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HYDROGEN COMBUSTION IN THE SUPERCHARGED SI ENGINE

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Abstract

The experimental results of combustion pressure processing from a supercharged spark ignition (SI) engine that was running on hydrogen are exposed in the paper. Hydrogen was delivered in two ways by an injector and mixer installed in an intake port. In–cylinder pressure while combusting hydrogen was analyzed with various coefficient of stechiometry and boost pressure. These parameters were limited by abnormal combustion known as "knock" combustion. Hydrogen fueled engine has tendency to generate "knock", especially this abnormal combustion phenomena increases with increase in boosting pressure. Hence, the thermodynamic parameters such as pressure and temperature of fresh air fuel mixture are elevated. The experimental numeric data analysis permit for compare to naturally aspirated engine such parameters as mean indicated pressure, indicated efficiency. Also for both cases, the coefficient of variation for mean indicated pressure was determined. It was found that combustion duration shortens itself with higher boosting pressure. Thus, optimal spark timing to get the maximum indicated mean effective pressure is shifted closer to the TDC. Another parameter that was expected to be increased was the knock intensity. It was observed, that knock intensity did not increase significantly and was still below the limit for pressure pulsations treated as combustion noise coming from light combustion instabilities.

Keywords: *hydrogen, knock, supercharged engine*

1. Introduction

Hydrogen as an engine fuel has it beginnings in the XIX century, and then idea of a hydrogen fueled engine was proposed by William Cecil. Nowadays, hydrogen as engine fuel might be in use as follows:

- fuel to a combustion engine,
- fuel to fuel-cells.

Hydrogen as engine fuel has specific properties, which may be counted as: wide flammability limits, no carbon in fuel particle, low ignition energy and high self ignition temperature, which is 856 K. These properties cause that exhaust gases from the hydrogen engine have only water and nitrogen. There are no exhaust components such as carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (HC) [1-4,12]. Additionally, nitrogen oxides (NO_x) are present. Their emission is caused by high in–cylinder temperature and sufficient combustion time. The maximum in–cylinder combustion temperature can be decreased in several ways: by running an engine with high excess air ratio (lambda) $\lambda>1(\phi<1)$, by exhaust gas recirculation (EGR). High velocity of laminar flame in a hydrogen engine approaches the engine combustion process to ideal constant–volume cycle, which improves thermal efficiency of such the engine [2]. Low energy of hydrogen ignition which is approximately 0.02 mJ (for gasoline 0.2 mJ) may cause pre–ignitions from hotspots located in the combustion chamber [5]. Furthermore, hydrogen can be used as an additional fuel into co–combusting with liquid fossil fuels like diesel fuel [6,12]. Unfavourable phenomena in a combustion engine fueled with hydrogen are backfires to intake manifold as Verhelst et. al wrote in [5], intensification of such phenomena occurs especially when the engine works with near stoichiometric and rich air – hydrogen mixtures. Because hydrogen features with lower energy density by volume, the hydrogen engine generates less power in comparison to the conventional gasoline fueled engine [2-4,7]. To compensate these power losses is to apply boosting the engine fueled with hydrogen [3] that leads to increase of fresh charge density or by direct injection of hydrogen into the engine cylinder [4]. Boosting the combustion engine leads to increase in thermodynamic parameters of fresh charge. As a result, especially in hydrogen engine, the probability of the knock combustion also increases with higher boosting pressure. As found, there is strong correlation between temperature of fresh charge and its dilution at ignition point and possibility of higher knock intensity [8]. Knock limits the maximum compression ratio, what leads to decreases on engine performance and efficiency [9] and affects negatively engine durability[10-13, 15]. The effective way to decrease knock phenomena is to add exhaust gases (EGR) to fresh charge [14]. Verhelst et. al [4] in his work proves that boosting the hydrogen engine can narrow the air-hydrogen ratio to lean at minimum $\lambda = 1.3...1.4$, as a measure for limiting potential backfires and pre–ignitions.

