

Optical Diagnostics of Fuel Injection and Ignition in a Marine Two-Stroke Diesel Engine

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ABSTRACT

A combination of optical and laser based methods have been employed for simultaneously studying fuel jet penetration and ignition behaviour of fuel jets inside the cylinder of a large marine two-stroke diesel engine during operation. Tests were performed on a four-cylinder Diesel engine with a bore diameter of 0.5 meter. Optical access was obtained through a custom designed engine cover. A double pulsed laser was employed for global illumination of the liquid fuel jet. For detection a dual camera set-up was employed, which allowed both simultaneous fuel jet and flame emission imaging, or dual frame fuel jet imaging for velocity measurements. From the data recorded the liquid penetration, jet cone angle, jet penetration velocity, ignition location, ignition time and flame lift-off could be extracted.

Data was recorded for two different charge densities and temperatures, for two different atomizer designs, and for two different fuels. The fuel jet was observed to ignite at a position around 1/4 of the length downstream. The penetration length, ignition time and lift-off length were found to decrease with increased cylinder pressure and temperature. A conventional atomizer was observed to produce a slightly narrower and longer fuel jet with increased lift-off, compared to a sliding valve atomizer. For heavy fuel oil an increase of width towards the end of the jet and a more wrinkled appearance was observed, compared to marine gas oil. Fuel jet front velocities were found to peak just above 100 m/s after about 0.3 CAD after start of injection.

CITATION: Hult, J., Matlok, S., and Mayer, S., "Optical Diagnostics of Fuel Injection and Ignition in a Marine Two-Stroke Diesel Engine," *SAE Int. J. Engines* 7(3):2014, doi:10.4271/2014-01-1448.

INTRODUCTION

Two-stroke Diesel engines dominate as prime movers for freight ships due to their unrivalled efficiency and reliability. The fuel injection systems of such engines differ from those of smaller engines in several respects. Fuel is injected from two or three atomizers, located at the periphery, with holes arranged in a non-symmetric fashion. The orifice diameters are typically in the millimetre range and injection durations can be tens of milliseconds. Data on fuel spray and auto-ignition for this size of Diesel injectors is a prerequisite for development and optimization of injection systems and for validation of computational fluid dynamic (CFD) tools. In contrast to the situation for smaller engines reference data for conditions representative of large marine engines, in particular from actual engine experiments, is very scarce. The aim of the work presented here was to acquire data on fuel jet and ignition development under realistic running conditions in a full size marine two-stroke engine, as a function of charge condition, atomizer design and fuel type.

Optical diagnostics has started to make progress in medium- and low-speed marine engines only over the last five years. Examples of techniques employed include high-speed photography [1, 2, 3, 4], IR imaging [5], laser Mie scattering for fuel jet imaging [5, 6, 7, 8, 9, 10], and even particle image velocimetry (PIV) for velocity measurements [11]. Detailed datasets on fuel jet, spray and ignition development have also been acquired in constant volume combustion chambers [12, 13, 14, 15, 16, 17, 18, 19, 20] and in rapid compression machines [21, 22] using optical techniques, under conditions relevant for large marine Diesel engines.

Implementation of optical diagnostics in a large marine engine is challenged by cylinder size, vibrations, thermal loads, soot loads, as well as safety requirements. Here, an engine cover featuring a number of optical ports was used to obtain optical access to one of the four cylinders of a marine Diesel engine. The engine features a bore diameter of 0.5 m and a stroke of 2.2 m. The engine cover has 24 optical ports from the side and the top, and through positioning of optical elements deep inside the optical ports efficient wide-angle illumination and detection can be achieved [5, 10]. All optical hardware was mounted directly onto the engine in order to reduce vibrational and

thermal drifts in alignment. Combined laser Mie scattering and flame emission imaging was employed to acquire detailed information on the liquid penetration, fuel cone angle, jet penetration velocity, ignition location, ignition time and flame lift-off. This imaging method was used to investigate effects of changing charge density and temperature, atomizer design, and type of fuel in order to build up a data-set of fuel jet propagation and ignition characteristics under real in-cylinder engine conditions. Representative examples from this data set are presented here.

EXPERIMENTAL ARRANGEMENTS

Engine

The engine used for the optical tests was the MAN Diesel&Turbo 4T50ME-X test engine. It is a production sized turbocharged low-speed two-stroke Diesel engine, fully equipped for extensive testing. The main characteristic data of the 4T50ME-X engine in standard configuration are summarized in [Table 1](#).

Table 1. 4T50ME-X engine specifications.

