

Soot Investigation on Fish Oil Spray Combustion in a Constant Volume Cell

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ABSTRACT

Maritime environmental regulations stipulate lower emissions from the shipping industry. To cope with these rules, improving the combustion processes, make use of cleaner alternative fuels and implement exhaust gas cleaning systems is necessary. Alternative fuels, like fish oil, have a potential to reduce soot formation during the combustion process and will be deeply investigated in this paper. For this purpose, two different types of fish oil and their blends with marine gas oil (MGO) have been tested in a constant volume pre-combustion cell (CVPC). The CVPC laboratory was built in collaboration between MARINTEK and NTNU. To generate similar injection condition in the combustion cell as in an internal combustion engine, the CVPC is heated using a chemical heating process. The CVPC is used as a fundamental investigation tool for studying the fuel injection system for large engine applications. Parameters that were studied include the combustion, spray development, fuel evaporation process and ignition delay. The general experimental setup of the test facility is described and the optical methods applied are explained for the investigation of fish oil. The aim is to study soot intensity and spray development and to compare the results to pure low-sulphur MGO as a reference fuel. The results conclude that the combustion and ignition properties of fish oil are very similar to marine gas oil and this makes it applicable as an alternative fuel for power generation in the maritime industry. The tests also showed a significant decrease in soot formation for the two fish oils.

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INTRODUCTION

As the earth's population and peoples standard of living increases, the global society is faced with an increasing energy demand. Fossil fuels have been a reliable source of energy in the past and will continue to be an important energy source in the future. However, fossil energy sources are finite and new energy sources must be investigated to ensure energy security in the future.

Biologically derived fuels have the advantage of being produced from organic material and are hence renewable. Biofuels are also carbon neutral and their use will prevent further build-up of carbon dioxide in the atmosphere. The marine industry is in these days facing stricter emission regulations and the introduction of new and expansion of existing emission controlled areas means that the industry will be needing cleaner fuels. As cleaner more refined petroleum products are expensive, biofuels can be an economically viable alternative.

Biofuel shows positive effects on greenhouse gas (GHG) emissions, but based on the production pathway the magnitude of savings are varying. A Well-To-Wheel (WTW) analysis conducted by the European Environment Agency in 2006 [1] shows GHG emission savings in the range of 50% - 90% and an analysis done by the European Commission in 2011 [2] conclude with savings in the range of 40% - 70%.

Studies on emission characteristics from the combustion of biodiesel are well documented and there seems to be an established consensus of the positive and negative impact biofuels have on emission characteristics. The main difference in chemical structure between biodiesel and petroleum diesel are the fuel bound oxygen found in the ester group of the biodiesel. This oxygen is believed to be the main reason for differences in emission characteristics. Increased oxygen content promotes the mixing process leading to a cleaner, more complete, combustion, which reduces the emissions of unburned hydrocarbons [3]. More oxygen also facilitates oxidation of carbon to carbon monoxide and further to carbon dioxide. This decreases the emissions of soot and carbon monoxide. The soot emissions are further decreased by the biofuels lack of aromatics, which is believed to be the origin of polycyclic aromatic hydrocarbons, also causing soot emissions [4]. In addition, emissions of sulphur oxides are eliminated due to the biofuels lack of sulphur. However, emissions of nitrogen oxides are believed to increase [5], [6], [7] and the heating value is reduced. This is also contributed to the increased oxygen content. The increased oxygen content improves the combustion process leading to a higher combustion temperature, which facilitates the oxidation of nitrogen. The oxygen also occupies volume otherwise used by hydrocarbons and these results in the biofuels lower energy content compared to petroleum diesel.

