IMPACT OF LEANING HYDROGEN-AIR MIXTURES ON ENGINE COMBUSTION KNOCK

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Abstract

Combustion of lean hydrogen-air mixtures in an internal combustion (IC) spark ignited (SI) engine in respect of combustion knock effect is presented in this paper. It is known that making the combustible mixture leaner leads to both decreasing in-cylinder peak temperature of combustion and lengthening ignition lag. It also increases combustion duration. Having these issues on mind it could be concluded that combustion knock intensity decreases as well. It is reported that such a hypothesis is also correct when hydrogen based fuels are combusted in the IC engine, although hydrogen as an engine fuel, on the contrary to gasoline, is very susceptible to knock generation throughout the entire combustion duration. At the beginning the paper examines the combustion knock intensity on the basis of in-cylinder pressure traces. Next, a test-bed and obtained experimental results of hydrogen combustion in the IC single cylinder CFR engine are showed. Finally, analysis of knock intensity referring to lean hydrogen-air mixture ratio, expressed by the excess air number so-called lambda, is carried out. Significant conclusion from the analysis is that there is strong negative correlation between the hydrogen knock intensity and the excess air number lambda. In the end, comparison with exhaust gas recirculation as alternative way to reduce combustion knock, and constraints for leaning the hydrogen-air combustible mixture for the IC engine are discussed in the paper.

Keywords: *IC engine, lean hydrogen-air mixture, combustion knock*

1. Introduction

Combustion knock occurring in an internal combustion (IC) engine is a phenomenon, which is sensitive to several quantities. They can influence on knock intensity at various strength. Some of these quantities are identified and their impact on the knock is more-less recognized. From chemical kinetics point of view, concentration of - OH radicals is considered as precursor for generating knock during hydrogen combustion in the IC engine. Apart from it, there are other quantities or engine parameters, which can make the knock effect more or less intensified. They can be distinguished as follows:

- temperature of preignition gases - it has significant impact on an induction time (preignition reactions) and strongly impacts on combustion knock [1],
- oxygen to hydrogen ratio, which might be expressed by the excess air factor lambda,
- oxygen dilution of the intake charge - provided by exhaust gas recirculation (EGR),
- compression ratio - impact on the preignition temperature,

- volumetric efficiency - impact on the preignition temperature,
- hot spots, exhaust residuals - they can work as extra sources for uncontrolled hydrogen ignition,
- initial swirls, intake manifold shape, combustion chamber shape,
- fuel dose - it provides energy released during combustion and also influences the knock intensity.

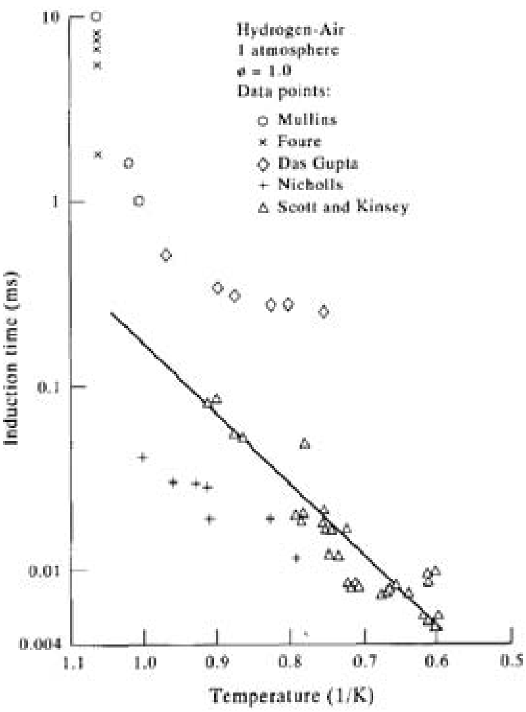

Fig. 1. Effect of temperature on induction time [1]

