DETERMINATION OF THERMAL EFFICIENCY OF THE SPARK IGNITION SYSTEMS

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Abstract

The paper presents results of measurements performed to determine thermal efficiency of spark ignition systems. Because of small pressure change after sparking process small volume chamber has been proposed for measurements. A direct measurement method of pressure increment determination has been c hosen. In this met hod one pressure chamber is used. The caloric ch amber is filled with nitroge n, which is a neutral gas. It is preferable medium than air because it is one-component gas and it has a precisely-known value of a specific gas constant. The value of specific gas constant is requested to calculate a value of discharge energy given to the gas. In the chosen method pressure increment in the chamber during spark discharge is measured. The pressure increment in the chamber during ignition is strictly related to the e nergy of spark disc harge. The energy balance calculations determined values of heat losses for two types of electrodes (normal and "thi n") and different initial pressure (p=0 bar and p=25 bar). The maximal value of the thermal efficiency was observed for the higher value of pressu re in chamber and thin electrodes of spark plug. It was also stated, that the higher thermal efficiency for" thin" spark plug electrodes is a result of reduced heat transfer.

The paper presents results of the tes ts carried out in the caloric chamber of 4.1 cm3 filled with nitrogen at ambient temperature using PCB transducer direct measur ement method. Results of the meas urements done using differential pressure transducer for the same parameters like in the first measurement method were similar.

Keywords: *combustion process, ignition system, thermal efficiency, spark plug, CNG*

1. Introduction

The main function of an ignition system is to deliver certain amount of energy to a charge containing an air-fuel mixture in order to increase a temperature so that decomposition of hydrocarbon bonds and next a kinetic reaction take place in a combustion process. A secondary circuit of an ignition coil delivers energy E_2 equal to approximately 60 mJ to electrodes of a spark plug. An ignition of a stoichiometric air-fuel mixture (λ=1) requires approximately 0.2 mJ of spark energy. Very rich or lean mixtures may require up to 3 mJ. Most of coils are capable of storing 60-120 mJ of energy and produce an output voltage of over 30 kV. Spark duration for a coil storage ignition (where spark energy is generated by a collapse of a built up magnetic field of a primary coil winding) runs between 1-3 ms. Energy required to ignite the CNG mixture, which is only a part of energy generated by the coil has to be delivered to a spark plug gap. Power is lost across a distributor gap, via leakage of wires' insulators and any in-line resistances such as wires and resistors inside spark plugs themselves. The biggest loss of energy is caused by heat transfer to electrodes that causes cooling of an ionization arc and by radiation of the ionization kernel. Longer spark duration and larger spark length both increase probability that a given mixture will be ignited by a spark plug. Turbulence in a mixture itself is also desirable, although too strong airflow can blow out a spark or prevent its formation.

2. Thermal efficiency

A small part of energy delivered by a secondary circuit is consumed by gaseous medium, what is observed by increase of temperature ΔT and thus internal energy E_i. Thermal efficiency of an ignition system is defined as ratio of an increase of internal energy and energy in the secondary circuit of the ignition coil:

$$\eta_{th} = \frac{\Delta E_i}{E_2} = \frac{\Delta E_i \cdot E_1}{E_2 \cdot E_1} = \eta_o \cdot \eta_e, \tag{1}$$

where:
η_{th} - thermal efficiency,
E_1 - energy in a primary circuit,
η_o - total efficiency,
η_e - electric efficiency of an ignition system.

Increase of internal energy in volume V with initial pressure p_1 can be determined as (2):

$$\Delta E_i = m \cdot c_v \cdot \Delta T_e, \tag{2}$$

where:
m - mass of gaseous medium,
cv - volumetric specific heat.

Assuming constant mass and individual gas constant R from the gas state equation temperature after sparking can be defined as follows (3):

$$T_2 = T_1 \cdot \frac{p_2}{p_1}, \tag{3}$$

where:
p_1, p_2 - pressure before and after process,
T_1,T_2 - temperature before and after process.