Two different biofuels and their blends (in sum six fuels) based on fish waste are tested in this study. One is an unprocessed crude fish oil (CFO) produced from category two aquatic products. Category two aquatic products is farmed fish that has died or been killed for other reasons than human consumption. The main problem with this fuel is the high viscosity and low volatility compared to petroleum diesel [8]. For these reasons, the other biofuel is processed through transesterification of fish oil to produce a biofuel with similar viscosity and volatility as petroleum diesel. Fatty acid oils contain triglycerides, which are esters that consist of one glycerol molecule and three fatty acid molecules. In the transesterification process, the oil is reacted with alcohol and a catalyst and the fatty acid molecules breaks of the glycerol molecule. Each of these fatty acid molecules then bonds with one alcohol molecule to form a fatty acid alkyl ester. The overall carbon atoms per fatty acid molecule will reduce and this lowers the viscosity [9]. In our case, ethanol is the alcohol used and hence is the biofuel a fatty acid ethyl ester (FAEE). Marine gas oil (MGO) is used as the baseline fuel and as the base for the different blends.

To use biofuels in the right way and to gain an advantage, it is necessary to understand the complex diffusion combustion occurring during the fuel injection. The knowledge of spray characteristic of biodiesel and blends with petroleum diesel is so far limited and especially for biofuel derived from fish. A closer study of blended fuels is important since biofuel will not be used pure in most application. It will be, and it is, used as a blend with petroleum diesel. In this study a constant volume pre-combustion cell (CVPC) has been used to study spray characteristics and the broadband radiation (intensity) during combustion of the two fish oils in blends with MGO. By analyzing the intensity, it is possible to determine qualitatively the soot formation when combusting different fuels. Both CFO and FAEE have been investigated. Because of the high viscosity of CFO it was necessary to blend 50% CFO with 50% MGO to be able to use this fuel on the test bed.

Agarwal and Chaudhury [10] tested Karanja biodiesel and investigated spray tip penetration, spray cone angle and spray area. The higher viscosity of biodiesel resulted in loss of flow efficiency and reduction in injection velocity, still spray penetration was marginally higher, cone angle was lower and liquid length higher for biodiesel due to poor atomization, higher boiling temperature and the heat of vaporization. Galle et al. [11] investigated the influence of different types of biodiesel on the injection and atomization processes. They observed slightly longer spray penetration for unprocessed bio oils compared to biodiesel and petroleum diesel. Similar cone angles were observed for all fuels. Zhang et al. [12] looked at soot formation and utilized the two-color method to confirm that biodiesel is producing less soot.

In terms of biodiesel from fish oil used in marine application there is a lack of knowledge regarding the spray formation in sense of spray angle, penetration length and lift-off length. Aesoev [13] and Ushakov et al. [3] showed that fish oil has a similar potential to reduce soot formation as biodiesel produced from other feedstocks. They also showed that it can be applied as fuel for marine engines, but no optical investigation has been conducted so far.

EXPERIMENTAL SETUP

The test facility used in this study is a so called Constant Volume Pre-Combustion Cell (CVPC) and it is a basic investigation tool to separate the combustion process from all other engine influences and to simulate similar ambient gas conditions as those of an internal combustion engine due to compression [14].

The pressure and temperature conditions in the test cell is obtained with a chemical heating process described in the pioneering study of Oren et al. [15] and others [16] [17]. The cylindrical volume in the CVPC has a diameter of 250 mm and a volume of 5 dm³. Two quartz glass windows with a diameter of 150 mm provide optical access to the combustion chamber from two sides. With this experimental setup, the CVPC is able to sustain a maximum vessel pressure of 100 bar due to stress limitations of the quartz glasses.

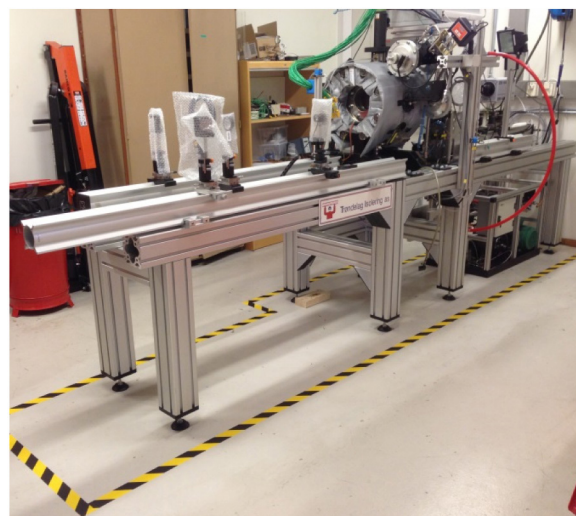


Figure 1. CVPC lab at Marintek/NTNU

For the pre-combustion heating process, the CVPC is filled with a combustible gas mixture of CO, N₂ and O₂, which is ignited before the injection starts. The gas is mixed outside of the CVPC in a specially designed gas mixer. After mixing, the gas is fed into the combustion chamber at a specific pressure and temperature.

