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HERCULES
Advanced Combustion Concepts
Test Facility: Spray/Combustion Chamber

Autor und Koautoren	Kai Herrmann
beauftragte Institution	LAV – IET ETH Zürich
Adresse	ML D44.3 – Sonneggstrasse 3, CH-8092 Zürich
Telefon, E-mail, Internetadresse	01-632 46 26, herrmann@lav.mavt.ethz.ch, www.lav.ethz.ch
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ZUSAMMENFASSUNG

HERCULES steht für ein international übergreifendes F&E Projekt (6. EU Rahmenprogramm), in welchem neue Technologien in Bezug auf Schiffsmotoren entwickelt werden Ein Teilprojekt befasst sich mit der Anwendung und Erweiterung von Verbrennungsprozess-Simulationsmodellen, für dessen Entwicklung und Validierung experimentelle Daten benötigt werden. Dieser Beitrag bezieht sich auf die Entwicklung eines experimentellen Versuchsträgers, welcher das Verbrennungssystem grosser Zweitakt-Schiffsdieselmotoren unter Berücksichtigung der charakteristischen Bedingungen weitestgehend repräsentieren soll und mit welchem die benötigten Referenzdaten generiert werden sollen.

Die Entwicklung eines neuen Versuchsstandes, mit welchem relevante Bedingungen des Verbrennungssystems grosser Zweitakt-Schiffsdieselmotoren experimentell realisiert werden können, ist auf einem erfolgversprechenden Weg. Dabei konnten Vorgaben hinsichtlich Dimensionen, Druck- und Temperaturbereichen weitestgehend berücksichtigt und allfällige Restriktionen gering gehalten werden. Das Kernstück der Anlage besteht aus einer "Spray/Verbrennungs-Kammer" mit äusserst flexibler optischer Zugänglichkeit, variablen realistischen Strömungsbedingungen und einem realen Einspritzsystem, deren konstruktive Auslegung fertiggestellt werden konnte. Unter Einhaltung der definierten Systemspezifikationen wurden zusätzlich erforderliche Elemente und periphere Komponenten der Gesamtanlage bereits umfassend evaluiert oder konstruiert. Anhand von numerischen Simulationen (in Zusammenarbeit mit *Wärtsilä Switzerland Ltd*) konnten die bestehenden analytischen Auslegungsberechnungen sowie konstruktive Anforderungen im Detail überprüft werden. Die Resultate bestätigten die konzeptionelle Überlegungen und förderten den weiteren Entwicklungsprozess. Im Hinblick auf die innerhalb dieses Projektes voraussichtlich einzusetzenden optischen Messverfahren, konnte mit Hilfe von Messungen der Brennstoffstrahlausbreitung (in einer bestehenden Versuchskammer HTDZ am *LAV*) zudem das mögliche Potential von Hochgeschwindigkeits-Kamerasystemen evaluiert werden.

Im nächsten Projektjahr sollen die konstruierten Elemente gefertigt, die evaluierten Komponenten beschafft und die Gesamtanlage aufgebaut werden. Anschliessend ist das sich ansatzweise bereits in Entwicklung befindende Steuerung- und Regelungssystem zu integrieren. Nach einer Phase der Inbetriebnahme sowie einer Adaption der optischen Messtechnik sind voraussichtlich gegen Ende Jahr erste Basismessungen im Hinblick auf experimentelle Referenzdaten möglich.

Project Objectives

HERCULES (High Efficiency R&D on Combustion with Ultra Low Emissions for Ships) stands for a large scale cooperative R&D project – set up as an Integrated Project (I.P.) in the context of EU's Sixth Framework Programme (fp6) – which will develop new technologies to drastically reduce gaseous and particulate emissions from marine engines and concurrently increase engine efficiency and reliability, hence reduce specific fuel consumption, CO_2 emissions and engine lifecycle costs [1]. The main project consists of different workpackages (WP) which are divided into two tasks each. This work is a contribution to the *Task 2.1: Combustion Process Simulation* within *WP-2: Advanced Combustion Concepts* [2]. The general aim of this task is to promote the application of advanced simulation models (extension and adaption of existing sub-models as well as development of new models) of key in-cylinder processes with respect to marine engine combustion, based on their validation against experimental data. For this purpose, advanced test facilities have to be developed, specifically in view of the fact that the performance of typical spray models (applicability commonly verified only for smaller engines with higher rpm) with respect to large two-stroke marine engines at low rpm, where in addition, a different kind of injection from the periphery into strongly swirling air flow takes place, is rather questionable. Moreover, since there is hardly any experimental data available allowing a direct validation of models describing the key phenomena under those conditions. Hence, the development of advanced models requires fundamental experimental investigation of spray processes associated to ranges of length and time scales similar to those present in two-stroke marine diesel engine combustion systems.

