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HERCULES

SPRAY COMBUSTION CHAMBER

Jahresbericht 2007

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ZUSAMMENFASSUNG

HERCULES steht für ein internationales 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, der das Verbrennungssystem grosser 2-Takt-Schiffsdieselmotoren unter Berücksichtigung der charakteristischen Bedingungen weitestgehend repräsentieren soll, um die benötigten Referenzdaten zu generieren.

Die Entwicklung bzw. die Inbetriebnahme des neuen komplexen Versuchsstandes hat im Berichtsjahr einige entscheidende Fortschritte gemacht. Zunächst wurde der Prüfstand durch die letzten noch fehlenden Elemente wie das Abgassystem oder die Stickstoff-Zufuhr vervollständigt. Zudem konnte das für die Prozessgasvorwärmung eingesetzte komplexe Aggregat durch neu entwickelte Druckverschraubungen im Hinblick auf den Netzanschluss erfolgreich modifiziert werden. Ferner konnte das hinsichtlich schiffsdieselmotorischer Verbrennung realistische Einspritzsystem vervollständigt, dessen Steuerung komplettiert, getestet und schliesslich in Betrieb genommen werden. Im Hinblick auf die Inbetriebnahme der Anlage bestand ein wesentlicher Aspekt auch in der Weiterentwicklung der relativ komplexen Steuerung, u.a. auch mit eigens entwickelten elektronischen Komponenten. Nach der Überprüfung aller Verbindungen und Signale zwischen den Schaltschränken und den individuellen Feldgeräten konnten auch die für den Betrieb und die Datenerfassung zur Steuerung eines Messprozesses erforderlichen spezifischen Komponenten erfolgreich getestet und in Betrieb genommen werden. Schliesslich konnten dadurch erste Experimente zur Visualisierung der Einspritzung durchgeführt werden.

Aufgrund der ersten messtechnischen Versuche bzw. der Inbetriebnahme dieses novitären Prüfstandes ist nun mit dem Projektende ein primäres Entwicklungsziel erreicht worden. Eine Bestätigung der bisherigen Anstrengungen bzw. des grossen Interesses an diesem Projekt [1] zeigt sicher auch die im Rahmen des internationalen CIMAC-Kongresses [2] erhaltene Auszeichnung "2007 BP Award on Health, Safety & Environment". Ein Gesuch in Bezug auf ein Nachfolgeprojekt (HERCULES β) innerhalb des 7. EU Rahmenprogrammes wird von den Verantwortlichen der EU voraussichtlich gutgeheissen. Im Rahmen dieser Weiterführung steht den Schweizer Forschungspartnern aus Industrie und Hochschule somit ein hoffentlich langfristig einsetzbares F&E-Instrument zur Erhöhung der internationalen Wettbewerbsfähigkeit auf diesem Gebiet zur Verfügung.

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, CO2 emissions and engine lifecycle costs [3]. 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* [4]. The general aim of this task is to promote the application of advanced simulation models (extension and adaption of existing submodels 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, 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 contribution refers 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 behaviour (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 regarding the comparability to large two-stroke diesel engine processes are also connected to considerations with respect to applicable measurement techniques. To avoid any disturbances of the involved flow field, of spray and combustion propagation as well as of emission formation processes, the use of (as far as possible) non-intrusive (optical, laser) measurement methods (active and passive) is absolutely favourable. Their specific properties and limits (spatial, temporal resolution) with respect to optical access and the operationally feasible repetition/sampling rate of the measurements (statistical relevance) have to be taken into account.

Based on the achieved development status (annual report 2006) of the test facility, the project focus is the completion of the entire experimental setup as well as specifically the commissioning of the control system in order to be able to operate the spray combustion chamber test facility. In addition, high speed camera recordings in combination with the shadow-imaging technique have to be performed as first preliminary tests (measurements) of the spray visualization.

The resulting specific **aims** for **the last project year** can be summarized as follows:

- **final setup**: test facility completion, exhaust system, power connection and nitrogen gas supply
- **injection system**: final compositon, control system test and commissioning
- **control system**: implementation of specific developed electronic control components
- **commissioning control system**: connection check and testing of individual components
- **operation and data acquisition**: triggering and control of the measurement process
- **measurements**: first preliminary tests of spray visualization

Accomplishments and Results obtained

Figure 1 shows the **final setup** of the experimental spray combustion chamber test facility. The pressure vessels can be seen behind the regenerator and spray combustion chamber, now including also the final exhaust system pipes connected to the pneumatically actuated exhaust valve. The main components of the injection system are located on the side of the regenerator and up rear. The control room is located behind the wall to the left (upper left image). A view from outside (upper right image) shows the finished exhaust gas path with condensate box, silencer and exit pipe as well as the air conditioning unit and its supply pipes. The fuel tank carrier/control oil aggregate system is clearly recognizable outside the laboratory facility to the right.

