustion concept is an effective way to meet these requirements. The purpose of this study is to analyze the influences of operating parameters such as intake charge temperature, the amount of fuel injected and the engine rotation in the development of HCCI combustion and to evaluate how its effect varies according to the start of the ignition. The fuel in this case is the commercial gasoline sold in Brazil that contains 22% in volume of anhydrous ethanol.

EXPERIMENTAL MODEL AND PROCEDURE

Experimental tests were performed in a single cylinder indirect injection four-stroke diesel engine. This engine is designed for applications with constant rotation (power generation, water discharge, etc).

The main features of the engine are shown in Table 1.

Table 1. Yammar Engine Characteristics

Description	**Characteristic**
Model	NSB50
Type	Monocylinder, 4 stroke
Cylinder displacement	331 cm^3
Bore	75 mm
Stroke	75 mm
Compression Ratio	23.1:1
Maximum Power	4.0 kW at 2400 RPM
Maximum Torque	15.4 N·m at 1800 RPM
Refrigeration System	Water
Injection System	Indirect

The experimental device is represented in Fig.1. The original diesel engine was modified to operate in HCCI combustion, some of these changes were:

(1) Intake system: a heating system for air intake was designed and installed in the air intake line of the engine (Fig. 1).

(2) Fuel injection system: a fuel injector was installed in the intake line at a distance of approximately 0.5 m of the inlet valve positioned on a T-shaped base structure.

(3) Measurement equipment: Sensors and transducers were located in the engine to monitor the pressure in the combustion chamber, the fuel injection pressure, engine rotation, fuel and air mass flow, exhaust temperature, etc.

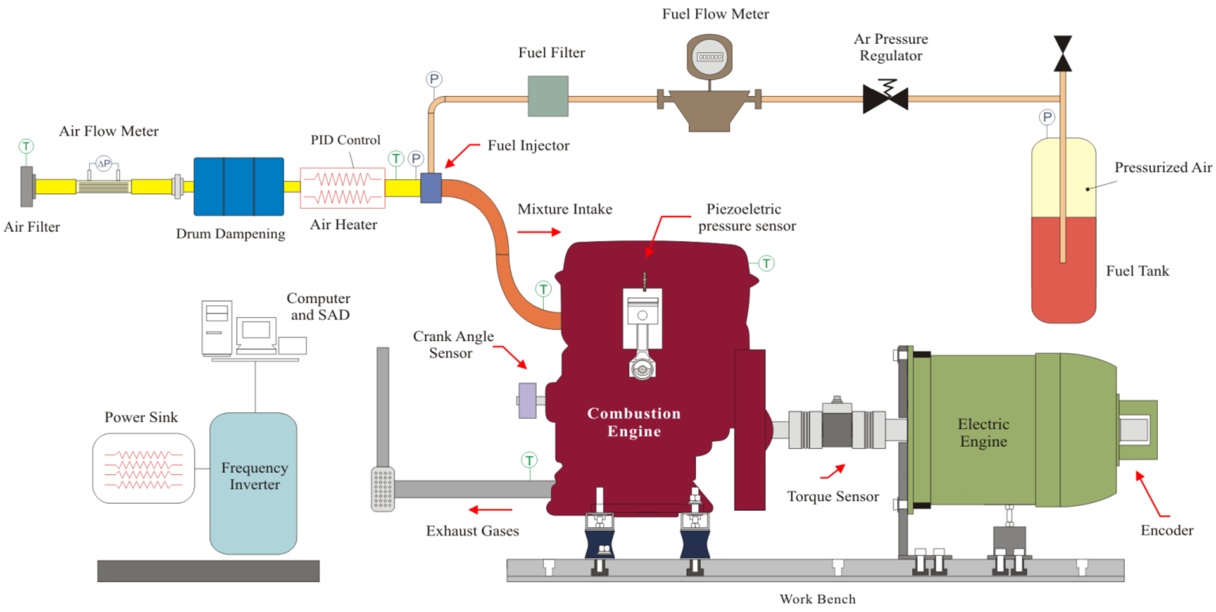

Fig. 1. Experimental device.

