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ANALYSIS OF THE IMPACT OF DEGREE OF RECIRCULATION OF EXHAUST GASES AND ENERGY FRACTION OF GASEOUS FUEL ON OVERALL EFFICIENCY AND BASIC PARAMETERS OF COMBUSTION PROCESS OF DUAL-FUEL DIESEL (SELF-IGNITION) ENGINE FED BY NATURAL GAS

ANALIZA WPŁYWU STOPNIA RECYRKULACJI SPALIN ORAZ UDZIAŁU ENERGETYCZNEGO PALIWA GAZOWEGO NA SPRAWNOŚĆ OGÓLNĄ I PODSTAWOWE PARAMETRY PROCESU SPALANIA DWUPALIWOWEGO SILNIKA O ZS ZASILANEGO GAZEM ZIEMNYM

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Summary

In the Internal - Combustion Engines and Vehicles Division of the Humanistic-Technological University named after Kazimierz Pułaski in Radom there have been carried out research for many years on self-ignition dual-fuel engine with using different substitute fuels of low value of cetane number. Previous research showed possibilities of using considerable energy fractions of gaseous fuel [1, 8, and 9]. In the present paper there are presented selected results of research concerning utilization of natural gas. During execution of examinations it was observed that together with the change in energy fraction of gaseous fuel and change of degree of recirculation of exhaust gases the change of overall efficiency of engine as well as the change of parameters of combustion process takes place. In this paper there was made an attempt of evaluating the impact of application of different fractions of gaseous fuel and the degree of recirculation of exhaust gases on the parameters of combustion process. There was also made an attempt to clarify causes of the changes in values of overall efficiency as a result of observed changes in the course of combustion.

Keywords: dual-fuel engine with self-ignition, natural gas, recirculation of exhaust gases, overall efficiency

Streszczenie

W Zakładzie Pojazdów i Silników Spalinowych Uniwersytetu Technologiczno-Humanistycznego im. Kazimierza Pułaskiego w Radomiu od szereg lat są prowadzone badania dwupaliwowego silnika o zapłonie samoczynnym z wykorzystaniem różnych paliw zastępczych o małej wartości liczby cetanowej. Dotychczasowe badania wykazały możliwości stosowania znacznych udziałów energetycznych paliwa gazowego [1, 8, 9]. W niniejszym artykule zaprezentowano wybrane wyniki badań dotyczących wykorzystania gazu ziemnego. W trakcie badań zaobserwowano że wraz ze zmianą udziału energetycznego paliwa gazowego oraz zmianą stopnia recyrkulacji spalin zmianie ulega sprawność ogólna silnika a także parametry procesu spalania. W artykule podjęto próbę oceny wpływu stosowania różnych udziałów paliwa gazowego oraz stopnia recyrkulacji spalin na parametry procesu spalania. Podjęto także próbę wyjaśnienia przyczyn zmian wartości sprawności ogólnej w wyniku zaobserwowanych zmian przebiegu spalania.

Słowa kluczowe: silnik dwupaliwowy o zapłonie samoczynnym, gaz ziemny, recyrkulacja spalin, sprawność ogólna

1. Introduction

Nowadays the piston internal-combustion engine is the most widespread engine applied for driving automotive vehicles and different types of stationary units. It is also used for driving rail vehicles and vessels. Very popular type of engine is self-ignition engine. Its common use is based on higher overall efficiency in relation to the efficiency of spark ignition engine. The higher overall efficiency of the engine is transferred into lower costs of its exploitation. It seems that in many applications (such as driving trucks, interurban coaches, locomotives, vessels) in the nearest future the piston internal-combustion engine with self-ignition will be prevailing if not the only solution. Challenges related to emission of pollutants and also the willingness of taking advantage of substitute fuels (which often favor decrease of emission of impurities) cause that the engine with self-ignition is subject

