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Cover/*Okładka*
I – Bugatti Chiron – 8-litre W16 quad-turbocharged engine
(*fot. fortune.com*), background (racing background © tofumax – *Fotolia.com*)
IV – Infiniti – Variable Compression-Turbocharged engine
(*fot. www.infinity.ca*)

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Joanna LEWIŃSKA

CE-2016-405

The influence of fuel injection pump malfunctions of a marine 4-stroke Diesel engine on composition of exhaust gases

The article presents results of a laboratory study on exhaust gas emission level from a marine diesel engine. The object of the laboratory study was a four-stroke marine diesel engine type Al 25/30 Sulzer, operated at a constant speed. The examination on the engine was carried out according to regulations of the Annex VI to MARPOL 73/78 Convention. The laboratory study consisted of 3 observations: the engine assumed to be operating without malfunctions, delay of the fuel injection by 5° of crankshaft angle in the second engine cylinder, and the leakage of the fuel pump on the second engine cylinder. Additionally, parameters of fuel consumption and thermodynamic parameters of the marine engine were measured during the research. Simulated malfunctions caused changes in total weighed NO_x, CO, and CO_2 emissions for all considered engine loads. All simulated malfunctions caused a small change in measured thermodynamic parameters of the engine. The engine operation with the delayed fuel injection and the fuel leakage in the fuel pump in one cylinder caused a decrease of NO_x and CO emission level. Fuel leakage in the fuel pump causes the CO_2 emission to decrease only at low engine load. Calculations of the weighed specific fuel consumption present a 1-2% change in the engine efficiency.

Key words: *marine diesel engine, malfunctions, fuel injection pump, exhaust gas*

1. Introduction

Diesel engines have found an application in a transport field as a source of propulsion for vessels. High pressure and high temperature conditions in a combustion chamber of these engines causes the emission of considerable amounts of gaseous compounds such as nitrogen oxides (NO_x) and particulate matter (PM). The standard that regulates permissible emission levels of toxic NO_x from marine diesel engines is the International Convention for the Prevention of Pollution from Ships – MARPOL 73/78 [1]. In addition to NO_x and PM, marine engines emit compounds such as hydrocarbons (HC) and carbon monoxides (CO). Due to the growing problem of greenhouse gas emissions, the International Maritime Organization (IMO) has adopted a regulation concerning "Energy efficiency for ships" [2] on the 1st of January, 2013. Since the beginning of a design stage of diesel marine engines, the aim is to achieve a high efficiency and reduced emissions of mentioned chemical compounds. Modifications in the construction of the engine and its components, changing the fuel composition and a aftertreatment of exhaust gases may be a basis for the reduction of excessive emissions coming from diesel engines [3]. In [3, 4, 5] Sarvi et al. presents work about emissions from large-scale, medium-speed diesel engines with technical parameters similar to marine diesel engines. It is well known that one of the factors responsible for correct combustion is fuel injection into the combustion chamber. A rate of fuel injection affects the process of the air-fuel mixture forming. Accordingly, the structure of the injection system and the geometry of an injection nozzle affect the fuel injection rate and sprayed fuel speed. The common rail and direct fuel injection technology has dominated the diesel engines car market. The first 4-stroke diesel engine with common-rail system has been installed on a ship in 2001 [6]. The common rail technology enables control of the dose and time of the fuel injection depending on load and engine speed. Sarvi et al. present [5] a study of an effect of combining common rail system with direct water injection system on a level of the marine engine's emissions. The common rail system reduces NO_x, CO, HC, and combined with direct water injection reduces NO_x emission by about 50%. In [7] a study of the impact of changes in rotational speed and injection pressure on emissions is presented. High pressure of fuel injection is beneficial for reducing emissions of compounds such as CO_2, CO, while low injection pressure is preferred for NO_x reduction. Disturbances in a normal fuel combustion process in the combustion chamber of the marine engine may lead to a noticeable difference in engine parameters and exhaust emission levels. Raeie et al. [8] present the research results of the influence of the fuel injection start position and injection pressure level on the composition of exhaust emissions. It has been stated that the fuel injection before top dead center results in the lowering of soot level by about 58%, but increases the NO_x emission level. Malfunctions of the marine engine's fuel system are often a result of damage or the consequence of wear processes of construction elements. Interference in the cylinder fuel supply process leads to disturbances in the regular process of fuel combustion and therefore affects the composition of the exhaust emissions.