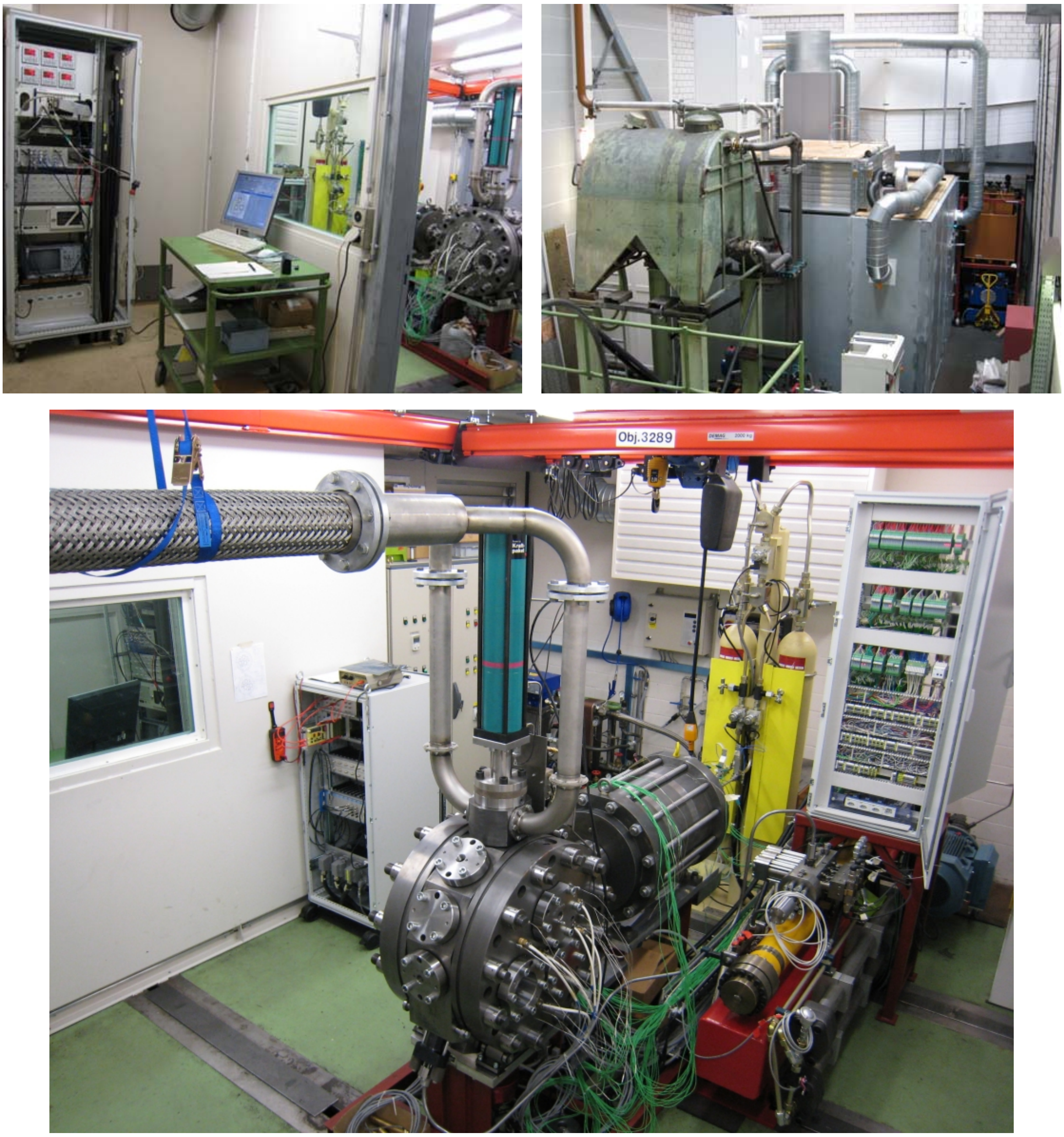

Figure 1: *Final setup of the experimental spray combustion chamber test facility: control room (upper left), view from outside (upper right) and the experimental laboratory (lower image) itself.*

The completion of the entire experimental setup involved various additional aspects: In particular, the specification of the surrounding laboratory facility posed some challenges in view of its integration into the existing building and infrastructure, its operation and maintenance as well as the requirements associated with the intended application of optical and laser-optical measurement technologies and last but not least for compliance with safety standards.

The newly designed SCC exhaust system is shown more detailed in Figure 2. Inside the laboratory, the system comprises a pneumatic valve with two solenoid control valves, a system of 6 bar pressure pipes for the operation of the valve and the exhaust pipe. The pressure pipe configuration was changed from the original design to make the exhaust valve opening slower and thus reduce the shock on the exhaust pipes. The restrictions of space for the exhaust in the laboratory made it necessary to move the required shock absorbing plenum and silencer on the other side of the wall; the main exhaust (brown) pipe then goes through the roof of the building. The expected exhaust pressures and temperatures dictated the shape, size and type of the piping.

Figure 2: *Exhaust system views inside and outside of the laboratory.*

On the process gas supply side, the high pressure compressor, suitable for operation on air and nitrogen, as well as the nitrogen gas supply was put into service. Air will be used to fill the accumulators in normal experiments, whilst nitrogen can help to emulate the whole process with the same boundary conditions (with respect to temperature, pressure) but without combustion. Figure 3 below shows the location of the compressor (left), a close-up of the nitrogen inlet pipe (middle)and the nitrogen bottles standing in a specially designed rack (right). The rack incorporates a pres-sure reduction to 5 bar – from approximately 200 bar in the bottles - for the transport of nitrogen to the compressor through a 20 mm copper pipe.

Figure 3: *Compressor with dual (air-N_2) operation capability.*

In the course of the erection of the regenerator, the design of the connectors of the heat conductor cables and the fittings for the fixation of these cables in the terminating cover was found to be impractical as it was not conceived for multiple assembly and disassembly. Hence, in view of the potential need for dismantling of the regenerator for modifications or maintenance at a later stage, particular cylindrical ceramic connectors are now brazed to the heating conductor cables still assuring an air-tight connection and perfect insulating resistance of the heat conductors. In combination with the specifically designed pressure fittings displayed in Figure 4 (finally mounted on the terminating cover), allowing the lead through of the heating conductor cables including those cylindrical ceramic connectors, this now enables any possibly necessary future dismantling and re-assembly of the regenerator without the risk of damage to the heat conductor cables.

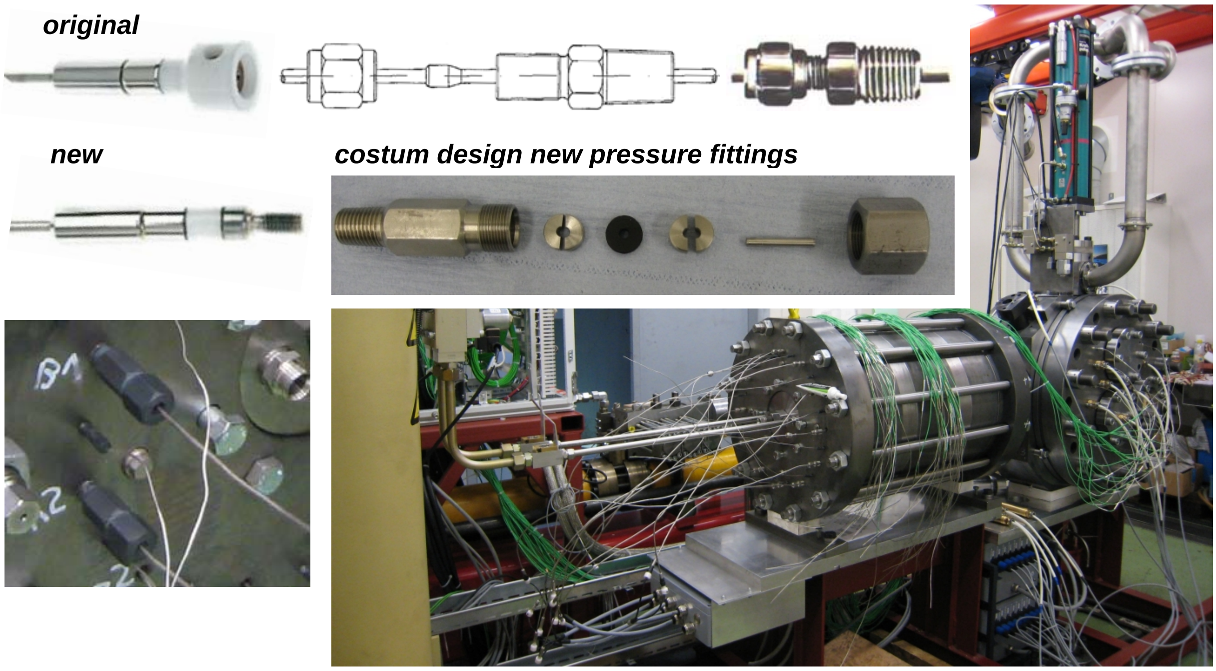

Figure 4: *Modified ceramic connectors and pressure fittings for the heat conductor cables of the regenerator.*

Figure 5 shows a general view of the **injection system** and a detailed view of the Injection Control Unit (ICU). The high pressure pipes have been custom designed for the geometrical attributes of the SCC setup.The three solenoid control valves on the ICU are operated remotely by the control system, and using control oil at 200 bar the fuel from the rail (up to 1000 bar) is released to the injector which has a needle opening pressure of 375 bar.

