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LABORATORY STUDY ON INFLUENCE OF THE EXHAUST DUCT THROTTLING ON EXHAUST GAS COMPOSITION IN MARINE FOUR-STROKE DIESEL ENGINE

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Abstract

Presented paper shows results of laboratory tests on the relationship between the throttling of a cross area of an exhaust outlet duct and the composition of exhaust gas from the marine engine. The object of research is a laboratory four-stroke diesel engine, worked with a load from 50kW to 250kW at a constant speed equal 750rpm. During the laboratory tests over 50 parameters were measured of the engine with technical condition recognized as a "working properly" and with simulated the exhaust outlet duct throttling. The simulation consisted of changing the angle of the barrier mounted in the exhaust duct after the turbine, limiting duct cross-sectional area. Results of laboratory research confirm that the best indicator of the throttling of the exhaust gas duct among considered thermodynamic parameters of the engine is pressure of exhaust gas after turbine. Unfortunately mentioned pressure is usually very little and for this reason technically difficult to measure during on-board operation. In the case of measuring the composition of exhaust gas, the throttling of the exhaust gas duct causes visible changes of the oxygen and carbon oxide quantity in the exhaust gas. Other measured gaseous components changed not significant during the throttling of the exhaust gas. The conclusion is that the results of measurements of the composition of exhaust gas may contain valuable diagnostic information about the technical condition of the exhaust gas duct of the marine engine.

Keywords: *marine diesel engine, exhaust gas composition, toxic emission, laboratory investigation, exhaust gas duct throttling*

1. Introduction

Diesel four-stroke engines used in marine applications must complying requirements of economic operation and environmental regulations. Necessary for this purpose is the preparation and delivery to the engine cylinders homogeneous combustible mixture in the whole engine load. Operation of the engine causes, in time, the deterioration of its work efficiency, due to various kinds of disability. These failures result in deterioration of the combustion process in engine cylinders. The effect of this situation is increased fuel consumption and changes in exhaust gas composition emitted from the marine engine [1 – 3]. Due to not effective combustion process of mixture in cylinders the composition of exhaust gas is changed [4 –7].

The fuel dose injected to the engine cylinder is fragmented and evaporated. After mixing the evaporated fuel with air the combustion process is started. Burning process causes changes in the air-fuel mixture with rotation of the crankshaft, the engine load and speed, and the technical condition of engine components and systems. Solid particles contained in the air and soot from the exhaust gas can cause damage to the turbine blades, the exhaust gas duct and other components of the engine charging system. This causes the exhaust gas duct throttling and changes in the parameters of the combustion process. The effect of these may be change composition of exhaust gas also.

The paper presents results of experimental studies on the effects of the throttling the cross area of the engine exhaust gas duct on the composition of exhaust gas.

2. Laboratory stand

The object of study is 3-cylinder, four-stroke, laboratory engine type AL25/30 Cegielski-Sulzer manufacturer, installed in the Laboratory of Internal Combustion Engines in Gdynia Maritime University. This engine is loaded with generator, electrically connected to the water resistance and supercharged by VTR 160 Brown-Boveri turbocharger. During tests the engine was fuelled by diesel oil and worked at a constant speed, equal to 750rpm. There were measured 56 parameters of the laboratory stand including the engine load and speed, parameters of the turbocharger, systems of cooling, fuelling, lubricating, and air exchange. The composition of exhaust gas was also recorded using electrochemical gas analyser. Pressure, temperature and humidity of air were recorded by laboratory equipment also. All mentioned results were recorded with a sampling time of 1 second. Injection pressures and pressures of combustion in all cylinders of the engine were also collected. Scheme of the laboratory stand is presented in Fig.1 and the engine parameters are presented in Tab.1.

