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ANALYSIS OF INDICATION ERRORS OF THE SI GAS ENGINE WITH A PRECHAMBER

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Summary. The paper presents indication results accuracy and accuracy of thermal processes analysis which particularly occurs in the cylinder of internal combustion engine. The characteristic values of IC (internal combustion) engine thermal cycle are: indicated efficiency and pressure and non-repeatability factor of indicated work. The paper presents results of measuring errors analysis and uncertainty of the above-mentioned values obtained from indication of the spark ignition internal combustion engine with a prechamber. The analysis shows that results of the indication of the piston engine should include information on measurement accuracy and uncertainty of the calculated values. This information has a significant influence on the final measurement results. Errors are the inseparable part of measurement result. Results without given errors are not complete. The indication of the internal combustion engine is currently a standard research method which allows us to find out information on temporary parameters of processes in the cylinder of IC engine. The indication of IC engine is generally considered to be a very accurate method with repeatability of results. On the basis of error analysis and measurement uncertainty it was confirmed that the main parameters are loaded with significant errors.

Key words: engine with two-stage combustion system, excess air factor, indicated work, indicated efficiency, non-repeatability factor of the indicated work.

INTRODUCTION

Experimental measurements of processes in a combustion engine are a source of necessary knowledge to optimize and improve the engine and can lead to reduction of emissions of harmful exhaust components, and reduction of fuel consumption. Basic experimental method of testing the working processes in the cylinder of internal combustion engine is indicated, consisting mainly in the measurement of fast-changing processes and instantaneous changes in the cylinder pressure. Information obtained from the indicated engine cylinder is the basis for the diagnosis and optimization of the combustion process and allows for a qualitative assessment of its work. Results of indicated engine piston analysis, in particular the results of the analysis of thermal processes occurring in the cylinder are in varying degrees dependent on the accuracy of measurements and the uncertainty of the result.

The test engine was constructed on the basis of a four-stroke compression-ignition engine manufactured by “ANDORIA” Diesel Engine Manufacturers of Andrychow, which, after some constructional changes, was designed for the combustion of gaseous fuel as a spark-ignition engine due to a new fuel supply system and an ignition installation. The main engine element that underwent modernization was the head (Fig. 1).

Tab. 1. Main engine parameters

displacement volume	1810 cm^3
number of cylinders	1
cylinder configuration	horizontal
cylinder bore	120 mm
connecting-rod length	275 mm
piston stroke	160 mm
compression ratio	8.6
engine speed	1000 rpm

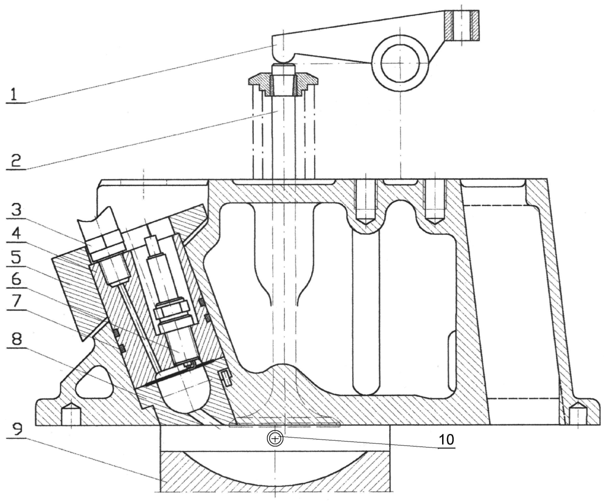

Fig. 1. Test engine head with prechamber
1 - valve rocker, 2 - inlet valve, 3 - flame suppressor,
4 - prechamber head, 5 - retaining cover, 6 - spark plug,
7 - sealing ring, 8 – prechamber body, 9 – piston, 10 – pressure sensor

The implemented changes allowed for an additional combustion chamber (prechamber) to be installed in the previously existing head of the S320 ER engine by setting the compression ratio to 8.6. The prechamber volume is approximately 4.5% of the total volume above the piston at TDC (top dead centre) and it is located asymmetrically regarding the cylinder axis. The applied changes have enabled the implementation of two-stage combustion system within the sectional combustion chamber.