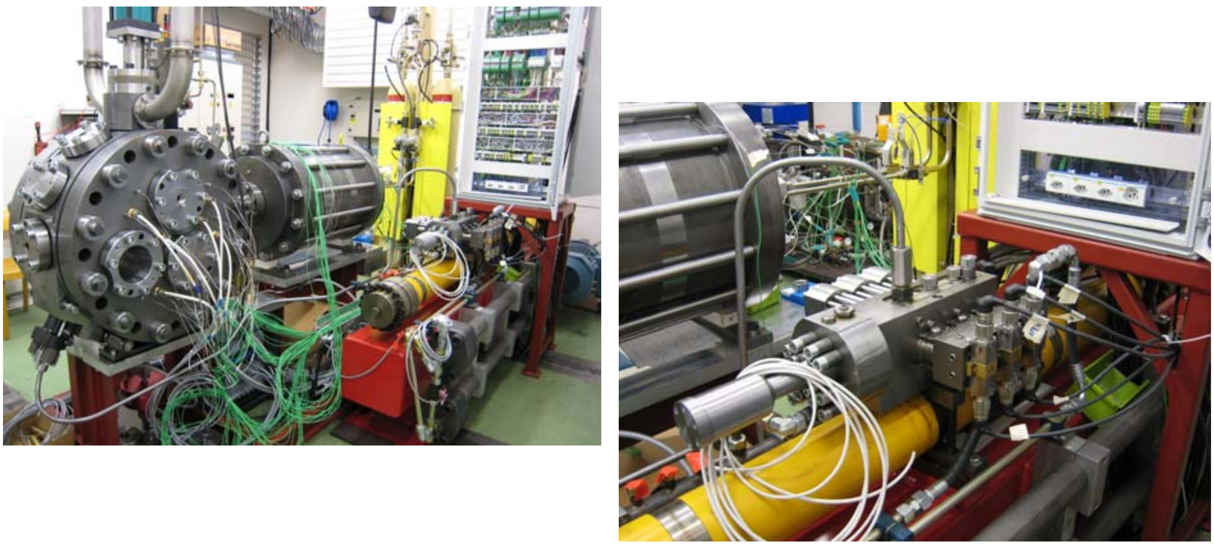

Figure 5: *Injection system with high pressure pipe from ICU (right image) to injector.*

The injection control system is based on a Programmable Logic Control (PLC) unit, which receives inputs from switches, sensors and the software and according to the logic it returns information for user monitoring and control signals for the field devices and controllers. This process is designed to maintain the rail pressure at the user-required level and operate the fuel and control oil conditioning. The system is currently at the commissioning phase, where checks are being made to en-sure every signal complies with the programmed logic; that is, it is checked if every input will trigger the correct sequence of events and provide the user with the required feedback.

Figure 6 shows the scheme of a specifically developed electronics for the **control system**, which is needed to control, activate and trigger the injection process. During the heat-up phase of the regenerator – when the rail pressure is maintained at a level below the needle opening pressure – it simulates a typical engine frequency (rpm) to ensure that operation conditions (in particular fuel temperature) applying are representative of regular engine operation. Before a measurement takes place, the engine simulation stops and the electronics switches to a second mode where a single injection is activated, shortly after the rail pressure has been increased to the desired level.

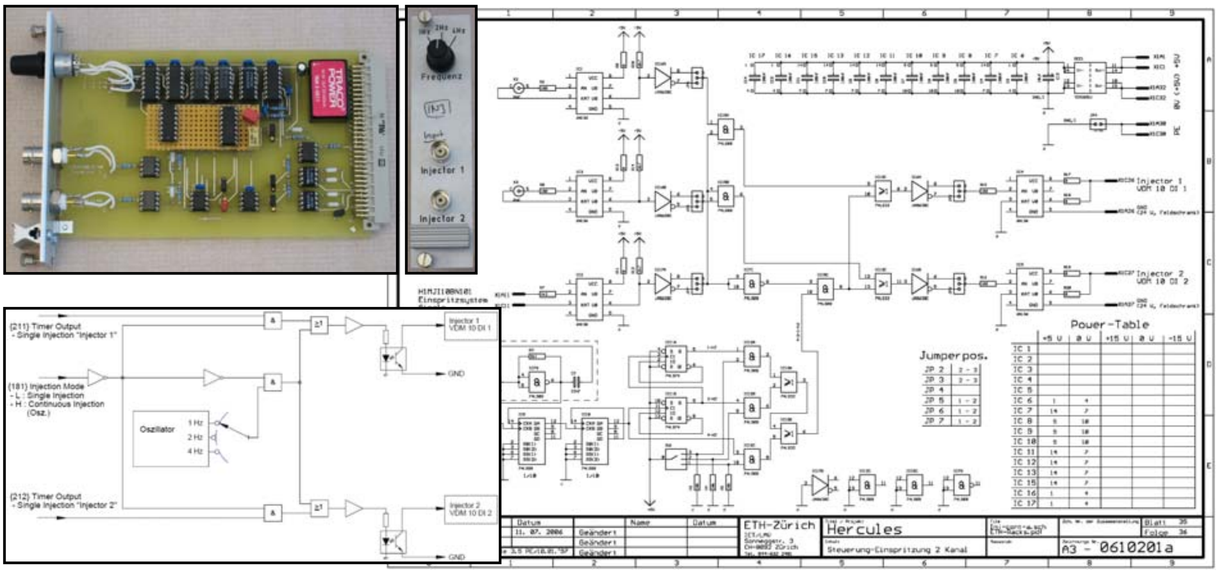

Figure 6: *Scheme of the electronics to simulate a typical engine frequency (rpm) at lower rail pressure (operation conditions) as well as to activate a single injection at high rail pressure level.*

Many other specifically designed electronic elements (e. g. for the activation and control of the exhaust valve) have been developed, also with respect to safety (hardware interlock) and software failure considerations. For instance, the so-called "waveform card" which basically releases the timing processes and triggers all devices (e. g. high speed camera) during a measurement, is also activated by a particular electronic device. Other examples are electronic devices controlling the base measurement (e. g. amplifiers for the fast thermocouples) as well as relating to facility monitoring (transmitters).

On the subject of **commissioning** of the **control system**, all cables, respectively their corresponding pin allocation on the plug had to be checked before finishing the hardware cabling. Afterwards, each and every connection between the various electrical cabinets or from the field cabinet to the specific field instruments had to be verified. This refers to the different signals as well as to the power supply.

The upper middle scheme of Figure 8 shows an overview of the connection principle of all devices with respect to signal transfer and power supply. The entire compilation of all electrical connection schemes is summarized in two folders. As an extract, one exemplary page of the electrical scheme of the field cabinet (left) as well as of the control cabinet (right) is displayed in Figure 8. The green highlighted connections had been verified at the time the picture was taken. Considering the complexity of the system together with the not to underestimate effort required, the successful verification of all the connections can absolutely be seen as an intermediate result with regard to the commissioning of the control system, respectively the operation of the test facility.

