Validation and Initial Application of a Novel Spray Combustion Chamber Representative of Large Two-Stroke Diesel Engine Combustion Systems

K. Herrmann*, A. Kyrtatos, R. Schulz and G. Weisser
Wärtsilä Switzerland Ltd
PO Box 414, CH-8401 Winterthur, Switzerland

B. von Rotz, B. Schneider and K. Boulouchos
ETH Zurich, Aerothermochemistry and Combustion Systems Laboratory
ETH Zurich, CH-8092 Zurich, Switzerland

Abstract

The application of state-of-the-art Computational Fluid Dynamics (CFD) tools to the simulation of combustion in large marine diesel engines continues revealing the need for further development of the models used for the description of the spray processes in particular. Such development is, however, suffering from the lack of relevant validation data, considering the physical dimensions and operational parameters involved, including flow characteristics of the process gas and fuel quality. Therefore, a novel experimental setup has been realized, allowing the study of spray and combustion processes at conditions typical of large two-stroke marine diesel engines. Its core element is a disk-shaped constant volume spray combustion chamber of diameter 500 mm with peripheral injection into a swirling flow and equipped with comprehensive options for granting optical access. In order to achieve realistic thermo- and fluid dynamic conditions at start of injection, the chamber is fed with pressurized and heated process gas provided by a pressure vessel/heat regenerating system, via inclined intake channels. The chamber design includes various injector arrangement options and the injection system is prepared for running on typical marine fuels. Following the completion of the setup, the first focus was its validation against the requirements and design specifications in terms of the pressure and temperature ranges envisioned as well as regarding the swirl pattern at start of injection. The initial application involved the visualization of the spray evolution of either single or multiple sprays from the injector tip by means of shadow imaging techniques, thereby varying temperature and pressure at start of injection and considering both non-reactive and reactive cases. These investigations have fully confirmed the potential of the setup for studying spray and combustion processes at conditions relevant to large marine diesel engine combustion and have provided valuable insight already into the spray characteristics at such conditions.

Introduction

Despite the fact that promising results have been reported for the application of currently available CFD tools for the simulation of combustion in marine diesel engines ([1], [2], [3]), limitations remain to apply in terms of their predictive quality, in particular when using them for the simulation of large two-stroke (marine) diesel engines (e.g. [4]). These can – at least partly – be traced back to uncertainties related to the description of the spray processes at conditions relevant to those engines, as the existing spray models have been developed for considerably smaller engines running at higher speeds and using fuel of much higher quality. As a consequence, their validation was commonly also performed against data from small spray combustion chambers operating on high-grade fuels and at conditions only partly reflecting the situation in large marine diesel engines. In fact, relevant validation data for those applications, considering their physical dimensions and operational parameters, were not available so far.

Therefore, in the context of the HERCULES research program [5] funded under EC's Framework Programmes [6], a novel experimental setup has been realized [7], allowing the study of spray and combustion processes at conditions typical of large two-stroke marine diesel engines, in particular involving the following features:

- A combustion chamber of sufficiently large dimensions with very pronounced swirl pattern of the process gas.
- Injection from the periphery of the combustion chamber, thereby simulating a two- or three-injector configuration, where the individual injectors may be equipped with multiple orifices of different orientation and partly also varying diameter, the size of the individual orifices being in the one millimeter range.
- Pressure and temperature levels at start of injection exceeding 120 bar and 900 K.

*Corresponding author

- A fuel system able to cope with a very large range of fuel qualities, including residual fuel types typically used in marine applications.

Obviously, such setup needs to additionally satisfy the usual requirements with respect to the application of both standard and (laser-) optical technologies for the intended generation of validation data.

Experimental Setup

For the investigation of in-cylinder phenomena, the availability of optical access plays a key role. Based on the requirement specifications, a window-equipped constant volume chamber of diameter 500 mm has been designed [7], which is representative of the dimensions of smaller two-stroke as well as larger four-stroke marine diesel engines. The fuel admission is realized by means of one or two injectors located at mid-height of the chamber on its circumference, which are fed by an injection system largely similar to the ones used on production engines of the latest design. In order to achieve realistic conditions at the start of injection, a heated and pressurized air (or N_2 for inert investigations) flow through inclined inlet ports is provided by a pressure vessel/heat regenerating system.