The paper presents results of experimental studies on the effects of simulated malfunctions of the fuel injection system on the composition of exhaust gas.

2. Experimental procedure

Laboratory studies presented in this article were carried out in the Internal Combustion Engines Laboratory at the Gdynia Maritime University. The test stand allows for conducting measurements in accordance with the ISO 8178 standard regulation. Three tests were conducted. The first test was carried out on the engine assumed to operate without malfunctions and two more during engine operation with

simulated malfunctions. Simulated engine malfunctions in the second engine cylinder are:
- the delay of the fuel injection by 5° of crankshaft angle,
- the leakage of the fuel pump.

2.1. The engine, fuels and test conditions

The subject of the laboratory tests was a marine diesel engine 3 Al 25/30 presented in [9]. The marine engine's laboratory parameters are shown in Tab. 1.

Table 1. Parameters of the test engine [10]

Parameter	Value	Unit
Max. electric power	240	kW
Rotational speed	750	rpm
Cylinder number	3	–
Cylinder diameter	250	mm
Stroke	300	mm
Compression ratio	12.7	–
Nominal start of injection	–18	°

The research object is 4-stroke laboratory diesel engine with direct fuel injection, supercharged by a turbocharger VTR 160 Brown-Boveri and charge air cooling. The engine is loaded by a generator electrically connected to the water resistance. The composition of exhaust gas was recorded using an electrochemical exhaust gas analyzer of type MRU 92/3D. Laboratory engine was supplied by light fuel oil. Simulated malfunction of the delaying fuel injection angle by 5°crankshaft angle was achieved by inserting a pad of a thickness of 1.5 mm under the fuel injection pump's housing. A leak in the fuel injection pump was simulated by partially opening an overflow duct connecting pressure and suction sides of the fuel injection pump.

2.2. Measurement procedure

Measurements were carried out in accordance with the requirements of Annex VI of MARPOL 73/78 and the NO_x Technical Code 2008. For analysis and calculation the test cycle E2 was used. It is designed for marine main propulsion engines with constant rotational speeds, including diesel electric propulsion. In order to perform correct measurements the E2 test cycle was adapted to the specifications of the laboratory engine. Therefore, the number, and order of the measurements and a range of loads at individual measurement points were established. Parameters' recording in each individual measurement point lasted between 3–5 minutes. Table 2 shows a cycle of E2 tests in accordance with Annex VI of MARPOL 73/78 and the NO_x Technical Code 2008 adapted to performing tests and exhaust emission calculations on the laboratory engine .

Table 2. E2 cycle engine adapter to the laboratory engine according to [9]

E2 cycle	Number of measurement	1	2	3	4
	Electric power P [kW]	240	180	120	60
	Rotational speed [rpm]	750	750	750	750
	Weight factor	0.2	0.5	0.15	0.15

The laboratory engine 3 Al 25/30 is designed to achieve a maximum power of 396 kW. The load of 240 kW was the highest achievable value by a laboratory engine working with simulated engine malfunctions for safety reasons. During the observations, recordings of parameters were made after the stabilization of exhaust gas temperature measured behind the turbine.

3. Results and discussions

In order to determine the effect of simulated malfunctions of the injection pump on the exhaust gas composition, a series of calculations based on data obtained during measurements were made. The obtained parameters and results of calculations of emission components from exhaust gas were collected and presented below. For calculations the method of carbon and oxygen balance was applied.

3.1. The total weighted values

The final result of the calculation was the total emission of NO_x, CO and CO_2 shown in Fig. 1. In order to compare obtained total weighted emissions by the engine assumed to be operating without malfunctions and with simulated malfunctions, on Fig. 1 the percentage values of changes in these emissions are shown. However, it should be noted that the cycle E2 (Tab. 2) assumes that the engine is operated with 75% load during 50% of all operation time. Most varied changes in total weighted emissions during simulation of chosen malfunctions were observed in the case of NO_x [9]. A significant reduction in NO_x compared to operation of the engine without malfunctions was observed during simulation of the fuel pump's malfunction in the cylinder No. 2.