For this purpose, our participation is related to the development of a spray/combustion chamber which should represent the combustion system present in large two-stroke marine diesel engines as close as possible. This experimental setup shall then be used to generate spatially and possibly temporally resolved reference data with regard to the advanced model development. A certainly necessary simplification of some design and operational parameters of the new test rig shall be kept to a minimum, to allow the investigation of spray, mixing and combustion still under conditions characteristic of marine engines, including spatial dimensions and component design (injector location), flow behavior (swirl) as well as pressure, respectively temperature levels during injection. In addition, the test facility should also allow inert (without combustion) investigations and, in relation to the investigation of fuel quality effects, shall be prepared for heavy fuel oil injection.

The described requirements according the comparability to large two-stroke diesel engine processes are also connected to other considerations with respect to applicable measurement techniques. To avoid any disturbances of the involved flow field, spray and combustion propagation as well as emission formation processes, the use of (as far as possible) non-intrusive (optical, laser) measurement methods (active and passive) is absolutely favorable. Their specific properties and limits, such as spatial (and possibly temporal) resolution with respect to feasible measurement locations have to be taken into account. Another question is also the operationally feasible repetition rate of the entire to projected system in view of requirements in terms of statistical relevance.

An iterative process of decision making to clarify system, respectively single components specifications – also taking general feasibility, expected limits and justifiable costs into account – represents the basis with regard to the development of the spray/combustion chamber test facility. The resulting specific **aims** for the first project year can be described as follows:

- **concept**: design and thermodynamic considerations to achieve desired conditions
- **design spray/combustion chamber**: optical access, characteristic swirl and injection
- **setup evaluation of entire test facility**: components, periphery and system specifications
- **proof of concept**: iterative development involving detailed CFD simulations
- **applicable measurement techniques**: evaluation and preliminary tests on existing facility

Accomplishments and Results obtained

An extensive **concept** study first lead to a review of major general considerations as well as the state of the art in the literature. In order to investigate in-cylinder phenomena, the availability of optical access obviously plays a key role. Considering the size of large two-stroke marine diesel engines, an "optical single-cylinder" facility is out of question. Due to the initial pressure and temperature conditions of about 130 bar and 900 K, a constant pressure test rig [3] under continuous flow (high repetition rate) is not feasible either. The most promising starting point corresponds to a constant volume cell with advantageous possibilities regarding optical access, whereas the isochoric character sets demands with respect to the initial and maximum p-/T-conditions. For typical engine combustion parameters (air/fuel ratio $\lambda_V \approx 2.0$ at load ≥25%), adiabatic equilibrium calculations (*CHEMKIN*) of n-heptane (C_7H_{16}) show a pressure rise up to 300 bar. Therefore a restriction of the initial pressure (p≈90 bar) and a leaner combustion ($\lambda_V \approx 4.0$) is required to avoid exceeding the typical engine peak cylinder pressure (p≈160 bar).

A possibility to reach proper initial conditions in constant volume chambers is the application of an internal pre-combustion of hydrogen [4] or specific gas mixtures [5], [6]. Figure 1 (left) shows the principle of a premixed H_2 combustion based pressure and temperature raise, followed by the diesel injection and combustion after a certain p-/T-level decrease. Detailed calculations (Fig. 1, right) have been performed to estimate a possible application in this project. A certain start level (30/40 bar, 300/400 K) is still necessary and a pure H_2/air mixture leads to a considerably lower oxygen concentration (15..16%), which strongly affects the diesel process. To avoid this, a costly mixture gas preparation with different partial pressures of H_2, O_2 and N_2 would be necessary, whereas the amount of remaining (and disturbing) vaporized H_2O is still about the same. However, the main disadvantage is the enormous flame propagation speed of H_2, which affects the very important creation of reproducible swirl conditions in this case. Therefore, this concept has been discarded, also with regard to the needed infrastructure (costs) for fulfilling the security requirements for handling of hydrogen.

