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# Combustion stability for early and late direct hydrogen injection in a dual fuel diesel engine

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*The paper presents an analysis of the experimental results of direct hydrogen injection in a dual-fuel diesel engine. The test object is a four-cylinder, four-stroke ADCR engine. The parameters like: indicated mean effective pressure, peak pressure, angle of maximum pressure and released heat were analyzed. Statistical analysis of the obtained results was carried out for each cylinder separately for four different hydrogen doses. Both early and late direct hydrogen injection were analyzed. The significance of the differences for each of the analyzed parameters and type of injection was determined. The stability of the combustion process was evaluated using the coefficient of variation CoV(IMEP).*

Key words: *diesel engine, direct hydrogen injection, dual fuel, combustion engine, hydrogen*



## 1. Introduction

The changed market trends for the further development of internal combustion engines [22] and alternative fuels in vehicles [20] have not stopped research work in this area. In particular, the use of hydrogen, both in the combustion process in internal combustion engines [1, 11, 12] and its obtaining [6, 22] has been consistently popular among scientists. Ongoing research involves both spark-ignition [21] and compression-ignition engines [9, 10]. The experiments conducted just a few years ago let us identify high-pressure direct injection and cryogenic injection technologies in internal combustion engines for further development [7, 8]. Although it is the automotive field internal combustion engines that have led the way over the past decades, they can be applied much more wider, i.e. in aviation [3, 5, 18], marine [2] and stationary applications [14, 15], which justifies their further research. The internal combustion engine emissions admittedly are problematic, but modern fuel cell electric vehicles also require much research and development [4].

The results presented in this publication are a continuation of the research that includes the analysis of the combustion process in a dual-fuel diesel engine with direct hydrogen injection.

The paper [16] presents the results of the study that compares particulate emissions in early and late hydrogen direct injection. The particulate emissions were investigated with a Semtech Ecostar exhaust gas analyzer. In general, the particulate emissions were lower for late hydrogen injection than for early, especially for lower hydrogen doses and loads. Overall, late hydrogen injection resulted in a 23% decrease in particulate emissions relative to early injection. Increasing the hydrogen dose resulted in a multiple increase in particulate emissions and approaching the engine rumble limit.

Combustion process analysis was continued in the paper [17] and the following parameters were studied then: indicated mean effective pressure, maximum pressure, peak pressure angle and heat released. This analysis focused on determining whether there are significant differences between early and late injection. The study case was a single cylinder.

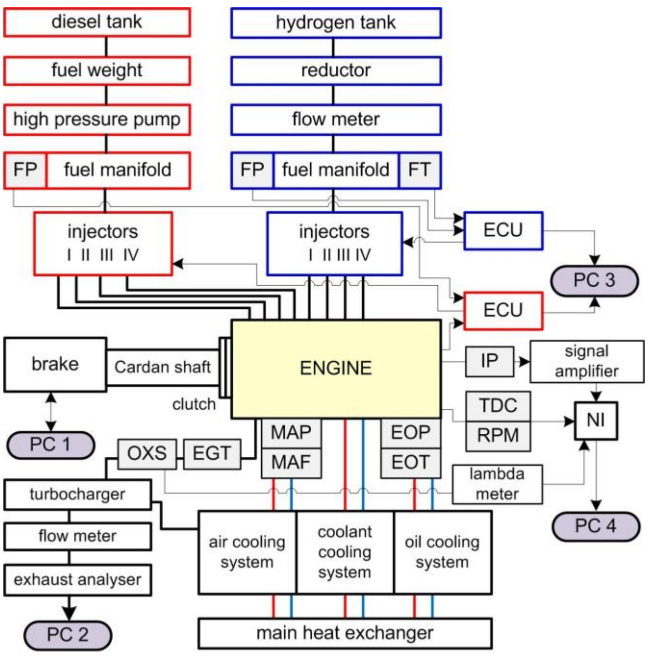
The statistical analysis in the designed experimental plan was globally performed for the various measurement points and indicated that there were no significant differences between early and late hydrogen injection. However, when the selected conditions were separately analyzed, the differences were statistically significant. The relatively large standard deviations for some measurement points may indicate instability in the combustion process. As the load and the share of hydrogen increased, the unrepeatability of the operating process increased. There was a clear phenomenon that required a more detailed analysis so, it was decided to check how the combustion process proceeded in each cylinder separately at the highest engine load. The results of the analysis are presented in this paper.

## 2. Materials and methods

The test object is an ADCR, 4-cylinder, 4-stroke engine with a displacement of 2,636 cm$^3$ and a compression ratio 17.5. The glow plugs were replaced by injectors of compressed hydrogen. A view of the test stand is shown in Fig. 1, and a schematic diagram is shown in Fig. 2.

The indicated mean effective pressure, peak pressure, the angle it occurs at and the heat released for four cylinders and four different doses of hydrogen were investigated. The unchanging parameter was the pilot dose of diesel fuel and the initiating torque was experimentally determined as the maximum for the research object. The research plan assumed changing only one parameter – hydrogen injection time, i.e. early (40° after TDC, E symbol) and late (160° after TDC, L symbol) injection. Thus, the effect of just this single parameter on the combustion process was evaluated. The hydrogen injection pressure was 1.2 MPa. During the tests, each point was recorded three times. The addition of hydrogen caused rumbling at some measurement points, despite the experimental being designed within a safety limit. The tests were planned for the 1500 rpm. This rotational speed was selected from the results of tests determining the load profile where the highest share has the engine load up to 40%, which is 1480 rpm for research object [16].

Fig. 1. Test bench




FP – fuel pressure sensor; FT – fuel temperature sensor; ECU – dedicated and original engine controller; NI – National Instruments; PC1-PC4 – computer units for individual systems; IP – indicator pressure sensor; TDC – crankshaft position sensor; RPM – rotation speed sensor; OP – oil pressure sensor; OT – oil temperature sensor; MAP – manifold absolute pressure sensor; MAF – mass airflow sensor; OXS – lambda sensor; EGT – exhaust gas temperature sensor

Fig. 2. Diagram of the dynamometer stand

The unrepeatability of the individual cylinders was analyzed and the significance of the differences was determined for the two types of direct hydrogen injection: early and late. Although hydrogen was supplied directly to the combustion chamber, the so-called early injection is similar to indirect injection. Late injection was specified from the preliminary tests of the object, in order to maximize the obtained power and not disrupt the combustion process.