Engine type	2-stroke Diesel
Cylinders	4
Bore	500 mm
Stroke	2.2 m
Stroke volume	0.423 m ³
Power	7 MW
Maximum speed	123 rpm
Maximum pressure	190 bar

The engine is of the uniflow scavenged type, with air intake ports at the bottom of the cylinder and a centrally located exhaust valve at the top. The in-cylinder flow is defined by a strong swirling motion introduced with the scavenging air. In standard configuration each cylinder is equipped with two separate fuel injectors, each having four nozzles, placed around the rim of the cylinder and injecting tangentially along the swirl direction. The fuel injection and exhaust valve systems are electronically controlled and hydraulically actuated. The cylinder used for optical testing can be independently controlled, and even motored, by the remaining cylinders, thus leaving large operational flexibility. For optical tests only a single one nozzle fuel injector was employed on the cylinder featuring optical access. For the tests presented here the engine was operated either on marine gas oil (MGO) or on heavy fuel oil (HFO). The fuel pump pressure was around 950 bar, with an expected pressure drop of about 50 bar to the sac volume. The engine was operated at an rpm of 77.5, corresponding to approximately 25 % load.

Atomizers

For this study two different single hole atomizers were employed on the test cylinder, both with a nozzle hole diameter of 0.8 mm. For all tests presented here around 2 g of fuel was injected per cycle using the single-hole injectors. The first atomizer was of the sliding valve type used on most modern marine two-stroke engines, see [Fig. 1 a](#)). In this atomizer an actuated shaft is used to cover and uncover the nozzle holes, thus minimizing the sac volume and injector dripping - leading to reduced emissions, reduced fuel consumption and improved cylinder conditions. In this design the fuel enters the centre of the hollow shaft upstream of the view covered in [Fig. 1](#). The entrance of the hole was electro discharge machined.

In the conventional atomizer a traditional needle and seat design was employed (seat located around 50 mm above the hole, out of view), see [Fig 1 b](#)). The fuel flow path inside the conventional atomizer is smoother, leading to a slightly larger discharge coefficient. The diameter of the central bore of the conventional atomizer is approximately the same as the shaft centre diameter of the sliding valve atomizer.

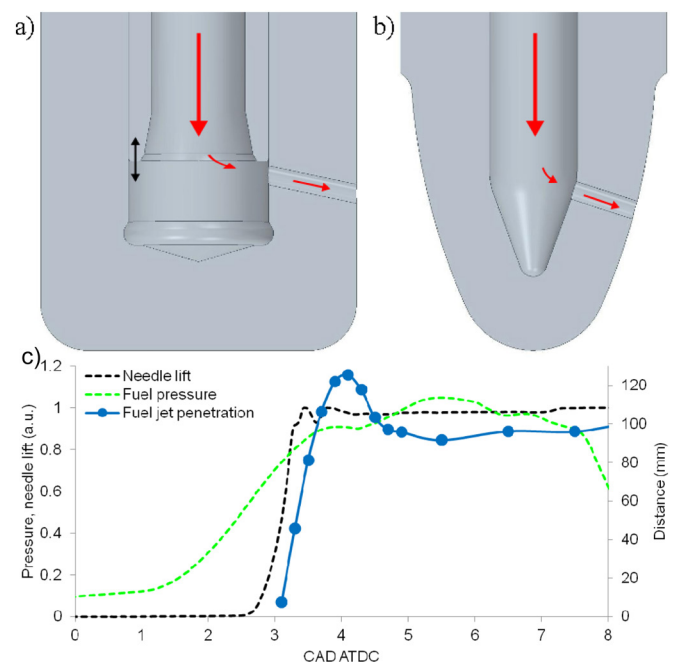


Figure 1. Schematic outline of a) sliding valve atomizer, b) conventional atomizer. c) Example of fuel pressure, needle lift and fuel jet penetration (optical).

An example of measured fuel pump pressure, needle lift signal and fuel jet penetration around start of injection is illustrated in [Fig 1 c](#)).

Optical Access

Optical access to the top of the cylinder is obtained through a custom designed optical engine cover, see Fig. 2 [10]. The cover sits at the top of the engine cylinder and is mounted between the cylinder liner and the exhaust valve housing. The optical engine cover features 24 ports, both from the top and from the side. Each of those ports can be used as either an optical port or fitted with a fuel injector. Unused ports are sealed with metal inserts. Inserts fitted with sapphire windows at the front are mounted into the ports used for laser illumination and for image acquisition. The optical clear diameter of a mounted window becomes 40 mm, determined by the inner diameter of the insert tube. Optical elements or modules can be mounted inside those inserts, and be brought to within a millimetre of the window, which allows for both wide angle illumination and imaging. By employing tight control over engine start-up, operation, and lubrication procedures the optical windows could be kept reasonably clear for up to several hours operation at low load when using MGO, eventually becoming limited by deposits from combustion and lubrication.