At small change of gas temperature from T_1 to T_2 volumetric specific heat c_v doesn't change. According to that it is possible to determine increase of internal energy (4):

$$\Delta E_i = \frac{p_1 \cdot V}{R \cdot T_1} \cdot c_v \cdot (T_2 - T_1) = \frac{p_1 \cdot V}{R \cdot T_1} \cdot c_v \cdot \left(T_1 \cdot \frac{p_2}{p_1} - T_1 \right). \tag{4}$$

After simplification this equation takes the form (5):

$$\Delta E_i = \frac{V}{R} \cdot c_v \cdot (p_2 - p_1) = \frac{V}{R} \cdot c_v \cdot \Delta p. \tag{5}$$

Increase of the internal energy depends on sparking volume, gas properties and pressure increase in this volume. Because of constant volume and known R and c_v the only unknown value is pressure increment Δp. The known parameters for nitrogen N_2 are listed below:

a) $R = \frac{(MR)}{M} = \frac{8314}{28} = 269.9$ J/(kg K),
b) c_p = 1043 J/(kg K) at 273 K,
c) c_p = 1069 J/(kg K) at 298 K,
d) $c_v = c_p - R$ =1069 – 296.9 = 772.1 J/(kg K) at 298 K (κ=1.384).

3. Method of determination of the thermal efficiency

The one chamber direct measurement method has been chosen for determination of pressure increment. A small volume chamber is proposed because of low change of pressure after sparking. The direct measurement method uses a very sensitive and high static pressure limited pressure piezoelectric transducer PCB Piezotronic 106B51 with the following parameters:
a) measurement range (for ±5V output) 35 kPa,

b) maximum pressure (step) 690 kPa,
c) maximum pressure (static) 3448 kPa,
d) sensitivity (±15%) 145 mV/kPa,
e) resonant frequency ≥ 40 kHz,
f) non-linearity < 1% FS.

Energocontrol VibAmp PA-3000 amplifier with three inputs and three amplification values for each channel (1, 10, 1000) was used for measurements. The piezoelectric sensor's main diameter equals to 15.7 mm. The sensor has an amplifier containing a transistor IGBT with unity amplification.

Scheme of filling the chamber together with fixing of a spark plug and the transducer is shown in Fig. 1.

