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## STUDY OF KNOCK OCCURRENCE OF ISOOCTANE AND N-HEPTANE BLENDS IN AN ADAPTED CFR ENGINE

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**Abstract.** This paper presents the results of an experimental knock investigation performed in an adapted CFR (Cooperative Fuel Research) engine. The tests were performed applying Isooctane (I) and n-Heptane (H) blends at the volumetric percentages: 1100H0, 180H20, 160H40, 140H60, 120H80 and 10H100. Each blend was evaluated at different ranges of compression ratio and spark timing. The range depends on the engine operation limits that are established by the knock limit for each fuel. The combustion chamber pressure was measured in bench tests and the knock frequencies were calculated from the pressure signal. Using a band pass filter, the knock pressure oscillation was detected and a knock factor was calculated by both, the Stochastic Knock Detection (SKD) and the Knock Intensity (KI) methods. For each fuel blend and compression ratio, the spark timing was increased until achieve audible knock condition. For each condition, the combustion chamber pressure was measured for 200 consecutive cycles. The results showed that the SKD method was more effective to quantify the knock intensity, as it simultaneously considers the intensity in each cycle and the knock recurrence over the cycles.

**Keywords:** Knock, Isooctane, n-Heptane, CFR, SKD

### 1. INTRODUCTION

Even with the trend towards vehicles electrification, the use of internal combustion engines in large scale tends to last for many years. The efforts to improve their efficiency are still important to reduce emissions of harmful gases to the environment and to meet the current and future environmental legislation. However, one of the main limitations of the increased efficiency of spark ignition engines is the knock.

Knock is a phenomenon with high potential of damage for the internal combustion engines and one of the main barriers to improve the thermal efficiency because it restrains the compression ratio rise with optimum phasing combustion. The knock is created due to a pressure wave originated from a local pressure rise, caused by the auto-ignition of the unburned mixture fraction inside the cylinder. After created, the pressure wave starts to travel through the combustion chamber at the local speed of sound reflecting on the cylinder walls and promoting oscillations in the chamber pressure. Under specific conditions, the oscillations amplitude is very high and produces a metallic noise that spreads through the engine structure. This noise sounds like a metallic knock, that originates the name of the phenomenon. This is a harmful phenomenon to the engine components, which can cause damages that make its operation unfeasible. The understanding of the conditions that lead to the occurrence of this phenomenon and the strategies to mitigate it are important to improve the development of internal combustion engines.

There is a standard test to measure the tendency of fuels to knock in which they are classified by their octane index. The higher octane index, the greater resistance of the fuel to auto-ignition and, consequently, to knock. The test of the fuel octane index is performed in a standard engine called CFR (Cooperative Fuel Research), in which the constructive characteristics allows the easy variation of the compression ratio, by a hand crank. There are two methods for performing this test: the Motor Octane Number - MON (ASTM/D2700, 2017) and the Research Octane Number - RON (ASTM/D2699, 2017). The n-heptane and isooctane are the fuels used in the aforementioned methods and, they are the reference fuels of low resistance to knock and high resistance to knock, respectively.

Usually, the knock can be identified according to the knock intensity (KI) in the combustion cycles. It is possible to define that an engine is under knock condition when a certain number of cycles (10%, for example) registers a combustion pressure oscillation above an established threshold (1 bar, for example). However, this method is unable to effectively identify both, the intensity and recurrence of the knock, since we can have 10% of heavy or light knock cycles (Tie Li et al., 2017). A method that quantifies the intensity in each of the cycle is the Stochastic Knock Detection (SKD) where a Knock Factor (KF) can be calculated.

Therefore, the aim of this study is to calculate and to compare the Knock Intensity (KI) and the Knock Factor (KF) generated in the isooctane and n-heptane blends combustion. This study was carried out in a CFR engine and the fuels used were isooctane (I), n-heptane (H) and their mixtures in volumetric proportions of I100H0, I80H20, I60H40, I40H60, I20H80 and I0H100, under different compression ratios. In each compression ratio, the spark timing was gradually advanced until the audible knock occurred.

## 2. METHODOLOGY

### 2.1 CFR engine adaptations and instrumentation

The CFR engine used in this work is shown in the Fig. 1. It was adapted to a better fuel injection and spark timing control, as explained next.



Figure 1. The CFR engine adapted to the tests.

The main CFR engine parameters after the modifications are shown in Tab. 1.

Table 1. CFR Engine Parameters.