## 3. Results and discussion

Observing the average values of the results only highlights differences between cylinders and injection times but their nature is unknown. This situation makes it difficult to analyze injection and its effect on the combustion process so box-and-whisker plots were made. Fig. 3 shows how the measurement points were marked.

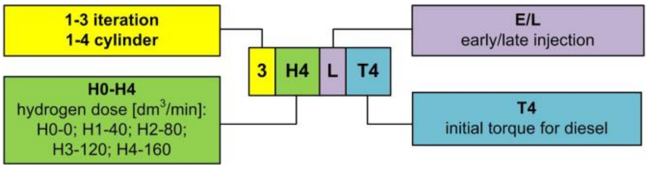



Fig. 3. Measuring points

Fig. 4–7 show the mean, standard error and standard deviation for the analyzed combustion parameters for each cylinder separately (C1–C4). Each measurement point was repeated and recorded three times. Fig. 4 shows the average values of the indicated mean effective pressure, Fig. 5 shows the maximum pressure values, Fig. 6 shows the values of the maximum pressure occurrence angles, and Fig. 7 shows the released heat for each cylinder separately (C1–C4). The first point is the values obtained for diesel fuel only (H0), the subsequent ones should be considered in pairs (H1E-H1L). The first is early injection (E), the second is late injection (L). The results are shown for four increasing hydrogen shares (H1–H4) and one initial torque for diesel T4 (150 Nm). The maximum torque obtained was 180 Nm at maximum hydrogen flow (H4).

The above graphs suggest the need for a closer analysis of the phenomena occurring in the individual cylinders. At certain measurement points, large standard deviations are apparent. The combustion process in the C4 cylinder deviates from the others at the highest shares of hydrogen. The combustion process needs to be examined in detail to understand the nature of the observed phenomena.

The pressure was measured using AVL GH14D pressure sensors installed in the combustion chamber. The indicated pressure in all cylinders and the crankshaft position were recorded. The heat release during combustion depends mainly on the fuel injection process in the combustion chamber. The heat release rate is determined by the volume of fuel burned per 1 CAD [13]. This value is used to determine the cumulative heat release. Calculation of the heat release rate is carried out based on the equation [24]:

$$\frac{dq_s}{d\alpha} = \frac{1}{\kappa - 1} \cdot \left( V_x \cdot \frac{dp}{d\alpha} + \kappa \cdot p \frac{dV}{d\alpha} \right) \quad (1)$$

where: p – in-cylinder combustion pressure; α – crank angle; $q_s$ – heat release during combustion; κ – the ratio of the specific heats ($c_p/c_v$) at constant pressure and constant volume, respectively, κ = 1.3; $V_x$ – in-cylinder volume.