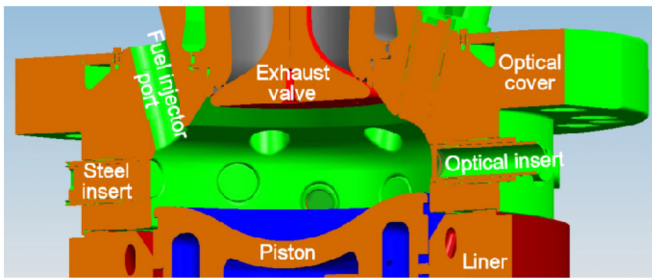


Figure 2. Schematic view of optical cover installed on the engine (green: optical cover, dark red: liner, blue: piston, light red: exhaust valve).

Optical Set-Up

The optical imaging system was mounted directly onto a plate, which was rigidly attached to the cylinder cover. By mounting the laser, cameras and all optics to the engine effects of vibrations and thermal drifts on optical alignment and beam-steering can be strongly reduced. This requires the use of highly ruggedized equipment capable of withstanding the rather violent engine vibrations. A schematic overview of the optical set-up employed for fuel jet visualization is shown in Fig. 3. The various fuel injectors tested were mounted from one of the top-ports. The fuel jet was illuminated by a divergent laser cone from behind, at a glancing angle. The light scattered from the liquid jet and droplets was then detected at approximately right angles using a dual camera set-up. The fuel jet visualization was performed close to TDC, when the top of the piston reaches the lower edge of the windows.

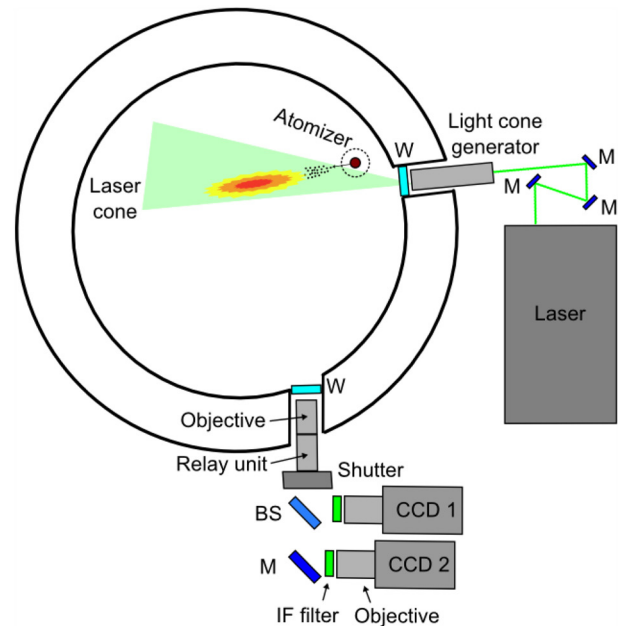


Figure 3. Schematic outline of experimental arrangement for fuel jet imaging (M: mirror, W: window, BS: beam splitter).

Illumination

For illumination a ruggedized dual cavity pulsed Nd:YAG laser was used. The maximum pulse energy at 532 nm was around 200 mJ. In Fig. 3 the illumination arrangement is shown. A number of mirrors were used for redirecting the beam into the optical port. A combination of three negative spherical lenses was used to generate a divergent light cone with a half-angle of around 25°. Two wedge prisms were used as the final elements, in order to direct the light cone at an angle of around 20° to the optical axis, in the direction of the fuel nozzle. The illumination optics were all mounted into a lens tube, which was then inserted into the optical insert and brought to within a few millimetres from the sapphire window.

Detection

A dual camera system was used for recording both scattered laser light and native flame emission. Two CCD cameras (2048×2048 pixels, 14 bits) were used, coupled to a common imaging system via a 50% beam splitter. A custom made relay imaging system, with a 50° viewing angle objective at the front, which fits inside the optical ports was used [10]. A mechanical shutter was built into the system in order to discriminate against the strong flame emission. Each camera was fitted with an interference filter, either 1 nm wide centred at the laser wavelength for capturing the laser Mie scattered signal from the fuel jet, or 200 nm wide centred around 500 nm for capturing flame emission. For the Mie scattering shutter times of 1 μs were used, and for the flame emission 15-30 μs. There was a delay of 10 μs between the exposures of the two cameras.

For a separate set of experiments a single high-speed camera was used for observing the flame emission during ignition. For this purpose the camera was coupled to the same custom designed imaging optics, but a different combination of imaging and atomizer ports was employed, offering a slightly different view.