Parameter	Value
Number of Cylinder	Single cylinder
Bore (mm)	82.55
Stroke (mm)	114.30
Displaced Volume (cm <sup>3</sup> )	611,30
Connecting-rod length (mm)	243
Compression ratio	From 4 to 18
Intake Valve Open	12° ATDC <sup>(1)</sup>
Intake Valve Close	197° ATDC <sup>(1)</sup>
Exhaust Valve Open	500° ATDC <sup>(1)</sup>
Exhaust Valve Close	720° ATDC <sup>(1)</sup>
Injector	PFI

<sup>(1)</sup> After Top Dead Center

The original fuel system with a multiple fuel tank, a single jet passage and a carburetor venturi was replaced by an intake pipe and a port fuel injector (Bosch-0309060311), as shown in the Fig. 2.

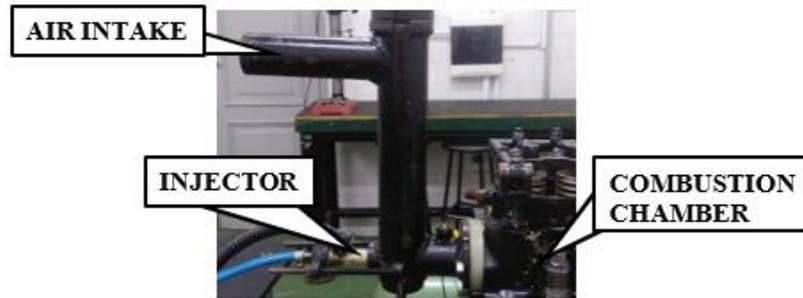


Figure 2. The intake pipe and the port fuel injector adaptations.

The spark plug used in the tests was an NGK - CPR8EA-9. The fuel injection and spark timing were controlled by an Electronic Control Unit (FuelTech™ FT300). A wideband oxygen sensor in the exhaust pipe was used to indicate the excess air factor ( $\lambda$ ). An Optrand™ D32294-Q pressure sensor was inserted in the engine combustion chamber to measure the cylinder pressure. This sensor can measure until 200 bar and a frequency band ranging from 0.1 Hz to 20 kHz. The fuel consumption was measured by a load cell. An encoder with 3600 pulses per revolution was fixed in the crankshaft to provide the engine angular position. The data were acquired by a National Instruments™ PCI-6221 device. Figure 3 shows the experimental setup schematic representation.

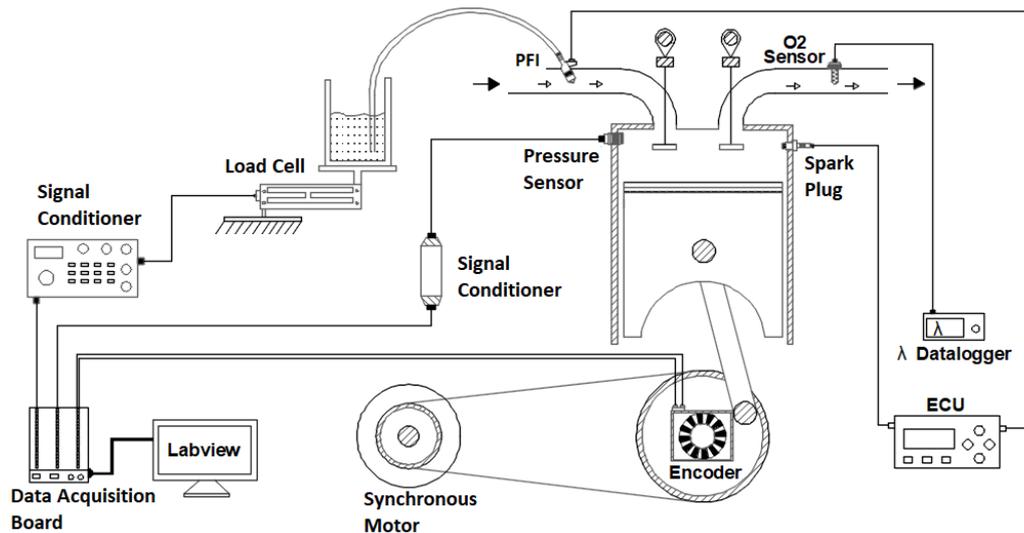


Figure 3. Experimental setup schematic representation.

The CFR engine is coupled by a belt with a synchronous motor that works at constant speed because it can work as a motor in some moments (in start condition, for example), or as a brake in others moments (at engine full load, for example). The original synchronous motor was designed to work electrically at 50 Hz and two different pulleys were made to connect it to the CFR, allowing the engine to work at 600 rpm or 900 rpm. The larger pulley (900 rpm) was used, however, in Brazil due to the electric power worked at 60Hz, the CFR speed increased to 1080 rpm. Thus, the engine test condition was the constant speed of 1080 rpm.

