KNOCK AND COMBUSTION RATE INTERACTION IN A HYDROGEN FUELLED COMBUSTION ENGINE

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Abstract

The paper describes correlation between combustion knock intensity and combustion rate calculated as the heat release rate from combustion pressure traces of a hydrogen fuelled spark ignited engine. Unlike a gasoline spark ignited (SI) engine, the hydrogen fuelled engine can easily generate knock during combustion at working conditions similar to a gasoline engine. However, the hydrogen knock does not necessarily come from hydrogen auto-ignition at the end phase of spark-controlled combustion process as it is typical at the gasoline fuelled engine. The phenomenon of hydrogen knock significantly differs from the gasoline knock due to different combustion mechanisms and different fuel thermo-chemical properties. The knock can be generated during hydrogen combustion itself as result of combustion instabilities. Intensity of this knock, expressed here by intensity of combustion pressure fluctuations, is several times lower in comparison with the combustion knock by fuel self-ignition process. This „light knock" is a matter of this paper. The tests of hydrogen combustion in the IC engine has been conducted at air to hydrogen stoichiometric ratio at various compression ratios with spark timing sweep from -10 to 4 crank angle degrees referring to top dead centre of the engine piston. Obtained results show, that there is a positive correlation between the knock intensity and the combustion rate. This correlation is particularly observed at tests taken on the engine with compression ratio of 10. The conclusions should provide good premises for combustion knock modelling and its prediction.

Keywords: *combustion knock, heat release rate, hydrogen, engine*

1. Introduction

Typical gasoline combustion knock is defined as noise caused by high frequency pressure oscillations resulting from self-ignition of unburned fuel at the end of the compression stroke [1,2]. The amplitude of these oscillations can be as high as peak of combustion pressure. Such a combustion shortens engine durability, thus from this point of view is managed as unwanted combustion phenomenon. Therefore, detection of combustion knock is a basic measure of a modern engine control system to prevent the engine from working with such the abnormal combustion. Usually, the detection is realized with a vibration sensor installed on the engine body. There is almost linear correlation between knock intensity and engine body vibration [4-6], thus such monitoring of combustion knock can be easily conducted. Although, running the engine under knock is undesirable due to affecting engine durability, but working just at the edge of combustion knock can provide conditions for maximum available engine performance. It is particularly observed in case bad quality fuels are applied. The knock detection system provides real-time monitoring of the engine and in case of the knock onset, the control system retards spark timing to eliminate this abnormal combustion. There are also other measures to eliminate or reduce the knock effect. Among the others, exhaust gas recirculation strategy and leaning combustible mixture can be applied [8-12] as the effective way to reduce the combustion knock. Anyway, the best for the engine is to work without knocking. Thus, prediction of potential combustion knock occurrence is the main target of research in the field. Theory and modelling the combustion knock can be valuable tools in computational simulation of engine working cycles and their analysis as presented in [13-19]. Although, several, experimentally determined, correlations between knock intensity and quantities as pre-ignition temperature and ignition delay are satisfactory recognized, but origin of this phenomenon still needs to be theoretically investigated in details. Thus, it will make the model of combustion knock more universal and will provide opportunity of knock prediction in various types of engines.

Karim et al. [3] presents a formula for knock prediction on the basis of a dimensionless energy criterion number. His modelling of knocking events was shown to be capable of predicting successfully the onset of knock in methane fuelled SI engines and was extended to consider cases when hydrogen was present as an additive. Finally they have worked out the criterion for pure hydrogen combustion. Moses et al. [20] in his work presents the model of combustion knock based on auto-ignition process of combustible mixture residuals at the end combustion phase. This work was focused on gasoline as a fuel for the spark ignited engine. Summing up, it should be mentioned that abnormal combustion occurring in the reciprocating engine is a matter of intensive research activities. At experimental tasks there is remarkable difficulty in proper combustion pressure data acquisition. It concerns detection of peak values in pressure oscillations with satisfied accuracy. This problem was taken by several researchers, e.g. [21-24].

2. Experimental set-up

The engine used for this research is a single cylinder CFR (Cooperative Fuels Research) engine manufactured by the Waukesha Motor Company. A specialized attribute of this engine is the ability to vary the compression ratio without disassembling the engine. The modified piston of this engine increased the range of compression ratio, that could be studied from 4–10 to 5.4–18.5.

