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ASSESSMENT OF CO_2 EMISSION BY TRACTOR ENGINE AT VARIED CONTROL SETTINGS OF FUEL UNIT

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ABSTRACT

The paper presents results of experimental studies concerning CO_2 emission of S-4003 diesel engine Ursus C-360 at a variable fuel injection advance angle and opening pressure of injectors. Measurements were made on the dynamometric stand on the test bench. The engine operated according to the load characteristic at two characteristic rotational speeds i.e., at the maximum torque velocity (1600 rpm) and at the rated speed (2200 rpm). In each measurement point of load characteristics, CO_2 concentration was measured in exhaust gases with the use of exhaust gases analyser M-488 Multigas Plus. For a more detailed analysis of the CO_2 content in exhaust gases, additional change of O_2 level emission was presented, which in the biggest amount combines elementary carbon included in fuel during combustion. The studies showed the CO_2 content reduction in exhaust gases at the reduced (by 3° of crankshaft rotations) fuel injection advance angle in comparison to the nominal angle by 4.5% at the rotational speed of 1600 rpm and by 5.7% at the speed of 2200 rpm (the average values for all measurement points of load - brake horsepower of engine). Similarly, CO_2 concentration decrease in exhaust gases of the investigated engine was reported for the increased (by 1.5 MPa) opening pressure of injectors in comparison to the nominal pressure, on average by 9.8% for the speed of the maximum rotational moment and by 4.5% for the rated speed.

Introduction

Among global environmental threats of the automotive industry and other sources (e.g., industry, agriculture) the intensification of emission of the so-called greenhouse gases is the most serious. Global climate changes caused by heating of lower layers of atmosphere, the surface of Earth and surface water result from intensification of the greenhouse effect. In case of exhaust gases, CO_2 emission has the biggest effect on global heating of Earth due to the scale of this phenomenon. The remaining greenhouse gases in exhaust gases, such as methane (CH_4), nitrous oxide (N_2O) or ammonium (NH_3) are incomparably lower (Chłopek, 2009).

In the agricultural sector, according to the national inventory reports prepared by the State Centre for Balancing and Management of Emissions, in 2015-2018 the Polish agriculture generated 7-8% of the national emission of greenhouse gases including ca. 0.2-0.3% of CO_2 (Pawlak, 2017; KOBIZE, 2020). Participation of CO_2 emitted to atmosphere by agriculture constitutes 15-20% of its total amount included in anthropogenic contaminations from particular industry branches (Moneo and Iglesias, 2004).

Carbon dioxide in nature occurs in the gas state in atmosphere and as an element of volcano gases and other underground gases. However, the biggest problem is CO_2 from human activity. Emission of carbon dioxide to atmosphere from liquid fuel combustion has systematically risen around the world (Górski and Radziewicz, 2020). Referred to combustion engines it is produced as a result of complete combustion of elementary carbon included in engine fuels. Combustion engines used in agricultural production emit CO_2 and other chemical compounds during their operation and toxic ones (CO, NO_x, PM) in various amounts, depending on the load (type of the performed agricultural activity) or performed rotational speed. One should remember that engine operation rates depend on its structural features (a shape of a combustion chamber, structure of the fuel injection system, inlet system structure) and exploitation features (a fuel type and features, technical condition of particular engine systems, assumed control settings) (Zając and Węgrzyn, 2008; Kousoulidou et al., 2010; Wasilewski and Krzaczek, 2014; Burski and Wasilewski, 2016; Silitonga et al., 2017; Arshad et al., 2018).

One of the most important engine systems, where structural and exploitation features significantly decide on the working parameters, including organic ones, is a fuel system. In tractor engines, due to the specificity of operation of a farm tractor that performs various farm works, often in dusted air and conditions of the rated engine load (e.g., when performing deep ploughing), the supply system is particularly exposed to wear and change of control settings values. Therefore, the aim of the paper is to verify and assess the impact of various control settings of the fuel unit (fuel injection advance angle, opening pressure of injectors) on the level of emission of the selected exhaust gases elements i.e., CO_2 and O_2. The engine operated according to the load characteristics at two characteristic rotational speeds i.e., at the velocity of the maximum torque and at the rated speed.

