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A "SPRAY COMBUSTION CHAMBER" FACILITY FOR INVESTIGATIONS IN RELATION TO LARGE 2-STROKE MARINE DIESEL ENGINE COMBUSTION SYSTEM OPTIMIZATION

Kai HERRMANN*, Beat VON ROTZ*, Reiner SCHULZ*, German WEISSER*,
Bruno SCHNEIDER and Konstantinos BOULOUCHOS****

* Wärtsilä Switzerland Ltd, PO Box 414, CH-8401 Winterthur, Switzerland
** ETH Zürich, Aerothermochemistry and Combustion Systems Laboratory, CH-8092 Zürich, Switzerland

ABSTRACT A unique experimental facility enables the investigation of injection and combustion processes in relation to 2-stroke marine diesel engines at relevant physical dimensions (bore) and operational parameters (pressure, temperature), including flow characteristics (swirl) and low fuel qualities (HFO) involved. The core element is a disk-shaped optical accessible constant volume spray combustion chamber of diameter 500 mm with peripheral injection into a swirl flow. Conditions at start of injection similar to those in real engines (up to 13 MPa, 930 K) are achieved by feeding the chamber via inclined intake channels with pressurized and heated process gas provided by a pressure vessel/heat regenerating system. The application of non-intrusive optical measurement techniques (e.g. shadow-imaging) contributes to a better understanding of the underlying in-cylinder phenomena in general and facilitates reference data acquisition for the validation of simulation models. Furthermore, component tests (e.g. lubrication system) and fuel investigations at relevant conditions are feasible.

Keywords: Diesel Injection and Combustion, Combustion Chamber, 2-stroke Marine Diesel Engine, Optical Diagnostics

1. INTRODUCTION

Various optically accessible combustion test rigs have been used to investigate injection processes, mixture formation, ignition behavior and combustion characteristics in diesel engine type combustion systems. These include engines or motored devices(1), rapid compression machines(2) or high-temperature and pressure constant volume vessels(3) which provide improved optical accessibility and simpler boundary conditions. This is why these latter are the preferred option for the application in the context of CFD model development; however, most of them were designed for operation on high-grade fuels at conditions representative of smaller (automotive or heavy-duty) engines, and, therefore, limitations apply regarding the transfer of the results to marine engine applications.

In recent years, various efforts have been undertaken to develop further experimental setups(4) allowing the investigation of processes(5) at conditions more representative of marine diesel engine operation(6). In this context, the characteristics of customary fuels were given particular attention, employing the fuel ignition analyzer (FIA)(7), optical accessible combustion chambers(8)(9)(10) and even engines(11)(12) for marine fuel-related investigations.

In spite of these efforts, there is still a lack of reference data relevant to the combustion system of large 2-stroke diesel engines. On the one hand, the mere dimensions involved here (injector orifice sizes, cylinder bore) are well beyond the range of existing setups. On the other hand, the configuration with injection from the periphery, thereby using multiple injectors with non-uniform orifice size distribution and varying angles relative to the strong swirl of the cylinder charge, poses new challenges to the specification of a suitable setup.

The requirements towards such test rig were hence formulated as follows:

- Combustion chamber of sufficiently large dimensions, pronounced swirl pattern of the gas phase.
- Peripheral injection, equipped with multiple orifices of different orientation, varying size of the individual orifices being in the one millimeter range, to be able to simulate a two- or three-injector configuration.
- Pressure and temperature levels at start of injection (SOI) exceeding 12 MPa and 900 K.
- Fuel system able to cope with a wide range of (low) fuel qualities.

On this basis, a novel experimental test facility has been realized(13) and taken into use for finally allowing the observation of in-cylinder phenomena and the establishment of reference data at conditions representative of large 2-stroke diesel engine combustion systems.

2. EXPERIMENTAL FACILITY

2.1 Principle and operation

The spray combustion chamber (Ø500x150 mm) allows the investigation of in-cylinder processes such as fuel injection and evaporation, ignition, combustion and emission formation. In order to achieve realistic conditions at start of injection, a heated and pressurized air (or N_2) flow through inclined inlet ports is provided by a pressure vessel/heat regenerating system as indicated in Figure 1. The inner core of this regenerator consists of a tensioned package of electrically heated discs with clusters of plates in between and is insulated against the housing by ceramic rings. Two types of those heat disks are used in order to enforce a labyrinth type flow of the process gas inside the regenerator. The radial passages for the flow between two neighbouring heat discs as well as the heat flux from the disks to the plates are provided by triangular distance plates fitted between the individual plates and disks. Shortly before the desired initial pressure in the chamber is reached, the accumulator valves close and injection starts, followed by combustion in the reactive cases. Finally, the exhaust valve opens, the regenerator is heated up again within a few minutes, while the compressor is refilling the accumulator with air or nitrogen.