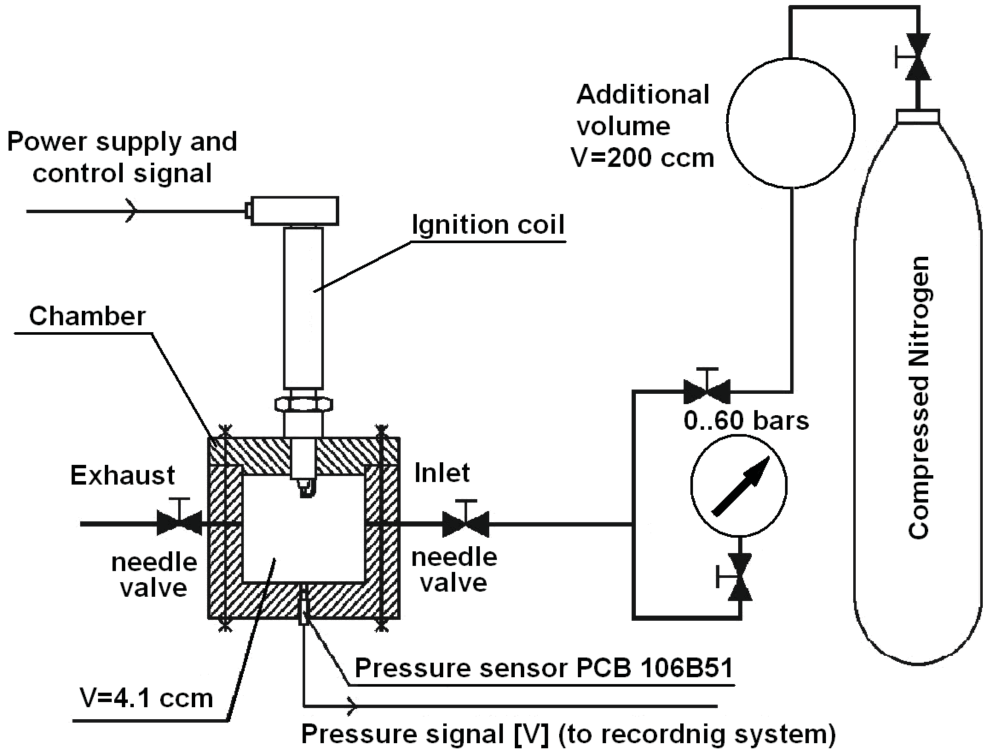

Fig. 1. Scheme of the direct pressure measurement method in the caloric chamber

The additional 200 cm^3 volume chamber is filled with nitrogen under given pressure (shown in manometer) from the pressure bottle. The caloric chamber is filled in from the volume chamber through the needle valves. After sparking the chamber is emptied by opening the other needle valve. The needle valves were used in order to decrease the dead volume in the pipes connecting the chambers. The total volume which equals to 4,1 cm^3 was measured by filling in the chamber with water. Fig. 2 shows the laboratory stand for the first measurement method of pressure increment during sparking. The caloric chamber was made from thick wall plexiglas in order to prevent heat exchange trough the walls to ambient air. The measurements were carried out at filtration of the electric noise above 1 kHz.

4. Results of measurements

The target of the test was to determine amount of thermal energy delivered to the charge in the chamber after sparking what means measurements of pressure increment in function of initial pressure. 10 measurements have been carried out to obtain one point of each characteristic. Two types of spark plug electrodes were used for the test:

a) standard electrode 2.8 mm wide,
b) "thin" electrode (25% of the normal electrode cross-section).

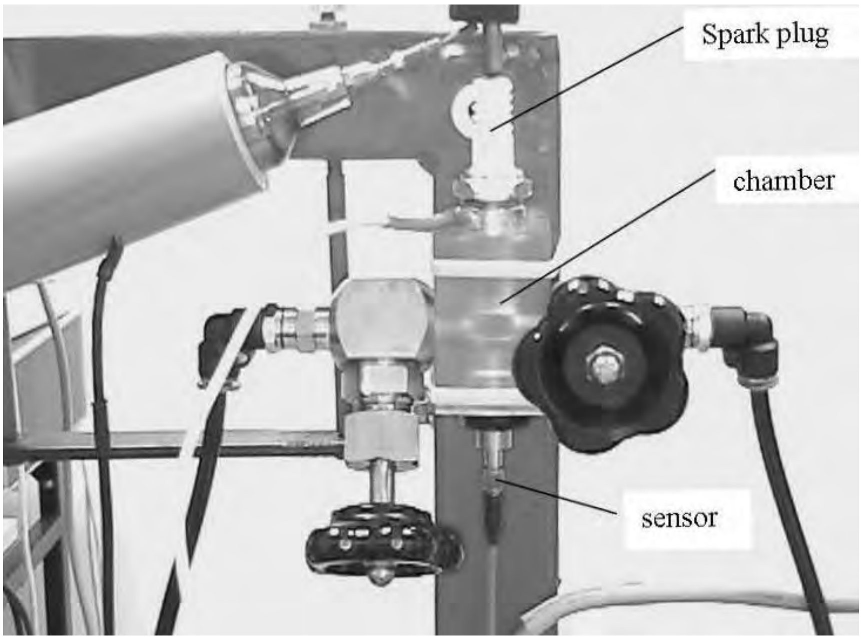

Fig. 2. Measurement chamber with needle valves, pressure sensor and spark plug

The measurements were carried out using nitrogen at initial pressure in the chamber corresponding to ambient conditions (overpressure 0 bar) and at 25 bar. Higher increment of pressure is observed for the "thin" electrodes than for the spark plug with normal electrodes both at low and at high initial pressure, despite the fact that energy delivered from the secondary circuit of the coil is almost the same. For the case with "thin" electrodes and initial pressure 1 bar thermal energy equals to 0.89 mJ only and thus thermal efficiency is about η_{th} = 1.29%. For the normal electrodes and initial pressure of 25 bar the same parameters equal to 4.23 mJ and η_{th} = 6.93%. Fig. 3 presents representative mean values for the defined test series obtained with the pressure of 25 bars and "thin" electrodes of spark plug. Secondary energy was determined by integrating voltage and current in the secondary circuit with small time step of integration.