An engine with a pump and mechanical control was used in the studies. Despite successive replacement of the machinery park in the Polish agriculture with modern tractors with advanced exploitation and emission-related solutions, engines of these types are still significantly exploited and cause possible ecological problems.

Material and Methods

The studies were performed on the dynamometer stand on the test bench belonging to the Department of Power Engineering and Transportation of the University of Life Sciences in Lublin. Figure 1 presents a schematic representation of the test stand.

The object of studies was a diesel engine S-4003 type of the farm tractor Ursus C-360. It is an in-line, four-cylinder naturally aspirated engine with a combustion system with direct fuel injection to a toroidal chamber in the piston. Characteristic technical data of the investigated engine was presented in table 1.

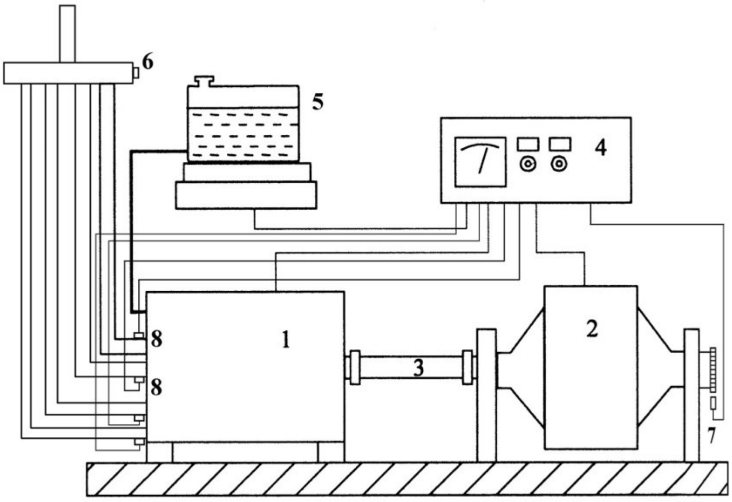

Figure 1. Schematic representation of the test stand: 1 – test engine, 2 – loaded break, 3 – engine to break shaft, 4 – control and measurement system, 5 – fuel consumption measurement system, 6 – exhaust gases intake, 7 – induction sensor of the rotational speed, 8 – sensors of exhaust gases temperature

Table 1.
Basic technical data of the investigated engine S-4003

Type [-]	Diesel engine
System of cylinders [-]	In-line vertical
Number of cylinders [-]	4
System of operation [-]	four-stroke
System of injection [-]	direct
Compression degree [-]	17:1
Step volume of an engine [dm^3]	3.12
Installed power [kW]	38.3
Rated speed [rpm]	2200
Maximum rotational speed [Nm]	186
Speed of the maximum torque [rmp]	1500-1600

K1-136B-E electric brake (induction ring generator) which also enables starting of an engine, served for loading the brake S-4003. A change of load was performed through a change of the field current of a brake with the use of a fluid resistor.

Rotational speed of an engine was measured with an induction sensor cooperating with the digital meter N05 type.

For testing the composition of exhaust gases, a multi-gas exhaust gases absorption analyser Multigas Plus type by Technotest was used (Kuranc, 2006).

During the tests performed on the dynamometric stand the engine S-4003 worked according to the load characteristics at two characteristic rotational speeds of the crankshaft i.e., rated speed (2200 rpm) and the speed of the maximum torque (1600 rpm) within the full range of load. In each measuring point of the engine, characteristics for various control settings of the injection unit measurement of exhaust gases measurement was performed (Fig. 1).

The following controls of the fuel injection system were performed:

– *fuel injection advance angle* (indirectly through the *fuel delivery angle*) to the value: 190° of crankshaft rotations, 22° of crankshaft rotations (nominal angle) and 25° of crankshaft rotations before TDC. Regulation of the fuel delivery angle was carried out directly on the engine through the injection pump rotation around the camshaft within the entire range of control of its torque. Getting the upper part of the pump closer to the engine, the angle was increased (for determination of the angle a torquemeter was used).
– opening pressure of injectors to the value: 15.5 MPa, 17 MPa (nominal pressure) and 18.5 MPa (sampler of injectors type PRW-3 was used). Moreover, tightness of injectors and quality of fuel spraying was verified.