The start of the HCCI combustion is highly dependent on the intake temperature. Currently, it is accepted that HCCI combustion is dominated by the reaction rates of chemical kinetics [1, 3], where its influence is related to the characteristics of the mixture composition (air-fuel) and the historical record of temperature and pressure. If a completely homogeneous mixture exists at the time of combustion, turbulence has little direct effect on HCCI combustion, but it could have an indirect effect by altering the distribution of temperature inside the cylinder. Small differences in temperature inside of the cylinder have a considerable effect on combustion because the chemical kinetics are very sensitive to temperature. [1].

The engine has been evaluated at different RPM and loads on a test bench equipped with a 7.5 kW dynamometer and an in-line torque transducer HBM, model T22, for highly accurate measurement of brake power and specific fuel consumption (Fig. 1). The cylinder pressure was measured using Kistler piezoelectric sensor, model 6052C, which was coupled through a charge amplifier to the acquisition system to turn on the signal of the pressure in the cylinder. To measure the engine rotation an optical encoder HS35B series was installed on the dynamometer and used.

For the measurement of the pressures in the intake line and the fuel injector inlet Omegadyne pressure sensors were used. For the measurement of air and fuel mass flow, a laminar flow meter and Coriolis mass flow meter were used, respectively. To measure the temperature, K type thermocouples and a PT-100 sensor were used.

The engine has been evaluated according to the conditions in Table 2.

Table 2. Engine Test Conditions.

Property	Value
Engine Rotation	1200 RPM to 2100 RPM
Air-fuel ratio	2 - 4
Intake air temperature	348 K – 368 K
Charge air pressure	1 bar
Fuel pressure	2 bar
Engine oil temperature	60 °C
Engine temperature	100 °C
Fuel	Gasoline type C

RESULTS AND DISCUSSION

HCCI auto-ignition is basically influenced by the composition of the air-fuel mixture and the conditions of temperature and pressure during the combustion process. Small variations in temperature inside the cylinder can cause the presence of problems at the start of the ignition and therefore the development of the combustion itself.

The results are presented for important parameters in HCCI: the air-fuel ratio, the intake charge temperature (air-fuel), and the specific fuel consumption (SFC). The results are expressed in terms of its effect on the start and duration of HCCI combustion, the maximum cylinder pressure and the development of a combustion knock.

Air-fuel ratio

The air-fuel ratio is the parameter used to control the mixture ratio in the cylinder by varying the amount of fuel or air [7, 8]. For this study, the effect of the air-fuel ratio was investigated by varying only the injected fuel quantity and keeping constant the amount of air sucked into the engine for a given rotation.

Normally this air-fuel ratio is known as “lambda factor (λ)”, which is defined as the ratio of air-fuel mass flow to real conditions on the ratio of air-fuel mass flow for stoichiometric conditions. Several authors [1, 2, 9, 10] agree that the engines operating in HCCI mode usually work in the range of λ from 2 to 4.

Fig. 2 shows the variation of lambda (λ) with different rotations and for the three intake charge temperatures. It can be confirmed that on the tests performed on the engine, lambda values were within the range of 2 to 4, it can also be seen that as the intake charge temperature increases, the lambda values rise because increasing the temperature limits the amount of fuel that can be injected. On the other hand, as the intake temperature increases, the air density tends to decrease causing less air mass inlet in the engine and therefore less amount of fuel injected to burn with its corresponding air mass.

Very high intake temperatures will make the engine work with too lean mixtures of fuel which could originate failure in the start of the combustion and instability within the cylinder; on the other hand, using very low intake temperatures would not present a direct effect in the start of the ignition because low temperatures fail to reach necessary thermal conditions to develop the proper thermal environment for the start of HCCI auto-ignition [10].

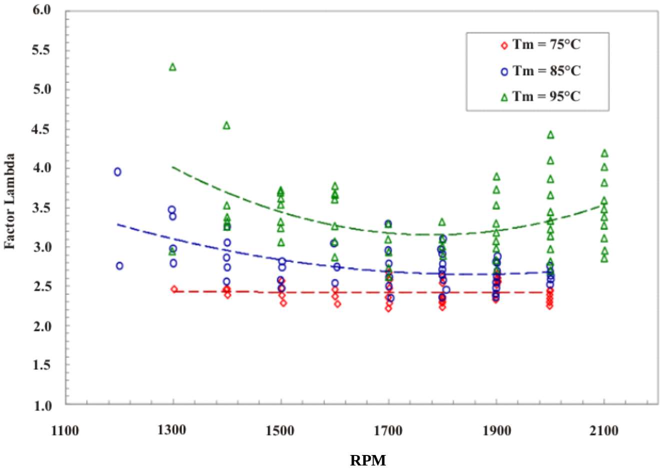

Fig. 2. Values of λ studied for different operating conditions (intake charge temperature and engine speed).

