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Impact of spark plug type on the cycle-to-cycle variability in an internal combustion gas engine

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An experimental study was conducted using a single-cylinder gas engine to determine the impact of spark plug type on engine cycle-to-cycle repeatability. Two types of spark plugs were used for the analysis: the first was a flat electrode spark plug, and the second was a conventional spark plug with a side electrode, designated as "J". The tests were carried out over an air excess ratio range of 1.0 to 1.4 and an ignition coil charging time range of 1.5 ms to 5 ms, at a constant engine speed of 1500 rpm and a load of 6 bar IMEP. The results indicate a significant improvement in engine repeatability when using a spark plug with a flat ground electrode. An average reduction of 61% in the IMEP variability coefficient was achieved in the air excess range of 1.0–1.3. The use of a spark plug with a side electrode "J" resulted in a reduction in the sensitivity of engine operation to changes in the mixture composition and coil charging time.

Key words: *ignition system, cycle-to-cycle variation, gas engines, lean burn*

1. Introduction

Spark-ignition gas engines are a crucial component in the development of drive systems and power generation systems, primarily due to their potential to reduce CO_2 and NO_x emissions [5, 24]. Gas engines are most commonly fuelled by natural gas, whose main component is methane. As a gaseous motor fuel, it has a lower ability to quickly initiate and sustain combustion reactions than conventional gasoline [2]. That fact leads to greater susceptibility to combustion instability. It has a negative impact on the possibility of burning lean mixtures, which can improve energy and environmental performance [16].

The combustion of lean mixtures is particularly beneficial when using advanced ignition systems, including laser plasma ignition systems, pre-chamber combustion systems, or hydrogen enrichment of 5–30% [7, 11, 18, 19]. This allows mixtures with an air excess ratio greater than 1.8 to be burned [6]. By further diluting the mixture, it is possible to reduce NO_x emissions by up to 75–90% and improve thermal efficiency by 2–9% [3, 13]. Increasing the excess air ratio above the stoichiometric composition is associated with a decrease in combustion temperature and heat release rate, affects ignition initiation disturbances, and increases susceptibility to loss of combustion process repeatability from cycle to cycle [10].

Due to the limitations resulting from working with lean mixtures, one approach to improving combustion stability is to modify the design of the spark plug and the configuration of the ignition system. In experimental studies [1], Abdel-Rehim compared four types of spark plugs and found that the configuration without a ground electrode reduced the coefficient of variation (COV) of IMEP by 23.8% and increased IMEP by 4.4% compared to the reference spark plug. Sjerić and co-authors [20] performed a numerical analysis of the effect of spark plug geometry on cyclic combustion variability, comparing a classic J-gap spark plug with an iridium spark plug with a thin central electrode. They showed that the use of an iridium spark plug reduced COV(IMEP) by up to 13.5% and reduced fuel consumption by approximately 1.25% in the partial load range of the engine.

Li et al. [14] compared single and twin spark plug configurations in a natural gas-fueled SI engine, analyzing the combustion process at different λ values and EGR ratios. It was demonstrated that the use of twin spark plugs reduced combustion time by ~20–30% and accelerated the achievement of CA50 (e.g., from 21.77°CA to 16.58°CA at λ = 1.5), resulting in improved combustion stability and increased maximum pressure compared to the single-spark system.

In a study by Gu et al. [8], the effect of spark plug orientation on combustion stability under severely lean conditions in a single-cylinder SI engine was analyzed using three spark plug settings relative to the flow direction. It was demonstrated that the optimal orientation (90° relative to the flow direction) increased the stable combustion limit from λ = 1.78 to λ = 1.96 at 2000 rpm, and significantly improved the combustion rate and heat distribution throughout the cycle.

Zhang and Chen [25] conducted optical studies of methane combustion at various ignition energies and spark plug gaps, examining the impact of these parameters on cyclic variability and flame formation under lean-burn conditions. They demonstrated that increasing the ignition energy and using a larger gap (1.20 mm) significantly improves combustion stability, reducing the coefficient of variation of the IMEP and extending the lean mixture limit to λ = 1.4.

