The effect of different ignition cables on spark plug durability

Abstract. The article presents the effect of different types of ignition cables used in combustion engines on the wear of spark plug electrodes and the quality of exhaust gases. The research and analysis of electrode wear were conducted by electronic scanning.

Streszczenie. W artykule przedstawiono wpływ różnych typów przewodów zapłonowych stosowanych w silnikach spalinowych na zużycie elektrod świec zapłonowych oraz jakość spalin. Badania i analizy zużycia elektrod przeprowadzono za pomocą skaningu elektronicznego. (Wpływ różnych kabel zapłonowych na trwałość świec zapłonowych).

Keywords: ignition systems, spark plug, spark discharge, energy, fumes.

Siowa kluczywne: układy zapłonowe, świece zapłonowe, wyładowanie iskrowe, energia, spaliny.

Introduction

This work is a follow-up to papers [1,2] presenting the analysis of ignition systems for which the effects of spark plug electrode wear on spark discharge energy is discussed. The attempt has been made to introduce the element representing different ignition cables into ignition model.

At present air pollution is not only a local but also an international problem. At one of the international road congresses, the results of environmental pollution in 12 major European cities were presented. They showed that transport emissions amount to more than 90% of CO, 76% of dust and almost 100% of lead. Therefore, the analysis of combustion engine and its ignition system is highly desirable. [4].

Voltage measurement at ignition cable ends

In general, ignition systems can be divided into systems with energy storage in inductance or in capacitance [1-3].

Figure 1 presents a general diagram of a mathematical model, where $R_b$ is the spark plug and $C_{45}$ and $R_{45}$ denote capacity and resistance, respectively.

By introducing state variables: $x_1=i_1$, $x_2=i_2$, $x_3=u_{C_{2}}$, $x_4=u_{C_{45}}$ to the equation (1):

\[
\begin{align*}
U_B - x_1R_b - L_1 \frac{dx_1}{dt} & + M \frac{dx_2}{dt} = 0 \\
L_2 \frac{dx_2}{dt} - M \frac{dx_1}{dt} + x_2R_3 + x_3C_{45} + R_{45} \frac{dx_4}{dt} & = 0 \\
x_3 = L_1 \frac{dx_1}{dt} - M \frac{dx_2}{dt} & = 0 \\
x_4 = \frac{1}{C_{45}} \int \left( \frac{dx_2}{dt} + x_1 + x_2R_3 + \frac{dx_3}{dt} \right) = 0 \\
\end{align*}
\]

Transforming the system of equations (1), we obtain:

\[
\begin{align*}
\frac{dx_1}{dt} = A_1x_1 + B_1x_2 + C_1x_3 + D_1U_B \\
\frac{dx_2}{dt} = A_2x_1 + B_2x_2 + C_2x_3 + D_2U_B \\
\frac{dx_3}{dt} = A_3x_1 + B_3x_2 + C_3x_3 + D_3U_B \\
\frac{dx_4}{dt} = A_4x_1 + B_4x_2 + C_4x_3 + D_4U_B \\
\end{align*}
\]

where the parameters are determined using the following relationships:

\[
\begin{align*}
A_1 &= \frac{R_1}{L_2} \left( 1 - \frac{M}{L_2} \right), & B_1 &= \frac{M}{L_2} \frac{R_2}{L_2} \left( 1 - \frac{M}{L_2} \right), \\
C_1 &= \frac{1}{L_2} \frac{M}{L_2} \left( 1 - \frac{R_2}{L_2} \right), & D_1 &= \frac{1}{L_2} \frac{R_2}{L_2} \left( 1 - \frac{M}{L_2} \right), \\
A_2 &= \frac{M}{L_2} \left( 1 - \frac{R_2}{L_2} \right), & B_2 &= \frac{M}{L_2} \frac{R_2}{L_2} \left( 1 - \frac{M}{L_2} \right), \\
\end{align*}
\]
C_2 = \left( \frac{1}{M^2 + \frac{M^2}{t_1^2}} \right), \quad D_2 = \frac{M}{L_1^2 + \frac{M^2}{t_1^2}}
A_3 = \frac{C_{A2}^2}{C_2}, \quad B_3 = \frac{\frac{C_{A2}^2}{C_2}}{1 + \frac{1}{C_2}}
C_3 = \frac{C_{A2}^4}{C_2}

(3)