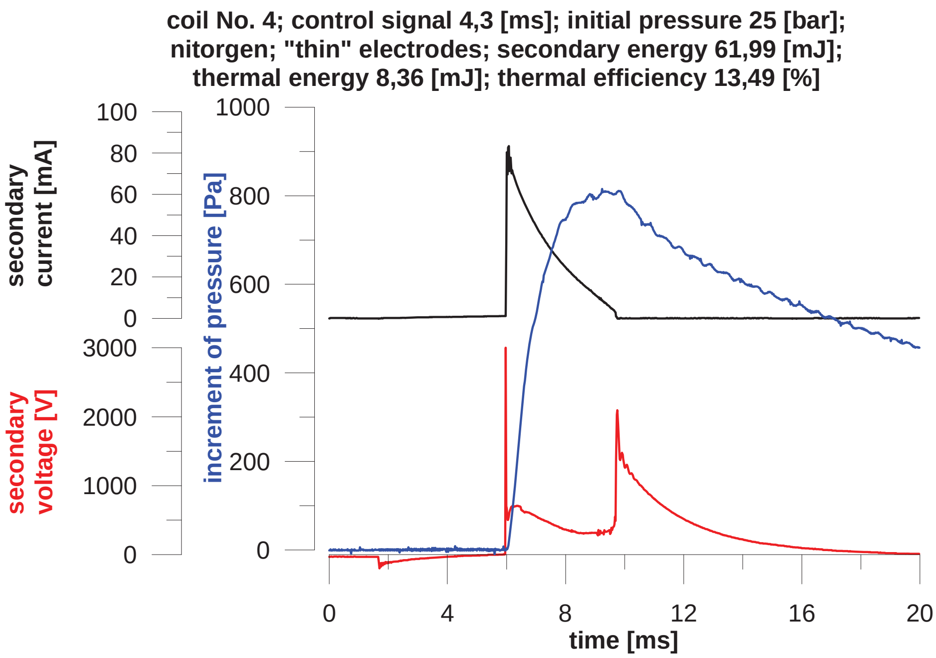

Fig. 3. Pressure increment in the chamber, secondary voltage and secondary current in the coil No. 4 at initial pressure of 25 bar for spark plug with "thin" electrodes

Secondary coil energy, maximum values of pressure increment, thermal energy delivered to the charge and thermal efficiency for both types of electrodes (normal, “thin”) at overpressure of 0 bar and 25 bar are shown in Fig. 4-7 respectively.

