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EXPLORING THE LIMITS OF LEAN BURNING PERFORMANCE IN A SINGLE CYLINDER RESEARCH ENGINE

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Abstract. *The demand for more efficient vehicles is growing worldwide. A promising technology is the Gasoline Direct Injection (GDI) engine combined with lean mixture (excess-air). An experimental investigation was performed to evaluate a GDI Single Cylinder Research Engine (SCRE) performance, fueled by a Brazilian premium gasoline in different air/fuel mixture conditions. Excess-air factor (λ) was set from 0.85 (rich mixtures) up to 1.50 (lean mixtures) in steps of 0.05, at engine full load and 4000 rpm. The engine spark timing was adjusted for Maximum Break Torque (MBT) condition or limited by knocking occurrence. Indicated Mean Effective Pressure, Indicated Specific Fuel Consumption, Mass Fraction Burned and Fuel Conversion Efficiency were obtained based on cylinder pressure and crankshaft position data. The combustion variability was analyzed from 200 recorded engine cycles for each operating condition. Results showed the use of lean mixtures can improve Indicated Specific Fuel Consumption, contributing to increase engine efficiency.*

Keywords: *lean burning, Brazilian premium gasoline, gasoline direct injection, single cylinder research engine.*

1. INTRODUCTION

Nowadays, most of the spark ignition engines are equipped with electronic management systems, in which the fuel injection can be realized by Port Fuel Injection (PFI) or Gasoline Direct Injection (GDI). In GDI system, gasoline is injected directly into the combustion chamber, while in PFI engines, fuel is introduced into intake valve ports. (Zhao, 2010; Baêta, 2006). GDI system can provide also higher fuel economy, especially together with downsizing and turbocharging (Zaccardi *et.al.*, 2009; De Bellis, 2016).

The improvement on consistent engine efficiency and engine performance working in lean burning conditions is investigated since 1908, but new researches are continuously developed to explore the advantages and minimize the drawbacks of this technology (Roso *et al*., 2019). Successful development of lean-burn Gasoline Direct Injection (GDI) engine technology is expected to enable 15% reduction in fuel consumption and CO_2 emissions in comparison to conventional gasoline engines with PFI systems (Spicher *et. al*, 1999; Zhao *et. al*., 1999; Harada *et. al*., 1997; Noguchi *et al*., 1976; van Basshuysen R., 2009).

In the literature, there are studies such as Roso, *et al*. (2019), Costa, *et al*. (2018) and Jung, *et al*. (2017), which are related to combustion process evaluation of lean mixtures under engine speeds from 1000 to 2250 rpm, representing the urban cycle of a passenger car. Bontorin and Oliveira (2016) also showed the lean mixtures could allow higher spark advance, improving the combustion process and engine efficiency.

A classical behavior of the excess-air factor (λ) effects on Power (P) and Specific Fuel Consumption is described in Heywood (1988), and indicates the lean mixtures correspond to smaller ISFC up to a specific point. In the present work, a SCRE under GDI configuration was used to investigate the effects on Power and in the ISFC of excess-air factor (λ), swept from 0.85 up to 1.50, using a Brazilian premium gasoline, which has 25% v/v ± 1% of anhydrous ethanol and minimum Anti Knock Index (AKI) of 91 (MAPA, 2015; ANP, 2013). A similar diagram of the Heywood (1988) was experimentally generated for the Brazilian premium gasoline, exploring the limits of engine operation using this type of fuel.

2. METHODOLOGY

The SCRE used in this work, Figure 1, is equipped with in-cylinder pressure transducer and combustion analyzer system, whose allows the evaluation of different parameters during the combustion process. Indicated Specific Fuel Consumption (ISFC), Indicated Mean Effective Pressure (IMEP), combustion stability, defined as IMEP covariance (COV IMEP), Fuel Conversion Efficiency (η_{cc}), crankshaft position corresponding to 50% of air/fuel mass fraction burned (MFB50) and spark timing ignition were evaluated. ISFC is calculated based on mass fuel flow (m_f) and indicated effective power (P_{ef}) according to Eq. (1) (Heywood, 1988).

$$ISFC = \frac{m_f}{P_{ef}} \tag{1}$$

The Fuel Conversion Efficiency (η_{cc}) considers the actual work performed as a function of the energy supplied through the fuel (Heywood, 1988). The η_{cc}, calculated using Eq. (2), is based on ISFC and the fuel Lower Heating Value (LHV).

