TEKA Kom. Mot. i Energ. Roln. – OL PAN, 2011, 11, 48–64

DUAL-FUEL FEEDING OF DIESEL ENGINE WITH GENERATOR GAS AND LIQUID FUEL

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Summary. The paper presents the results of research carried out at the Institute of Internal Combustion Engines and Control Technology of the Czestochowa University of Technology in the period from 2007 to 2010 under Research & Development Project R10 019 02 "The piston combustion engine in the sewage sludge gasification installation" financed by the Ministry of Science and Higher Education in Warsaw. Testing results for a turbocharged piston engine fed with generator gas obtained from a dried sewage sludge gasification plant are discussed.

Key words: piston engine, generator gas, sewage sludge, gasification.

INTRODUCTION

Sewage sludge is generated in a sewage treatment plant as a by-product of the biochemical processes of sewage treatment. The calorific value of dried sludge is approx. 11 MJ/kg and is comparable with the calorific value of crude wood (8 MJ/kg), brown coal (9-11 MJ/kg), and dry peat (14 MJ/kg), and this means that the dried sludge can be utilized as an energy raw material. Sewage sludge with a moisture content not exceeding 10% and a calorific value not lower that 10 MJ/kg is not biodegradable and may only be disposed of by thermal transformation [21]. Within the meaning of the waste management regulations in force, sewage sludge is regarded as hazardous waste of category B33, Annex no. 2 [24], and therefore its storage and processing is subject to regulatory restrictions. The gasification of sewage sludge and using thus obtained generator gas for feeding an internal combustion engine to drive a stationary electric current generator is a variation of the waste thermal neutralization process.

With a view to the applicable EU environmental regulations and requirements [21, 19], the Institute of Internal Combustion Engines and Control Technology of the Czestochowa University of Technology has carried out, under Research & Development Project R10 019 02 financed by the Ministry of Science and Higher Education of Warsaw, research aimed at investigating the possibility of gasifying dried sewage sludge generated by sewage treatment plants, and utilizing it for double-fuel feeding a piston engine to drive a generating set.

The fuel gasification process is a variation of the incomplete combustion process conducted with a considerable oxygen deficiency. Installations gasifying various organic substances, mainly lumped wood, charcoal, peat, etc., were fairly common at the turn of the 19^{th} and 20^{th} centuries, and are extensively described in both archival [1, 6] and contemporary literature, e.g. [13, 14, 15, 23], which indicates some renaissance of interests in this technology. The available literature lacks, however, relevant data on any plants enabling gasification of dried sewage sludge.

Table 1 gives generator gas composition obtained from measurements on the installation, at an average bed temperature of 850°C.

Table 1. Averaged values of composition of the generator gas obtained from sewage sludge gasification, along with calorific values and theoretical air demand values

	H_2	CO	CO_2	CH_4	W_{dm}	W_{dg}	L_t	O_2
	[%]	[%]	[%]	[%]	[MJ/m^3]	[MJ/m^3]	[m^3/m^3]	[%]
Average value	3.81	13.40	7.69	0.97	1.63	2.44	0.50	3.84
Maximum value	4.17	14.18	8.10	0.98	1.67	2.54	0.52	3.99
Standard deviation	0.13	0.79	0.41	0.01	0.04	0.09	0.02	3.69

INDICATING OF THE DOUBLE-FUEL PISTON ENGINE FED WITH LIQUID FUEL AND GENERATOR GAS

The generating set driven by the 6CT107 turbocharged engine [20] was adapted to double-fuel operation by furnishing it with an additional gas supply system [3, 22, 24] and liquid and gaseous fuel dosage control systems completed from parts supplied by WOODWARD. The engine of this set was adapted to simultaneous indication of all the six cylinders and equipped with measuring instrumentation necessary for taking measurements of basic load characteristics and with a set of analyzers to measure chemical composition of generator gas supplied to the engine. The engine and electric generator control systems allow either the powering of a group of loads isolated from the power grid or parallel operation with this power grid. The final tests of the sewage sludge gasification installation and the generating set were carried out on the premises of PPUH „MARSZ" M. Szymor of Nowa Gorzelnia near Czestochowa [3].

The tests included simultaneous, synchronized measurements and recording of pressure variations in the individual cylinders of a turbocharged six-cylinder 6.56 dm^3 displacement engine adapted to double-fuel operation being fed with a liquid and gaseous fuels (Fig. 1). The engine drove, at a constant rotational speed of 1500 rpm, a synchronous electric generator loaded with resistances being switched on sequentially.

Fig. 1. The generating set connected to the gasification installation during the indication of the double-fuel engine [3]

Pressure variations and CRA and TDC tracer signals were recorded as a function of time at a frequency of 50 kHz. Recorded in a digital form, the signals were subjected to resampling at the moments of successive CRA tracer pulses, which made it possible to obtain the variations of pressure as a function of CRA angle with a strep of 0.5° CRA [2, 8, 12, 17]. At the same time, the basic parameters of gasification unit operation and composition of produced generator gas were also recorded. For the acquisition of all fast-varying signals, a USB HS1608 eight-channel module operated by its own program was used. In each recorded measurement series, 495 engine cycles were recorded. A schematic of the engine indication system is shown in Figure 2.

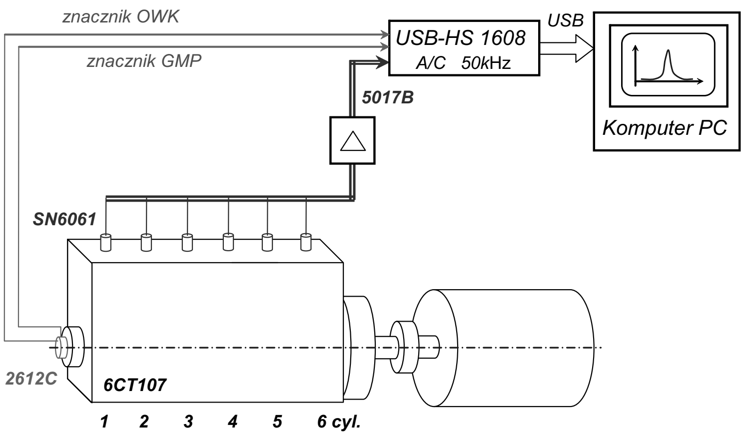

Fig. 2. A schematic of the engine indication system: 2612C – crank angle transmitter, SN6061 – piezoquartz pressure pickups , 5017B – eight-channel charge amplifier [3]