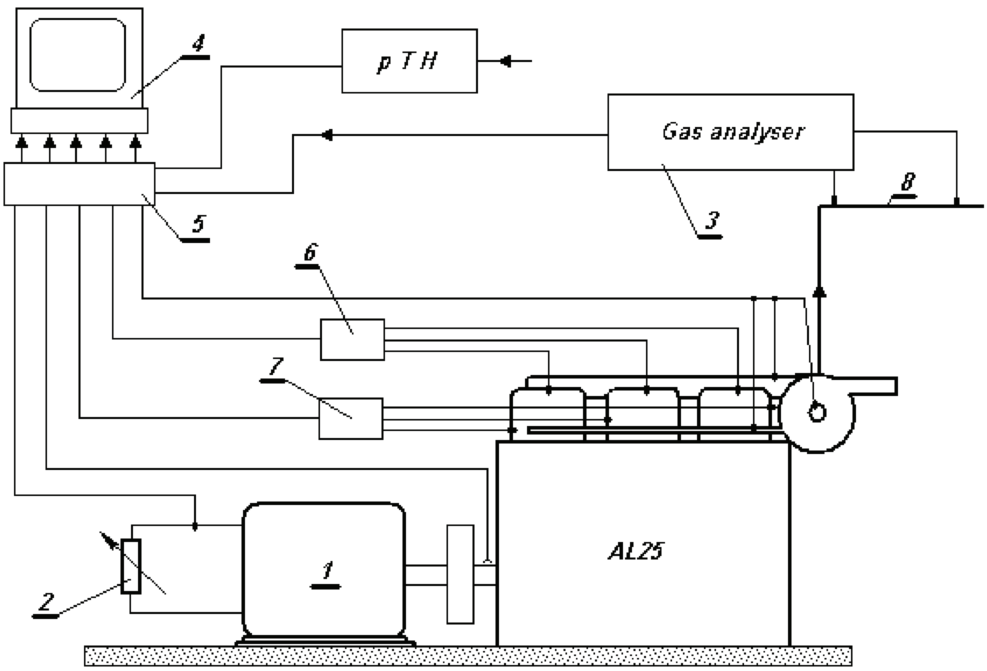

Fig.1. Laboratory stand scheme. 1 – generator, 2 – water resistance, 3 – gas analyser, 4 – computer, 5 – A/C converter, 6 – combustion pressure indicator, 7 – injection pressure indicator, 8 – exhaust gas duct

Tab.1. Parameters of the Al25/30 engine

Parameter	Value	Unit
Max Power	250	kW
Rotational speed	750	rpm
Bore diameter	250	mm
Piston stroke	300	mm
Compression ratio	12,7	–

During each start of observation, the engine was loaded to maximum load equal 250kW, and after stabilizing temperature of exhaust gas after the turbine, engine operating parameters were recorded for 3 to 5 minutes. After this the load of the engine was decreased by 10kW and after stabilizing temperature of exhaust gas after the turbine, engine operating parameters were recorded again. Observation was continued with loads up to 50kW. The engine did not work with a load of 190kW due to resonance vibrations.