This so called Pre-Combustion (PC) heats up the charge in the CVPC and supports a definite pressure and temperature for the main injection and combustion of the diesel fuel. The PC is initiated by a spark plug. After PC is completed, the combusted gas content has an oxygen level of 21 vol% and is an air simulated oxidizer for the main combustion when injection of fuel starts. The combusted gas was analyzed with a Horiba PG250 and the gas mixing process was optimized in order to get a residual O₂ content of about 21 vol%.

Figure 2 presents the schematic function of the CVPC. The PC premixed gas is fed and regulated by a gas inlet valve and mixed with a fan to get more homogenous conditions. After PC and injection of the fuel the exhaust gas is flushed out with air (opening the air inlet valve) through the exhaust valve. The control of the experimental procedure and the data acquisition is done by an in-house generated system in LabView.



Documents

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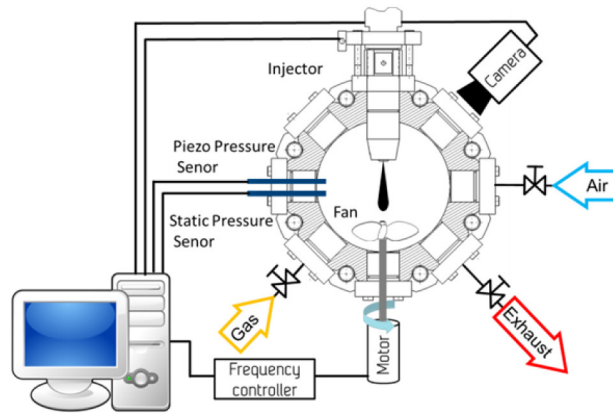