The tests performed on the supercharged piston engine double-fuel fed with generator gas and liquid fuel batched to the engine in varying energy fraction proportions have demonstrated that the double-fuel feeding of an engine is an effective method to reduce the engine susceptibility to rapid variations in chemical composition of generator gas and its calorific value [3, 7]. Some of the indication results are given in Figures 3 through 9. The most favourable engine operation conditions occur in the situation of a partial electric generator load of approx. 40 kW corresponding to approx. 50% of the generator rated power attained with the liquid fuel alone. The process of combustion of fuels in the engine double-fuel fed with generator gas (with an energy fraction of 75%) and liquid fuel (with an energy fraction of 25%) is run with an excess air factor of approx. 2.85, corresponding to 14% of oxygen content in the generator gas-air mixture and proceeds correctly. The engine attains then a high overall efficiency of 40%, which is better than the efficiency of 32% attainable when being fed with 100% liquid fuel. A maximum combustion pressure of 8.5 MPa occurs during feeding the engine with the sole liquid fuel, and then it monotonically decreases down to 7.2 MPa as the liquid fuel energy fraction is reduced to 25%. The maximum value of the cylinder pressure derivative, $dp/d\alpha$, attains its highest level of 0.94 MPa/°CRA during the operation of the engine fed with the sole liquid fuel and then monotonically decreases to 0.5 MPa/°OWK as the liquid fuel energy fraction is reduced to 25%.

Under the conditions of the full load corresponding to approx. 100% of the generator's rated electric power, which is 80 kW, the fuel combustion process in the double-fuel fed engine has characteristics differing unfavourably from the respective characteristics occurring for partial loads corresponding to engine loading with a power of 40 kW. With the full engine load, the liquid fuel energy fraction could not be lower than 73%. In that case, the fuel combustion process is conducted with the excess air factor reduced to approx. 1.5, corresponding to an oxygen content of the generator gas-air mixture of 15%, and no longer proceeds correctly, since the exhaust gas smoking, the maximum combustion pressure, $dp/d\alpha$ and the pulsation amplitude of the variable indicated pressure component considerably increase. During engine operation with the full power, a maximum combustion pressure of 11 MPa occurs when feeding the engine with the liquid fuel alone, and then monotonically increases up to 13 MPa as the liquid fuel energy fraction is reduced to 63%. The maximum value of the cylinder pressure derivative, $dp/d\alpha$, attains its lowest level of 0.70 MPa/deg during the operation of the engine fed with the sole liquid fuel, and then monotonically increases to 1.5 MPa/°CRA as the liquid fuel energy fraction is reduced to 63%.

The liquid fuel batch energy fraction equal to 25% corresponded to a liquid fuel unit consumption of approx. 52 g/kWh, as related to the generated electric energy, which, for the diesel oil price of 4.5 PLN/litre, corresponds to a rather high unit cost of this fuel, namely 0.28 PLN/kWh of generated electric energy (Fig. 9). With a view to the quite high unit cost of the liquid fuel batch as against the price for 1 kWh of electric energy possible to be achieved in settlements with power utility companies, which (according to the VATTENFALL offer valid as per Jan. 31, 2011) is within the range from 0.2934 PLN/kWh (night-time) and 0.3537 PLN/kWh (whole day) to 0.4033 PLN/kWh (day time), it can be stated that the gasification of dried sewage sludge in the installation in question will oscillate around the level of economic viability.

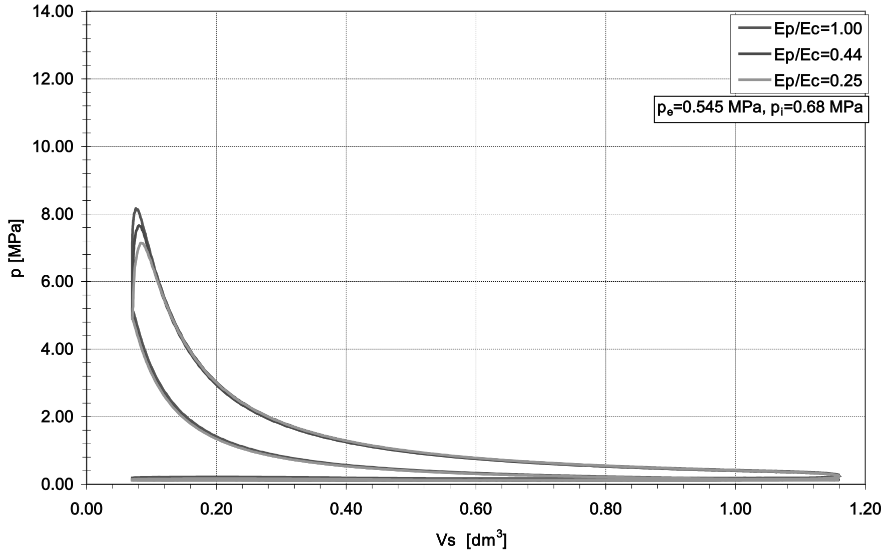

Fig. 3. Indicator diagrams of the double-fuel engine for varying magnitudes of the liquid fuel batch energy fraction (E_p) of the total energy amount contained in the liquid and gaseous fuels (E_c) (the averaged run for 495 cycles, pe=0.545 MPa)

