THE INFLUENCE OF LIQUID VISCOSITY ON ATOMIZED FUEL MEAN DROPLET SIZE DETERMINED BY THE LASER DIFFRACTION METHOD

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Abstract. The article presents the impact of viscosity of fuel on its atomization, which constitutes an important element of controlling the quality of the fuel-air mixture in compression ignition and direct injection engines. An experiment has been made using a three-hole atomizer of an engine with nominal power of 110 kW and revolutions n = 2800 min^{-1}. Fuel was delivered by a PRW-2M injection pump intended for testing injectors. Fuel was sprayed in the atmospheric air. Three petroleum product liquids used for the experiment had a viscosity of, respectively, 3.93, 16.73 and 36.41 mm^2/s. The fuel droplet size in a spray was determined by the laser diffraction method by means of a Spraytec STP 5929 analyzer. The quantity adopted for comparative purposes was the Sauter Mean Diameter D32. The results confirmed that a change of fuel viscosity within the range recommended by ship engine manufacturers has a strong impact on the size of sprayed fuel droplets. Shipowners have a limited choice of low sulphur fuel grade (up to 0.1% S), which forces the engine room personnel to use currently available fuels. Depending on the supplier, marine fuels may vary in viscosity and, according to the recommendations of engine manufacturers, they do not require heating. The increase in the size of the droplets injected into the fuel combustion chamber may affect the quality of the fuel-air mixture, increase of fuel consumption and a greater content of harmful exhaust constituents.

Keywords: marine diesel engine, fuel viscosity, fuel atomization

INTRODUCTION

Emissions of harmful components of compression ignition engines are a serious issue for the natural environment. Pollutants come from vessels powered by compression ignition engines, especially in ports and areas with heavy vessel traffic.

The composition of engine exhaust gases depends on physic-chemical properties of the fuel used and the arrangement of the combustion process in the engine combustion chamber. The necessary condition for creating a fuel-air mixture of required quality is to spray fuel into droplets with specific microstructure (droplet diameters) and macrostructure (spread angle and spray penetration). The shape of the spray should be suited to the dimensions of the combustion chamber, i.e. to fill it as much as possible, provided that the fuel droplets do not reach the walls of the chamber, particularly the cylinder liner.

Parameters of fuel spray atomized in the combustion chamber of a compression ignition engine with direct injection depend on a number of engine design and operational factors (Argyros el at., 2014, Zabłocki, 1976). The design parameters relate primarily to the drive of injection pumps, its construction, adjustment of fuel dose and injection pressure, as well as the injector construction including its most essential element, the atomizer. The atomizer has a specific number of nozzles of characteristic dimensions (diameter, shape and length). The number, shape and cross sections of atomizer nozzles and injection pressure are designed for the nominal dose of the specific fuel grade. The operational factors with the greatest influence on the atomization parameters (injection pressures and air pressure in the combustion chamber) are the engine rotary speed and load.

The impact of physical characteristics of the liquid on the droplet size is apparent in the criterial numbers of the atomization phenomenon, such as Reynolds number Re, Ohnesorge number Oh and Weber number We.

$$Re = \frac{w_f d_o \varrho_f}{\eta_f} \qquad Oh = \frac{\eta_f}{(\varrho_f \sigma d_o)^{0,5}} \quad We_A = \frac{w_f^2 d_o \varrho_A}{\sigma} \tag{1}$$

where:
w_f - fuel discharge velocity from the nozzle, m/s;
d_o - diameter of atomizer nozzle, m;
ϱ_f – fuel density, kg/m^3;
σ – surface tension of fuel, Nm;
We_A - gaseous Weber number,
ϱ_A – the air density in the combustion chamber, kg/m^3.
The values of Re, Oh and We are criteria for liquid jet breakup mechanisms, critically affecting the size of droplets. The limit above which the atomization proper takes place is determined by the relationship (Lefebyre, 1989, Liu, 2000):

$$Oh \geq 100Re^{-0,92} \text{ or } We_A > 40,3 \tag{2}$$

The mechanism of jet breakup of the fuel flowing out of the nozzle in the area above the curve resulting from equation (2) provides the smallest droplets. The relationship from formula (2) is a necessary condition to be met for the fuel atomizer nozzles in compression ignition engines with direct injection.