Engine control and monitoring was performed using a target-based rapid-prototyping system [25] 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 mass-air-flow (MAF), manifold absolute pressure (MAP), wide-band air/fuel ratio (UEGO), and crank position sensor. Electronic actuators included a digital ignition coil, throttle, and port fuel injectors for both liquid (gasoline) and gaseous (hydrogen) fuels. The pressure data were acquired with a National Instruments BN-2111 analog to digital converter (100 kSamples/second-channel) on the engine test bed. The data were recorded at constant air to fuel ratio respective for stoichiometric combustion of hydrogen ($\lambda = 1$) and at variable spark timings (-10...4 crank angle degrees) and compression ratios of 6, 8 and 10.

3. Results and discussion

Analysis of the experiments presented in the paper is based on in-cylinder pressure data acquisition. Computed quantities were averaged over 300 consecutive engine work cycles of the each experimental series. The examples of combustion events presenting knock with two different intensities are depicted in the Fig. 1a and 1e. The knock shown in the Fig. 1a can be treated as light knock, which comes from unstable deflagration combustion of hydrogen in the engine with compression ratio (CR) of 10. Typical combustion knock, caused by spontaneous combustion of hydrogen-air mixture in the engine with CR = 12 at the end phase of controlled combustion, is presented in the Fig. 1e. The pressure oscillations corresponding to knock by hydrogen auto-ignition (Fig. 1f) are almost ten times higher than oscillations specific for light knock (Fig. 1b). These high frequency pressure components of in-cylinder pressure were filtered from the main pressure trace with the digital high-pass Butterworth filter with the cut-off frequency of 4 kHz. On the basis of the absolute pressure trace the MFB (Mass Fraction Burned) profile was determined for the each combustion event (Fig. 1c, 1g). Next, the rate of MFB was calculated (Fig. 1d, 1h). If one assumes, that the cumulative heat release is directly proportional to the mass of the fuel burnt, then, the rate of heat release should directly correspond to the rate of MFB, however, the rate of MFB is managed as a dimensionless quantity. From the MFB profile, the 10%, 50% and 90% MFB (0.1 0.5 and 0.9 MFB respectively) were determined and these values were averaged over the 300 MFB profiles computed from the individual combustion events.