Figure 1 shows the schematic drawing of the test facility setup. A pressure vessel system equipped with fast opening valves feeds process gas via a so-called regenerator to the spray combustion chamber. 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. This assembly results in a high overall surface to volume ratio in order to achieve an optimum heat transfer from the heated core. The flow through the tilted intake channel generates engine similar swirl in the spray combustion chamber, through appropriate selection of angle and flow area. The fast filling process in combination with the heated chamber walls ensures low heat losses. 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, and a compressor is refilling the accumulator with air or nitrogen within a few minutes, which are also required for reheating the regenerator.

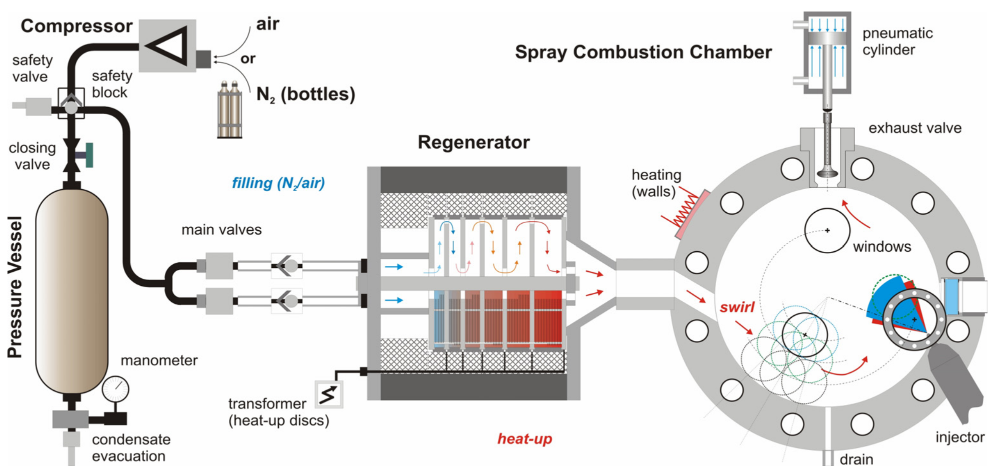

Figure 1. Schematic drawing of the test facility setup, indicating operational (filling, heat up, swirl, injection) and functional aspects (window position, exhaust valve)

Note that the intake channel remains open throughout the process for allowing a certain expansion of the combustion chamber content and thus attenuating the limitations with respect to the maximum pressure otherwise applicable to the isochoric chamber. The regenerator thereby acts as a flame arrester while the exhaust gas flowing back assists in its reheating. The exhaust valve (actuated by a pneumatic cylinder) opens to the exhaust side and enables blowing off in case the pressure in the chamber exceeds a critical value. A drain valve is fitted at the bottom of the chamber for evacuating unburnt fuel in case of inert N_2) investigations.

The bare spray combustion chamber (Ø500×150 mm) connected to the regenerator is displayed in Figure 2 (left). 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. It is designed to handle pressures up to 200 bar. As the main interest is in the spray and combustion processes, the setup needs to be particularly versatile with respect to the injector configuration and the location of the windows relative to the position of the individual injectors for allowing access also to regions directly adjacent to the injector tips. For this purpose, the three holes of the covers are located at different radial positions relative to the axis of rotation, starting from an outer position, where the tip of the injector is within the observation area. Optical access is achieved by mounting sapphire windows (Ø120 mm) in the holes of the cover plates, which can be rotated in sufficiently small incremental steps of 15 degrees relative to the body of the chamber. In the schematic representation of the combustion chamber in Figure 1, the light grey circles indicate possible window positions superimposed with their baseline placement.