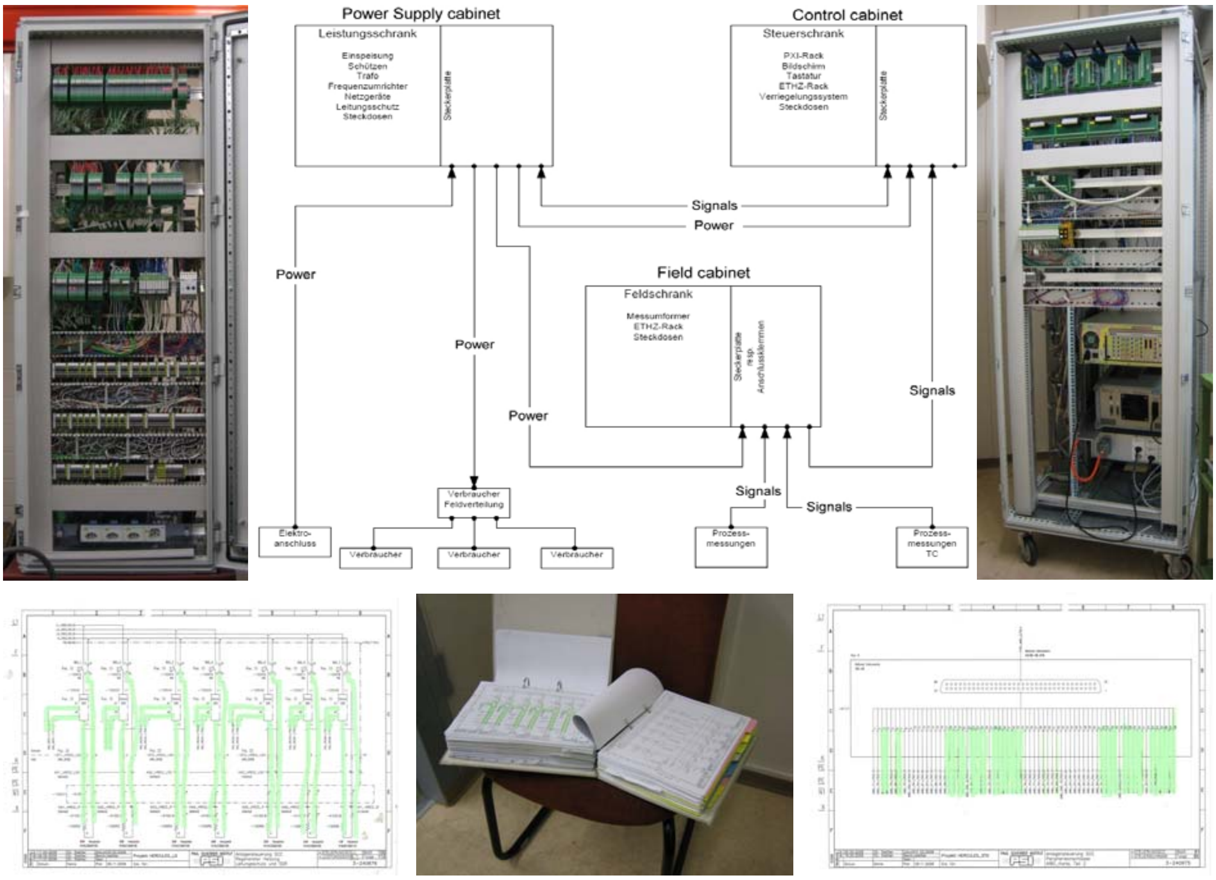

Figure 8: *Principle of all signal and power supply connections between the electrical cabinets and field instruments as well as an impression of checking them all.*

Apart from the connection check between the cabinets and/or field instruments also each signal (digital input/output) or analog indicator transfer from the control software to the field instruments or vice versa had to be checked. This was done by means of a software tool provided by LabVIEW ("Measurement and Automation Explorer" to configure measurement devices), which is displayed in Figure 7.

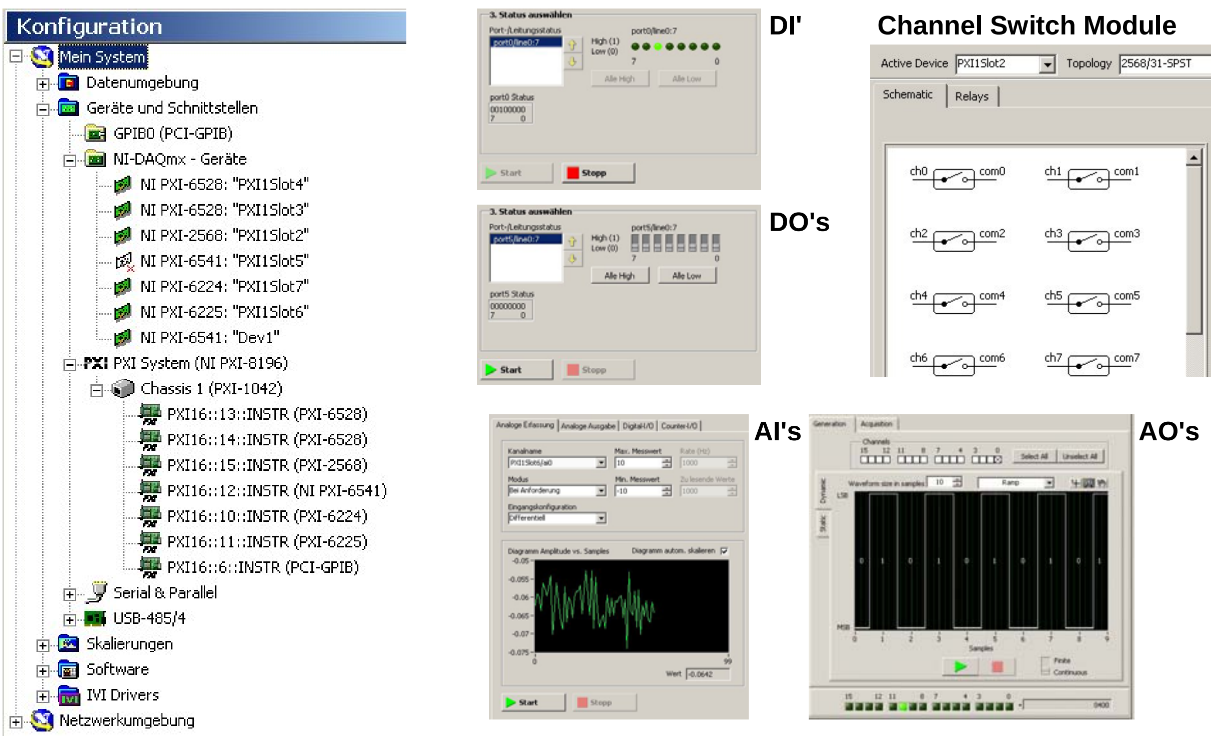

Figure 7: *Overview measurement devices and the tools in order to generate or acquire digital inputs or outputs (DI/DO), analog inputs or outputs (AI/AO) as well as switched channels.*

The user can manually switch the channels (digital outputs, DO) or could generate an analog indication and observe the response from the field. In addition, digital (DI) as well as analog inputs (AI) can be viewed and acquired. Thus, one can determine whether a potential problem comes from the inputs, respectively outputs or if the control software programme is faulty. Several initial programming but also conceptual errors were found and solved during the commissioning phase of the software.