to substantial modifications, especially in the range of feeding system. Ideas of using gaseous fuels to that type of engine are emerging most often. Altogether implementing gaseous fuel guarantees the decrease of concentration of solid particles and hydrocarbons in the exhaust gases. Still the problem appears of a firm and correct initiation of ignition of gaseous fuels in front of the fact that as a rule these fuels characterize themselves with low value of cetane number. Because of that reason one cannot rely on firm self-ignition of that fuel not mentioning the difficulty related to execution of its injection to combustion chamber and necessity of substantial increase of the compression ratio of that engine. What is most often seen as a solution to the above mentioned problems emerging from the different properties of gaseous fuel in comparison to the properties of traditional fuel (diesel oil) is application of the dual-fuel feeding unit. The/m statement is testified by numerous publications resulting from research carried out in many research-scientific centers, as for example [1, 5, 7 - 11]. That solution of the feeding unit allows for initiation of ignition of prepared in advance and compressed mixture of gaseous fuel and air, from already burning injected previously a small dose of diesel oil. As previous researches have shown at correct selection of parameters of injection of initiating dose, the process of burning substitute fuel can be brought to volumetric character what brings this process closer together to being considered as very beneficial one, described also by many researchers of HCCI system. It should be emphasized that in dual-fuel solution there is guaranteed the full control over the angular position of the start of combustion process what presents a lot of difficulties in case of typical HCCI solution. Diagram of dual-fuel feeding is presented on Fig. 1.

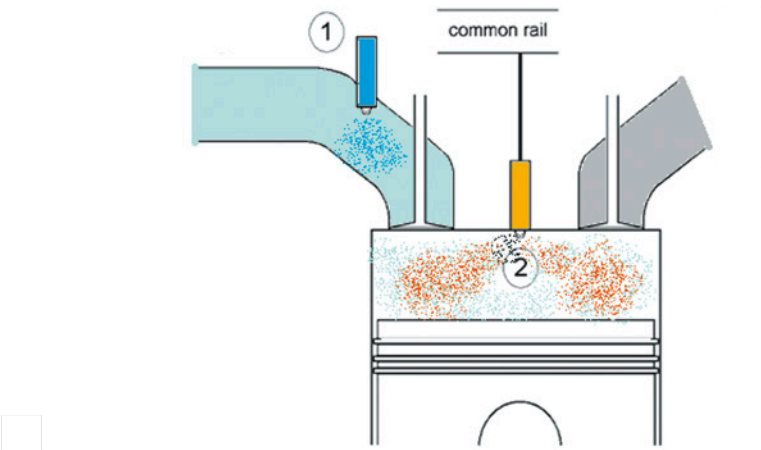


Fig 1. Diagram of dual-fuel diesel engine (internal-combustion engine with self-ignition) by natural gas
1) gas injector; 2) diesel oil injector

It should be clearly emphasized that all contemporary self-ignition engines are equipped with the system of recirculation of exhaust gases. These are turbocharged engines what makes that selection of control parameters of dual-fuel engine grows to be a complicated

issue. It is very essential as both the change of energy fraction of substitute oil as well as the change of degree of recirculation of exhaust gases influences the value of overall efficiency of engine and series of its working parameters. In this paper there are presented selected results of research of dual-fuel self-ignition engine fed by natural gas.

The earlier research showed that the overall efficiency of dual-fuel engine is subject to the degree of recirculation of exhaust gases as well as energy fraction of gaseous fuel in relation to energy supplied by the two fuels. Then there was made an attempt of explaining reasons of decreasing the value of overall efficiency of dual-fuel engine together with the increase in degree of recirculation of exhaust gases and energy fraction of gaseous fuel. For this purpose the variability of parameters of combustion process was analysed. In the course of the examination the researchers were striving to keep constant value of excess air number (combustion air factor) (total for both applied fuels) for each assumed stage of recirculation of exhaust gases , and also the constant value of engine load (by torque moment M=~23Nm). The examination was executed at constant rotational speed of engine n = 1200 1/min on one-cylinder test engine of AVL company. During the examinations the fraction of gaseous fuel has been changed from E_{NG} = 10% to E_{NG} = 70%. The index of energy fraction of gaseous fuel is described by the formula

$$E_{NG}\,[\%] = \frac{E_{NG}}{E_{NG} + E_{ON}} \cdot 100[\%] \tag{1}$$

E_{NG} – energy originating from a dose of natural gas [J/cycle]
E_{ON} – energy originating from a dose of diesel oil [J/cycle]