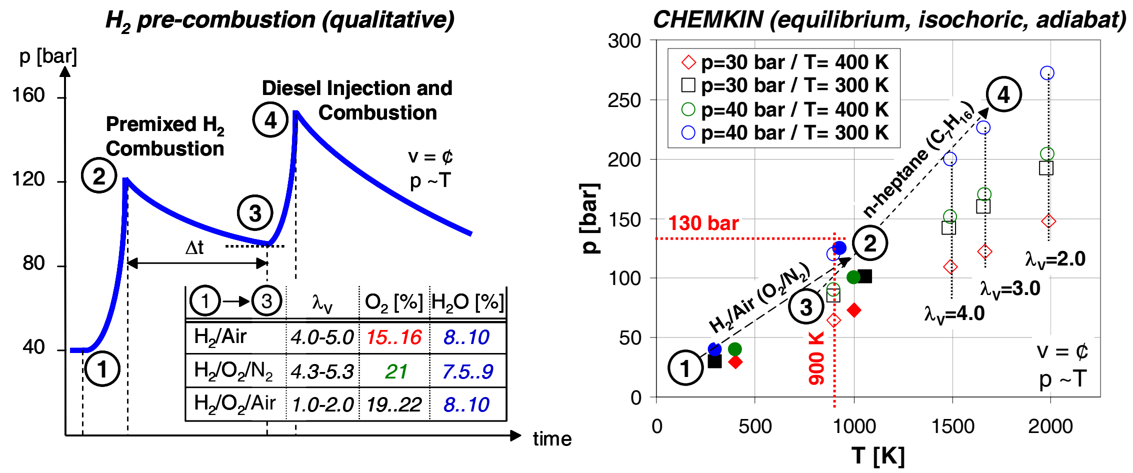

Fig. 1: Concept and calculation results of hydrogen pre-combustion in a constant volume cell.

Another possibility to achieve the initial pressure and temperature conditions consists in the application of a kind of pressure/heat accumulator. This is usually a more challenging way, but offers specific advantages with respect to the spray/combustion chamber requirements. A so-called "high pressure/high temperature cell" has already been developed at the LAV-IET und successfully used for spray investigations [7]. The "autoclave system" provides already heated process gas under full pressure. An identical adaption to this project is not advisable, due to the much smaller dimensions, a different injection system, required flow conditions (swirl) and other general demands. Nevertheless, the experience from the existing cell was very helpful in guiding the design of the present cell. In the course of the present work, a layout shown in Figure 2, based on a pressure accumulator/heat regenerator system, has finally been developed and is based on thermodynamics and fluid dynamics calculations.

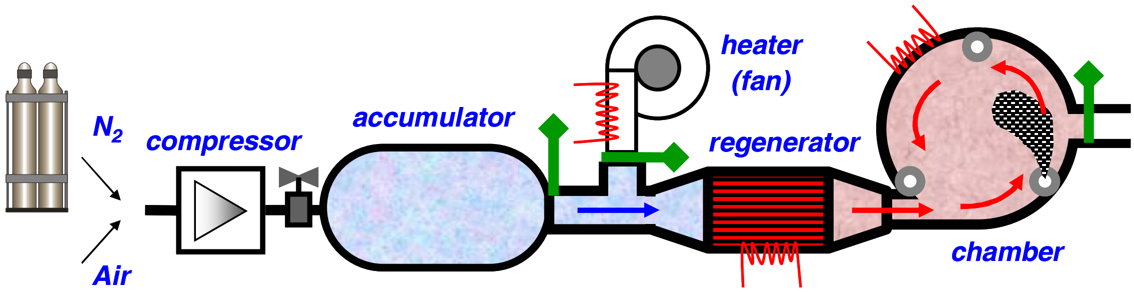

Fig. 2: Principle of spray/combustion chamber with the pressure accumulator/regenerator system.

A so-called regenerator is heated up to about 900° C – externally through electrical devices and internally through a heater, which also heats up the inner cell walls. It consists of heat recovering material of enough mass and provides small flow cells to achieve a high surface to volume ratio. When the desired temperature is reached, a fast valve, coupled to an accumulator bottle under the pressure of 200 bar, opens, and air or nitrogen (inert investigations) is heated up by flowing through the regenerator. The connection to the spray/combustion chamber generates engine similar swirl and the fast filling process provides low heat losses. Once the initial pressure is reached, the accumulator valve closes and the injection/combustion takes place. Finally, the exhaust valve opens, the regenerator is heated up again, and a compressor is refilling the accumulator.