MEASUREMENT PROCEDURE

The tests were conducted at a constant rotational speed of n = 1000 rpm. The engine was brought to full loading after prior thermal stabilisation, that is, the cooling water was brought to boiling (the evaporation cooling system). The main chamber and prechamber of the test engine was powered by propane-butane gas LPG (liquefied petroleum gas). The tests included three main measurement series allowing for a different ratio of thermal energy input with fuel to the prechamber - Q_{in}, to the thermal energy input to the whole engine - Q_{tot}. The pressures occurring in the engine combustion chambers were recorded for Q_{in}/Q_{tot} = 2.5%, for Q_{in}/Q_{tot} = 5% and for Q_{in}/Q_{tot} = 8%, while the combustion air factor changed in the range from 1.4 to 2.0 and the ignition advance angle in the range from 6 deg to 18 deg before the TDC. The recording was made for 95 successive operation cycles every 1 deg with specialised software [1]. At the same time, other quantities necessary for the subsequent analysis of indication results [2] were three times measured, such as rotational speed, air consumption, gas fuel consumption, air temperature, combustion-gas temperature and ambient pressure and temperature.

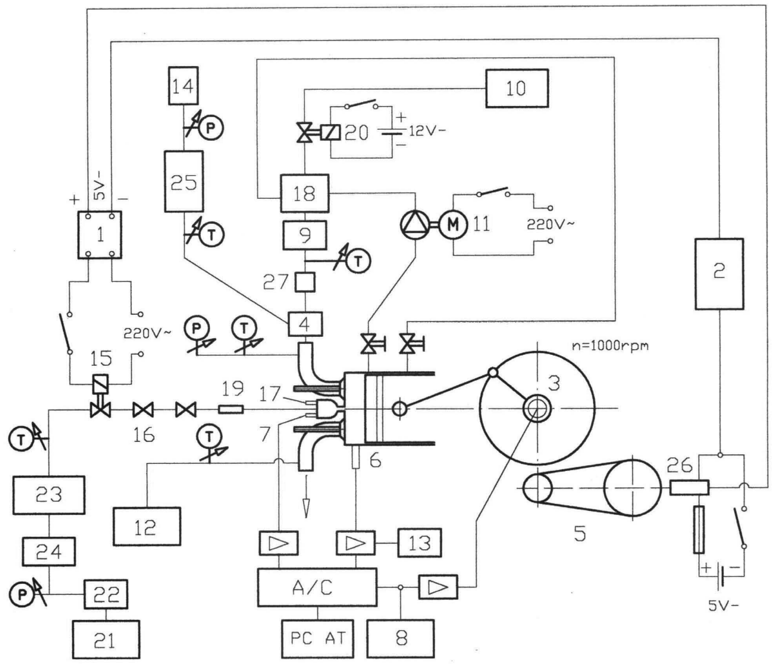

Fig. 2. Schematic diagram of the testing stand

1 – electronic relay, 2 – pulse generating system, 3 – CA angle transmitter, 4 – gas mixer, 5 – belt transmission, 6 – main chamber pressure sensor, 7 – prechamber pressure sensor, 8 – counting module, 9 – gas flowmeter, 10 – main gas fuel tank, 11 – circulating-water pump, 12 – combustion-gas analyser, 13 – oscilloscope, 14 – measuring orifice, 15 – solenoid valve prechamber, 16 – non-return valve set, 17 – spark plug, 18 – reducer-evaporator, 19 – flame suppressor, 20 – gas solenoid valve, 21 – gas fuel tank prechamber, 22 – pressure regulator, 23 – pressure fluctuation damping reservoir, 24 – set of measurement rotameters, 25 – equalizing tank, 26 – magnetic induction sensor, 27 – metering valve

The value of excess air factor of fuel mixture gas analyzer was measured by the AI Radio 9600 on the basis of the oxygen in the exhaust of the engine. For the analyzer measurement the range of excess air factor contained from 0 to 2, and the measurement resolution was 0.01.

The paper presents an analysis of measurement error of the indicated work and the indicated efficiency. The performed analysis of uncertainty determination for the indicated work which determines the dispersion (spread) around the average value calculation results indicated work in the individual cycles of the three measurements containing 95 registered engine cycles. Uncertainty analysis was performed for the indicated efficiency with the three measurements of speed, the time consumption of propane-butane gas in the cylinder, the propane-butane jet delivered to the prechamber and for the three average values indicated work was performed. The study also calculated the uncertainty of determining the non-repeatability factor of indicated work which defines the uniqueness of the engine test cycles.

ANALYSIS OF MEASUREMENT RESULTS

Characteristics based on an analysis of the measurement results show that the energetic share of enriching fuel in the prechamber in the engine with a two-stage combustion system has an influence on the indicated efficiency, the indicated work and the stability of the engine work and repeatability of the cycles. The best effects of the test engine were achieved for the lowest analysed energetic share of enriching fuel, which was 2.5%.