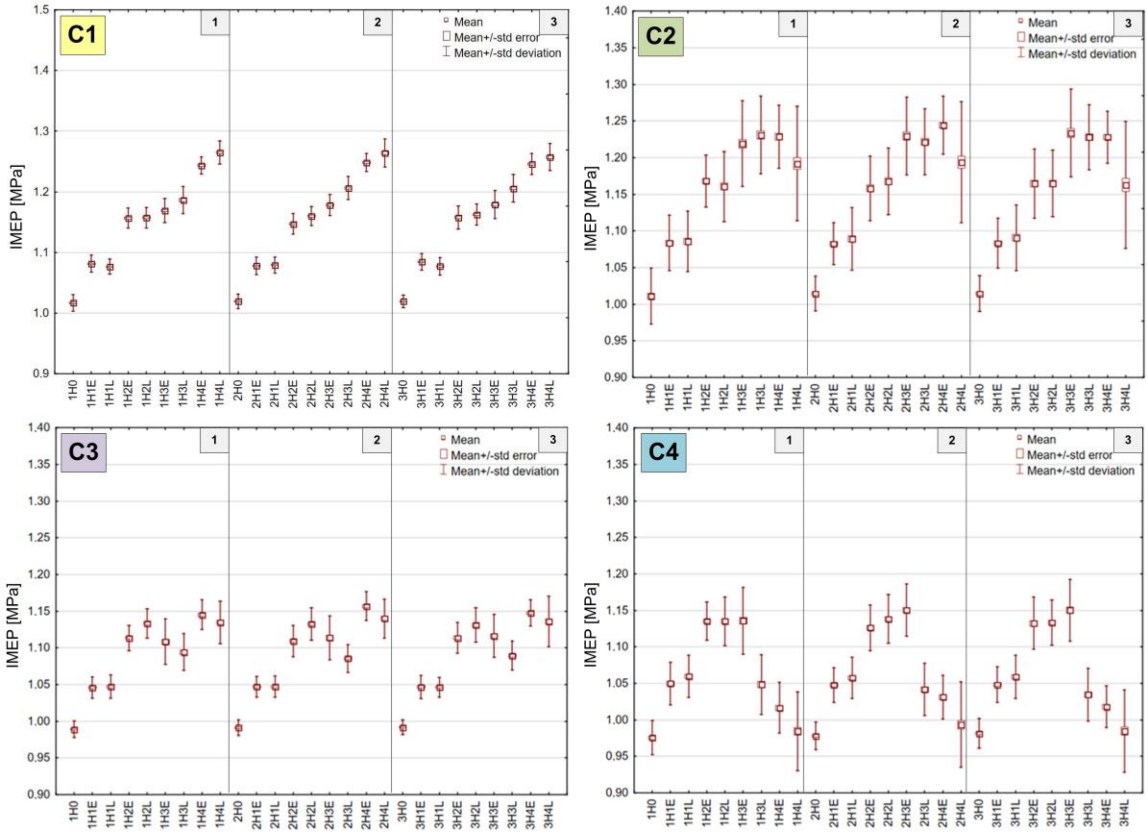



Fig. 4. Box-whisker for the IMEP in all cylinders

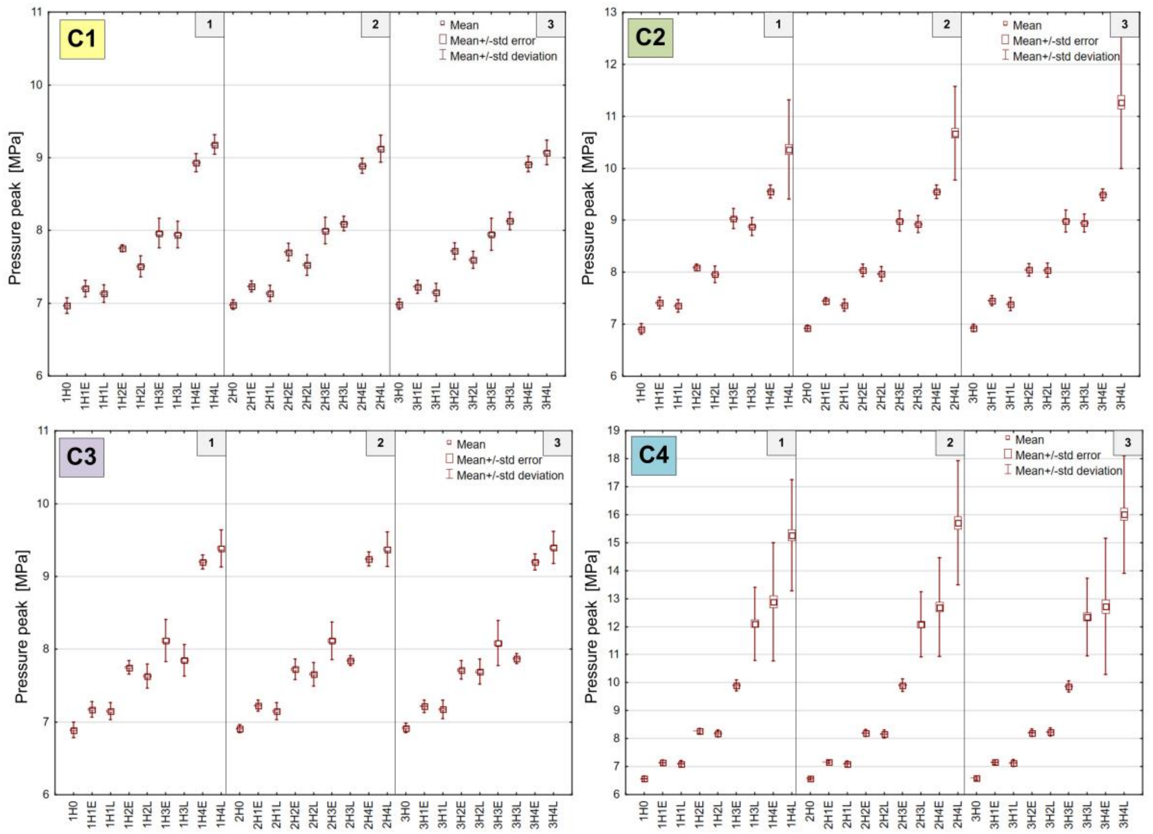



Fig. 5. Box-whisker for the pressure peak in all cylinders

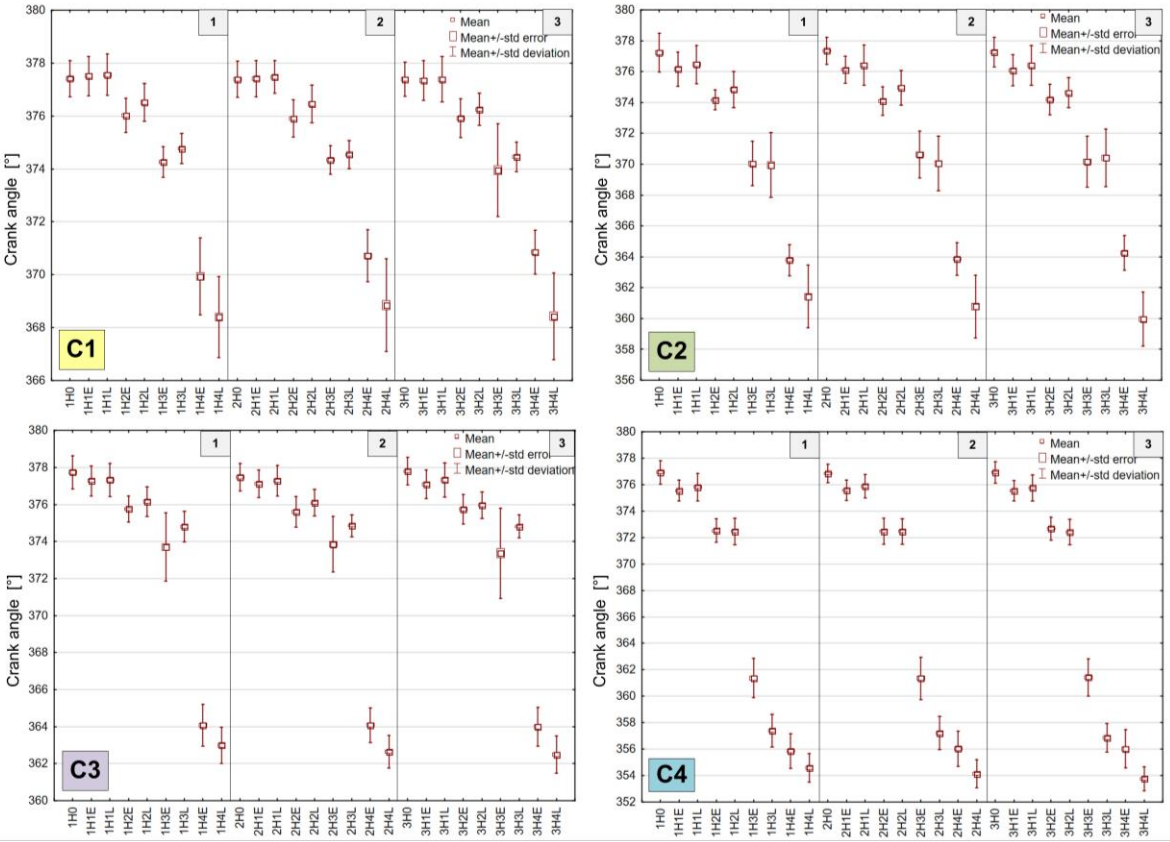



Fig. 6. Box-whisker for the crank angle of pressure peak in all cylinders

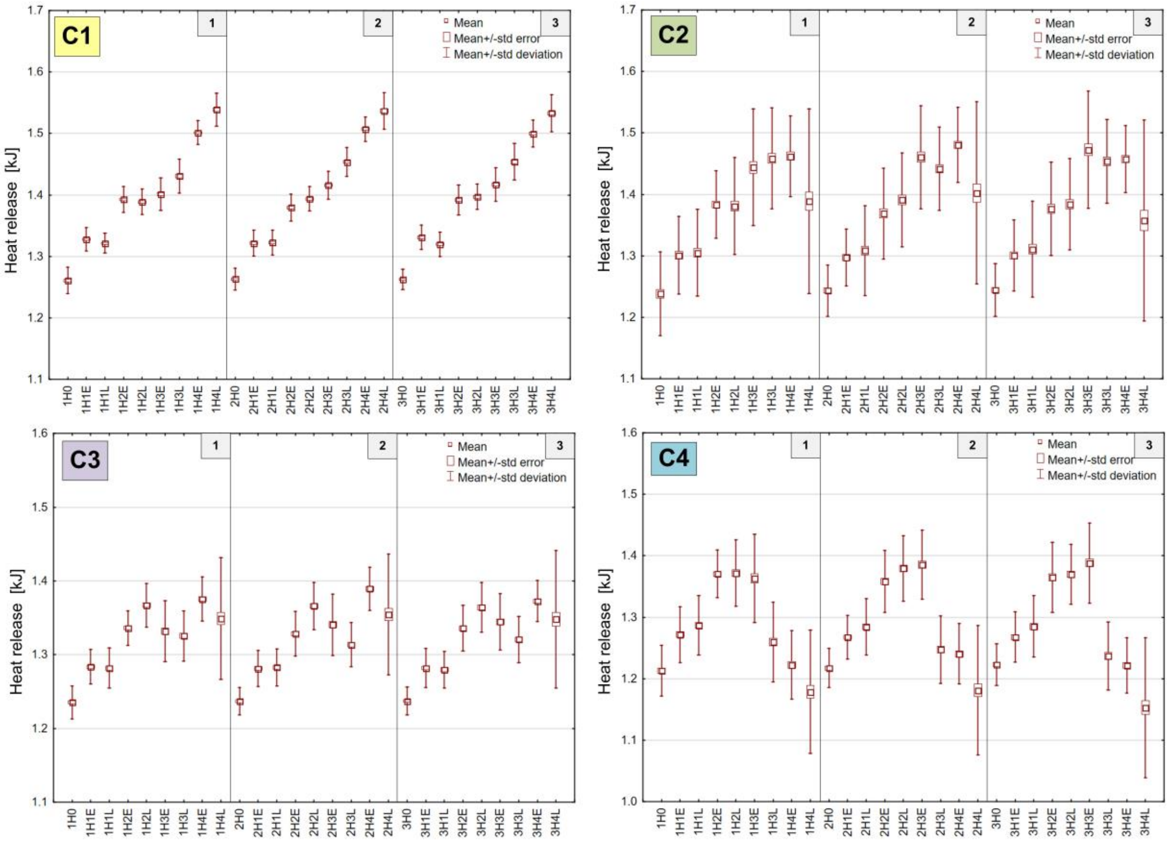



Fig. 7. Box-whisker for the heat released in all cylinders

## 4. Analysis

The main purpose of the analysis is to determine whether there are significant differences between early and late hydrogen injection for a single cylinder for the selected combustion process parameters. A comparison of the combustion process between cylinders is also an important part of the study.

A Student's t-test analysis was performed for this purpose, and the significance of differences between the analyzed parameters was determined. The null hypothesis of the absence of significant differences between groups was put forward in the following form:

$$H0: \beta i = \beta i^*$$

and the alternative (there are differences between the groups):

$$H1: \beta i \neq \beta i$$

A significance level of $\alpha = 0.05$ was chosen. For the indicated significance level, $t_\alpha = 1.984$ was the boundary value.

The same methodology was followed for all the conducted analyses. The Student's t-distribution tables let us claim that:

1. The results of the analysis are not in the critical area, as $t_i < t_\alpha$ for the analyzed parameters. This means that, according to the analysis, there are no significant differences between the analyzed groups so at a significance level of $\alpha = 0.05$, there are no grounds to reject the null hypothesis H0 in favor of the alternative hypothesis H1.

or

2. The results of the analysis are in the critical area, since $t_i > t_\alpha$. This means that, according to the analysis, there are significant differences between the studied groups so at a significance level of $\alpha = 0.05$, there are reasons to reject the null hypothesis H0 in favor of the alternative hypothesis H1.

The results of the analyses are shown in the following plots for the individual cylinders when the time of hydrogen injection changed and when only diesel fuel (H0) was burnt. Both single artifacts and instability throughout the entire measurement can be seen. To compare the effect of injection timing, early vs. late hydrogen injection pairs were analyzed. To discuss the combustion uniformity, the six pairs of cylinders (cylinder to cylinder) were analyzed.

Figures 8–11 shows the indicated mean effective pressure to compare the early and late injection for four cylinders and four hydrogen doses, i.e. for 16 pairs of early vs. late. The IMEP curves illustrate a regular combustion process for C1 cylinder. In the other cases, cyclic fluctuations or singular irregularities are apparent.