3. Results and discussion

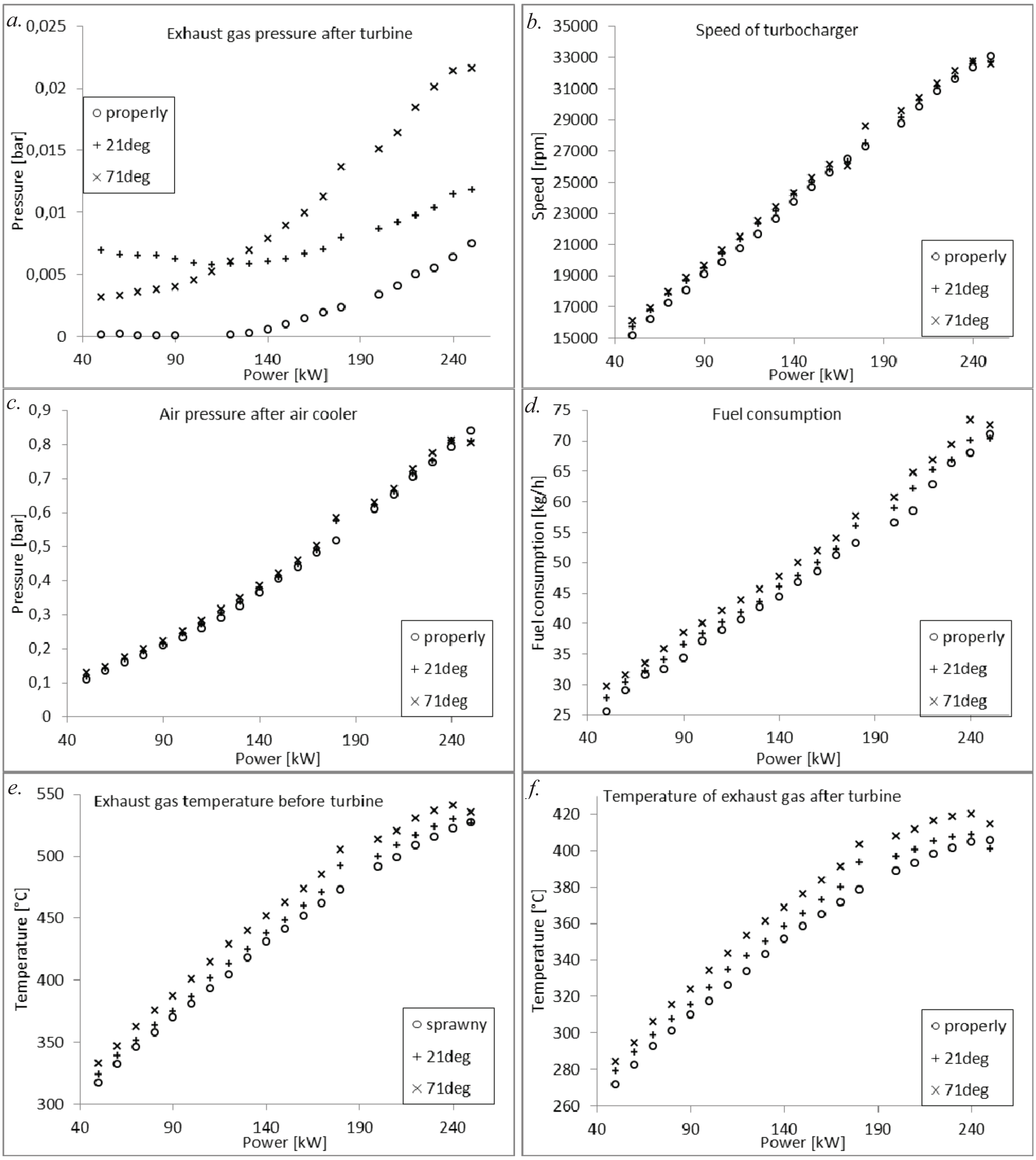

Fig.2. Thermodynamic changes during the throttling of the exhaust duct: a. Exhaust gas pressure after turbine, b. Speed of turbocharger, c. Air pressure after air cooler, d. Fuel consumption, e. Exhaust gas temperature before turbine, f. Temperature of exhaust gas after turbine

Presented laboratory study consists of 3 stages:

- first stage consists of 4 observations during operation of the engine assumed as “working properly”,
- second stage consists of 3 observations during operation of the engine with the throttling of the cross area of the exhaust gas duct by changing the barrier angle mounted in the exhaust gas duct after the turbine by 21 degrees,
- third stage consists of 3 observations during operation of the engine with the throttling of the cross area of the exhaust gas duct by changing the barrier angle mounted in the exhaust gas duct after the turbine by 71 degrees.

Scheme of the throttling of the cross area of the exhaust gas duct is presented in Fig. 2.