Marine compression ignition engines can be designed for the combustion of a wide range of liquid and gas fuels, those from petroleum and biofuels, with different ranges of physical characteristics. Fuel equipment is tailored for a specific fuel grade. Its selection takes account of, inter alia, fuel viscosity and temperature, which affects the design of the injection pump (range of clearance between the plunger and the barrel) and the injector, e.g. the number and diameter of atomizer nozzles. In marine engines, adjusted to the combustion of residual fuels, fuel equipment is intended for the continuous operation of these engines fed with RM fuel of relatively high viscosity. Marine engine makers allow the use of distillate fuels (DM) with low viscosity, but only for short periods of running times, for instance to flush the fuel installation before an overhaul or in an emergency.

In most cases the prime movers of commercial vessels are designed to run on liquid petroleum fuels. Other types of fuel make up a small share in the global commercial fleet. It seems that in the years to come no radical changes will take place: projected share of LNG on marine fuels market till 2030 is estimated at approx. 10% (Argyros et al., 2014).

Properties of each type of liquid marine fuel are defined in the standard ISO 8217:2017 Petroleum products — Fuels (class F) — Specifications of marine fuels (ISO 8217:2017, 2017). The fuels are divided into two basic categories: distillate DM and residual RM, which differ mainly in viscosity values. The viscosity range of DM fuels (2 to 11 mm^2/s at 40°C) makes it usable at the temperature of storage, while residual fuel (10 to 700 mm^2/s at 50°C) requires heating during storage in fuel tanks and before injection pumps of the engine. The temperature is raised to reduce viscosity and to ensure optimal fuel atomization in the engine combustion chamber.

Fuel viscosity required before the injection pump is indicated by the engine manufacturer. As the elements of injection equipment can be lubricated by fuel, the adopted minimum value of viscosity is 2 mm^2/s, while the maximum value is 20 mm^2/s (CIMAC, 2013, MAN Diesel & Turbo, 2014, Winterhtur Gas and Diesel, 2015). Typical viscosity recommended for a modern ship engine, designed to use residual fuels falls in the range 10 to 15 mm^2/s (Winterhtur Gas and Diesel, 2015).

The control of minimum and maximum fuel viscosity makes use of the dependence of viscosity on temperature. Distillate fuels, low sulphur in particular, with inherent low viscosity and use at high temperatures of the engine room, should be cooled before the engine to maintain their minimum viscosity (CIMAC, 2013, MAN Diesel & Turbo, 2014). On the other hand, for marine fuels with highest viscosity (700 mm^2/s in 50^{o}C) there is a limit of maximum heating temperature due to possible evaporation of lightest fuel fractions and formation of vapour, mainly in fuel pumps. Makers of marine piston engines recommend not to exceed the temperature of 150°C of the fuel before injection pumps (MAN Diesel, 2009, Winterhtur Gas and Diesel, 2015).

Along with increasing temperature of fuel, its viscosity decreases, and so do density and surface tension, physical quantities that affect the criterial numbers of liquid atomization. The observed differences between the densities of each of the DM fuels (preheating not required) oscillate within 10%. Changes in RM fuel density heated to a temperature in the 50 do 150°C range show even smaller differences.

The surface tension of petroleum products is within a relatively narrow range of 24 to 38 mNm Spieght, 2005). Surface tension falls when temperature increases. For marine fuels, surface tension of fuels heated to a temperature 50-150°C may differ by ±15%.

In emission controlled areas (ECA) ships may use fuels with maximum sulphur level of 0.1%, or higher, provided that the ship has an installation removing SO_x from exhausts.

Shipowners who have chosen the option of low sulphur fuels today are experiencing problems with access to these fuels in bunker ports. The ship's crew, planning a voyage, sometimes is forced to purchase low sulphur fuel with viscosity as is available, and the only criterion of suitability is the sulphur content. Depending on the trading area, suppliers offer low sulphur fuels that actually have a viscosity matching the specification of ISO 8217 for distillate fuels of DM subcategory, or higher viscosity, characterizing RM fuels (Krause, 2016). As the last resort, the shipowner may choose automotive diesel oil (ADO) as low sulphur fuel, but the requirements in this case are the flash point of minimum 60°C and minimum viscosity recommended by the engine manufacturer.