One of the parameters determining the performance of the combustion engine is the indicated work:

$$L_i = \frac{\sum_{0}^{720} \frac{p_n + p_{n+1}}{2}(V_{n+1} - V_n)}{V_s}, \tag{1}$$

where: p_n, p_{n+1} are instantaneous values of the pressure in the cylinder [MPa], V_n, V_{n+1} are instantaneous values of the cylinder volume [m^3], V_s is displacement volume [m^3].

For Q_{in}/Q_{tot} = 2.5%, indicated work decreased with increasing excess air factor. L_i ranged from 0.72 to 0.55 MJ/m^3 (Fig. 3).

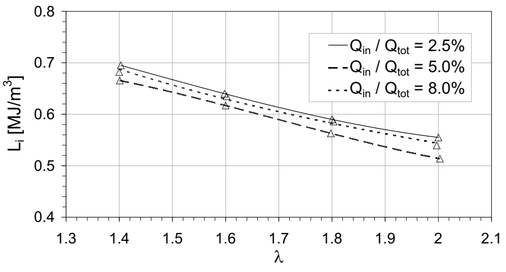

Fig. 3. Indicated work versus excess air factor

The practical measurement of physical quantities is related to measurement error and the uncertainty of the result. The measurement error of the indicated work consists of measurement error in the engine cylinder pressure and the error of measurement of the instantaneous cylinder volume. The measurement error of the indicated work can be determined from the dependence [3]:

$$\delta L_i = \sqrt{\delta p^2 + \delta V^2}, \tag{2}$$

where: δp is measurement error in the cylinder pressure [%], δV is measurement error of the instantaneous cylinder volume [%].

The measurement error in the cylinder pressure is the sum of the piezo quartz pressure sensor error, the amplifier error and the error of the measurement a/d card.

$$\delta p = \sqrt{\delta cz^2 + \delta w^2 + \delta(a/d)^2}, \tag{3}$$

$$\delta cz = 0.5\% \ [4],$$

$$\delta w = 3\% \ [5],$$

where: δcz is error of the piezo quartz pressure sensor [%], δw is amplifier error [%], δ(a/d) is error of the measurement card [%].

The error of the measurement card is quantization error of the a/d converter with the processing of ±10V and a resolution of 12 bit [6]:

$$\delta(a/d)=\frac{\theta}{FSR}100\%, \tag{4}$$

$$\theta=\frac{FSR}{2^r},$$

$$\delta(a/d)=0.024\%,$$

where: θ is quantization interval of the a/d converter [V], FSR is range of a/d converter [V], r is resolution of the a/d converter.

The measurement error of the instantaneous cylinder volume is the sum of CA crank angle transmitter error and error of measurement a/d card:

$$\delta V=\sqrt{\delta k^2+\delta(a/d)^2}, \tag{5}$$

where: δk is error of CA crank angle transmitter [%].

The error of CA crank angle transmitter was calculated with respect to the perpendicular position of the connecting rod relative of the crankshaft crank arm. It is calculated as the ratio of change in volume of the cylinder, for 0.5 deg - half the value of the step crank angle transmitter, to the displacement volume:

$$\delta k=\frac{\Delta V}{V_s}100\%=0.45\%, \tag{6}$$

where: ΔV is change in cylinder volume corresponding to pulse duration of the course of a rectangular tag of the crank angle transmitter [m^3].

According to relation (2) measurement error of the indicated work is equal to $\delta L_i \approx 3.1\%$.

The uncertainty designation of the indicated work, determine the dispersion (spread) around the average value calculation results of the indicated work in the individual cycles of the three measurements containing 95 registered engine cycles. It was assumed that the uncertainty designation of the indicated work has a normal distribution and it was calculated from the relation [3]:

$$\Delta L_{ii}=t_s\sigma_{Lii}, \tag{7}$$

where: t_s is coefficient of the t-Student distribution for N-1 degrees of freedom and for the most commonly adopted technique in the 95% confidence level, N is the number of measurements.

The standard deviation of the indicated work:

$$\sigma_{Lii}=\sqrt{\frac{1}{N-1}\sum(L_{ii}-L_i)^2}, \tag{8}$$

where: L_{ii} is value of the indicated work of cycles [MJ/m^3], L_i is average value of the indicated work of the three measurements containing 95 registered engine cycles [MJ/m^3].