The **design of the spray/combustion chamber** is displayed in Figure 3. The inner diameter of 500 mm corresponds to a smaller commercial two-stroke marine diesel engine. It consists of a ring and two cover plates, which include three holes where for each measurement one window and two cover dummies (containing p-,T-sensors) on each side are mounted. As a consequence of the window location at three different radius values on concentric circles, practically every desired observation view in the area of interest can be arranged by turning the cover plates in a defined step width of 15°. Together with further window mount possibilities in the inner circle, the wide range of optical access allows two-dimensional spray injection and combustion observation by different optical measurement techniques (see below). In contrast to the location in the engine cylinder cover, the injectors are mounted in the inner ring, such that optical access to the nozzle tip is also possible. The lower right main injector is fixed, whereas in order to investigate spray interaction, a second injector can be operated, separated by an angle of 180° or 120° from the first one, corresponding to typical engine designs with either two or three injectors.

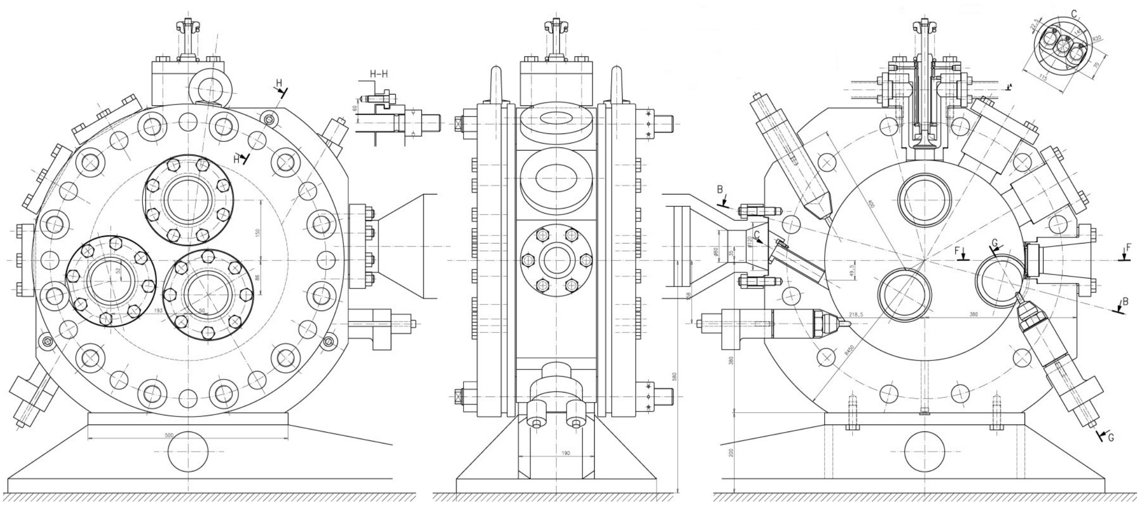

Fig. 3: Design of the spray/combustion chamber with windows, injectors, intake and outtake.

The intake channel is located across the main injector and consists of three bores in line, whose diameters can be adjusted for realizing different swirl levels and characteristics. It remains open to offer a certain volume increase with respect to the topic of maximum pressure peak in isochoric environment, the exhaust gas at the same time assisting to re-heat the regenerator. The entire spray/combustion chamber is designed to handle pressures up to 200 bar. A proposed exhaust valve opens against outside and thus at the same time acts as a security valve at critical pressures. An example of window placement and the resulting optical access at the outer border through the combustion chamber with a depth of 150 mm is shown in Figure 4. The sapphire windows, mounted in specifically designed holders, are able to resist to pressures up to 250 bar.

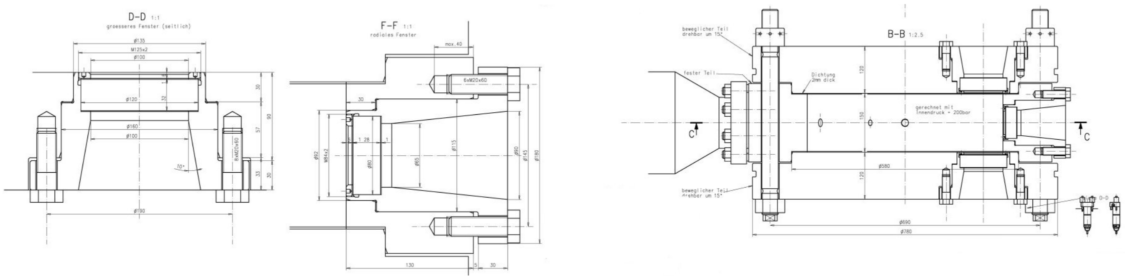

Fig. 4: Windows (D=120, 80 mm), holders, mounting location in the spray/combustion chamber.