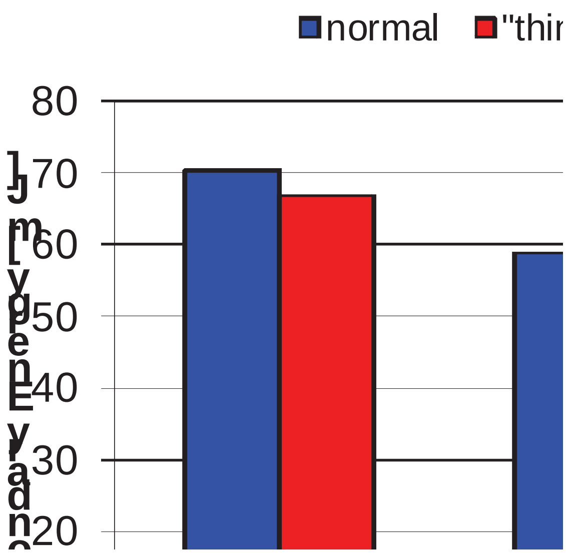

Fig. 4. The secondary circuit energy of ignition system

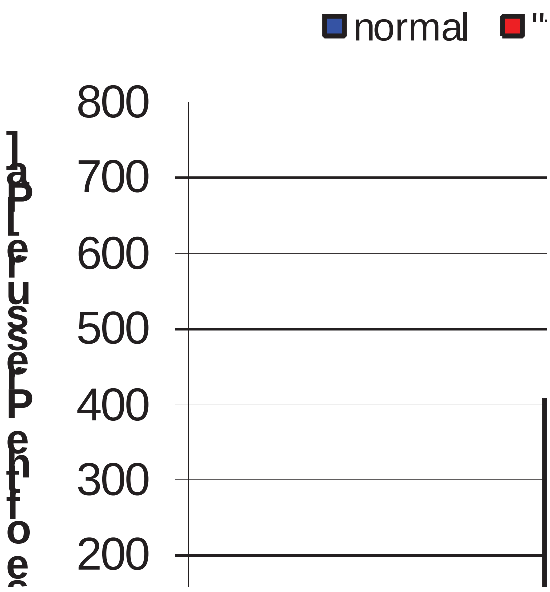

Fig. 5. The increase of the pressure in the chamber

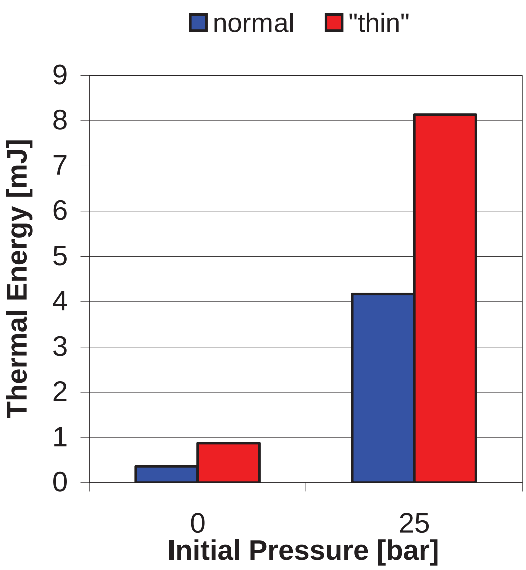

Fig. 6. Thermal energy delivered to the nitrogen

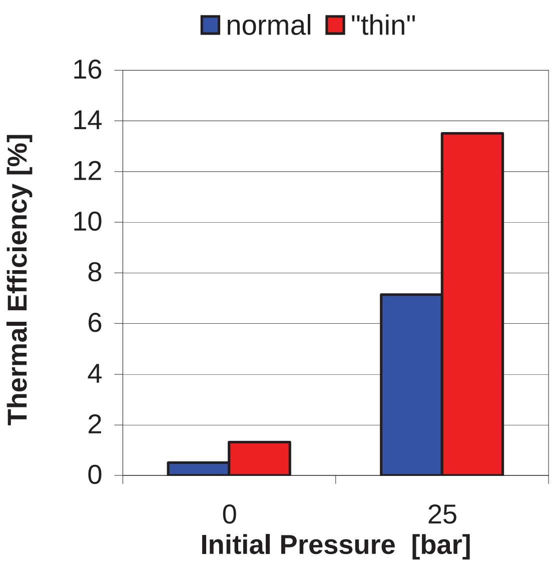

Fig. 7. Thermal efficiency of ignition system

5. Balance of energies

On the basis of the carried out experimental tests and the theoretical considerations flow of energy delivered to the chamber from the secondary circuit of the coil can be shown using Sankey’s chart. The carried out calculations determined following values of heat losses for the measurements with initial pressure of 25 bar and spark plug with the normal electrodes:

a) radiation E_r=7,8 mJ,
b) ionization E_i=7,2 mJ,
c) heat transfer E_h=31 mJ,
d) kinetic energy E_k=9 mJ.

