Impact of Evaporation, Swirl and Fuel Quality on the Characteristics of Sprays typical of Large 2-Stroke Marine Diesel Engine Combustion Systems

B. von Rotz[*1], K. Herrmann[1], G. Weisser[1], M. Cattin[2], M. Bolla[2] and K. Boulouchos[2]
1: Wärtsilä Switzerland Ltd, PO Box 414
CH-8401 Winterthur, Switzerland
2: Aerothermochemistry and Combustion Systems Laboratory, ETH Zürich
CH-8092 Zürich, Switzerland

Abstract

The acquisition of fundamental reference data with regard to the spray and combustion characteristics in large marine diesel engines is an absolute prerequisite for the systematic application of existing computational models. For this purpose, a novel experimental test facility has been realized to reproduce the operational characteristics of marine diesel engines at start of injection with respect to the thermo- and fluid dynamic conditions as well as regarding the physical dimensions. First reference data generated on the spray evolution (penetration, cone angle) by means of shadow-imaging contribute to the generally improved understanding of in-cylinder processes and allow the validation of simulation models. Based on preceding analyses of measurements at evaporating conditions, additional experiments have been performed to study the spray evolution in a non-evaporating environment at different gas densities. Moreover, the effect of the swirl level on the injected fuel spray has been investigated in order to obtain a better understanding of the interaction of the spray and the gas flow. Finally, the influence of fuel quality variations has been assessed by comparing data from first tests, where heavy fuel oil was used instead of light fuel oil.

Introduction

In the field of 2-stroke marine diesel engines, the availability of appropriate reference data is a basic requirement for the development and optimization of the combustion system supported by currently used Computational Fluid Dynamics (CFD) tools (e.g. [1]). The special characteristics associated with the sheer dimensions (bore/stroke ratio up to 960/3150 mm) as well as the involved operating conditions (e.g. injector size, nozzle hole sizes up to 1 mm and above) and time scales (between 61 and 135 rpm) impose particular demands on the calculation models and the simulation methodology, which both are hitherto based on the validation against reference data generated by combustion chambers or engines of smaller size and using fuel of much higher quality than commonly used in marine diesel engines.

In recent years, several encouraging results have been reported [2-4], but nevertheless limitations remain to apply in terms of the predictive quality of the available simulation models. The fuel injection and the ensuing mixture formation, ignition behaviour and combustion has been investigated using engines or motored devices [5, 6] to study the according in-cylinder phenomena. Additionally, for further scientific findings various test rig concepts have been realized with regard to an improved optical accessibility and the simplification of boundary conditions. Some designs of experimental combustor vessels are open flow-through constant pressure systems [7, 8], and accordingly, have a high repetition rate but are deficient in the ability to reproduce the pressure rise following the ignition, flame establishment and heat release. Other optically accessible closed chamber concepts such as rapid compression machines [9, 10] as well as high-temperature pressure constant volume vessels [11-13] have been employed to overcome this insufficiency and investigate the corresponding processes.

It has to be noted, however, that those efforts identify a clear lack of reference data relevant to the combustion system of large 2-stroke marine diesel engines. The spray models used so far have commonly been validated against data from those "small" spray combustion chambers operating on high-grade fuels at conditions representative of "smaller" (automotive, truck and off-road) engines [e.g. 14, 15]. In order to reflect the situation in large marine diesel engines various experimental facilities have been developed to study the spray and combustion processes [16-20].

A novel experimental setup [21] has been realized, in the context of the HERCULES (High-Efficiency R&D on Combustion with Ultra Low Emissions for Ships) research program [22] funded under EC's Framework Programmes [23], to investigate the spray and combustion behaviour. The specific requirements, especially regarding the combustion chamber design with its large dimensions as well as the pressure and temperature levels at

[*] Corresponding author: beat.vonrotz@wartsila.com

start of injection (SOI) exceeding 12 MPa and 900 K have been considered. Furthermore, the injection from the periphery into pronounced swirl is realized via multiple orifices of varying orientation and size of the individual orifices with the option of simulating two- or three injector configurations. Two parallel fuel systems enable the operation on a variety of different fuels including residual fuel types (HFO) customarily used in marine diesel engines. The optical accessibility for the appropriate application of both standard and (laser-) optical technologies for the generation of reference data is granted by the flexible window location design allowing to observe all regions of interest in the combustion chamber and the vicinity of the injection in particular.

Test Facility and Measurement Method

The spray combustion chamber (Ø500x150 mm) enables the investigation of in-cylinder processes at relevant conditions (up to 20 MPa peak firing pressure) such as fuel spray propagation and evaporation, ignition, combustion and emission formation [24]. The dimension of the optically accessible constant volume chamber is representative for smaller 2-stroke as well as larger 4-stroke marine diesel engines. At start of injection, realistic operating conditions are achieved by a pressure vessel/heat regenerating system (see Figure 1, left) providing heated and pressurized air (or nitrogen) through inclined inlet ports into the chamber.