In seven cases, the Student's t-test did not reject the hypothesis of equality, i.e. it did not detect significant differences between early and late injection, but four of these seven cases involve all four cases for C2 cylinder only, while the remaining three cases involve one each for cylinders C1, C3 and C4 for hydrogen dosage H1 or H2 (1H2, 3H1, 4H2). The reason for such an interpretation of the test

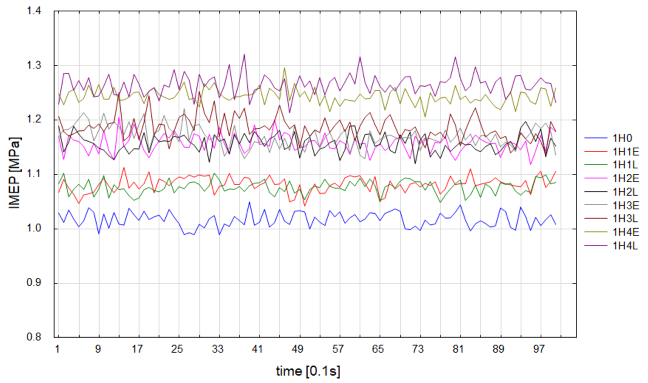



Fig. 8. The IMEP in C1 cylinder

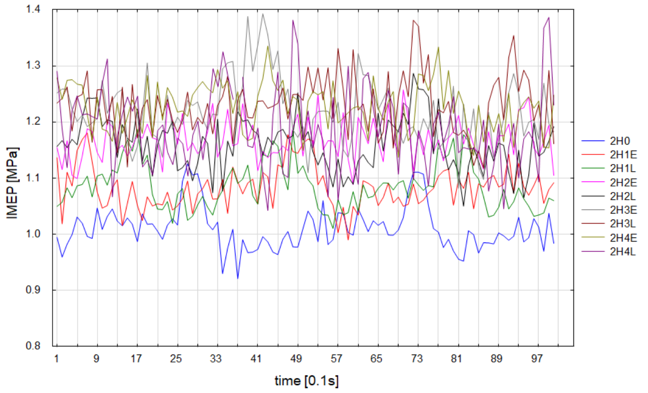



Fig. 9. The IMEP in C2 cylinder

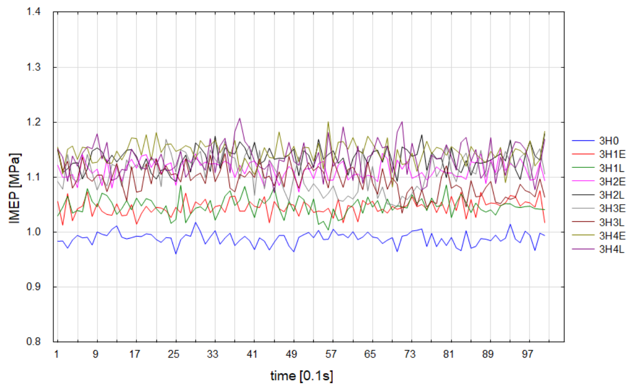



Fig. 10. The IMEP in C3 cylinder

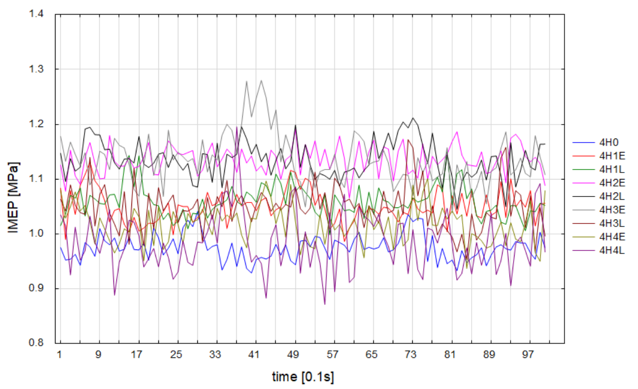



Fig. 11. The IMEP in C4 cylinder

may be more due to large standard deviations than none of differences, which shows the Fig. 4. The application of higher hydrogen doses (H3, H4) shows significant differences for six of the eight measurement points, and for lower doses (H1, H2) for three of the eight points. It can be concluded that the time of injection was statistically significant for IMEP in nine of the sixteen cases of early vs. late injection pairs analyzed.

The indicated mean effective pressure in the individual cylinders was also analyzed for diesel fuel only in order to assess the combustion homogeneity (Fig. 12).

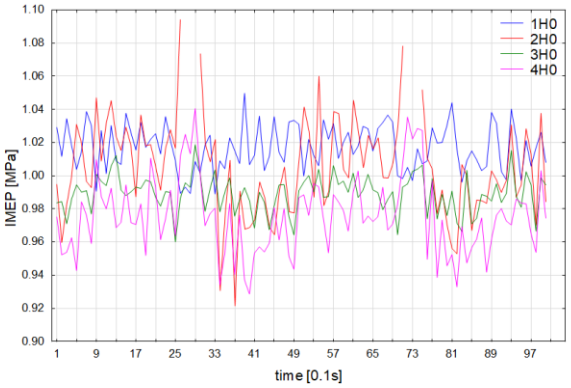



Fig. 12. The IMEP in all cylinders only for diesel fuel

In five of the six cases of the analyzed comparisons, the Student's t-test indicated statistically significant differences. This fact suggests the need to consistently analyze the combustion process independently for each cylinder. The differences may be related to the adopted method of analysis or to the non-uniformity of the test injectors, which may be influenced by the research controller software.

To determine combustion stability and evaluate the differences between early and late injection, coefficient of variation analysis was performed [19]. To evaluate combustion stability, the coefficient of variation of the indicated mean effective pressure CoV(IMEP) is usually taken. This is the standard deviation of the measurement divided by the mean value. CoV(IMEP) was separately determined for each cylinder at successive measurement points. The values of CoV(IMEP) below about 5 % are usually considered desirable since such levels of cyclic fluctuation guarantee smooth engine operation. Figure 13 shows the CoV(IMEP) levels for the recorded operating points. For late injection in the two cylinders at the maximum hydrogen dose, the desired levels of CoV(IMEP) were exceeded, whereas at the other measurement points, the combustion process was stable.