Reduction of NO_x in the considered load range and simulated malfunctions were between 18% and 21% (Fig. 1a). Simulated engine malfunctions did not cause significant changes in total weighted CO_2 emission compared to the engine operated without malfunctions. Changes were in the range of 1% (Fig. 1). On the other hand, for CO a significant decrease in the total emission by 34% was observed during the operation of the laboratory engine with a simulated malfunction of delayed fuel injection angle (Fig. 1).

3.2. The specific fuel consumption in g/kWh

To determine the specific fuel consumption (SFC) a method of measurement of combustion time and the specific volume of fuel was used. The results of calculations of SFC for the engine assumed as operating without malfunctions and with considered simulated malfunctions are summarized in Tab. 3. In addition, weighted averages of SFC based on the test cycle E2 were specified (Tab. 2)

Table 3. The specific fuel consumption in g/kWh [9]

No.	Power [kW]	The engine assumed as operated without malfunctions	The delay of the fuel injection by 5° of crankshaft angle	The leakage of the fuel pump
1.	240	277	277	285
2.	180	286	283	288
3.	120	315	315	331
4.	60	477	475	403
weighted SFC according to E2		317	316	311

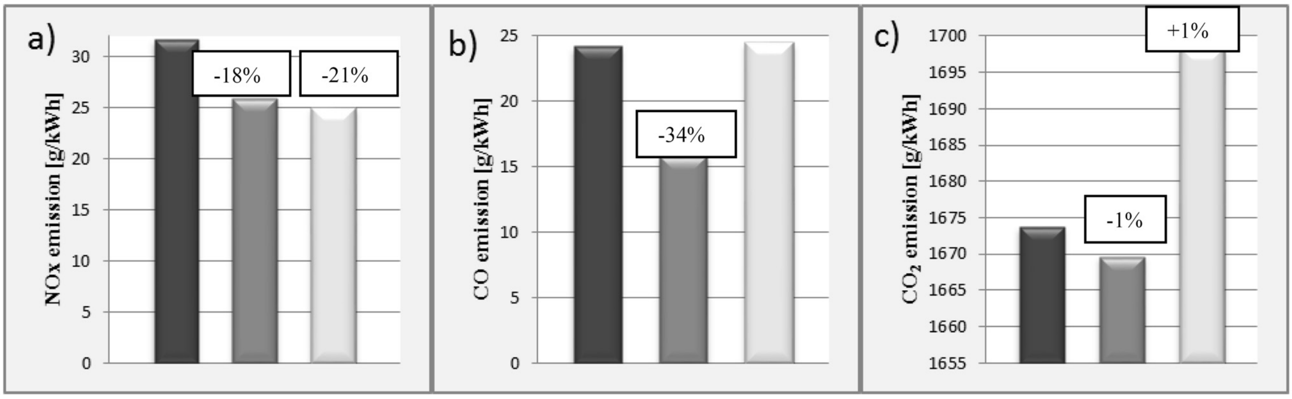

Fig. 1. Values of the total weighted: a) NO_x, b) CO, c) CO_2 emissions: ■ – engine assumed as operated without malfunctions, ■ – the delay of the fuel injection, □ – the leakage of the fuel pump

