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An experimental study of emission and combustion characteristics of marine diesel engine with fuel pump malfunctions

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HIGHLIGHTS

- Chosen malfunctions of the fuel injection pump of marine engine are simulated.
- Changes of thermodynamic parameters of marine engine are analyzed.
- Changes of CO, CO_2 and NOx emission characteristics of marine engine are analyzed.
- Injection pump malfunctions take significant changes in emission characteristics.

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ABSTRACT

Presented paper shows the results of the laboratory study on the relation between the chosen malfunctions of a fuel pump and the exhaust gas composition of the marine engine. The object of research is a laboratory four-stroke diesel engine, operated at a constant speed. During the research over 50 parameters were measured with technical condition of the engine recognized as "working properly" and with simulated fuel pump malfunctions. Considered malfunctions are: fuel injection timing delay and two sets of fuel leakages in the fuel pump of one engine cylinder. The results of laboratory research confirm that fuel injection timing delay and fuel leakage in the fuel pump cause relatively small changes in thermodynamic parameters of the engine. Changes of absolute values are so small they may be omitted by marine engines operators. The measuring of the exhaust gas composition shows markedly affection with simulated malfunctions of the fuel pump. Engine operation with delayed fuel injection timing in one cylinder indicates CO_2 emission increase and NOx emission decreases. CO emission increases only at high the engine loads. Fuel leakage in the fuel pump causes changes in CO emission, the increase of CO_2 emission and the decrease of NOx emission.

1. Introduction

In classic technical solution of a ship engine room a few diesel engines are installed. One or more diesel engines are installed as a main propulsion. Usually there are low speed, two-stroke diesel engines operated with fixed pitch propeller [1], or medium speed, 4-stroke diesel engines, operated at constant speed (with variable pitch propeller). Moreover, there are 2 or more power generators and one emergency power generator on the ship engine room. The power generator usually contains medium speed, 4-stroke diesel engine, operating at a constant speed. Other design solutions are encountered, e.g. based on a gas or steam turbine or electric motor with power generators. However, they are rarely used because of the lower energy efficiency of this type of systems. The marine internal combustion engines are the turbocharged diesel engines with direct fuel injections to cylinders, fueled with marine diesel oil or heavy fuel oil. A fuel delivery system of such engine consists of mechanically controlled Bosh type fuel pump and injectors with multi-hole nozzle type [2]. The first Common Rail system in marine, medium speed 4-stroke diesel engine was installed in 2001. It should be noted that in the year 2011 more than 50% of the fleet in the world had been older than 15 years (over 42.5 thousands ships above 100 gross tonnage) [3].

Operation of a marine engine causes its condition changes and decreases its efficiency. The effect of this is toxic compounds emission changes. It should be noted that the average main propulsion marine engine (nominal power equal 10 MW) emits over 3 tons of nitric oxides (NOx) per 24 h to the atmosphere, even if they meet the emission standards. A change of the technical condition, arising from the wear of engine components, causes general

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Nomenclature:

NOx	nitric oxides
CO	carbon oxide
CO_2	carbon dioxide
SFC	specific fuel consumption [g/kWh]
EGR	exhaust gas recirculation
MIP	mean in-cylinder pressure
λ	air/fuel excess ratio

deterioration of fuel spray condition [4], fuel vaporization and fuel combustion in engine cylinders. The effect of these phenomena is the increase of fuel consumption and thus the increase of carbon oxide (CO) and carbon dioxide (CO_2) emissions. The increase of fuel consumption (carbon content in fuel equals 0.35 in a molar [2]) by 1% (1.9 g/kWh) causes the increase of CO_2 emission from mentioned 10 MW power output engine by 7 tons per 24 h. Note, that presented fuel consumption change is difficult to detect in practice. The reason for this is the methodology of fuel consumption measuring on board. The standard method of fuel consumption measure is periodically checking the amount of fuel in ship tanks. It should be noted that fuel is stored on board in several tanks with overall volume often excess 100 m^3 and the fuel volume in the fuel tanks depends of all on board engines fuel consumption and temperature in fuel tanks.