## 2.2 Experimental conditions

The tests were performed to the fuel blends I100H0, I80H20, I60H40, I40H60, I20H80 and I0H100, where “I” stands for Isooctane, “H” stands for n-Heptane and the number after the letter is the volumetric percentile of each fuel. The tests were performed to several compression ratio and spark timing to achieve the spark timing to knock occurrence in each fuel blend. As it was not possible to achieve the same compression ratio to all fuel blends, the methodology summarized below was adopted:

- For each fuel blend was found the maximum and minimum compression ratio to knock occurrence;
- For each compression ratio was found the spark timing to knock occurrence;
- It was performed a data acquisition (200 cycles) for a range of spark timing around the knock spark timing;
- The spark timing advance in each compression ratio was limited by the audible knock occurrence.

Table 2 shows the conditions that were possible to be tested following the methodology described above.

Table 2. Test conditions.

Blend	Compression Ratio	Spark Timing (°BTDC)
I100H0	8	40,42,44,46,47
	10	20,22,24,25,26
	12	12,14,15,16,17
	14	6,8,10,11
	16	2,4,5,6
I80H20	6	36,38,40,42,43,44,45
	8	14,16,18,19,20
	10	0,1,2,2.5,3
I60H40	5	42,44,46,47,48
	6	22,24,26,27,28
	8	0,2,4,5,6
I40H60	4	44,46,48
	6	17,18,20,21
	7	6,7,8,9,10,11
I20H80	4	44,46,48
	5	18,24,26,28,29,30
	6	12,14,16,18,19
	7	-2,0
I0H100	4	34,36,38,39,40
	5	18,20,22,24,25,26
	6	10,12,14,15,16

### 2.3 Data Analysis - Knock Factor

Applying a Fast Fourier Transform to combustion chamber pressure trace (Fig. 4-(a)), it was observed that the frequencies associated with the knock occurrence were 6 kHz, 10 kHz and 13.5 kHz, as shown in Fig. 4-(b).

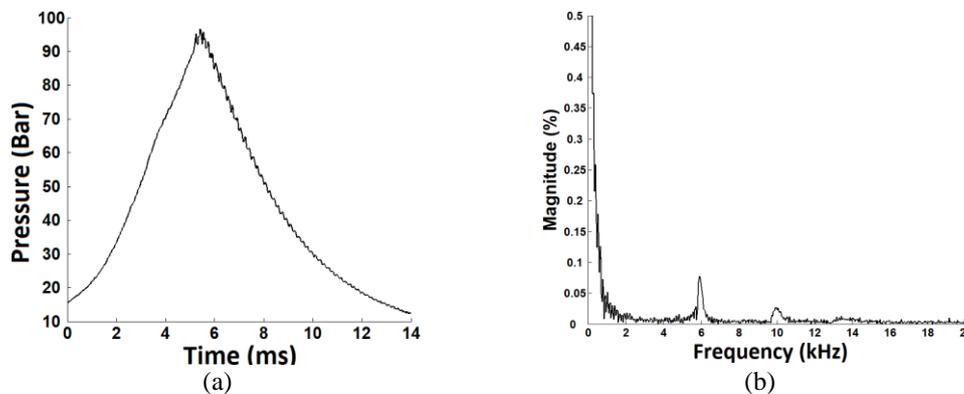


Figure 4: (a) Time-domain pressure cycles and (b) frequency spectrum with knock occurrence.

Using a band pass filter from 4 kHz to 14 kHz, these frequencies are extracted from the pressure signal and the result is the amplitude of the pressure oscillation caused by the knock phenomena, as shown in Fig. 5. This amplitude was defined as MAPO (Maximum Amplitude of Pressure Oscillation).

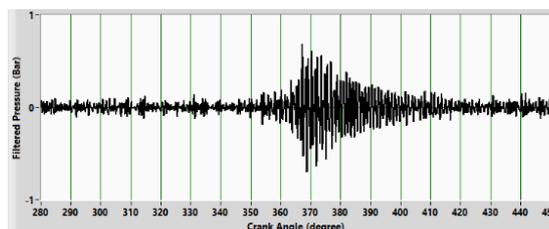


Figure 5: Pressure signal for the combustion chamber filtered in the range from 4 kHz to 14 kHz.