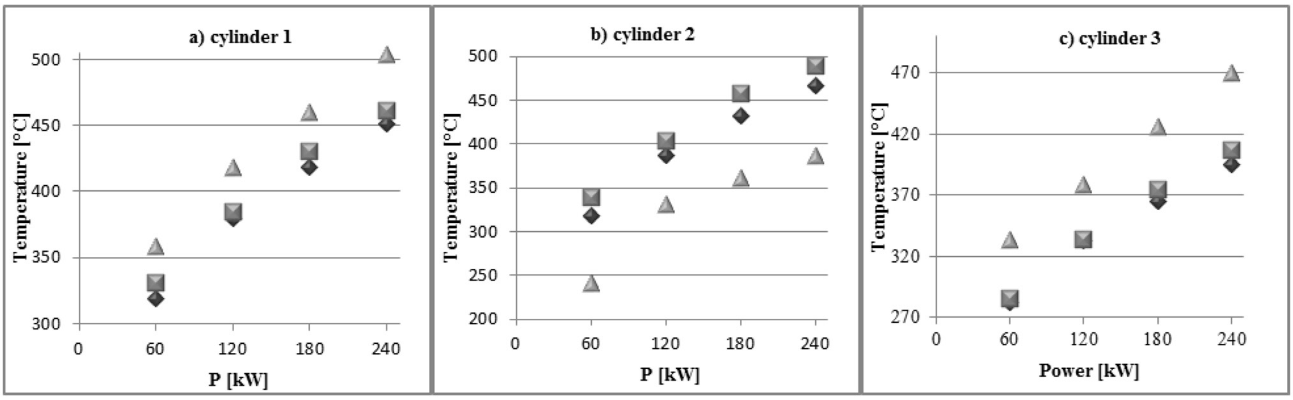

Fig. 2. Exhaust gas temperature behind the cylinder: ◆ – engine assumed as operated without malfunctions, ■ – delayed fuel injection, ▲ – the leakage of the fuel pump

3.3. The fuel injection delay by 5° of crankshaft angle

In an operation of marine diesel engines a surface wear and/or a displacement of a fuel cam on a camshaft may lead to disturbances in normal fuel supply to a cylinder [6]. In the result of this phenomenon the delay of fuel injection into the cylinders and displacement of the combustion process to the expansion stroke may occur. Disturbances in the normal process of fuel combustion in the marine engine's combustion chamber may lead to a noticeable difference in the engine's parameters and the exhaust emission levels. Figure 2 shows temperatures of exhaust gases behind cylinders. Simulated delay of the fuel injection causes the increase of exhaust gas temperature behind cylinders by 4–7% (Fig. 2) as compared to exhaust gas temperature behind cylinders of the engine assumed to be operating without malfunctions at all considered the engine loads. The temperature rise of the exhaust gas leaving the combustion chamber provides more energy to the turbocharger, thus increasing the volume of air supplied to the cylinders. Noticeable differences were observed in NO_x and CO emissions (Fig. 3). The CO emissions decrease by 40% during the engine operation with 60 kW and 120 kW loads and decrease approximately by 34% during the engine operation with 180 kW and 240 kW loads respectively in comparison to the engine operation without malfunctions.

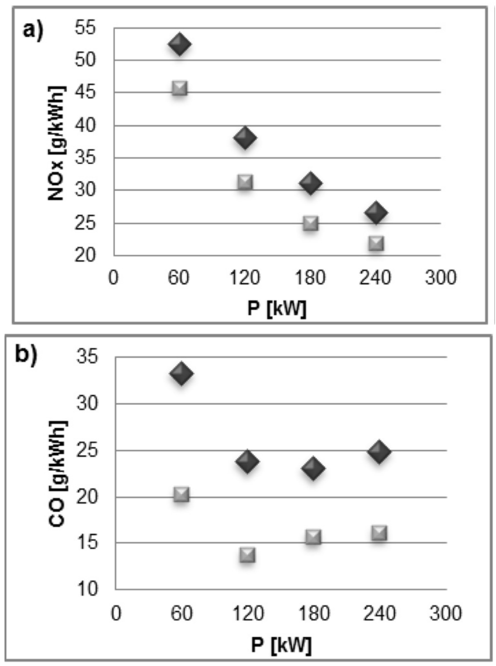

Fig. 3. The results of a) NO_x, b) CO emissions: ◆ – engine assumed as operated without malfunctions, ■ – the delay of the fuel injection

The simulated malfunction did not cause a significant change in the CO_2 emission and SFC (Tab. 3). Mentioned