In front of the fact that modern engines are equipped with the system of recirculation of exhaust gases, it was ruled also to analyze the impact of the degree of recirculation of exhaust gases on the basic working parameters of engine. Four values of this index were taken: 10%, 20%, 30%, and 40%. The degree of recirculation of exhaust gases EGR % was determined by the formula below.

$$EGR[\%] = \frac{CO_{2int} - CO_{2air}}{CO_{2exh} - CO_{2int}} \cdot 100[\%] \tag{2}$$

$CO_{2\ int}$ – concentration of CO_2 (carbon dioxide) in suction collector [ppm]
$CO_{2\ air}$ – concentration of CO_2 (carbon dioxide) in air [ppm]
$CO_{2\ exh}$ – concentration of CO_2 (carbon dioxide) in exhaust collector [ppm]

2. Description of test stand and assumed program of research

The research was carried out on the test stand of AVL firm equipped with one-cylinder self-ignition engine adapted to dual-fuel feeding as a result of supplying natural gas by using injector seated in the suction collector of the engine. Both the place of seating of the injector and the parameters of the injection of ignition initiating dose of diesel oil were assumed and established on the base of examinations carried out earlier [6, 7]. The general view of test stand and control room is presented on Fig. 2.

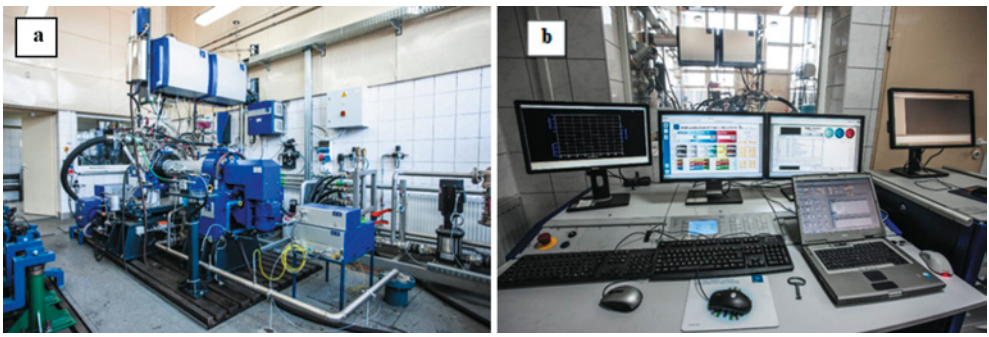


Fig. 2. The view of engine positioned on the engine test stand (Fig. a), and the view of the control room (Fig. b).

The test stand consists of:

- one-cylinder test engine of AVL 5402 company,
- AVL electro-rotational brake,
- system for indication (Indi Com),
- supercharging system (AVL boost – electrically fed compressor),
- system for analysis of exhaust gases (SESAM I 60),
- system of measurement of mass concentration of solid particles (Micro Soot Sensor),
- system of measurement of mass flow of diesel oil used by engine with temperature conditioning,
- system of measurement of mass flow of natural gas used by engine (mini CORI - FLOW).

Table 1. Basic technical data of AVL 5402 engine

Number of cylinders	1
Diameter of cylinder	85,01 mm
Piston stroke (travel)	90,00 mm
Displacement volume	511,00 cm^3
Combustion system	self-ignition (diesel)
Timing gear	four valve
Compression ratio	17,5
Feeding system	cell system (Common Rail)
Maximum power output without supercharging	6 kW
Maximum power output with supercharging	16 kW
Rated rotational speed	4200 min^{-1}
Injection pressure	180 MPa

As a result of the measurement of reached torque moment, rotational speed and mass rate of flow of diesel oil used by the engine, there were calculated values of overall efficiency of engine. Recording of the course of pressure in cylinder in the combustion process let for calculating the thermal efficiency and consequently the mechanical efficiency of the engine. Command of courses of indicated pressure depending on crank angle let for determining, specified below, the basic parameters characterizing the combustion process, dependent on the fraction of energy of gaseous fuel and different values of the degree of recirculation of exhaust gases:

- the maximum pressure of agent in combustion process ,
- the angular position of the maximum pressure of agent in combustion process,
- the maximum speed of building up of pressure of agent in combustion process,
- the angular position of the start of combustion process,
- the angular position of burning out 50% and 90% of charge.