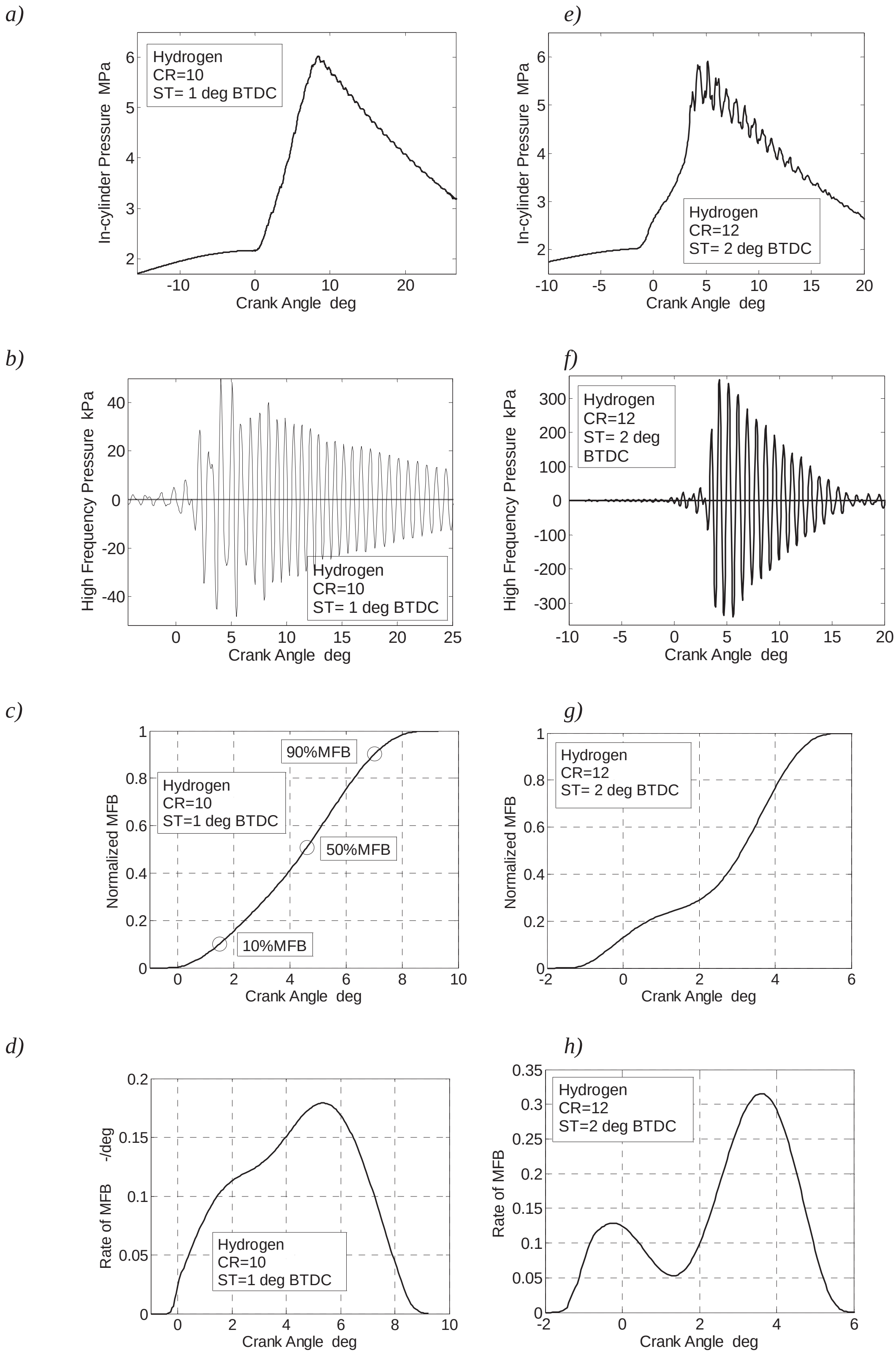

Fig. 1. Combustion events of hydrogen fuelled engine: at light knock (a, b, c, d) and strong knock (e, f, g, h): a, e) in-cylinder combustion pressure, b, f) high frequency pressure component, c, g) MFB profile, d, h) rate of MFB

Next step of the analysis was to determine knock intensity. The metrics for knock was defined as the maximum amplitude, denoted here as the PP (peak pressure), and was taken from the single combustion event. Such the metrics was successfully applied in evaluation of pressure oscillations in the compression ignition engine as well as in the spark ignited one [26, 27]. The 95th percentile of the PP statistical distribution of the 300 individual PP's was used as the metrics, which satisfactory corresponds to level of combustion knock intensity for the entire engine test series. The 95th percentile value stands for such the PP of high frequency pressure, for which the cumulative density function (cdf) of this PP distribution equals 0.95. The 95th percentile of the PP distribution is defined as follows [5, 28]:

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

where:

μ - mean value of the PP distribution,

σ - standard deviation of the PP distribution.

Its graphical interpretation is shown in the Fig. 2.

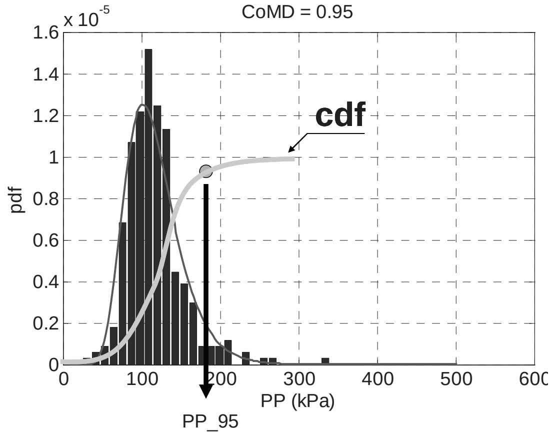

Fig. 2. Definition of the PP_95 percentile [xx]

The locations of 10%, 50% and 90% MFB with spark timing sweep from -10 to 4 crank angle deg for hydrogen fuelled engine with the CR = 10 are plotted in the Fig. 3. Additionally, the location of the maximum rate of MFB is inserted there. As seen, the gap between locations of the 50%MFB and the maximum rate of MFB is almost constant over spark timing for hydrogen combustion, even as the knock occurs. One can conclude, that location of the centre of combustion knock can be expressed by the location of the maximum rate of MFB and for the hydrogen engine the knock goes throughout the whole combustion process, unlike gasoline, where the knock is characteristic for the end combustion phase. Additionally, hydrogen combustion duration managed as 10-90%MFB is also invariable.