The next analyzed parameter was maximum pressure (Fig. 14–17). Following the same methodology, for maximum pressure, significant differences did not occur only in two cases out of the sixteen analyzed early vs. late injection pairs (1H3, 3H1). This means that the timing of early or late injection in almost 90 % of the analyzed measurement points (14 out of 16) was statistically significant for the maximum pressure values. For the largest applied hydrogen content in the C2 cylinder, single deviations are evident for late injection. In the C4 cylinder, both early and late hydrogen. injection was accompanied by rumbling at the highest (H4) hydrogen dose.

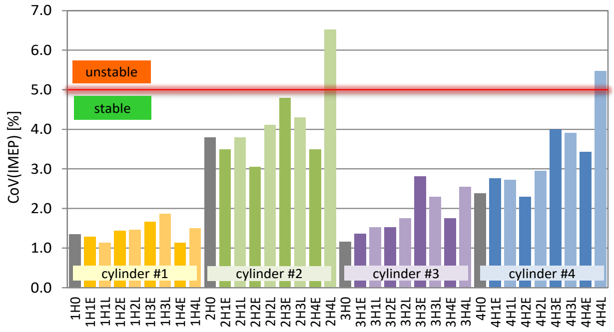



Fig. 13. Coefficient of variation of IMEP for all operating points

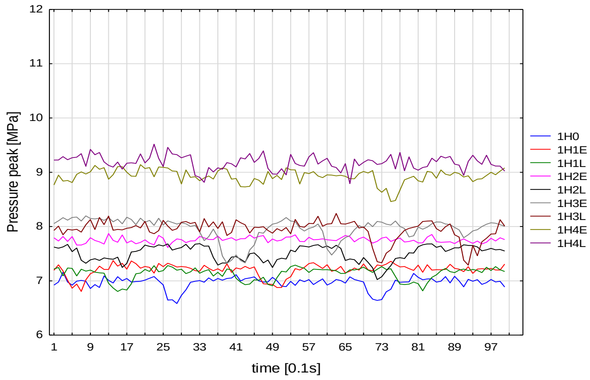



Fig. 14. Peak pressure in C1 cylinder

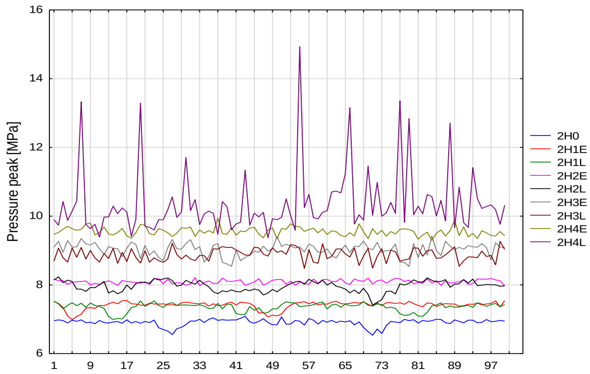



Fig. 15. Peak pressure in C2 cylinder

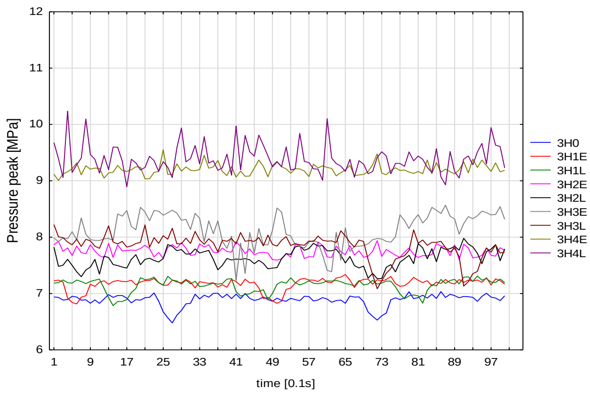



Fig. 16. Peak pressure in C3 cylinder

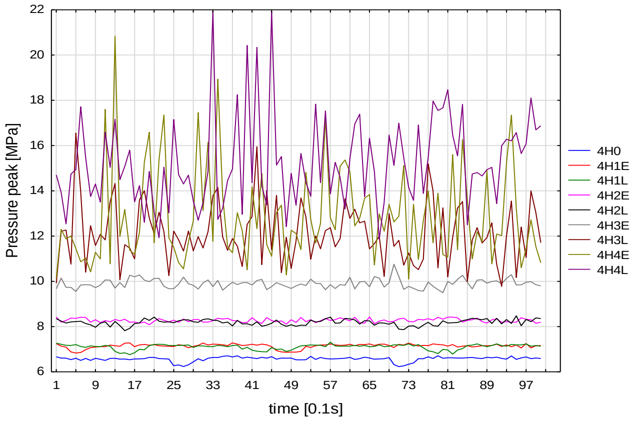



Fig. 17. Peak pressure in C4 cylinder

The maximum pressure in each cylinder was analyzed only when diesel fuel was supplied (Fig. 18). Two pressure fluctuations were observed whose timing matches the IMEP peak in the C2 cylinder. It can also be seen that the maximum pressure in the C4 cylinder is lower than in the other three cylinders.

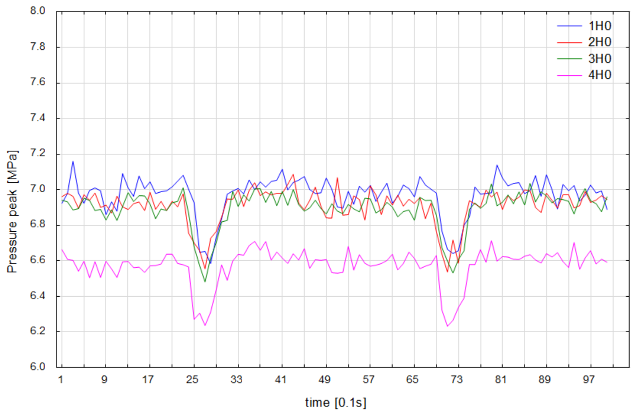



Fig. 18. Peak pressure in all cylinders only for diesel fuel

In five out of the six cases for the four groups analyzed, the Student's t-test indicated statistically significant differences.