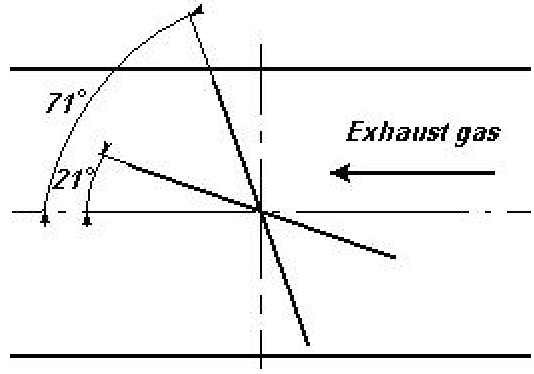

Fig.3. Scheme of the throttling of the cross area of the exhaust gas duct

Presented results are average values for individual engine loads and observations.

3.1 Thermodynamic changes

The throttling of the cross area of the exhaust gas duct decreases pressure of exhaust gas after turbine and increases its temperature before and after turbine. Fig.2a shows visible changes of exhaust gas pressure. According to results presented in Fig.2e and Fig.2f temperature of exhaust gas before and after turbine increases average of 2% for the throttling with angle 21deg. and 5% for the throttling with angle 71deg. Changes in temperature and pressure of exhaust gas are so insignificant that there do not affect the speed of turbocharger. Mentioned speed is presented in Fig.2b. Lack of changes in speed of turbocharger takes effect no changes in pressure of air, delivered to the engine. Pressure of air after air cooler is presented in Fig.2c. Abnormalities in the combustion process causes growth of fuel consumption. Figure 2d shows measured fuel consumption for all considered states of the engine. The throttling of the exhaust gas duct by change of the barrier angle by 21deg. causes average increase of fuel consumption by 3,7% and 8,2% for changing the barrier angle by 71deg respectively. It should be noted that the fuel consumption is very important parameter from an economic point of view but in a practical marine applications very difficult to measure.

Assuming the measuring thermodynamic parameters are not enough to indicate abnormal throttling of the exhaust gas duct. According to presented results best indicator of the throttling of the exhaust gas duct among considered thermodynamic parameters of the engine is pressure of exhaust gas after turbine. Unfortunately mentioned pressure is usually very little and for this reason technically difficult to measure during on-board operation.

3.2 Exhaust gas composition changes

Figure 4a presents oxygen mole fraction in exhaust gas. According to presented results increasing the throttling of the exhaust gas duct decreases mole fraction of oxygen in exhaust gas.