The interactive and parallel performance of thermo- and fluid dynamical calculations, chamber design and periphery component considerations as well as CFD simulations (see below) lead to a detailed **setup evaluation** and a definition of the **entire test facility** system specifications. A schematic overview of all main components, resulting and operational phases is displayed in Figure 5. In addition to the previous description, the advantageous optical access properties of the chamber are shown with respect to injection nozzle and angles. The exhaust/security valve is driven by a pneumatic cylinder. Heat cartridges will keep the insulated cell walls on a constant temperature of about 200 °C. This should still allow window handling but reduces the heat loss and hopefully helps to evacuate the chamber of unburned fuel (inert experiments) through a drain valve. On the other side, the pressure accumulator (75 l/360 bar) has large fittings to provide the required mass flow rate. The entire piping system, including periphery elements, is evaluated and designed, whereas the intake must probably be cooled. The main valves responsible for fast filling can open in 80 ms and close in 120 ms. The compressor can be driven by air or nitrogen and is able to refill the pressure accumulator within 5-10 minutes.

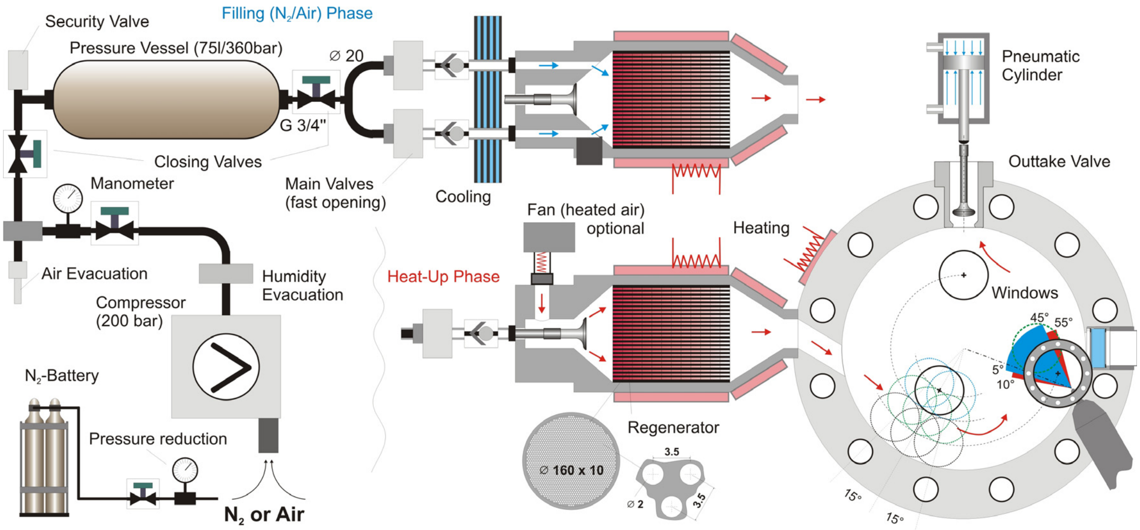

Fig. 5: Schematic drawing of the entire test facility setup, including operation phases.

This is about the same time as required for re-heating the regenerator after a shot, whereas at the beginning of an experiment a heat up time of a few hours should be expected. The regenerator system consists of a larger pressure coat, insulated against an electrically heated inner core. The inner core consists of either plates with thousands of small wholes, a bundle of pipes, or a plate construction. The thermodynamic requirements have been estimated and reviewed (CFD, see below) – the optimum design with regard to the enormous electrical heating up to 900 °C is still under investigation. Also depending of design aspects, an optional hot air fan might be used, which could also pre-heat the inner walls and the windows of the spray/combustion chamber. Due to the open intake, exhaust gases will also contribute to the heating, whereas from the security point of view, the regenerator also acts as a flame arrester. Other facilities representative of the present development (corresponding to inert operation [8], in the absence of swirl [9]) are also reported. In the present effort, the previous limits of pressure, temperature and swirl number are further considerably extended.

The **proof of concept** is based on an iterative development review according strongly relying on the utilisation of advanced simulation tools. In collaboration with our group, numerical simulations have been performed by *Dr. Reiner Schulz* of *Wärtsilä Switzerland Ltd* and his team [10], using the *STAR-CD CFD code*. In those simulations a model was build and tested for the case of non-reactive flow under conditions similar to those of the experiment design. Representative results of the velocity magnitude and temperature distribution at a certain time step are shown in Figure 6.