To identify the phenomena responsible for combustion instability, model studies replicating the conditions of ignition and flame propagation are necessary, as confirmed by the results of experimental work on the dynamics of combustion reactions [4, 17, 26]. At the same time, engine testing under real conditions is of key importance, as it allows the impact of design solutions on the performance and environmental indicators of the unit to be assessed [13, 21].

Cyclic combustion variability (CCV) arises from turbulence fluctuations, local variations in mixture composition, and random disturbances in flame initiation and propagation, resulting in each engine cycle operating under slightly different physical and chemical conditions. As a result, even with constant control parameters, fluctuations in pressure and combustion rate occur, leading to differences in IMEP, Pmax, and combustion phase between successive cycles [12].

The non-repeatability of engine operation is most often described using statistical indicators, such as COV(IMEP), COV(Pmax), and COV(CA50), which enable the determination of the dispersion of energy and phase combustion parameters from one cycle to the next [15]. However, COV(IMEP) and COV(CA50) limits are not the same for all cases; they depend on the type of engine, fuel, and cylinder configuration. In single-cylinder gas engines, COV(IMEP) often exceeds 3–5% during lean-burn operation, reflecting higher susceptibility to cyclic combustion variability. In multi-cylinder production units, fluctuations in individual cylinders are partially compensated, resulting in lower observed values of these indicators [9].

The current state of knowledge suggests that surface spark plug designs, such as those analyzed in this article, have not been previously studied on an engine in terms of their impact on cyclic combustion variability and ignition stability. Previous work by the authors [23] included optical identification of electrical discharge in a constant volume chamber (CVC), which showed that a flat electrode spark plug generates a larger arc surface area, higher luminescence intensity, and shorter discharge duration compared to a conventional spark plug. These effects favor improved ignition of lean mixtures, especially in gas engines. However, CVC model studies did not allow for an unambiguous assessment of the impact of this design on the combustion process in the cylinder and the repeatability of engine operation; therefore, it was necessary to extend the analysis to include tests of the actual combustion process in a piston unit.

In the next stage, the authors focused on the parameters of ignition system control (including coil energy and saturation time) [22]. The presented article combines both approaches, spark plug type analysis and ignition parameter analysis, conducting comprehensive engine tests under lean-burn conditions to assess the impact of spark plug geometry on combustion stability during the cycle and improve engine performance indicators.

2. Research methodology

2.1. Spark plug geometries under investigation

To determine the impact of spark plug electrode section geometry on the repeatability of the combustion process in a gas engine, two different spark plugs were used, differing in shape and the degree of exposure of the discharge zone. The first variant is a spark plug generating a half-surface discharge, designated as SPF. In contrast, the second variant is a conventional spark plug with a side electrode of the "J" type, designated as SPJ (Fig. 1). The technical data for both spark plugs are presented in Table 1.

Fig. 1. View of SPF and SPJ spark plugs used for the engine tests

Due to the absence of a side ground electrode, the SPF spark plug is designed for engines with rotary pistons and high-performance engines operating under high thermal loads. The SPJ spark plug used is a modern classic design, widely used in most SI engines.

Table 1. Technical data of the tested spark plugs

Parameter	SPF	SPJ
Model No.	NGK LMAR8BI-9	NGK R0465B-10
Central electrode	iridium	nickel
Ground electrode	platinum	–
Electrodes gap	0.9 mm	1.3 mm

Previous experimental studies conducted in an isochoric chamber using both spark plugs have shown that the arc generated by the SPF spark plug is characterized by a higher energy concentration, resulting from a shorter discharge time. In contrast, the SPJ spark plug allows for a geometrically stable arc; at a lower energy concentration, the discharge phase is longer than in the case of SPF.