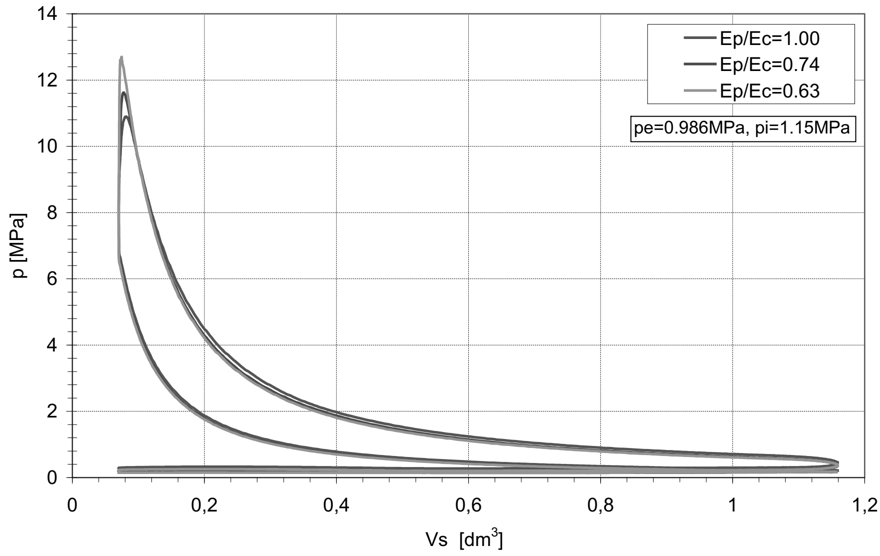

Fig. 4. Indicator diagrams of the double-fuel engine for varying magnitudes of the liquid fuel batch energy fraction (E_p) of the total energy amount contained in the liquid and gaseous fuels (E_c) (the averaged run for 495 cycles, pe=0.986 MPa)

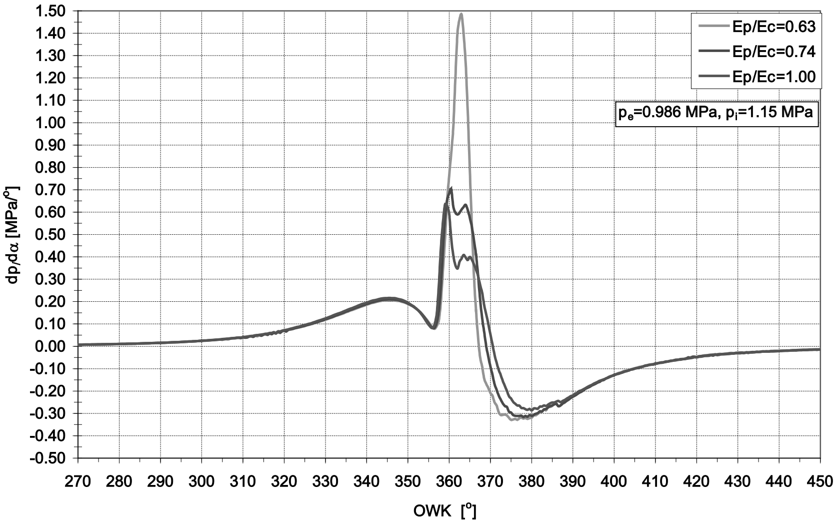

Fig. 5. Pressure derivative, dp/dα for varying magnitudes of the liquid fuel batch energy fraction (E_p) of the total energy amount contained in the liquid and gaseous fuels (E_c) (the averaged run for 495 cycles, p_e=0.986 MPa)

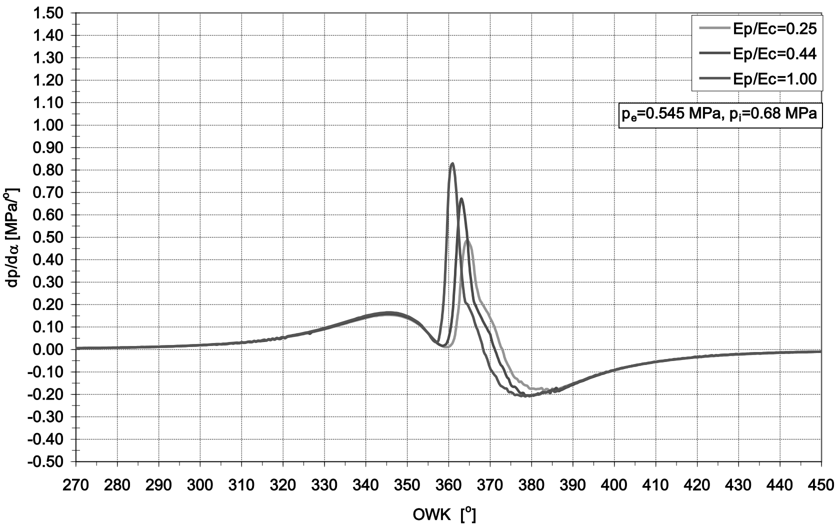

Fig. 6. Pressure derivative, dp/dα for varying magnitudes of the liquid fuel batch energy fraction (E_p) of the total energy amount contained in the liquid and gaseous fuels (E_c) (the averaged run for 495 cycles, p_e=0.545 MPa)

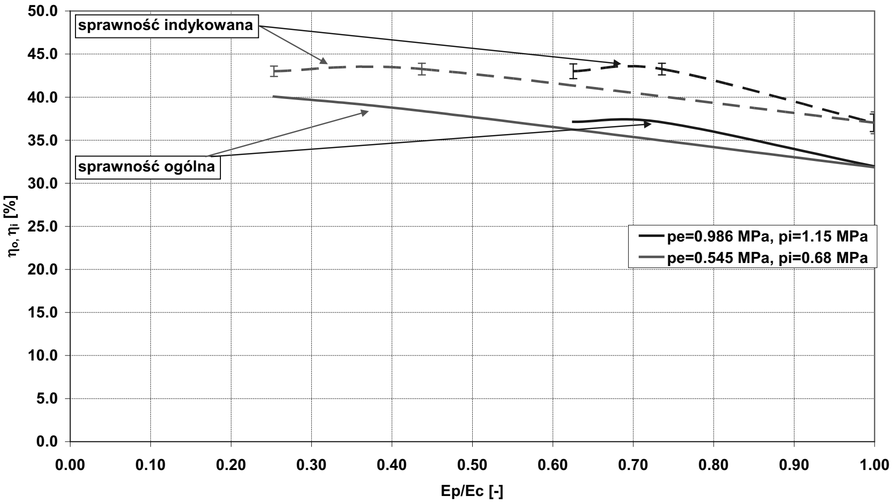

Fig. 7. Overall generating set efficiency related to the active electric power and the indicated engine efficiency as dependent on the liquid fuel batch energy fraction (E_p) of the total energy amount contained in the liquid and gaseous fuels (E_c)