However, many of these quantities are not independent, for example fuel dose and lambda, that could change the knock. For example, wanting to recognize the impact of lambda on combustion knock under criterion of keeping a hydrogen dose constant, it is necessary to deliver the proper amount of in-cylinder air by setting the throttle at correct position. Thus, with respect to changing lambda, the entire air-hydrogen mixture also varies, as result, volumetric efficiency varies too when port fuel injection is used. Furthermore, when leaning the H2-air combustible mixture, then combustion duration becomes longer. To keep the maximum brake torque (MBT) adjusting the spark timing (ST) to optimal location vs crank angle is required in this case. However, combustion chamber geometry at the start of combustion is not the same if the spark timing varies. In summary, it is difficult to correctly recognize impact of an individual quantify, as eg. the lambda, on the hydrogen combustion knock intensity. Therefore, both investigation and discussion about lambda influence on the knock, described in this paper, was carried out under the H2 dose and spark timing constant. Although, the combustion duration varies significantly with lambda change, the start of combustion changes insignificantly when the spark timing is fixed. Assuming, hydrogen knock starts early in combustion [4], then accepting this premise is justified. Finally, when changing the lambda, the volumetric efficiency also changes. So, in fact, the paper describes combined impact of both lambda and the total mass of the in-cylinder mixture on the combustion knock in a hydrogen fueled engine.

A reason for leaning the hydrogen-air mixture is to achieve higher engine indicated efficiency (Fig. 2) as provided by Karim Ghazi [2] among the others. Although power drops within lambda increase (equivalence ratio from the Fig. 2 is inverse to the lambda) but it can be improved by boosting the engine.

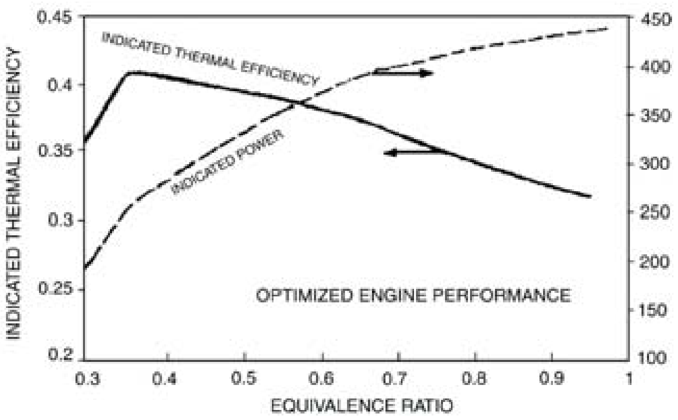

Fig.2. Typical variations in the indicated power output and efficiency with leaning of equivalence ratio for hydrogen operation using optimum spark timing [2]

2. Test Bed Description

The engine used for this research is a single cylinder CFR (Cooperative Fuels Research) engine manufactured by the Waukesha Motor Company. The engine was chosen for its versatility and robustness of construction which is important because of the intended study of combustion knock. A specialized attribute of this engine is the ability to vary the compression ratio without disassembling the engine. Characteristics of the test bed and engine are shown in Fig. 3 and listed in Tab. 1 respectively. Numerous modifications to the engine were made to meet the requirements in these studies. This included changing the compression ratio of the engine by modifying the piston. The modified piston increased the range of compression ratio, that could be studied from 4-10 to 4.5-17.5.

