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A Study on the Possibility of Estimation of In-Cylinder Pressure by Means of Measurement of spark Gap Breakdown Voltage

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ABSTRACT

In-cylinder pressure of an IC engine is considered to be a major source of information about combustion process. It is a generally accepted method to obtain an in-cylinder pressure signal using a pressure sensor (transducer). In this paper, a different approach is presented. Information about the in-cylinder pressure can be obtained by measuring breakdown voltage across the spark-plug gap. A simple means for measurement of such voltage is developed. The breakdown voltage threshold depends on the density of the gas in the combustion chamber. A strong correlation between the measured breakdown voltages and in-cylinder pressure has been established.

INTRODUCTION

Continuously growing interest and increasing requirements to electronic engine control have led to the development of several different control strategies. These strategies are based on different sensor technologies. The most generally accepted technology uses a lambda sensor as the main source of information about the combustion process. Another approach, based on a pressure sensor, is gaining popularity now. The in-cylinder pressure measurement can provide the most complete information about the combustion process. The method has long been used for research purposes, and only recently emerged as the production engine applications.

Our method of engine diagnostics is based on the phenomenon of electrical breakdown in gas. In this respect it differs from another method of in-cylinder diagnostics based on a spark plug [1, 2].

The limit at what a breakdown ensues is called "breakdown threshold". The threshold is determined by the nature of gas and, at a given gap, by the gas density, i.e. the number of gas particles per unit of volume. The density is, in turn, a function of the gas temperature and pressure.

Among the factors determining the breakdown voltage, the following merit special consideration: (1) gap width, (2) gas nature, (3) gas pressure, (4) gas temperature. Such factors as the shape of the electrodes, their material, their temperature, gas humidity and initial ion concentration, play a role too, but by far less significant than the major four.

The gap width and the pressure are frequently considered together, as far as both of them affect the breakdown voltage in a similar fashion. That is why the product *Pd* (where *P* is pressure and *d* is the gap width) is widely used as a parameter when comparing different gaps. In the case of a given gap, it is therefore pressure that matters. The above mentioned is true if temperature of gas remains constant.

In order to take into account temperature, we should introduce a special parameter -- so called "gas density" *n*, which represents the number of particles (molecules) of gas in unit volume. For ideal gas:

$$n = \frac{P}{kT}, \qquad (1)$$

where: *P* is pressure,
T is temperature, and
k is Boltzman constant ($1.38 \cdot 10^{-23}$ J/K)

Operating with d and n (instead of P), we can write for breakdown voltage V_s:

$$V_s = f(nd) \qquad (2)$$

The formula (2) represents the Pashen's law (Pashen, 1889). In a very wide range of *n* and *d* it is the value of *nd* which determines the breakdown voltage. The function (2) in the area of gas densities typical for a combustion chamber are fairy linear [5].

The method described in the present paper is a further development of the approach introduced by the authors earlier [3, 4].

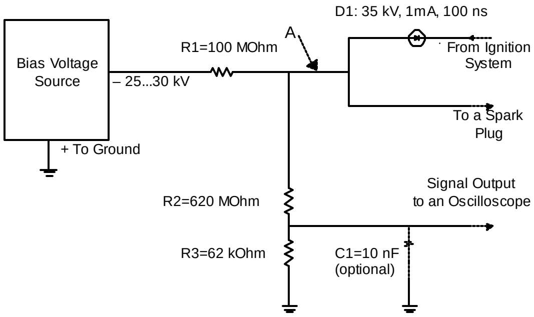


Figure 1. Schematic diagram of the measurement circuit. An additional diode can be installed in the line marked "A"

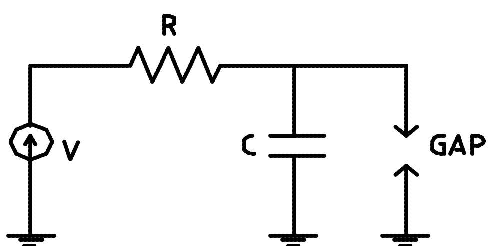


Figure 2. A self-oscillating circuit.