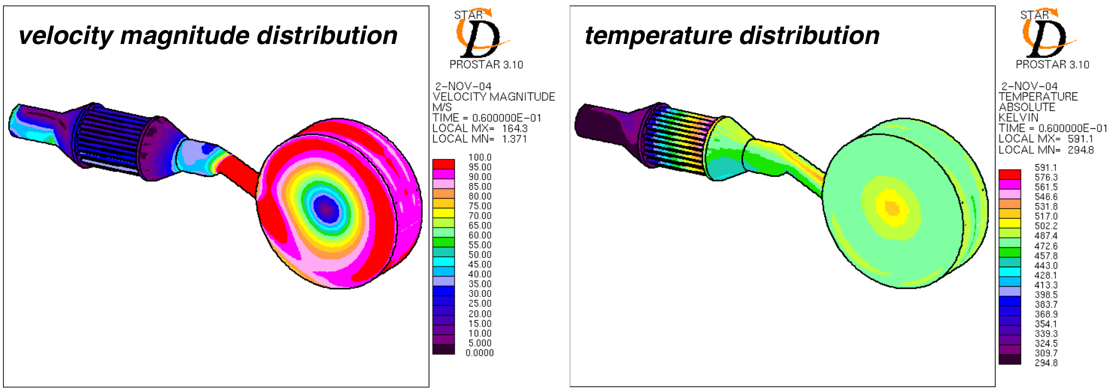

Fig. 6: Computed spatial velocity magnitude and temperature distribution of a regenerator with the chamber

Those results were very helpful in confirming the validity of the parameters obtained by the rest of the design procedure. In particular, this applies to the dimensioning of the chamber intake channel bore diameters to achieve realistic swirl conditions and to the regenerator design (Figure 7).

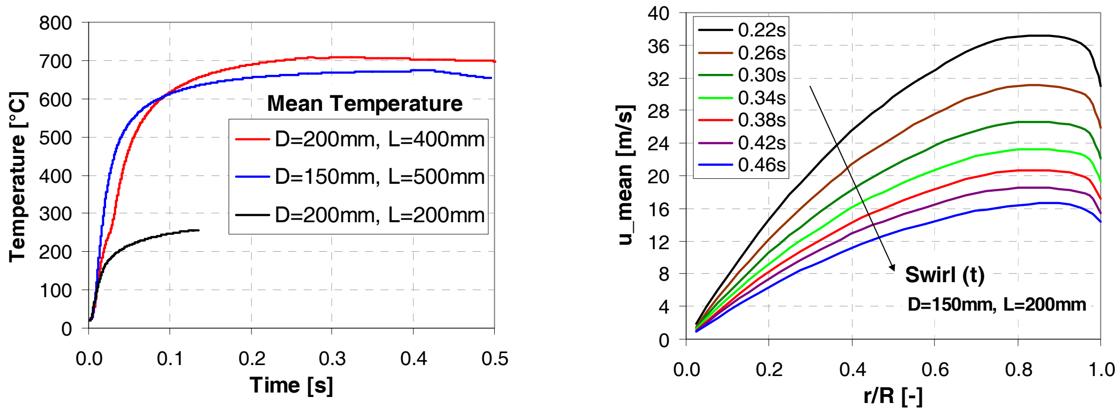

Fig. 7: Mean temperature for different regenerator designs (left) and swirl behavior (right) in the chamber

The identification of **applicable measurement methods** is another important point, which has been taken into account in the development so far. Here, the passive optical measurement methods *Shadow-Imaging*, to investigate the spray penetration (liquid phase), and the *Schlieren* technique, to identify spray phase zones (liquid, vapour) are of main interest. According to the specific characteristics of large two-stroke marine diesel engines, information with regard to the flow field, respectively swirl is also of strong benefit. A possible application of *Particle Image Velocimetry* (*PIV*), to measure series of quantitative two-dimensional vector fields, followed by a statistical analysis would also be very attractive. Nevertheless, the feasibility is at risk due to the high pressure levels of the present investigation. However, the advantages of the experimental techniques available should be fully exploited. Because of the relatively low repetition rate of the test facility, fast image acquisition rates would be desired. We used the availability of the existing high pressure high temperature cell [7] at our laboratory and took advantage of the opportunity to test high-speed camera systems currently available on the market. The cell was operated at 40 bar / 400 K under standard conditions of 500 bar injection pressure and 1.2 ms injection time.

