ANOMALIES IN COMBUSTION OF HYDROGEN IN A SI ENGINE MODIFIED TO WORK AS A SUPERCHARGED ONE

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Abstract

The paper describes combustion anomalies of various types randomly or permanently occurring while hydrogen is burnt in a supercharged spark ignited reciprocating engine. The anomalies were mainly identified as result of combustion pressure data analysis. Originally, the engine was a compression ignition one fuelled with diesel fuel. Modifications done on the engine dealt with decrease in its geometric compression ratio and equipping it with a spark plug located in diesel fuel injector position. The anomalies presented in the paper are typically associated with several abnormal phenomena as follows: flame propagation into intake manifold called back-fire, hydrogen spontaneous ignition by hot surface, flame propagation during valves overlap and extinguishing spark discharge flame kernel by high turbulence around a spark plug. These anomalies were observed in the supercharged engine, however, some of them were also detected while the engine was operated as a freely aspirated one. As investigated, some of these malfunctions would have been removed by change in engine operating parameters. Others need major changes in both exhaust pipeline geometry, hydrogen injection system, engine cylinder geometry and valve timing.

Keywords: *combustion, hydrogen, internal combustion engine, supercharging*

1. Introduction

Various cases of abnormal combustion taking place in a supercharged hydrogen fuelled spark ignited engine are presented in the paper and discussed. Unlike other research tests [1, 2] the engine was supercharged up to 1.6 bar positive pressure generating the IMEP of 2 MPa, respectively. As known from the literature [3, 4], the engine knock in the hydrogen fuelled engine is primarily considered as the abnormal combustion. However, for the engine with direct injection of hydrogen Sato did not mention on knock occurrence even though the engine compression ratio was 13 [5]. As state-of-art in this matter is rich of both theoretical and experimental analysis [6,7] this phenomena is not discussed. Furthermore, the abnormal combustion described in the paper mainly resulted from uncontrolled hydrogen ignition, unlike the engine knock, which characterizes the "end gas" combustion going on at significantly higher rate and usually caused by its self-ignition at high temperature above the fuel auto-ignition temperature. Unlike combustion anomalies presented in [8], these abnormal combustion cases originally concern "low temperature" ignition phase by spark electric discharge and result from several randomly or periodically occurring phenomena, which are as follows:

- surface ignition (pre-ignition),
- backfires,
- uncontrolled, advanced ignition by the spark plug,
- non-firing.

Both the surface ignition and backfires are generally caused by hot spots present in the in-cylinder combustion chamber. Uncontrolled ignition by the spark plug concerns ignition at the moment the ignition coil is charged then a low energy spark discharge might occur. Non-firing events were caused by inappropriate gap at the sparking plug.

2. Results and discussion

The abnormal combustion events were observed during tests on supercharging a single cylinder spark ignited engine with the specifications depicted in Tab. 1.

Tab. 1 Test bench specifications

Engine	
Make, type	Water-cooled, 4-stroke, single cylinder, horizontal, modified from the Andoria 1HC102
Displacement	980 ccm
Bore	102 mm
Stroke	120 mm
Compression Ratio	8.6
Rotational Speed	1270 rpm
Fuelling System	port injected
IMEP	up to 2 MPa
Dynamometer	
Synchronous motor	3 x 230 V
Power output	20 kVA
Boosting system	
EATON compressor	
Boosting positive pressure	0 - 1.6 bar
Intake gas temperature	25°C

The engine used for the research purposes was modified from its origin 1HC102 manufactured by the Andoria Factory. The main modifications concerned decrease in compression ratio from 17 to 8.6 through changing shape of the piston crown. The engine was equipped with the spark ignition system triggered by pulses generated by the encoder with 1024 resolution per rev. installed on the engine camshaft. To provide supercharging the engine intake pipeline was equipped with the EATON M65 compressor, which was driven separately by an electric 3-phase motor of 7kW power.

In-cylinder surface ignition

The ignition is usually caused by hot exhaust gases residuals, deposits or hot surface. It starts after closure of the intake valve (IVC = 122 CA deg before TDC). The exemplary test combustion series were depicted in the Fig. 1.