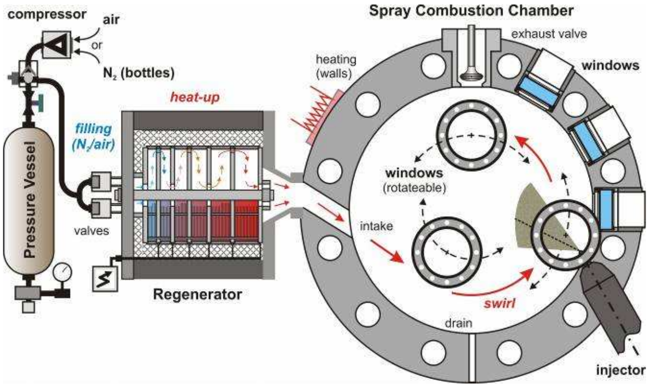

Fig.1 Sketch and principle of the experimental setup, indicating operational (filling, heat up, swirl, injection) and functional aspects (window position, exhaust valve).

When operating the test facility, pressure, temperature and swirl in the spray combustion chamber at start of injection can be adjusted by varying the accumulator pressure and/or the opening valve timing and the regenerator core temperature. The setup has been thoroughly validated against the requirement specifications – pressure and temperature levels of up to 13 MPa and more than 930 K (before injection/combustion) as well as the swirl level range (15-25 m/s) can be achieved at the same time$^{(14)}$.

Figure 2 gives an impression of the entire test facility setup including various subsystems. The pressure accumulator bottles connected to the regenerator can be recognized at the rear and the LFO injection system (common rail, pressure up to 100 MPa) similar to those installed on the most recent production engines is located aside. The spray combustion chamber is designed to handle pressures up to 20 MPa peak firing pressure and is equipped with heating cartridges to maintain a wall temperature of approximately 200 °C. It consists of a main body and two cover plates, which both include three holes each, where windows or cover dummies (containing heating cartridges or pressure and temperature sensors) can be mounted. Optical access (Ø100 mm) is granted by sapphire windows located at different radial positions in the revolvable covers. Fuel admission is realized through (one or two interacting) injectors located at mid-height of the chamber on its circumference, which are fed by a either the LFO or an external separate HFO (see below) fuel system.

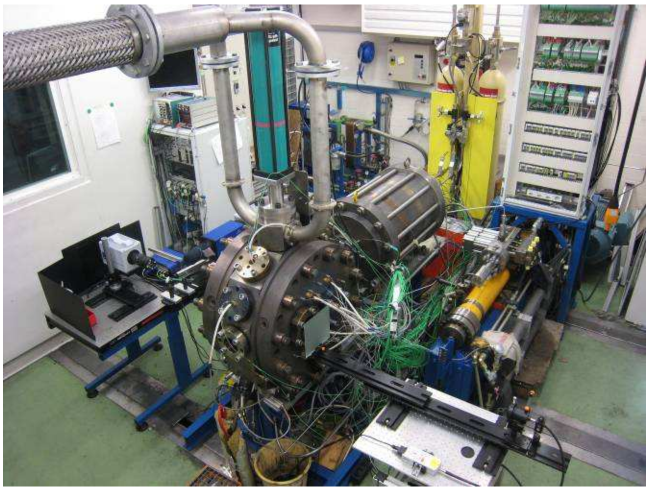

Fig.2 The genuine spray combustion chamber test facility.

2.2 Separate fuel system for HFO operation

In order to be able to investigate all type of customary marine diesel fuels, the setup has been extended by adding a second, independent heavy fuel oil (HFO) injection system, connected to the existing in-house HFO fuel supply infrastructure. It consists of a separate fuel rail (Figure 3) equipped with an injection control unit which enables the release of the pressurized HFO (up to 1200 bar) through a high-pressure fuel pipe connected to the injector (not displayed here) mounted in the spray combustion chamber. The rail device as well as the entire high-pressure connection pipes are heated (steam, partly electrical) and insulated.