MATERIAL AND METHOD

Schematic diagram of a one-cylinder breakdown voltage measurement circuit is shown in Fig. 1.

When no spark voltage is applied from the ignition system, the diode D1 separates the rest of the circuit from ignition system.

The voltage divider (R2 and R3) has a sufficiently high impedance and, thus the network made of the bias voltage source, the resistor R1, and the spark plug can be considered separately.

A spark plug can be viewed as a discharge gap with a certain stray capacitance connected in parallel. An equal circuit of the measuring circuit Fig. 1 can be then represented as shown in Fig. 2.

The spark gap volt-ampere characteristic is non-linear. The gap does not conduct electricity (barring a small ion current, if any) while the applied voltage is lower than what is known as breakdown threshold. Because this small current is carried by charged particles generated by other means than the discharge itself, this region of the volt-ampere characteristic of the gap is called "not self-sustained discharge"

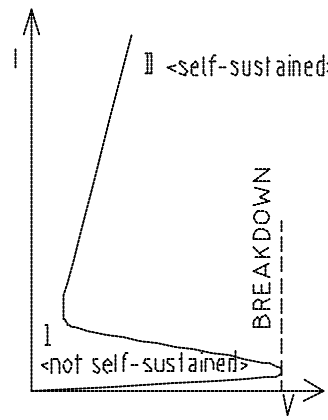


Figure 3. A simplified volt-ampere characteristic of a discharge gap.

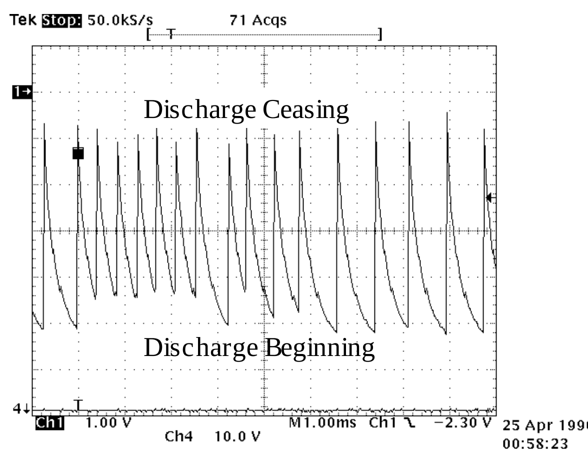


Figure 4. A sample waveform of the oscillations in the measurement circuit.

After a breakdown is achieved, the current trough the gap may be very large whereas the voltage drop is small. In this case, the charged particles (electrons and ions) are generated by the processes of gas ionization in the discharge. That is why it is called "self-sustained discharge". A type of volt-ampere characteristic shown in Fig. 3 is called S-type characteristic. Neon lamps and thyristors are other than a spark gap common examples of elements with S-characteristics.

A circuit made of a resistor, a capacitor and an S-type non-linear element (Fig. 2) is known as a relaxation generator. The circuit works as follows. Initially, the stray capacitance of the spark plug is discharged. When a bias voltage is applied, this capacitance is being charged trough the resistor R1.

As soon as a breakdown threshold is achieved, a discharge is developed in the gap, creating a high-conductive channel between the electrodes. The capacitance is rapidly discharged through this gap. This process is called a spark discharge, but, in the case of our circuit, the sparks have a very low energy (see below.) The capacitance is not, however discharged fully. A discharge will cease when its current drops below a certain minimum value, leaving a small residual voltage on the stray capacitance.

These processes of charging and discharging are repeated with the frequency determined by the applied bias voltage, breakdown threshold voltage, minimum discharge current, and the values of the resistor R1 and the stray capacitance of the spark plug. A sample waveform of the oscillations in the measurement circuit when a negative bias voltage applied is shown in Fig. 4. This waveform was captured with the engine not operating. In such steady conditions, all breakdowns were initiated at approximately the same voltage and the residual voltage was approximately the same for all the discharges.