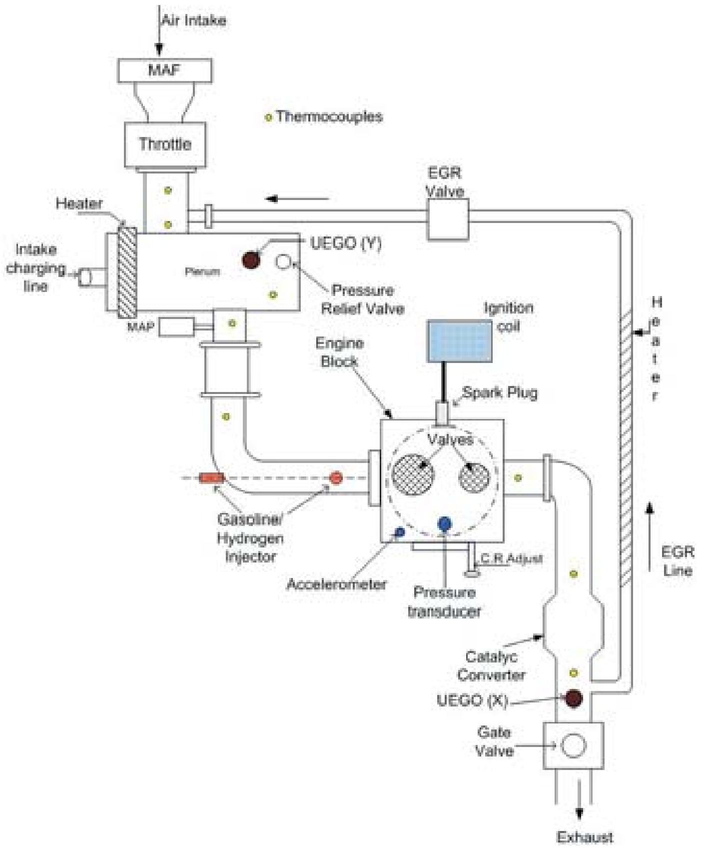

Fig. 3. Diagram of the CFR engine test bed

Tab. 1. CFR Engine Characteristics

Compression Ratio	4.5-17.5
Bore (cm)	8.26
Stroke (cm)	11.43
Connecting Rod Length (cm)	25.4
Displacement (cm^3)	611
IVO	10° ATDC
IVC	34° ABDC
EVO	40° BBDC
EVC	15° ATDC

Engine control and monitoring was performed using a target-based rapid-prototyping system [7] with the electronic sensors and actuators installed on the engine. Sensors monitored flow rate, pressure, and temperature of the working fluid at various regions of the engine along with engine position determined from a sensor on the crankshaft. Sensors included MAF, manifold pressure (MAP), UEGO, and crank position sensor. Electronic actuators included a digital ignition coil, throttle, EGR valve, and port fuel injectors for both liquid (gasoline) and gaseous (hydrogen) fuels.

Data from the in-cylinder pressure and engine mounted piezoelectric accelerometer along with an engine position sensor were acquired with a National Instruments BN-2111 analog to digital converter. Data for 300 engine cycles at 100 kSamples/second-channel was acquired.

3. Combustion Knock Metrics

The 95th percentile of the peak pressure (PP) distribution of fluctuating component of in-cylinder pressure was used as the metrics, which satisfactory corresponds to level of combustion knock intensity. The 95th percentile value stands for such a PP of fluctuating component of in-cylinder pressure, for which the cumulative density function of this PP distribution equals 0.95. The 95th percentile of PP distribution is defined as follows [5, 8]:

$$PP\_95 = \exp\left\{ erfinv\left[\left(\frac{95}{50} - 1 \right) \cdot \sqrt{2} \cdot \sigma \right] + \mu \right\}, \qquad (1)$$

where:

μ - mean value of the PP distribution,
σ - standard deviation of the PP distribution.

4. Experimental Results and Discussion

The tests were conducted under combustion parameters as follows:

1. Fuels Applied: industrial compressed hydrogen,
2. Lambda excess air factor of the in-cylinder mixture was varying from 1.0 to 1.7,
3. Energy in the single fuel dose delivered to the cylinder equaled E_{fuel} = 950J and 1490J which corresponded to 8 and 12 ms of hydrogen injection, respectively,
4. Spark timing was varying from 5° before top-dead-center (BTDC) to 0° (at top-dead-center (TDC),

5. Compression ratio of CR=8:1,
6. Engine speed 900 rpm.

4.1. H2 dose impact on knock intensity

As it was stated in previous section the hydrogen dose is important quantity for generating the knock. Nearly linear relationship was noticed between knock intensity expressed by the PP_95 knock intensity metrics and the hydrogen dose. The tests were conducted under the spark timing constant and for the stoichiometric H2-air mixture (Fig. 4).