The pressure vessels aggregate is equipped with fast actuating valves, which feed process gas via a so-called regenerator to the spray combustion chamber. This electrically powered heat exchange device grants a rapid temperature increase of the process gas flowing through it. Between several heating disks a cluster of metal plates is located and this design provides a high overall surface to volume ratio in order to achieve optimum heat transfer. The tilted intake channel generates an engine similar swirl in the spray combustion chamber, through appropriate selection of angle and flow area. In the chamber body multiple heating elements are implemented to ensure lower heat losses in combination with the fast filling process into the spray combustion chamber. The accumulator valves close just before the desired initial pressure and temperature condition in the chamber is reached and the fuel injection starts, followed by combustion in the reactive case. Afterwards the exhaust valve opens and the pressure is released. A compressor is refilling the accumulator with air or nitrogen and the regenerator is reheated again to the desired set conditions. Moreover, the setup allows the pressurization of the spray combustion chamber directly with the compressor. Thus, experiments without swirl acting on the injected spray can be investigated.

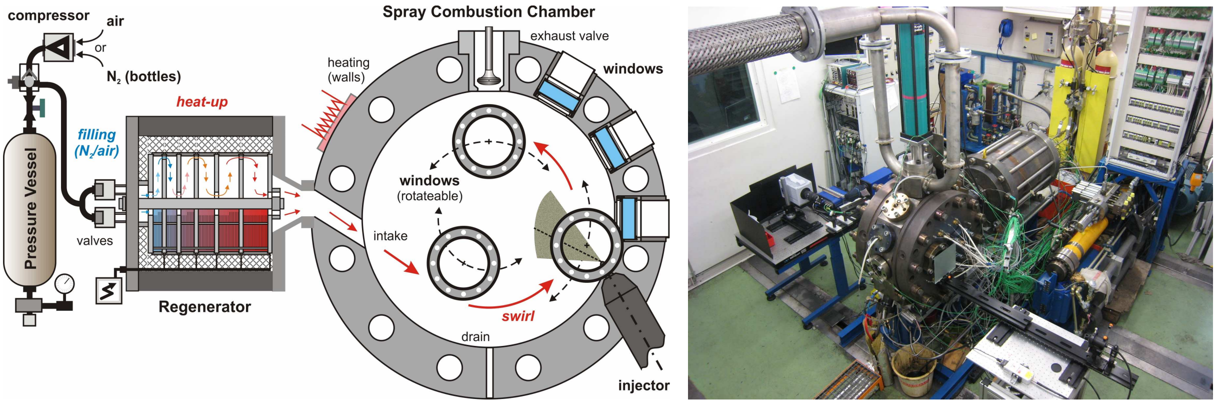
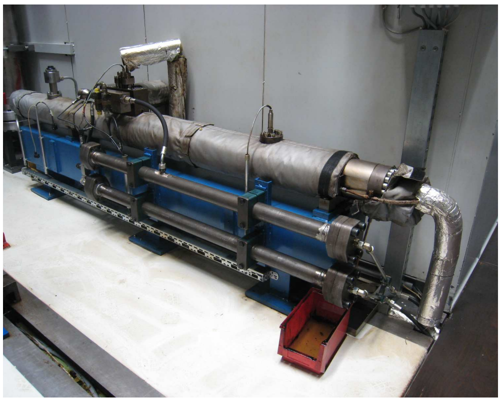


Figure 1 Left: Principle/schematic of the experimental setup, exemplifying the operational (filling, heat up, swirl, injection) and functional aspects (window position, exhaust valve). Right: Impression of the spray combustion chamber test facility.

An impression of the entire test facility setup including various subsystems can be seen in Figure 1 (right). To provide optical accessibility into the spray combustion chamber it consists of a main body and two cover plates with each including three holes, where a window holder or a dummy can be mounted. The view is granted by sapphire windows (Ø100 mm for the cover and Ø80 mm for the housing), which can be located at different radial positions relative to the axis of rotation. The special design of the chamber allows the rotation of the covers in sufficiently small incremental steps of 15 degrees relative to the chamber body.