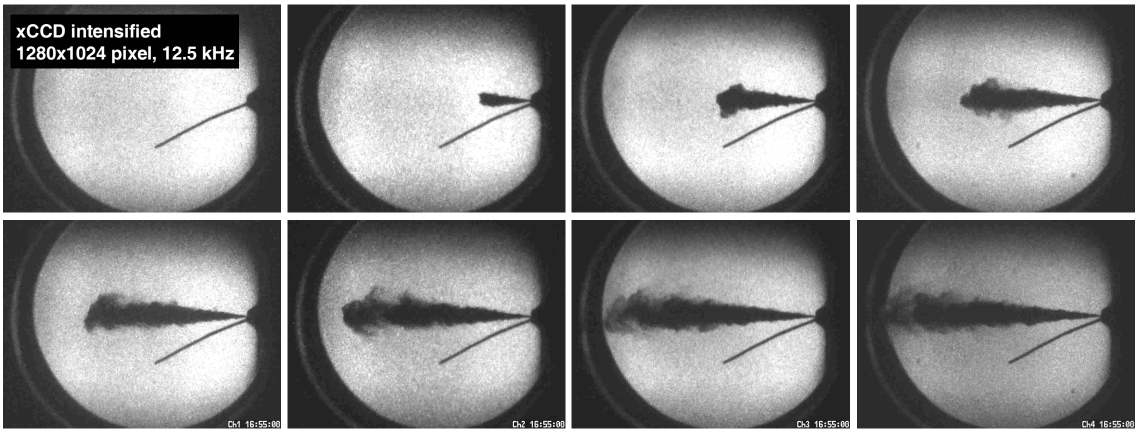

Fig. 8: Shadow-imaging test recordings of a high-speed multi-ICCD-camera (12.5 kHz, 1280x1024 pixels).

The first camera system consists of a combined setup of four intensified CCD cameras, which can be controlled individually; this allows the simultaneous application of several measurement methods. The minimum interframing time distance is in the ns-range, but no more than 8 images with full resolution can be recorded in total. Figure 8 shows a typical example of a time-resolved spray propagation recording with this system.

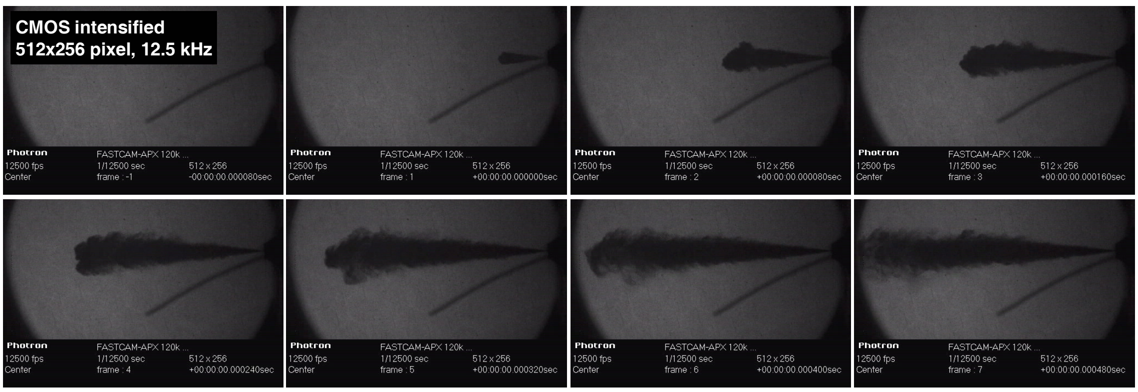

Fig. 9: Shadow-imaging test recordings of a high-speed CMOS-camera (12.5 kHz, 512x256 pixels).

Meanwhile also competitive high-speed CMOS cameras are available, which have much faster sensor readout but usually lower light sensitivity. We tested a new product of a light intensified CMOS camera. It records continuously (overwriting memory) in a fixed frequency based on the set resolution and offers a pre-trigger option.

Both available camera type systems have its advantages and disadvantages. With regard to the present investigations, and in particular the spray propagation, a multi-CCD system might be preferable according the very short incidence times. The high injection pressure leads to high velocities of the spray, which has to be captured with a very high acquisition rate within the limited area of view through the windows. In addition, such a system also would allow the simultaneously application of different measurement techniques in the future.

National Collaborations

On the national level, two other partners are involved in the same part of the project: *Wärtsilä Switzerland Ltd* (*WCH*) and the Paul Scherrer Institute (*PSI*).