$$\eta_{cc} = \frac{1}{ISFC * LHV} \tag{2}$$

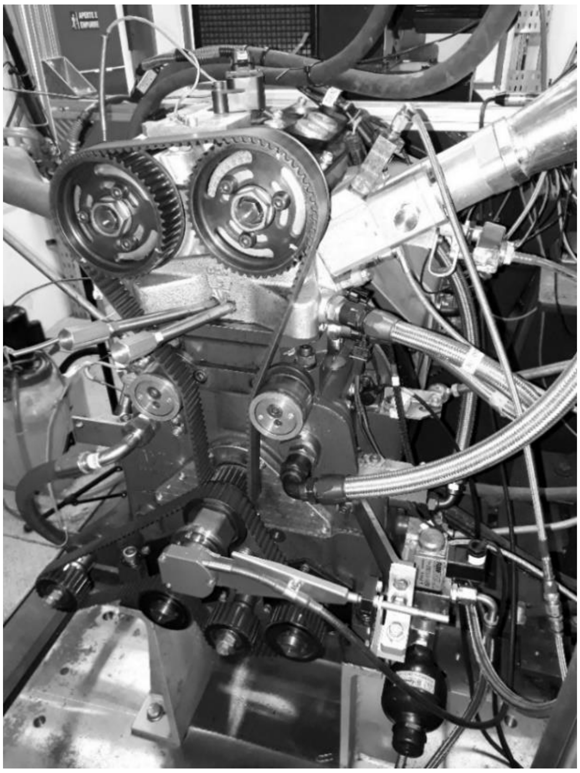

Figure 1. Single Cylinder Research Engine of UFMG.

The spark timing ignition adjustment provides the time required for the combustion to start and contribute to maximize the production of work by the piston during the expansion stroke (Ayala et al., 2006). Usually, the MFB50, set in the region from 8 to 10° CA ATDC (Crankshaft Angle After Top Dead Center) is used to optimize the spark timing at Maximum Brake Torque (MBT) condition (Klimstra J., 1985). These parameters were used to evaluate the influence of excess-air factor (λ) from rich to lean conditions in the GDI engine fueled by a Brazilian commercial premium gasoline.

2.1 Fuel selection

A Brazilian premium gasoline sample was characterized by physical chemical properties based on International ASTM and Brazilian NBR standards. The main properties are shown on Table 1.

Table 1. Brazilian premium gasoline properties

Fuel Properties	**Value**	**Analytical method**
Ethanol v/v (%)	26.2	NBR 13992
Density 20°C (kg/m^3)	763.4	ASTM D4052
Reid Vapor Pressure (kPa)	53.5	ASTM D5191
MON	91	ASTM D2700
RON	101	ASTM D2699
Lower Heating Value (MJ/kg)	38.54	ASTM D4809
Stoichiometric air/fuel ratio	12.9:1	-

2.2 Test bed characteristics

The engine test bed is composed by a dynamometer AVL DynoDur 160 (160 kW, 400 Nm and 10000 rpm). All tests were based on NBR ISO 1585 standard (ABNT, 1996). Engine water coolant, lubricant oil temperature and pressure were controlled by AVL 577 unit. Engine water and oil temperatures were set at 80 ^{o}C and 90 ^{o}C, respectively. Fuel mass flow measurement and temperature control were performed by AVL 733S (Fuel mass flow meter) and AVL 753C (Fuel temperature control). Fuel temperature was set at 20 ^{o}C to avoid light hydrocarbon evaporation. A Gasoline Direct Injection Fuel Pump was driven externally and set at 100 bar.

2.3 Single Cylinder Research Engine (SCRE) and experimental tests characteristics

The SCRE was tested at 4000 rpm and full load (WOT – wide open throttle), varying lambda from 0.85 to 1.50. The Electronic Control Unit (ECU), model AVL 427, was also used to control fuel injection and ignition timing parameters. An angle encoder (AVL 365C) was used to determine crankshaft angle (°CA) to run and synchronized engine events and data acquisition system.