Continuous sparking in a cylinder filled with a combustible mixture can pose a problem of preignition. This problem can be avoided if the energy of each spark is kept below the minimum ignition energy. With the stray capacitance C_{sp} of a spark plug and connecting wires in order of 5 pF and the characteristic breakdown voltage V_s at typical operation conditions (*see below, Results and Discussion*) in order of 7 kV, the maximum energy E_{sp} available per spark can be written as:

$$E_{sp} = \frac{C_{sp} V_s^2}{2} = \frac{5 \cdot 10^{-12} \cdot (7 \cdot 10^3)^2}{2} \approx 0.12 \cdot 10^{-3}\ \mathrm{J} \qquad (3)$$

This energy is below the minimum ignition energy 0.3 mJ cited in [6]. Moreover, taking into account that fact that the stray capacitance is never fully discharged, the energy available per spark will be even less.

Preignition does occur, however, if the frequency of the oscillations in the measurement circuit is too high. In our experiments, the safe limit appeared to be about 3 kHz. That is why, we controlled the frequency by choosing an appropriate value of the resistor R1. By the other words, the resistor R1 limits average current drawn from the bias voltage source.

The bias voltage must be well over the breakdown threshold at any conditions. In our experiments, bias voltage of 25 kV was used. It is desirable to prevent penetration of ignition voltage into the measuring equipment as well as to avoid any effect of the measurement device itself on the ignition system. It is accomplished by a cut-off diode D1. The resistors R2 and R3 form a voltage divider used for an oscilloscope coupling. The capacitor C1 may be used to reduce high-frequency noise.

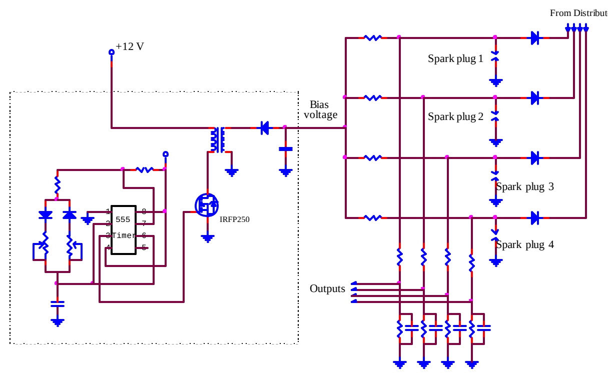


Figure 5. The four-channel measurement circuit, including the high voltage source.

Our measurement circuit resembles that used for ion current measurement. The only difference is a much higher bias voltage in our experiments. Initially, this high voltage was supplied from the power supply or an exhaust gas treatment plasma system which was simultaneously investigated in our laboratory. Later, a compact unit based on an ignition coil was developed.

The schematic diagram of the four-channel measurement system is shown in Fig. 5. This unit includes a step-up voltage converter and a voltage distributing network. The converter uses an ignition coil as a step-up transformer. Current trough the coil is switched by a field-effect transistor (IRFP250) actuated by a pulse generator (555 timer.) The high voltage pulses from the coil are rectified by a diode. A capacitor is used as a ripple filter.

When the engine is running, the breakdown threshold and the residual voltage of the discharge ceasing vary according to the conditions in the cylinder. The oscillations in the measurement circuit reflect these variations. Figure 6 shows the simultaneously observed traces of in-cylinder pressure and voltage drop over the spark plug (breakdown voltage.) With the cylinder pressure changing in the course of engine operation, the breakdown threshold changes as well. It can be seen that the pattern of the breakdown voltage follows that of the pressure.

This effect resembles that of amplitude modulation as it can be accomplished using a thyratron. In a thyratron, the breakdown threshold is being offset (and, thus, the pulse amplitude is modulated) by means of applying a modulation voltage on the grid, whereas in the case of a spark plug, the breakdown threshold is affected by conditions in the cylinder.