3. Characteristics of variability of overall, thermal and mechanical efficiency of engine – results of research

As a result of executed examinations and appropriate calculations the courses of overall, thermal and mechanical efficiency were determined in each measuring point. The results are set in drawing 3.

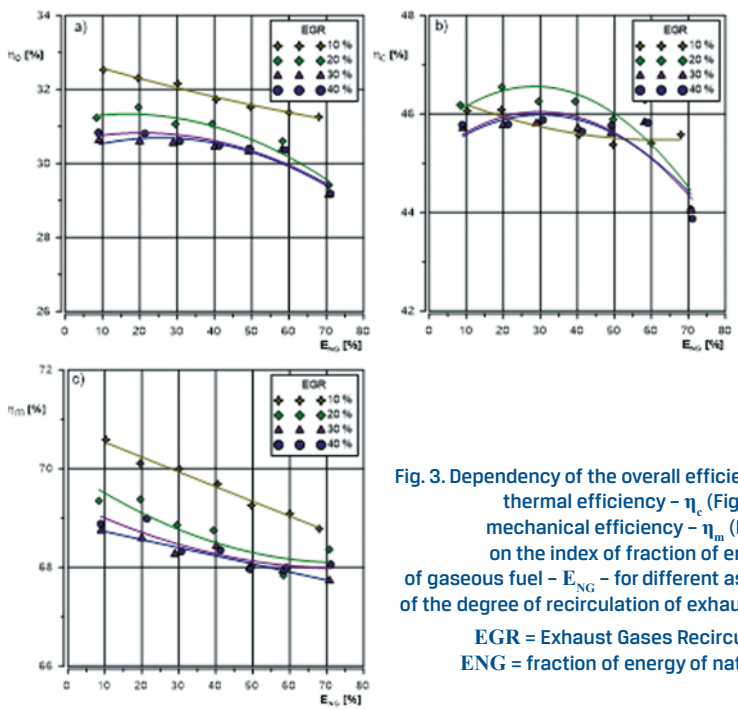


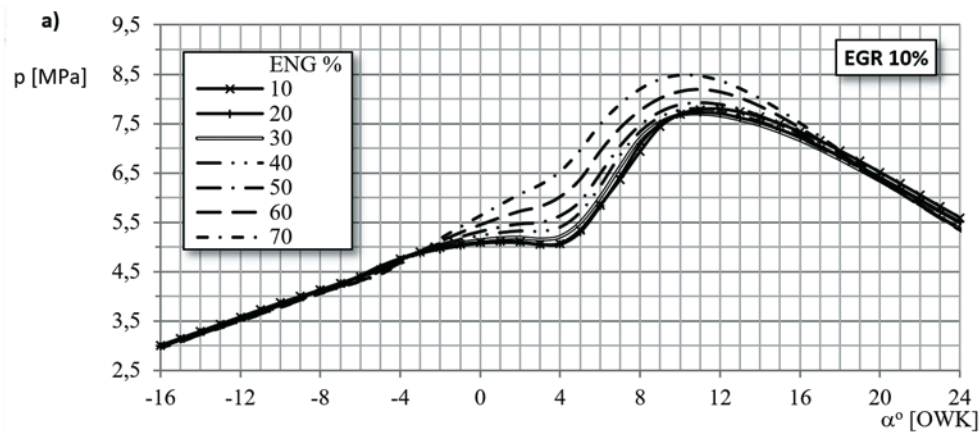
Fig. 3. Dependency of the overall efficiency – η_o (Fig. a), thermal efficiency – η_c (Fig. b), mechanical efficiency – η_m (Fig. c) on the index of fraction of energy of gaseous fuel – E_{NG} – for different assumed values of the degree of recirculation of exhaust gases – E_{GR}.