The accuracy of determining the average value of a specified quantity is dependent on the number of measurements and the uncertainty limit of average value is called. For indicated work of the uncertainty the determination of the average value was calculated according to [3]:

$$\Delta L_i = t_s \frac{\sigma_{Lii}}{\sqrt{N}}. \tag{9}$$

Figure 4 shows the uncertainty intervals designation of the indicated work $\pm\Delta L_{ii}$ and the uncertainty intervals designation of the average value of the indicated work $\pm\Delta L_i$. They were placed on the characteristics of the average value of L_i changes in the function of the excess air factor, the $Q_{in}/Q_{tot} = 2.5\%$. The uncertainty value $\pm\Delta L_{ii}$ ranged from ±0.008 MPa for $\lambda = 1.6$ (1.3% of the average value of the indicated work) to ±0.03 MPa for $\lambda = 2.0$ (5% of the L_i value). The uncertainty value $\pm\Delta L_i$ ranged from ±0.0005 MPa for $\lambda = 1.6$ (0.08% of the average value of the indicated work), to ±0.002 MPa for $\lambda = 2.0$ (0.29% of the L_i value).

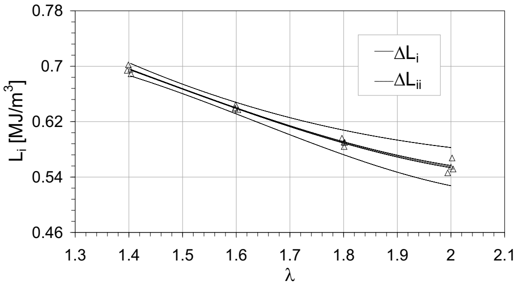

Fig. 4. Indicated work with uncertainty intervals determination of the indicated work ΔL_{ii} and its average value ΔL_i, for $Q_{in}/Q_{tot} = 2.5\%$

The highest indicated efficiency, equal to $\eta_i = 36.5\%$, test engine achieved when the share of enriching fuel mixture in the prechamber was 2.5%.

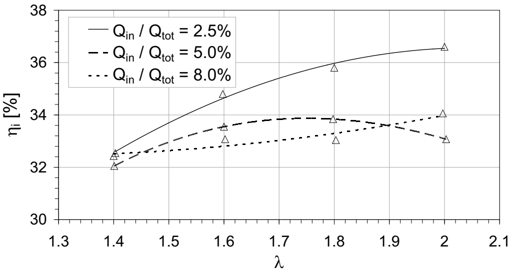

Fig. 5. Indicated efficiency versus excess air factor

The indicated efficiency is the ratio of the indicated work done in the operating cycle of the engine to the heat supplied to the engine over the cycle. During the tests the measurement of heat applied in a single cycle was not possible because the measured value was the amount of heat brought in during a few hundred cycles (about 500). The indicated efficiency was defined as the ratio of the indicated work in the cylinder volume, averaged during the measurement of fuel consumption to the average amount of heat. The measurement error of the indicated efficiency average is the sum of the measurement error of the indicated work average, and the measurement error of the total heat supplied to the engine.

The average value of the indicated efficiency, expressed in % is equal to:

$$\eta_i = \frac{L_i V_s}{Q_{tot}} 100\%,$$

$$\eta_i = \frac{L_i V_s}{Q_{cyl} + Q_{in}} 100\%, \tag{10}$$

where: Q_{tot} is total heat supplied to the engine [MJ], Q_{cyl} is heat supplied to the engine cylinder [MJ], Q_{in} is heat supplied to the prechamber [MJ].

The measurement error of the average value of the indicated efficiency:

$$\delta\eta_i = \sqrt{\delta L_i^{\ 2} + \delta Q_{tot}^{\ 2}},$$

$$\delta Q_{tot} = \sqrt{\delta Q_{cyl}^{\ 2} + \delta Q_{in}^{\ 2}},$$

$$\frac{\delta Q_{tot}}{Q_{tot}} = \sqrt{\left(\frac{\delta Q_{cyl}}{Q_{tot}}\right)^2 + \left(\frac{\delta Q_{in}}{Q_{tot}}\right)^2},$$

$$\frac{\delta Q_{tot}}{Q_{tot}} = \sqrt{\left(\frac{\delta Q_{cyl}}{Q_{cyl} + Q_{in}} \frac{Q_{cyl}}{Q_{cyl}}\right)^2 + \left(\frac{\delta Q_{in}}{Q_{cyl} + Q_{in}} \frac{Q_{in}}{Q_{in}}\right)^2},$$

$$\delta Q_{tot} = \sqrt{\left(\frac{Q_{cyl}}{Q_{cyl} + Q_{in}}\right)^2 \delta Q_{cyl}^{\ 2} + \left(\frac{Q_{in}}{Q_{cyl} + Q_{in}}\right)^2 \delta Q_{in}^{\ 2}},$$