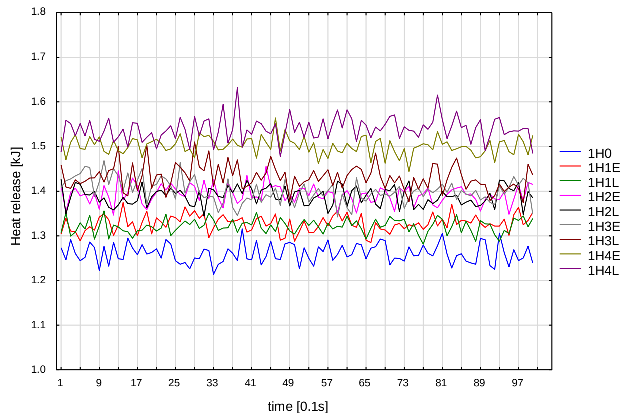



Fig. 19. Heat released in C1 cylinder

The next parameter analyzed was the heat released during combustion in each cylinder and for different hydrogen doses (Fig. 19–22). In the case of C1 cylinder, there are no artifacts, in C3 cylinder they are single, while in C2 and C4 cylinders irregularities in the combustion process for the highest hydrogen doses are well visible. While the early injection caused an increase in heat release, the later injection of hydrogen disrupted the combustion process. The hydrogen dose was not probably completely burned.

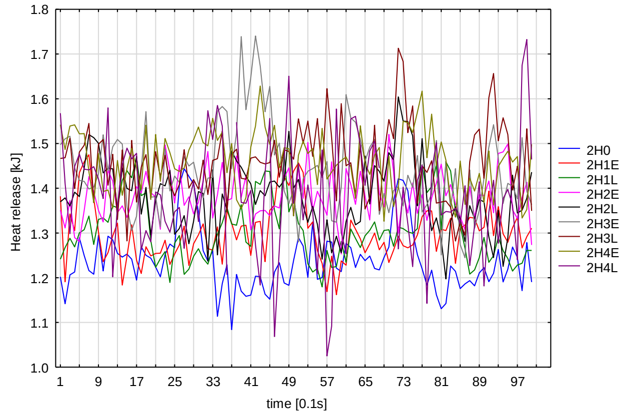



Fig. 20. Heat released in C2 cylinder

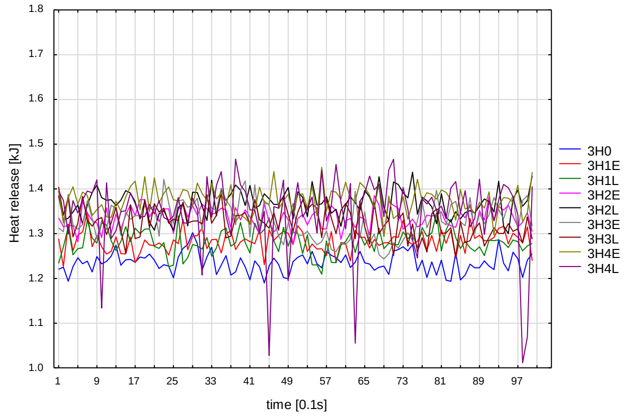



Fig. 21. Heat released in C3 cylinder

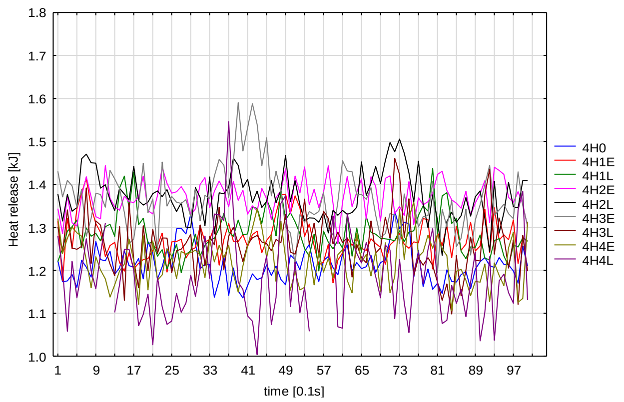



Fig. 22. Heat released in C4 cylinder

The amount of heat released in the individual cylinders on diesel fuel only was analysed (Fig. 23). A heat peak in the C2 cylinder is clear and coincides in time with a local decrease in maximum pressure.

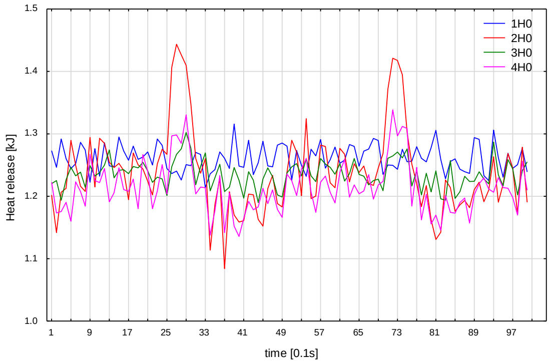



Fig. 23. Heat released in all cylinders only for diesel fuel

In five out of the six cases, the Student's t-test indicated statistically significant differences.

The last parameter analyzed is the angle of maximum pressure occurrence for early and late hydrogen injection (Fig. 24–27). The dominant value for most measurement points is approx. 375 CAD. An increase in the proportion of hydrogen makes maximum pressure occur faster by up to 20 CAD. The late hydrogen injection decreased this value more than the early injection, i.e. it made maximum pressure occur faster.