The total calculated energy losses equal to 55 mJ. Measurements shown that thermal energy delivered to the charge equals to E_{th} = 4.23 mJ. Measured energy delivered by the secondary circuit equals to E_2 = 61.05 mJ. The other non-considered heat losses equal to E_c = 1.82 mJ. The percentage participation of the particular heats equal to: E_r =12.7%, E_i =11.8%, E_h =50.8%, E_k = 14.7%, E_{th} = 6.93%, E_c = 3.07% Sankey's diagram for both normal and "thin" electrodes is shown in Fig. 8.

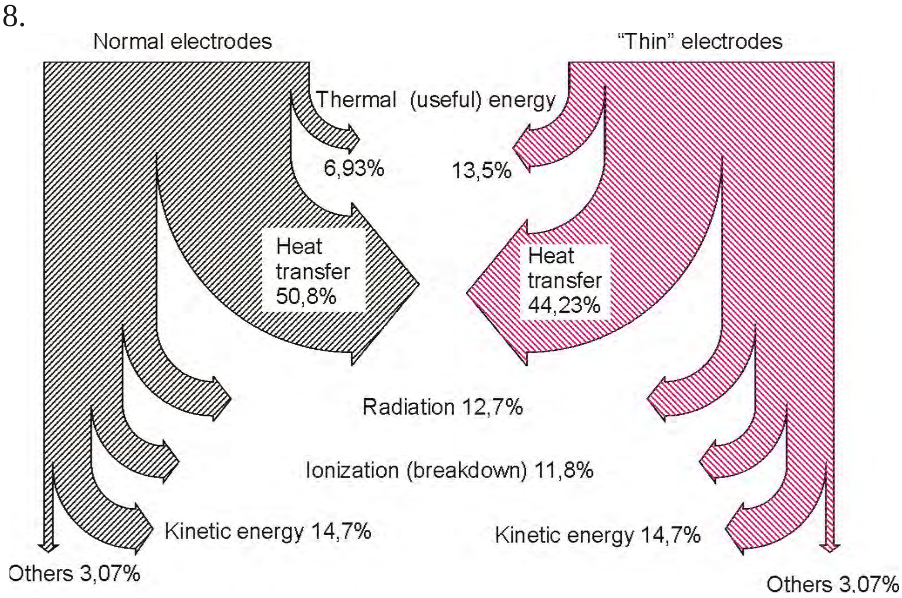

Fig. 8. Balance of energy in a conventional ignition system for two types of electrodes

The energy balance shows that heat transfer to the electrodes consumes half of energy delivered during sparking process. Decrease of the electrodes' cross-section to 25% of their initial value increases thermal efficiency almost twice with decrease of heat transfer to the electrodes. The work done by Liu et al [12] shows that discharge efficiency of conventional spark ignition system is below 0.1 (10%) despite higher coil energy (above 100 mJ).

6. Remarks and conclusions

This article presents results of the tests carried out in the caloric chamber of 4.1 cm^3 filled with nitrogen at ambient temperature using PCB transducer direct measurement method only. Results of the measurements done using differential pressure transducer for the same parameters like in the first measurement method were similar. As a result of carried out measurements following conclusions can be drawn:

a) increment of internal energy depends on an initial pressure inside the chamber. The higher the initial pressure is the bigger internal energy and thermal efficiency are;
b) for conventional ignition systems only up to 15% of secondary energy is consumed by the charge (even if secondary energy exceeds 60 mJ);
c) maximal thermal efficiency was obtained at initial pressure of 25 bar and reached 13.5% for the spark plug with "thin" electrodes and was only 1% at ambient pressure and temperature;
d) spark plugs with "thin" electrodes have higher thermal efficiency than those with normal electrodes. This is due to smaller heat exchange with electrodes' walls;
e) energy losses consist of heat exchange, ionization energy (breakdown), radiation and others. Theoretical studies show that highest contributions to loose have heat transfer to spark's electrodes and radiation. The tests were carried out at stagnation of the charge (without turbulence), which causes smaller heat transfer from ionization kernel to the charge;
f) experiments performed by other scientists show that only up to 10% of energy delivered to a charge increases its internal energy.

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