Figure 2. Schematic flow plan CVPC

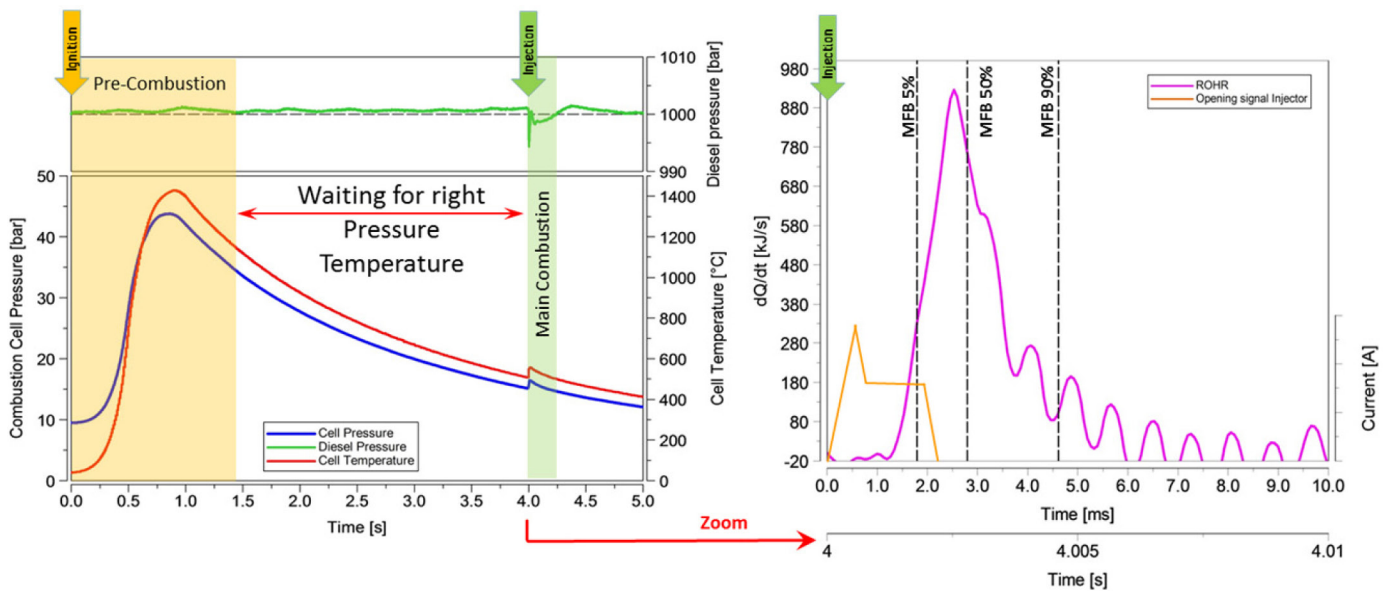


Figure 3. Pre-combustion process (left) and ROHR of injected fuel (right)

Figure 3 (left side) shows the experimental procedure with the pre-combustion (PC) and a waiting period followed by the injection of the fuel at the wanted temperature. During the PC, temperature (red line) and pressure (blue line) in the chamber increase. Due to the heat losses to the wall, temperature and pressure decrease until the fuel is injected. The burning fuel again increases the pressure and the temperature, but much less than during PC. The pressure traces are used to calculate rate of heat release (ROHR) of the burning fuel (Figure 3 right side). For the ROHR a new time line introduced where zero is counted when the electrical opening signal is sent to the injector.

For the injection system, a L'Orange solenoid medium speed engine injector was used with an single-hole nozzle. The injector was special produced for these experiments. A single-hole injector makes the spray investigation easier because the spray can be centered in the optical access and there is no interference of other sprays.

Table 1. Injector nozzle parameters

Description	Value	Units
Single hole injector outlet diameter	0.38	mm
Nozzle K factor	0.7	-
Q100	751	ml/min
Spray full included angle	0	deg

The injector is connected to a common rail system with a high pressure pump able, to supply a maximum pressure of 1800 bar, and a fuel temperature conditioning system. The system is designed for all kinds of biofuels and this means all pipes, hoses, valves, etc. are resistant to fuels with a high corrosive tendencies. In Table 1, the important injector parameters are summarized.

Table 2. CVPC Dimension

Description	Value	Units
Exterior diameter	420x420x400	mm
Interior diameter	D250xL100 (cylinder)	mm
Cell volume	5	dm ³
Max. gas temp	1800	K
Number of optical accesses	2	-
Quartz Glass diameter	150	mm

Table 3. Common Rail System

Description	Value	Units
Maximal pump pressure	1800	bar
Maximal piping pressure	2500	bar
Fuel temperature condition	288 - 333	K
Fuel resistance	All kind of bio fuels	-

CVPC TEST CONDITIONS

For all experiments, the cell temperature was set to 873 K with a constant gas density of 12.2 kg/m³. The oxygen level of the gas was 21 vol% to simulate air. It was very important to keep the cell gas properties during the test as constant as possible. Small variation in the gas temperature would lead to different combustion behavior of the fuel (like ignition delay, soot radiation and spray formation). The gas density in the cell could, during the time of the experiments, not exceed 12.2 kg/m³, because the peak pressure of the pre-combustion was limited to 100bar. There are now further plans to redesign the cell for higher density in future studies.

The injection pressure was chosen to 800 bar, 1000 bar and 1400 bar to investigate the spray and combustion characteristic at different pressure levels. During the experiments the injected energy for all fuels was held constant to 3011 J by adjusting injection duration (see section fuel properties).

Table 4. Injection and spray combustion condition

Description	Value	Units
Cell density	12.2	Kg/m ³
O ₂ concentration after pre-combustion	21	vol%
Gas temperature	873	K
Diesel rail pressure	800-1000-1400	bar

IMAGE PROCESSING

For the experiments two different optical methods on reactive sprays are used, Schlieren method to analyze the spray geometry and direct imaging to evaluate the soot intensity. With Schlieren, technique the first spatial derivative of the gas density in the chamber is detected, which makes this method useful to evaluate macroscopic spray scales [18].