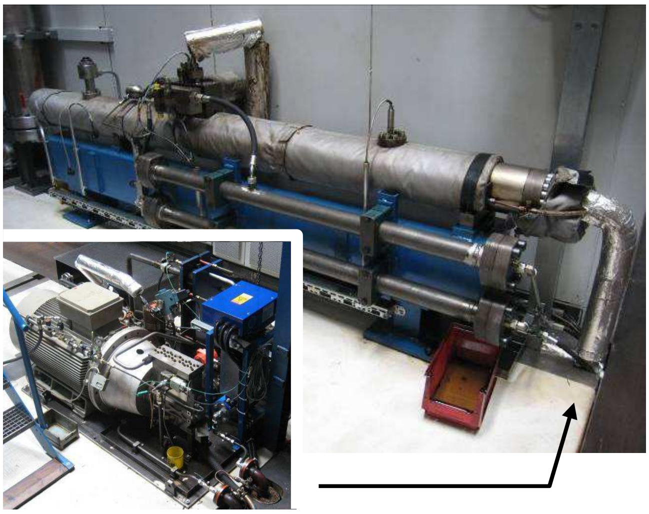

Fig.3 Separate HFO injection system outside of the laboratory.

The rail feeding HFO aggregate (Figure 3 lower left) includes a heater (up to 50 kW) and the viscosity can be observed by an implemented viscosimeter which allows controlling of the fuel properties. The control system monitors pressure, temperature and level indicators and controls safety valves and a leakage return aggregate in order to enable the automatic operation of this HFO system.

2.3 Engine like injector adaption

The so-called "injector-in-dummy" concept shown in Figure 4 enables an assembly of the injector (similar to the engine design) through the cover. This provides further flexibility related to investigations of commercial marine diesel injector nozzle layouts and with regard to optical access for the simultaneous spray observation through front and side windows. The piping from the injection control unit on the fuel rail to the injector is separated by a distribution block which is axis-symmetric to the revolvable cover. This offers the advantage to adjust the spray location directly with the rotatable injector so that the measurement position for optical techniques can remain fixed.

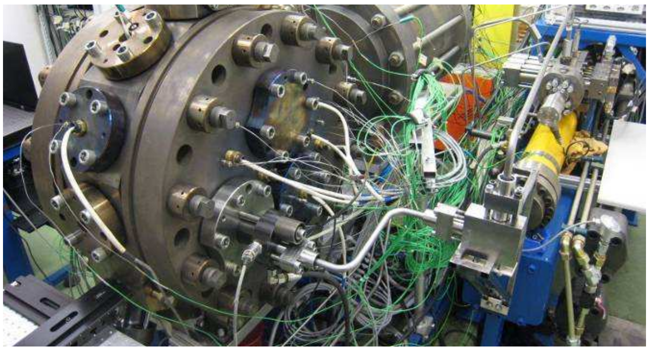

Fig.4 "Injector-in-dummy" configuration.

3. OPTICAL MEASUREMENT TECHNIQUES

3.1 Shadow-imaging

The spray propagation inside the chamber has been visualized by means of an improved "Shadow-imaging"(15) method. The upper sequence of Figure 5 shows a series of images illustrating the ignition process of a two spray configuration at conditions of 9 MPa and 900 K in the spray combustion chamber at start of injection. In this case, the ignition is occurring within the observation area at a position rather on the lee side of the sprays and combustion is then spreading both towards their tips and the injector. These image series are based on a standard background illumination with an arc lamp light source. Obviously, the flame luminescence is dominating the background illumination once the combustion is fully developed. The sensor of the camera gets overexposed and this clearly represents a problem for the visualization of the spray in the late phase.

Fig.5 Shadow-imaging recordings with regular arc-lamp (top row) and laser background light source (bottom row).

A solution for this problem has been found in applying an alternative illumination concept, consisting in a pulsed diode laser (690 nm) light source. Due to the very short 50 ns laser pulse within a 1 μs exposure time of a high-speed CMOS-camera (20 kHz frame rate, 512x512 pixel) in combination with an appropriate narrow band pass filter (CWL 689.1 nm, T 60%, FWHM 10.6 nm), a high signal-to-noise ratio in the recordings is achieved. Due to the short exposure time, the flame light is almost completely suppressed and spray visualization becomes feasible even under reactive conditions. As a consequence, considerably "sharper" images are obtained and it is possible to continue observation of sprays even after ignition has taken place. This is demonstrated in the lower sequence of Figure 5, which refers to the same configuration and conditions as in the upper and where the propagation of the sprays remains clearly detectable well beyond their ignition.