EGR = Exhaust Gases Recirculation;
ENG = fraction of energy of natural gas

In front of clear relation of the character of course of overall efficiency (Fig. 3a) to the course of value of mechanical efficiency (Fig. 3c) it was recognized that the character of the changes of overall efficiency complies with the variability of mechanical efficiency. There was made an attempt also to clarify the reason of observed change of the value of mechanical efficiency together with the change of the degree of recirculation of exhaust gases and also the change of index of fraction of gaseous fuel. Calculated and recorded courses show that maximum values of mechanical efficiency are accompanied by the lowest values of the degree of recirculation of exhaust gases. It is also worth noticing that the value of mechanical efficiency decreases together with the increase of the fraction of gaseous fuel. The attempt of clarifying the above mentioned changes in mechanical efficiency was made on the base of recorded courses of pressure of agent in cylinder, depending on the crank angle. These courses let for determining the remaining essential parameters of combustion process.

4. Examination of changes of the basic parameters of combustion process

During the examinations in each measuring point there were recorded the courses of pressure of agent in relation to crank angle. These courses were set in Fig. 4. It should be mentioned that during the examinations there were kept constant parameters of injection of the dose of diesel oil initiating ignition. The dose was divided into two parts, pre-dose and the main dose as it happens in most of contemporary diesel engines with self-ignition. The parameters of injection of these doses (angles of the start of injection and the values of doses) were set on the base of earlier research [6].



EGR = Exhaust Gases Recirculation
OWK - Crank angle

Fig. 4.

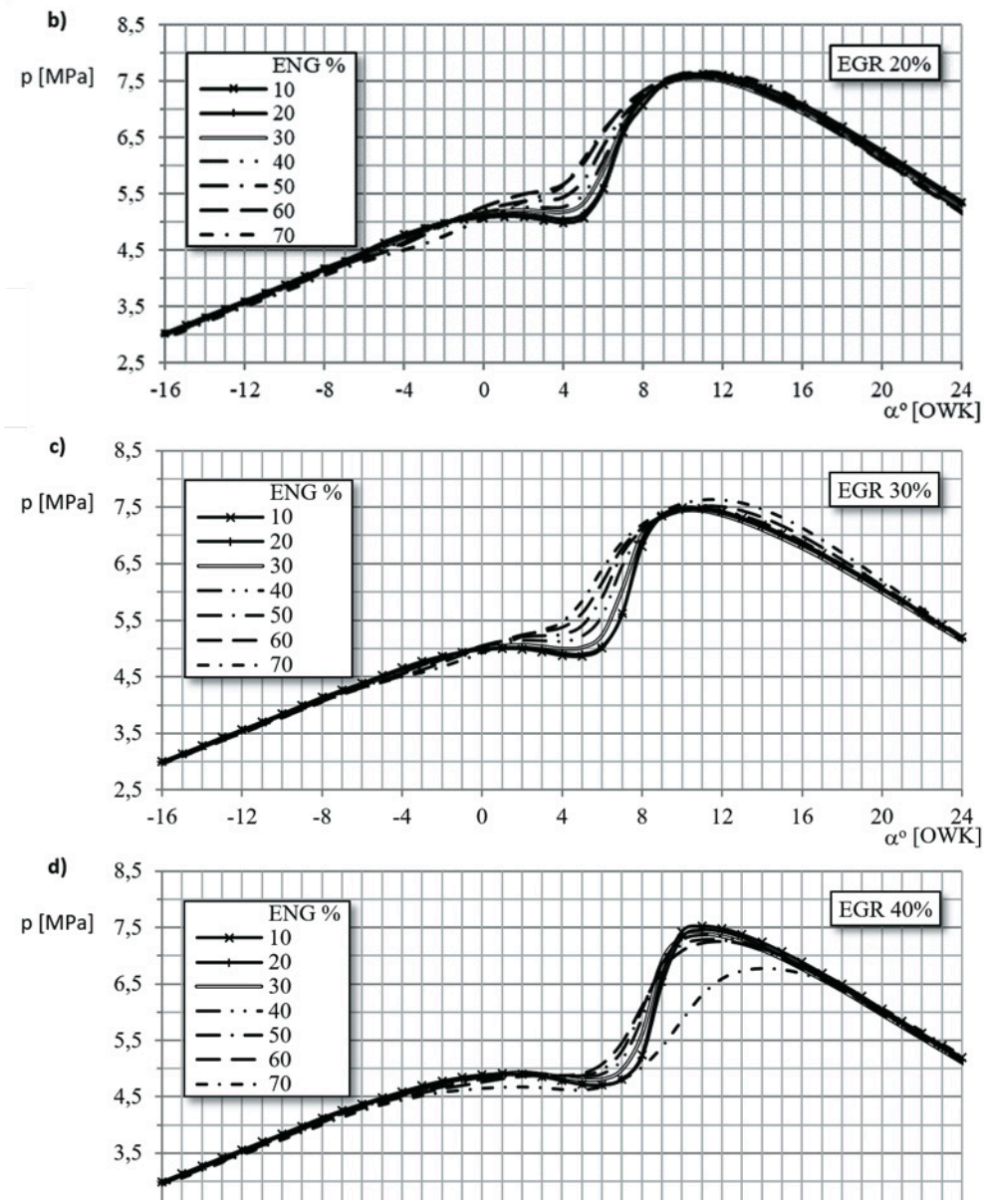
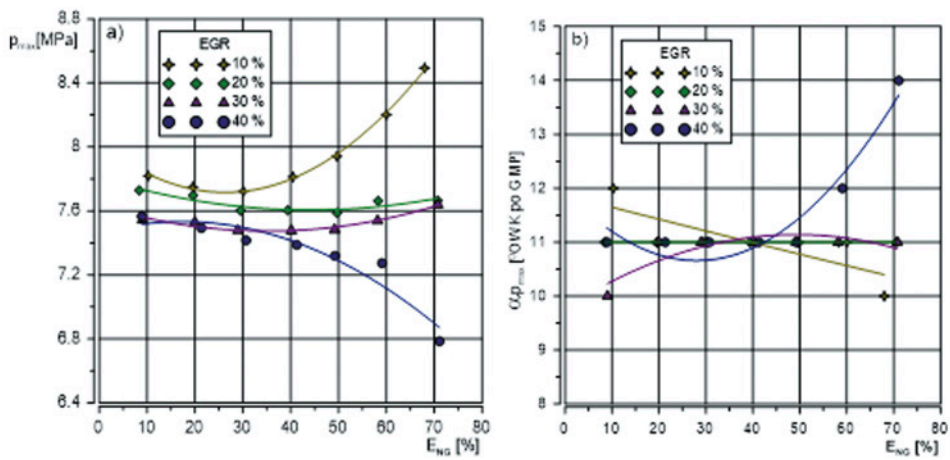