To examine the effect of lambda values in the HCCI combustion, the intake charge temperature was fixed. In this case the results for the intake charge temperature of 85°C are presented; this temperature was characterized during the tests because it was where the engine obtained the best results regarding the performance parameters (torque, brake power, fuel consumption, etc). Fig. 3 shows the variation of the cylinder internal pressure as a function of the interval of lambda values studied for a rotation of 1900 RPM; this rotation was also characterized by presenting the more stable pressure and torque values compared to other rotations. As observed in Fig. 3, as the amount of fuel injected (lower values of lambda) increases, the internal pressure curves tend to have higher values due to the increased fuel burning and consequently more useful work will be generated as can be corroborated by the values obtained from the mean effective pressure (MEP), thus, rising the amount of fuel, higher values of MEP are obtained.

Another effect presented in Fig. 3 is that when the amount of fuel increases the internal pressure curve tends to shift to the left because increasing the amount of fuel for a given intake temperature brings forward the start of HCCI ignition and therefore the start of combustion.

Another important feature concerning the effect of the air-fuel ratio in HCCI combustion as can be seen in Fig. 3 is the presence of a combustion knock. When working with low values of lambda (high amount of fuel injected), the pressure curves begin to have irregularities. In addition, this combustion knock is characterized by the presence of a high combustion noise, experimental bench instability and high variation in levels of torque; therefore, more fuel consumption.

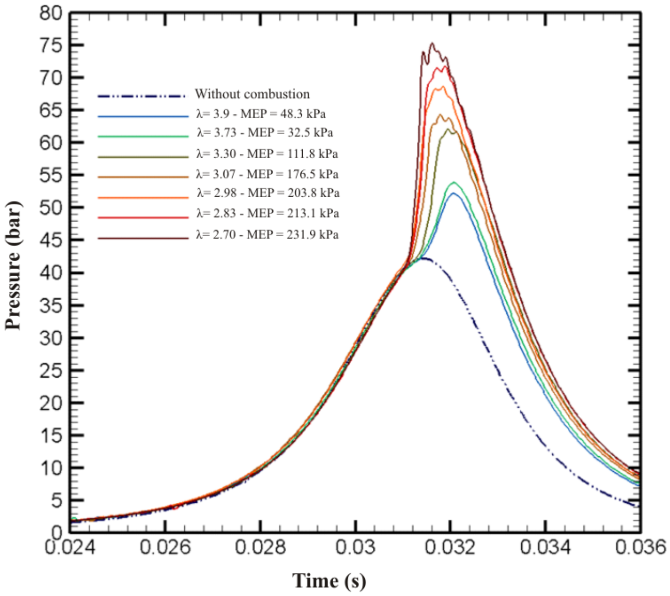

Fig. 3. Internal Pressure in function of time for different values of lambda for intake charge temperature of 85°C and a rotation of 1900 RPM.

On the other hand, for high values of lambda (low amounts of fuel injected), that is, lean fuel mixtures; ignition failure is presented as a problem for the development of HCCI combustion. When working with lean fuel mixtures, the engine cannot maintain the necessary conditions for the next cycle of operation, which can originate ignition failure or even the complete shutdown, which leads to higher fuel consumption.

Therefore, as can be noticed in Fig 3, for current operating conditions (intake charge temperature of 85°C, rotation of 1900 RPM) lambda values below 2.7 only originate a very knocking combustion that could severely damage the engine and lambda values above 4 don't develop a proper combustion; being this cases (knocking and failure ignition) defined as the limits of operation of the engine working in HCCI mode.

Intake Charge Temperature

The intake charge temperature is considered one of the most important factors affecting HCCI combustion because this type of combustion is dominated by auto-ignition chemical reactions, so the reaction system must have an appropriate temperature. Low temperatures will not lead to auto-ignition, while too high temperatures may result in knocking combustion. [10].