2.2. Engine test stand and measurement apparatus

The tests were conducted on a single-cylinder AVL 5804 research engine (Fig. 2) adapted for gas fuel. The engine had an open hemispherical combustion chamber, indirect fuel injection, an independent engine control system, and external electric supercharging. The technical data are presented in Table 2.

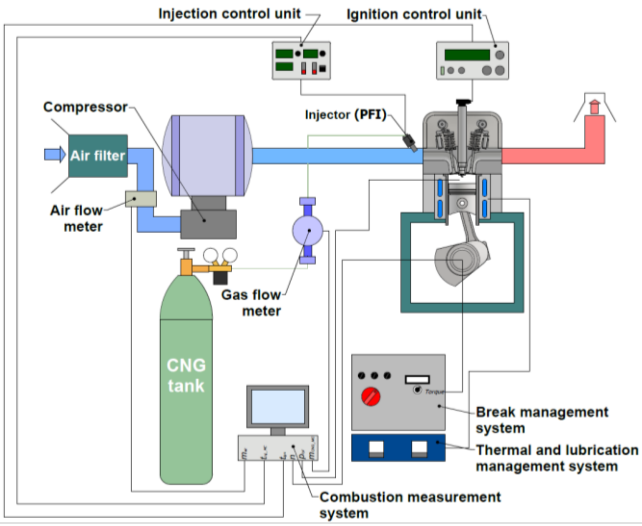

Fig. 2. Schematic of the test bench equipped with an AVL 5804 test engine

The AVL IndiSmart DAQ system with an AVL 365C angle sensor, an AVL GH14D combustion pressure transducer (0–250 bar, ±0.3% FS), a Micro Motion ELITE Coriolis flow meter (0.1–2 kg/h, ±0.25% RD), and an ABB Sensy-Flow thermal air flow meter (0–720 kg/h, ±1% RD).

Table 2. Technical data for the AVL 5804 single-cylinder test engine

Type	AVL 5804 | R1 | DOHC | PFI
Bore × stroke	85 × 90 mm
Compression ratio	15
Displemance	0.5107 dm^3
Cooling system	liquid – dual-circuit system with heat exchanger
Intake system	28 mm electronically controlled throttle valve Mechanical supercharging

2.3. Scope of research and data processing

At each measurement point, a series of 100 consecutive engine cycles was recorded. The scope of the tests included a constant rotational speed with a gradual change in the air excess ratio from λ = 1.0 to 1.4, achieved by adjusting the throttle opening. The fuel dose was adjusted to achieve approximately 6 bar IMEP and remained constant throughout the entire test. The ignition discharge energy was adjusted by varying the ignition coil charging time from 1.5 ms to 5.0 ms. The λ value was determined based on the mass flow rate of air and fuel supplied to the engine. The ignition timing was adjusted individually for each engine operating point during testing to ensure a combustion center position of CA50 = 8° aTDC. For the recording of 100 consecutive cycles, the ignition timing was fixed. For each configuration, the values of COV(IMEP), CA50 variability, and COV(Pmax) were calculated. The weighted distance method was used to develop contour maps.

3. Results and discussion

3.1. Cycle-to-cycle variation in in-cylinder pressure curves

The combustion process in a spark ignition engine is characterized by natural uniqueness, which results in cyclical unevenness of pressure waves in the cylinder, directly resulting from the characteristics of heat release. Figure 3 illustrates an example series of 100 consecutive cycles recorded at λ = 1.0 (stoichiometric charge) and a coil charging time of 3 ms, corresponding to a maximum current of 8.2 A. The curves obtained for the SPF spark plug are marked in red, while those for the SPJ spark plug are marked in blue; the bold line represents the average curve for a given set of cycles. Under the conditions presented, the SPF spark plug was characterized by a smaller spread of Pmax values, which was 3.62 bar lower than for the SPJ spark plug. Since very good repeatability indices characterize the use of stoichiometric mixtures, the visible differences primarily result from changes in the spark plug, rather than from variations in mixture formation conditions.