The initial spark timing was set at 20° BTDC (Before Top Dead Center) and spark timing adjustment procedure was performed from this angle until MBT condition or knocking phenomena occurrence. These phenomena were observed through the in-cylinder pressure oscillation curve during the tests by AVL IndiCom Software and AVL Concerto for post processing data. The Knock Frequency (KF) were also considered as a combustion parameter indicator (normal or not). In cases of knocking occurrence event greater than 5% in a 100-cycle window measurement, KF parameter mean an abnormal combustion condition and spark timing ignition was reduced by 2 degrees. This condition was considered as Lower Detonation Limit (LDI).

In-cylinder pressure is measured with crankshaft angle interval of 0.1 °CA using an AVL IndiModul 622. Three piezo-electric transducers were used to measure the intake port instantaneous pressure (AVL-LP11DA), in-cylinder pressure (AVL-GU22CK) and exhaust port instantaneous pressure (AVL-GU21C). Lambda was determined by oxygen concentration in exhaust manifold, measured by Bosch LSU 4.2 wide-band sensor. The data were acquired in steps of 60 seconds during 200 cycles. This acquisition was made one minute after stabilization of operating conditions. SCRE calibration was performed according to Figure 2. Table 2 shows the operating conditions of the SCRE defined as reference for the experimental tests.

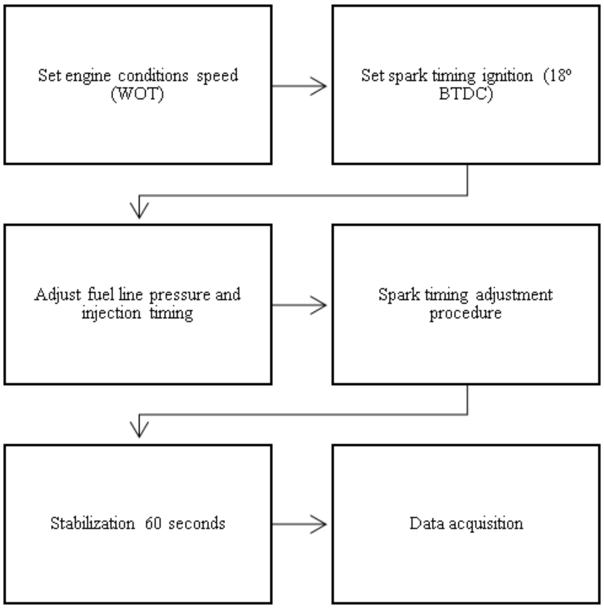

Figure 2. Diagram of SCRE calibration process.

Table 2. Single Cylinder Research Engine operating conditions.

Volumetric Compression Ratio	12:1
Injection System	Gasoline Direct Injection - GDI
Injection Pressure	80 bar
Engine speed	4000 rpm
Engine Load	WOT
Excess-air factor (λ)	From 0.85 up to 1.50 in steps of 0.05
Mixture formation	Homogeneous (Single Squirt)
Coolant and oil temperatures	80ºC / 90°C
Fuel temperature	20°C
Intake valve opening /exhaust valve closing	0° | 0°

3. RESULTS AND DISCUSSION

The SCRE performance results operating with commercial Brazilian premium gasoline at 4000 rpm and WOT are presented and discussed in this section. For all lambda conditions it was possible to reach MBT. It was necessary to adjust the spark timing to provide a compensation for combustion rate reductions observed when lambda is increased to lean burn conditions.

Analysis of variance (ANOVA) was performed to identify similar statistical results of the engine performance at the different conditions tested. According to CALADO *et al*. (2003), ANOVA uses multiple comparison methods, which reduce the overall confidence interval. Statistical analysis adopted significance level of 95%.

Figure 3 presents the results of Indicated Specific Fuel Consumption (ISFC) and Net Indicated Mean Effective Pressure (NIMEP), as a function of lambda.