Fig. 4. Recorded courses of the pressure of agent in cylinder dependent on crank angle - α for different values of the index of fraction of energy of gaseous fuel – ENG and different values of the degree of recirculation of exhaust gases – EGR: a) 10%, b) 20%, c) 30%, d) 40%.

Even the initial visual analysis of the courses presented on Fig. 4 shows that character of the course of the pressure of agent in cylinder in relation to crank angle depends clearly on both the index of fraction of energy of gaseous fuel and the degree of recirculation of exhaust gases. It was decided then to draw up the characteristics of basic parameters characterizing the combustion process as a function of fraction of energy of gaseous fuel for assumed four values of degree of recirculation of exhaust gases. Recorded and presented (Fig. 4) courses of pressure of agent in cylinder let for determining the courses of basic parameters characterizing combustion process such as:

- the maximum pressure of agent in combustion process ,
- the angular position of the maximum pressure of agent in combustion process,
- the maximum speed of building up of pressure of agent in combustion process,
- the start of combustion process,
- the angular position of burning out 50% and 90% of charge.

The results of calculations and analyses in the form of characteristics were set on Fig. 5, 6, 7.



po = after; przed = before

Fig. 5. Dependence of the values of the maximum pressures - p_{max} (Fig. a), angular position of the maximum values of combustion pressure - $\alpha\ p_{max}$ (Fig. b), on the index of fraction of energy of gaseous fuel – E_{NG} for different assumed values of the degree of recirculation of exhaust gases – EGR.