Finally, Figure 9 shows the last important step in commissioning of the control system where the timing of specific signals during the measurement process is checked directly at the measurement cabinet. Those signals are generated by the so-called National Instruments "wave form generator" measurement device which is basically freely programmable.

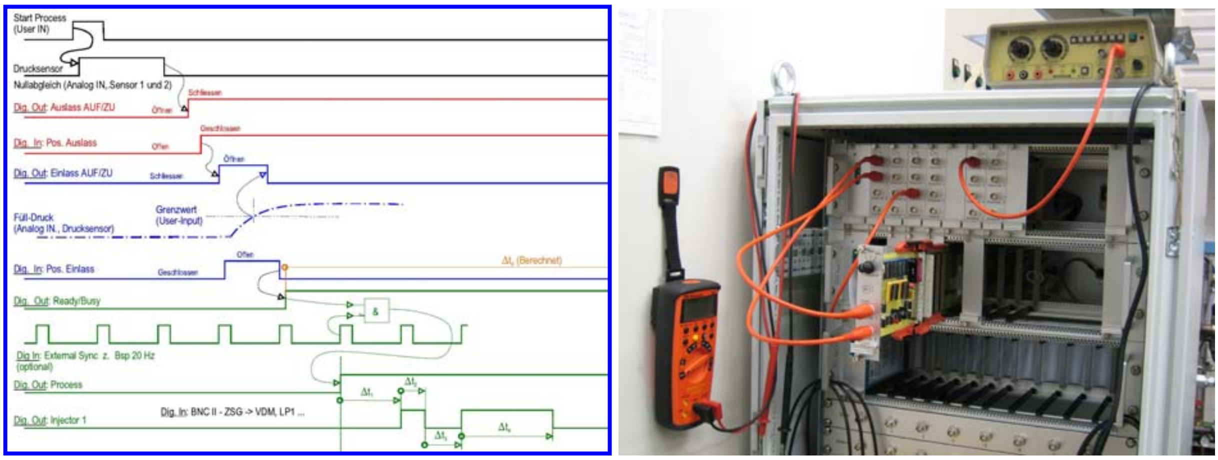

Figure 9: *Timing definition of the measurement process and checking of the corresponding signals generated by the "waveform generator" device directly at the measurement cabinet.*

The successful completion of the entire commissioning process of the control system was another intermediate result of the implementation of the test facility.

On the subject of **operation and data acquisition**, the control system for the experimental test facility setup has been developed in such a way that later on also less experienced persons will be able to operate the installation. Therefore, a lot of effort has been put into a logical, almost self-explanatory and clearly structured graphical user interface.

Figure 10 shows an extract of two sub-control fields: The process gas supply (left image) and system pressure indication and the heat up (right image) of one of the spray combustion chamber covers. The upper right schematic display of the whole test facility setup with the most important information in regard to pressures, temperatures etc. is always visible – independent from the respective selected sub-control field – and will look identical in the final version.

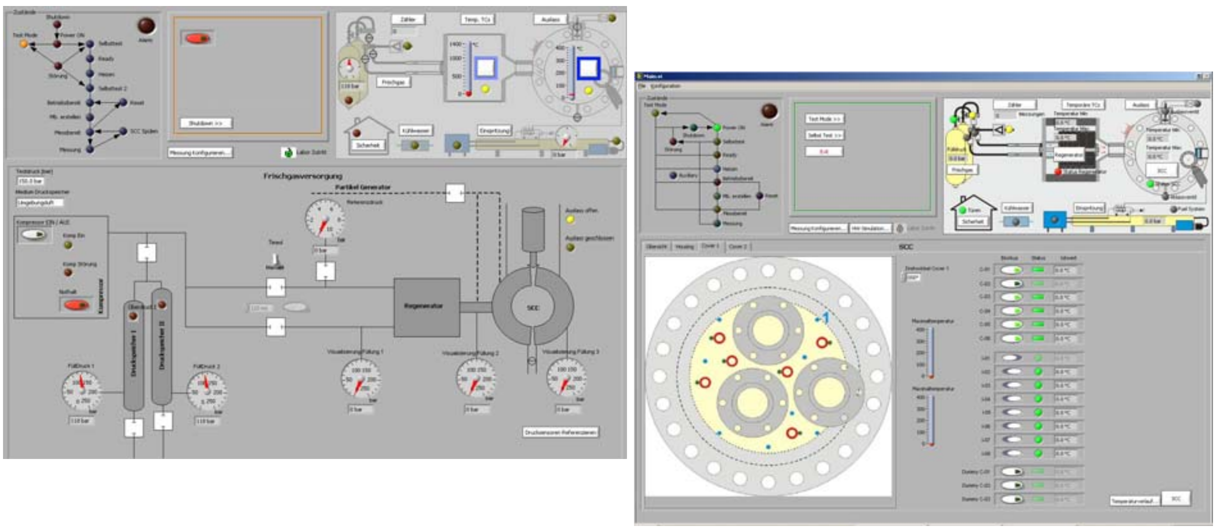

Figure 10: *Graphical user interface extracts of the control system.*

The software comprises two modes, a manual and an automatic mode: In the former, the user has almost unlimited freedom to intervene to the filling, heating, injection and data recording processes, although some steps are password protected for enhanced security. In contrast, in the automatic mode, the user can only give a certain number of fundamental inputs – such as temperature and pressure of the process – while the software performs the required operations to arrive at these, always going through safety checks in strict order.

The completely populated electrical control cabinet is displayed in Figure 11. Starting at the top, it contains the different controllers (①) for the heat-up of the spray combustion chamber as well as for the regenerator, including also a software-independent stand alone controller for safety shut down in case of an overheating. At the lower level, the National Instruments LabVIEW controller (②) with its various measurement cards, internally connected to corresponding wiring, is located – inclusive of the interface transducer as well as the breakout-box of the waveform generator device (see below). Next, the line driver/line receiver system (③) in order to improve the signal-to-noise ratio of the signal transfer is mounted. Below that, another data acquisition box (④) allows the gathering of further collected (measurement cabinet) analog or digital signals from the field. Finally, all "fast" data signals (pressure, temperature) to be acquired during a measurement process can be recorded and stored with the "Transient Recorder" (⑤), a high speed data acquisition (20 MHz) device. At last, an oscilloscope (⑥) is also included in order to be able to prepare as well as to check interesting signals during the operation.