$$\delta\eta_i = \sqrt{\delta L_i^{\ 2} + \left(\frac{Q_{cyl}}{Q_{cyl} + Q_{in}}\right)^2 \delta Q_{cyl}^{\ 2} + \left(\frac{Q_{in}}{Q_{cyl} + Q_{in}}\right)^2 \delta Q_{in}^{\ 2}}, \tag{11}$$

where: δL_i is the measurement error of the indicated work [%], δQ_{tot} is the measurement error of the total heat supplied to the engine [%], δQ_{cyl} is the measurement error of the heat supplied to the engine cylinder [%], δQ_{in} is the measurement error of the heat supplied to the prechamber [%].

The heat supplied to the engine cylinder:

$$Q_{cyl} = \frac{V_{cyl}\, \rho_{LPG} W_{LPG}}{0{,}5\, n\, t}, \tag{12}$$

where: V_{cyl} is volume of propane-butane delivered to the engine cylinder [m^3], ρ_{LPG} is density of propane-butane [kg/m^3], W_{LPG} is calorific value of propane-butane [MJ/kg], n is speed engine [rpm], t is time consumption of propane-butane delivered to the engine cylinder [min].

The measurement error of the heat supplied to the engine cylinder:

$$\delta Q_{cyl} = \sqrt{\delta V_{cyl}^{\ 2} + \delta\rho_{LPG}^{\ 2} + \delta W_{LPG}^{\ 2} + \delta n^2 + \delta t^2}, \tag{13}$$

where: δV_{cyl} is measurement error of volume of propane-butane delivered to the engine cylinder [%], $\delta\rho_{LPG}$ is an estimated error of propane-butane density [%], δW_{LPG} is estimated error of calorific value of propane-butane [%], δn is measurement error of speed engine [%], δt is measurement error of time consumption of propane-butane delivered to the engine cylinder [%].

The measurement error of propane-butane volume delivered to the engine cylinder is expressed in % and was calculated as a ratio scale interval of gas flowmeter to the measured value of propane-butane volume:

$$\delta V_{cyl} = \frac{dz.elem.}{V_{cyl}} 100\% = 1\%. \tag{14}$$

The estimated error of propane-butane density [7]:

$$\delta \rho_{LPG} = 6.8\%.$$

The estimated error of calorific value of propane-butane [7]:

$$\delta W_{LPG} = 1.8\%.$$

The measurement error of speed engine is expressed in % and was calculated as a ratio scale interval of the speed measurement system to the measured value of speed engine:

$$\delta n = \frac{dz.elem.}{n} 100\% = 0.1\%. \tag{15}$$

The measurement error of time consumption of propane-butane in engine cylinder is expressed in % and was calculated as a ratio scale interval of the timer to the measured value of time:

$$\delta t = \frac{dz.elem.}{t} 100\% = 0.2\%. \tag{16}$$

The heat supplied to the prechamber of the engine:

$$Q_{in} = \frac{V'_{in}\, \rho_{LPG} W_{LPG}}{0{,}5\, n}, \tag{17}$$

where: V'_{in} is propane-butane jet delivered to the prechamber [m^3/min].

The measurement error of the heat supplied to the prechamber of the engine:

$$\delta Q_{in} = \sqrt{\delta V'^{2}_{in} + \delta \rho_{LPG}^{2} + \delta W_{LPG}^{2} + \delta n^{2}}, \tag{18}$$

where: $\delta V'_{in}$ is measurement error of propane-butane jet delivered to the prechamber [%].

The measurement error of propane-butane jet delivered to the prechamber of the engine is expressed in % and was calculated as a ratio scale interval of gas rotameter to the measured value of propane-butane jet:

$$\delta V'_{in} = \frac{dz.elem.}{V'_{in}} 100\% = 5\%. \tag{19}$$

According to relation (11) measurement error of the average value of the indicated efficiency is equal $\delta \eta_i \approx 7.3\%$.

The uncertainty of the indicated efficiency depends on the uncertainty of the indicated work, engine speed, time consumption of propane-butane in the engine cylinder and propane-butane jet delivered to the prechamber. The uncertainty of the indicated efficiency was determined from three measurements of engine speed, consumption time of propane-butane in the engine cylinder and propane-butane jet delivered to the prechamber as well as the three average values of the indicated work.