3.2 Mie scattering

The scattering of electromagnetic radiation by spherical particles is depending on the particle size relative to the light wavelength λ – the term "Mie-scattering" is commonly used for sizes larger than 10% of λ. In combustion diagnostics especially, (fuel) sprays and droplets fall into this size range. Mie-scattering basically is an inverted shadow-imaging method so that for the investigated object no illuminated background is required.

Figure 6 shows the Mie-scattering setup at the spray combustion chamber. In order to have sufficient illumination power combined with a high laser pulse frequency, a Nd:YLF laser was employed. It provides a 20 kHz repetition rate with very short laser pulses (ns) of sufficient energy which can be synchronized with the exposure time of the high-speed camera operating at the same frequency. The laser beam itself has to be aligned so that its path is adjusted to 50% beam splitters dividing it into two beams which are expanded and shaped by a specific lens system to illuminate (around the camera) the desired observation area through the front window of the spray combustion chamber

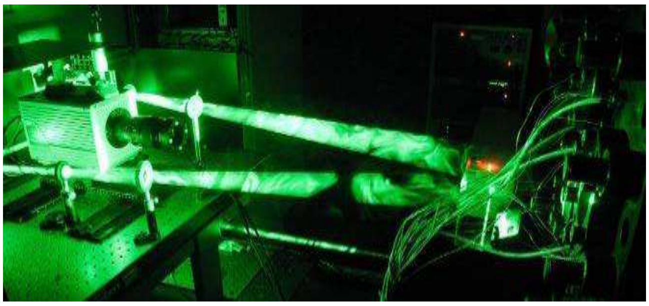

Fig.6 Nd:YLF laser beam alignment with front illumination to perform high-speed Mie-scattering spray recordings.

4. FUNDAMENTAL INVESTIGATIONS

An extensive number of systematic shadow-imaging measurements for determining the spray evolution and ignition behaviour at various chamber conditions (3/6/9 MPa, 930 K) and injection parameters (nozzle tip configurations and fuels) have been performed(15). The injection pressure has been set to 1000 bar in order to assure comparable injection behaviour as in marine diesel engine applications.

4.1 Qualitative spray behaviour

Figure 7 shows the single-hole nozzle (∅ 0.875 mm) cases with spray orientation varying from counter-swirl, perpendicular to the swirl, co-swirl, and a co-swirl injector-co-axial orientation. The three lower left images originate from two-hole nozzle cases (counter-swirl to co-swirl) with identical orifice diameters (∅ 0.875 mm) and varying angles between the individual sprays. The lower right image refers to a five spray case representative of injectors typically used on engines of similar size with pronounced orifice size distribution (decreasing from ∅ 0.975 mm to ∅ 0.675 mm with co-swirl orientation). The effect of spray

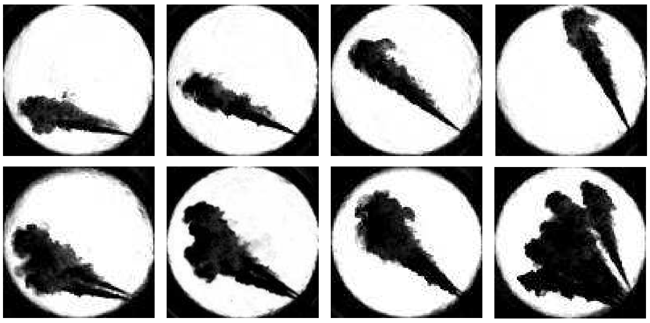

Fig.7 Sample nozzle tip configurations applied.

orientation is materializing in reduced penetration in the counter-swirl orientation case, whereas the width of the plume is clearly increased compared to the co-swirl cases.

At the two spray configurations case shown in Figure 8, the well-known dependence of spray behaviour on the gas density is observed: With increasing chamber pressure, the penetration is reduced and the spray plumes are becoming wider, especially near the spray tips. Furthermore, there seems to be a shielding effect exerted by the more counter-swirl oriented spray which reduces the interaction of the second spray with the gas flow in the combustion chamber, resulting in a longer conservation of the initial momentum of this spray. This effect is also present in the five spray case (Figure 7), where the penetration of the sprays increases with more pronounced co-swirl orientation – in spite of the fact that the decreasing orifice sizes generally result in lower penetration.