WCH is the Swiss branch of *Wärtsilä Corporation*, a Finnish company holding a leading position both as a ship power supplier and as a provider of power plants for decentralized power generation. Originating from *Sulzer Brothers*, *WCH* has a long history of developing low- to medium-speed diesel engines and is today, within Wärtsilä Corporation, focusing on the design, development and after-sales business of large two-stroke engines for marine propulsion applications. In the context of the present overall cooperative R&D project, *WCH* has initiated the activities within Task 2.1 and now acts as the coordinating party. With respect to the development of the experimental facilities, *WCH* and *ETH* are in very close collaboration as the *WCH* expertise not only with respect to large engine technology necessary for the identification of the requirements towards the experimental setup but also regarding the design, manufacturing and operating aspects of installations of the size in question is essential in this context. As a matter of fact, the limitations at *ETH* with respect to the latter have even led to the decision of erecting the test facility at *WCH's Diesel Technology Center* in Oberwinterthur, where important parts of the infrastructure required are either already existing or need only moderate adaptation to the purpose of the intended investigations. Already during the present concept and development phase, the collaboration between *WCH* and *ETH* is very intensive: In addition to the continuous discussion of the requirements and the technical as well as organisational aspects, *WCH* supported the activities by providing capacities for extensive CFD simulations of the thermo- and fluid dynamic layout of the system and the design of the components.

The collaboration with the *Combustion Research Laboratory* at *PSI* is based on the expertise in measurement techniques available at both sites and the earlier cooperation in this area, through which a close contact and continuous exchange has been established. Currently, we are working on the clarification of the suitability of various optical measurement methods. Their identification is an iterative process within the development of the spray/combustion chamber with regard to optical access (window properties), operational conditions and measurement technique specific possibilities. Based on our own experience, a primary selection has been made, whereas *PSI* is now responsible for investigating the adaptability and specific limits of the methods in question in more detail. A final report on this topic (identified as a deliverable within the work plan of Workpackage 2 – Task 2.1) will be prepared.

International Collaborations

The *HERCULES* (High Efficiency R&D on Combustion with Ultra Low Emissions for Ships) project is set up as an Integrated Project (I.P.) in the context of EU's Sixth Framework Programme (fp6). It is related to the fp6 Surface Transport Priority 1.6.2 (Area: Sustainable Surface Transport, Objective 1, Research Domain 1.4) and is supported by the European Commission (Proposal/Contract

No.: TIP3-CT-2003-506676) as well as by the Swiss Federal Government. The consortium consists of more than 40 participants from ten countries representing the following sectors: 60% Industrial partners (engine manufacturers, shipping companies, component suppliers, and equipment manufacturers), 19% Universities and 12% Research Institutions. The project is structured into 9 workpackages, with 18 Tasks and 54 Subprojects.

The participation of *ETH* is related to Workpackage 2 (WP-2: Advanced Combustion Concepts), Task 2.1 (Combustion Process Simulation), where we have the leading role in the Subproject 2.1.1 Test Facilities. In addition to the Swiss partners listed above, there are four additional parties directly involved in the same Task:

- *Abo Akademi University (AAU)*
- *Helsinki University of Technology (HUT)*
- *National Technical University of Athens / LME (NTUA/LME)*
- *Wärtsilä Corporation, Finland (WFI)*

The partners from the various European universities are focusing on the development and application of simulation methods and, in this context, very much interested in using the results from the experimental investigations for the validation of their models. Therefore, a close cooperation for identifying the requirements towards the measurement technologies with respect to the applicability for validation purposes is indispensable already during this initial phase. Ultimately, the enhanced simulation tools shall be employed for the identification of suitable options for combustion system optimisation, which is the main motivation for the involvement of the engine developers *WFI* and *WCH*.

Conclusions 2004 and Outlook 2005

A test facility has been designed to experimentally realize conditions relevant to the combustion system present in large two-stroke marine diesel engines. Dimensions, pressure and temperature ranges and restriction levels have been evaluated. The main part consists of a spray/combustion chamber with optical access, realistic swirl conditions and a real engine injection system, whose constructive design has been completed. Further components and peripherals of the entire test facility have been evaluated or designed and the system specifications were defined. In collaboration with *Wärtsilä Switzerland Ltd*, numerical simulations were performed for different conditions similar to the experimental design. The results confirmed the validity of the design and promoted the construction procedure. Finally, high-speed camera systems for the fast image acquisition of spray propagation have been evaluated in order to identify the optimum system for this purpose.

During the next project year, large main components will be ordered from external manufacturers, whereas specific smaller parts will be produced by ourselves. Another focus will be on the arrangement of the test facility location, respectively the assembly itself as well as the commissioning of the spray/combustion chamber. At the same time, the control system will be designed, tested and integrated. In addition, baseline measurements will be prepared and performed in collaboration with *PSI*. The first measurement campaigns of experiments in the spray/combustion chamber are planned for the end of the year.

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