The pressure curve in the cylinder has a significant influence on the rate of pressure increase in the initial phase (CA10–CA20), especially in the case of gas supply, as methane has a higher ignition temperature than traditional gasoline. Cycle-to-cycle variability is primarily influenced by engine operating conditions such as load, rotational speed, charge homogenization degree, and mixture composition as determined by the λ coefficient, as well as spark discharge energy.

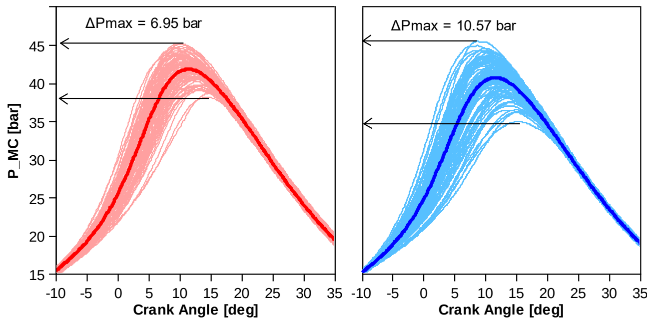

Fig. 3. Cylinder pressure for 100 cycles, at lambda 1.0 and coil charging time 3 ms. Results for SPF – red lines, SPJ – blue lines

3.2. Statistical distribution of IMEP for varying excess-air equivalence ratios

The non-repeatability of the combustion process, as demonstrated in the previous chapter, results in different IMEP values being obtained in successive engine cycles. Figure 4 illustrates the distribution of IMEP values obtained from 100 cycles for various degrees of mixture lean (λ = 1.0–1.4) at a constant coil charging time of 3 ms.

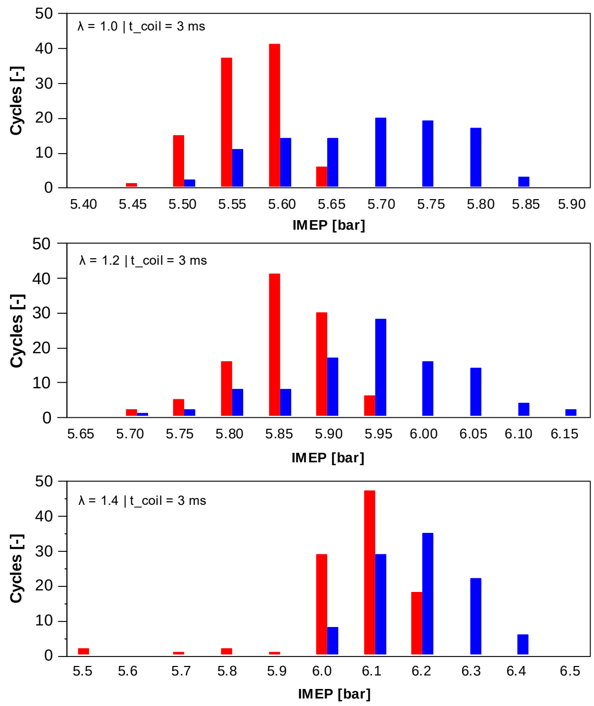

Fig. 4. The influence of the air excess coefficient λ on the dispersion of the mean indicated pressure IMEP

Throughout the entire λ range presented, higher IMEP values were obtained using the SPJ spark plug, while lower values were obtained for the SPF spark plug. Mixture leaning using the SPF spark plug in the range of λ = 1.0–1.2 does not cause significant changes in the distribution. However, when burning the leanest loads, near the flammability limit, some cycles exhibit reduced IMEP values. In the case of the SPJ spark plug, a symmetrical distribution was obtained each time, but it was characterized by a significantly higher degree of dispersion than for the SPF spark plug.