In order to satisfy the requirements towards versatility of the setup in terms of injector configuration, the design of the main body also includes three holes for mounting standard injectors as applied on engines of that size: In addition to one baseline location foreseen at the bottom right of the chamber, two additional locations above and below the intake channels are provided. This allows reproducing the 120 and 180 degree angular distance of the atomizers as present in the three- or two-injector configurations commonly used on engines, which thus enables the investigation of interaction effects of sprays originating from different injectors.

Figure 2 (right) gives an impression of the entire spray combustion chamber test facility setup including various subsystems. The pressure accumulator bottles can be seen behind the regenerator and spray combustion chamber which is equipped with heating cartridges to maintain the temperature at approximately 200 °C.

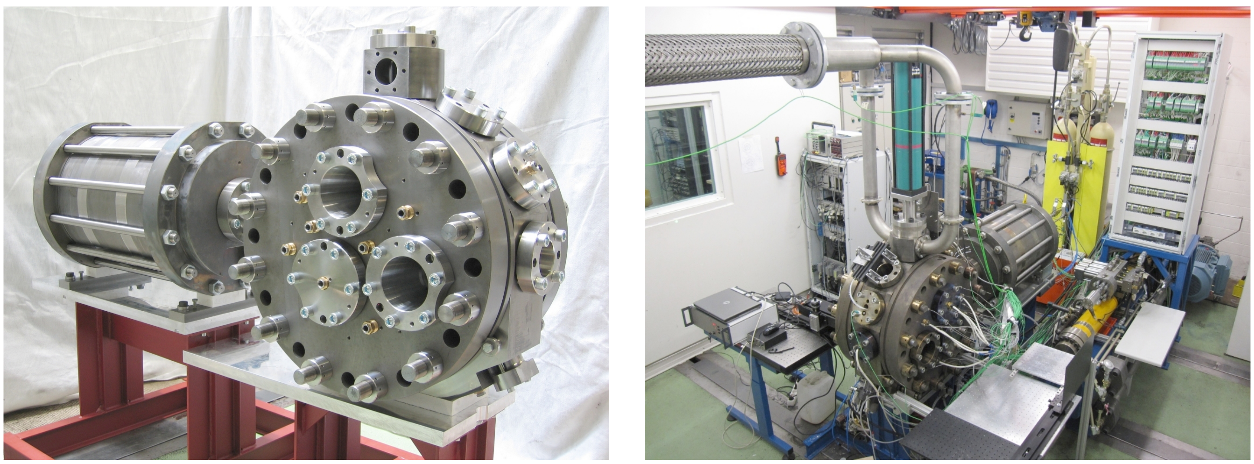

Figure 2. Spray combustion chamber / regenerator assembly (left) and complete experimental test facility (right)

The common rail injection system is currently operated on light fuel oil but is prepared for the use of different fuels (including HFO). Its main components are located up rear where on the right side the electrical motor of the high-pressure pump feeding the fuel rail can be seen. The latter is located beside the regenerator, lying underneath an electrical cabinet used for control device signal collection and distribution.

The control room is located behind the wall to the left, where a bullet-proof window allows the observation of the spray combustion chamber during operation. The control cabinet inside (partly visible) is connected to another electrical cabinet (located next to the window) used for measurement data signal collection. The surrounding laboratory facility accomplishes the specifications in view of its integration into the existing building and infrastructure, facility operation (air conditioning) and maintenance as well as the requirements associated with the intended application of optical measurement techniques and last but not least for compliance with safety standards.

Validation

During the operation of the test facility, the conditions of the process gas, the fuel injection system, heated or pressurized components as well as positions of switches, valves or other devices are monitored extensively. Pressure data acquisition is performed by means of water-cooled piezoelectric sensors, calibrated at each filling process by a piezoresistive one. Temperatures are measured with standard Type K sheath thermocouples, using such with 0.5 mm diameter at critical locations for an optimum of response time and durability. These thin thermocouples were each soldered in a metal sleeve which then was inserted into the combustion chamber through pressure fittings.