The fuel admission is realized by an engine like injection system (common rail, pressure up to 120 MPa) through (one or two) injectors located at mid-height of the chamber on its circumference. The possibility to reproduce the 120 and 180 degree angular distance of the atomizers enables the investigation of spray interaction effects in the three- or two-injector configurations used on engines. The standard fuel injection system is used to run on fuels with a higher fuel quality (e.g. LFO, Diesel). In order to study all types of customary marine diesel fuel, the setup has been extended by building up a second, independent fuel oil system designed especially for the use with heavy fuel oil. It consists of a rail unit (Figure 2, left), an injection control unit and a HFO supply aggregate (Figure 2, right), representing the most important devices of the fuel injection system. The separate fuel rail is able to release pressurized HFO (up to 120 MPa) through a high-pressure fuel pipe connected to the atomizer mounted in the spray combustion chamber. For operation reasons the rail unit, the piping and the supply aggregate are heated (steam, partly electrical) and hence, insulated to minimize heat losses. The supply aggregate includes an electrical heater, filter unit, high-pressure pump as well as pressure and temperature indicators. Furthermore, a viscosimeter is installed to measure and control the fuel properties (kinematic viscosity and density). The implementation of overpressure valves, level indicators and an emergency system ensures safe, automatic and autonomous operation of the heavy fuel oil injection system.



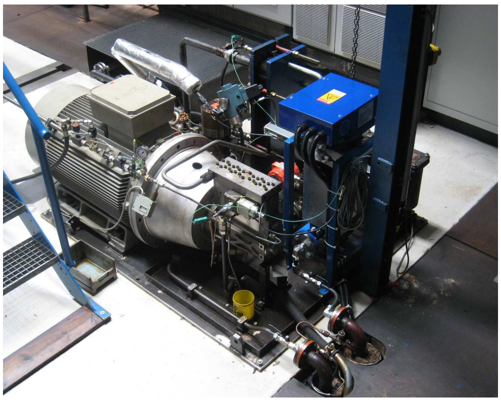


Figure 2 HFO fuel rail unit with the injection control unit on top (left) which is connected to the fuel supply aggregate (right).

To set the desired operation conditions pressure, temperature and swirl in the spray combustion chamber at start of fuel injection the accumulator pressure and/or the opening time of the fast actuating solenoid valves as well as the regenerator temperature have to be adjusted accordingly. The corresponding fill process is recorded with several pressure and fast responding temperature indicators installed at different positions in the spray combustion chamber setup.

The validation against the requirement specification of pressures up to 13 MPa and temperatures of more than 930 K (before injection/ignition) as well as target (swirl) velocity range 15-25 m/s has confirmed that all these conditions can be reached simultaneously [25].

An improved "Shadow-imaging" method [14] consisting of a pulsed diode laser light source and an appropriate narrow band pass filter (CWL 689.1 nm, T 60%, FWHM 10.6 nm) has been applied for visualizing the spray morphology inside the spray combustion chamber. The very short laser pulse within a 1μs exposure time of a high-speed CMOS-camera (20 kHz frame rate, 512x512 pixels) enables a high signal-to-noise ratio in the recordings. Moreover, the measurement method allows further observation and visualization of the fuel spray despite the ignition and combustion as the combination of filter and short exposure time suppresses the flame light.

Measurement campaign and analysis

Based on preceding results [26] of 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 behaviour, the effect of swirl as well as the influence of fuel quality (HFO) focusing on a 90 deg co-swirl (injector co-axial) nozzle case. Table 1 summarizes the experimental settings regarding the atomizer (nozzle) and operational conditions such as gas density, combustion chamber temperature, swirl, the used process gas (air: reactive; N_2: non-reactive) and the fuel properties of light fuel oil and heavy fuel oil.

To analyse the evaporation behaviour of the injected fuel spray nitrogen has been used as a process gas during the measurements. The non-reactive visualization of the spray gives a better insight of the spray morphology than reactive measurements as the complete evaporation cannot be observed due to the occurring combustion. Three different gas densities in the spray combustion chamber have been taken into account (33.7, 21.5 and 11.2 kg/m^3) at a constant temperature level of 900 K. The corresponding non-evaporating experiments were measured at the same gas densities but with a lower ambient temperature (400 K) inside the chamber. For the investigation of the swirl effect the chamber was pressurized directly (not via accumulator) with the compressor aggregate to the again same gas density and temperature levels for the non-evaporating experiments and hence, the fuel spray was injected in absence of swirl.