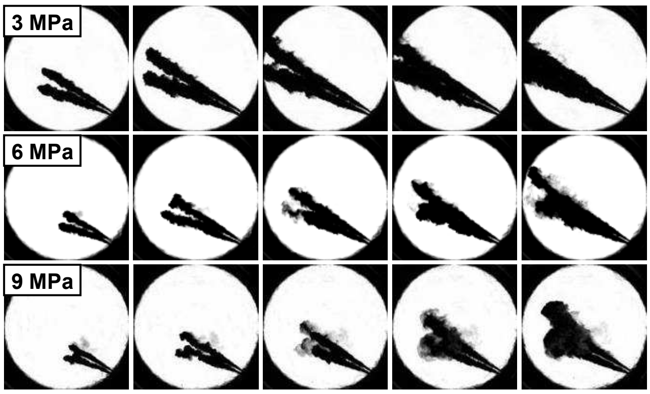

Fig.8 Two-hole nozzle spray evolution at different chamber pressures at 930 K.

4.2 Acquisition of quantitative reference data

In order to obtain quantitative reference data with respect to spray evolution (penetration, angle), the single-hole nozzle cases (∅ 0.875 mm) at various orientations of the spray relative to the swirl have been investigated and analyzed at inert conditions by using nitrogen as process gas. Due to the practical limitations regarding window size, data from several measurement series have to be superimposed. As the identification of the spray outlines is directly dependent on the minimum detectable droplet concentration, thresholds of 90% (spray contour) and 10% (dense core) of the background gray scale level are employed (Figure 9) for its definition(16). The penetration is obtained by measuring the distance from the nozzle tip to the leading edge of the spray where three cone angles (lower, upper, total) due to the swirl deflection have been defined.

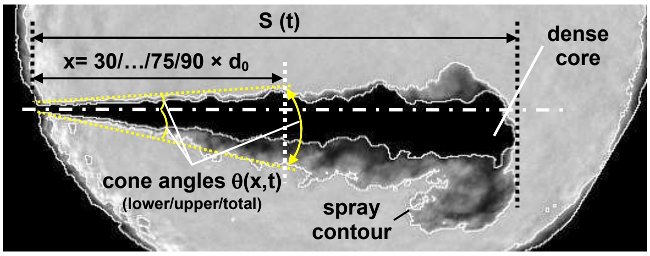

Fig.9 Analysis of spray penetration and cone angles on the basis of two threshold levels (spray contour, dense core).

Despite the fact that the entire setup is operating in a highly repeatable manner, each injection is a separate process. Its adjustment to the others on the basis of the simultaneously acquired needle lift signal allows an analysis of spray penetration and cone angle evolution for a complete measurement series. Sample results are shown in Figure 10 (top: Spray penetration with injector co-axial nozzle – contour/dense core; bottom: Cone angles with swirl perpendicular nozzle) for a variation of chamber pressure.