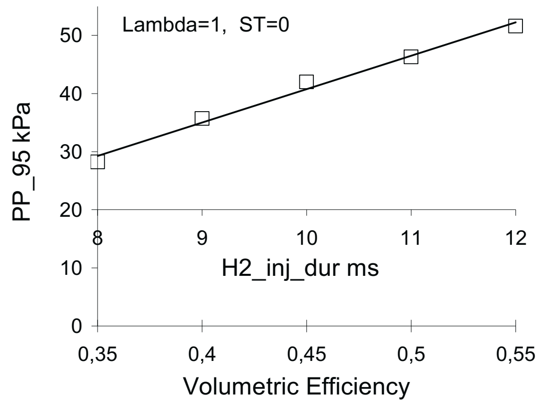

Fig. 4. PP_95 vs hydrogen dose expressed by hydrogen injection duration in ms

4.2. Lambda impact on the knock

The Fig. 5 shows 3 experimentally determined curves of the PP_95 for 3 different test conditions. Two different H2 doses and two different spark timings were applied. As it was mentioned, volumetric efficiency changes due to lambda change under the H2 dose constant. Volumetric efficiency varies from 0.35 to 0.60 due to lambda change from 1 to 1.7 for H2_inj_dur (hydrogen injection duration) = 8ms. In the test of H2_inj_dur = 12ms, volumetric efficiency varies from 0.54 to 0.65 with respect to lambda change from 1.02 to 1.21. Maximal values of volumetric efficiency were achieved at nearly widely open throttle (WOT). A negative correlation between the PP_95 and the lambda was noticed for all conducted tests. A linear regression is shown to express this correlation.

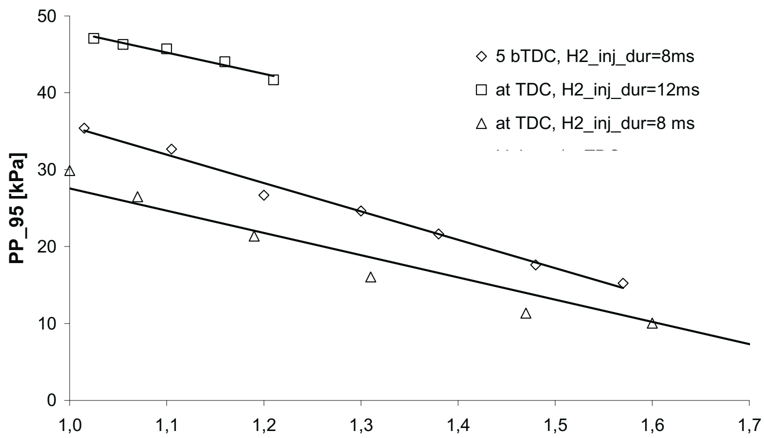

Fig. 5. PP_95 vs lambda for combustion knock in the H2 IC CFR engine

4.3. Hydrogen combustion characteristics

Knock intensity is strictly correlated with front flame propagation speed. In general, the fastest speed appears for close to the stoichiometric in-cylinder combustible mixture [9]. Combustion knock also is the most damaging at stoichiometric ratio of the hydrogen-air mixture as it is stated in this paper among the others. It was found from the investigation, that leaning the H2-air in-cylinder charge makes combustion duration longer. There was also another issue noticed. Higher amounts of hydrogen burn faster as presented in the Fig. 6. This is because of higher molar concentration of both hydrogen and air in the intake. Additionally, the faster combustion in this case might be explained by more intensive combustion knock occurring for combustion with the larger H2 dose as it was presented in the Fig. 3. Thus, more intensified knock results in faster hydrogen combustion. Combustion duration was defined here as crank angle directly corresponding to a time, which passes from 10% MFB (Mass Fraction Burnt) until 90% MFB.