The studies used diesel fuel that met the requirements of PN-EN 590 standard: 2017, without FAME content.

Statistical analysis was performed with the use of uni-variate analysis of variane to compare the means. The level of significance of $\alpha = 0.05$ was obtained for inference.

Results and Discussion

The fuel injection advance angle was determined directly though the fuel delivery angle (angle α_{PT}). At the rotational speeds of the engine applied in the tests, values of both angles were similar.

Figure 2 and 3 presents a course of changes of the CO_2 emission level in exhaust gases of the investigated engine that operates at rotational speeds respectively of 1600 rpm and 2200 rpm for various values of fuel delivery angles. Figure 4 and 5 presents courses of changes of O_2 content in exhaust gases corresponding to these characteristics and regulations of the fuel unit.

The average in the entire range CO_2 emission level for the reduced by 3° of crankshaft rotations fuel delivery angle was lower for the nominal angle (22° of crankshaft rotations before TDC), by 4.5% at the rotational speed of the engine of 1600 rpm and by 5.7% at the rotations 2200 rpm (Fig. 2 and 3). On the other hand, the increase of the angle α_{PT} in comparison to the nominal value (by 3° of crankshaft rotations) resulted in a higher CO_2 concentration in exhaust gases on average by 2.4% (1600 rpm) and by 4% (2200 rpm).

A delay in fuel injection caused the increase of the O_2 emission level, while the fuel injection advance angle caused a decrease of the O_2 content in exhaust gases (fig. 4 and 5). For the angle $\alpha_{PT} = 19°$ of crankshaft rotations before TDC, the average increase of concentration of this element of exhaust gases within the entire range of the engine load, was 5% (1600 rpm) and 3.8% (2400 rpm) while for the angle $\alpha_{PT} = 25°$ of crankshaft rotations before TDC, the decrease in O_2 concentration in exhaust gases – respectively by 0.5% (1600 rpm) and by 1% (2400 rpm).

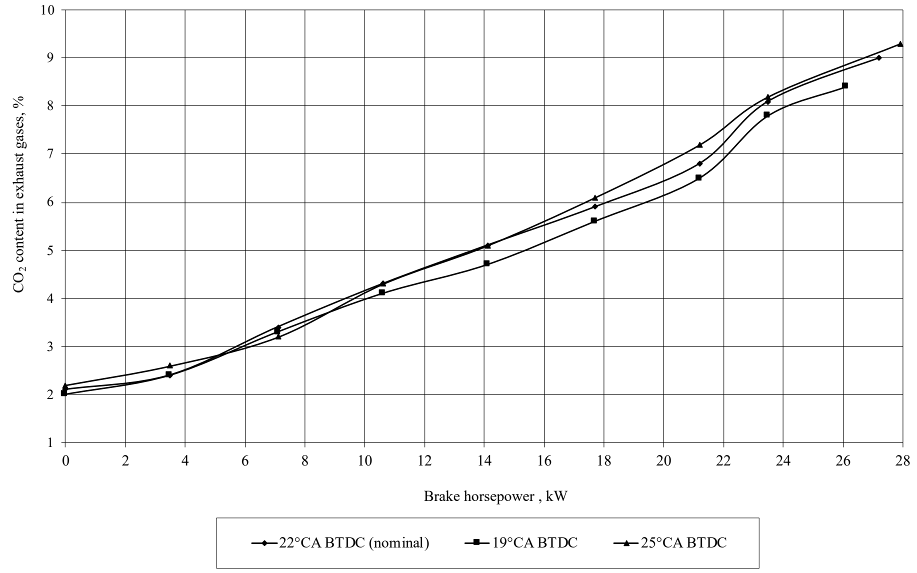

Figure 2. CO_2 emission in exhaust gases as a function of brake horsepower of engine S-4003 at variable fuel delivery angle and rotational speed of engine of 1600 rpm