Data Processing

The images acquired from the two cameras were first mapped to a common coordinate system. They were then filtered using both median and Gaussian smoothing filters in order to reduce noise. The fuel jet images were then segmented, using a threshold value, into fuel jet and background. In Fig. 4 a) an example of Mie scattering signal from the fuel jet is shown, with the segmented boundary outlined by the solid white line. The penetration length S and fuel jet angle θ were then calculated from the segmented image following the approach of Naber and Siebers [23]: The penetration distance, illustrated by the position of the $\theta/2$ arc terminating the jet centre line, is defined as the distance to the location where 50% of the pixels on an arc of $\theta/2$ are fuel pixels. In this example it is 138 mm. The fuel jet angle is then defined as the arctangent of the projected fuel jet area of the first upstream half of the jet divided by the square of half the penetration distance. The fuel jet angle is illustrated by the dashed lines, and is 9.8° in this example.

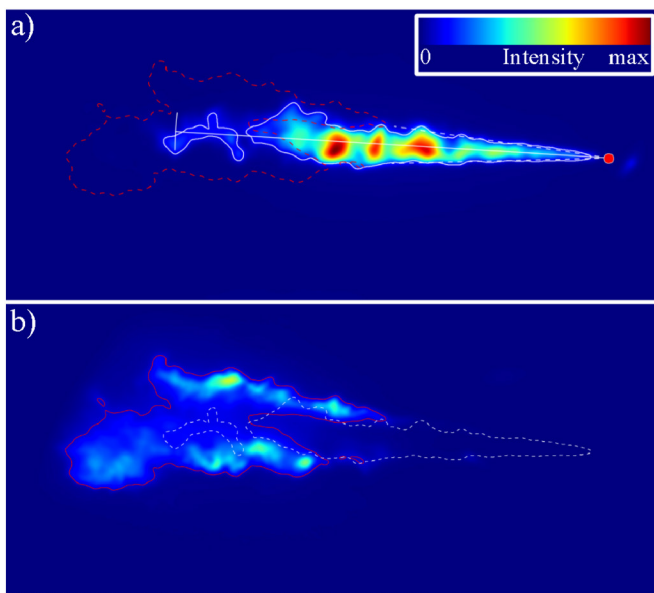


Figure 4. Example of simultaneously acquired a) fuel jet and b) flame emission images. In a) the white contour indicates the segmented fuel jet, and the dashed red contour the segmented flame. The penetration length and fuel jet angle are indicated by the straight white lines. The red dot indicates the position of the atomizer hole. In b) the solid red contour indicates the segmented flame and the dashed white line the segmented fuel jet. Field of view: 208×92 mm.

The simultaneously acquired flame emission image was also segmented using a threshold, see Fig. 4 b). From the segmented flame image the flame lift-off could be calculated. One can calculate both a global minimum distance to the atomizer hole position, as well as a minimum distance for both the top and bottom halves of the flame (72 and 89 mm here), as well as the average distance within half the fuel jet angle (100 mm here). At the time of ignition the centres of the individual ignition spots were also extracted.

Results

On the test cylinder a single atomizer, with a single 0.8 mm diameter nozzle hole was employed in order to produce a fuel jet suitable for optical characterization. The base case was a sliding valve atomizer operating on MGO. This atomizer was tested under two different operating conditions, resulting in different charge density and temperature, as well as for two different fuels, MGO and HFO. Finally, a different atomizer design was tested.

Sliding Valve Atomizer

A sequence of simultaneously measured single-shot fuel jet and flame emission images are shown in Fig. 5. In the left column the Mie scattering from the laser illuminated fuel jet, captured on CCD 1, is shown. It represents the liquid fuel jet and droplets, and thus illustrates the liquid penetration length. The simultaneously measured flame emission captured on CCD 2 (without laser illumination) is shown in the right column. The images corresponding to different CAD are captured in different cycles, but are plotted as a sequence here to illustrate the injection evolution. The estimated cylinder charge conditions at start of injection were a pressure $P=42$ bar, a temperature $T=750$ K, and a density $\rho=21.2$ kg/m³.

In this example the fuel jet is seen to first exit the atomizer at 2.7 CAD ATDC, and then rapidly propagate until 4.1 CAD. The jet ignites on the top side at 3.7 CAD, about one fourth of the distance from the nozzle to the jet tip. The flame then spreads downstream on both sides and engulfs the jet tip around 4.5 CAD. At 6.5 CAD it has evolved into a full flame at a stable liftoff length. The flame tip reaches the end of the optical view around 6 CAD, and after that appears clipped at the left side. Thus the full length of the flame is not captured here. At around 10 CAD the injection ends. The Mie scattering signal then quickly diminishes and the flame advances towards the nozzle - before blowing off.

The fuel jet appears to retract to a stable length after 5 CAD. This retraction could be due to increased rates of evaporation after onset of combustion, or an artefact due to partial obscuration by the soot cloud. The first part of the flame is clearly transparent to a certain degree, as Mie scattering is observed within areas covered by flame emission, see Fig. 4. After the development of the luminous flame head, around 5 CAD in this case, the measured fuel jet penetration length should be treated with caution.