Based on the above distributions, it can be concluded that the use of an SPF spark plug in stoichiometric and slightly lean mixtures reduces the dispersion in IMEP values from cycle to cycle. The increased energy concentration in the arc generated by the SPF helps to eliminate the negative effects of mixture heterogeneity and intensify the charge kinetics in the vicinity of the electrodes. However, the shortening of the arc glow phase of this spark plug, despite the increased power concentration, has a negative effect on engine performance with lean mixtures. The short exposure time of the electric arc causes a delay in the CA0–CA10 phase, resulting in cycles with a reduced IMEP value. Under these conditions, using an SPJ spark plug with a stable and longer arc is a better solution.

3.3. Influence of λ and ignition energy on combustion repeatability

The best measure of engine non-repeatability is the IMEP variability coefficient. It is most widely used because it represents the measurable energy effect of the combustion process transferred to the crankshaft, whose kinematics and dynamics are directly felt by the user. Load depletion slows down combustion and increases the energy required to initiate ignition. Figure 5 shows the COV_IMEP curve as a function of λ for three coil charging times, corresponding to maximum charging currents from 5.4 A to 10.5 A.

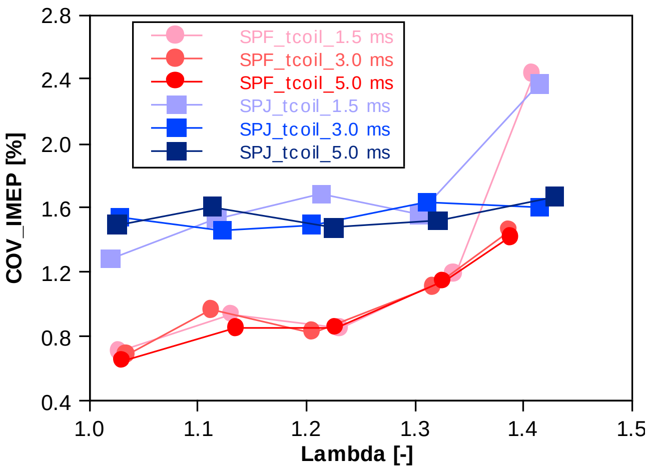

Fig. 5. The influence of the air excess ratio and ignition coil saturation time on the IMEP coefficient of variation (COV_IMEP)

As λ increases, COV_IMEP increases, indicating that engine repeatability deteriorates; however, within the range of λ = 1.0–1.3, these changes are mild. There is a clear advantage of the SPF spark plug, for which COV_IMEP values more than twice as low were obtained in this range. At maximum mixture lean, a charging time of 1.5 ms proves insufficient for both spark plugs – the ignition energy is too low, resulting in a loss of operating stability (typically above 5% COV_IMEP). The graph also shows that the charging time has a much greater impact in the case of the SPJ spark plug, while for SPF above 3 ms its impact is practically negligible. The SPJ spark plug ensures relatively stable COV_IMEP values along the entire λ characteristic, while for SPF, an increase in λ causes a significant increase in COV_IMEP, although the level of variability itself remains significantly lower than for SPJ. Since SPF enables very stable operation with richer mixtures, any deviation in the λ value is clearly visible. In the case of SPJ, the overall level of stability is lower, and changes in λ have a smaller relative impact on the COV_IMEP value.

3.4. Two-dimensional interpolated maps of combustion variability indicators

To more fully illustrate the impact of control parameters on engine repeatability, contour maps were developed based on the measurement points, marked with red markers on the graphs. Figure 6 shows the relationship between the λ coefficient and the coil charging time t_coil as a function of the COV_IMEP value for the SPF (a) and SPJ (b) spark plugs. Both maps utilize the same color scale, enabling a direct comparison of the results.