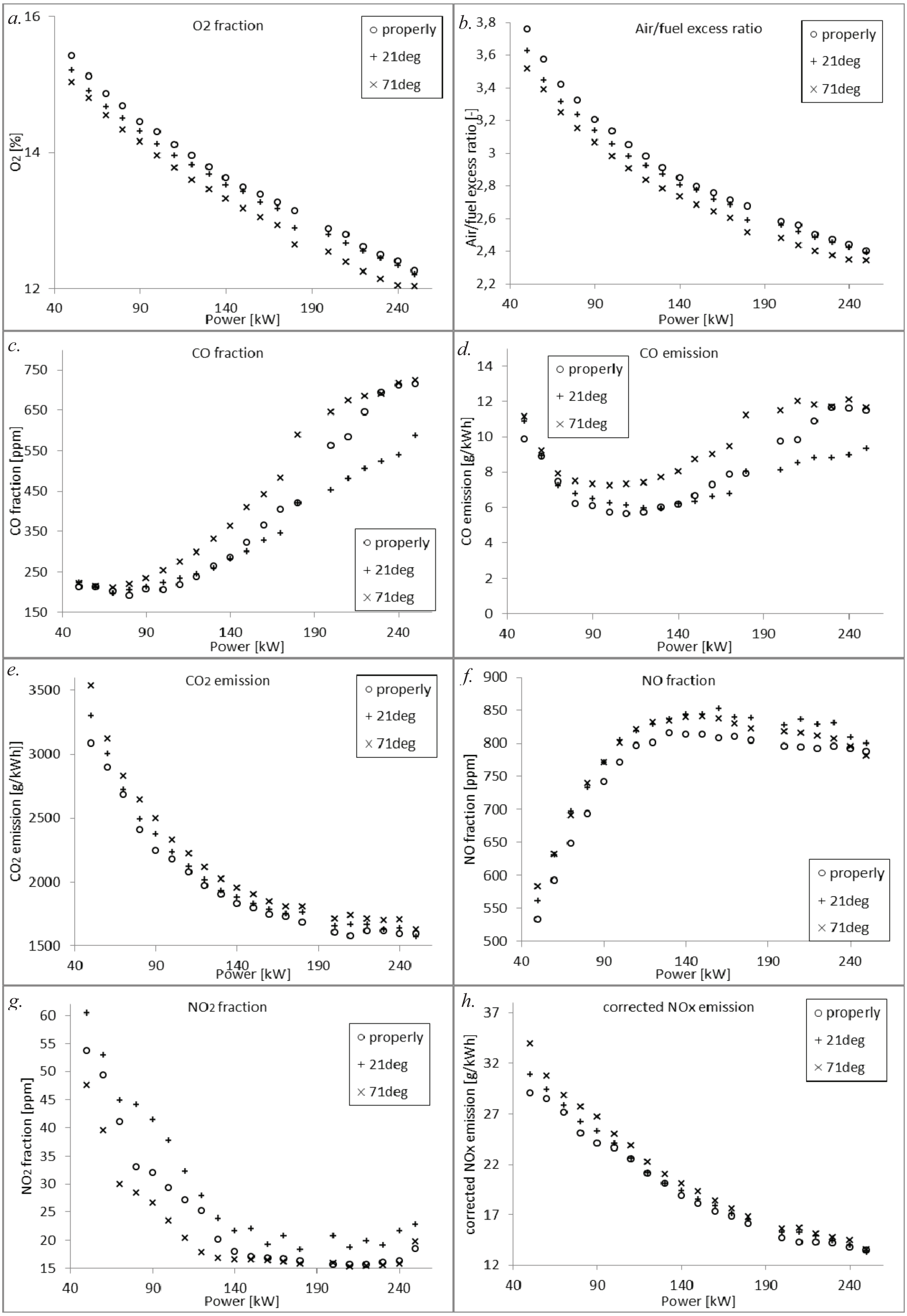

Fig.4. Exhaust gas composition: a. Oxygen fraction, b. Air-fuel excess ratio, c. Carbon oxide fraction, d. Carbon oxide emission, e. Carbon dioxide emission, f. Nitric oxide fraction, g. Nitric dioxide fraction, h. Corrected nitric oxides emission

It means that though not changed pressure of air after air cooler (Fig.2c) and turbocharger speed (Fig.2b) the quantity of air delivered to the engine decrease. The reason of this situation is increasing temperature of air. Simultaneously with this phenomenon the quantity of delivered fuel is increase. The effect of this is combustion richest mixtures in cylinders. The confirmation of this state of affairs is decreasing of air-fuel excess ratio. Figure 4b presents dependences between calculated air-fuel excess ratio and the load of the engine in the different throttling of the exhaust gas duct.

The air-fuel excess ratio was calculated according to the following dependence:

$$\lambda = \frac{21\%O_2}{21\%O_2 - U_{O2}}, \quad (1)$$

where:

λ – air-fuel excess ratio [-],

$21\%O_2$ – mole fraction of oxygen in air,

U_{O2} – mole fraction of oxygen in exhaust gas.

Similarly to earlier presented results the air-fuel excess ratio decreases average by 1,8% for the 21deg. angle of barrier in the exhaust gas duct. The 71deg. angle of barrier in the exhaust gas duct causes decreasing of the air-fuel excess ratio average by 4,5%. The effect of the throttling is more apparent in high load conditions. Decreasing among of air delivered to engine cylinders causes the combustion process of a mixture consisting of more fuel. This situation promotes extension of the combustion process in time [8]. The effect of this is increasing the exhaust gas temperature after and before the turbine (Fig.2e and Fig.2f).