Among the factors (other than processes in a cylinder) which may affect the breakdown voltage, the most important are the spark gap value and parameters of the measurement circuit. If the latter can be controlled, the former might be a problem. In our experiments, the gaps (1.1 mm) were checked regularly. We did not find any significant spark plug wear. Neither any spark plug fouling was noticed.

RESULTS AND DISCUSSION

All results have been obtained using a four-cylinder 2300 cc OHC SONATA-I gasoline engine. The experiments were confined to its fourth cylinder due to possibility of a more convenient installation of a pressure sensor.

As noted earlier, there is a correlation between the cylinder pressure and breakdown voltage (Fig. 6) In this paper, we investigate the correlation between peak pressure in the cylinder and maximum (peak) breakdown voltage.

Figures 7 and 8 show cylinder pressure and breakdown voltage respectively, measured at 2400 rpm and different loads. The traces of both pressure and breakdown voltage shown in Fig. 7 and 8 are average traces of 100 engine cycles. In addition, the signal of breakdown voltage was conditioned by a low-pass *RC* filter implemented in order to suppress switching noise from the step-up voltage converter.

The trace of breakdown voltage has two peaks. The main peak corresponds to the maximum gas density in the combustion chamber. The smaller maximum is a response of the measurement circuit to a pulse of sparking voltage applied from the ignition system.

This effect could have been avoided by means of an additional diode installed between the sparking circuit and the measuring circuit in the line marked "A" in Fig. 1. For a four-cylinder circuit, for diodes are required. The diodes need to be high voltage and fast recovery. However, such diodes are expensive. Installation of regular rectifying diodes does not solve the problem because of their slow recovery -- in order of or even longer than the sparking pulse duration. As far as maximum values of breakdown voltage were found not to be affected by this effect, no diodes were installed.

Higher maximum pressure corresponds to higher maximum breakdown voltage. The same tendency was found in the other experiments: at 1200, 1800, and 3000 rpm.

A high voltage ignition pulse passes trough the voltage divider with a low-pass filter (R2, R3 and C1 in Fig. 1) and is added to the measured breakdown voltage.

Plotting maximum pressure against maximum breakdown voltage, we can obtain the graphs shown in Fig. 9. The graphs a, b, c, and d represent the correlation between these parameters at 1200, 1800, 2400, and 3000 rpm respectively.

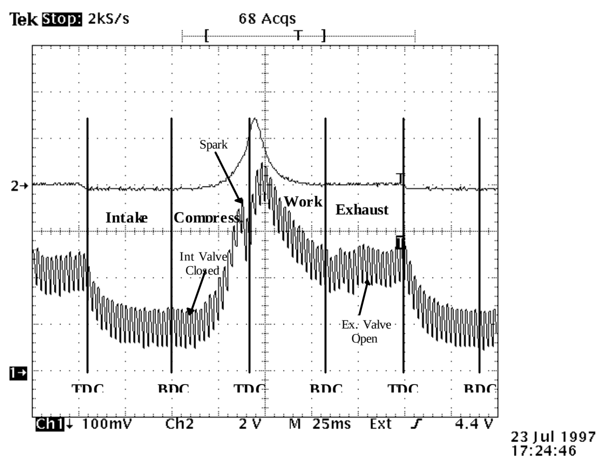


Figure 6. A sample of simultaneously obtained cylinder pressure (upper curve) and breakdown voltage (lower curve). Conditions: idle, 680 rpm Breakdown voltage has been inverted in order to highlight its correlation with the cylinder pressure

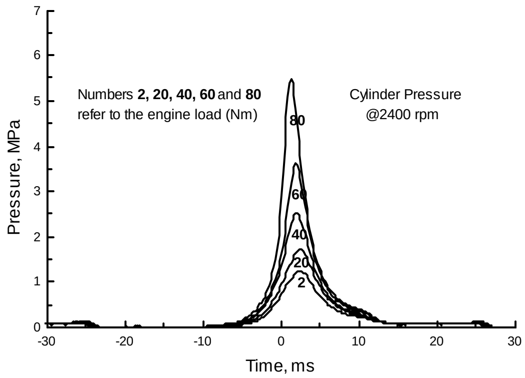


Figure 7. Cylinder pressure at 2400 rpm, different loads.