The left diagram in Figure 3 shows exemplary pressure and temperature data of a typical filling process (accumulator pressure of 340 bar, valve actuating time of 750 ms, regenerator inner core temperature of 950° C) before injection. The pressure p_{inlet} is measured at a position close to the inlet of the regenerator right after the fast actuating valves of the pressure accumulator bottles. T_{flange} illustrates the regenerator exit, respectively spray combustion chamber inlet temperature at a sensor position in the flange in between. The spray combustion chamber condition acquiring sensors (p_{SCC}, T_{SCC}) are located opposite to the swirl producing intake channels.

Flow investigations were performed by means of a common LDV system (seeding silver-coated hollow glass spheres) specified for velocity measurements up to 150 m/s. The results obtained at a radial position of the measurement point on the centre plane at 200 mm from the chamber axis are shown in the right diagram in Figure 3.

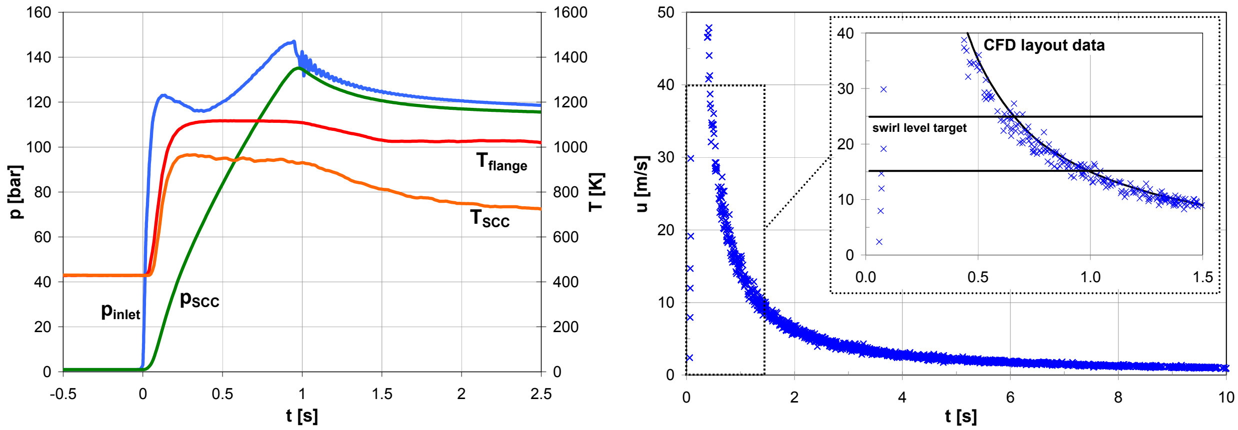

Figure 3. Pressure, temperature (left) and swirl (right) evolution during a sample filling process (without injection)

The pressure and temperature histories illustrate the working principle of the setup: Following the opening of the fast actuating valves, p_{inlet} rises sharply, whereas p_{SCC} increases much slower due to the high pressure loss in the regenerator. Both reach their maximum some time after the closing of the valves, followed by a subsequent gradual decrease as a consequence of the heat losses. These are also clearly visible in the temperature histories, where also the effect of the distance from the regenerator can be seen in the difference of the two signals T_{flange} and T_{SCC}.

The flow measurement results are consistent with the data obtained in extensive CFD simulations performed as part of the development [8] and thus confirm the selection of the inlet port geometry, which was made on that basis. The observed swirl decay characteristic seems to be independent of the pressure and temperature levels considered due to the presence of overcritical conditions in the gas supply system at those levels. The target velocity range is reached at about 0.75 s. Hence, considering the pressure and temperature levels present in the chamber by that time, one can state that the targeted levels of 120 bar and 900 K have been reached. These conditions can then be adjusted by varying the accumulator pressure and/or the opening valve time and the regenerator core temperature.

Initial Application

The spray propagation inside the chamber has been visualized by means of the "Shadow-imaging" (background illumination) method [9] using an arc lamp source and a high-speed CMOS-camera. The illumination and observation windows were mounted in the outer position for obtaining optical access to the region directly adjacent to the injector tip in order to allow the observation of the initial spray propagation.