Gas density ρ [kg/m³]	Temp. [K]	Swirl	Process gas	Comments
33/22/11	900	yes	N_2	non-reactive
33/22/11	900	yes	N_2	non-reactive, HFO
33/22/11	400	yes	air	non-evaporating
33/22/11	400	no	air	non-evaporating

Nozzle hole ∅:	0.875 [mm]
Nozzle hole angle:	90 [deg] (Injector co-axial)
Regenerator temperature:	900/100 [°C]
Intake valve actuating time:	400 [ms]
Swirl flow level:	15 – 25 [m/s]
Chamber temperature:	900/400 [K]
Injection pressure:	1000 [bar]

Properties	Unit	LFO	HFO	Method
Density at 15°C	kg/m³	851.4	1001.1	ISO 12185
Viscosity at 40°C	mm²/s	2.928	-	ISO 3104
Viscosity at 50°C	mm²/s	-	1255	ISO 3104
Gross Heat of Combustion	MJ/kg	45.02	42.74	ASTM D240/D4809
Water Content	% V/V	<0.10	<0.10	ASTM D6304
Carbon Residue	% m/m	<0.10	17.84	ISO 10370
Sulphur	% m/m	0.09	0.806	ISO 8754/ASTM D2622
Ash	% m/m	<0.01	0.018	LP 1001/ISO 6245
Flash Point	°C	58	103	ISO 2719
Pour Point	°C	<-6	6	ISO 3016
Calculated Cetane Index	-	47	-	ISO 4264

Table 1 Summarized experimental settings and operational conditions (left) and fuel specifications (right) of the used light fuel oil (LFO) as well as heavy fuel oil (HFO).

In order to study the behaviour during sufficiently relevant periods, fuel spray recordings taken at various window positions had to be superimposed as indicated in Figure 3, with the number of positions needed depending on the chamber conditions (reactive/non-reactive, evaporating/non-evaporating). The deflection of the spray plume and the blown away fuel due to the swirl in the non-evaporating experiments were considered and measurement locations more on the left side of the axis of the orifice chosen. Furthermore, Figure 3 illustrates the measured spray evolution with typical examples of assembled spray recordings at evaporating (a), non-evaporating without swirl (b) as well as non-evaporating with swirl (c) conditions.

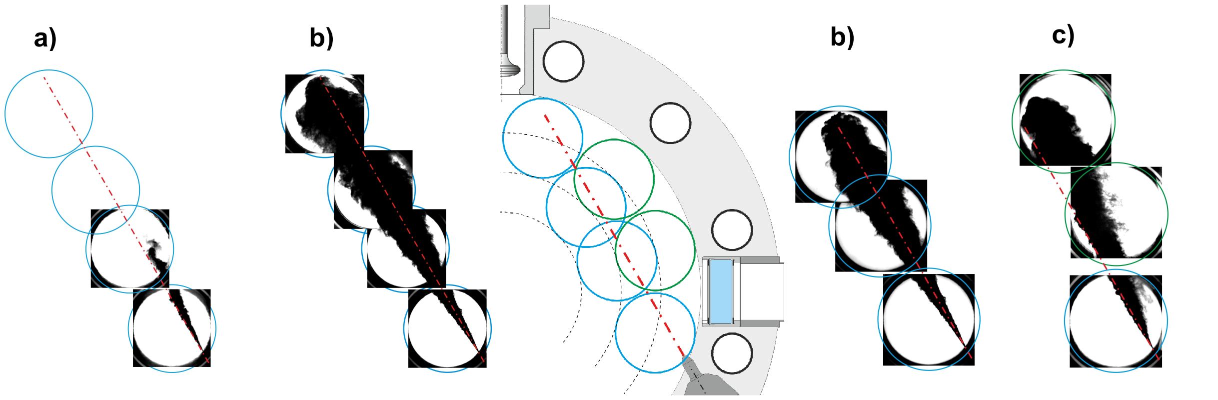


Figure 3 Visualization of the measured window locations and assembled sprays a) evaporating, b) non-evaporating without swirl and c) non-evaporating with swirl.

Quantitative reference data generation requires accurate detection of spray evolution with respect to spray tip penetration and cone angles. The recorded spray images of the measured data sets are post-processed including image intensity distribution correction and thereafter peak-stretching to ensure the comparability between each injection sequence. The outline of the spray is directly dependent on the minimum detectable droplet concentration and identified according a certain percentage of the background gray scale value (see Figure 4). A threshold of 90% defines the spray contour and 10% of the gray scale value outlines the dense core of the injected fuel spray. Decisive for the spray penetration is the axial distance from the atomizer tip to foremost point of the fuel spray. The cone angle Θ(x, t) of the spray corresponds to the angle between the upper and the lower periphery of the spray at a certain distance from the orifice and the respective angles to the spray axis define the "upper", "lower" angle of the fuel spray. Essential for the quantitative description is the identification of the magnification factor (mm/pixel) and the correct localization of the spray parameter, especially with regard to several measured window positions to visualize the entire spray evolution.