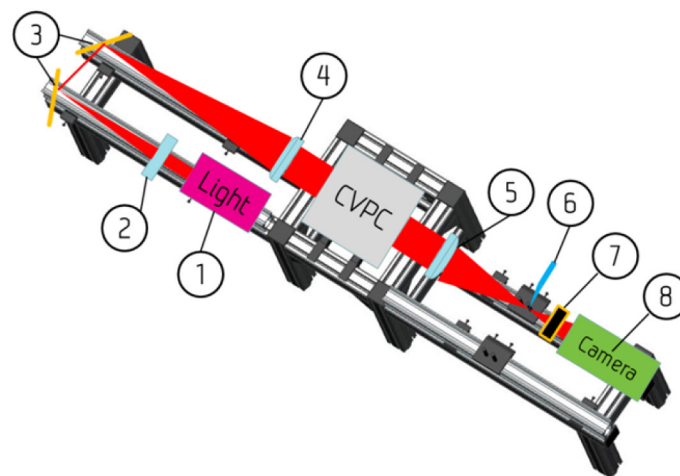


Figure 4. Optical setup

Eight injections were done at each injection pressure for all fuels, and the results were averaged to get a basis for statistical evaluation as well as to limit the risk of drawing conclusions based on faulty experiments.

In Figure 4 the schematic Schlieren setup is illustrated. A LED lamp (1) was used in combination with a condenser lens (2) to generate a dot shaped light source. With two mirrors (3), the light is led to the other optical rail. This rail was in line with the CVPC and the light beam was widened and parallelized in the first collimating lens (4) before entering the optical access. After the light beam has penetrated the CVPC, the light passes a second collimating lens (5) where the beam was again focused. A knife-edge (6) was positioned in the focal point of the second collimating lens. The knife-edge was oriented vertically to cut the focal point from the side to study density gradient in the spray direction. The CCD camera (8), Photron APX, is located behind the knife-edge and a KG1 colored glass band pass filter (7) (315 - 725 nm) was used.

In case of direct imaging, the first optical access (left side) of the CVPC was blocked, the optical equipment on the left side (position 1 until 4) and the knife-edge (6) was not used. The KG1 colored Glass band pass filter (315 - 725 nm) was in front of the camera. To analyze and compare the different soot emission levels of the different fuels the average background image is calculated and the cumulative intensity of the images was computed. To reduce the influence of the background noise, the intensity of the first picture with no combustion is subtracted from all the other pictures. The averaging of the broadband radiation (captured in digital intensity) of the image for every time step can be used for qualitative soot formation

estimation, because more soot will introduce more broadband radiation and therefore higher intensity [19] [20] [21]. Figure 5 illustrates the position of the injector and the camera view. The single-hole spray develops in the injector axis and traveled from the top until to the lower part of the window.

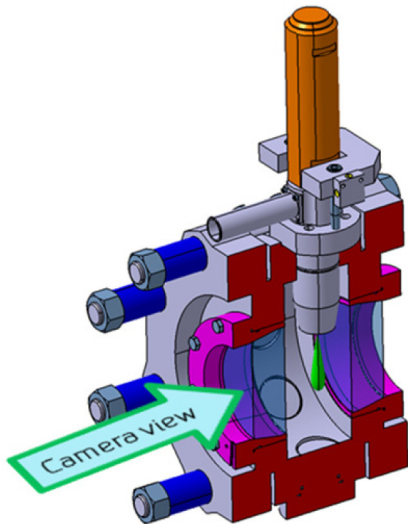


Figure 5. Camera and injector position

Figure 6 shows an example result of the two optical methods (Schlieren (a) and direct imaging (b)). A script in Matlab was written to convert the raw gray scale pictures captured from the high-speed camera to a dimensionless intensity picture. The intensity classification was specified with the minimum and maximum intensity values after subtracting the background noise (Figure 6 right side).