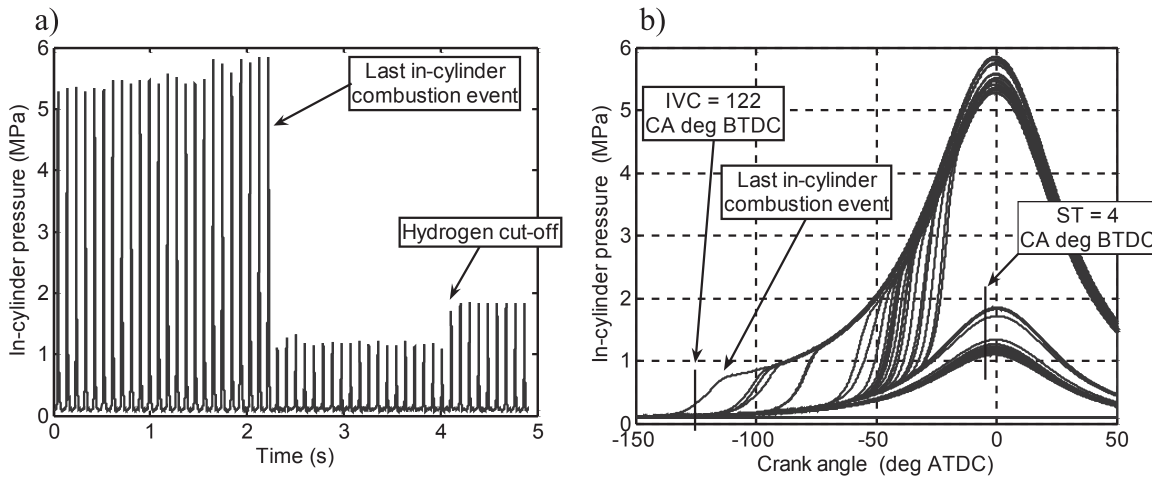

Fig. 1. Time based in-cylinder pressure (a), crank angle based in-cylinder pressure (b) from the hydrogen fuelled engine with supercharging of p_{boost} = 0.2 bar, λ = 1 and ST = 4 CA deg BTDC

As observed in the Fig. 1.b the start of combustion (SOC) varies in the range from approximately 25 to 110 CA deg BTDC. This pressure history corresponds to combustion events located in the first period of engine work of 2s, as shown in the Fig. 1.a. With increase in the average in-cylinder temperature the start of combustion (SOC) for following consecutive combustion events is systematically occurring earlier, that affects the in-cylinder temperature in positive feedback. Thus, cycle-by-cycle the SOC is moving towards the IVC.

As far as the SOC is not stabilized, the mentioned period of engine work should be treated as unstable one with continuous increase in the in-cylinder temperature. Due to early combustion initiation, the combustion is completed before the piston achieves its TDC location that leads to significant drop in IMEP, so does the engine torque and power. While the SOC occurs before the IVC as result of its tendency to become earlier and earlier, then flame rapidly ignites combustible mixture in the intake manifold as is typical for backfiring phenomena. Thus, hydrogen is entirely burnt there and the piston compresses only exhaust gases (nitrogen and steam/water). This phenomena is observed between the 2^{nd} and the 4^{th} second presented in the Fig. 1.a. Just pass the 4^{th} second hydrogen was cut off, hence non-firing events are observed in further engine test.

Summing up, the abnormal combustion described in this section can be caused by coincidental ignition of the hydrogen-air mixture inside the cylinder. This randomly occurred ignition can result from hot spots residuals present inside the engine cylinder or hot surface taken place elsewhere in the combustion chamber. However, hot surface of the spark plug electrodes can be considered as the most probable reason for this uncontrolled pre-ignition.

Backfires

Backfiring events presented in this section concern flame propagation from the exhaust to the intake through valves overlap. Reason explaining fresh charge ignition in the exhaust pipe was the hot surface of the O2 ("lambda") sensor installed in the exhaust manifold in too short distance from the engine outlet. The wide-band O2 sensor applied to the test bench was the LZA03 by NGK/NTK. Its working temperature is 600°C (873.15 K) and is higher than auto-ignition temperature of hydrogen-air stoichiometric mixture.

As depicted in the Fig. 2, just pass the proper combustion event (on the left) the next event features itself with remarkably lower peak pressure. The second trace shows pressure in the intake manifold.