D_3 = \frac{i_2 R_1}{L_1} \frac{t_1^2}{2C_2} \frac{t_2^2}{2C_2} \frac{t_3^2}{2C_2}
A_4 = \frac{\frac{M^2}{t_2^4} \frac{M^2}{t_2^4} \frac{M^2}{t_2^4}}{2C_2}
C_4 = \frac{\frac{M^2}{t_2^4} \frac{M^2}{t_2^4} \frac{M^2}{t_2^4} \frac{M^2}{t_2^4}}{2C_2}

The solution to Equation (2) has the form:

(4)

x_1 = x_2, \quad A = \begin{bmatrix} A_1 & B_1 & C_1 & 0 \\ A_2 & B_2 & C_2 & 0 \\ A_3 & B_3 & C_3 & E_3 \\ A_4 & B_4 & C_4 & E_4 \end{bmatrix}, \quad B = U_B \begin{bmatrix} D_1 \\ D_2 \\ D_3 \\ D_4 \end{bmatrix}

At the first switch-on, the initial conditions are zero and Eq. (4) assumes the form:

(5)

\frac{dx}{dt} = Ax + B, \quad x = e^{At} x_0 + \int_0^t e^{A(t-\tau)} B d\tau

The solution to the system of equations obtained for the control block in the non-contact state by using the state variable method is presented as relationship (9), where the initial conditions, i.e. the final conditions from the previous state, need to be calculated from the formulae for the control block in the contact state for the time equal to the time of contact.

(6)

u_{C2} = L_2 \frac{di_2}{dt} + M \frac{di_2}{dt} + M \frac{dx_2}{dt} + i_3 R_3 - u_{C45} = 0

u_{C2} = i_2 R_4

(7)

\frac{dx_1}{dt} = a_1 x_1 + b_1 x_2 + c_1 x_3 + d_1 x_4 + e_1 U_B

\frac{dx_2}{dt} = a_2 x_1 + b_2 x_2 + c_2 x_3 + d_2 x_4 + e_2 U_B

\frac{dx_3}{dt} = a_3 x_1 + b_3 x_2 + c_3 x_3

\frac{dx_4}{dt} = b_4 x_2 + d_4 x_4

For the system of equations (7) the parameters a_1,...,d_4 are defined by the relationships:

a_1 = \frac{R_2 (M - L_1)}{L_2 (M - L_1 + M M - L_2)}, \quad b_1 = \frac{M (R_2 + R_3)}{L_2 (M - L_1 + M M - L_2)}

(8)

c_1 = \frac{R_2 (M - L_1 + M M - L_2)}{M}, \quad d_1 = \frac{L_2 (M - L_1 + M M - L_2)}{M}

e_1 = - \frac{\epsilon_1}{L_2}

a_2 = \frac{a_3 L_2}{M} b_3 = \frac{b_2 L_2}{M}, \quad c_2 = \frac{L_2 (M - L_1 + M M - L_2)}{M}, \quad d_2 = \frac{d_1 L_2}{M}

e_2 = \frac{\epsilon_2}{L_2}

b_4 = \frac{1}{C_{45}}, \quad d_4 = \frac{1}{C_{45} R_4}

The solution to Equation (7) has the form:

(9)

x_1 = x_2, \quad A = \begin{bmatrix} a_1 & b_1 & c_1 & d_1 \\ a_2 & b_2 & c_2 & d_2 \\ a_3 & b_3 & c_3 & 0 \\ 0 & b_4 & d_4 \end{bmatrix}, \quad B = U_B \begin{bmatrix} e_1 \\ e_2 \end{bmatrix}

\frac{dx}{dt} = Ax + B, \quad x = e^{At} x_0 + \int_0^t e^{A(t-\tau)} B d\tau

x_0 = \text{initial conditions, or final conditions from the previous state, to be calculated from the formulae for the control block in the contact state for the time equal to the time of contact.}

The time t will be counted from the moment the block is no longer in the contact state.

Three types of ignition cables consistent with ISO 3808-02 standard were tested. A series of measurements were taken on a test stand modelling the actual arrangement of the ignition cables. In Fig. 1 the tested cables were labelled 1, 2 and 3.