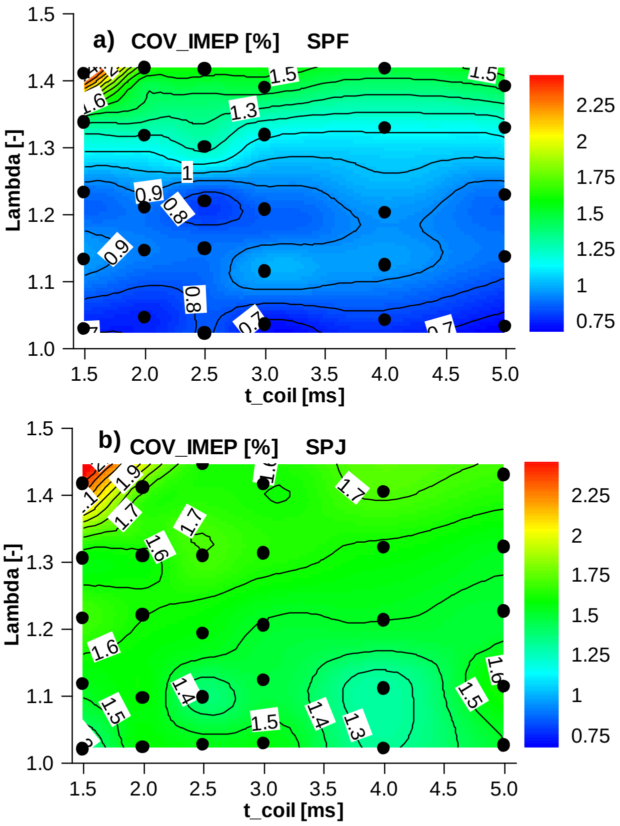

Fig. 6. Contour maps of the IMEP coefficient of variation (COV_IMEP) as a function of the air excess coefficient λ and ignition coil charging time: a) SPF spark plug, b) SPJ spark plug

In the case of the SPF spark plug, the range of low COV_IMEP values (0.75–1.00%) dominates, while for the SPJ spark plug, the range corresponding to values of approximately 1.5% prevails. For SPF, a clear influence of λ increase on COV_IMEP increase is observed. In contrast, for SPJ, the λ coefficient does not show a significant impact across the entire analyzed engine operating range. In both cases, a coil charging time of 1.5 ms proves insufficient, which prevents stable operation in lean mixture regions. The short discharge time in the SPF spark plug ensures high repeatability of the combustion process, but at the same time increases sensitivity to changes in control parameters. In contrast, the SPJ spark plug is characterized by poorer repeatability but shows less susceptibility to changes in operating conditions.

In the case of COV_CA50 (Fig. 7), the predominance of positive values is interpreted as less variability in the position of the combustion center for the SPJ spark plug. This is due to a longer glow phase and a more stable discharge, which reduces sensitivity to local differences in the mixture in the initial phase of flame development. The differences between the spark plugs gradually disappear at the extreme measurement points, where the boundary conditions of combustibility limit the influence of the control parameters.