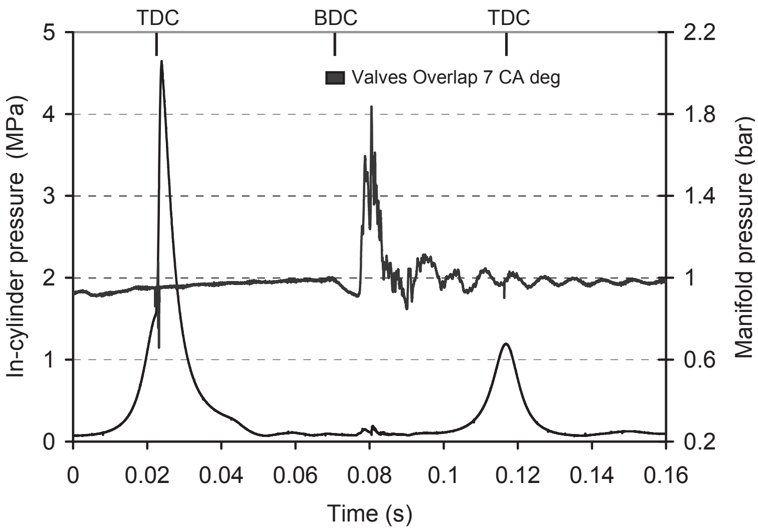

Fig. 2. In-cylinder pressure and intake manifold pressure in the hydrogen fuelled engine with supercharging p_{boost} *= 0.2 bar, λ = 1 and ST = 4 CA deg BTDC*

Rapid increase in this pressure during valves overlap leads to conclusion that the mixture was ignited. Someone assumes that fresh hydrogen mixture, passing through the cylinder into the exhaust manifold while overlapping, is ignited in the exhaust manifold by the O2 sensor hot surface and then flame propagates back at extremely high speed through valves overlap into the intake manifold.

The phenomenon was not observed while the engine was working as the freely aspirated one. In case the O2 sensor was switched off the backfire was not observed as well.

Pre-ignition by the spark plug ignition system

Hydrogen-air stoichiometric mixture features itself with extremely low minimum ignition energy of 0.017 mJ at NTP [9] that provides high probability of coincidental ignitions at various moments in time. For instance, gasoline minimum ignition energy is approximately 0.29 mJ. This unexpected ignition was observed while the ignition system applied to the engine generated short discharge resulted from positive slope of the current flowing through the ignition coil. Such discharge was unable to ignite gasoline mixture but it was found to be effective enough to initiate burning hydrogen. As shown in the Fig. 3.a these abnormal combustion events are randomly distributed over time. The Fig. 3.b depicts the same pressure history against the engine crank angle. These random combustion events start around the point located at 40 CA deg BTDC. At that time start of charging the coil, followed by rapid increase in the current, took place.

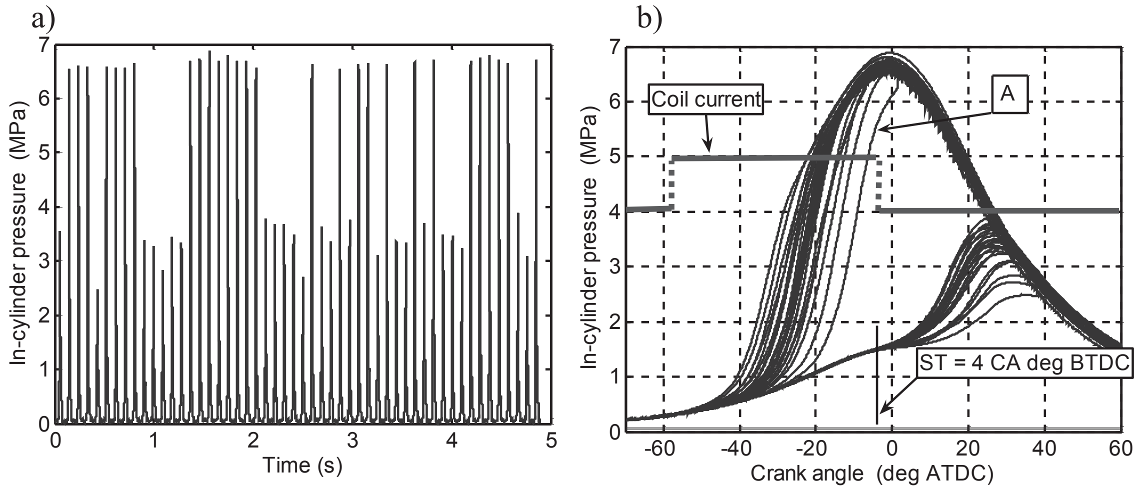

Fig. 3. Time based in-cylinder pressure (a), crank angle based in-cylinder pressure (b) from the hydrogen fuelled engine with supercharging p_{boost} = 0.4 bar, λ = 1 and ST = 4 CA deg BTDC