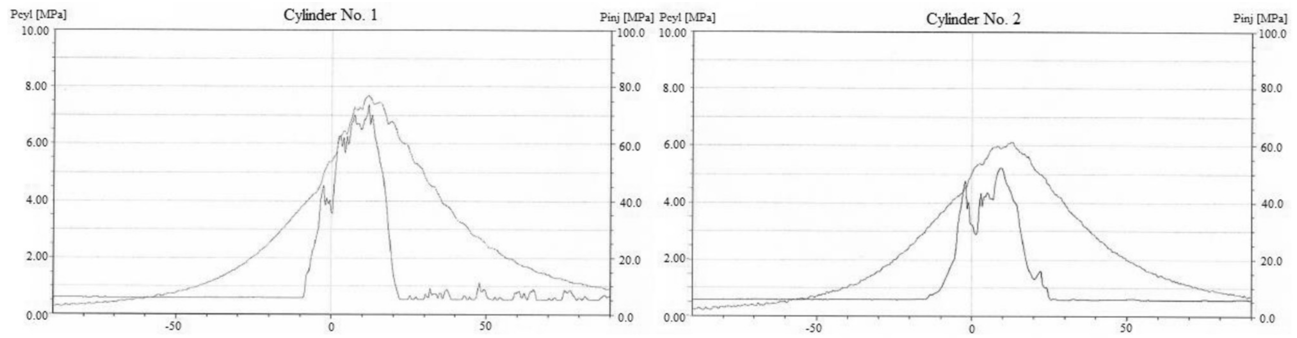

Fig. 4. The example diagram of combustion pressure and the injection pressure for P = 180 kW

differences fluctuate in a 1% range. The value of λ for the engine with a simulated malfunction was almost unchanged compared to the engine assumed as operating without malfunctions. The increase in the volume of air supplied to the combustion chamber and the displacement of the combustion process on the expansion stroke caused a decrease in the maximum pressures prevailing in the cylinder, and thus have contributed to the reduction of NO_x (Fig. 3 b). NO_x emissions with a simulated malfunction decreased by 13–19% in comparison to the engine operation without malfunction.

3.4. The leakage of the fuel pump on the second engine cylinder

Malfunctions of the marine engine's fuel system are often a result of damage or consequence of wear processes of construction elements. For example, the wear of precision pairs of the fuel pump or the injector leads to reduced performance of the fuel injection and the combustion process. Interference in the process of fuel supply to the cylinder leads to disturbances in the regular process of fuel combustion and therefore affects the composition of the exhaust gas. During the study it was not possible to determine the value of the simulated leakage. Fig. 4 presents diagrams of combustion and injection pressures, recorded during the test. Diagrams were created for cylinder No. 2 – with a simulated malfunction and cylinder No. 1 – assumed as operated without malfunction.

One of the important parameters of fuel injection into the combustion chamber are duration and fuel injection pressure. Achieving an appropriate pressure and fuel injection time affects the quality of the created fuel-air mixture. Marine engine injection pump's leaks were one of the causes of a deterioration of the fuel combustion process, its pressure and temperature reduction, and a resulting change in composition of exhaust gas. On presented graphs (Fig. 4) the pressure reduction in the combustion chamber and the injection pressure reduction in the cylinder No. 2 in comparison with the cylinder No. 1 can be observed. The reduction in pressure caused the deterioration of fuel spraying by increasing the diameter of fuel drops injected into the cylinder. Together with the increase in the diameter of the drops the fuel evaporation and combustion is lengthened. Simulated leakage caused the reduction in exhaust gas temperature behind the cylinder No. 2 (Fig. 2) of around 17–24% and the increase temperature behind other cylinders in comparison to the engine assumed as operated without malfunctions. The malfunction in one of the cylinders, resulting in energy loss must be compensated by other cylinders. Accordingly, the simulated leakage of the fuel pump in the cylinder No. 2 increases the SFC and the temperature of the gas behind cylinders No. 1 and No. 3. Engines with the classic valve timing are regulated in order to obtain the best efficiency during operation near the nominal load. Weighted specific fuel consumption according to cycle E2 decreased by approximately 2% (Tab. 3). In the load range from 120 kW to 240 kW SFC increases from 1% to 5%. For the lowest load the SFC was reduced by 16%. The engine's efficiency was improved in the lowest load range. An amount of fuel supplied to the cylinders is associated with the emission rate of CO_2 and CO (Fig. 5 b,d). Improving engine's efficiency resulted in a reduction of CO_2 and CO emissions by 15% in the lowest considered load. For other considered loads CO_2 emission increases by 2–6%. In the load range from 120 kW to 180 kW CO emission increases by 8%. The increase of exhaust gas temperature behind the cylinder (Fig. 2), as with previously described studies, causes increase of the efficiency of the turbocharger, therefore a larger volume of air is provided into the engine. The size of the air fuel excess air ratio, (λ) presented in Fig. 5c, shows minimal differences compared to the engine operated without malfunctions. In this article, λ was determined according to the formula presented in [11]. Uneven amount of fuel supplied to the cylinder, reducing fuel injection pressure and extension of the combustion process in time resulted in lower maximum temperatures and combustion pressures in the second cylinder and thus to the reduction of NO_x emission for all considered engine loads (Fig. 5 a).