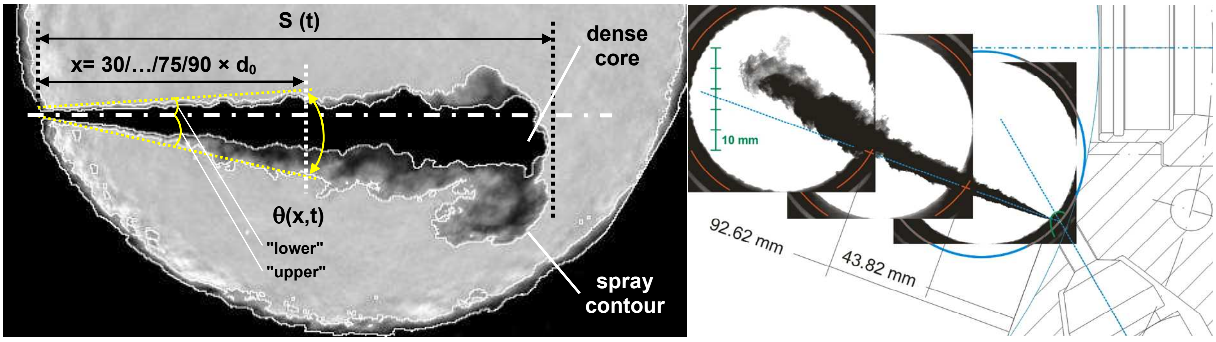


Figure 4 Spray penetration and cone angles (total, "upper", "lower") analysis according to two threshold levels (spray contour, dense core) and post-processing procedure/scale image.

The setup of the spray combustion chamber is operating in a highly repeatable manner. But each fuel injection is an independent event and therefore, variations and fluctuation in the fuel injection cannot be excluded completely. This uncertainty within each measurement set is adjusted corresponding to the simultaneously acquired needle lift signal. Hence, the according time scale is based on the start of needle lift (SONL). The individual sequences of the series of measurement sets are statistically evaluated (median) to obtain the data for the final analysis for the penetration and cone angles.

Results and Discussion

On the basis of the extensive measurement campaigns accomplished Figure 5 shows the spray tip penetration of the spray contour (left) and corresponding cone angle (right) of the single-hole co-axial nozzle configuration under variation of the gas density (33.7/22.5/11.2 kg/m^3) at two different temperature levels (900/400 K) inside a non-reactive (nitrogen) spray combustion chamber atmosphere. Besides the well-known spray propagating behaviour [27, 28], where during the initial phase the spray penetrates linearly proportional to the time and in a later phase a decrease of the gradient of the curve is clearly visible.

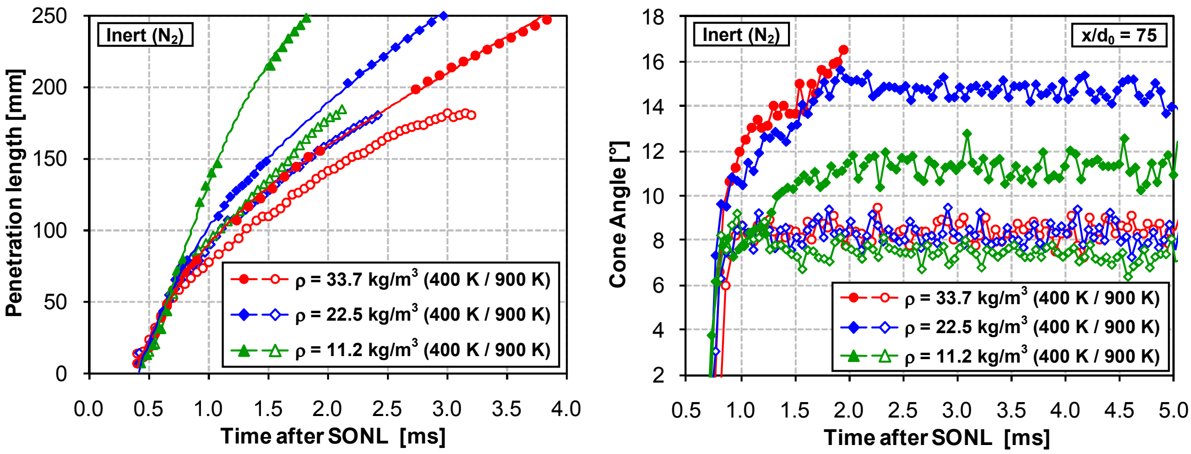


Figure 5 Impact of evaporation on the fuel spray penetration (contour, left) and cone angle (dense core, right) at x/d$_0$ = 75 after start of needle lift (SONL)

