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HERCULES
Advanced Combustion Concepts
Test Facility: Spray/Combustion Chamber

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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 des neuen komplexen Versuchsstandes hat im Berichtsjahr grosse Fortschritte gemacht. Alle erforderlichen Komponenten bzw. Bauteile für den gesamten Versuchsträger konnten definiert, organisiert bzw. in Auftrag gegeben sowie weitgehend hergestellt werden. Die eigentliche "Spray/Verbrennungs-Kammer" und der das heisse Prozessgas liefernde "Regenerator" wurden schliesslich aus hunderten von Einzelteilen zusammengesetzt. Zur Untersuchung der statischen und dynamischen Belastungsfähigkeit der Kammer wurden detaillierte Finite-Elemente-Rechnungen durchgeführt, welche einerseits einige Designverbesserungen ergaben und andererseits die Auslegung bzw. die Robustheit der Brennkammer bestätigten. Alle kritischen Komponenten wurden ausschliesslich aus zertifizierten Materialen hergestellt und zusätzlich noch verschiedenen Prüfungen (Zugversuch, Risse) unterzogen. Zusätzlich konnten der Kompressor, das Druckspeichersystem, das Einspritzsystem sowie das Laborgebäude definitiv ausgelegt werden, wobei deren Fertigung in vollem Gange ist. Schliesslich wurde das komplexe System für die Steuerung der gesamten Apparatur und die Datenerfassung der globalen Messgrössen konzipiert. Aufgrund der zunehmenden Komplexität der Anlage hat sich gegenüber der Planung leider eine gewisse Verzögerung ergeben, wobei alles daran gesetzt wird die Projektziele im folgenden Jahr trotzdem vollumfänglich zu erreichen.

In der verbleibenden Projektzeit werden die Infrastruktur der Peripherie des Versuchsstandes und das Steuerungs- und Datenerfassungssystem fertig gestellt. Nach einer ausführlichen Testphase des gesamten Systems sollen zunächst Messungen des Strömungsfeldes und der Gemischaufbereitung (Strahlausbreitung, insbesondere flüssige Phase) in inerter Umgebung durchgeführt werde. Anschliessend sind gegen Projektende Experimente mit Verbrennung angedacht.

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, 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 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 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 favorable. 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 2004) of the test facility, the project focus is the spray/combustion chamber assembling, based on evaluation, ordering and production of all parts. In addition, also other peripheral facility components have to be taken into account.

The resulting specific **aims** for the **second project year** can be described as follows:

- **final design**: spray/combustion chamber and regenerator (ultimate concept and drawings)
- **layout confirmation**: selection certified materials, FE analysis and alloy tests
- **production**: supplier evaluation, order, manufacturing, transport, delivery and logistics
- **assembling**: build up of complete test facility at the test bed location
- **test facility components**: compressor air/N_2 pressure accumulator and further equipment
- **development**: test bed facility and its controls, base measurement and injection system

Accomplishments and Results obtained

The **final design** and the final assembled spray/combustion chamber itself are displayed in figure 1. As a reminder, two of the first sketches –the one presented at the (1) kick-off meeting and the (2) first drawn to scale draft – are shown at the upper left. Based on those concepts, all drawings of the completed final design have been optimized regarding material, manufacturing and assembling considerations as well as with respect to strength calculation (FE analysis, see below) results. A three-dimensional view (3) of the ultimate spray/combustion chamber design points out the development progress so far. The complete set of the ultimate drawings allowed the manufacturing of all specific parts, respectively were the basis of the finally assembled (4) spray/combustion chamber. The "real thing" should and obviously does correspond well to the 3-D model.