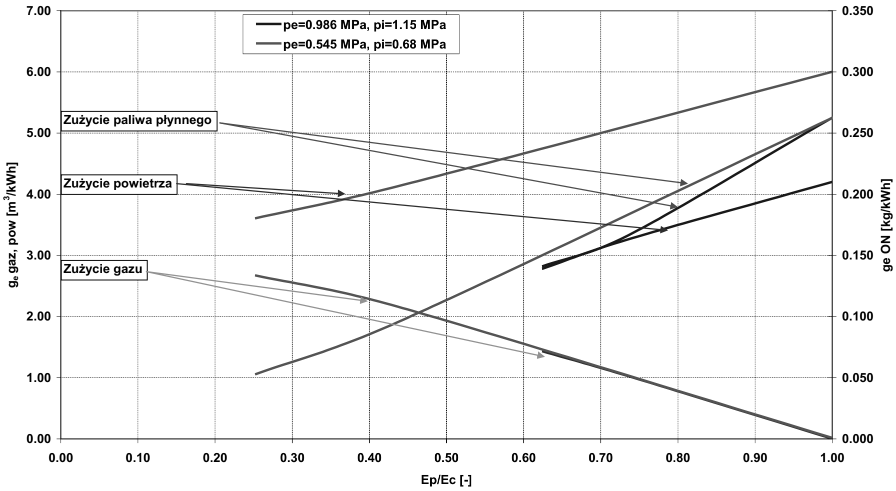

Fig. 8. Unit consumption of the gaseous and liquid fuels and air as dependent on the liquid fuel batch energy fraction (E_p) of the total energy amount contained in the liquid and gaseous fuels (E_c)

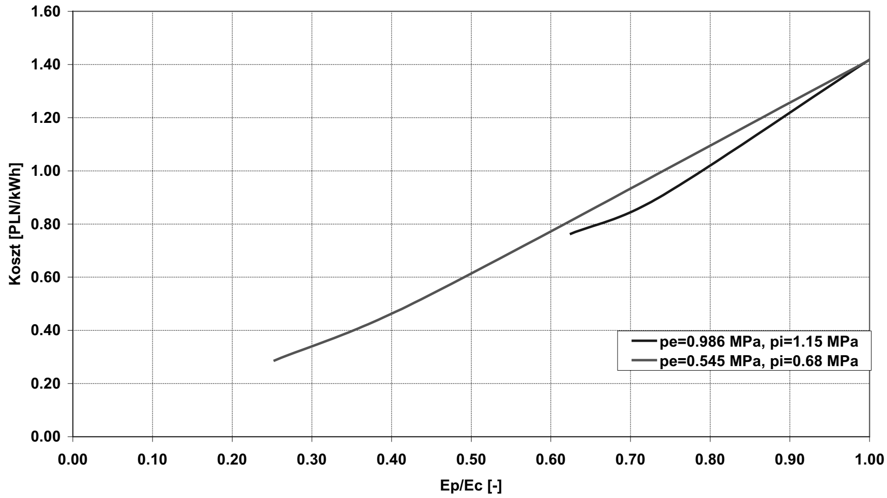

Fig. 9. Unit cost of liquid fuel as calculated for the diesel oil price of 4.5 PLN/litre related to the active electric power, as dependent on the liquid fuel batch energy fraction (E_p) of the total energy amount contained in the liquid and gaseous fuels (E_c)

EVALUATION OF OPERATION REPEATABILITY OF THE DOUBLE-FUEL INTERNAL COMBUSTION ENGINE

In order to evaluate the effect of fuel composition on the repeatability of operation of individual engine cylinders, statistical probability density distributions were made for the maximum pressure, maximum pressure derivative and indicated work for engine cylinder no. 1 based on the analysis of 495 successive operation cycles [3, 4, 16, 18]. Figures 10 through 14 represent the statistical distributions of selected physical quantities for the engine fed with the liquid and gaseous fuels at varying engine loads (p_e=0.545 MPa and p_e=0.986 MPa).

For a partial engine load, increasing the gas fraction of the fuel causes a reduction in the maximum values of pressures, whereas at the nominal load, increasing the amount of gas in the fuel increases the magnitudes of maximum pressures.

Figures 11 and 12 represent the statistical distribution of the maximum pressure derivative for different fuel compositions in the first engine cylinder for p_e=0.545 MPa and p_e=0.986 MPa. Similarly as for maximum pressures, for the partial engine load, too, increasing the gas fraction of the fuel results in a reduction in the maximum values of the pressure derivative. At the nominal load, on the other hand, decreasing the diesel oil amount in the fuel to a value of E_p/E_c=0.625 increases the maximum pressure derivative values, while increasing their scatter around the mean value, at the same time.

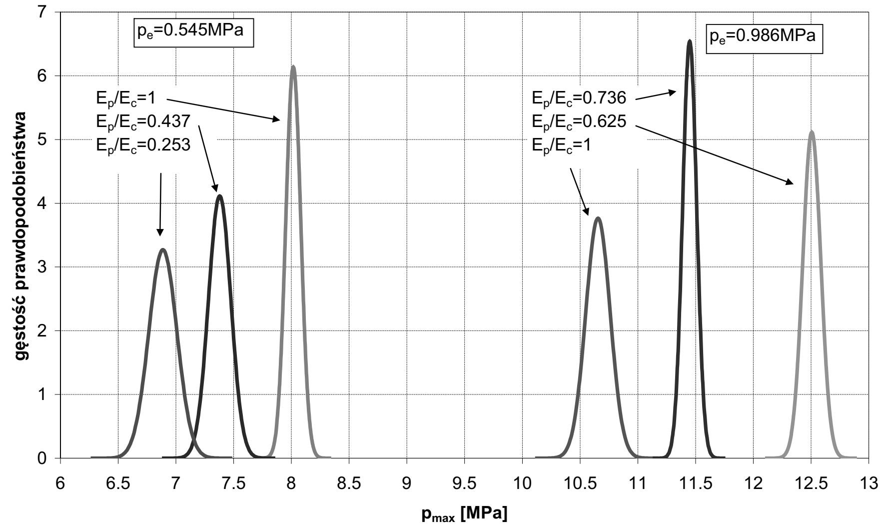

Fig. 10. Maximum pressure probability density at a load of p_e=0.545MPa and p_e=0.986 MPa in the first cylinder for varying liquid fuel energy fractions