4. Conclusions

The article presents laboratory research results of the four-stroke marine diesel engine, type 3 Al 25/30 Sulzer. Emissions of NO_x, CO, CO_2 and SFC were measured according to the requirements of Annex VI to the MARPOL Convention. The E2 measurement cycle has been used. Measurements for simulated malfunctions delay of the fuel injection by 5° of crankshaft angle in the second engine cylinder and the leakage of the fuel pump on the second engine cylinder were performed. Obtained results allow to formulate the following conclusions:

– Simulated fuel pump's malfunctions causes changes in the total weighted emission of examined gas components. NO_x emission is noticeably reduced for both simulated malfunctions and CO as well but only for the delayed fuel injection angle of 5° crankshaft angle in the cylinder No. 2. For CO_2 emission no changes were observed.
– Simulated malfunctions caused changes in thermodynamic parameters and SFC. The simulated delay of fuel injection angle increased the maximum temperatures behind cylinders. The simulated fuel pump leakage in the cylinder No. 2 caused a significant reduction in exhaust gas temperature behind the cylinder with the simulated malfunction and the increase of exhaust gas temperature for the remaining cylinders. The increase in exhaust temperature for cylinders contributes to improved efficiency of the turbocharger and the increased volume of air supplied to the engine.
– Simulated leakage of the fuel injection pump in cylinder No. 2 caused a reduction of both the maximum pressure in the combustion chamber and the fuel injection pressure. Therefore, the deterioration of efficiency in highest engine load range and the increase in CO_2 emission were observed. Improved efficiency and reduced emissions of CO_2 and CO were observed only in the lowest load range. It should be noted that engines with classic valve timing are adjusted in order to achieve the best performance during operation with nominal load. Delayed fuel injection angle did not cause any noticeable changes in the engine efficiency and CO_2 emission.
– Displacement of the fuel combustion process to the expansion stroke in the marine engine combustion chamber and the reduction of the maximum combustion and injection pressures resulted in the reduction of CO and NO_x emissions for all considered engine loads.

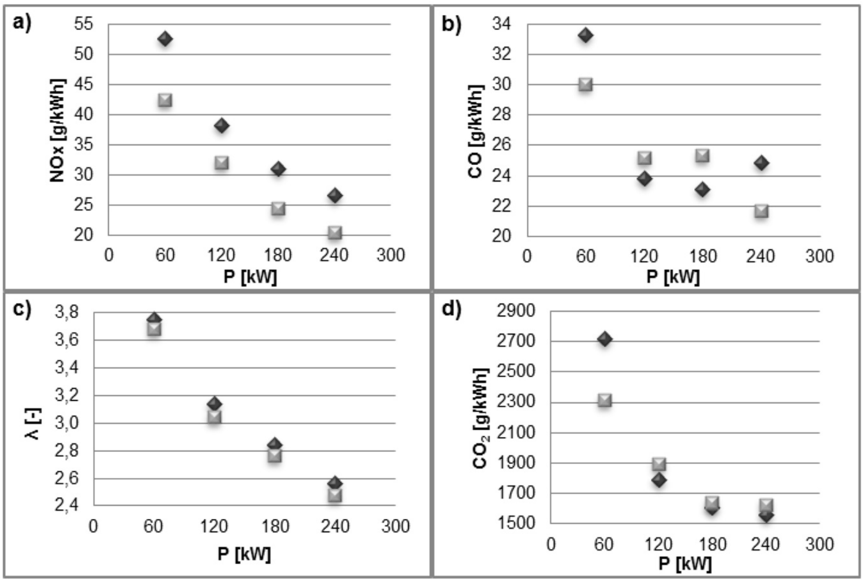

Fig. 5. The results of the a) NO_x, b) CO, c) λ, d) CO_2 emissions: ◆ – engine assumed as operated without malfunctions, ■– the leakage of the fuel pump

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Bartosz GAWRON
Tomasz BIAŁECKI

CE-2016-406

Measurement of exhaust gas emissions from miniature turbojet engine

This paper presents a methodology developed to measure exhaust gas emissions during operation of a miniature turbojet engine, using a laboratory test rig. The rig has been built for research and development works aimed at modelling and investigating processes and phenomena occurring in jet engines. The miniature jet engines, similarly to full–scale ones used commonly in air transport, are characterized by variable exhaust gas emissions, depending on engine operating parameters. For this reason, an attempt has been made to determine the characteristic features of miniature engine operation modes and to define the variability of operation parameters and exhaust gas emissions as a function of time. According to the authors, the preliminary tests allowed for defining specific profile of engine test, which enables proper measurement regarding exhaust gas emissions using the miniature jet engine. The paper also presents test results for Jet A-1 fuel, according to the used methodology.