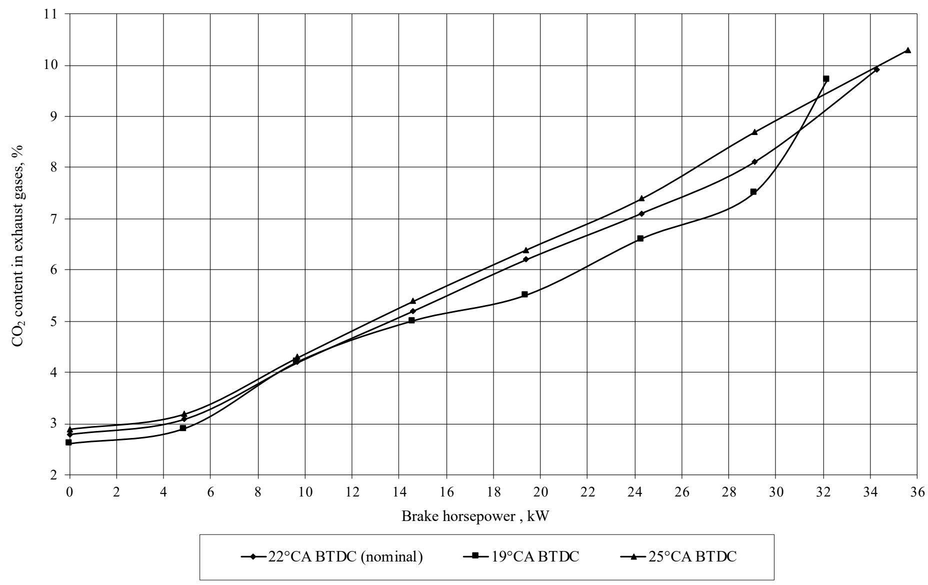

Figure 3. CO_2 emission in exhaust gases as a function of brake horsepower of engine S-4003 at variable fuel delivery angle and the rotational speed of engine 2200 rpm

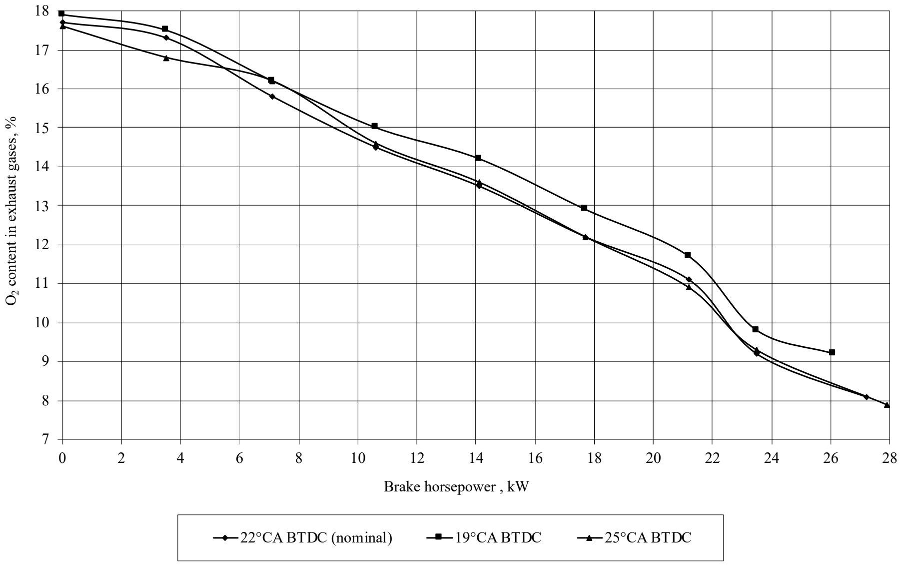

Figure 4. O_2 emission in exhaust gases as a function of brake horsepower of engine S-4003 at variable fuel delivery angles and the rotational speed of engine of 1600 rpm