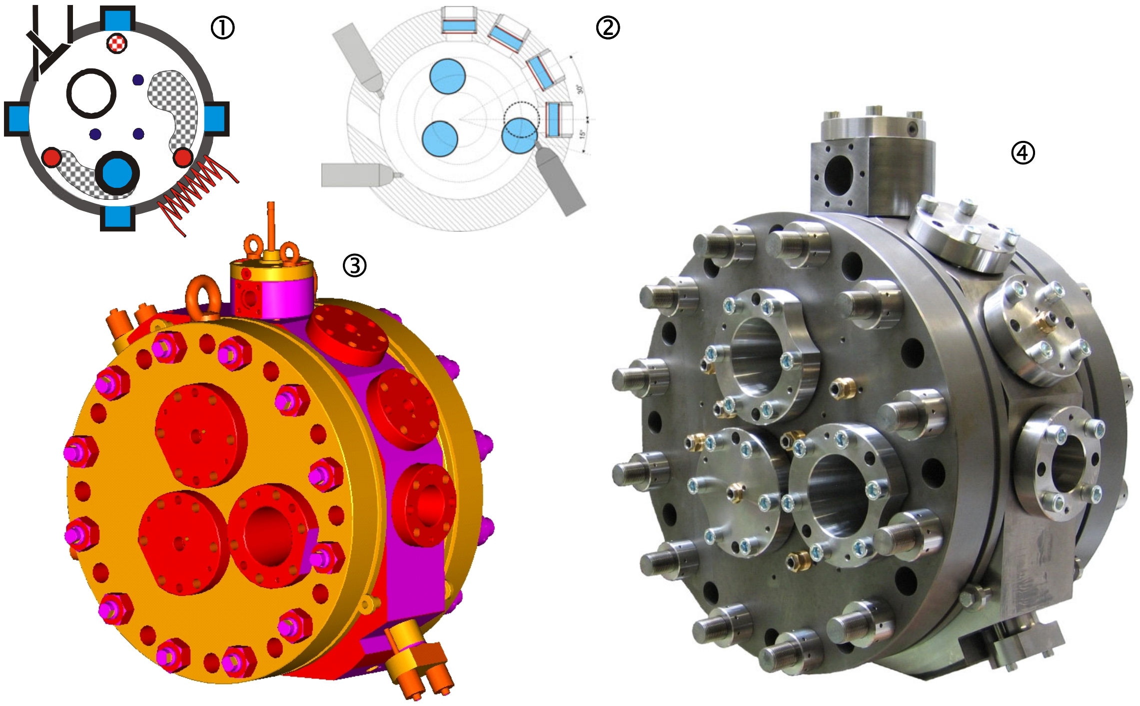

Fig. 1: Progress of the spray/combustion chamber development: (1) sketch kick-off meeting, (2) drawn to scale draft, (3) 3-D CAD outline and (4) finally assembled spray/combustion chamber.

With regard to a **final design**, also the regenerator which provides the process gas (air, N_2) has been optimized. It now consists of a tensioned package of heat discs and a cluster of plates held in distance with triangle distance plates. The heat discs with a heat conductor cable inside, respectively the whole package of sufficient heat recovering material can be electrically heated up to 900°C. The design of the two different heat discs (type A, B) with respect to their location in combination with the heated plates provides small flow cells to achieve a high surface to volume ratio in order to achieve an optimum flow circulation respectively heat convection. Figure 4 shows the principle of this flow and heat transfer through the inner core package of heated discs and plates.

Figure 5 shows the regenerator connected to the spray/combustion chamber, whereas the flange in-between offers a certain flexibility with regard to the base measurement system and further possible changes of the intake channel. The regenerator consists of the heated inner core, surrounded by ceramic rings with excellent isolation behavior to thermally insulate the boiler pipe from the extreme heat strain. The pipe is clamped between two terminating covers which exhibit a series of pressure fittings that allow the lead-through of the heating conductor cables and thermocouples as well as the measuring of the thermal expansion during operation. The inner pre-loaded tie rod and the corresponding nut consist of very high temperature resistant alloys.