Furthermore, the relation of the gas density and the spray tip penetration can be recognized as the penetration is less pronounced with increasing density levels. The comparison of fuel injected in an evaporating (900 K) as well as non-evaporating environment (400 K) at constant pressure/temperature ratios illustrates the influence of evaporation on the fuel spray propagation: An increased spray tip penetration length at non-evaporating conditions can be observed with the effect becoming more distinct towards lower gas densities. The higher ambient temperature is causing evaporation of the droplets at the spray tip and periphery. This changes the penetration behaviour in such a way that the spray is propagating less far compared to the non-evaporating case. The spray injection at lower gas density level inside the chamber is enhancing this effect. It can be recognized that the cone angles of the spray at non-evaporating conditions are much wider opened as under evaporating conditions (see Figure 6). The impact of the gas density on the cone angle is much lower than the influence of evaporation. Note that the swirl is having a severe impact on the spray morphology: The cone angle of the measurement with the highest gas density cannot be evaluated completely due to the strong increase of the swirl-induced drift such that the spray outline is outside of the measurement range.

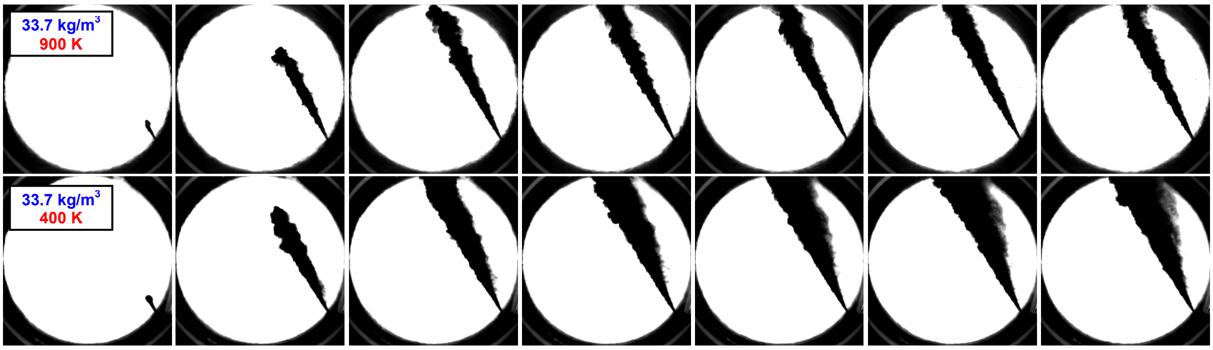


Figure 6 Visualization of the fuel spray at evaporating and non-evaporating conditions.

As indicated, it should be noted that these effects are clearly supported by the swirl flow influencing the fuel spray. In Figure 7 the results of the swirl vs. no swirl investigations can be seen. The experiments were performed at non-evaporating conditions (gas temperature of 400 K) and again, with the same gas density level variation. The absence of swirl affects the injected fuel spray such that clearly more pronounced reduction of the penetration length compared with the swirl influenced spray propagation is recognized, in addition to the above mentioned gas density dependency of the spray evolution. With a decreasing level of the gas density in the chamber, the influence becomes less distinct. The non-evaporating droplets of the fuel spray with swirl can penetrate faster into the combustion chamber as the momentum of the swirl flow is acting on them. The increase of the distinction with higher ambient density is due to the bigger aerodynamic forces taking effect on the spray plume and its fuel droplets. The cone angles show a significant influence of the swirl on the injected fuel spray. The comparison of the "upper" and "lower" angle values of the spray injected without the swirl indicate the much more uniform distributed spray shape. The strong deflection of the spray observed at injections into the swirl is clearly recognizable.