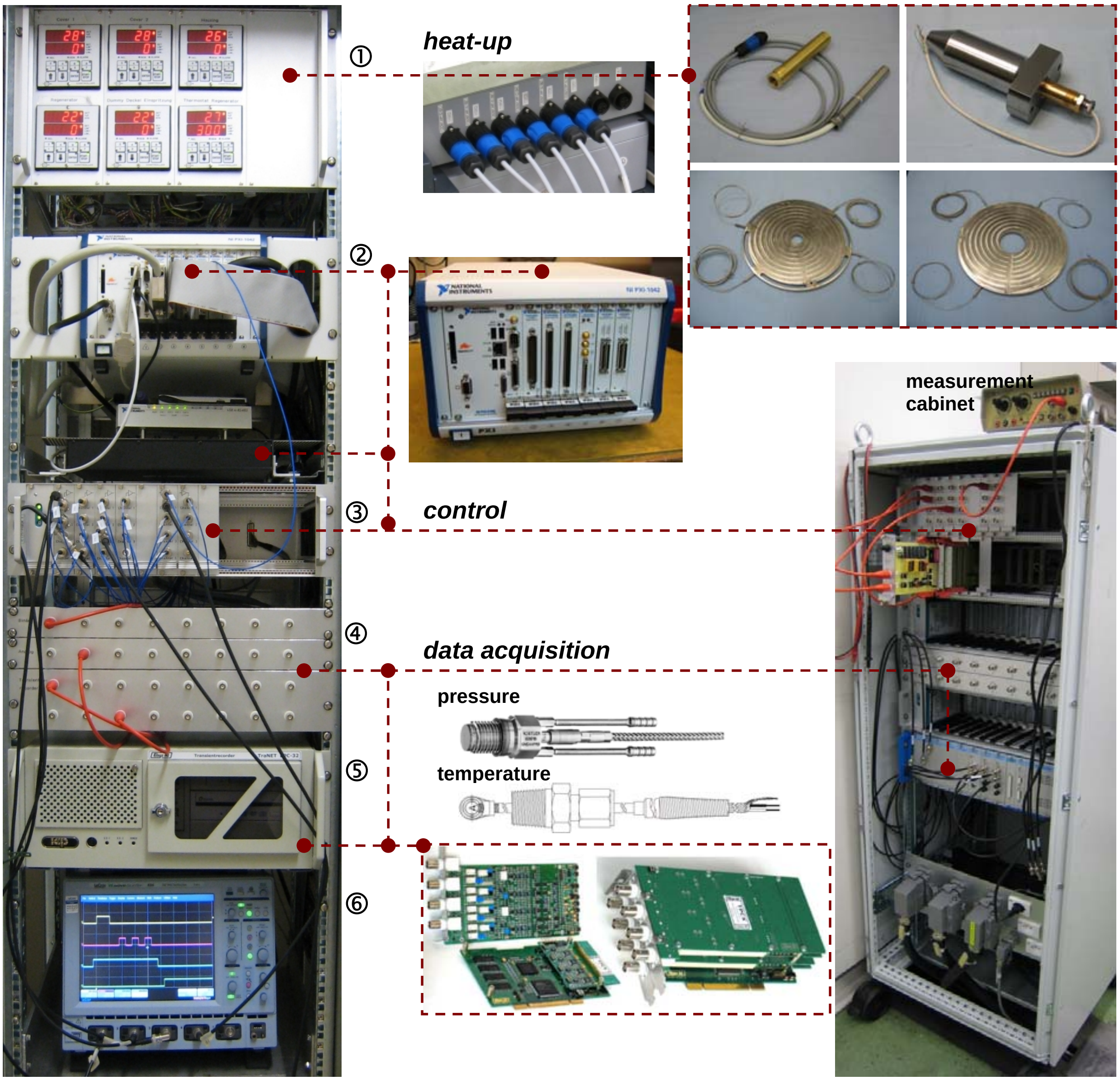

Figure 11: *Control cabinet of the control system: the heating controllers (①), the National Instruments LabVIEW controller (②), the line driver/line receiver system (③), the analog/digital data acquisition box (④), the "Transient Recorder" (⑤) and an oscilloscope (⑥).*

A major autonomous device in the entire operation is the so-called high-speed digital waveform generator/analyzer which features maximum clock rates of 50 MHz. 32 channels can be freely programmed with a bit pattern of select voltage levels ranging from 1.8 to 5.0 Volts. The clock frequency (resolution) can be set from 48 Hz up to 50 MHz, with resulting sequence durations of 370 hours, respectively 1.28 seconds. This device is used with the intention of freely defining triggering signals in order to synchronize the high speed camera, possible additional lasers as well as other necessary devices based on the defined timing sequence during a measurement process.

Figure 12 shows the trigger definition setup (upper scheme) of a synchronous mode process under consideration of the application of a pulsed laser, the defined timing sequence (lower scheme) and an exemplary output of the waveform generator device displayed in the graphical user interface.