Based on the above analysis, it can be concluded that among the physical characteristics of fuels for marine piston engines directly affecting the size of droplets in a spray, viscosity has the widest possible range of variation, from a minimum of 2 mm^2/s for DM fuels to a maximum of 20 mm^2/s for RM fuels. For this reason, viscosity is chosen as the most relevant parameter in the atomization of the liquid and impact on the size of fuel droplets.

The problem faced by engine department personnel is that in some areas of ship operation they may be forced to use fuels with viscosity values significantly different from nominal ones. Therefore, the question arises whether fuel viscosity change within permissible minimum and maximum values, as recommended by the manufacturers, significantly affects the size of the atomized fuel droplets.

This experiment aims to quantify the viscosity impact, including typical values recommended by the marine engine manufacturers on the fuel droplets size in the atomized spray.

MATERIALS AND METHODS

The test injector is one used in a compression ignition engine of 359 type, fed with diesel oil with viscosity of 2 to 4,5 mm^2/s at 40°C. Nominal power and rpm of the engine are, respectively, 110 kW and 2800 $min.^{-1}$.

The experiment was performed at the test rig shown in Figure 1, located at the Fuel, Hydraulic Fluids and Environmental Protection Research Centre, Marine Engineering Faculty of the Maritime University of Szczecin (Fig. 1).

The atomization of test liquids was performed in stationary atmospheric pressure air. The injector W1F-01 with a three-hole atomizer H1LMK 148/1 (1) was mounted in such a way that the laser beam would pass through only one stream. This type of injector and atomizer was chosen for the experiment due to its design features, making it possible to perform measurements of a single spray of fuel. To avoid the impact of adjacent fuel sprays on the measurement results, the other two sprays were discharged through closed tubes (not shown in Fig. 1).

Before the experiment the injector was adjusted at the test rig with the aid of a PRW 2M pump and calibration oil HAD 400 from Delphi. The injector was checked for correct work, tightness, and the opening pressure was set to 22±1 MPa.

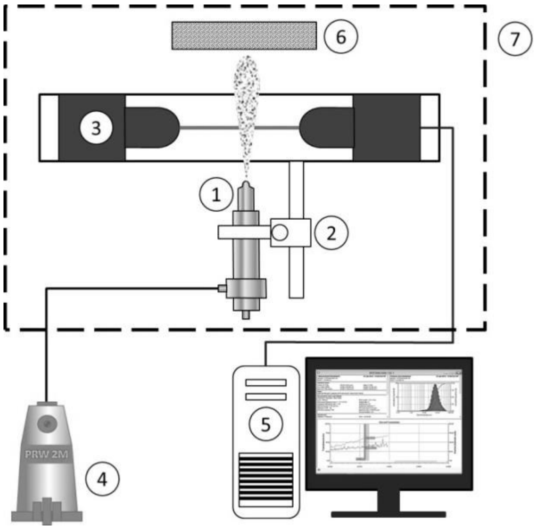

Fig. 1. The test rig:
1 - injector, 2 - holder with injector position adjustment, 3 - Spraytec analyzer,
4 - injection pump PRW-2M, 5 - computer and monitor, 6 - fuel absorber,
7 - fume cupboard housing

The injector at the test rig was fed by an injection pump PRW 2M with a maximum pressure of 35 MPa and delivery of 0.52 ml/inj.

Three different liquids were used as fuel: calibration oil HAD 400 from Delphi for injector testing, hydraulic oil Hydrol L-HM/HLP (viscosity grade ISO VG 15) produced by Orlen, further denoted H15, and a mixture of oils H15 and HAD 400 in the proportion 70%/30% by volume.

The viscosity, density and surface tension values of the tested liquids are given in Table 1. Kinematic viscosity was determined according to EN ISO 3104 using the capillary apparatus TV 2000 PMT Tamson. Liquid density was determined as per standard EN ISO 12185 with the DMA 4500 apparatus from Anton Paar. Surface tension values of the liquids were obtained by means of a Sinterface-made DVA1 device.

Table 1.
Properties of tested liquids.