Figure 4 shows images of first test series at inert conditions (N_2), operating the chamber at 90 bar and 723 K at start of injection, injection pressure (p_{inj}) of 700 bar (case D: 500 bar), varying the injector specification (orientation of a single orifice, single vs. two-orifice and five-orifice injector similar to the one used on corresponding engines).

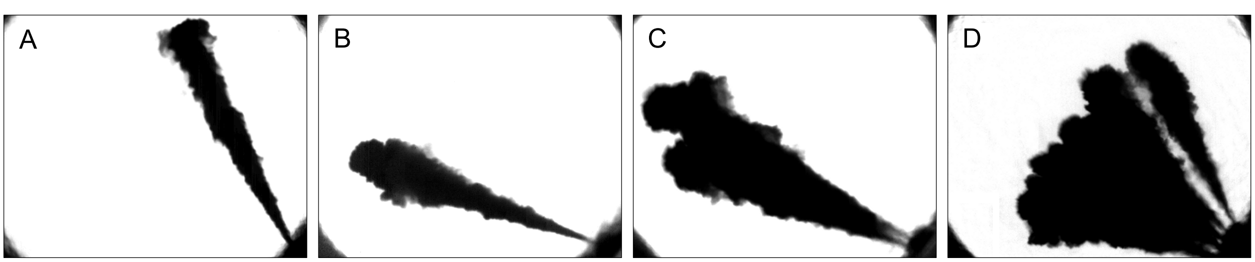

Figure 4. Shadow image samples taken at 500 µs after start of injection from tests with different nozzle tips at p_{SCC}=90 bar, T_{SCC}=723 K at inert (N_2) conditions, p_{inj}=700 bar (A, B, C), respectively 500 bar (D)

Case A represents an injector-co-axial spray (orifice diameter 0.875 mm). Due to the mounting angle of the injector, this corresponds to a spray inclination of 40 deg from a cross-flow orientation in the direction of the swirl. In contrast, case B is oriented exactly perpendicular to the swirl. Whereas there is no substantial effect discernible regarding the penetration of the spray (in spite of a 0.1 mm smaller orifice diameter) compared to case A, its radial expansion is clearly affected: The more pronounced exposure to cross-flow leads to a wider plume in the region behind the tip of the spray. Case C involves a two-orifice injector, one orifice being identical to the one of case B, the second orifice at a diameter 0.95 mm inclined by 10 deg in direction of the swirl. Here, despite the fact that the two sprays are starting to overlap already very early after leaving the injector tip, obvious differences in their behaviour are discernable: While the structure of the first spray is largely similar to the corresponding single-injector case, the second spray is characterized by a higher penetration and a considerable widening of the plume close to its tip, where it is no longer shielded from the action of the cross-flow by the first spray. This shielding effect can however also be expected to contribute to the higher penetration. With the five-orifice case D (note that the injection pressure is considerably lower here and the penetration correspondingly reduced), this is even more pronounced: Whereas the orifice size distribution, ranging from 0.975 mm of the more cross-flow oriented sprays down to 0.675 mm for the one inclined most in the direction of the swirl, would imply that the penetration should tend to decrease from the former to the latter, there are hardly any differences observed – in fact, the sprays originating from the smallest orifices seem to have the highest penetration. Again, the radial expansion of the sprays is decreasing with the orientation in direction of the swirl, resulting also in a lower degree of overlapping of the individual sprays.

The temporal evolution of the spray plume originating from an injector-co-axial single orifice is illustrated in Figure 5 by a sequence of shadow images taken at a time step of 50 µs.