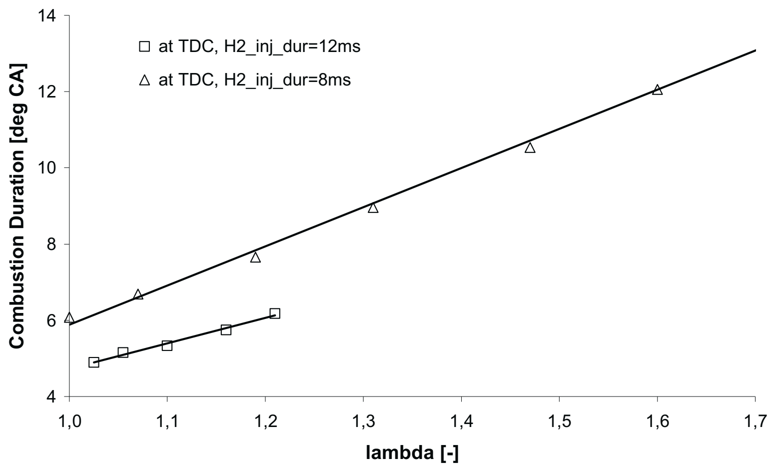

Fig. 6. Hydrogen combustion duration against lambda in the H2 IC CFR engine

Fig. 7 shows the 50% location of mass fraction burnt (MFB) of the hydrogen-air mixture for two different hydrogen doses and two different spark timing. The 50% of MFB was chosen for its direct correlation with engine torque.

Leaning the mixture shifts the 50% location of MFB into a position further TDC. Therefore, the spark timing should be optimized for MBT when the lambda varies.

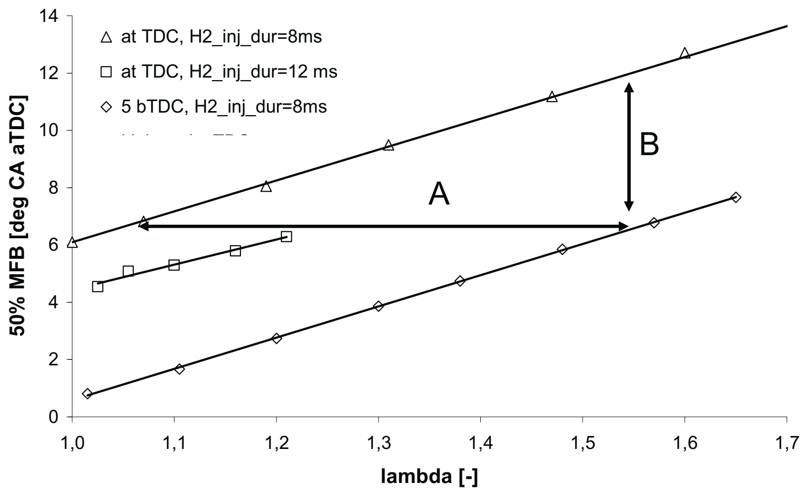

Fig. 7. Location of 50% of MFB during hydrogen combustion in the H2 IC CFR engine

Holding 50% MFB and fuel dose constant with 50% MFB = 6.5 deg aTDC (Fig. 7 A) then it would be possible to determine the knock intensity in the middle of combustion under the same crank angle position, so under the same working volume of the combustion chamber. This comparison of the PP_95 knock intensity metrics presented in Fig. 8 (bars A and AB) yields information about the combustion knock for two different lambdas: 1.07 and 1.55, two different ignition timings: 0 and 5 deg bTDC, but for the same combustion chamber geometry meaning the 50% location of MFB was kept constant. Holding lambda, fuel dose and spark timing constant (Fig. 7 B) the bar B in Fig. 8. presents combustion knock for the 50%MFB equaling 12 deg aTDC, thus it takes place in larger working volume of the combustion chamber.