Atomized liquid	Kinematic viscosity N at 20°C	Kinematic viscosity v at 40°C	Density ϱ at 15°C	Surface tension σ at 20°C
	[mm^2/s]	[mm^2/s]	[kg/m^3]	[mNm]
HAD 400	3.93	2.53	825.84	30.16
70/30 H15/ HAD 400	16.73	8.44	851.10	32.78
H 15	36.41	15.44	863.36	33.01

The droplet diameters in a fuel jet spray were determined by a Malvern-made Spraytec STP 5000 analyzer 2 (Fig. 1), serial number MAL 1057129, with 300 mm lens, and particle size range 0.1 to 900 μm, 2.5 kHz sampling frequency. Sauter mean diameter (SMD) values and other parameters of the injection were recorded using the Spraytec software version 3.30. The measurement cross section of the spray was set at 40 mm from the atomizer's nozzle tip. The data from the entire injection time from the trigger point till the spray vanished (100% transmission) were used for the determination of mean droplet diameter. Each point (for viscosity value) is the mean value of six measurements of Sauter mean diameter (SMD).

THE RESULTS

D32 (SMD) was adopted as the comparative criterion for droplet size in a spray. To illustrate the results, relative diameters were used, while as a reference diameter the SMD was taken, determined by atomizing calibration oil HAD 400, whose viscosity is found well in the limits of diesel oil and close to lower values of DM fuels. Figure 2 contains relative diameters (ratios of SMD H15 to SMD HAD 400, SMD 70/30 to SMD HAD 400) depending on the viscosity of the atomized fuel.

Figure 2 also indicates the viscosity limits of distillate fuels defined by standard ISO 8217: 2017 and the viscosity range of residual fuels or other fuels with viscosity higher than that of distillate fuels, recommended by engine manufacturers.

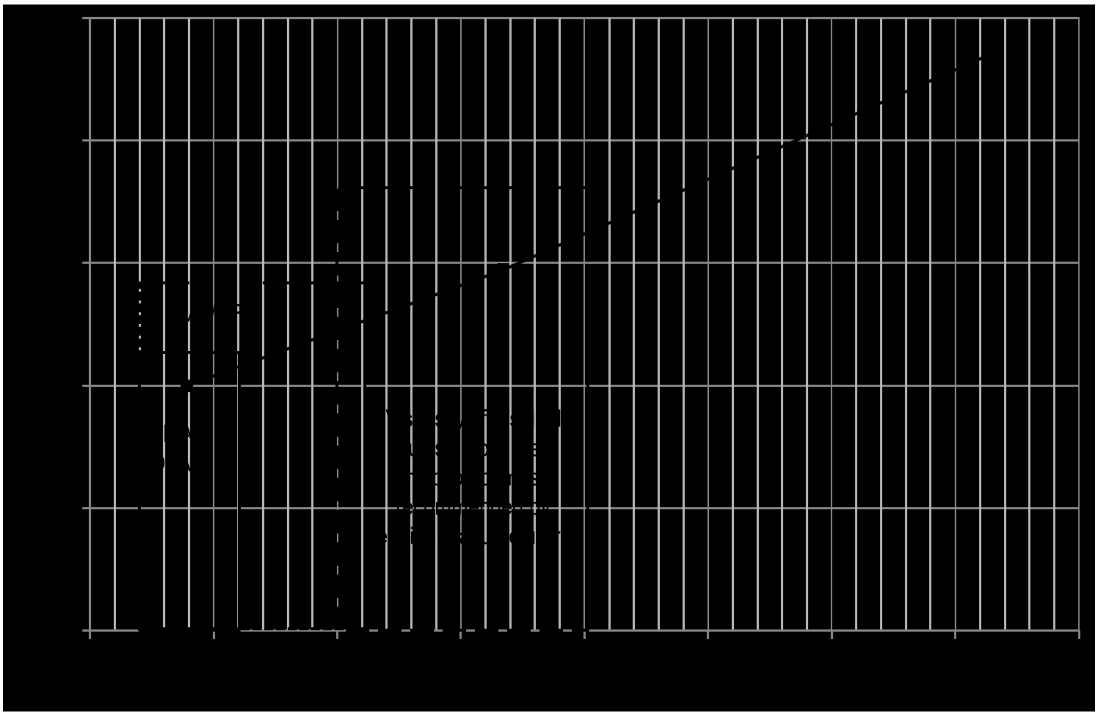

Fig. 2. Relative change in SMD diameter depending on the viscosity of the fuel.