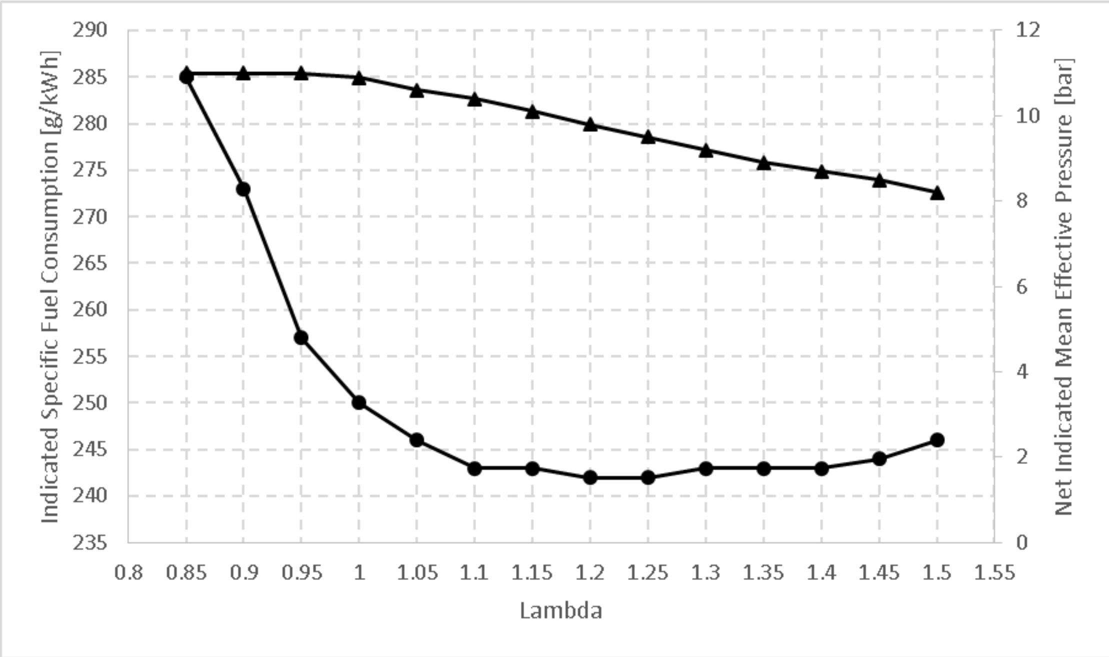

Figure 3. ISFC (●) and NIMEP (▲) at different excess-air factor (Lambda).

When the combustion process occurs under rich mixture conditions (lambda < 1.00), the NIMEP reaches the maximum values of 11.0 bar approximately, but the ISFC increase 14%, from 250 g/kW.h at stoichiometric condition (lambda = 1.00) to 285 g/kW.h at lambda 0.85.

On the other hand, if the combustion process occurs under lean mixture conditions (lambda > 1.00) the NIMEP decreases continuously until the minimum value of 8.2 bar at lambda = 1.50 (reduction of 24.4%). In the lean region, ISFC reaches a minimum value of 242 g/kW.h at lambda 1.20 and start to increase again up to 246 g/kW.h at lambda 1.50. Other important parameter is the combustion quality (stability) measured by the covariance of the IMEP (COV IMEP) as a function of lambda, presented in Figure 4.