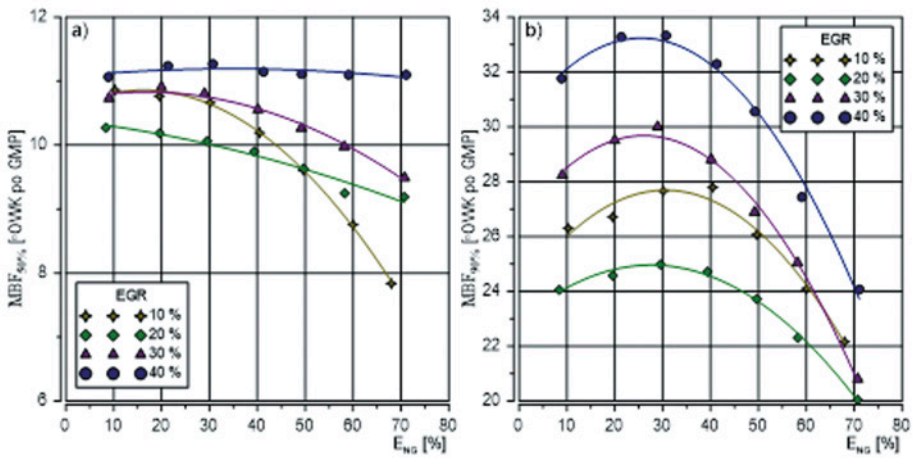


Fig. 6. Dependence of position of crank shaft corresponding to burning out of charge of 50% (Fig. a) and 90% (Fig. b), on the value of index of fraction of energy of gaseous fuel – E_{NG} for different assumed values of the degree of recirculation of exhaust gases – EGR.

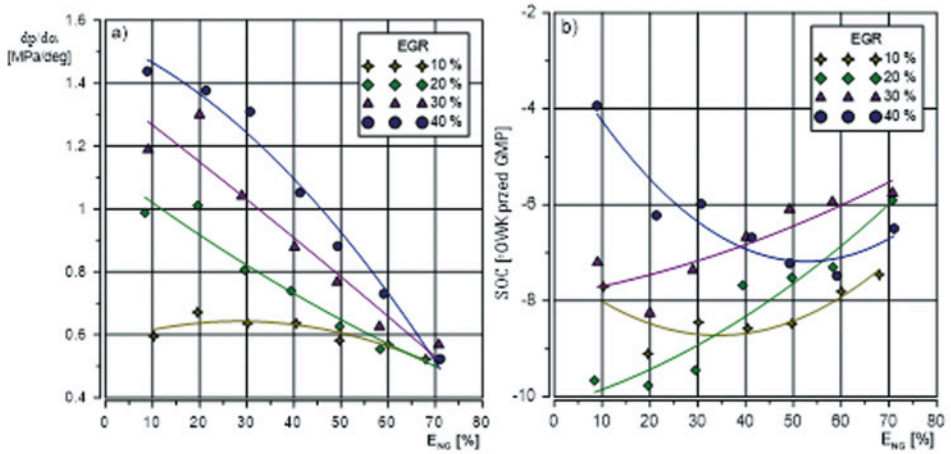


Fig. 7. Dependence of the value of maximum speed of building-up of combustion pressure – dp/d α (Fig. a), the angular position of start of combustion – SOC (Fig. b), on the index of fraction of energy of gaseous fuel – E_{NG} for different assumed values of degree of recirculation of exhaust gases – EGR

The analysis of presented dependencies shows that the value of basic, essential parameters of combustion process of engine depends on both, the degree of recirculation of exhaust gases and the index of fraction of energy of gaseous fuel. It was decided then to analyze the impact of the basic parameters of combustion process on mechanical efficiency and as it was mentioned before related strongly to it the overall efficiency of dual-fuel engine in two areas: at small fraction of gaseous fuel $E_{NG} = 10\%$ and at the maximum fraction of gaseous fuel $E_{NG} = 70\%$.

In the range of small energy fractions of gaseous fuel together with increase in the degree of recirculation of the exhaust gases it can be observed that

- the self-ignition lag of ignition initializing dose of diesel oil increases sharply (the start of combustion approaches GMP in compression stroke Fig. 7b),
- the value of maximum speed of building up of combustion pressure increases sharply (Fig. 7a).