Atomization of a liquid with kinematic viscosity of approximately four times higher (oil 70/30), caused almost 50% increase of SMD. It should be noted that the viscosity of 70/30 oil is still within the limits recommended by the engine manufacturers, without preheating requirement. Atomization of fuel with viscosity of almost ten times higher (H15) results in further increase of SMD size, approximately 2.5 times.

DISCUSSION

The relationships presented in Fig. 2 confirm the results of multi-year research on liquid atomization, indicating that viscosity has a significant impact on the size of droplets in a spray. In this experiment, however, the most essential finding is the magnitude of changes in the spray droplets for the range of fuel viscosity recommended for marine engine operation. In the range typical of residual fuels, from 10 to 15 mm^2/s, the mean diameter may change by as much as 20%.

Droplets of larger size have longer time of evaporation in the combustion chamber, which in the engine working cycle determined by the rotary speed (rpm) may lead to incomplete combustion. The droplet size affects their spread angle and spray penetration in the combustion chamber (Ghahremani et al., 2018, Hiroyasu, 1985, Lefebrve, 1989, Zhan et al., 2018), thus affecting the process of mixing fuel with air (Heywood, 1988).

The injector used for the experiment is intended for atomization of typical diesel oils with viscosity of 2 to 4.5 mm^2/s. The use of the similarity theory of atomization allows us to convey the results onto injectors and atomisers of larger engines and for fuels with other viscosity.

Geometric parameters of the atomizer and combustion chamber result from design and optimization for a specific fuel grade. In each case of increased or reduced viscosity relative to the reference fuel, if the size of the droplets changes, spray parameters may also change. This, in turn, may cause changes in combustible mixture quality, and thus lead to increased fuel consumption and higher emissions of noxious exhaust constituents.

The results of the research into the impact of fuel viscosity increase on the increase in the fuel droplets in a spray direct the attention on the specific issues related to the operation of marine engines. On vessels with engines running on residual fuels, a situation may occur where the fuel used will be characterized by viscosity much lower than the standard 10 to 15 mm^2/s, e.g. permissible minimum 2 mm^2/s. Apart from the reduction of fuel droplets, lower viscosity leads to increased spread angle and shorter penetration of the spray, which changes the conditions of mixing fuel with air. Therefore, the relevant research should concentrate on finding, if it is the case, how burning low viscosity fuels in engines designed for residual fuels influences the atomization, combustion and emission of harmful exhaust gas constituents. The question is justified in relation to ships that may be operated for a longer period of time depending on the size of ECA area and voyage plan.

The answer may be found through measurements of fuel consumption and emission of harmful exhaust components carried out on a ship. The presented here extended research on micro- and macro-structure of fuel spray can be very helpful for the preliminary evaluation of the changes in atomized fuel parameters.

CONCLUSIONS

The experiment has confirmed the impact of fuel viscosity on the size of droplets in a fuel spray. The test liquids used were mineral oils with the viscosity range typical of marine engines adjusted to burning both distillate and residual fuels. The following conclusions can be drawn from this work:

1. The recommended by engine makers range of fuel viscosity values before injection pumps is relatively wide (2 to 20 mm^2/s),
2. Changes in mean droplet diameter in a spray in the range recommended by marine engine makers may be a multiple of the diameters measured in sprays obtained from atomized calibration oil having a viscosity typical of diesel oil.
3. Changes in mean droplet diameter in a narrower range of atomized liquid, 2 to 15 mm^2/s (recommended for residual fuels), may reach more than 50%.
4. Such significant differences in the size of droplets may affect the spread angle and spray penetration, which translates into changed mixing of fuel with air, evaporation and combustion, and consequently fuel consumption and emissions of harmful exhaust constituents.
5. In emission controlled areas the ship's engine, designed to run on residual fuel, may happen to be supplied with fuel of distilled fuel viscosity, which requires further research on the effects of such fuel on the atomization, fuel consumption and the amount of harmful exhaust gas constituents.

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