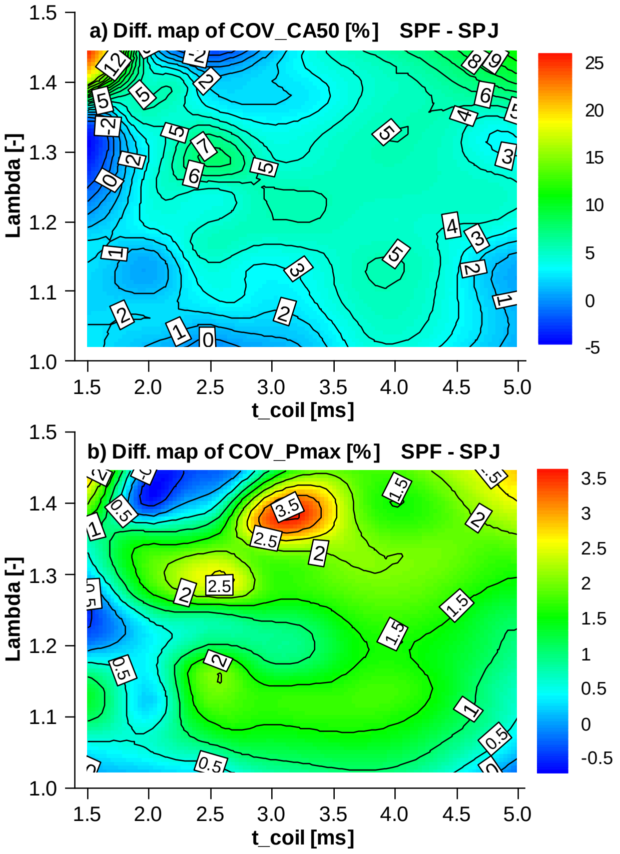

Fig. 7. Differential maps of coefficients of variation: a) COV_CA50 and b) COV_Pmax, determined as the difference between the values obtained for the SPF and SPJ spark plugs (SPF − SPJ)

For the COV_Pmax indicator, the map also shows lower values across the entire analyzed area for the SPJ spark plug. However, these differences are much smaller than in the case of COV_CA50, because Pmax is a parameter that is more strongly dependent on the average combustion rate and thermodynamic conditions in the TDC region, and to a lesser extent on local differences in ignition initiation. As a result, the stability of Pmax for both spark plugs differs less clearly, which reflects the limited sensitivity of this indicator to changes in electrode geometry.

3.5. Scatter analysis of the CA50–IMEP relationship

The analysis of the CA50 scatter relative to IMEP allows for the simultaneous assessment of combustion phase variability and indicated operation, providing a precise tool for identifying cyclical process instability. Figure 8 shows the sets of points obtained for different values of λ at a constant coil charging time of 3 ms, illustrating the effect of mixture depletion on the co-occurrence of CA50 and IMEP deviations. The last panel represents the operating point with the lowest stability, reflecting the maximum dispersion of cycles under conditions of a mixture close to the flammability limit.

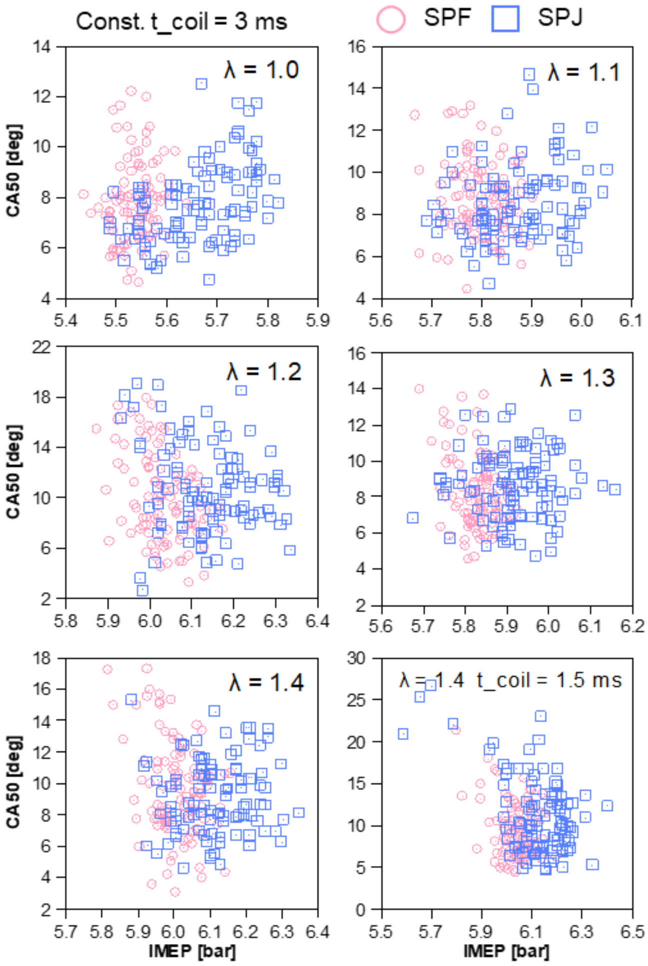

Fig. 8. Cycle-by-cycle spread of the CA50 angle relative to the mean indicated effective pressure IMEP for different values of λ and for the extreme case λ = 1.4 and t_coil = 1.5 ms