The uncertainty of the indicated efficiency was calculated according to [3]:

$$\Delta\eta_{ii} = \sqrt{\left(\frac{\partial\eta_i}{\partial L_i}\Delta L_{ii}\right)^2 + \left(\frac{\partial\eta_i}{\partial n}\Delta n_i\right)^2 + \left(\frac{\partial\eta_i}{\partial t}\Delta t_i\right)^2 + \left(\frac{\partial\eta_i}{\partial V'_{in}}\Delta V'_{ini}\right)^2}, \tag{20}$$

$$\frac{\partial\eta_i}{\partial L_i} = \frac{0.5 V_s n t}{\left(V_{cyl}\,\rho_{LPG} W_{LPG} + V'_{in}\, W_{LPG}\, t\right)},$$

$$\frac{\partial\eta_i}{\partial n} = \frac{0.5 L_i V_s t}{\left(V_{cyl}\,\rho_{LPG} W_{LPG} + V'_{in}\, W_{LPG}\, t\right)},$$

$$\frac{\partial\eta_i}{\partial t} = \frac{0.5 L_i V_s n (V_{cyl}\,\rho_{LPG} W_{LPG} + V'_{in} W_{LPG}\, t) - 0.5 L_i V_s n t V'_{in} W_{LPG}}{\left(V_{cyl}\,\rho_{LPG} W_{LPG} + V'_{in} W_{LPG}\, t\right)^2},$$

$$\frac{\partial\eta_i}{\partial V'_{in}} = \frac{-0.5 L_i V_s n t^2 W_{LPG}}{\left(V_{cyl}\,\rho_{LPG} W_{LPG} + V'_{in}\, W_{LPG}\, t\right)^2}.$$

The uncertainty of the engine speed:

$$\Delta n_i = t_s\,\sigma_{ni}, \tag{21}$$

where σ_{ni} is the standard deviation of the engine speed [rpm].

The uncertainty of the time consumption of propane-butane in the engine cylinder:

$$\Delta t_i = t_s\,\sigma_{ti}, \tag{22}$$

where σ_{ti} is the standard deviation of the time consumption of propane-butane in the engine cylinder [min].

The uncertainty designation of the propane-butane jet delivered to the prechamber of the engine:

$$\Delta V'_{ini} = t_s \sigma_{V'ini}, \tag{23}$$

where $\sigma_{V'ini}$ is the standard deviation of the propane-butane jet delivered to the prechamber [m^3/min].

The uncertainty of the average value of the indicated efficiency was calculated according to [3]:

$$\Delta\eta_i = \sqrt{\left(\frac{\partial\eta_i}{\partial L_i}\Delta L_i\right)^2 + \left(\frac{\partial\eta_i}{\partial n}\Delta n\right)^2 + \left(\frac{\partial\eta_i}{\partial t}\Delta t\right)^2 + \left(\frac{\partial\eta_i}{\partial V'_{in}}\Delta V'_{in}\right)^2}, \tag{24}$$

The uncertainty of the average value of the indicated work:

$$\Delta L_i = t_s \frac{\sigma_{Lii}}{\sqrt{3}}, \tag{25}$$

The uncertainty of the average value of the engine speed:

$$\Delta n = t_s \frac{\sigma_{ni}}{\sqrt{3}}, \tag{26}$$

The uncertainty of the average value of the time consumption of propane-butane:

$$\Delta t = t_s \frac{\sigma_{ti}}{\sqrt{3}}, \tag{27}$$

The uncertainty of the average value of the propane-butane jet delivered to the prechamber:

$$\Delta V'_{in} = t_s \frac{\sigma_{V'ini}}{\sqrt{3}}, \tag{28}$$

Figure 6 shows the uncertainty intervals of the indicated efficiency $\pm\Delta\eta_{ii}$ and the uncertainty intervals of the average value of the indicated efficiency $\pm\Delta\eta_i$. They were placed on the characteristics of the average value of η_i changes in the function of the excess air factor, the Q_{in}/Q_{tot} = 2.5%. The uncertainty value $\pm\Delta\eta_{ii}$ ranged from ±1.2% for λ = 1.6 (3.6% of the average value of the indicated efficiency) to ±2.7% for λ = 2.0 (7.4% of the η_i value). The uncertainty value $\pm\Delta\eta_i$ ranged from ±0.7% for λ = 1.6 (2.1% of the average value of the indicated efficiency), to ±1.6% for λ = 2.0 (4.3% of the η_i value).