1) Class "F" cable of the diameter of 7mm, using double insulation (silicone) layers separated by nylon fiber reinforcement. Wire-wound reactive core using twisted resistive wire;
2) Class D cable of the diameter of 7mm, built of one insulation layer (EPDM). Carbon-acrylic core;
3) Class "E" cable, of the diameter of 7mm, built of two silicone (insulation) layers separated by nylon fiber reinforcement. Carbon-Kevlar Core.
4) For different ignition cables, in the ignition system, the discharge energy was determined on the basis of results presented in Fig. 2 and the measurements taken on a real object. It amounts to:
5) for cable 1, class "F", 33,8mJ;
6) for cable 2, class "E", 33,1mJ;
7) for cable 3, class "D", 32,6mJ.
8) As can be seen the output voltage waveform differs from the response of the conductor represented by the concentrated resistance. Therefore, it is reasonable to assume that the ignition wire for short times of voltage pulses build-up can be treated as a long line.
In the next stage of the study aiming to determine the effect of the ignition cable on the voltage of spark discharge, the waveforms of the ignition coil output voltage and the voltage at the end of the ignition cable, (that is, the supply voltage for the ignition of spark plug) were recorded. The experiments were carried as shown in the diagram in Figure 3 and their results are presented in Figure 4.

The average results of measurements using a programmable LRC bridge at frequency $f = 250 \text{ kHz}$ are presented in Table 1.

| No of cable | Impedance at idle $|Z|_{\text{idle}}$ | $Z_{\text{c}}$ $|Z|_{\text{sh}}$ |
|-------------|---------------------|---------------------|
| 1           | 2.200 $-j13.040$    | 6.079 $-j0.0089$ |
| 2           | 3.880 $-j11.864$    | 9.186 $-j0.3614$ |
| 3           | 3.800 $-j12.872$    | 8.570 $-j0.3229$ |

The subsequent stage of the study included numerical experiments. Their purpose was to determine voltage at the end of ignition cable $u_2(t)$, that is, the supply voltage for the ignition of spark plug. The supply voltage is defined as follows:

\[
U_2 = U_1 \left( ch\gamma l - \frac{Z_C}{Z_0} sh\gamma l \right) 
\]

Wave parameters that appear in (11) are determined from the following equations:

\[
Z_C = \sqrt{Z_0 Z_2}, \quad h\gamma l = \frac{Z_C}{Z_0}
\]

where: $Z_0$ – input impedance of a long line at idle, $Z_2$ - input impedance of a long line in short circuit, $Z_C$ – wave impedance of a long line, $\gamma$ - propagation constant of a long line, $l$ - the length of the line.

For the $u_1(t)$ sinusoidal voltage at the input of the line and wave parameters of the examined ignition cables calculated on the basis of measurement results from Table 1, the voltage waveforms at the end of the line were obtained. They are presented in Fig. 4. It is easy to notice that $u_2(t)$ voltage was shifted in phase relative to $u_1(t)$ and decreased the amplitude.

On the basis of simulation results it can be concluded that the approximation of ignition cable by means of a long line gives positive results. A time shift of $u_2(t)$ voltage and the change of its amplitude are observed.

The effect of the ignition cable on the operation of spark plug

The investigations performed under real operating conditions involved observing the microscopic gap between the spark plug electrodes before the tests and after every 500 hours of operation. The tests were carried out using a purpose-built setup presented in Fig. 5.

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Figure 6 shows the digital microscope produced by a Japanese company HIROX, model KH-8700. The device has the magnification of 35 to 5000. It enables us to measure geometrical quantities as well as images of the profiles of the examined surface.

The operational tests were performed for the systems with cables 1, 2 and 3 in the same, defined operational conditions. The analysis of spark plug wear was conducted by electronic scanning. Case examples of spark plug wear are presented in Fig.7.

The photographs presented in the next part of the paper show some results of the experiments on the wear of spark plug electrodes after a 500-hour operation. The experiments are continued for temperature changes.

Conclusion

The research on the ignition system for three types of ignition cables indicates that the type of the cable has considerable influence on the value of spark discharge energy, the electrode burnout and the composition of exhaust gases.

Laboratory tests allow for the verification of computer simulations. They show that the value of electric discharge energy depends on both the quality of fuel delivered to the combustion chamber and the wear of the spark plug electrodes. It should also be noted that the wear of spark plug electrodes significantly affects the value of electric discharge.

As can be seen the value of spark discharge has a major impact on the wear of the spark plug electrodes.

The results suggest that if pressure in the combustion chamber is also considered some interesting conclusions concerning its influence on spark discharge energy can be drawn and investigated. The authors think that the novelty of this paper is the possibility (based on experimental results) to select such R and C of spark plug that allows the mathematical modelling of its wear using the proposed model (without necessity to conduct the experiment).
REFERENCES