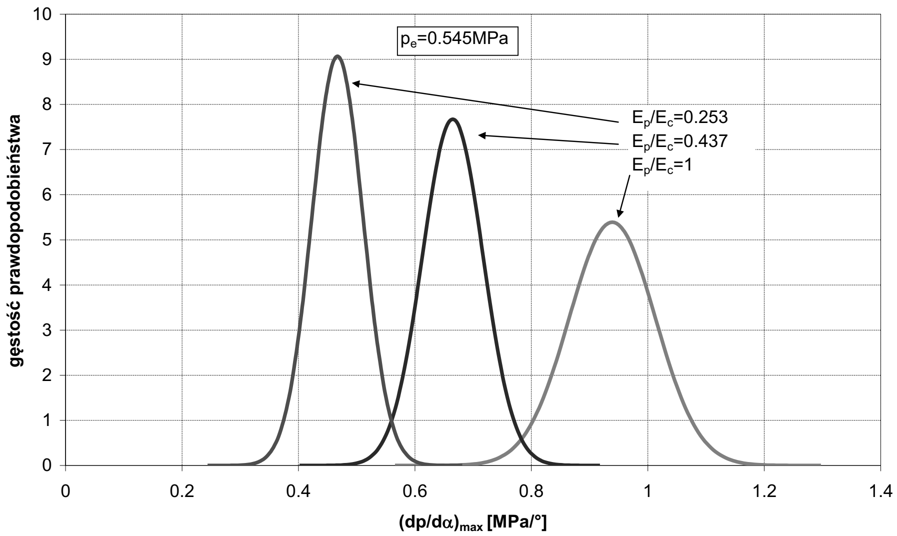

Fig. 11. Maximum pressure increment probability density at a load of p_e=0.545 MPa in the first cylinder for varying liquid fuel energy fractions

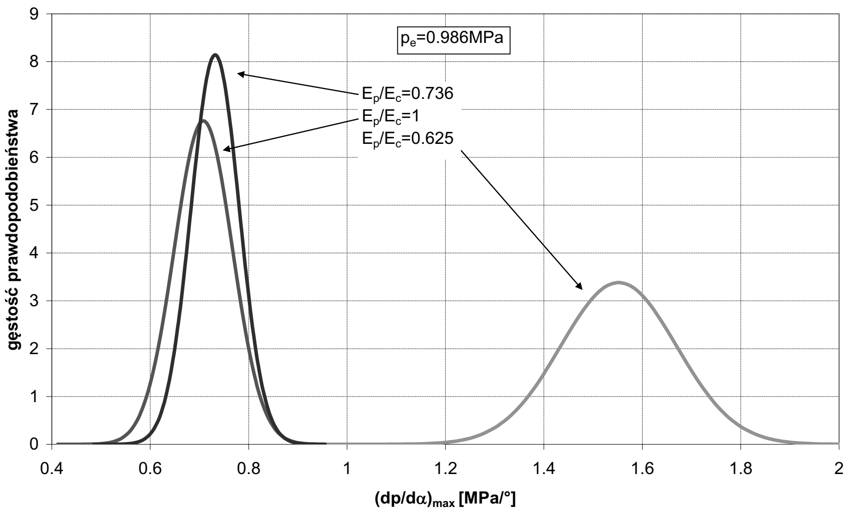

Fig. 12. Maximum pressure increment probability density at a load of p_e=0.986 MPa in the first cylinder for varying liquid fuel energy fractions

Figures 13 and 14 represent the statistical distributions of indicated work for different fuel compositions in the first engine cylinder for p_e=0.545 MPa and p_e=0.986 MPa. For a partial engine load, increasing the gas fraction of the fuel causes a small increase in indicated work, while simultaneously reducing its scatter around the mean value. At the minimal load, on the other hand, increasing the gas fraction of the fuel practically does not charge the value of indicated work, but markedly reduces its scatter around the mean value.

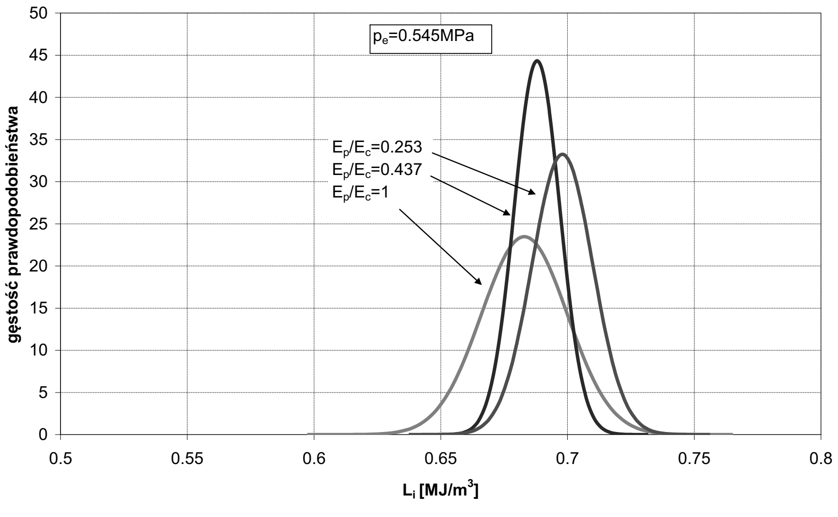

Fig. 13. Indicated work probability density at a load of p_e=0.545 MPa in the first cylinder for varying liquid fuel energy fractions

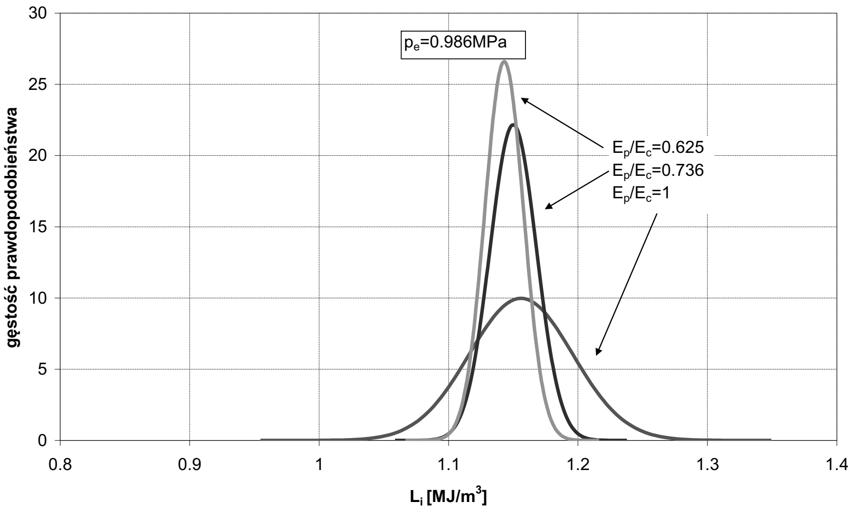

Fig. 14. Indicated work probability density at a load of p_e=0.986 MPa in the first cylinder for varying liquid fuel energy fractions