2. Test bed description

The test bed is equipped with the 1HC102 engine modified to work as supercharged hydrogen fueled one. It is coupled with a synchronous power generator. Test bed data are depicted in the Tab. 1. As mentioned, the engine was modified to run on hydrogen and equipped with a capacitive ignition system and a spark plug mounted in a diesel injector seat. The synchronous generator is controlled by the frequency converter, thus it works as a motor to start up the engine. After the synchronization with the power grid, the synchronous generator is used as a dynamometer and to stabilize engine rotational speed. Compression ratio (CR) of the engine was decreased from CR = 16 to CR = 8.6, by modification of a piston crown and the in-piston combustion chamber. Test bed is also equipped with the Root’s type screw supercharger EATON (M 65) powered by an asynchronous motor and a fresh charge intercooler mounted pass the supercharger in the intake manifold.

During research, the following signals were recorded:

- in – cylinder pressure (Kistler 6055sp100),
- intake pressure (MPX 4250),
- fresh charge temperature (DS 18B20),
- crank angle (encoder with resolution 1024 imp/rev),
- top dead centre pulse (encoder with resolution 1024 imp/rev),
- air consumption by the engine (rotor flow meter COMMON CGR – 1),
- hydrogen consumption by the engine (rotor flow meter COMMON CGR – 1),
- oxygen content in the exhaust with wide-band oxygen sensor NGK/NTK with controller UEGO TC 6300A.

Voltage signals from sensors were collected on a PC computer with aid of the LabView software and the data acquisition system NI USB 6251.

During research the in–cylinder pressure for the naturally aspirated (NA) and the supercharged (SC) engine were collected. Hydrogen was delivered to the engine by mixing device fixed in the intake port. On the basis of measurements, parameters as follows were determined: ignition timing for maximum IMEP (Indicated Mean Effective Pressure), maximum IMEP, coefficient of variance for IMEP (COV_{IMEP}), combustion phase defined as difference between peak combustion pressure angle (PPA) and ignition timing (IT). Boost pressure for the supercharged engine was varied in the range $p_{boost} \approx 1.5...1.9$ bar. The temperature of fresh charge for both type of the engine was in range $T_C = 19...75$°C. The excess air ratio for air–fuel mixture was in range $\lambda = 0.5...1.8$. In both cases for the NA and the SC engine the ignition timing was sweeping from 0 to -10 CA deg ATDC (after TDC). A list of test parameters is presented in the Tab. 2.

Tab. 1. Parameters of test bed 1HC102[12]

Parameters	Dimension	Value
Engine		
Type	-	4 stroke, water cooled, spark ignition
Number of cylinders	-	1 - horizontal
CR	-	8.6
Revolution speed	Rpm	1270
Bore	Mm	102
Stroke	Mm	120
Displacement	Ccm	980
Dynamometer		
Synchronous motor	V	3x230
Output power	kVA	20
Boost system		
Supercharger		EATON M65
Boost pressure	Bar	0÷1.9

Tab. 2. Parameters for hydrogen combustion tests in the NA and the SC engine

	NA engine	SC engine								
P_{boost} bar	–	1.5	2.0	1.95	2	1.91	1.92	1.91	1.93	1.88
$T_{\text{ład}}$ ° C	15	20	19.8	22.2	52	56	67	70		75
α_{zap} deg	0-7	0-12	0-4	0-4	0-8	0-4	0-4	2		2
λ	1.8	1.3	0.57	1.27	0.7	0.5	1.42	1.24	0.75	1.5

Boost pressure was set by a bypass channel with a throttle in the supercharger.