The knock severity was calculated using the Stochastic Knock Detection (SKD). In this method both, knock intensity in each cycle and frequency of occurrence, are considered in the calculation. McKenzie et al., 2016, noticed that the Maximum Amplitude of Pressure Oscillation around the knock occurrence has a probability log-normal distribution, represented by Eq. (1):

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{\left(\frac{-(\ln(x)-\mu)^2}{2\sigma^2}\right)} \quad (1)$$

where  $\mu$  is the logarithmic mean, represented by Eq. (2):

$$\mu = \frac{1}{n} \sum_{j=1}^n \ln(x_j) \quad (2)$$

and  $\sigma$  is the standard deviation logarithmic, represented by Eq. (3):

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{j=1}^n (\ln(x_j) - \mu)^2} \quad (3)$$

A log-normal distribution of the MAPOS for the test points with the compression ratio 14 and the 10° BTDC and 11° BTDC spark timing are shown in the Fig. 6-(a).

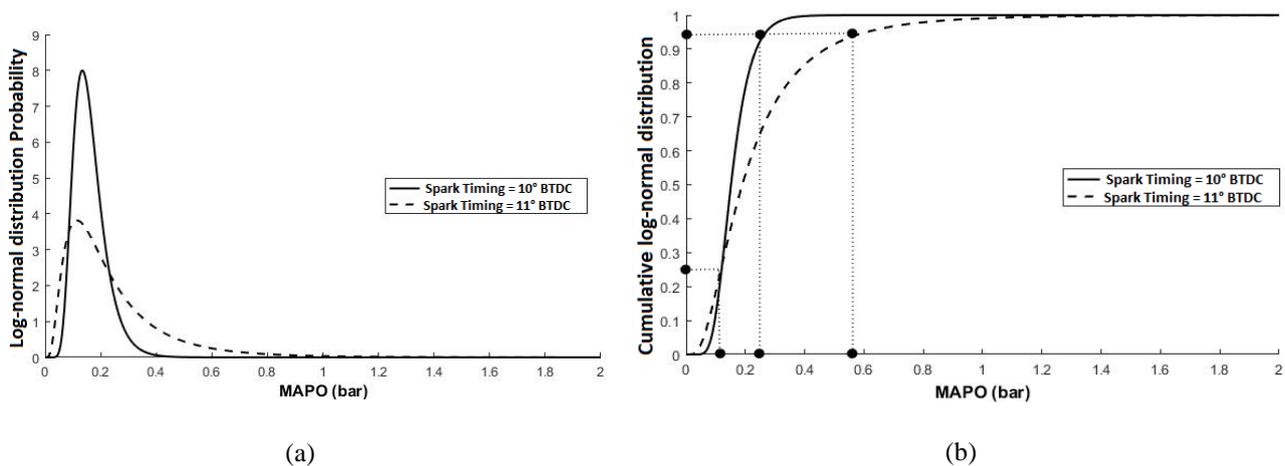


Figure 6: (a) Probability curves following the MAPOS log-normal distribution and (b) accumulated log-normal distribution of MAPOS.

From Eq. (1), a cumulative log-normal distribution (Figure 6-(b)) can be calculated by Eq. (4):

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^x \frac{1}{t} e^{\left(\frac{-(\ln(t)-\mu)^2}{2\sigma^2}\right)} dt \quad (4)$$

The knock factor is defined by the ratio of the MAPO 95% and 25%, according to Eq. (5):

$$FK = \frac{MAPO(0.95)}{MAPO(0.25)} \quad (5)$$

### 3. RESULTS

During the experiments, the audible knock identification was the parameter used to stop the spark time advancing. It was observed that, for some compression ratio and specific fuel mixtures, the spark timing for the start of the knock occurrence was very evident due to a high pressure oscillation amplitude. Under other conditions, it was not possible to clearly identify the severity of the knock just by hearing, as the noise characteristic of this phenomenon was confused with the inherent engine operation noise. In this case, the pressure oscillation amplitude is low, although the knock recurrence is high. Even to this last case, the knock can damage the engine due to its high recurrence.

Figure 7 shows the distribution of MAPOs over the 200 cycles acquired for the pure isooctane fuel (I100H0) at compression ratio 16 and at ignition timings  $2^\circ$ ,  $4^\circ$ ,  $5^\circ$  and  $6^\circ$  BTDC. Figure 8 shows the distribution of MAPOs over 200 cycles for the fuel containing 80% of isooctane (I80H20) at compression ratio 8 and ignition timings  $16^\circ$ ,  $18^\circ$ ,  $19^\circ$  and  $20^\circ$  BTDC. It is observed in the first case (Fig. 7) that for the ignition timings  $2^\circ$ ,  $4^\circ$  and  $5^\circ$  BTDC, the MAPO is close to zero for almost all cycles, i.e., there are few cycles with combustion chamber pressure oscillation. When the ignition timing advances to  $6^\circ$  BTDC, high pressure fluctuations occur in several cycles. In some of them, the amplitude of the oscillation exceeds the value of 10 bar. This is a test condition where the occurrence of the audible knock is clearly noticeable and, consequently, it is the ignition timing limit to this compression ratio.