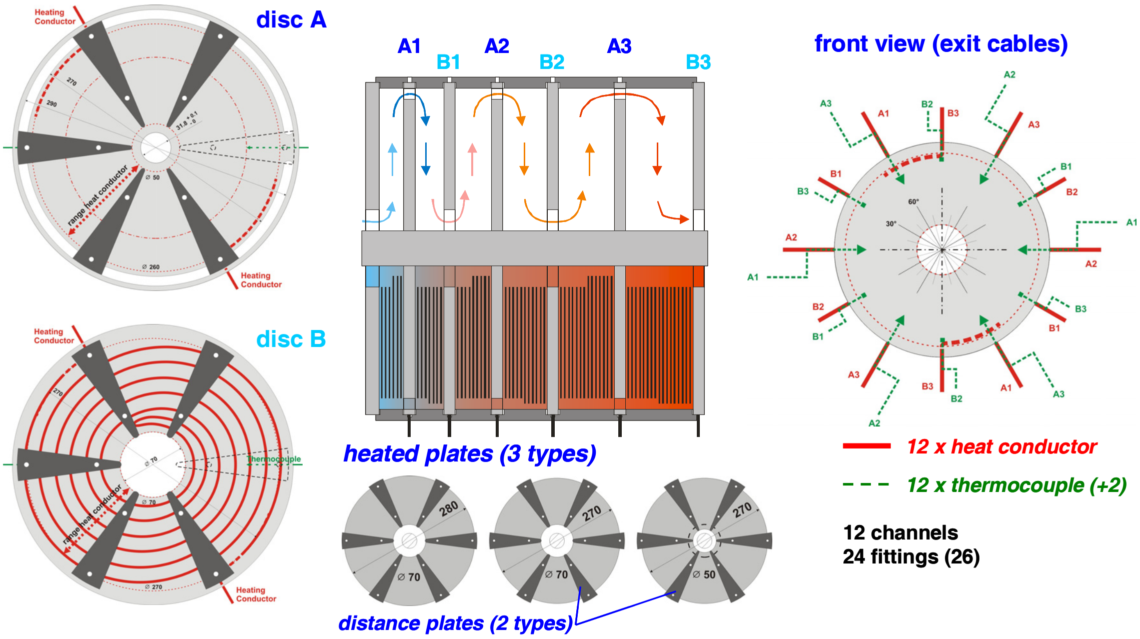

Fig. 2: Regenerator concept of flow and heat transfer through package of heated discs/plates.

Further design aspects, such as centering of all inner devices, dimensioning of the heat-resistive cup spring and the corresponding distance bush with regard to thermal expansion have been taken into account. In order to avoid leakage at the inner core border of the flow cells, a pressure equilibration is designated in the distance bush in front. Finally, also the question how to assemble all parts within this complex component had to be taken into account right away.

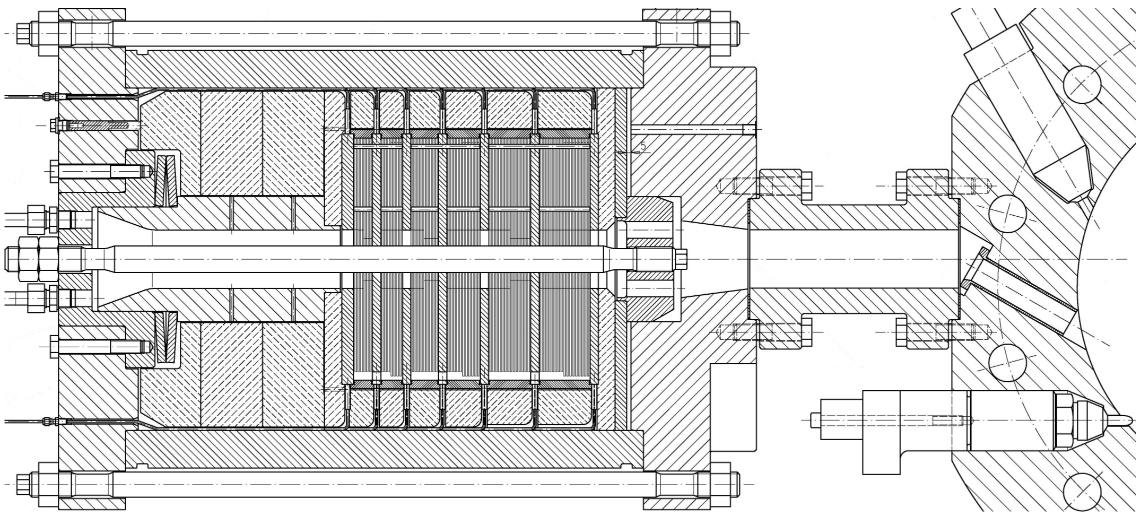

Fig. 3: Assembly drawing of the regenerator, connected with a flange to the spray/combustion chamber.

In general, extensive investigations with regard to tensile strength of the critical components, careful estimates of the thermal expansion as well as considerations about flow and volume aspects have been performed. Further, the regenerator is extendable with further heat discs in case that the heat power would not be sufficient.