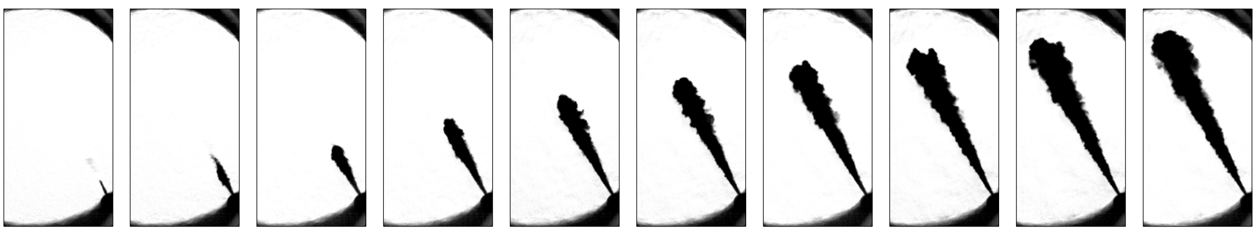

Figure 5. Temporal (50 µs) spray plume evolution p_{SCC}=75 bar, T_{SCC}=873 K, p_{inj}=700 bar

The qualitative behaviour is well in line with what has been observed in former investigations at smaller length scales [10]: During an initial phase, the spray is penetrating with constant speed, then eventually slowing down and forming a wider plume behind the tip of the spray. In the course of this second phase, the effect of the swirl is also becoming more apparent, whereas, in the initial phase, there are hardly any indications of a spray/swirl interaction: Despite the fact that the injector is inclined in swirl direction and the swirl effect must hence not be expected to be very pronounced, the plume behind the tip of the spray is clearly expanding more towards the direction of the swirl.

The irregular and random nature of the spray is also clearly visible in the formation of well-defined structures at its boundaries, which requires proper consideration in the (statistical) analysis of the shadow imaging data.

Figure 6 shows spray patterns obtained in different measurement series (8 out of total 20) at the same conditions (75 bar, 823 K, 700 bar injection pressure) at a given time of 350 µs after start of injection.

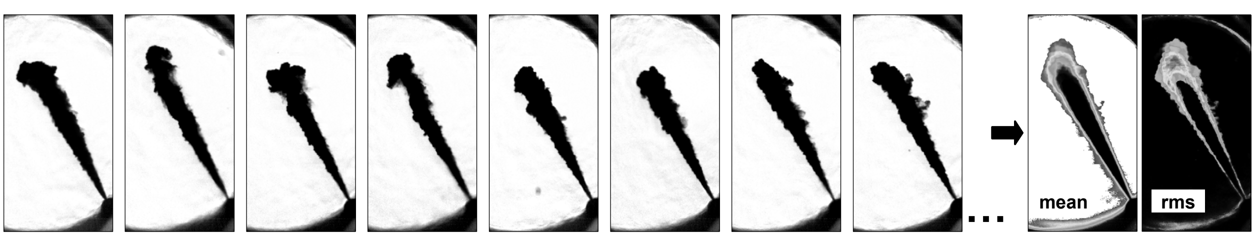

Figure 6. Sample shadow images from different measurement series at same conditions (p_{SCC}=75 bar, T_{SCC}=873 K, p_{inj}=700 bar), 350 µs after start of injection, including ensemble averaged and RMS data

These data confirm the robustness of the setup in showing a good reproducibility of key parameters such as spray penetration, which allows the statistical analysis of the data for the further evaluation of the results on the basis of a reasonably small number of individual experiments.

Reactive investigations have been performed for assessing the ignition behaviour at various chamber conditions. Figure 7 shows two sequences of images illustrating the ignition process at both low pressure and temperature and high pressure and temperature conditions in the spray combustion chamber at start of injection.