As mentioned earlier during the throttling of the cross section area of the exhaust gas duct the richest mixture is combusted in engine cylinders. This phenomenon takes effect of deteriorations in the combustion process and changes with carbon oxide fractions in exhaust gas. Figure 4c shows dependences between the mole fraction of carbon oxide in exhaust gas and load of the engine and the throttling of the exhaust gas duct. The exhaust gas duct throttling causes increasing of mole fraction of carbon oxide in low loads of the engine. The maximum load of the engine decreases of mentioned mole fraction. The effect of decreasing of carbon oxide mole fraction is most visible during the little throttling. It means that the efficiency of the combustion process is changed with the load of the engine [9]. Figure 4d presents a level of carbon oxide emission from the engine for all considered loads of the engine and all considered states of malfunctions. Levels of emission of all mentioned chemical compounds of exhaust gas are calculated according to ISO 8178 standard regulations [10]. According to presented results the low throttling of the exhaust gas duct take effect low increase of carbon oxide emission in low loads of the engine. Average increase is 4,5%. Working the engine in loads from 140kW to 250kW decreases the carbon oxide emission level average by 14%. It should be noted that the throttling of the exhaust gas duct takes effect of changing the shape of both the carbon oxide mole fraction and the emission from the engine according to results from the “worked properly” engine. It means that the high throttling of the exhaust gas duct causes increasing of the carbon oxide emission level average for 5,1% for very low and very high loads of the engine and average for 26% for loads of the engine between 80kW and 210kW.

Increasing the dose of fuel delivered to the combustion process increases carbon dioxide fraction in exhaust gas [9]. Decreasing of the engine load and increasing of the throttling of the exhaust gas duct increase the carbon dioxide emission from the engine. Fig.4e presents the calculated emission level of carbon dioxide from engine. According to presented dependences the low exhaust gas duct throttling increases the level of carbon dioxide emission average by 3% in all considered loads of the engine. More appearance effects are in the higher throttling conditions.

The high throttling causes increasing of the carbon dioxide emission level average by 7%. Obtained results are compatible with results of increasing fuel consumptions (Fig.2d).

Figures 4f and 4g present dependence of the engine load on the mole fractions of nitric oxide and nitric dioxide in exhaust gas respectively. Low load of the engine take effect minimal fraction of nitric oxide and maximum fraction of nitric dioxide. During increasing load of the engine nitric dioxide mole fraction decreases but nitric oxide mole fraction increases. The relation between nitric oxides and nitric dioxides is like 8 to 1 in low loads of the engine and increases to 1 to 40 for high loads of the engine. Obtained results are qualitatively consistent with other results [6]. According to presented dependences the 21deg. throttling of the exhaust gas duct increases both the nitric oxide and nitric dioxide mole fraction in exhaust gas. Observed average increasing is 4,3% for nitric oxide and 21,4% for nitric dioxide respectively. The 71deg. throttling of the exhaust gas duct take different effect. During the high throttling nitric oxide increases average by 4% (similar to the 21seg. throttling) but at the same time mole fraction of nitric dioxide decreases in exhaust gas by 10% average for all considered loads of the engine. The explanation of this phenomenon is great changes in the combustion process. It's possible that changes of the throttling of the exhaust gas duct causes changing in chemical reactions during the combustion process. It should be noted that mole fractions of chemical compounds in exhaust gas not depends on an exhaust gas flow rate.

Fig.4h shows dependences between a corrected nitric oxides emission and the load of the engine and the throttling of the exhaust gas duct. The nitric oxides emission, calculated from a sum of nitric oxide and nitric dioxide mole fractions, depends not only on parameters of the working engine but on parameters of surrounded the engine air. Mentioned parameters are temperature, pressure and humidity of air. According to ISO 8178 standard regulations measured parameters of air for the nitric oxides correction are:

- pressure – 101,3kPa,
- temperature – 25°C,
- humidity – 10,71g_{H2O}/kg of air.