In order to achieve a **layout confirmation**, the CAD data has been exported to shape a *Finite Element* (FE) analysis model geometry with a grid structure (see Fig. 4) of sufficient resolution to perform structure-mechanical calculations.

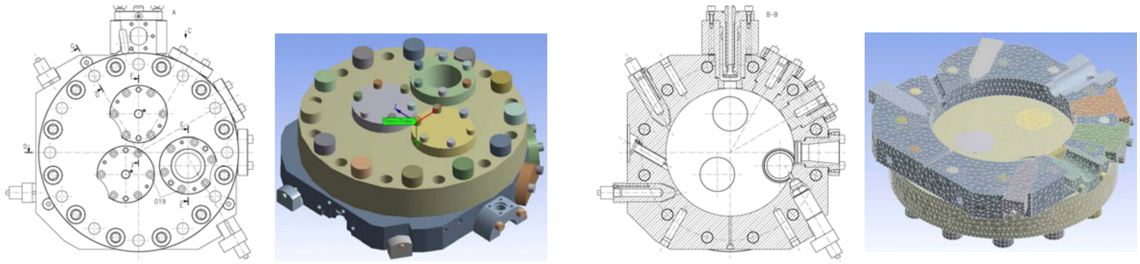

Fig. 4: CAD drawing and corresponding grid model for FE analysis calculations.

First, a stationary FE analysis under constant conditions in the spray/combustion chamber has been performed. The specifications of the used materials, respectively alloys have been taken into account. Investigations at the limiting (mechanical/thermal) design layout conditions at different wall temperatures lead to several conclusions.

The dimensioning of the designed layout seems to be sufficient. The major influence with respect to tension has the level of the temperature gradient – cold walls result in comparatively higher comparison stresses. A comparison of the mechanical alloy properties as well as the pre-tension of the screw with the resulting comparison stresses shows local tensions below material or design limits. Nevertheless, the stationary FE analysis evaluated weak spots where local design modifications were necessary. For example, the intake bores as well as the injector tip bore had to be modified to decrease local tension peaks. Furthermore, also the pre-tensioned stud bolts were modified in terms of an increased extend rang. The most important design optimization was the complete relocation of the main gasket position in order to reduce the stress in the covers of the spray/combustion chamber significantly. Last but not least, also the maximum thermal expansion of the test chamber with regard to the fixation with cup springs could be analyzed.

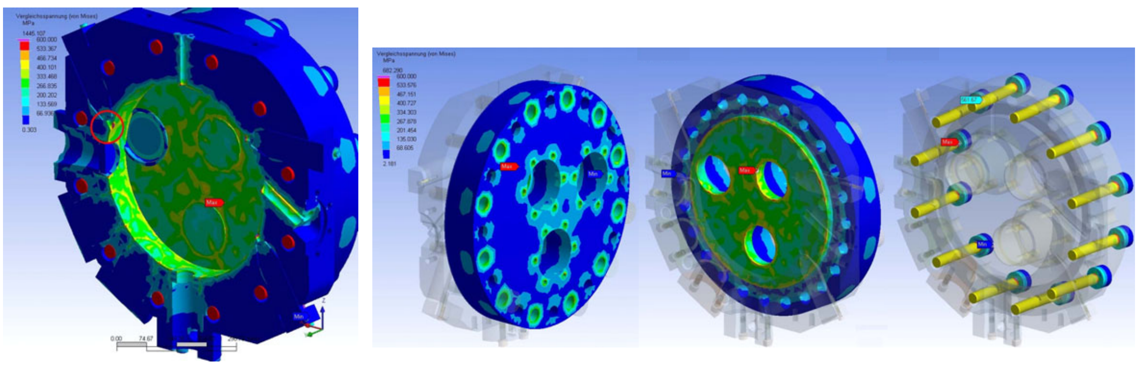

Fig. 5: Results of a structure-mechanical analysis at a critical time instant (max. temperature gradient).