These two effects result in close values of the maximum pressures (Fig. 5a) (not big dependency of the value of this parameter on the degree of recirculation of exhaust gases). It is worth noticing that the position of the maximum pressure of agent in the combustion process for all values of the degree of recirculation of exhaust gases concentrate relatively close together to GMP (Fig. 5b).

According to the authors the decrease of the value of mechanical efficiency and consequently the overall one, for analyzed values of the degree of recirculation of exhaust gases in the area of small energy fractions of natural gas (Fig. 3c) results from the increase of mechanical loads of main and crank bearings in the virtue of gaseous forces, as a result of emerging of the maximum values of combustion pressure too close to GMP.

In the range of the maximum fractions of gaseous fuel $E_{NG} = 70\%$ it can be observed that:

- self-ignition lag of the dose of diesel oil initiating ignition (start of combustion is dependent to the slight degree on the degree of recirculation of exhaust gases Fig. 7b) increases slightly together with the increase of the value of degree of recirculation of exhaust gases,
- the values of the maximum speed of building -up pressure of agent in combustion process, are also being clearly stabilized and do not depend on the degree of recirculation of the exhaust gases (Fig. 7a),
- localization of the maximum pressure of circulation moves clearly to expansion stroke especially for greater values of the degree of recirculation of exhaust gases (it falls on greater deflection of double crank of crank shaft after GMP Fig. 5b), what is also proved by the location of burning out of 50% charge (Fig. 6a).

According to the authors it is the increase of the friction losses in the cylinder-piston system as a result of the increase of values of normal forces originating from gaseous forces especially for greater values of the degree of recirculation of exhaust gases which is responsible for the decrease of mechanical efficiency in the given area (great energy fractions). That fact results from the described above shift in the maximum circulation pressure in the direction of extension stroke. It seems that it is the predominating effect

in spite of the decrease in the values of the maximum pressures of circulation, together with the increase of the degree of recirculation of exhaust gases.

5. Summary

The analysis of presented results of examinations leads to the following conclusions:

- Variability of the values of overall efficiency of dual-fuel engine (Fig. 3a) equipped with system of recirculation of exhaust gases, depends clearly on the variability of mechanical efficiency (Fig. 3c).
- The changes of values of mechanical efficiency result from the changes in combustion process which depend strongly on the fraction of energy of gaseous fuel and also the degree of recirculation of exhaust gases.
- At applied during the research, constant regulations of parameters of injection of the dose of diesel oil initiating ignition versus the values of the a/m indices: the fraction of energy of gaseous fuel and the value of degree of recirculation of exhaust gases, the parameters such as mentioned below undergo change i.e.: the maximum value of pressure of agent in combustion process, the start of combustion process, angular position 50% and 90% of burning-out charge, the maximum value of speed of building-up pressure of agent in combustion process. In the result of described phenomena according to the authors the mechanical losses are subject to substantial changes in the virtue of normal forces of reaction (interaction) of piston on cylinder and forces which load the bearings of the crank shaft.
- Possibility of improvement of the overall efficiency through the improvement of mechanical efficiency is ascribed in implementing regulation of parameters of injection of the dose of diesel oil initiating the injection. These regulations should be dependent on the degree of recirculation of exhaust gases as well as the value of index of energy fraction of gaseous fuel. The point is both about the division of the injection initiating dose of diesel oil according to the value and the position of pre-dose and main dose. The necessity of the a/m division of dose of diesel oil was noted also by Prof. Stelmasiak [10]. These problems in case of dual-fuel engine are more complicated than in the case of engine fed normally. It is most likely that implementing variable regulation of parameters of injection of the dose of diesel oil initiating ignition will contribute also to the improvement of the value of thermal efficiency of the engine especially at greater energy fractions of gaseous fuel.

The full text of the article is available in Polish online on the website http://archiwummotoryzacji.pl.

Tekst artykułu w polskiej wersji językowej dostępny jest na stronie http://archiwummotoryzacji.pl.

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