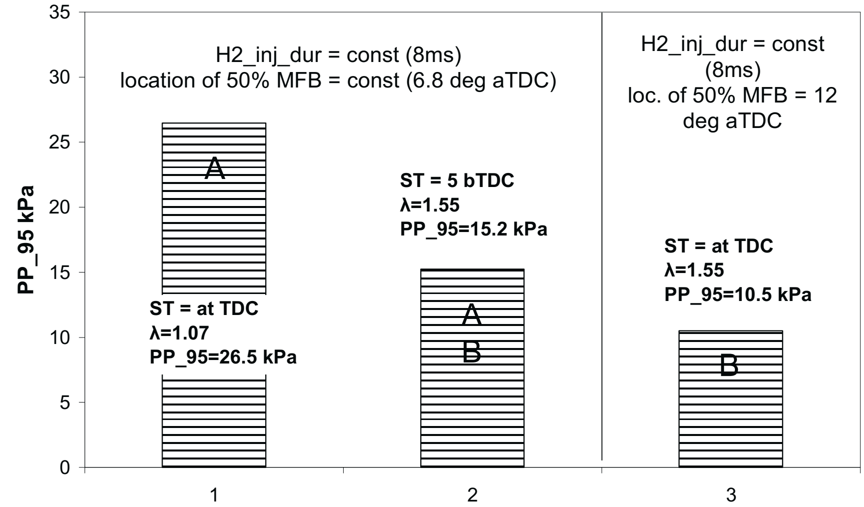

Fig. 8. 95th Percentile of PP of combustion knock for two different lambdas under the same fuel energy and the same 50% MFB location, ST = Spark Timing

4.4. Cycle-by-cycle repeatability

In comparison with air-gasoline lean mixture, lambda increase for hydrogen-air mixture does not cause misfires, thanks to wide flammability limits of hydrogen in air. Therefore, hydrogen combustion under lean mixture range does not appear worse. Even it could be noticed, that leaning hydrogen-air mixture up to the range presented in the Fig. 9, causes the engine run more stable and

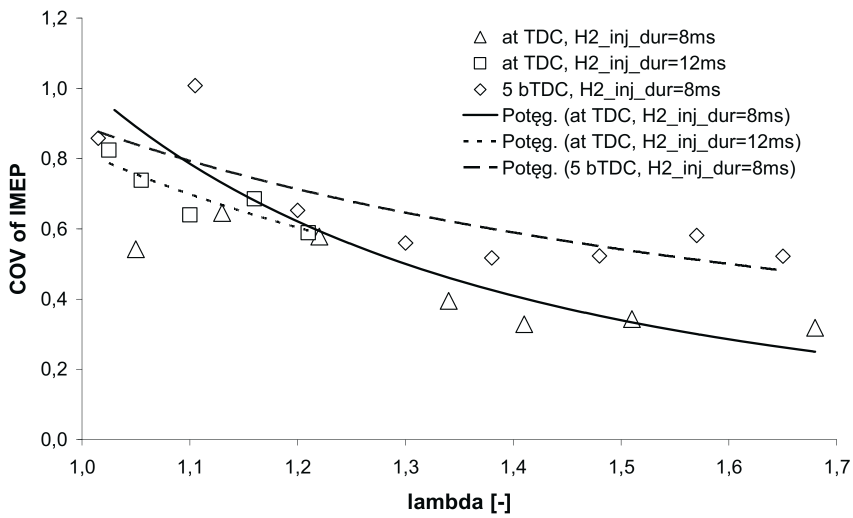

Fig. 9.Cycle by cycle repeatability expressed by COV of IMEP vs lambda for H2 IC CFR engine

smooth unlike the engine fueled the stoichiometric mixture. The engine cycle-by-cycle run can be statistically quantified by the coefficient of variation (COV) of indicated mean effective pressure (IMEP). It is defined as follows:

$$COV\ of\ IMEP = \frac{\sigma_{IMEP}}{mIMEP}, \quad (2)$$

where:

σ_{IMEP} - standard deviation,
mIMEP - mean of indicated mean effective pressure.

The COV of IMEP vs lambda goes down (Fig. 9) showing more stable engine run in comparison to mixture composition close to stoichiometric ratio.