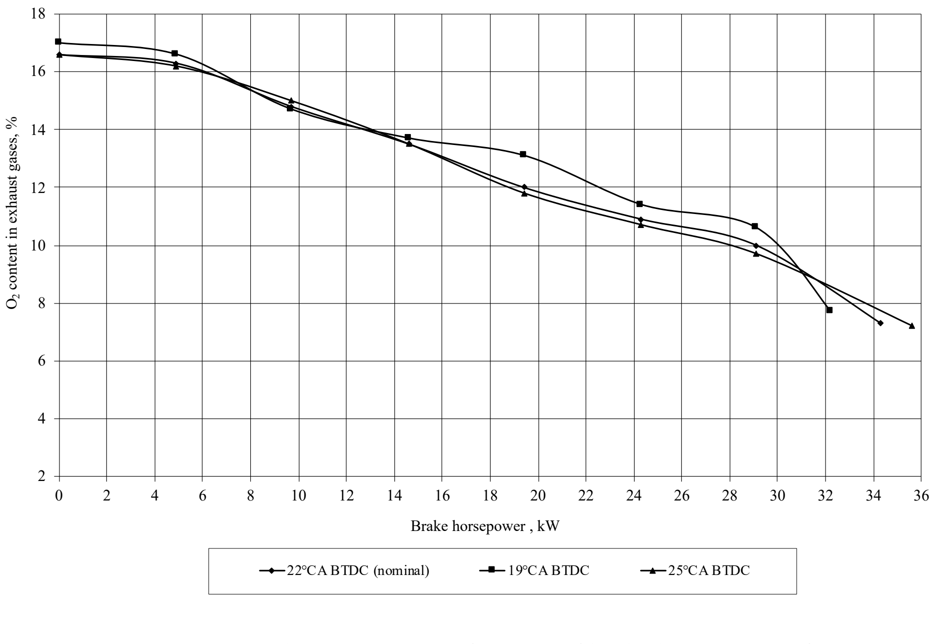

Figure 5. O_2 emission in exhaust gases as a function of brake horsepower of engine S-4003 at variable fuel delivery angle and rotational speed of engine 2200 rpm

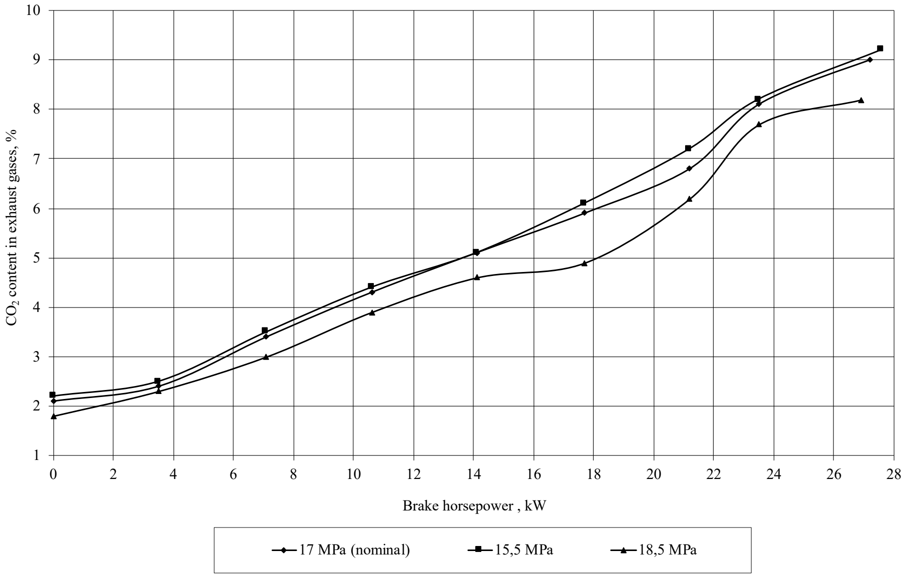

Figure 6. CO_2 emission in exhaust gases of brake horsepower of engine S-4003 at variable opening pressure of injectors and rotational speed of engine 1600 rpm