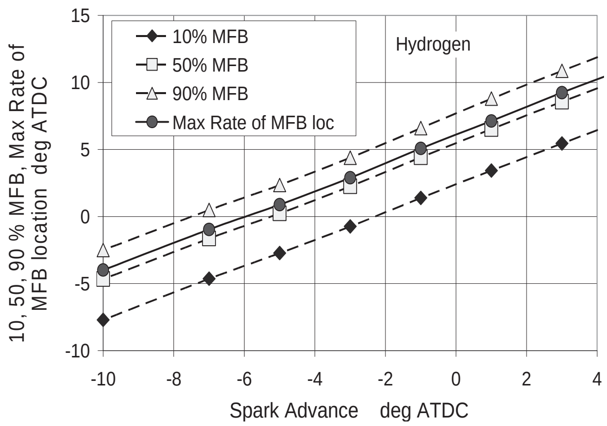

Fig. 3. 10, 50, 90% MFB and maximum rate of MFB locations vs. spark timing for the hydrogen engine with CR = 10

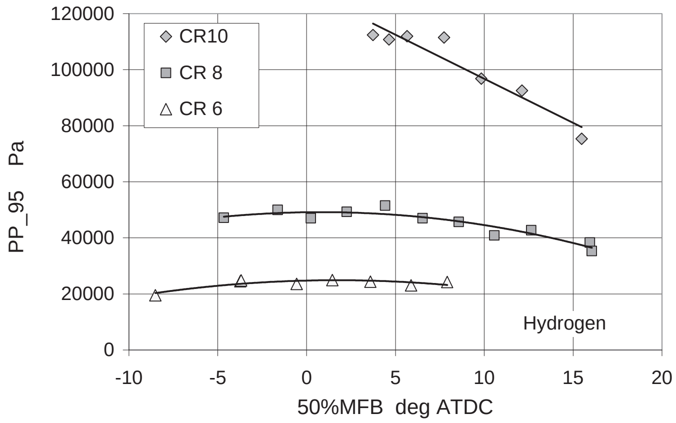

Fig. 4. Knock intensity PP_95 vs. 50% MFB location for the hydrogen fuelled engine

In the Fig. 4 knock intensity PP_95 vs. location of 50%MFB at engine various compression ratios (CR) of 6, 8 and 10 is shown. At compression ratio of 6 the knock is hardly detected. At compression ratio equalled 8 the knock occurs but its intensity does not increase with advance in spark timing and is not harmful for the engine. Relatively high knock of approximately 100 kPa was observed at compression ratio of 10 and it rapidly increases with the 50%MFB location approaching to the TDC that corresponds to advancing spark timing. However, this knock does not come from hydrogen end-gas self-ignition, but it results from unstable and accelerating flame propagation while deflagration combustion of hydrogen is in progress.

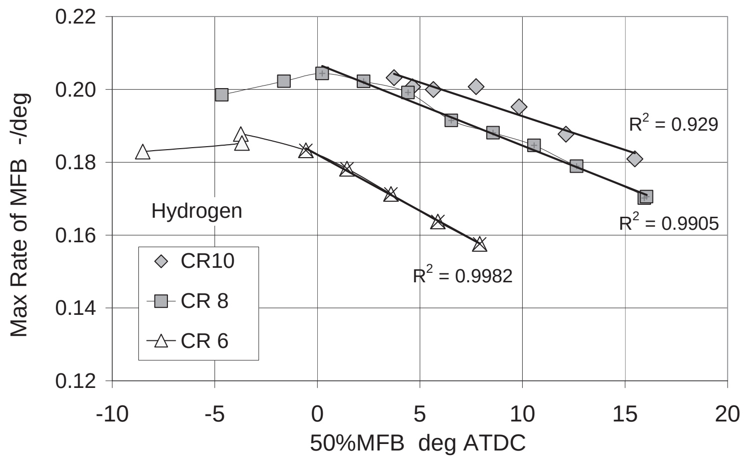

Fig. 5. Maximum rate of MFB against 50% MFB location for the hydrogen fuelled engine at CR=6, 8, 10