In addition, evaluation was made of the effect of the gaseous fuel energy fraction on the values of so called cycle parameters unrepeatability indicators [9] (i.e. the indicated work, X_{pi}; maximum combustion pressure, X_{pmax}; and the crank angle, for which combustion pressure attains a maximum value, X_a). Figure 15 shows the values of respective unrepeatability indicators:

- indicated pressure:

$$X_{pi} = \frac{\sigma_{pi}}{\overline{p}_i}, \tag{1}$$

- maximum combustion pressure angle:

$$X_{p\alpha} = \frac{\sigma_{p\alpha}}{\overline{\alpha}_{p\max}}, \tag{2}$$

- maximum combustion pressure:

$$X_{p\max} = \frac{\sigma_{p\max}}{\overline{p}_{\max}}, \tag{3}$$

where:

n – number of successive cycles,

p_{max} – mean value of the maximum combustion pressure,

$\overline{p}_i$ – mean value of indicated pressure,

$\overline{\alpha}_{p\max}$ – mean value of the maximum combustion pressure angle.

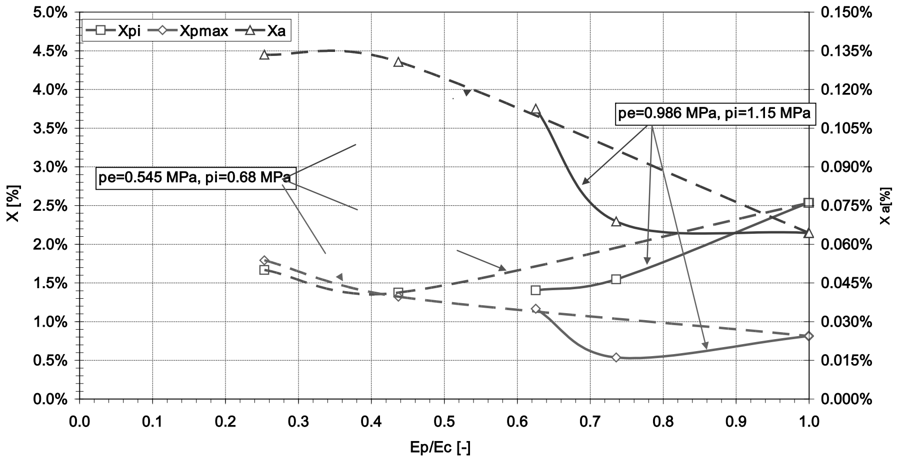

Fig. 15. Cycle unrepeatability indicators at a load of p_e=0.545 MPa and p_e=0.986 MPa in the first cylinder for varying liquid fuel energy fractions

In the graphs of cylinder pressure time variations for the engine operating under full load with a large gaseous fuel fraction, pressure pulsations of a frequency in the range of (5.5-12) kHz was observed to occur in the combustion phase. In order to determine the intensity of those pulsations recorded as a function of time at a frequency of 50 kHz, they were subjected to high-pass filtration by a filter with a limiting frequency of 4 kHz.

Figures 16 and 17 represent pressure pulsation variations obtained from this filtration, against the background of the cylinder pressure variation for p_e=0.545 MPa. It is visible that pressure pulsations in the combustion phase occur for all the fuel compositions, while attaining the greatest intensity for a fuel composed of diesel oil alone, in which case their maximum amplitude value approaches 120 kPa. Increasing the gas fraction of the fuel (decreasing the E_p/E_c ratio) causes a clear reduction in pressure oscillation intensity to a level of 10 kPa with bringing the liquid fuel energy ratio down to a value of E_p/E_c=0.253.

The maximum amplitude of the variable pressure component occurs at the beginning of the combustion process, which indicates that these pulsations are caused by the rapid combustion of the gaseous fuel-air mixture without any indication of autoignition, which would have generated considerable pulsations in the end phase of the combustion process [10, 11].

Figures 18 and 19 represent pressure pulsation variations obtained as a result of high-pass filtration, against the background of the cylinder pressure variation for p_e=0.986 MPa. It is visible that pressure pulsations in the combustion phase occur also for all the fuel compositions. Under the maximum engine load, however, their level changes with changing fluid fuel energy fraction in a different manner. For the sole diesel oil, their level is comparable with the pressure pulsations observed for p_e=0.545 MPa and does not exceed 100 kPa. Increasing the gas fraction of fuel to a level of E_p/E_c=0.736 (reducing the E_p/E_c ratio) reduces them slightly (by approx. 10%); however, further increasing the gas fraction of fuel (up to a level of E_p/E_c=0.625) results in a distinct increase in the pressure pulsation amplitude up to 200 kPa.

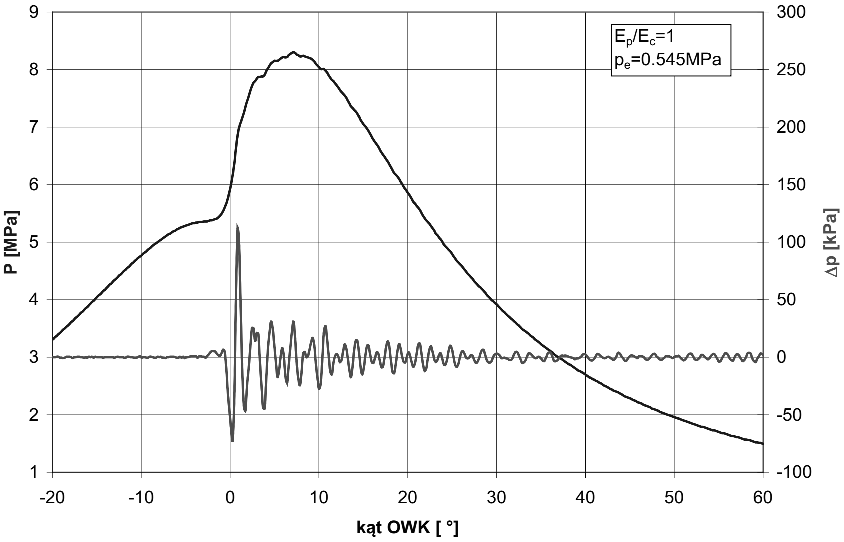

Fig. 16. The variable pressure component of one of the highest intensities with the cylinder pressure variation superposed against the background, for a liquid fuel energy fraction of E_p/E_c=1, p_e=0.545 MPa