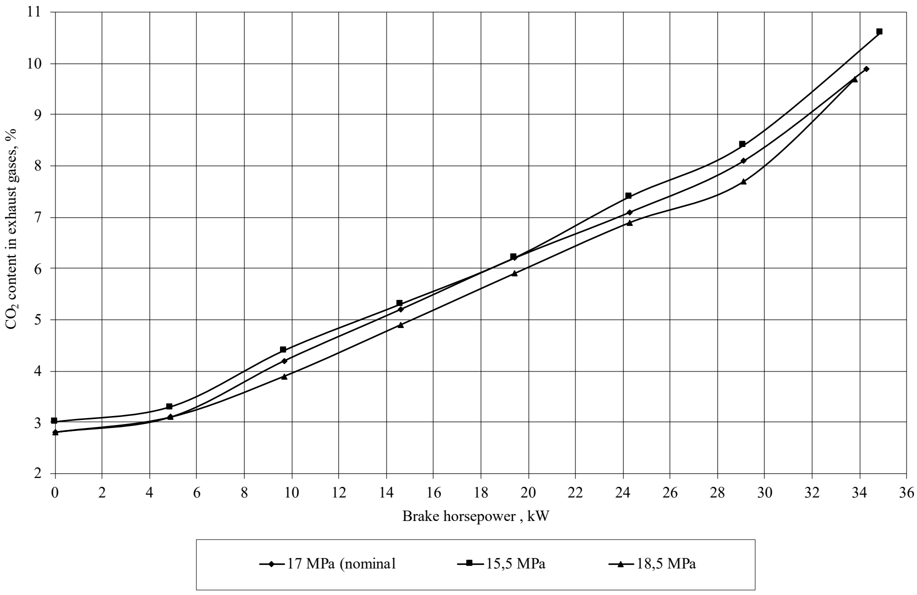

Figure 7. CO_2 emission in exhaust gases of brake horsepower of engine S-4003 at variable opening pressure of injectors and rotational speed of engine 2200 rpm

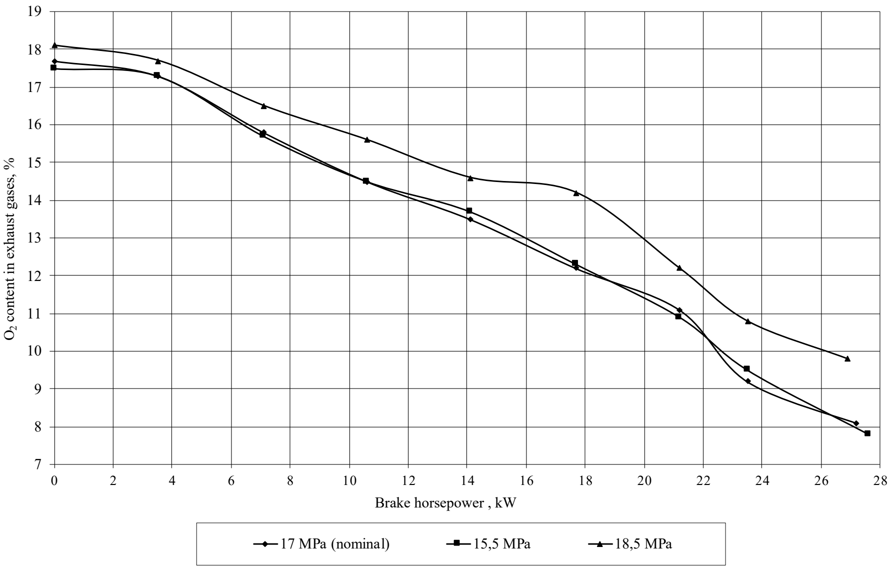

Figure 8. O_2 emission in exhaust gases as a function of brake horsepower of engine S-4003 at variable opening pressure of injectors and rotational speed of engine 1600 rpm