To examine the effect of the intake charge temperature on HCCI combustion, the initial pressure and the value of lambda factor were fixed at 100 kPa (1 bar) and 2.7 respectively, for a rotation of 1900 RPM. Fig. 4 shows the effect of the temperature on HCCI auto-ignition; the advance in the start of the ignition is achieved increasing the intake charge temperature. The influence of the intake temperature varies depending on its value, for the interval from 75°C to 85°C, it doesn't have a strong influence on the start of the combustion, reaching a maximum pressure variation of 500 kPa (5 bar); but for the interval from 85°C to 95°C, there is a greater influence on the start of the ignition, affecting significantly and displacing the pressure curve to the left which did not happen to the previous interval studied with a variation of around 1500 kPa (15 bar). On the other hand, the intake charge temperature also affects the development of a knocking combustion because when the intake temperature increases for a fixed value of lambda, the pressure curve increases notably and under certain conditions where the combustion takes place quickly, a rapid heat release occurs and originates high levels of pressure and temperature inside the cylinder which results in the explosion of the fuel. As a result, an unstable combustion can be observed at 95°C, it begins to show the effects of the knocking in the pressure curve followed by the acquisition of high levels of pressure.

Other important feature of the effect of the intake charge temperature is that when this temperature is below a certain value, the combustion process becomes incomplete which is represented by the instability of the combustion and variations of the pressure curves from cycle to cycle. As the intake temperature is increased, the duration of the combustion is slightly reduced. Higher values are displaying greater influence on the burning time, which directly affects the start of the combustion to those values where the internal conditions cause the occurrence of the phenomenon of knocking.

Specific fuel consumption

To find suitable conditions of temperature and amount of fuel to be injected allows the development of improved thermal conditions for the HCCI combustion, reflected in the increase of the thermal efficiency. Also the way the combustion is developed in respect to its stability and variations from cycle to cycle, is an indicator of how the main performance parameters are behaving. Fig. 5 shows the specific fuel consumption for the interval of rotations studied as a function of values of lambda for the intake charge temperature of 85°C. The best values are in the interval from 1700 to 1900 RPM that was the interval in which the best conversion of fuel into thermal energy for all values of lambda studied was obtained. For the other rotations, the specific consumption values were above which indicate that those areas are where HCCI operation is not well developed either because the system instability or the presence of an incomplete combustion which could be confirmed by the analysis of pressure curve.

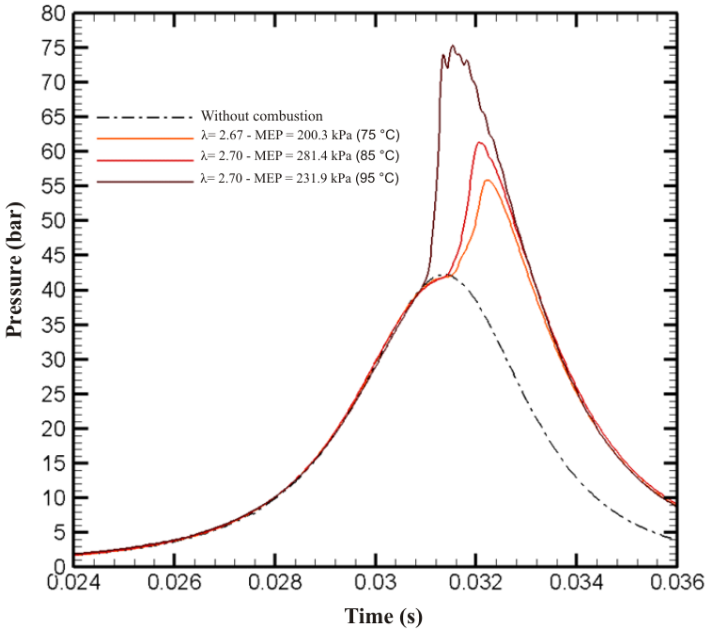

Fig. 4. Internal pressure in function of the time for different intake charge temperatures, λ = 2.7, 1900 RPM.