Relatively small changes in the efficiency of marine engines are not being detected by the ship automation systems also. Mentioned systems of mechanical and thermodynamic parameters of the engine are set to alarm only at the extreme values. Extreme parameter values usually appear during the engine load close to the nominal or minimum. Engine generators on board usually work at partial loads. The reason for this is safety. Otherwise, a temporary increase of the demand for electric power on the ship could cause the engine overload. Presented set of automatic systems on the ship is justified by the efficiency of the ship operation. Automatic systems alert the ship's crew only in case of a significant change in mechanical and thermodynamic parameters of the engine. Only such changes should oblige to carry out repairs. Each repair increases general cost of ship operation. The effect of this approach is the situation where marine engines are being operated for a long period of time with reduced performance, resulting in a significant increase of toxic compounds emission. Therefore, it is necessary to know the impact on damage of various functional systems of marine engine not only to the mechanical and thermodynamic parameters, but the emission of toxic compounds also. Unfortunately, there are relatively few data on this subject in the literature.

Deteriorations in the combustion process cause significant changes not only in thermodynamic parameters of the engine but also in emission characteristics also. According to results, presented in Ref. [5] process of preparing the combustion mixture in the cylinder is critical for the level of toxic emissions and engine efficiency. The indirect injection causes decrease of the NOx and CO fractions in exhaust gas but decrease of the engine efficiency. Generally the delay of the injection timing causes decrease of the combustion temperature and NOx mole fractions in the engine cylinder [6] and NOx emission in exhaust gas [7]. The result of this is increase of the CO fractions. Asad et al. [8] proposed fuel injection timing control algorithm to heat release optimization for small diesel engine with common rail and EGR systems. This trend is visible in different engine constructions; in the low heat release engines [9] with pistons coated with ceramic materials and heavy duty engine with common rail system [10]. According to results, presented in Ref. [11] the NOx emissions decrease for very early injection (38° before top dead center of the crankshaft position). The reason of these phenomena could be the decrease of heat release rate [7]. It should be noted that delaying of the injection fuel increases soot emission [12,13]. Commonly used strategy is the fuel multiple injection. This strategy was studied in Refs. [14,15]. According to presented results the early pilot fuel dose injection causes decrease of NOx, CO and soot emission in exhaust gas and heat release rate also. In 2004 Lindgren et al. [16] showed the emission characteristics of toxic compounds from two diesel engines (low nominal power compared to power of marine engines) operated in transient conditions. The results showed that transients in engine speed and torque in most cases increase the fuel consumption and emission amounts.

The NOx emission characteristic of the engine depends on humidity of air. The experimental investigations results of diesel combustion with water emulsion [17] show that the 20% addition of the water steam to the air inlet duct decreases the NOx and CO_2 fractions in exhaust gas but increases the CO fraction in overall the engine speed condition. Similar results are reported in Refs. [18,19] for 10% and 15% of the steam water addition.

The influence of the fuel properties on the engine emission characteristics was extensively studied. According to [20] increasing diesel fuel cetane number gives earlier ignition with less time for pre-ignition mixing and lower level of the NOx emission.

Only Ref. [20] of the presented relation to the medium speed diesel engines which parameters are close to parameters of marine engines. It should be noted, that a lot of works about combustion and emission from the diesel engines can be find in the scientific literature. Mentioned works concerns, however, small engines used in on road and off-road vehicles. Marine engines have a different design and a different the combustion process organization.

The most important differences are: a low speed, a lengthened stroke, a shortened angle of fuel injection, and an extended the combustion process into the expansion stroke. These differences mean that the conclusions from the experimental studies on small engines are not applicable for large marine engines.

Lack of new research activities concerning the impact of the marine diesel engine malfunctions on emissions forced the author to undertake the research work. The main goal of the manuscript is finding qualitative dependences between the selected malfunctions of marine diesel engine fuel pump and change of both thermodynamic parameters and toxic emissions. Mentioned dependences may be useful to looking for the signals to recognize the malfunctions of the engine during on board operation.

This paper presents the results of laboratory tests on the effects of selected fuel pump malfunctions on the level of emissions.

2. Laboratory setup and procedure

The study were carried out using a marine, 3-cylinder, four-stroke, direct injection diesel engine type AL25/30 Cegielski–Sulzer manufacturer with an intercooler system, installed in Laboratory of Internal Combustion Engines in Gdynia Maritime University. The engine was loaded with a generator electrically

Table 1
Diesel fuel oil properties.

Parameter	Value	Unit
Density at 15 °C	827.3	kg/m^3
Kinematic viscosity at 40 °C	2.636	mm^2/s
Cetane number	53.2	–
Sulfur content	3.8	mg/kg