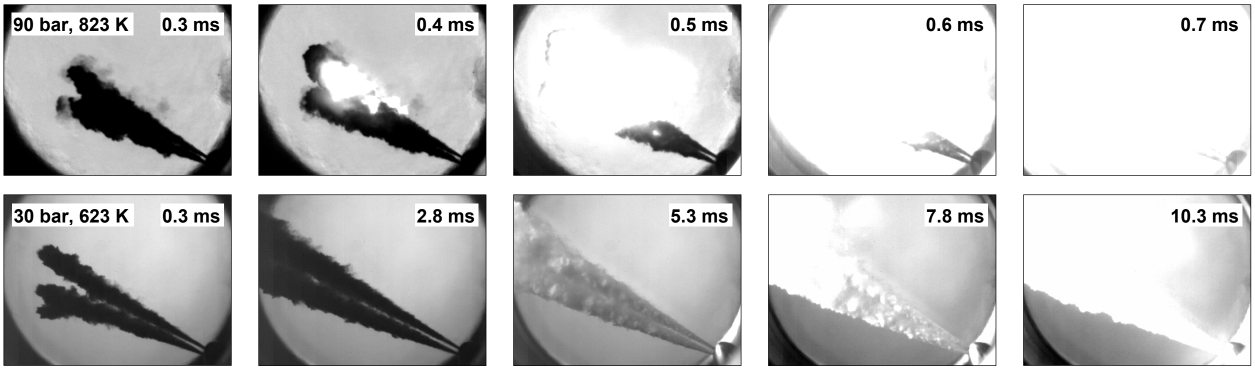

Figure 7. Ignition visualization for a low-pressure/temperature (bottom) and a high-pressure/temperature case

With the high pressure and temperature 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. When injecting into a low pressure and temperature environment, the ignition takes place considerably later and outside of the visible range and the flames are then propagating back towards the injector. The flame luminescence, dominating the background illumination once the combustion is fully developed, obviously represents a problem for the visualization of the spray in the late phase, which may however be overcome by using a pulsed light source in combination with a filter instead.

Conclusions

Following the realization of the experimental setup, its applicability for the investigation of spray and combustion processes at conditions typical of large marine two-stroke engines has been assessed by validating its performance against the requirement specification. Both in terms of the thermodynamic conditions and the flow characteristic inside the spray combustion chamber it could be demonstrated that the target levels have clearly been achieved.

The initial application has confirmed the robustness of the setup by showing a good reproducibility, which can be considered a good starting point for the following regular utilization of the setup for reference data generation on the basis of the statistical analysis of individual results.

First investigations under both non-reacting and reacting conditions have already provided valuable insight into the spray and combustion characteristics; in particular with respect to the effect of injector specification (orifice number, size and orientation) as well as swirl-interaction effects. This will be further enhanced in the later course of the application by extending the scope of the tests and utilizing also more advanced experimental techniques.

Acknowledgements

The present work has been conducted as part of the HERCULES-β project within EC's 7th Framework Program, Contract SCP7-GA-2008-217878. Financial support by the Swiss Federal Government (SER & SFOE) is gratefully acknowledged. We thank Mr. U. Müller (www.optolution.ch) for his extensive support in the flow investigations.

References

1. Rodatz, P., Weisser, G., Tanner, F.X, *SAE Congress 2000*, Detroit, USA, SAE 2000-01-0948.
2. Endo, H., Oda, Y., Okabe, M., Sakaguchi, K., *CIMAC Congress*, Hamburg, Germany, May 2001, pp. 665-672.
3. Kim, C.S., Lee, D.H., Cho, Y.S., *CIMAC Congress*, Hamburg, Germany, May 2001, pp. 1141-1148.
4. Weisser, G., Schulz, R., Wright, Y., Boulouchos, K., *CIMAC Congress*, Kyoto, Japan, June 2004, Paper No. 211.
5. Kyrtatos, N.P., Kleimola, M., Marquard, R., *CIMAC Congress*, Vienna, Austria, May 2007, Paper No. 31.
6. http://cordis.europa.eu
7. Herrmann, K., Schulz, R., Weisser, G., *CIMAC Congress 2007*, Vienna, Austria, May 2007, Paper No. 98.
8. Semadeni, S., Schulz, R., Wärtsilä Switzerland, Internal Report 2004.
9. Schneider, B., *ETH PhD thesis*, 2003, No. 15004.
10. Hiroyasu, H., Arai, M., Structures of Fuel Sprays in Diesel Engines, 1990, SAE 900475.