5. EGR and Leaning Mixtures for Knock Reduction

Apart from leaning the combustible mixture, exhaust gas recirculation (EGR) is also considered as another remedy for effective knock reduction. It provides oxygen dilution in the air inducted into a cylinder. Consequently, front flame speed of hydrogen-air mixture drops down forcing combustion duration longer and also the combustion knock intensity reduced. Fig. 10 shows 95th percentile of the peak pressure from the fluctuating component of in-cylinder pressure vs EGR ratio [3, 6].

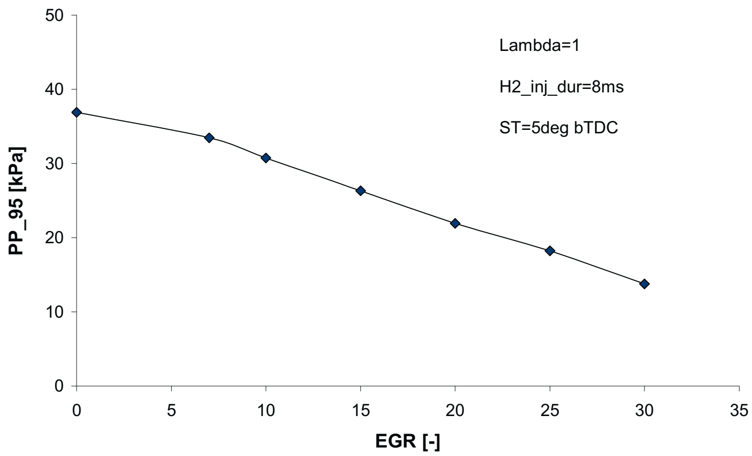

Fig. 10. PP_95 vs EGR (CR=8, H2=8ms, ST=5deg bTDC)

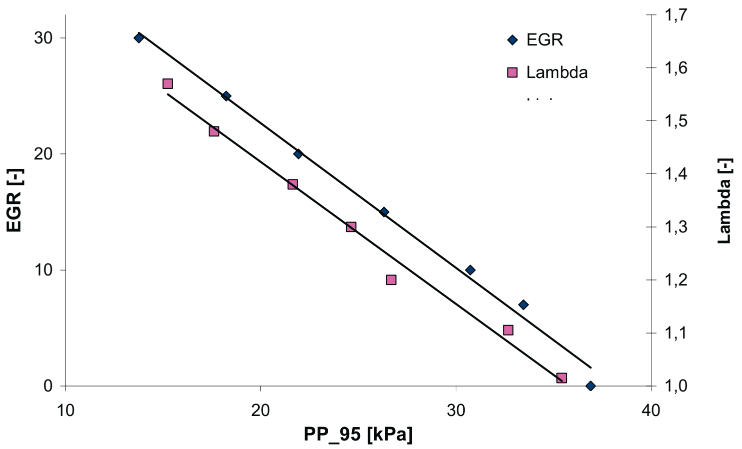

Fig. 11. Comparison between lambda change and EGR change to obtain the same reduction of PP_95 (spark timing, H2 dose, CR are all constant and the same for these two tests)

Here someone would suggest, which way would occur better for hydrogen knock reduction. The Fig. 11 presents how much the selected quantity should be changed to obtain the same final result of knock intensity reduction. EGR increase of 20% and lambda change from 1.0 to 1.43 cause the same combustion knock reduction.

6. Conclusions

- Intensity of combustion knock depends on several quantities. It is difficult to isolate impact of a single quantity on the combustion knock intensity in a hydrogen fueled engine,
- greater hydrogen dose makes combustion knock more intensive under the same lambda. Then intensified knock significantly shortens combustion duration even if a mass of hydrogen is higher,
- combustion knock intensity decreases when H2-air mixture becomes leaner. The dependence between lambda and PP_95 is nearly linear,
- the hydrogen fueled engine works more smoothly at lean mixtures in comparison to stoichiometric one,
- with respect to a catalytic converter installed on the exhaust pipe line, applying EGR appears as better solution for knock reduction then leaning the H2-air mixture because the catalytic converter needs stoichiometric mixture for effective NOx reduction.

7. Acknowledgements

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