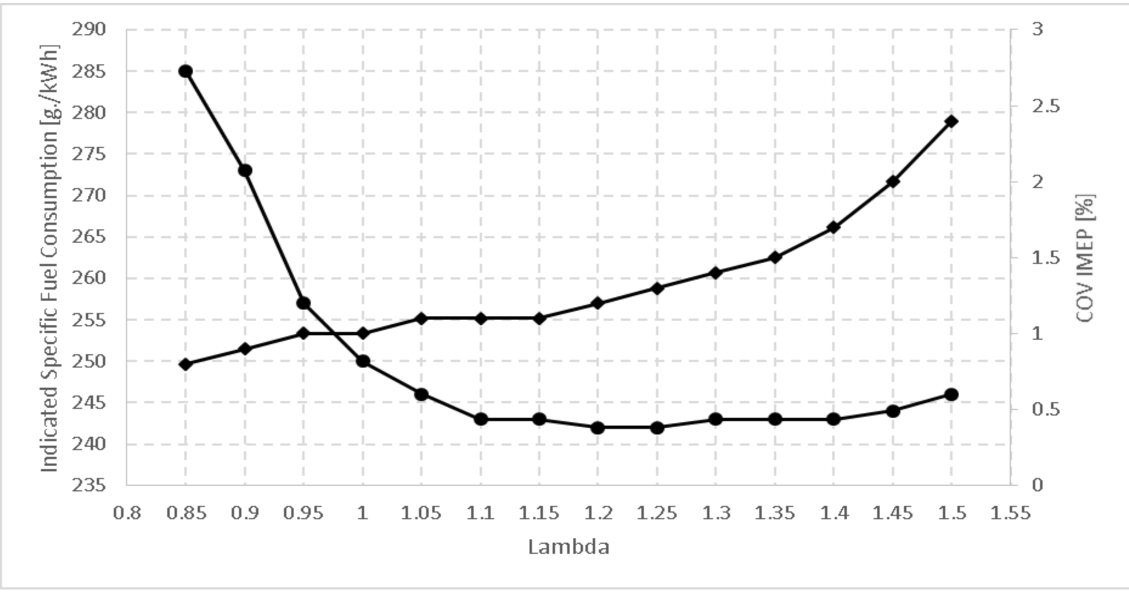

Figure 4. ISFC (●) and COV IMEP (♦) at different excess-air factor (Lambda).

Figure 4 shows the covariance of IMEP increases from 1.0% at lambda 1.00 up to 1.52% at lambda 1.40. Despite this increase, the COV IMEP was below 2.0%, which indicates reasonable combustion stability up to lambda 1.45. According to the literature, COV IMEP higher than 2% may cause vehicle drivability problems (Binjuwair *et al*., 2016). Only for lambdas 1.45 and 1.50 this parameter became higher than 2.0%, indicating the combustion became more unstable, and presenting more probability to misfire. The Brazilian premium gasoline presented excellent combustion stability even when using lambda near 1.45, which represents a large range of operation. This may be related to the 25% v/v of ethanol content in the Brazilian gasoline and its positive influence to increase the flame propagation speed.

The fuel energy, described by the Lower Heating Value (LHV), is used to calculate Fuel Conversion Efficiency (η_{cc}) according to Eq. (2). The η_{cc} behavior at different lambda values is presented in Figure 5. When lambda is varied from rich to lean mixture conditions (from lambda 0.85 to 1.50) the η_{cc} starts at 33% and reach a maximum value of 38.2 % with lambda 1.20, dropping to 38% with lambda 1.50.

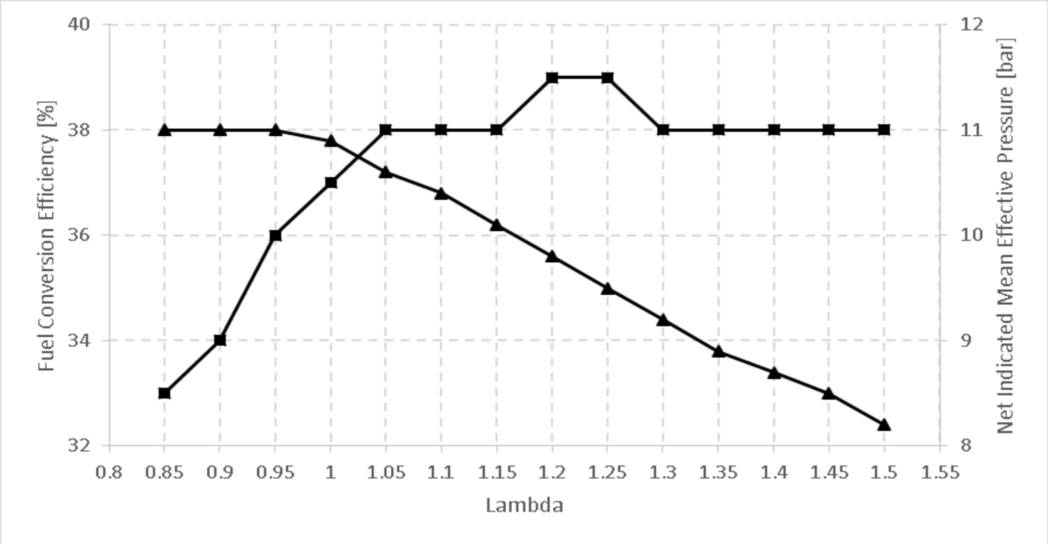

Figure 5. Fuel Conversion Efficiency (■) and NIMEP (▲) at different excess-air factor (Lambda).

The behavior of the engine spark timing adjustment and combustion phase can be seen in Figure 6. It can be noted a positive linear correlation of this parameter as a function of lambda (higher absolute values states for more advanced spark timings in relation to TDC). Due to the reduction of the combustion rate with leaner mixtures (lambda higher than 1.00), it was necessary to advance the spark timing to keep the MFB50 at approximately 8º BTDC and calibrate the combustion phase at MBT condition. The Brazilian premium gasoline presented an excellent behavior, allowing calibration at MBT condition even for lambda 1.50. This can be related to its high-octane rating (Table 2) and 25% v/v of ethanol content, which has positive influence on increasing the flame propagation speed.