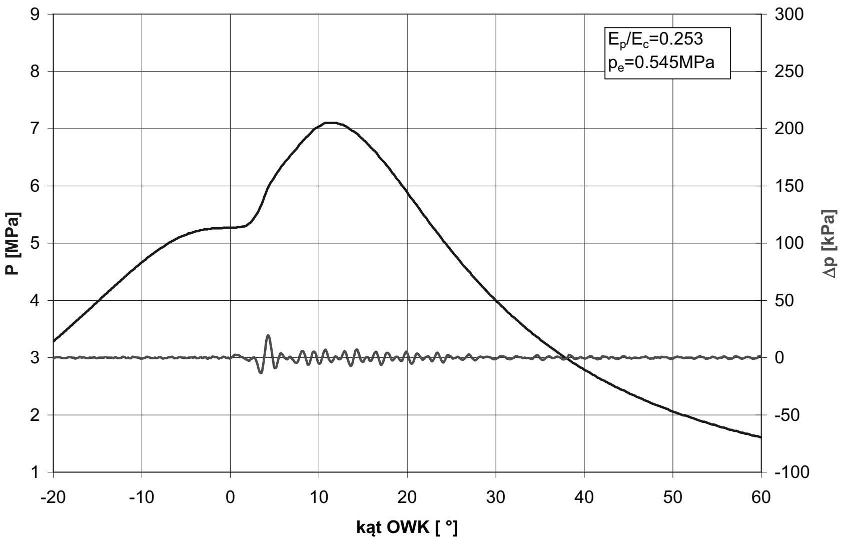

Fig. 17. The variable pressure component of one of the highest intensities with the cylinder pressure variation superposed against the background, for a liquid fuel energy fraction of E_p/E_c=0.253, p_e=0.545 MPa

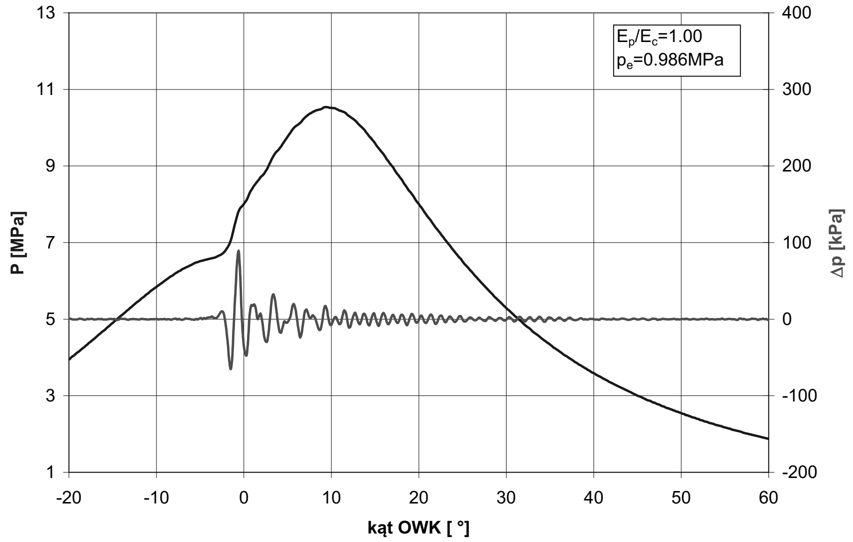

Fig. 18. The variable pressure component of one of the highest intensities with the cylinder pressure variation superposed against the background, for a liquid fuel energy fraction of E_p/E_c=1, p_e=0.986 MPa

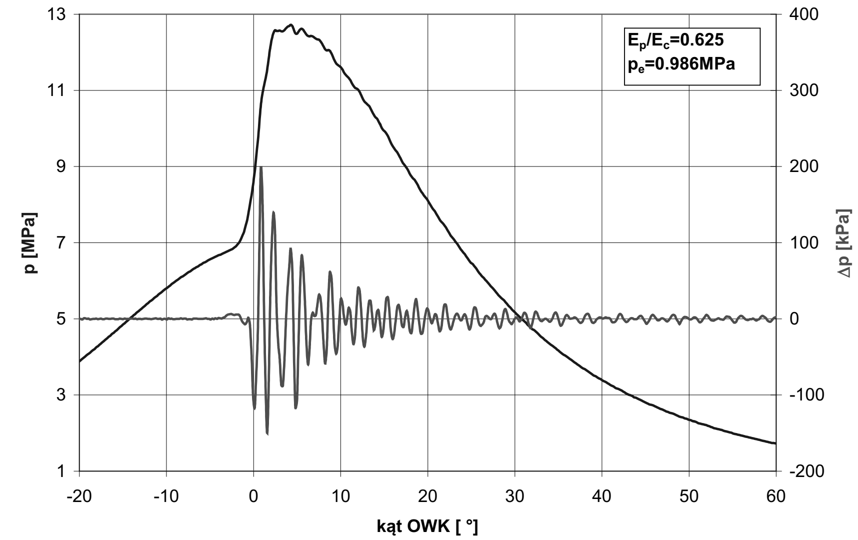

Fig. 19. The variable pressure component of one of the highest intensities with the cylinder pressure variation superposed against the background, for a liquid fuel energy fraction of E_p/E_c=0.625, p_e=0.986 MPa

The obtained results show that when the engine runs with a full power of 80 kW, the mechanical loads on the crankshaft assembly of the double-fuel fed engine increase unfavourably compared to the respective loads occurring when the engine operates fed with the sole liquid fuel, while attaining the same power.