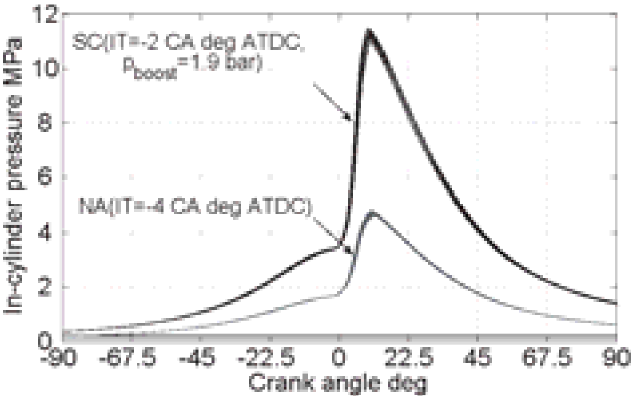

Fig. 1. Comparison between combustion pressure in the NA and the SC engine

Figure 1 shows exemplary test series consisted of 20 engine working cycles from the NA and the SC engine. On the basis of the test series the calculations for the mean indicated parameters were done. These plots were used to compare the parameters for the NA and the SC engine.

3. Results and discussion

Figure 2 shows IMEP and COV_{IMEP} against ignition timing (IT) for the NA engine, there the excess air ratio was $\lambda = 1.3$ and $\lambda = 1.8$ and the SC engine. These plots show how the ignition timing impacts on the maximum IMEP. As found, the optimal spark timing α_{IT} equals nearly -4 CA deg after TDC for the NA engine at lambda varying from 1.3 to 1.8.

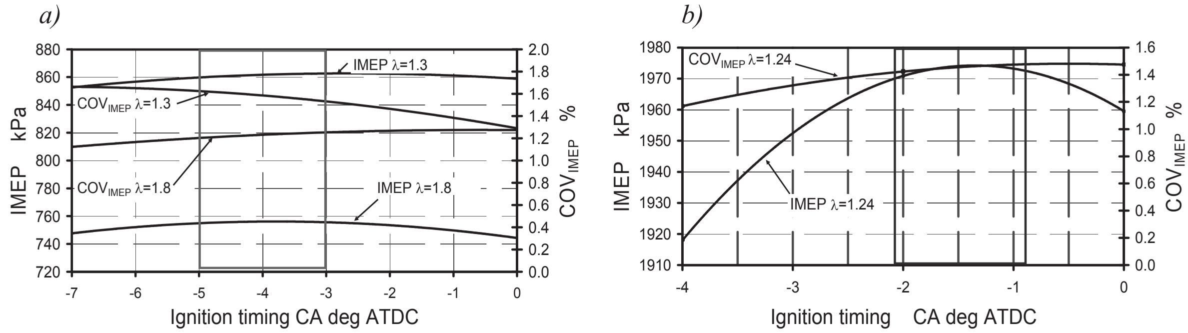

Fig. 2. IMEP and COV_{IMEP} for the NA engine (a) and the SC engine (b)

Indicated mean effective pressure at this optimal ignition timing takes maximum value as shown in the Fig. 2 marked with a hatched area. The highest indicated mean effective pressure at the excess air ratio $\lambda = 1.8$ was IMEP = 757 kPa and at the excess air ratio $\lambda = 1.3$ was IMEP = 862 kPa. Coefficient of variance for IMEP at the excess air ratio $\lambda = 1.8$ was in range $COV_{IMEP} = 0.8…1.6$ % and at the excess air ratio $\lambda = 1.3$ was in range $COV_{IMEP} = 1.6...1.8$ %. Temperature of fresh charge was approximately $T_C \approx 51°$ C. For SC engine where the excess air ratio lambda was $\lambda = 1.24$ optimal ignition timing to get the maximum IMEP was $\alpha_{IT} = -2$ deg ATDC. Maximum value for indicated mean effective pressure for SC engine was IMEP = 1970 kPa and coefficient of variance for IMEP was in range $COV_{IMEP} = 1.2…1.5$ %.