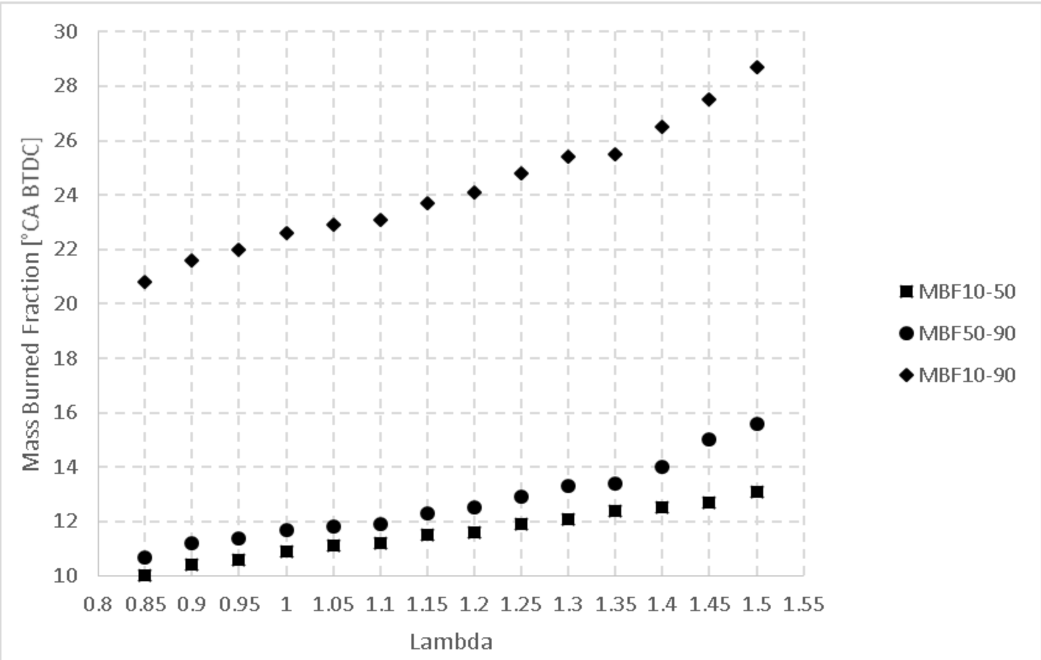

Figure 6. Spark timing ignition at MBT and MFB50 at different excess-air factor (Lambda).

4. CONCLUSIONS

In this work the performance of a Single Cylinder Research Engine at 4000 rpm and WOT, using a Brazilian premium gasoline varying the air-fuel mixture from rich to lean conditions (lambda from 0.85 to 1.50) was investigated. The spark timing was set for MBT for each mixture condition.

The enrichment of the mixture using lambda lower than 1.00 did not provide an effective increasing on indicated work produced by the engine, at the same time caused a progressive reduction in fuel conversion efficiency. As the lambda increases, it was verified a direct impact on the reduction of indicated torque, but with a reduction of indicated specific fuel consumption and increased fuel conversion efficiency. These effects were verified mainly in the region near lambda 1.20, which presented the best combustion efficiency. Leaner mixtures with lambda smaller than 1.20, caused an increased indicated fuel specific consumption, with lower fuel conversion efficiency. This reduction is related to lower combustion rate, and lower flame speed. This lower turbulent flame propagation velocity requires increasing the spark advance to set the engine at MBT.

The results for the engine operating with lean mixtures confirmed this condition as an effective strategy to reduce fuel consumption and improve engine efficiency. Nevertheless, the magnitude of lambda shall be assessed, as for lambda greater than 1.20, the efficiency decreases. The combustion stability is another important parameter to be monitored, once it is reduced as the mixture becomes leaner.

The Brazilian premium gasoline presented excellent combustion stability, with a COV IMEP lower than 2.0% even when using lambda near 1.45, which represents a large range of operation. This may be related to the octane rating (RON 101) and the ethanol content in the Brazilian gasoline and its positive influence on increasing the flame propagation speed.

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