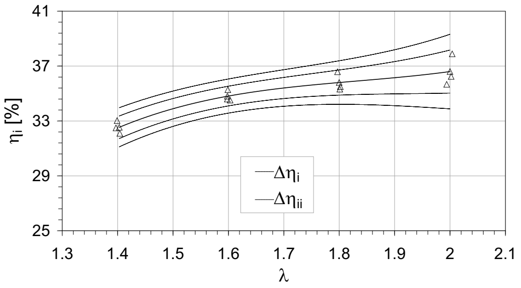

Fig. 6. Indicated efficiency with uncertainty intervals determination for indicated efficiency $\Delta\eta_{ii}$ and its average value $\Delta\eta_i$ for Q_{in}/Q_{tot} = 2.5%

One of the main criteria for evaluating the work of the internal combustion engine is non-repeatability of engine cycles. In the present study, the non-repeatability cycle phenomenon was defined by the factor of the non-repeatability factor of the indicated work engine COV_{Li}. It is expressed in % and calculated as the ratio of the standard deviation of the engine indicated work to the average value of its three measurements containing 95 registered engine cycles.

$$COV_{Li} = \frac{\sigma_{Lii}}{L_i} 100\%. \tag{29}$$

In conventional SI engines, the combustion process of the correct mixture takes place in a fairly narrow range of λ. Depletion of the fuel mixture to a level at which the value of the excess air ratio exceeds 1.5 causes irregular engine performance manifested by, inter alia, misfire and non-repeatability of engine cycles. According to literature [10], the limit of the correct operation of the internal combustion engine, expressed by the maximum of the non-repeatability factor of the indicated engine work COV_{Li} is equal to 10%.

Figure 7 shows that the minimum value COV_{Li} coefficient equal to 0.66% for the Q_{in}/Q_{tot} = 2.5% was obtained with λ equal to approximately 1.6.

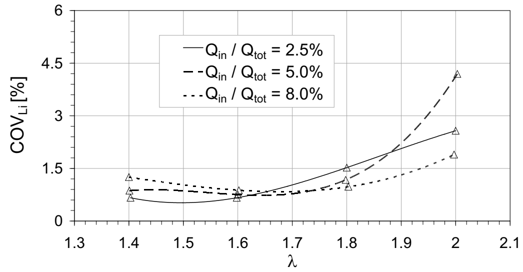

Fig. 7. Non-repeatability factor of indicated work versus excess air factor

Assuming that uncertainty of the non-repeatability factor of the indicated work COV_{Li} is normally distributed, it was calculated from the correlation [3]:

$$\Delta COV_{Li} = t_s\, \sigma_{COVLi}, \tag{30}$$

where σ_{COVLi} is the standard deviation of the coefficient COV_{Li} [%].

The standard deviation of the non-repeatability factor of the indicated work COV_{Li} depends on the uncertainty of the standard deviation of the indicated work σ_{Lii} and the uncertainty determination of the uncertainty of the indicated work L_i. The standard deviation of the non-repeatability factor of the indicated work COV_{Li} was calculated using the following dependence of the variance function of two variables [11]:

$$\sigma_{COVLi}{}^2 = \left(\frac{\partial COV_{Li}}{\partial \sigma_{Lii}}\right)^2 \sigma_{\sigma Lii}{}^2 + \left(\frac{\partial COV_{Li}}{\partial L_i}\right)^2 \sigma_{Li}{}^2, \tag{31}$$

where $\sigma_{\sigma Lii}$ is standard deviation of the standard indicated work deviation [MJ/m^3], σ_{Li} - standard deviation of the average value of the indicated work [MJ/m^3].

When you differentiate, the standard deviation of the non-repeatability factor of the indicated work COV_{Li}:

$$\sigma_{COVLi} = 100\% \sqrt{\left(\frac{1}{L_i}\right)^2 \sigma_{\sigma Lii}{}^2 + \left(-\frac{\sigma_{Lii}}{L_i{}^2}\right)^2 \sigma_{Li}{}^2}. \tag{32}$$

The standard deviation of the standard indicated work deviation (relative uncertainty σ_{Lii}) [3]:

$$\sigma_{\sigma Lii} = \sigma_{Lii} \frac{1}{\sqrt{2(N-1)}}. \tag{33}$$

The standard deviation of the average value of the indicated work:

$$\sigma_{Li} = \frac{\sigma_{Lii}}{\sqrt{N}}. \tag{34}$$

The uncertainty of the non-repeatability factor of the indicated work decreases with an increase in the number of measurements N. An increasing number of repetitions of measurements lead to a decrease in the value of $\sigma_{\sigma Lii}$ and σ_{Li} and a more reliable test. As a consequence, the uncertainty of the coefficient COV_{Li} determination is lower.