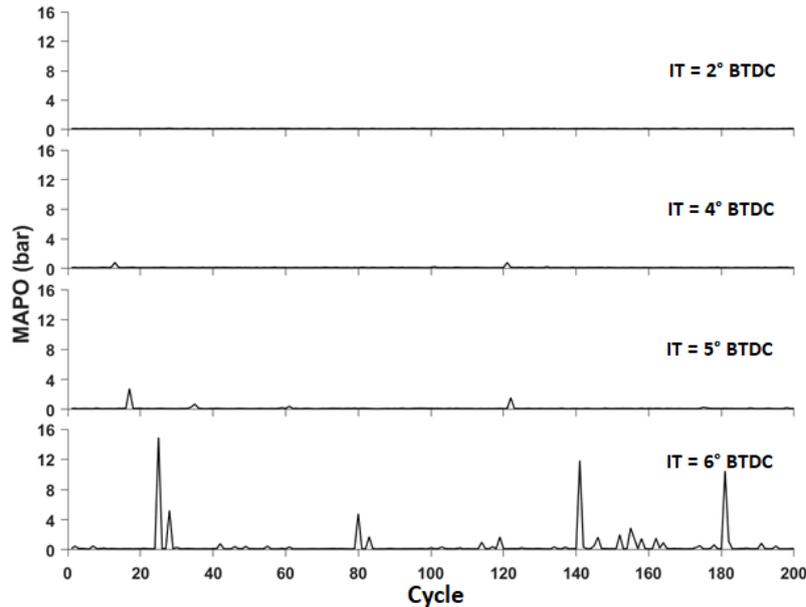


Figure 7: MAPOs distribution over the 200 cycles acquired. Fuel = Isooctane (I100H0); CR = 16

In Fig. 8, it can be seen that for the  $16^\circ$  BTDC ignition timing, almost all cycles show no combustion chamber pressure oscillation. As for the  $18^\circ$  and  $19^\circ$  BTDC ignition timings, pressure oscillation occurs in several cycles, however with low intensities. In these two points, the occurrence of the audible knock is not clear because the noise produced by these low-pressure fluctuations can be confused with the natural noise of the engine running. It is also observed that, when advancing the ignition timing to  $20^\circ$  BTDC, the occurrence of knock becomes more frequent. Although the intensities are still lower than the  $6^\circ$  BTDC ignition timing condition of the Fig. 7, in this case the audible knock could be identified due to the recurrence, hence, it was also the limit ignition timing advance in this operating condition.

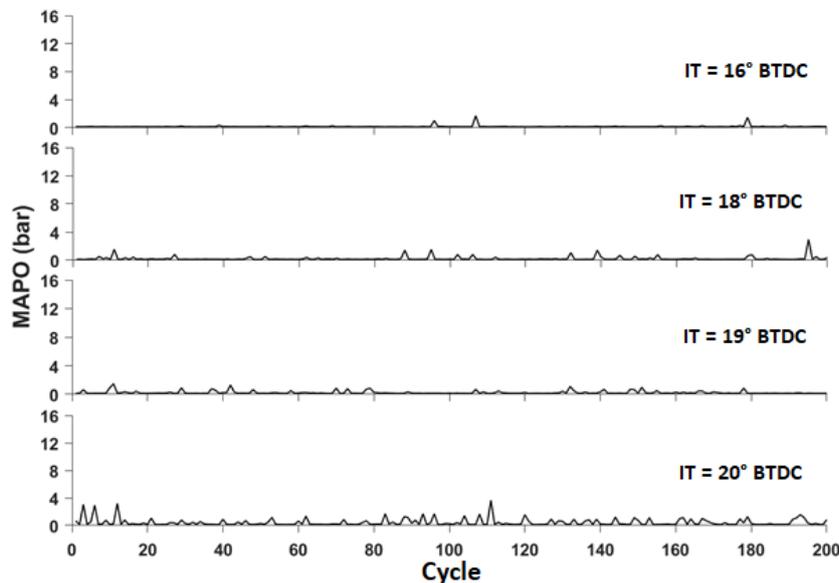


Figure 8: MAPOs distribution over the 200 cycles acquired. Fuel = I80H20; CR = 8

In addition, the MAPO value of 0.5 bar was arbitrarily chosen as a reference to quantify the number of cycles that exceeded this limit at each operating point. According to the results presented in Fig. 9, for the fuel blend I100H0, in the compression ratio 16 and ignition timing 6° BTDC, 11% of the cycles exceeded the prescribed limit of 0.5 bar. For the fuel blend I80H20, at compression ratio 8 and ignition timing 20° BTDC, 25% of cycles exceeded the limit of 0.5 bar. The points identified by the arrows are audible knock points, clearly identified during the tests.