Key words: *combustion process, effect on environment, exhaust gas emission, miniature turbojet engine*

1. Introduction

Aviation is one of the fastest growing modes of transport. During recent years, the increasing number of aircrafts has been associated with higher intensity of carried out aviation operations. This causes an increasing demand for fuel, which is the power supply for jet engines that leads to an increase of harmful exhaust emissions. Aviation is currently the fastest growing source of CO_2 emissions [1]. Generated pollutants negatively affect the quality of the air that surrounds us and conduce to greenhouse effect intensification.

For this reason, in 2012, the EU emissions trading system (EU ETS) was introduced into aviation sector. The system will include the exhaust emissions generated by civil aviation. Airlines carrying out flights all over Europe, and to and from Europe, are obliged to obtain entitlement to emissions generated during such flights. Such deliberations justify the advisability of taking various research and development works regarding the effect of aviation on environment [2, 3].

Turbine engines as the propulsion of modern aircrafts, depending on engine operating parameters, are characterized by variable emissions of harmful exhaust gases. The aviation engines whose rated thrust is greater than 26.7 kN are subject to emission certifications. The measurement procedure and assessment of harmful exhaust emissions are included in Annex 16 to the Convention on International Civil Aviation – Environmental protection (Volume II – Aircraft Engine Emissions). Landing and Take Off cycle consisting of ground–based tests. The separate test steps correspond to the following operating modes: take off, climb, approach and taxi/ground idle (Fig. 1).

The engine is tested at specified thrust settings [5]. The reference emissions of LTO cycle for the calculation and reporting of gaseous emissions are represented by the following time in each operating mode (Tab. 1).

Due to high costs of tests using the test rig with full scale jet engine, more and more tests are conducted using miniature jet engines [6, 7]. Such engines are used not only in scientific and research work, but are also used as a propulsion for aerial targets.

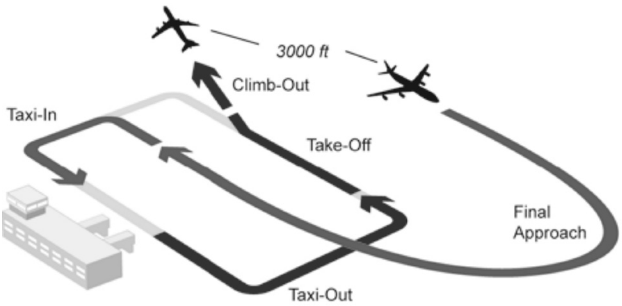

Fig. 1. ICAO reference LTO cycle [4]

Table 1. LTO operating mode

Operating mode	Thrust setting	Time in operating mode [min]
Take-off	100% rated thrust	0.7
Climb	85% rated thrust	2.2
Approach	30% rated thrust	4.0
Taxi/ground idle	7% rated thrust	26.0

The main advantage of the miniature turbojet engine application is a small amount of fuel necessary for tests. This is especially important in case of research work regarding alternative jet fuels. Nowadays availability of new, experimental fuels or components is the major restriction for large–scale tests on real jet engines. The reason for that situation is that most of innovative technologies for aviation biofuels are in an experimental stage, and only small volumes of such products are available.

The use of alternative fuels for aviation is currently very important regarding ecology. One of the main methods to restrict the harmful exhaust emission is to introduce various components into aviation fuel, including biocomponents and biofuels. The subject literature includes many publications related to alternative fuel testing using a small scale turbine engine [8–11].

In case of full–scale turbine engines there is a test procedure regarding harmful exhaust gas emissions (LTO cycle). There are no standards concerning miniature engines of considerably lower thrust. It seems that a proper selection of