According to mentioned European Standard all emissions of nitric oxides from diesel engines measured in other air conditions must be corrected to standard parameters by using the correction formulas. The dependencies from Fig.4h show that, despite results presented in the Fig.4f and Fig.4g, increase the throttling of the exhaust gas duct increases the emission level of nitric oxides for all considered loads of the engine. Increasing of the load of the engine decreases the level of corrected nitric oxides emission. Changes of the nitric oxides emission with the throttling of the exhaust gas duct are little visible. For the 21deg. throttling the average increase of the nitric oxides emission is 2,7% and for the 71deg.% throttling the nitric oxides emission increases average by 6,7%.

Presented results show that the throttling of the exhaust gas duct causes visible changes of the oxygen and carbon oxide quantity in exhaust gas. Other measured gaseous components changed not significant during the throttling of the exhaust gas.

4. Conclusions

The paper presents results of laboratory tests carried out on the four-stroke diesel engine for marine applications. The study consisted in determining the impact of the throttling of the exhaust gas duct on the engine operating parameters including the composition of exhaust gas. The obtained results allow concluding that the measuring thermodynamic parameters are not enough to indicate the abnormal throttling of the exhaust gas duct. According to presented results best indicator of the throttling of the exhaust gas duct among considered thermodynamic parameters of the engine is pressure of exhaust gas after turbine. Unfortunately mentioned pressure is usually very little and for this reason technically difficult to measure during on-board operation.

Presented results of exhaust gas composition show that the throttling of the exhaust gas duct causes visible changes of the oxygen and carbon oxide quantity in exhaust gas. Other measured gaseous components changed not significant during the throttling of exhaust gas.

Obtained results allow concluding that the composition of exhaust gas can give with its image important diagnostic signals about the technical condition of the engine exhaust gas duct.

Acknowledgments

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References

[1] Kowalski J., *Laboratory study on influence of air duct throttling on exhaust gas composition in marine four-stroke diesel engine*, Journal of Kones Powertrain and Transport, Vol. 19, No 1, pp. 191 – 198, Warsaw 2012.
[2] Kowalski J., *Wpływ wybranych niesprawności układu paliwowego na skład emitowanych spalin z czterosuwowego silnika okrętowego*, Zeszyty Naukowe Nr. 178A AMW w Gdyni, Wydawnictwo AMW w Gdyni, str. 133 – 138, Gdynia 2009.
[3] Kowalski J., *Wpływ wybranych niesprawności układu doładowania na skład emitowanych spalin z czterosuwowego silnika okrętowego*, Zeszyty Naukowe Nr. 178A AMW w Gdyni, Wydawnictwo AMW w Gdyni, str. 139 – 144, Gdynia 2009.
[4] Hountalas D.T., Kouremenos A.D., *Development and application of a fully automatic troubleshooting method for large marine diesel engines*, Applied Thermal Engineering, Vol. 19, pp. 299-324, Elsevier 1999.
[5] Hountalas D.T., *Prediction of marine diesel engine performance under fault conditions*, Applied Thermal Engineering, Vol. 20, pp. 1753-1783, Elsevier 2000.
[6] Kuo K.k., *Principles of combustion,* Willey & Sons Inc., New Jersey 2005.
[7] Poinsot T., Veynante D., *Theoretical and numerical combustion,* Edwards 2005.
[8] Kluj S., *Diagnostyka urządzeń okrętowych,* Studium Doskonalenia Kadr S. C. WSM, Gdynia 1995.
[9] Heywood J. B., *Internal Combustion Engine Fundamentals*, McGraw-Hill 1988.
[10] ISO 8178 - *Reciprocating internal combustion engines*.