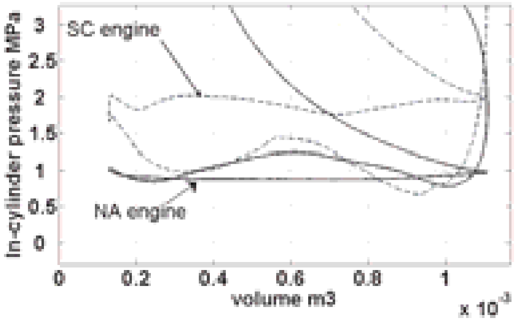

Fig. 3. Charge exchange area in the p-V diagram for the NA and the SC engine

Figure 3 shows charge exchange area in the p – V diagram for both the NA and the SC engine. The boosted engine is characterized with higher intake pressure, it was almost twice higher than in the NA engine. As seen, the in-cylinder pressure during compression stroke is also significantly higher in the SC engine than in the NA engine that results the peak combustion pressure increases due to both higher amounts of fresh charge and higher energy delivered to the cylinder.

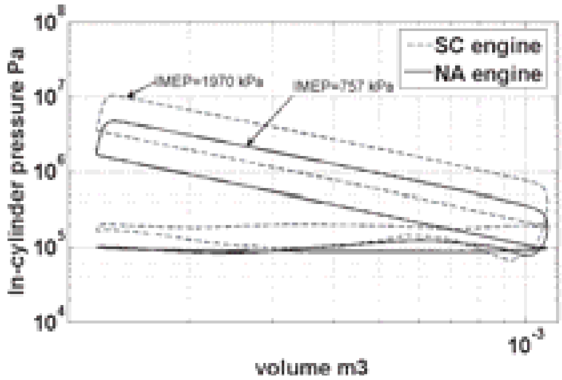

Fig. 4. p – V diagram in logarithmic scale for the NA and the SC engine

As depicted in the Fig. 4, the overall IMEP comes not only from higher combustion pressure but also it is increased by the positive area of the charge exchange. However, its influence is marginal in comparison to combustion area.

Figure 5 shows combustion phase CA_{pp}-CA_{IT} against ignition timing.

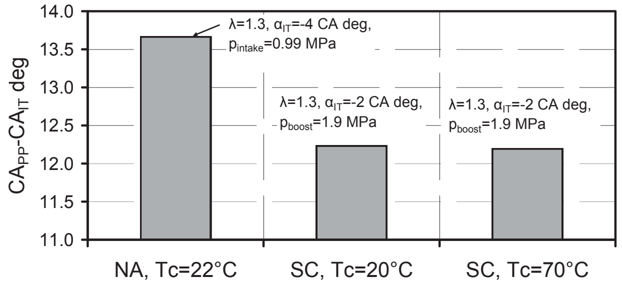

Fig. 5. CA_{pp}-CA_{IT} for NA and SC engine

As depicted, in the NA engine the CA_{pp}-CA_{IT} parameter is higher then in the SC engine by approximately 1.5 CA deg. In the SC engine the CA_{pp}-CA_{IT} insignificantly varies with intake temperature increase from 20 to 70°C that resulted from the intercooler removal. At optimal spark timing of -2 CA deg ATDC, the CApp-CAIT equals 12.2 CA deg in the SC engine. The CApp-CAIT can be considered as the combustion duration as defined earlier.

Figure 6 shows crank angle based history of the high frequency pressure fluctuations filtered from the in–cylinder combustion pressure (p_{fluc}) for these two engines. It was determined for working cycles at fixed both the ignition timing and the lambda. As seen, the mean peak pressure fluctuations in the boosted engine do not increase remarkably with temperature change from 22 to 70°C. It does not exceed 50 kPa (Fig.6.a-b) that should lead to conclusion about light, near marginal hydrogen combustion knock similar pressure fluctuations generated during stable combustion and called as combustion noise [10]. While the engine was naturally aspirated the pressure fluctuations dropped by twice to 20 kPa (Fig.6.c). Such the insignificant pressure fluctuations were mainly generated as result of relatively low engine compression ratio, so lower temperature at ignition.