For both spark plugs, the CA50 (IMEP) relationship exhibits characteristics typical of SI engines, in which slight deviations of the combustion center position from the set value (CA50 = 8° aTDC) result in changes in IMEP due to modifications to the effective duration of the main combustion phase. In the case of the SPF spark plug, the scatter of points is significantly smaller, confirming a more repeatable achievement of the set combustion phase and lower sensitivity of IMEP to small deviations in CA50. For SPJ, the distribution of points is wider, indicating greater energy variation among cycles with comparable CA50 offsets.

As λ increases, both the range of IMEP values and the CA50 dispersion gradually increase, with the effect of mixture depletion being more pronounced for the SPJ spark plug. Higher λ values cause a slowdown in the early combustion phase, which is reflected in greater point dispersion and increasing sensitivity of the CA50(IMEP) relationship to slight fluctuations in ignition initiation. For the SPF spark plug, the observed increase in variability is milder, which confirms the beneficial effect of a higher concentration of discharge energy on the stabilization of the early combustion phase with moderately lean mixtures.

In the final case, corresponding to operation near the stability limit, the CA50(IMEP) relationship undergoes a significant expansion, and the dispersion structure loses its regular character. For both spark plugs, especially at lower ignition energies, cycles with significantly reduced IMEP appear, despite ignition control ensuring a nominal CA50 of 8° aTDC. This phenomenon is typical for operation with a mixture of limited reactivity, in which minor disturbances in combustion initiation can lead to a significant reduction in the combustion rate in the CA0–CA10 phase, and thus to the formation of cycles with low energy quality. As a result, this point represents the operating condition with the lowest stability, consistent with the observed maximum dispersion of CA50 and IMEP.

4. Summary

The results of research on the impact of spark plug type on the repeatability of gas engine operation from cycle to cycle are presented in this paper. The use of two different spark plugs were compared: a conventional spark plug widely used in SI and DI engines, and one that does not have a classic "J" electrode. As a result of the research conducted under conditions of variable air excess ratio and coil charging time, the following conclusions were drawn:

1. Significant impact of spark plug design on engine repeatability from cycle to cycle under variable λ conditions in the range of 1.0–1.4 and coil charging time of 1.5–5 ms.
2. In the range of λ 1.0–1.3, using an SPF spark plug, significantly lower values of the coefficient of variation of the indicated mean pressure were obtained.
3. Changing the coil charging time does not significantly affect the tested engine repeatability; however, a value below 2 ms does not ensure the required engine repeatability under the poorest conditions.
4. Despite the improvement in engine repeatability represented by COV_IMEP, an increase in the dispersion of other thermodynamic indicators of engine repeatability (COV_CA50, COV_Pmax) was observed.
5. Shortening the discharge time using SPF results in an increase in the concentration of electric arc energy. However, shortening the discharge causes high sensitivity of the early combustion phase CA0–CA10 to local charge dynamics, which translates into an increase in the CA50 and Pmax variability coefficients.
6. The use of an SPJ spark plug, which generates a more stable discharge over a longer period, helps reduce the impact of engine operating conditions (λ, t_coil) on cycle-to-cycle repeatability.

Nomenclature

CA0–CA10	interval 0% to 10% mass fraction burned	EGR	exhaust gas recirculation
CA50	crank angle of 50% fuel burned	IMEP	indicated mean effective pressure
CCV	cyclic combustion variability	Pmax	maximum in-cylinder pressure
COV	coefficient of variation	SI	spark-ignition
COV(CA50)	coefficient of variation of CA50	SPF	surface plug with flat electrode
COV(IMEP)	COV of indicated mean effective pressure	SPJ	spark plug with J-gap electrode
COV(Pmax)	COV of maximum in-cylinder pressure	t_coil	ignition coil charging time
CVC	constant volume chamber	λ	excess air coefficient

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