Such the advanced spark ignition can lead to knock. Following these expectation, some combustion events (e.g. cycle A) were found to be charged with the knock, as it was seen on the combustion pressure trace in the Fig. 4.

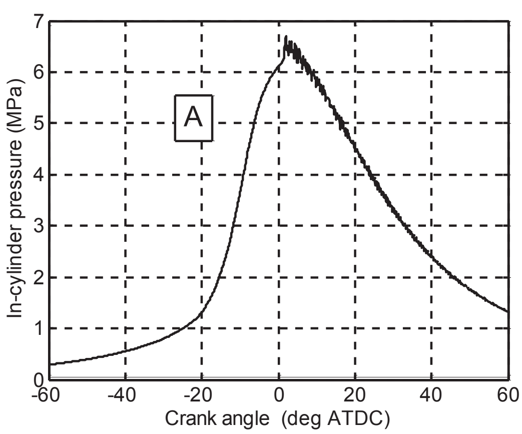

Fig. 4. In-cylinder pressure with knock symptoms in the hydrogen fuelled engine with supercharging p_{boost} = 0.4 bar, λ = 1 and ST = 4 CA deg BTDC

Non-firing events

Although abnormal combustion deals with firing events but non-firing events can be treated as the combustion anomaly leading to unstable engine work. It was observed that non-firing events could occur in the engine fed hydrogen even though the spark ignition system properly works and provides discharge between spark plug electrodes as depicted in the Fig. 5. Such phenomenon was observed while the engine was working with boosting pressure systematically increasing. Above the boosting pressure threshold of 0.5-0.6 bar the engine stopped working. As found the spark gap was too long. Hence, flame kernel was highly wrinkled by high turbulence and quickly extinguished with no chance to be re-ignited. By reducing the gap from 0.7 to 0.3 mm the engine was working stable at boost overpressure increased up to 1.6 bar.

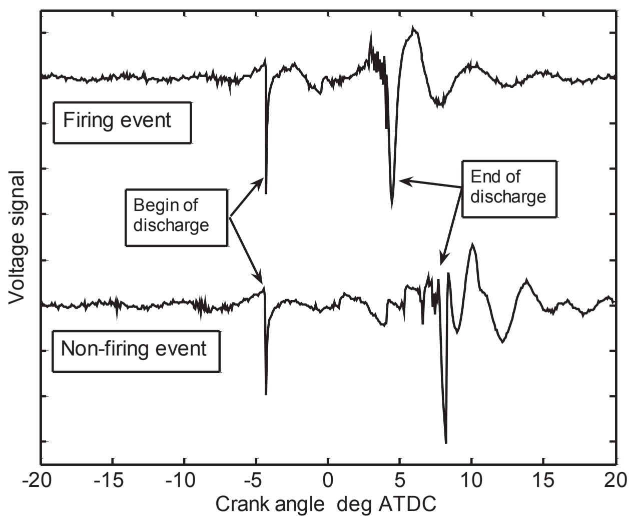

Fig. 5. Signal from a high-voltage probe for firing and non-firing event

3. Conclusions

To avoid or reduce the abnormal combustion to marginal effect the following measures should be taken into account:

– The most difficult is to eliminate hot spots located in the cylinder combustion chamber. As they are not only deposits but also some exhaust residuals coming from unburnt lubricating oil the effective remedy to be proposed is to reduce combustion temperature, e.g. by burning lean mixtures or applying EGR.
– Eliminate spark discharge while positive slope of the ignition coil current appears. It requires modifications in an electronic system for generating ignition pulses.
– Decrease the spark plug gap to provide the spark discharge stable and prevent flame kernel from blowing out.
– For supercharged engines: eliminate engine overlap, even though the charging pressure would not be remarkably high.

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