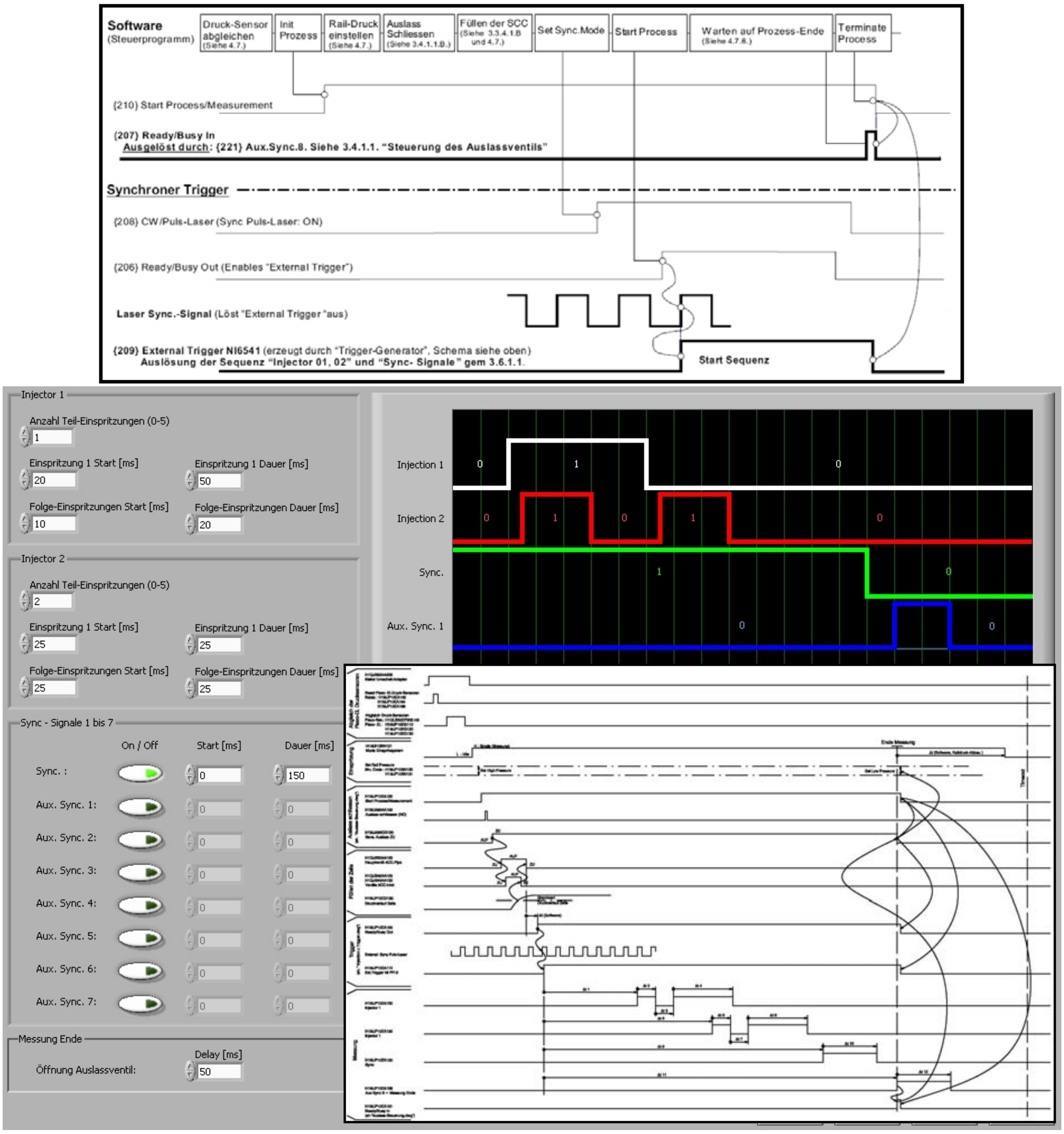

Figure 12: *Trigger definition setup (upper scheme) of a synchronous mode (pulse laser) measurement process, waveform device output and timing sequence (lower scheme).*

After completion of the commissioning, the experimental test facility can now be operated by this quite complex control system. Note that the safety standards have been given particular attention in the course of its development by including various safety features (both software and hardware types) for making sure that incidents as a consequence of operational failures or other undesired events can be precluded as far as possible.

In order to demonstrate the potential of the new experimental setup regarding **measurements** and evaluate its applicability for the intended purpose, first preliminary tests with injection into a cold and quiescent environment have been performed. The spray propagation inside the chamber has then been visualized by means of the "Shadow-imaging" (background illumination) method.

For this purpose, the spray combustion chamber has been pressurized to 40 bar; however without pre-heating the process gas in the regenerator. Also, the injection was not started directly after the filling of the chamber but several minutes afterwards, such that the swirl could be assumed to be fully decayed and the temperature of the gas in the chamber to be at room temperature (300 K).

The tests have been made with a single-orifice injector nozzle (diameter 0.875 mm), applying an injection pressure of 500 bar. The illumination and observation windows were mounted in the outer position for obtaining direct optical access to the region directly adjacent to the injector tip in order to allow the observation of the initial spray propagation.

The shadow images have been recorded by means of a CMOS-camera with a frequency of 12.5 kHz – an image every 80 μs – at an exposure time of 50 μs with an image resolution of 512 x 384 pixels. Figure 13 shows a conceptual sketch and an overview of the setup.

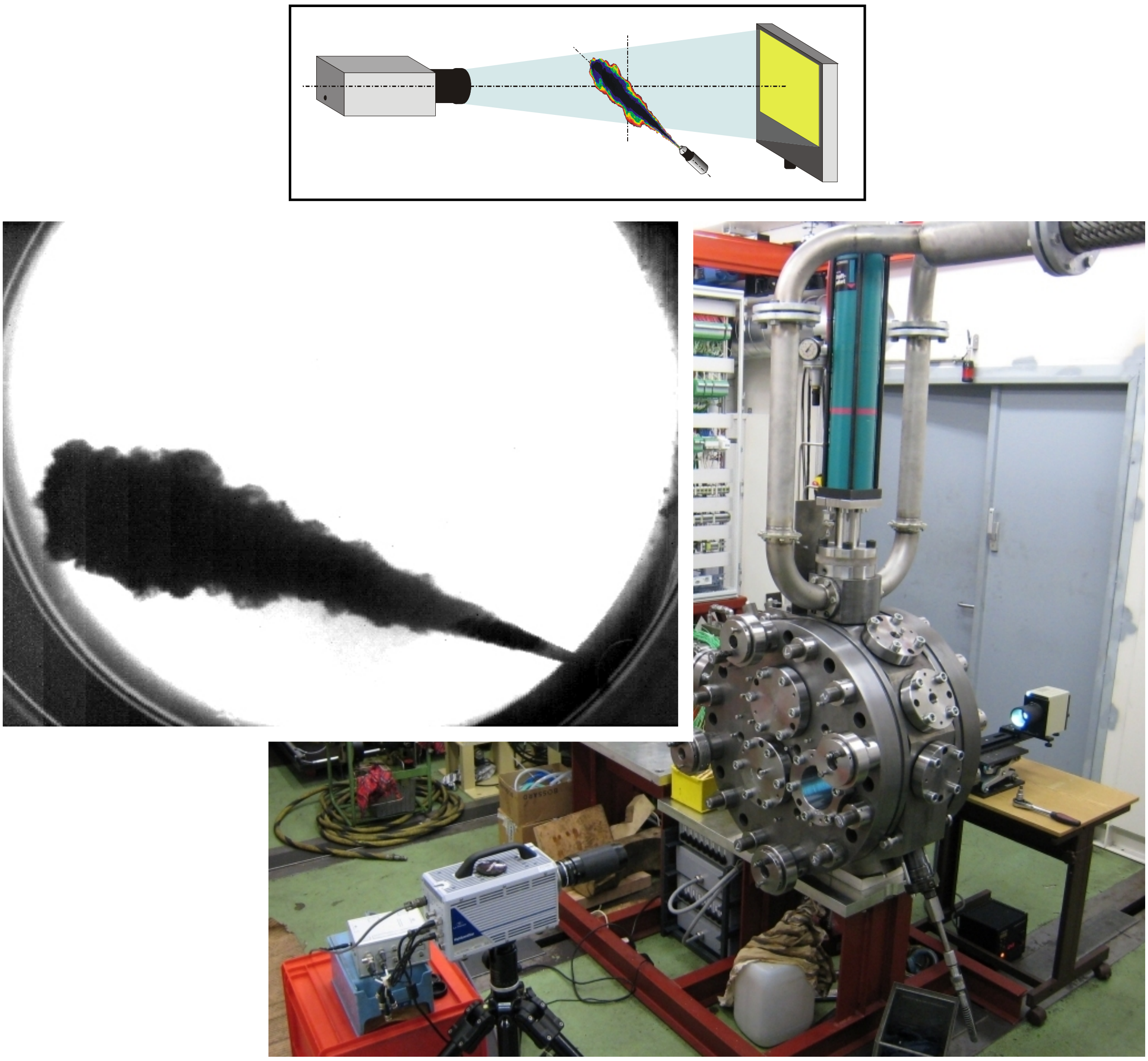

Figure 13: *First (provisional) setup of the high-speed CMOS-camera (12.5 kHz, 50 μs, 512x384 pixels) in order to perform spray visualizations with shadow-imaging.*

A sequence of images (every 2nd recording) from those tests is shown in Figure 14, illustrating the temporal evolution of the spray plume at cold, i.e. non-evaporating conditions. Obviously, as the spray is propagating almost linearly along its axis, there is no more swirl at the time of injection; otherwise, the plume would have been deflected in the direction of the swirl. The irregular and random nature of the spray is also clearly visible in the formation of pronounced structures at its boundaries. Such behaviour will in later regular tests have to be catered for by averaging techniques applied to a sufficient number of images from different tests at the same conditions and appropriate statistical analyses.