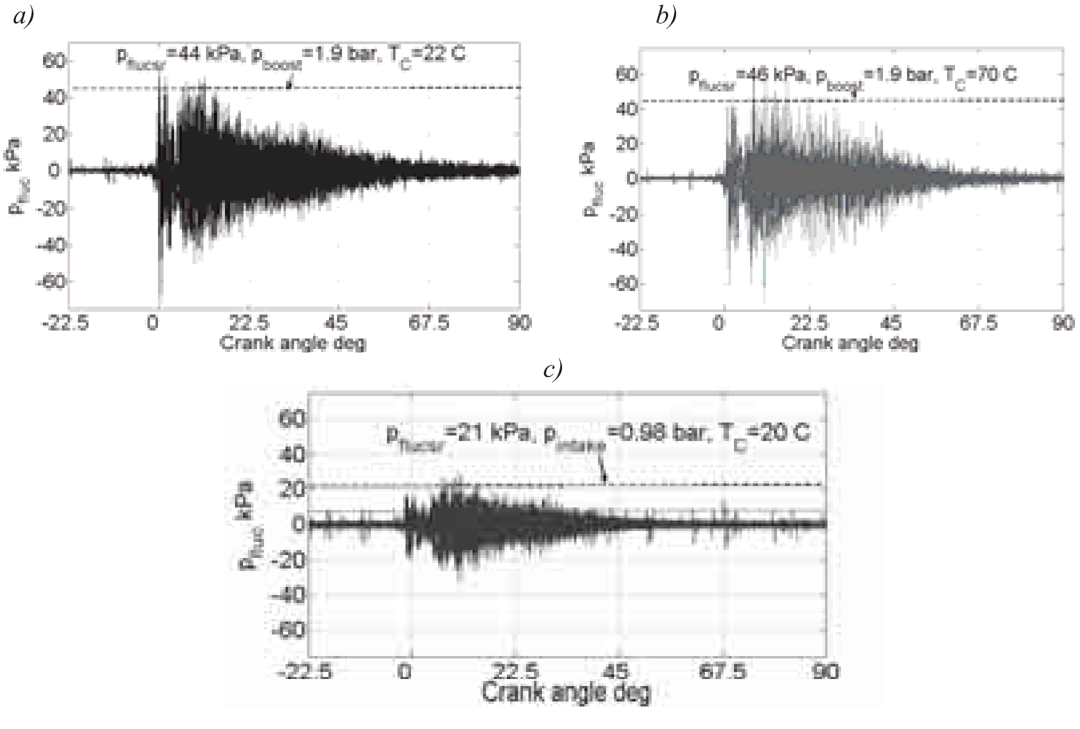

Fig. 6. p_{fluc} for the SC engine (a,b) and the NA engine (c) with the parameters provided in the figures

4. Conclusions

On the basis of measurements done during research plan with the fueled hydrogen both naturally aspirated and supercharged engine the following conclusions can be obtained:

- supercharging the hydrogen fueled engine is effective measure to increase engine performance without potential knock symptoms at reasonable compression ratio of 8.6 as taken to these tests. The highest IMEP of 1970 kPa was achieved at boost pressure of 1.95 bar, lambda $\lambda = 1.3$ and ignition timing -2 CA deg ATDC. Mixture with lambda 1.3 provided stable combustion without backfires. Enriching the mixture to stoichiometric ratio made several backfires to the intake manifold,
- with the fresh charge, temperature increase from 20 to 70°C, and the boost pressure of 1.9 bar increase in the knock intensity was marginal. Knock intensity expressed by the mean from maximal fluctuations was 46 kPa at this combustion case. Such the insignificant knock intensity was mainly caused by relatively low compression ratio of 8.6,
- optimal spark timing to obtain maximum in the IMEP for the supercharged engine with boosting pressure of 1.9 bar was around -2 CA deg ATDC on the contrary to the same type but naturally aspirated engine, where the optimal spark timing was more advanced and equalled -4 CA deg ATDC in this case.

Acknowledgment

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