The minimum value achieved of specific consumption was about 228 g/kW·h that was approximately 12.3% lower than the value obtained from consumption when the engine operates in its original form (diesel mode); on the other side, the engine operating in HCCI mode was only able to generate a torque of 6 N·m, that was approximately 41% lower than in its original form which indicates that HCCI engines work with low concentrations of fuel compared to diesel engines and most of that fuel is converted into mechanical work because the entire air-fuel mixture participates in the combustion process almost simultaneously which leads to a rapid heat release and high thermal efficiencies, despite the fact of working with small amounts of fuel, that represents an economy in terms of costs.

An important feature of the process of HCCI operation is its restriction to operate only in partial rotations and loads. The engine speed has an effect on HCCI combustion, at low speeds the thermal conditions cannot be maintained, causing difficulty to start the ignition, since there are large heat losses through the cylinder walls due to the increased time available for the exchange of heat from the mixture (air-fuel) into the cylinder walls. On the other hand, at high speeds the combustion time is reduced and requires more fuel inlet to generate high temperatures inside the cylinder and higher levels of pressure, which causes instability in the ignition and presence of knocking combustion.

In Fig. 5, the rotation interval used for the analysis of HCCI operation can be observed. For low speeds and based on the pressure curves, values below the maximum permissible can be observed, in some cases presenting problems of variations from cycle to cycle and instability for the development of the combustion. In reference to the performance of specific consumption, it is observed that at low rotations for some values of lambda there is a good conversion of fuel into thermal energy but still above the optimal values for this parameter (260 g/kW·h) and this same tendency for high speeds is presented, where for some values of lambda a good fuel conversion is shown. For the interval from 1700 RPM to 1900 RPM the best results of specific consumption were observed since this interval is where the engine works more efficiently and gets a better fuel use.

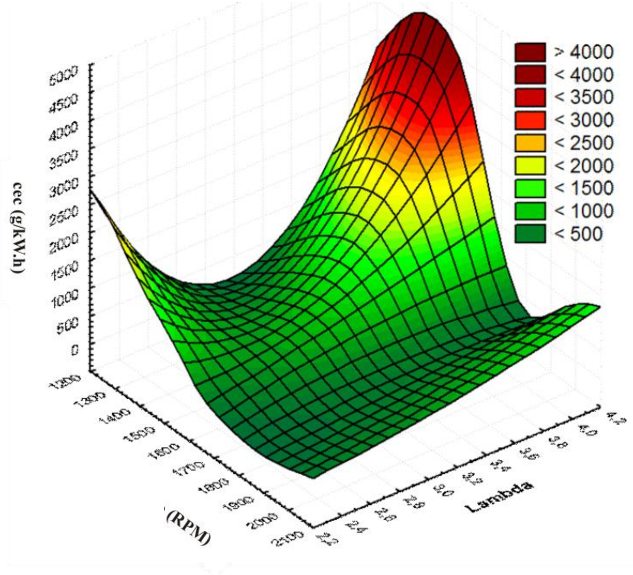

Fig. 5. Specific fuel consumption as a function of lambda and the speed engine for a intake charge temperature of 85°C.

CONCLUSIONS

Experiments in a single cylinder four-stroke single diesel engine have been performed to study the effects of operating conditions on the ignition and HCCI combustion. The intake charge temperature, the air-fuel ratio and the speed engine were varied and their influence on the auto-ignition process was analyzed.

The studies carried out showed that the HCCI combustion was characterized by its stable and rapid combustion process. The duration of combustion in an engine operating in HCCI mode was affected by all engine operating parameters investigated.

Both, the auto-ignition timing and the maximum pressure were very sensitive to all operating parameters investigated, among which the intake charge temperature had the greatest effect against the HCCI combustion timing and the maximum pressure levels generated. The air-fuel ratio (lambda factor) has a direct effect on HCCI combustion and the start of the combustion is brought forward when the lambda value is diminished. This has a negative effect on the engine performance because the pressure increases when this ratio is varied during the compression stroke.

Increasing progressively the intake charge temperature has a significant effect on the start of the combustion in HCCI mode and an effect of this parameter on the advance in the ignition stage, reaching in some cases the knocking combustion area, can be observed. The interval where HCCI engine operates is limited, applying only to certain rotations. Varying the amounts of fuel and temperature allows the increase of this operating range; this may involve a risk of reaching the detonation or an ignition failure.

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