In the Fig. 5 knock intensity maximal rate of MFB vs. location of the 50%MFB is plotted. As observed, the highest value of the max. rate of MFB appears when the middle combustion phase (expressed by the 50%MFB) approaches to the TDC point. Similar trend is observed in the Fig. 4. The regression lines calculated for various compression ratios show that the correlation between these two parameters depicted in the Fig. 5 is almost linear. The R2 stands for the coefficient for determination and the value 1 shows that the correlation matches exactly the equation for the regression line. Thus, it additionally confirms the linearity between locations of the middle combustion phase (50%MFB) and the max. rate of MFB. As seen, this linear relation is valid for the 50%MFB located in the range from 16 deg ATDC to 0 TDC.

Knock intensity PP_95 vs. maximal rate of MFB is depicted in the Fig. 6. It can be noticed that higher maximum rate of MFB goes with higher knock intensity. It is observed for combustion at compression ratio of 8 and 10. The maximum rate of MFB and the knock intensity PP_95 are in feedback with each other as they interacts on each other in several combustion instability mechanisms. It should be also noticed that compression ratio impact on combustion knock is crucial. However, temperature of the combustible hydrogen-air mixture plays the most important role in this correlation. As studied case of impact of the compression ratio of 6, someone can conclude that knock occurrence in such the engine does not contribute to significant increase in hydrogen combustion rate.

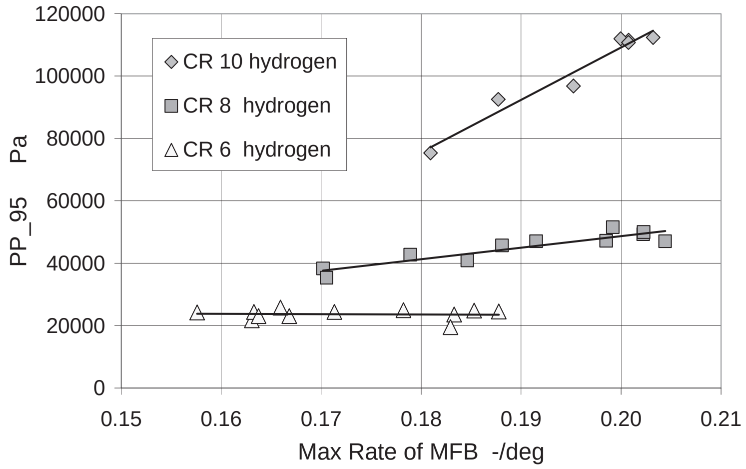

Fig. 6. Knock intensity PP_95 vs. maximal rate of MFB for the hydrogen fuelled engine at CR=6, 8, 10

4. Conclusions

Investigation described in this paper deals with light and medium intensity knock generated in the hydrogen fuelled engine. This knock is usually formed as a result of hydrogen combustion instabilities, and it has nothing in common with auto-ignition of the unburned combustible mixture at the end phase of combustion process. The conclusions drawn from investigation are as follows:

- There is a correlation between knock intensity and maximal combustion rate of hydrogen in the spark ignited internal combustion engine. This correlation becomes stronger with combustion knock gets more intensified as it was observed for both knocking events for engine tests at compression ratio of 10. This correlation is positive, thus, higher combustion knock accelerates combustion, resulting in higher combustion rate.
- The hydrogen knock starts with ignition of the hydrogen-air mixture and it goes through all the combustion phases unlike the gasoline combustion knock, which usually occurs at the end phase of combustion and it is caused by auto-ignition of the unburned air-gasoline combustible mixture.
- Intensity of this hydrogen knock is almost in linear correlation with a time distance of the 50%MFB location from the TDC.
- Referring to combustion phases of hydrogen, the knock location follows the location of 50%MFB and it is not changed itself with knock increase.
- Both the highest knock intensity and the highest combustion rate are observed in case the 50%MFB is around the TDC location of the piston.

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