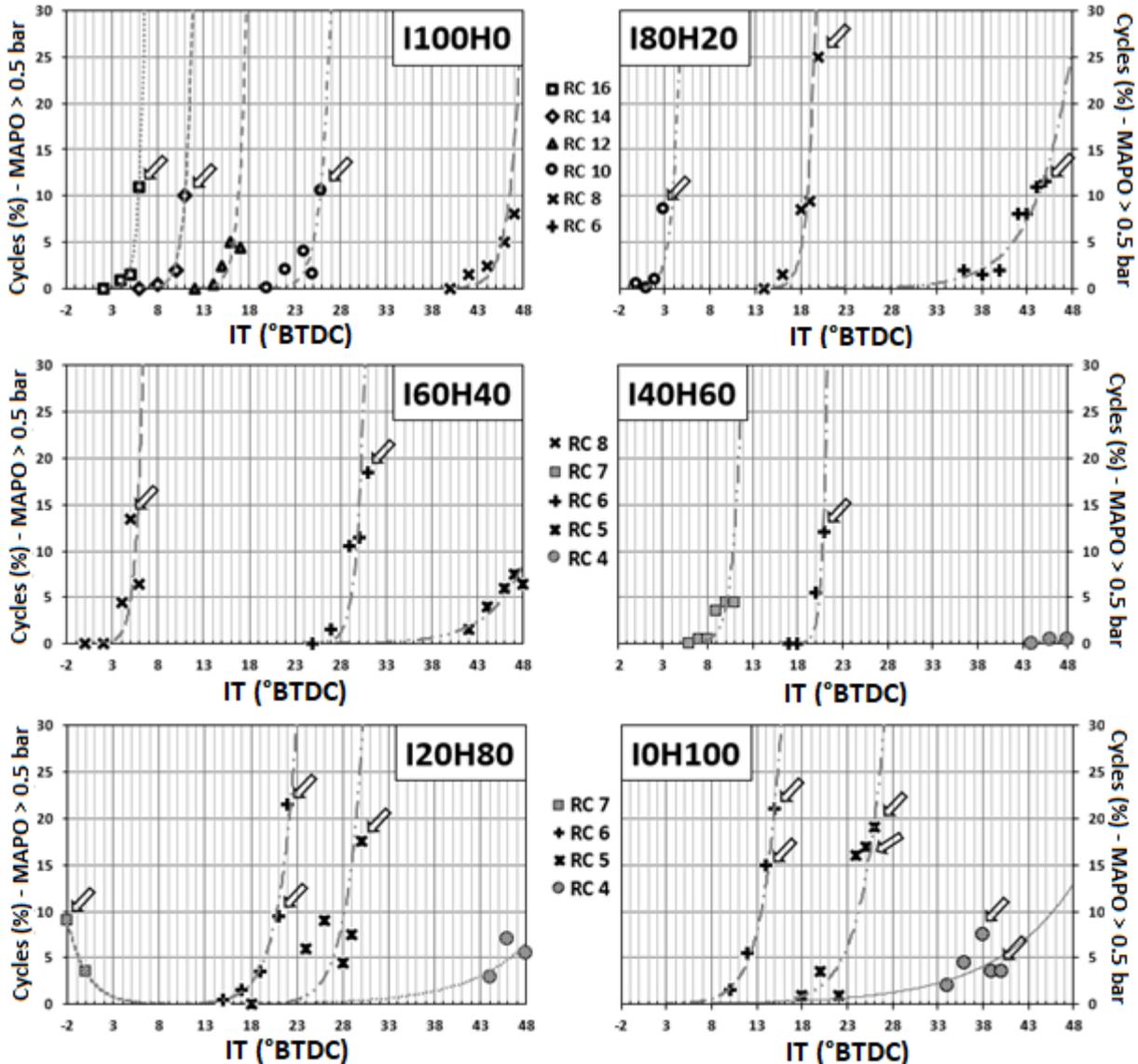


Figure 9: Percentage of cycles with MAPO > 0.5 bar.