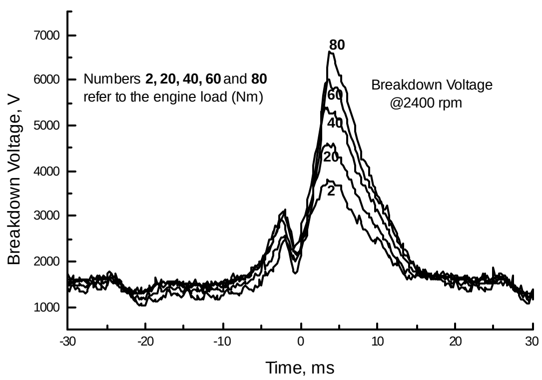
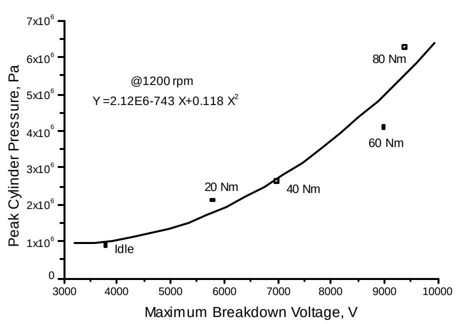
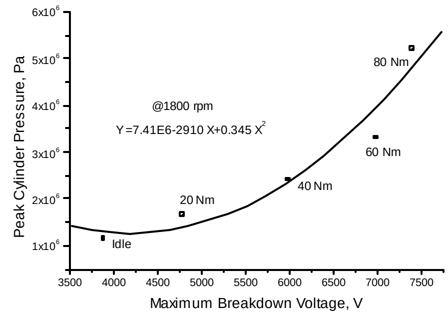


Figure 8. Breakdown voltage at 2400 rpm, different loads.



a



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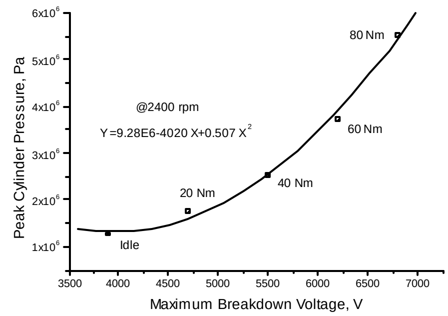

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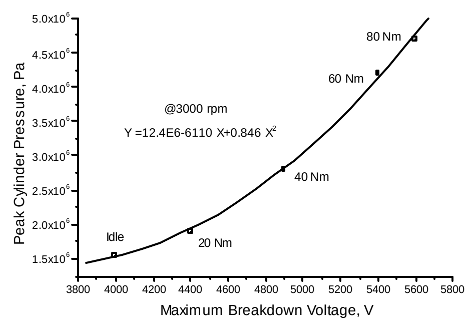

d

Figure 9. Peak Cylinder Pressure vs. Maximum Breakdown Voltage. The fitting curves are second order polynomial functions: $y=Ax^2+Bx+C$

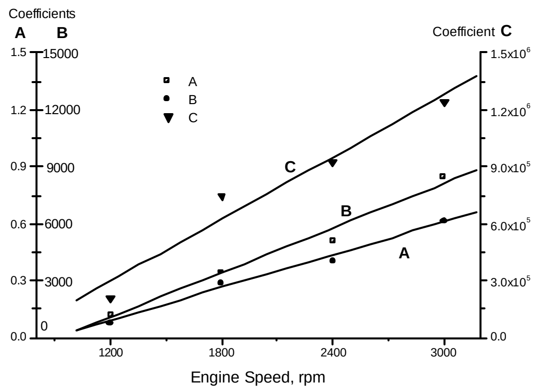

Figure 10. The polynomial coefficients are linear functions of engine speed.