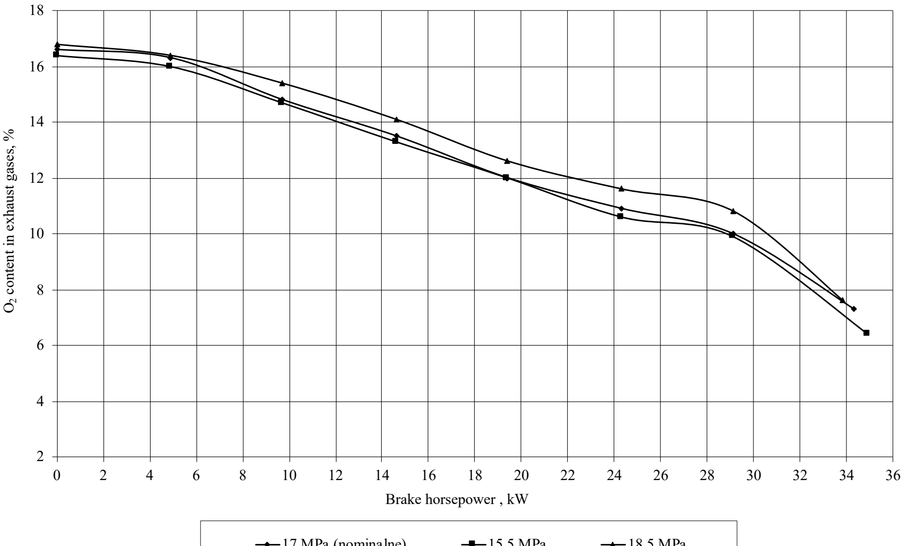

Figure 9. O_2 emission in exhaust gases as a function of brake horsepower of engine S-4003 at variable opening pressure of injectors and rotational speed of engine 2200 rpm

Engine S-4003 was subjected to tests of the exhaust gases composition in the aspect of variable opening pressure of injectors (pressure of fuel delivery). Figure 6 and 7 presents changes of CO_2 emission level for various opening pressures of injection (p_{ow}) during the engine operation with the rotational speed respectively of 1600 rpm and 2200 rpm whereas in fig. 8 and 9 – changes of O_2 emission level.

The opening pressure of injectors increased by 1.5 MPa in comparison to the nominal pressure (17 MPa) caused reduction of CO_2 concentration in exhaust gases of the investigated engine by 9.8% at the engine operation with the speed of 1600 rpm and by 4.5% at 2200 rpm (average values for all the measured values of brake horsepower – fig. 6 and 7). The reduced pressure of fuel delivery to the value of 15.5 MPa resulted in the increase of the CO_2 emission level for both rotational speeds of the engine on average in the entire range of load by 3% (1600 rpm) and by 4.4% (2200 rpm).

The effect of the reduced CO_2 emission at the increased pressure of the injection beginning (p_{ow} = 18.5 MPa) is the highest participation of O_2 in exhaust gases (Fig. 8 and 9). At the engine operation according to the load characteristics with the speed of 1600 rpm, the O_2 content in exhaust gases increased in the investigated range of power by 9.2% at the speed of 2200 rpm by 4.3% in comparison to the nominal value. Whereas, at the pressure p_{ow} = 15.5 MPa, reduction of O_2 concentration in exhaust gases reduced in comparison to the value of the nominal pressure on average by 0.5% (1600 rpm) and by 2.7% (2200 rpm).

Statistical analysis for all analysed cases proved that differences in means are not statistically significant (at the level of significance $\alpha = 0.05$). Similar dynamics of changes of the CO_2 and O_2 content in exhaust gases was reported.

The research on the influence of the selected control settings of a self-ignition engine on the ecological parameters of diesel engines, both in terms of the injection advance angle (Kowalek, 2016; Jiaqiang et al., 2018; Li et al., 2019) and injection pressure (Kowalek, 2014; Kumar et al., 2019; Ağbulut et al., 2020), was carried out for both conventional fuel (DF) and biofuels. The results of these tests indicate, as in this publication, a relatively small impact of the change of the injection advance angle (in relation to the nominal angle) on CO_2 emission, and more significant on the content of toxic exhaust gas components, such as: CO, NOx or PM. Subsequent exhaust emission tests will be conducted on modern agricultural engines, both in field conditions and in dynamometers.

Conclusions

A prevailing source of CO_2 emission from transport means are passenger cars with spark ignition. However, emissions that accompany field works with farm tractors cannot be disregarded. Although the basic methods of fighting the emission is the increase of performance of vehicles or a change of the used fuel, in case of farm tractors changes may be obtained through changes of control settings. The paper shows that the change of the selected control settings of a self-ignition engine of a farm tractor may influence the CO_2 emission level and in particular:

1. Delay in fuel injection proved to be favourable from the point of view of CO_2 emission in exhaust gases of the investigated engine. Ca. 5% of its decrease in comparison to the nominal angle of the fuel delivery (fuel injection advance) was reported.