Figure 8 shows the uncertainty intervals determination of the non-repeatability factor of the indicated work $\pm\Delta COV_{Li}$. They were placed on the characteristics of the COV_{Li} changes in the function of the excess air factor, the $Q_{in}/Q_{tot} = 2.5\%$. For the whole range λ, the value of uncertainty $\pm\Delta COV_{Li}$ was equal to 8.3% of the value of the non-repeatability factor of the indicated work COV_{Li} and ranged from 0.05% for $\lambda = 1.6$ to ±0.21% for $\lambda = 2.0$.

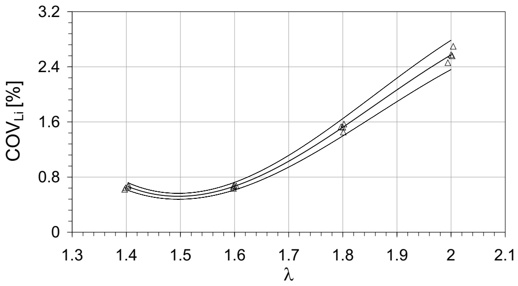

Fig. 8. Non-repeatability factor of indicated work COV_{Li}
with uncertainty intervals determination COV_{Li} for $Q_{in}/Q_{tot} = 2.5\%$

CONCLUSIONS

As practice shows, no measurement, regardless of the diligence of its execution, can provide a completely accurate result. The size of measurement errors is an integral part of the measurement process. The measurement result with unknown error is the result which tells us nothing. The indication process of the combustion engine is now the standard test method used in the field of internal combustion piston engines. It allows the registration of the instantaneous values parameters of the processes occurring in the cylinder. Indication results allow for an analysis of the impact of various factors on the parameters of the combustion process. Common opinion about the precision of the computer systems and sensors used during the indication process leads to the belief that it is a very accurate, reliable and repeatable test procedure and that it meets the requirements for measurement accuracy [12]. Based on analysis of errors and uncertainty of measurement results of the internal combustion engine, an indication process can be established that sets the main parameters characterizing the operation of the engine containing significant errors and uncertainties in measurements. The measurement error of the indicated work is equal to $\delta L_i \approx 3.1\%$. The maximum value of uncertainty determination of the indicated work: $\Delta L_{ii} = 5\%$. The measurement error of the indicated efficiency of the test engine is equal to $\delta\eta_i \approx 7.3\%$. The maximum value of uncertainty determination of the indicated efficiency is $\Delta\eta_{ii} = 7.4\%$. The uncertainty determination of the non-repeatability factor of the indicated work engine: ΔCOV_{Li}

= 8.3%. In conclusion, it can be stated that the reliable interpretation of study analysis resulting from indication of spark ignition internal combustion engine should include the values of measurement errors and measurement uncertainties. The characteristic changes in the measurement results should be supplemented by error range or measurement uncertainty intervals [14].

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ANALIZA BŁĘDÓW INDYKOWANIA GAZOWEGO SILNIKA ZI Z KOMORĄ WSTĘPNĄ

Streszczenie. Wyniki indykowania silnika tłokowego, a w szczególności wyniki analizy procesów termicznych zachodzących w cylindrze silnika są w różnym stopniu uzależnione od dokładności pomiarów oraz niepewność uzyskanego wyniku. Wielkościami charakteryzującymi pracę silnika spalinowego pod względem jego osiągów są wskaźniki pracy silnika takie jak: sprawność i ciśnienie indykowane oraz współczynnik niepowtarzalności pracy indykowanej. W pracy przedstawiono analizę błędów pomiarowych i niepewności uzyskanych wyników wyżej wymienionych wielkości podczas indykowania silnika spalinowego o zapłonie iskrowym z komorą wstępną. W wyniku przeprowadzonych obliczeń można stwierdzić, że aby można było wiarygodnie interpretować wyniki analizy indykowania tłokowego silnika spalinowego powinny one zawierać wartości błędów i niepewności pomiarowych, gdyż ich wielkość ma znaczący wpływ na końcowy wynik pomiaru. Na podstawie przeprowadzonej analizy błędów i niepewności pomiarowych wyników procesu indykowania silnika spalinowego można stwierdzić, że wyznaczone główne parametry charakteryzujące prace silnika są obarczone dość znacznym błędem i niepewnością pomiaru.

Słowa kluczowe: silnik z dwustopniowym systemem spalania, współczynnik nadmiaru powietrza, praca indykowana, sprawność indykowana, współczynnik niepowtarzalności pracy indykowanej.