In a second stage of the FE analysis, transient analysis calculations with regard to the fill and combustion process and its pressure, temperature and fuel/air-ratio conditions have been performed. Temporal profiles of pressure, temperature and heat transfer courses (including swirl) have been given by simulations and careful analytical estimations. As the gas-wall temperature gradient has been identified as having a major influence, a time resolved thermic analysis at three particular locations of most probably maximum strain has been performed. In addition, together with the material selection up to now, a second alloy – as a heat resistant alternative with regard to tensile and yield strength, respectively – was also investigated.

In general, analog to the stationary analysis, the layout, design and dimensioning is assessed as reasonable again. The mechanical properties of the used alloys are sufficient compared to the determined comparison stresses. Especially the investigated heat-resistant alternative ("hot work" tool steel) is absolutely favorable to use as a blank material for maximum stressed components such as the covers, the housing or stud bolts of the spray/combustion chamber with respect to creep resistance. Figure 5 shows the calculated tensions for this alloy at a certain time of maximum temperature gradient at a particular location. The sapphire window has been included (see left image) and its strain seems to be far from critical values.

Alloys	• **X38CrMoV5-1 (ESU)** *R_m=1100-1300 N/mm^2*	**to be annealed, "hot work" tool steel ($R_m/R_{p0.2}$ 500°C)** *SCC housing, covers, stud bolts / REG pipe, covers, flanges, bush*
	• **30CrNiMo8 (34CrNiMo6)** *R_m=900-1300 N/mm^2*	**annealed ($R_m/R_{p0.2}$ 200-300°C)** *SCC sight glass, dummies / REG stud bolts*
	• **34CrMoV4 (X39CrMo17-1)** *R_m=900-1100 N/mm^2*	**annealed** *(cup springs)* *SCC nuts / REG hexagon nut*
	• **Inconel 600 / 718** *R_m=650 N/mm^2*	**heat and corrosion resistant** *SCC sleeves / REG plates, rings, cup springs*
	• **Nimonic 90 / 80A** *R_m=1100 N/mm^2*	**heat resistant ($R_m/R_{p0.2}$/creep resistance 900°C)** *REG rod, round nut*
Ceramic	➢ **CaSI parts: CS 950/1002SI** *R_m=30-50 N/mm^2, λ=0.2-0.5 W/mK*	**temperature resistance, low shrinking and isolation** *REG isolation rings, inner core back plates*
Sapphire	❖ **Al_2O_3 windows** *R_m=2050 N/mm^2, λ=35 W/mK*	**hardness, scratch & thermal shock resistant** **thermal conductivity & expansion similar as steel**

Tab. 1: Summary properties and use of considered and finally selected specific materials.

The conclusions of the structure-mechanical analysis as well as careful analytical estimates confirmed the material selections. Table 1 shows a summary of selected materials and their application in specific parts of the spray/combustion chamber (SCC) and regenerator (REG). The main stressed components (cover, housing, stud bolts) of the spray/combustion chamber consist of hot work tool steel, which is characterized by high hot tensile strength and toughness, a good thermal conductivity and insusceptibility to hot cracking. This alloy has to be annealed after pre-machining, so that with a specific heat treatment the most favorable toughness (tensile and yield strength) in combination to an agreeable brittleness can be set. A disadvantage is the necessary secondary machining process after annealing.

All other major components (window holders, dummies) are made out of heat-treatable steel for high strained construction components, which was already annealed. The most stressed components (pre-loaded tie rod, heat discs/plates regenerator) consist of very specific high-temperature alloys (Inconel, Nimonic), having a high stress-rupture strength and creep resistance at temperatures to about 900°C as well as good resistance to corrosion and oxidation.

The major blank materials have been purchased with the corresponding certificates. In addition, material tests for all critical components have been performed. An ultrasonic test checked for volume cracks, respectively a magnetic particle test for surface cracks. A tensile test of the stud bolts confirmed the designated tensile and yield strength achieved by the heat treatment. Further, lots of other usual construction steels, for example as gaskets, guides are applied in the setup.

Another specifically used material is ceramic (CaSi). It features high temperature resistance, small shrinking and good isolation behavior together with (at least) some mechanical comprehensive strength. Finally, also the idea to use sapphire windows has been confirmed. It is the second hardest natural material (after diamond), therefore very scratch and (thermal) shock resistant and its thermal conductivity respectively expansion is similar to steel.