2. The accelerated fuel injection (by 3° of crankshaft rotations) in comparison to the nominal value resulted in the increase of the CO_2 emission level within 2-4% for both performed rotational speeds of the engine.
3. In case of O_2 emission in exhaust gases a contrary trend occurs. For the angle $\alpha_{PT} = 19°$ of crankshaft rotations, the O_2 concentration in exhaust gases increased by 3-5% and for the angle $\alpha_{PT} = 25°$ of crankshaft rotations decreased by ca. 1% compared to the nominal value.
4. A few-percent increase of the CO_2 concentration in exhaust gases was reported for the reduced opening pressure of injectors and reduction of its level for the increased pressure in comparison to the nominal value (on average by ca. 10% at the speed of the maximum torque of the engine).
5. The impact of the change of pressure of fuel delivery on O_2 emission is contrary to CO_2 emission, achieved differences between mean values in comparison to nominal parameters are similar.
6. It was stated that both the delay of fuel delivery and as a result of fuel injection as well as the increase of the opening pressure of injectors in comparison to the nominal settings caused the reduction of the brake horsepower (visible in characteristics at a full load of engine) – by 5.1% for the angle α_{PT} = 19° of crankshaft rotations and by 1.3% for p_{ow} = 18.5 MPa (mean values for the performed loads and rotations of the engine). For the remaining settings, different from nominal ones, a contrary trend was obtained i.e., increase of the engine power was obtained, on average by 3.2% (α_{PT} = 25°of crankshaft rotations) and by 1.6% (p_{ow} = 18.5 MPa).

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OCENA POZIOMU EMISJI CO_2 PRZEZ SILNIK CIĄGNIKOWY PRZY RÓŻNYCH NASTAWACH REGULACYJNYCH APARATURY PALIWOWEJ

Streszczenie. W pracy zaprezentowano wyniki badań eksperymentalnych poziomu emisji CO_2 silnika wysokoprężnego S-4003 ciągnika rolniczego Ursus C-360, przy zmiennym kącie wyprzedzenia wtrysku i ciśnieniu otwarcia wtryskiwaczy. Pomiary wykonano na stanowisku dynamometrycznym w hamowni silnikowej. Silnik pracował według charakterystyki obciążeniowej przy dwóch charakterystycznych prędkościach obrotowych, tj. przy prędkości maksymalnego momentu obrotowego (1600 rpm) oraz przy prędkości znamionowej (2200 rpm). W każdym punkcie pomiarowym charakterystyk obciążeniowych mierzono stężenie CO_2 w spalinach, przy wykorzystaniu analizatora spalin typu M-488 Multigas Plus. W celu pełniejszej analizy zawartości CO_2 w spalinach, przedstawiono dodatkowo zmianę poziomu emisji O_2, który w największej ilości wiąże węgiel elementarny zawarty w paliwie podczas spalania. Badania wykazały spadek zawartości CO_2 w spalinach przy zmniejszonym (o 3° OWK) kącie wyprzedzenia wtrysku w stosunku do kąta nominalnego, o 4,5% przy prędkości obrotowej 1600 rpm i o 5,7% przy prędkości 2200 rpm (wartości średnie dla wszystkich punktów pomiarowych obciążenia – mocy efektywnej silnika). Podobnie spadek koncentracji CO_2 w spalinach badanego silnika zanotowano dla podwyższonego (o 1,5 MPa) ciśnienia otwarcia wtryskiwaczy w stosunku do ciśnienia nominalnego, średnio o 9,8% dla prędkości maksymalnego momentu obrotowego i o 4,5% dla prędkości znamionowej.

Słowa kluczowe: poziom emisji CO_2, silnik ciągnikowy, nastawy regulacyjne aparatury paliwowej, hamownia silnikowa, charakterystyki obciążeniowe