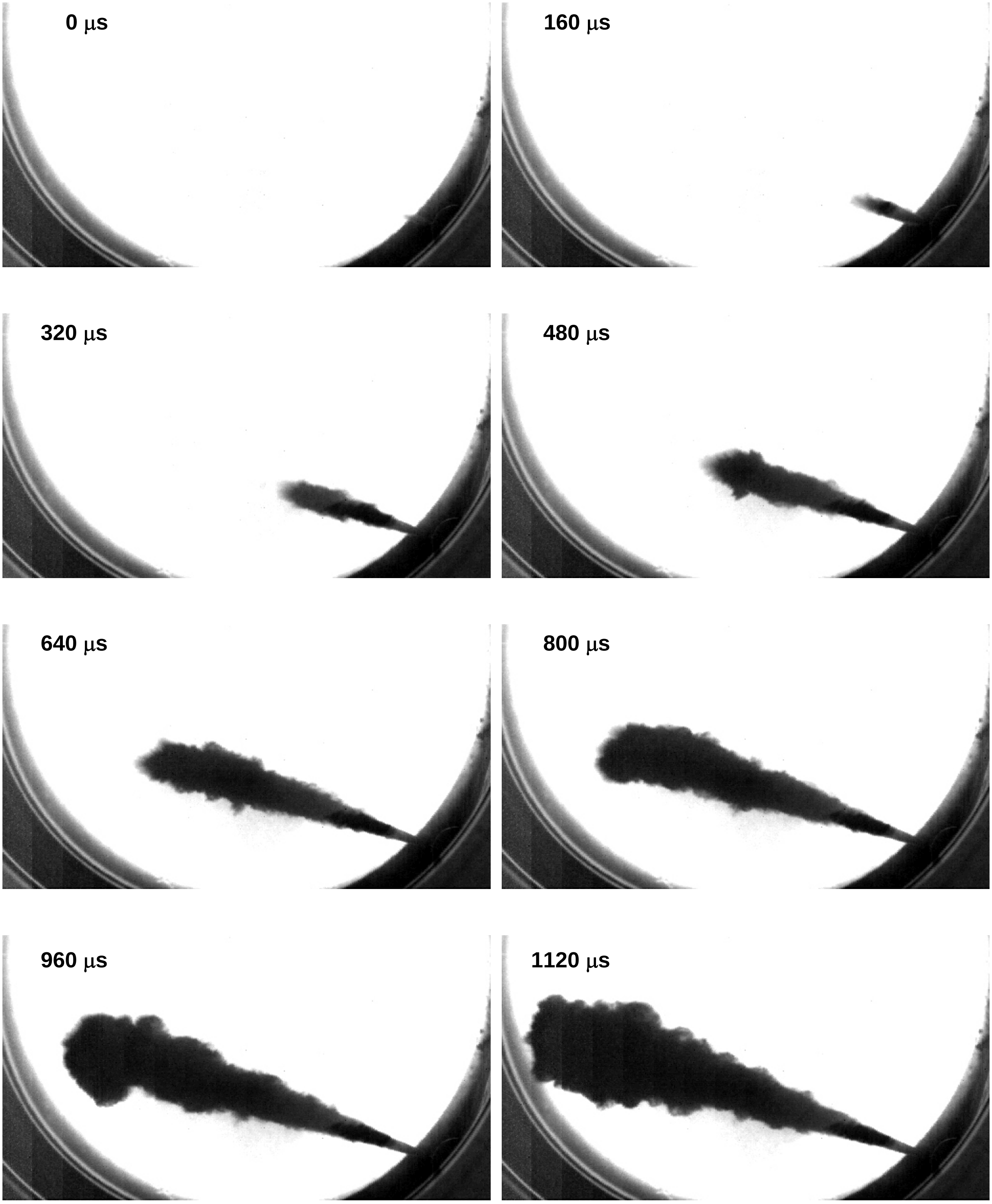

Figure 14: *Shadow-imaging recordings of the fuel injection spray (p = 40 bar, T = 300 K, p_{inj} = 500 bar).*

The applicability of the setup and the validity of the general concept could be clearly confirmed in those first preliminary tests. These will be further extended in the course of the commissioning of the complete setup and then transferred into regular operation for generating the desired reference data for validation. This will finally allow the more in-depth characterization of fuel spray, mixing and combustion processes in marine engines targeted with this project.

National Collaboration

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. As in the first and second year, the collaboration between *WCH* and *ETH* was intensive and very fruitful. Numerous aspects of infrastructure and the test rig itself could be solved, especially with regard to the new designed laboratory facility building. The main support was given in the optimal configuration selection and commissioning of the complex fuel injection system, where the company's experience was indispensable.

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. Furthermore, it now also includes a very close collaboration with respect to the definition, design and implementation of the control and operating/data acquisition system of the entire spray combustion chamber test facility. This refers especially to the evaluation of all electrical devices as well as the design, layout and the wiring diagrams of the specific electrical cabinets, which have been also manufacturing at the *PSI*.

International Collaboration

The *HERCULES* (<u>H</u>igh-<u>E</u>fficiency <u>R</u>&D on <u>C</u>ombustion with <u>U</u>ltra-<u>L</u>ow <u>E</u>missions for <u>S</u>hips) 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, 12% Research Institutions and 9% User/Operator companies. 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 are, 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 the first stages of the design and manufacturing process of the facility. Ultimately, the enhanced simulation tools shall be employed for the identification of suitable options for combustion system optimization, which is the main motivation for the involvement of the engine developers *WFI* and *WCH*. So far, the work on the test facility has been received very positively.

Conclusions 2007 and Outlook 2008

The design as well as the commissioning of the new experimental spray combustion chamber test facility has made substantial progress within this project reporting year. First of all, the test bed could be completed with all missing elements, such as exhaust system or the nitrogen gas supply. In addition, also the pressure fittings and the power connection of the process gas supplying heat-up aggregate have been successfully modified. Further, the realistic (compared to real marine diesel engines) fuel injection system has finally been commissioned by completing it with missing elements and by testing its control system independently. A major aspect regarding the commissioning of the entire experimental spray combustion chamber test facility was the further development of the complex main control system where specifically designed electronics have been implemented. After the inspection of the signal transfer connections between the electrical cabinets and the field devices, all control system components and units with respect to the operation and data acquisition as well as to the triggering of the measurement process have been tested and commissioned. Finally, preliminary tests of spray visualization measurements have been performed.

As a result of the first measurement tests as well as the comissionning of the novel experimental test facility itself the primary aim of this development stage has been realized. A confirmation of the successful efforts undertaken so far and the general interest for such a test rig within the research community might also be pointed out by the obtained award ("2007 BP Award on Health, Safety and Environment") at the international CIMAC Congress [2]. The proposal a follow-up project (HERCULES β) in the context of EU's seventh framework programme (fp7) will most probably be accepted by the responsible officers of the EU. The continuation will provide the Swiss research partners a R&D instrument that can be hopefully used to increase the competitive advantages in this area.

References

[1] K. Herrmann, R. Schulz, G. Weisser: *Development of a Reference Experiment for Large Diesel Engine Combustion System Optimization*, paper no. 98, CIMAC Congress 21st – 24th May 2007, Vienna.

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