It can be observed that counting the number of cycles in which pressure oscillation amplitudes occur above a predetermined value is a method that may fail to identify some knock occurrences. Although there is knock only in a few cycles, these can have high pressure oscillations and can severely damage the engine (like the 6° BTDC point in Fig. 7, for example). As already mentioned by Li et al., 2017, when using the methodology for counting the number of cycles (the KI method) in the engine calibration process, the choices of pressure oscillation thresholds are necessary for knock detection in several operating conditions so, it would be more prudent to choose different limits in each operation zone. The choice of these thresholds is not trivial and depends on the design specifications since the knock intensities affect the durability of the engine as well as performance and emissions results. This work is usually complex and takes a lot of time because it requires tests and calibration of the knock sensor under different conditions.

From those observations, the calculation of the knock factor was an alternative to assess the occurrence of knock by means of the Stochastic Knock Detection, where were considered both the knock intensity and recurrence. The knock factor (KF) was calculated for each fuel mixture and the results are shown in Fig. 10 as a function of the ignition timing (IT) and the compression ratio (RC). The points identified by the arrows are audible knock points, clearly identified during the tests.

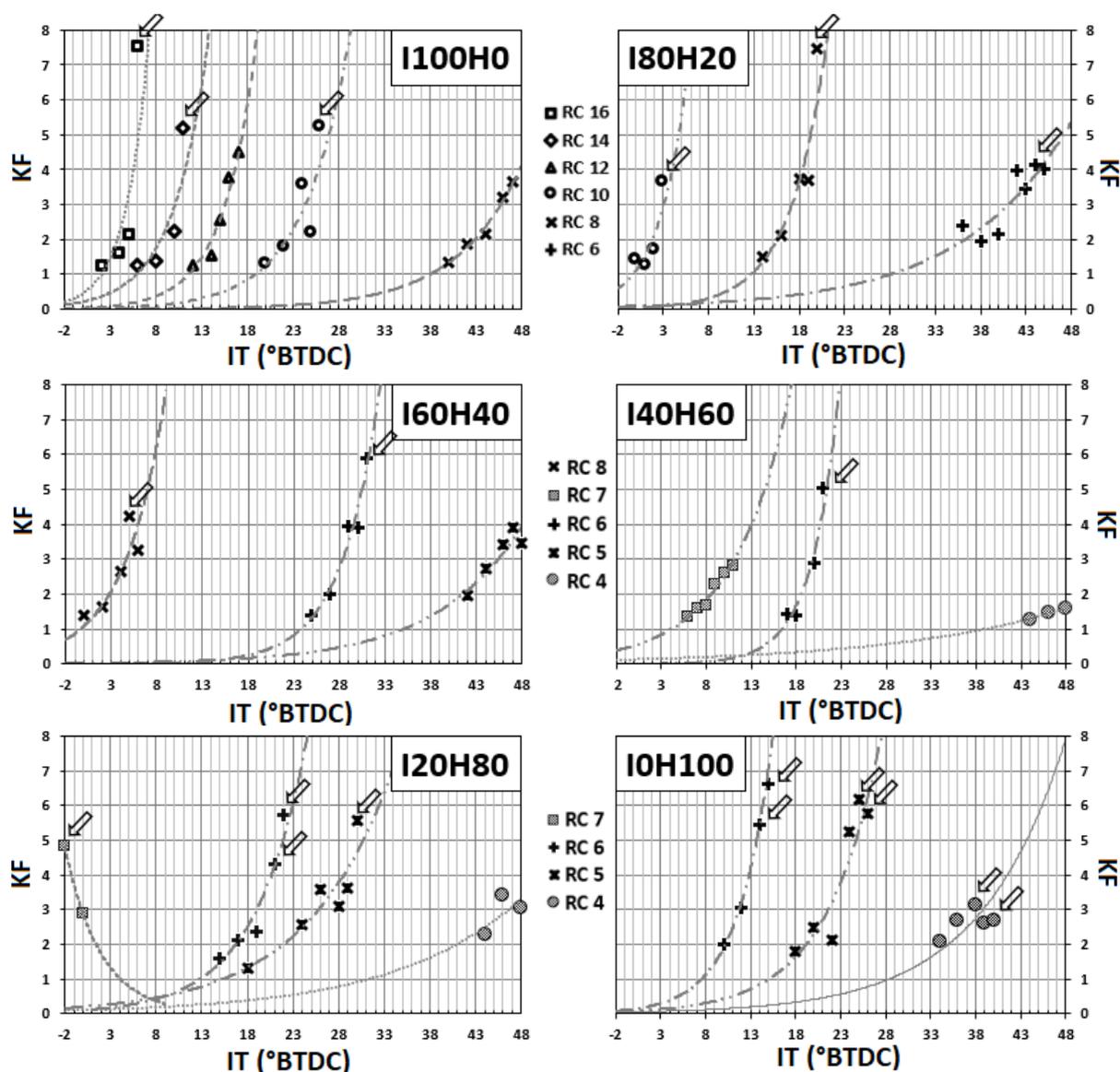


Figure 10: Knock factor (FK) obtained by the ignition timing (IT) for each compression ratio and each fuel tested.