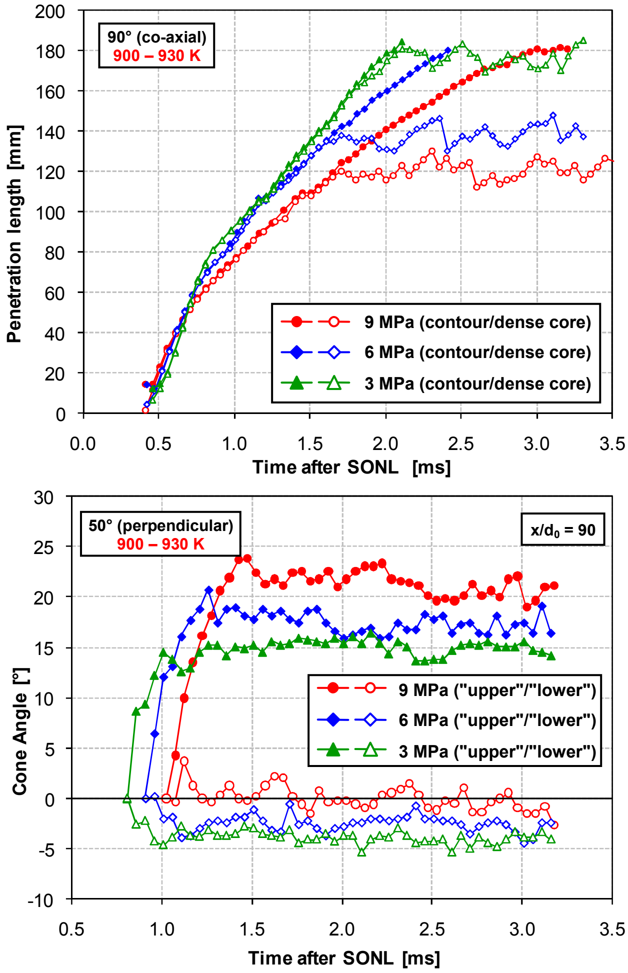

Fig.10 Spray penetration (contour/dense core) and cone angles for single-hole injector cases.

This experimental data was employed to assess the predictive capability of existing models. Good agreement with respect to spray penetration and cone angles was found following calibration of model constants relating to the droplet secondary break-up(17). Afterwards, when keeping the calibrated model constants fixed, good agreement was achieved over a wide variety of operation conditions. Fig-

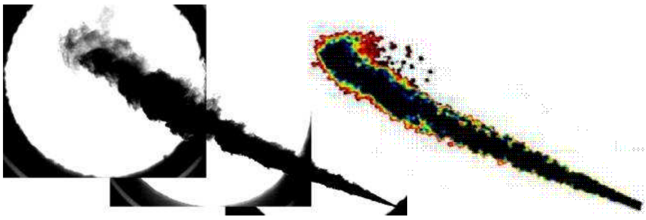

Fig.11 Experimental and simulated spray evolution and density.

ure 11 exemplarily gives a visual impression of an assembled measured spray compared to its simulated propagation and droplet shadow density (identical data processing) along the spray evolution path.

In addition to the inert measurements for determining spray morphology (penetration, cone angle) at evaporating gas conditions, further extensive measurement campaigns have been performed for investigating the non-evaporating behavior at constant density(18). As indicated in Figure 12 (left) the injection spray at such conditions (non-reactive, non-evaporating) has been observed up to the chamber wall. On the right side of Figure 12 the deflection due to the swirl is recognizable.

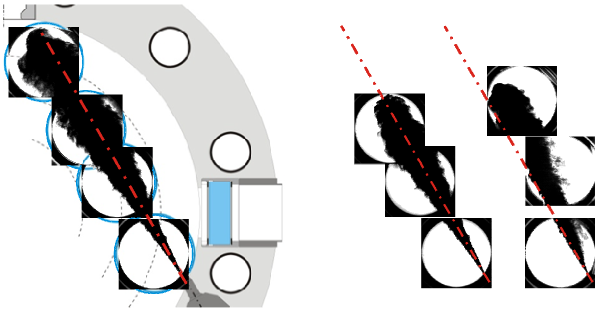

Fig.12 Spray evolution at non-evaporating conditions.

4.3 Initial studies of fuel quality impact

Following initial experiments with HFO for validating the functionality and performance (e.g. reproducibility) of the setup with the separate HFO injection system, first sets of regular measurements have been performed. In order to allow the assessment of fuel quality effects, the spray behavior and morphology has been investigated for the same set of conditions – injection into air (reactive), chamber pressures 9/6/3 MPa at constant temperature (900K) – as already used in the LFO experiments. Figure 13 shows a comparison of spray propagation with the two fuel types for the 9 and 6 MPa pressure cases. As expected, the penetration of the sprays is largely similar; however, there seem to be non-negligible differences in the primary breakup of the spray, leading to the establishment of a wider angle already close to the injector tip. This also has an effect on the ignition location, as can be recognized from this data. It remains to be seen if this is a general pattern or rather a consequence of factors that are not yet entirely understood. For this purpose, in addition to the measurement methods used so far, future investigations will also feature advanced techniques such as flame emission spectroscopy.

5. COMPONENT TESTS

The versatility of the spray combustion chamber can also be used to test components (e.g. injectors) or to investigate the functionality of subsystems at realistic conditions.