CONCLUSIONS

The largest combustion pressure pulsation amplitude in the case of a small and medium engine loads (up to p_e=0.545 MPa) occurred for the engine being fed with sole diesel oil (the maximum pulsation amplitudes in individual combustion cycles approached a level of about 120 kPa). During co-combustion of diesel oil with gaseous fuel, a drop in the maximum pulsation amplitude down to about 10 kPa was observed. At the same time, an elongation of the combustion process was observed, which caused a more gentle increase in combustion pressure and a delay of the moment of the maximum pressure occurring. The generator gas being fed as the additional fuel was characterized by large contents of incombustible components – with the nitrogen content being at a level of approx. (55-65) %.

Hence, it can be supposed that the generator gas acted on the combustible charge existing in the cylinder as a "diluter". The air oxygen and the combustible mixture formed from evaporated diesel oil were primarily diluted. In this case, the effect of the generator gas could be compared to that of combustion gas recirculation. The first combustion phase, which is the kinetic burning of a combustible mixture with the oxygen ratio reduced due to that combustible mixture being diluted by other gases, slows down, as can be seen in the pressure increment graph. Pressure pulsations are a result of a rapid, unstable combustion process. The largest pressure pulsations occur immediately after the combustible mixture ignition and fall into the kinetic combustion phase which, in a compression-ignition engine, proceeds fastest. Hence, as a result of the combustion process slowing down in this phase, the pressure pulsations have definitely decreased. With increasing generator gas energy fraction, the oxygen content of the generator gas-air mixture decreased to about 15% (for λ=1.4) and was significantly lower than that of the air. The hydrogen concentration in the pure generator gas was normally at a level of about (4-6)%, while in the generator gas-air mixture it was much lower. Presumably, the effect of hydrogen and carbon monoxide on the combustion process comes down to accelerating the ignition initiating reactions, and thus to the growth of H and OH radicals caused by the presence of free hydrogen.

In the case of the engine operating under a maximum possible load (p_e=0.986MPa), an increase in the maximum pressure pulsation amplitude from 100 to 200 kPa was found as the generator gas energy ratio increased. Similarly as before, the occurrence of the maximum combustion pressure pulsations was immediately after the ignition in the first, kinetic combustion phase. Increasing the amount of gas added to the air being sucked causes the acceleration of the kinetic combustion process, which results, among other things, in an increase in pressure pulsations. The faster combustion process might also have been in that case due to generator gas burning initiated by the autoignition of the diesel oil. As a result of increasing the gas ratio of the unchanged amount of the gas-air combustible mixture being forced to the cylinder, the mixture composition had changed from a lean mixture for an engine fed with the sole liquid fuel to a near-stoichiometric mixture for a double-fuel fed engine, which caused the concentrations of the combustible gases, hydrogen and carbon monoxide, to have exceeded the lower flammability limit resulting in rapid burning of these gases and the occurrence of intensive pressure pulsations. In the case at hand – a large load on the engine – intensive fuming of the combustion gas was also observed, caused by incomplete burning of the diesel oil, which could additionally confirm the claim about separate gas and diesel oil combustion. Burning faster, the gas "took away" the oxygen, whose deficiency had a strong effect of causing incomplete burning of the diesel oil and fuming. With the double-fuel operation of the engine under large load and gas fraction conditions with associated intensive pressure pulsations at a level of 200 kPa, a high-pitch sound characteristic of knock-combustion, as determined by organoleptic methods, could be heard. This sound faded out as the load was reduced and those combustion pressure pulsations were decreased. The position of the maximum pressure pulsations in the initial combustion phase suggest that the emitted sound was caused by combustion proceeding violently in this phase, and not by knock-combustion due to a potential autoignition of the gas in the end combustion phase.

The double-fuel engine version developed within the Project can be recommended to be practically applied in a dried sewage sludge gasification installation as a double-fuel engine to drive en electric generator loaded with active electric power reduced to 40 kW (which accounts for approx. 50% of its rated power), since this is the power level at which the optimum conditions for the operation of an engine double-fuel fed with liquid fuel and generator gas are achieved. Under the round-the-clock operation conditions, a gasification installation operating with this engine will be able to gasify about 1.8 tons of dried sewage sludge containing approx. 10% of water, and to generate 8.960 MWh of electric energy during this time, while consuming approx. 50 kg diesel oil for this purpose. The amount of dried sewage sludge generated by a sewage treatment plant in a town with 250 thousand inhabitants is about 13.5 tons/day, thus being approx. 7.5 times larger than the capacity of the test installation in question. The economic relationships achieved so far could be improved by thorough modernization of the liquid fuel engine supply system to reduce the minimum liquid fuel dose necessary for assuring the correct operation of the piston engine under the conditions of double-fuel feeding with liquid fuel and a generator gas-air mixture in which the oxygen concentration could decrease to a level below 15%. In that case, the gasification of dried sewage sludge might turn out to be a technology more competitive than the incineration of sewage sludge in rotary tunnel kilns used e.g. in cement mills.

The effects achieved so far from this installation prove that the dried sewage sludge gasification installation developed within the Project, when carried out in an appropriately enlarged installation equipped with a double-fuel engine with a reduced liquid fuel energy fraction, allows the combustion of gaseous fuel of chemical composition varying as a function of time.

This scientific research has been financed from the resources allocated to science in the years 2007 to 2010 under Research Project R10 019 02 "The piston combustion engine in the sewage sludge gasification installation".

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DWUPALIWOWE ZASILANIE SILNIKA ZS GAZEM GENERATOROWYM I PALIWEM PŁYNNYM

Streszczenie. W referacie przedstawiono wyniki zrealizowanego w latach 2007-2010 w Instytucie Maszyn Tłokowych i Techniki Sterowania Politechniki Częstochowskiej projektu badawczego rozwojowego R10 019 02 "Tłokowy silnik spalinowy w instalacji zgazowania osadu ściekowego" sfinansowanego przez Ministerstwo Nauki i Szkolnictwa Wyższego w Warszawie. Omówiono wyniki badań doładowanego silnika tłokowego zasilanego pozyskiwanym gazem generatorowym w instalacji zgazowującej osuszony osad ściekowy.

Słowa kluczowe: silnik tłokowy, gaz generatorowy, osad ściekowy, zgazowanie.