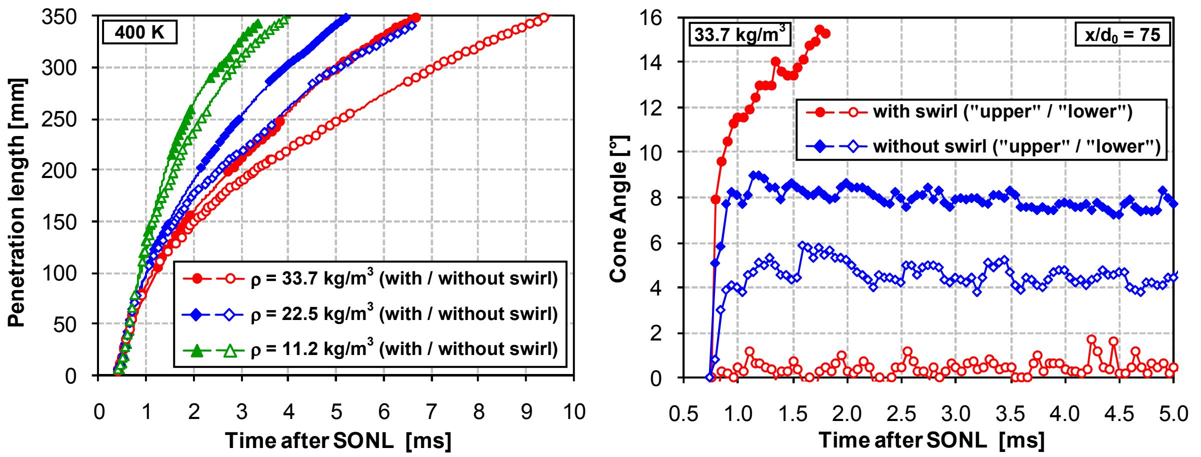


Figure 7 Spray penetration (contour) and comparison of the "upper" / "lower" angles at x/d_0 = 75 with and without swirl inside the combustion chamber.

In order to allow an evaluation of fuel quality effects, in particular the comparison of heavy fuel oil to the light fuel oil used in previous investigations, a second, parallel fuel injection system suitable for such media has been added to the installation. First measurement campaigns with the extended injection system have been performed. Figure 8 is showing the impact of the fuel quality on the spray parameters (spray penetration, angles) at various gas density levels. The spray tip penetration of injected light fuel as well as heavy fuel oil is visualized. The comparison of light fuel and heavy fuel oil sprays injected at evaporating conditions indicates that the fuel properties influence spray evolution and morphology consistent with earlier investigations using different fuels [29]. The changed fuel composition and properties of the injected fuel have a large influence on the length of the dense core. At the beginning of the spray propagation the behaviour of the two fuel types are in line with each other. At a later stage of the spray evolution, the dense core of the light fuel oil spray stabilizes at a certain distance. The injected HFO spray is on the contrary propagating further into the chamber as the differences of the fuel property (e.g. saturation pressure) have an impact on the evaporation process and the spray evolution. The corresponding cone angles of the spray reflect the increased influence of the ambient gas density on the spray and the slower evaporation at the spray periphery of the injection with HFO.

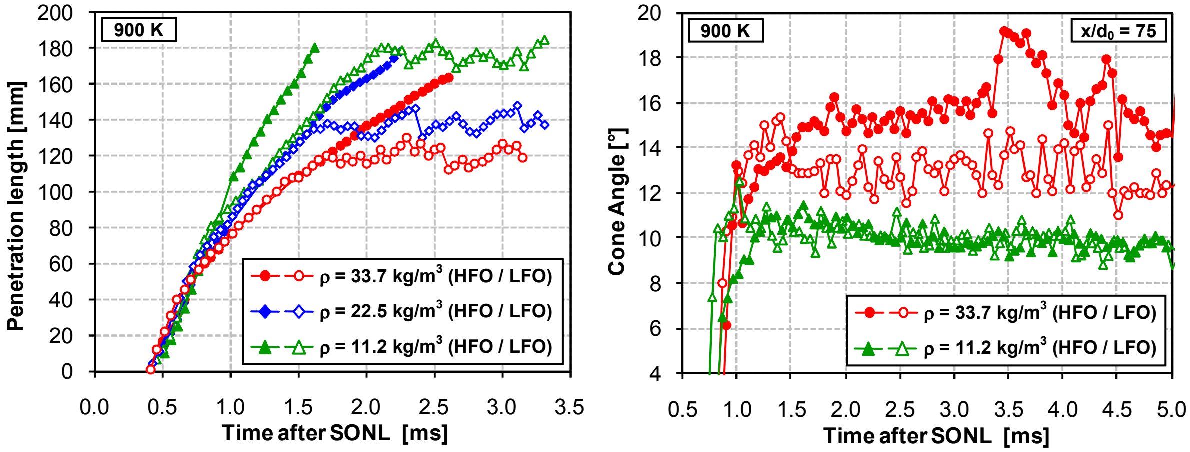


Figure 8 Comparison of light fuel and heavy fuel oil influence on spray tip penetration (dense core) and the cone spray angles (dense core) at $x/d_0 = 75$.

Conclusion

The extensive measurement campaigns accomplished at evaporating (non-reactive) and non-evaporating conditions as well as investigations with different fuel types under variation of ambient gas density contribute to an enhanced understanding of evaporation swirl and fuel quality on the characteristics of sprays typical of large 2-stroke marine diesel engine combustion systems. The reported results determine relevant impact on the spray characteristics such as penetration and spray angles.

A further reflection of the correlations between the macroscopic spray parameter findings will give more information about the complex processes of the macroscopic spray behaviour, especially with regard to the swirl influence on the spray evolution. The next steps will involve an assessment against empirical spray propagation models and in addition, more detailed investigations on the influence of the boundary conditions (e.g. injection system) and studies of microscopic spray parameters.