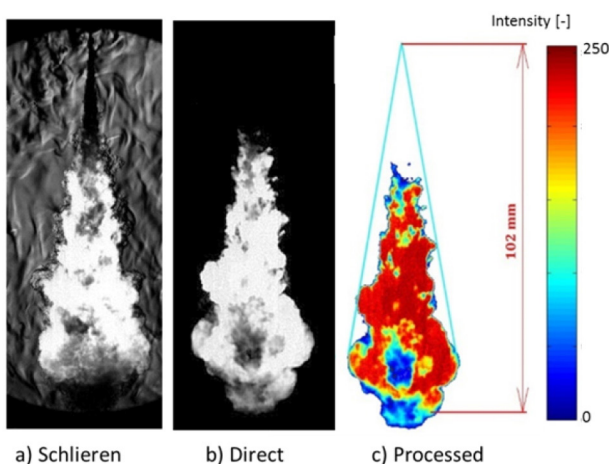


Figure 6. Intensity converted picture of spray combustion

Figure 7 demonstrates the picture average intensity history during a fuel combustion spray like in Figure 6. For all pictures during the combustion sequence, the averaged intensity value was calculated and plotted over the time scale. This diagram gives information about the qualitative soot formation during the combustion and quantifies the start and end of combustion.

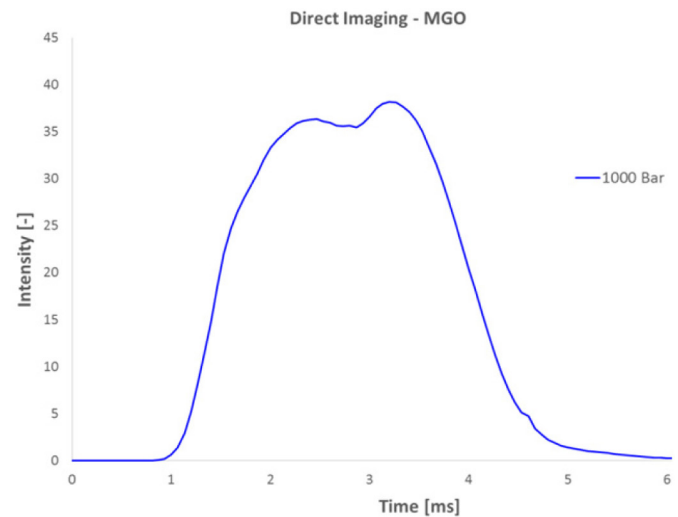


Figure 7. Averaged picture intensity history

Diffusion flame parameters like penetration length, cone angle and lift-off length (LOL) plays an important role in the mixing and combustion process. These parameters can be extracted from the captured images using an in-house developed analysis program (code in Matlab).

The first step is to establish a scale between pixels and a distance (mm) to measure the penetration length and LOL. This was done (before starting the experiments and after adjusted the camera) with an implemented ruler in the CVPC approximately where the spray appeared. Comparing the length of the ruler with number of pixels leads to the scaling factor. To measure the penetration length and the LOL, the picture was cut from the spray area of interest. With a constant threshold (value 125 RGB) the area of spray and background was subtracted. This process is also called masking procedure of the spray edges and turns the picture from gray scale into a black and white picture. After the picture is turned into black and white, the penetration length, cone angle and LOL can be found by searching minimum and maximum values along the nozzle injector axes.

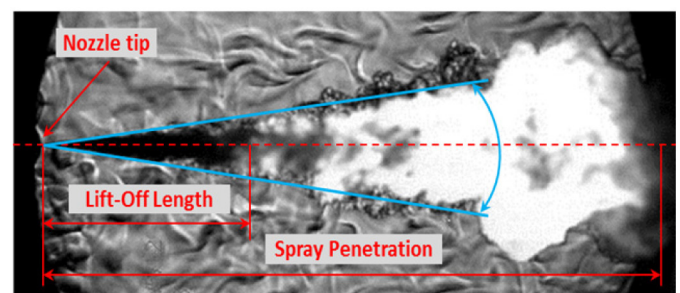


Figure 8. Definition spray penetration, spray cone angle and Lift-Off length

Figure 6 (right side) shows the masked picture cut in the way to investigate the spray of interest. Figure 8 illustrate the measured penetration length and LOL.

For all different fuels, the optical adjustments like shutter timing pictures per second and aperture were kept constant to be able to compare the results directly. The used components and the camera settings are listed in Table 5.