The actual **production** started after collecting deliverable blank materials from suppliers all over Europe. According to the "dry" steel market, the evaluation of the actual availability was one of the main challenges in this project phase. The entire test facility now consists of about 150 components with more than 1000 single pieces, whereas it can be spoken of about 400 different parts.

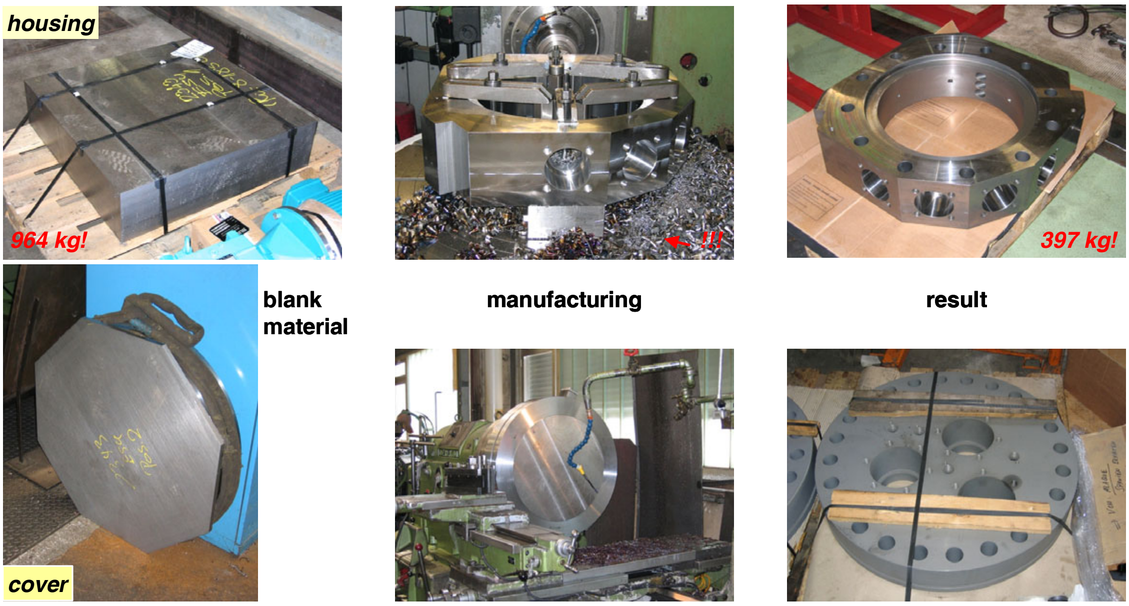

Fig. 6: Impressions of the production process from blank materials to the machined components

An impression of the **assembling** of all manufactured parts belonging to the spray/combustion chamber is given in fig. 7. The empty foot basement was implemented by the housing. Afterwards, the covers were mounted, all window holders/dummies placed and finally the stud bolts arranged.