These studies finally enable acquiring insight into the key in-cylinder processes at conditions relevant for large marine diesel engine combustion systems, using also fuels typically applied in this sector. This is also expected to enhance the development of CFD models [30] for this purpose, with the ultimate target of applying them for the predictive simulation and optimization of those systems.

Acknowledgement

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 Contract 154269, Project 103241) is gratefully acknowledged.

References

[1] Weisser G., Schulz R., Wright Y., Boulouchos K., *CIMAC Congress*, Kyoto, Japan, June 2004, Paper No. 211.
[2] Rodatz P., Weisser G., Tanner F.X., *SAE Congress*, Detroit, USA, 2000, SAE 2000-01-0948.
[3] Endo H., Oda Y., Okabe M., Sakaguchi K., *CIMAC Congress*, Hamburg, Germany, May 2001, pp. 665-672.
[4] Kim C.S., Lee D.H., Cho Y.S., *CIMAC Congress*, Hamburg, Germany, May 2001, pp. 1141-1148.
[5] Bruneaux, G., Verhoeven, D., Baritaud, T., SAE 1999-01-3648 (1999)
[6] Desantes, J.M., Pastor, J.V., Payri, R., Pastor, J.M., *At. Sprays* 15:517–543 (2005)
[7] Koss, H.J., Brüggemann, D., Wiartalla, A., Bäcker, H., Breuer, A., *Final Report of JOULE Project on Integrated Diesel European Action* (IDEA), 1992.
[8] Vogel, S., Hasse, C., Gronki, J., Andersson, S., Peters, N., Wolfrum, J., Schulz, C., *Proc. Combust. Inst.* 30:2029–2036 (2005).
[9] Akiyama, H., Nishimura, H., Yasumitsu, I., Iida, N., *JSAE Rev.* 19:319–327 (1999).
[10] Balles, A., Heywood, J.B., SAE 880206 (1988).
[11] Pickett L.M., Siebers D.L., *Combustion and Flame* 138:114-135 (2004).
[12] Bruneaux G., *Atomization and Sprays* 11:533-556 (2001).
[13] Yu J., Bae C., Proc. Instn Mech. Engrs 217:1135-1144 (2003).
[14] Schneider B., *PhD thesis*, No. 15004, ETH Zurich, 2003.

[15] Wright Y.M., Margari O.-N., Boulouchos K., De Paola G., Mastorakos E., *Flow Turbulence Combust* 84:49-78 (2010).
[16] Negus C.R., Dale B.W., Stenhouse I.A., McNiven A.J., *CIMAC Congress*, Warsaw, Poland, 1987, Paper No. D-78.
[17] Takasaki K., Tajima H., Nakashima M., Ishida H., *CIMAC Congress*, Hamburg, Germany, May 2001.
[18] Nakagawa H., Oda Y., Kato S., Nakashima M., Tateishi M., *COMODIA 90*, pp. 281-286, 1990.
[19] Buchholz B., Pittermann R., Niendorf M., *CIMAC Congress*, Vienna, Austria, May 2007, Paper No. 129
[20] Imahashi T., Tomita E., Kimoto T., , *CIMAC Congress*, Vienna, Austria, May 2007, Paper No. 177
[21] Herrmann K., Schulz R., and Weisser G., *CIMAC Congress*, Vienna, Austria, May 2007, Paper No. 98.
[22] Kyrtatos N.P., Kleimola M., Marquard R., *CIMAC Congress*, Vienna, Austria, May 2007, Paper No. 31.
[23] http://cordis.europa.eu
[24] Herrmann K., von Rotz B., Schulz R., and Weisser G., *ISME 2011, 9th International Symposium on Marine Engineering*, Kobe, Japan, October 2011
[25] Herrmann K., Kyrtatos A., Schulz R., and Weisser G., *ICLASS 2009, 11th Triennial International Annual Conference on Liquid Atomization and Spray Systems*, Paper No. 005, Vail, Colorado USA, July 2009.
[26] Herrmann K., et al., *ILASS – Europe 2010, 23rd Annual Conference on Liquid Atomization and Spray Systems*, Paper No. 139, Brno, Czech Republic, September 2010
[27] Hiroyasu H., Arai M., SAE 900475 (1990).
[28] Naber J.D., Siebers D.L., SAE 960034 (1996).
[29] Higgins B.S., Mueller C.J., and Siebers D.L. SAE 1999-01-0519 (1999).
[30] Schulz R., Herrmann K., von Rotz B., Hensel S., Seling F., Weisser G., Wright Y.M., Bolla M., Boulouchos K., *CIMAC Congress*, Bergen, Norway, June 2010, Paper No. 247.