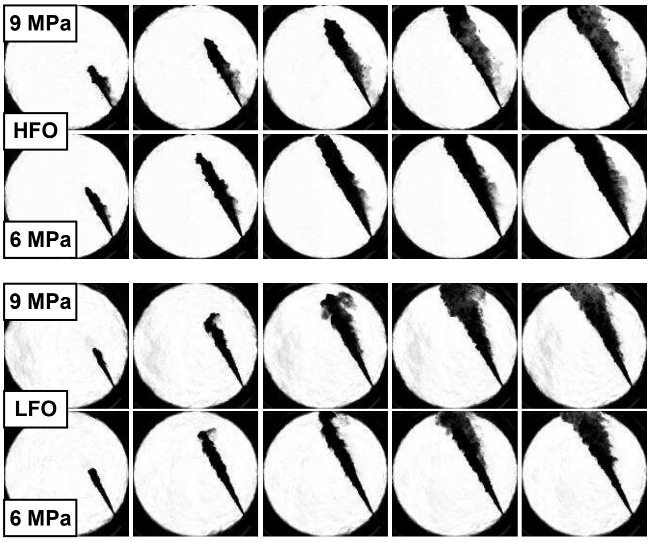

Fig.13 Spray evolution with LFO and HFO at two different chamber pressures at 900 K.

5.1 Production engine fuel injectors

Figure 14 shows two exemplary images of a high speed (20 kHz) injection recording based on front illumination for visualizing single sprays originating from the nozzle tip of a genuine injector. The scattered light intensity is proportional to the droplet concentration and the square of the droplet diameter but a quantitative analysis (droplet sizes) is hardly possible. Nevertheless, the technique is able to deliver a lot of information about the injection sprays and their evolution, such as penetration, cone angle, injector quality (reproducibility, needle bouncing), and the detection of the effective (hydraulic) injection start/end.

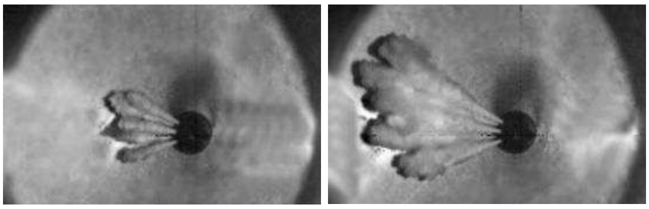

Fig.14 Preliminary front illumination visualization tests of original injection nozzle tips.

5.2 Lubricant injectors

Another important issue related to 2-stroke marine diesel engine operation is the performance of the cylinder lubricating system. For systems based on the injection of the lubricant (Figure 15), their performance is dependent on a variety of design (e.g. number of orifices, diameter in the

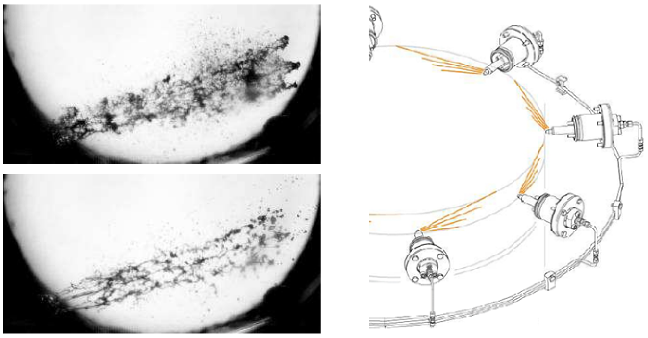

Fig.15 Scheme cylinder lubricating system (right) and preliminary lube oil visualization at different conditions (left).

range of 0.2 – 1.0 mm) and operational (e.g. injection pressure between 20 bar and 80 bar) parameters, which also need to be optimized by means of appropriate tests. For this purpose, such prototype system has been mounted on the spray combustion chamber and first visualizations of the lube oil jet propagation have been realized (Figure 15 left).

6. CONCLUSIONS AND OUTLOOK

A new experimental facility allowing the investigation of spray and combustion processes at conditions typical of large 2-stroke diesel engines has been put to productive use. The results yield valuable insight into the behaviour of individual as well as pairs or groups of sprays at relevant conditions in terms of pressure, temperature and flow pattern at start of injection. With the recent addition of a separate injection system for HFO, the impact of fuel quality, including customary marine fuels, can now be assessed in more detail. The results are thoroughly analyzed for generating relevant reference data for CFD model development and the validation against these data has already brought about clear improvements of the predictive quality of CFD simulations. However, the potential of the experimental facility goes well beyond this classical application. It could be shown that it is equally suited for testing of key engine components such as fuel or lube oil injectors – its highly versatile design lends itself for a big variety of applications. Therefore, it will be employed both for more fundamental investigations, including also more advanced experimental techniques for spray investigations, and in the context of product development by performing dedicated component performance and system optimization tests.

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