Comparing the test points of fuel I100H0, at compression ratio 16 and ignition timing 6° BTDC (Fig. 7) and the fuel I80H20, at compression ratio 8 and ignition timing 20° BTDC (Fig. 8), it is seen that the knock factors are 7.54 and 7.48 respectively. The knock factors are similar for different cycle behaviors since in the first case there is high pressure oscillations in a few cycles and, in the second case, there is low oscillations pressure for a high number of cycles. This behavior shows that the knock factor calculation method considers both: amplitude and recurrence of pressure fluctuations.

According to the results presented in Fig. 10, an increase in the knock factor was observed as the spark time was advanced at each compression ratio. This result occurs because, the greater the ignition advance, the sooner the auto-ignition temperature is reached and a larger fraction of unburned mixture oxidizes instantly, causing a greater local pressure rise and, consequently, greater knock intensity. In only a few cases, the advance of the ignition timing led to a reduction in the knock factor going in the opposite direction to the trend presented. As an example, the condition to the fuel I100H0 in the compression ratio 10 of the ignition timing 24° BTDC to 25° BTDC are mentioned and for the fuel I20H80 in the compression ratio 7 of the ignition point of -2° BTDC to 0° BTDC. This anomalous reduction in the knock factor can be associated with the knock's own stochastic characteristic associated with the cyclical variability inherent in the engine. The variations in the homogenization of the air and fuel mixture, mainly near the region of the start of combustion, the amount of air admitted in the cylinder, the fraction of residual gas and the temperature of the gas charge inside the cylinder, lead to variations in the knock intensity. In addition, the cooling temperature of the combustion chamber is another important factor that can help to explain this behavior, which is opposite to the general trend of knock intensity with the advance of the ignition timing. It was observed during the experimental procedure that,

even though the cooling temperature was kept in the range of 89 °C to 91 °C, this difference of up to 2 °C was enough to affect the occurrence of knock, especially close to the beginning of the occurrence zone. Furthermore, at the same condition operation, there was greater intensity and propensity for the knock to occur when the temperature was closer to the upper limit. This behavior indicates that there is a very small threshold between knocking or not under certain conditions.

The influence of n-heptane in the knock occurrence is also evident because, the greater its fraction in the fuel, the lower the compression ratios achieved. For example, for the I100H0, the maximum compression ratio achieved was 16 and, when 20% n-heptane was added to the isoctane (I80H20), the maximum compression ratio achieved was 10. For the pure heptane (I0H100) it was tested until the compression ratio 6, because for  $CR = 7$  there was already an intense knock even with the spark time on the top dead center. In addition, comparing the same compression ratio, it is observed that the ignition timing limited for knock is lower for fuels with a higher percentage of n-heptane. As an example, it is observed that at compression ratio 10, the limit ignition timing for the knock is 26° BTDC for I100H0 and only 3° BTDC for I80H20. This result highlights the greater tendency of n-heptane to autoignition. Summarizing, the tendency of knock factor increasing with the spark timing advancing is shown by the tendency lines for each compression ratio in each fuel blend. The compression ratio achieved in blends with higher n-heptane percentiles were smaller compared to blends with a higher isoctane percetile due the higher tendency of n-heptane to knock.

#### 4. CONCLUSIONS

It is concluded that due to the cyclic variability inherent to internal combustion engines, the knock has a stochastic characteristic. Even though the engine is under audible knock condition, the phenomenon does not occur in most of the cycles and, in the cycles in which the knock occurs, it has different intensities. This fact makes it is important to find a way of detecting knock intensity that considers a statistical factor of both knock recurrence and intensity in a certain engine operating condition. The knock factor calculated by the stochastic method proved to be a good tool for this task because it was possible to identify the knock intensities for more specific work conditions of the engine with more coherence. When compared to the method of counting the number of cycles where knock occurs, the SKD method proved to be more effective. In cases where there were few cycles with very high knock intensities, the knock factor presented high magnitudes, quantifying the potential of knock damage. Also, the lower knock resistance of n-heptane was evidenced by the decrease of maximum compression rate achieved with the increase of its fraction in the fuel.

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