In each case, a curve was fitted. In each case, it was a second-order polynomial function $y = Ax^2 + Bx + C$.

The coefficients A, B, and C are different in each case. However, the coefficients appear to be linear functions of engine speed, as it is shown in Fig. 10.

This correlation provides a convenient means for estimating the peak cylinder pressure of a SI engine given that the of breakdown voltage can be easily measured using a simple equipment.

The method introduced in this paper is related to the ion current method, but has some advantages over the latter.

First of all, the ion current depends on the concentration of charged particles (ions) already present (for example, created by combustion) in the gas. That is why a measurable ion current signal (in order of tens microamperes) can be detected only during combustion process -- approximately between the crank shaft positions from 20^0 BTDC to 50^0 ATDC, as it is shown in [1]. During the rest of the engine cycle, ion current is practically absent.

On the contrary, a certain value of breakdown voltage will be measured at any crank shaft position, regardless of the combustion process. The breakdown voltage depends chiefly (at a given spark gap and bias voltage) on the gas density in the combustion chamber, or, by other words on the concentration of all particles (ionized and neutral), not only ions.

This fundamental difference gives a possibility to estimate in-cylinder pressure not only during combustion, but also during intake, compression and exhaust strokes.

It is seen in Fig. 6 that, for example, that the breakdown voltage changes significantly (and in accordance with the pressure change) when an intake stroke (suction) begins. No ion current can be detected at this time.

Moreover, using the breakdown voltage method, in-cylinder pressure can be estimated even when there is no combustion at all, as when an engine is being motored. This latter possibility can be used, for example, for an immediate diagnostics of starting problems.

Unlike ion current, breakdown voltage is in a higher degree affected by certain "secondary" factors, not (or, at least, not directly) related to the combustion processes itself. Among these factors, the spark gap value is the most important, as it follows from formula (2).

With the spark gap varying, the breakdown voltage will vary accordingly. It means that with aging spark plugs, breakdown voltage will tend to be higher at the same conditions. An engine control system will have to deal with this problem. Fortunately, it is possible to estimate pressure in a cylinder during an intake stroke independently (taking into account manifold pressure and the throttle position.) Having this value, a control system can compare it with that estimated from breakdown voltage and do the necessary scaling.

Another important issue is spark plug fouling. If a spark plug insulator is covered with sufficiently conductive carbon deposit, no breakdown voltage can be measured.

The preliminary results reported in this paper were obtained with a fixed spark gap and in an absence of spark plug fouling. Further experiments will deal with those (and many other) issues.

At the point, it is too early to discuss the accuracy of our method. The breakdown voltage depends of quite a number of factors, not all of them are well understood. The theory of breakdown is much more complicated than that described by the formula (2). The gas composition changes during combustion. It means that every time a different function f will have to be implemented.

Lacking a comprehensive model describing the behavior of gas in the cylinder from the point of view of electrical breakdown, we considered an approach based on engine mapping. The values of peak pressure and the corresponding values of maximum breakdown voltage for a number of speed/load sites are stored in the controller's memory. The crank shaft positions at which these peaks and maximums are reached are stored there as well.

An engine controller and its software using these stored data for optimization of the engine performance are currently being developed in our laboratory.

CONCLUSIONS

1. We have developed a new method of engine diagnostics. The method uses a spark plug as a sensor and is based on measurement of the spark gap breakdown voltage.

2. The method allows to estimate maximum cylinder pressure using the maximum breakdown voltage measurement.

3. A very high bias voltage (exceeding the spark gap breakdown threshold) is essential for pressure signal reconstruction.

4. The method based on breakdown voltage gives a possibility to estimate in-cylinder pressure not only during combustion, but in any cycle.

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