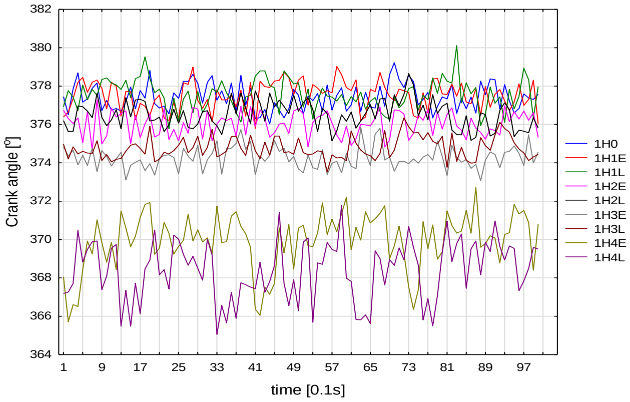



Fig. 24. Crank angle of pressure peak in C1 cylinder

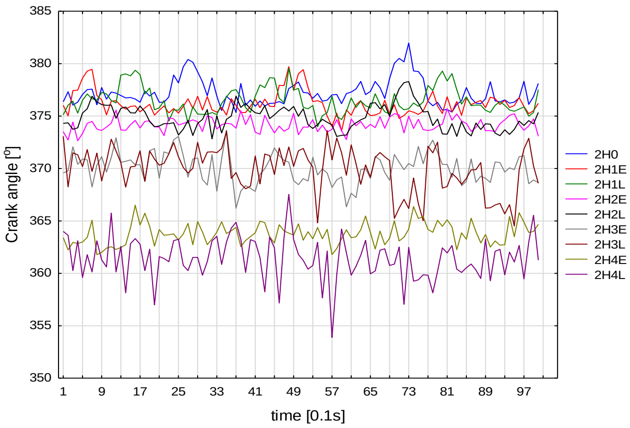



Fig. 25. Crank angle of pressure peak in C2 cylinder

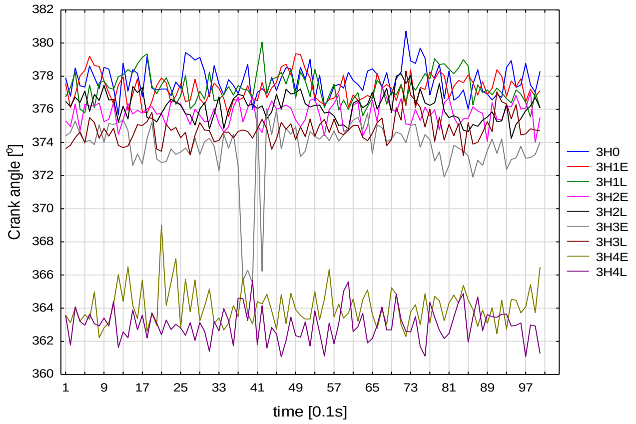



Fig. 26. Crank angle of pressure peak in C3 cylinder

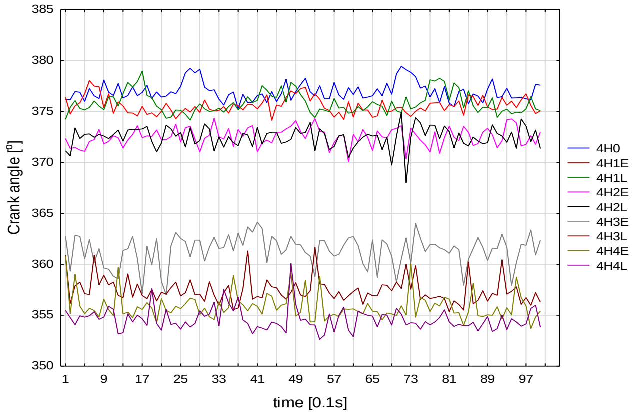



Fig. 27. Crank angle of pressure peak in C4 cylinder

The peak pressure angle in the individual cylinders fed with diesel fuel only was also analyzed (Fig. 28). Here, too, the evident irregularity in the C2 cylinder temporarily disturbed the combustion process. In four of the six cases, the Student's t-test indicated statistically significant differences between the cylinders.

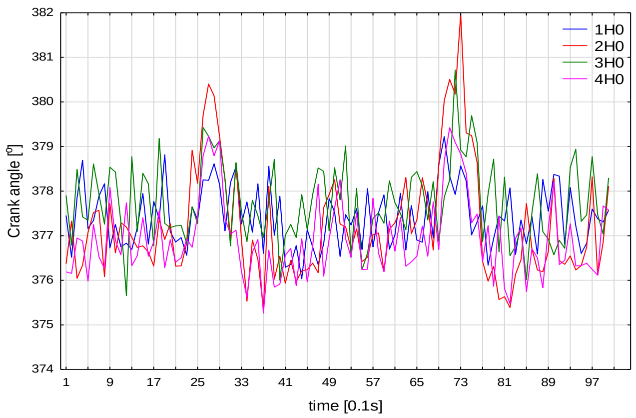



Fig. 28. Crank angle of peak pressure in all cylinders only for diesel fuel

## 5. Conclusions

The conclusions drawn from the research and analysis carried out are that if the combustion process is investigated, it is advisable to consider separately and multidimensionally the phenomena occurring in individual cylinders of an internal combustion engine. When a research object is holistically analyzed, it can be difficult, even for single-cylinder units, to determine the causes of the phenomena occurring. This is especially important in the case of research work using innovative propulsion systems. We should examine source data that is as raw as possible because such an approach helps us draw more comprehensive conclusions on processes that occur in the research engine. Any additional factor and transformation can distort the interpretation of the combustion process. The choice of data processing methods is not indifferent to results obtained, which may be the reason behind research diversity in evaluating the soundness of direct hydrogen injection in diesel engines.

Certain specific conclusions about the measurement points studied have been drawn from the analysis:

– There are statistically significant differences between the tested combustion process parameters for early and late injection based on the analysis by the Student's t-test at $\alpha = 0.05$: IMEP: 9 out of the 16 cases (56%), peak pressure: 14 out of 16 (88%), heat released: 9 out of 16 (56%), crank angle for peak pressure: 9 out of 16 (56%).
– In 34 out of the 36 (94%) measurement points, the coefficient of variation of the IMEP did not exceed 5%, which means a stable combustion process.
– It can be concluded that the change of direct hydrogen injection timing from early to late has an effect on the combustion process only. The significance of this effect depends, among other things, on the hydrogen dose and initial torque. In the analyses, when the highest hydrogen doses were supplied, the limit of the maximum load acting on the research object was nearly reached and rumbling began to occur, which may explain the irregularities in the presented results. This justifies further research on using hydrogen in diesel engines.

## Nomenclature

| | |
|---|---|
| CAD | crank angle degree |
| CoV | coefficient of variation |
| CI | compression ignition |
| DI | direct injection |
| E/L | early/late hydrogen injection |
| H0–H4 | hydrogen dose |
| IMEP | indicated mean effective pressure |

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