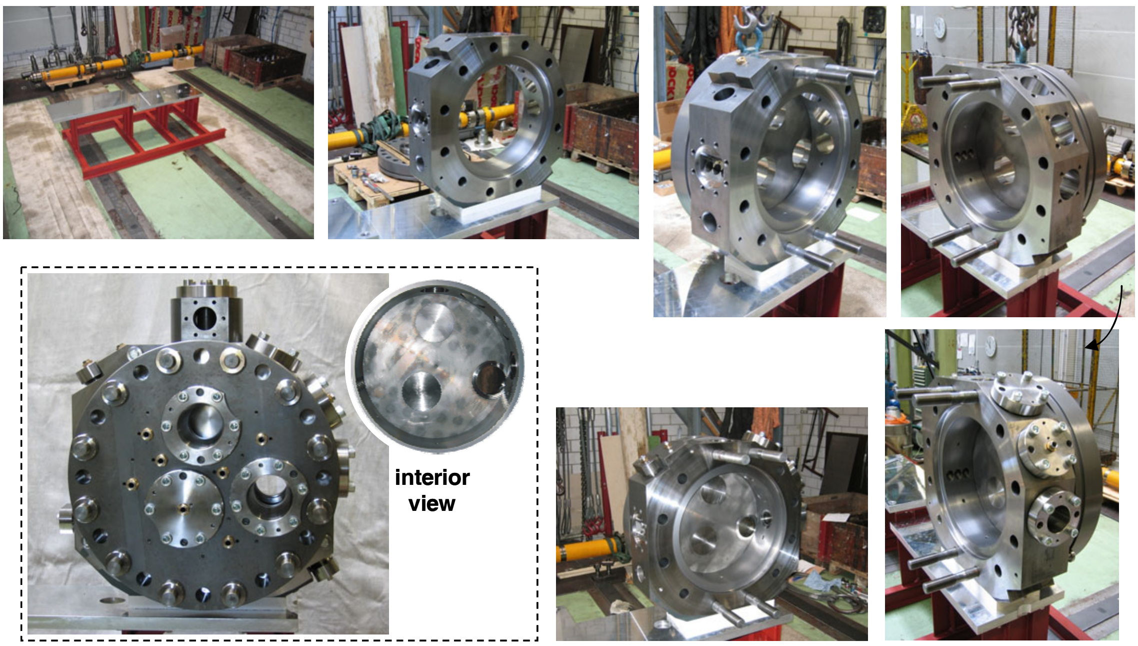

Fig. 7: Assembling of the spray/combustion chamber

The assembling of the regenerator core, which is surrounded by the pressure pipe, was even more complex. A detailed part overview is given by fig. 8. The implementation between the lower round nut along the stud bolt started with the back panel plates of Inconel (1) and ceramic (2). Above the latter, the first heat disc is located, followed by the first package of heat plates (3) combined with the distance holders/rods (4) providing the largest starting flow cells. It is delimited by a locking ring (5), which again is surrounded by a ceramic ring (6) to protect the pressure pipe.

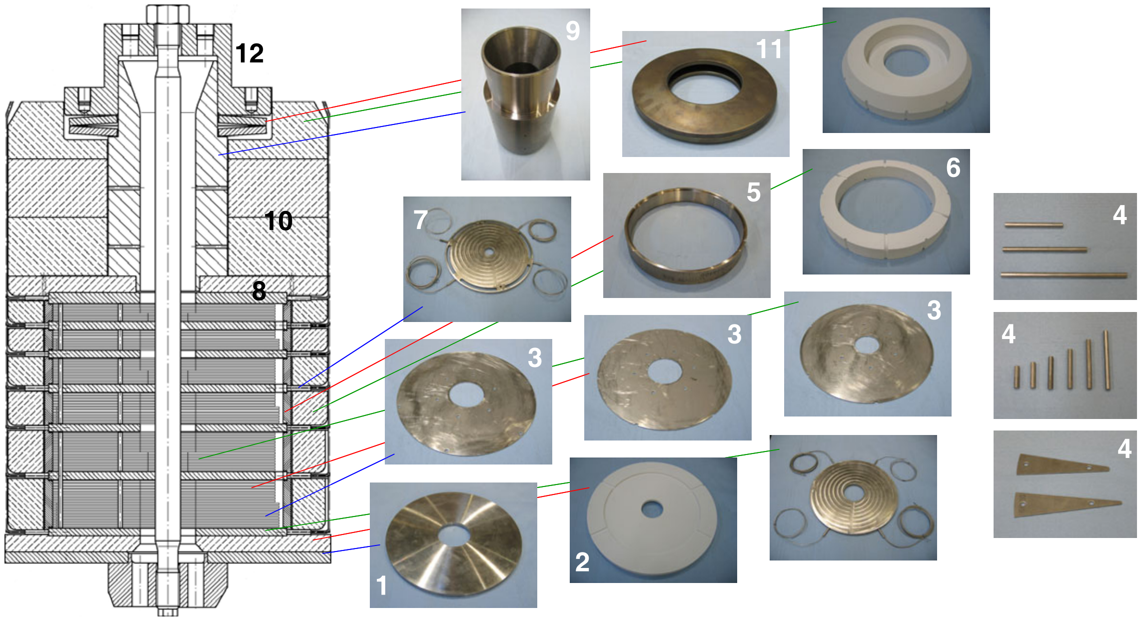

Fig. 8: Selection of important heating relevant parts of the regenerator core

At the next stage, the other kind of the heat disc (7) is applied and the following "flow cells" are assembled up to a locking plate (8). The distance bush (9), encircled by more ceramic heat protection rings (10) and the cup springs (11) located at the top guide flange (12) complete this setup.

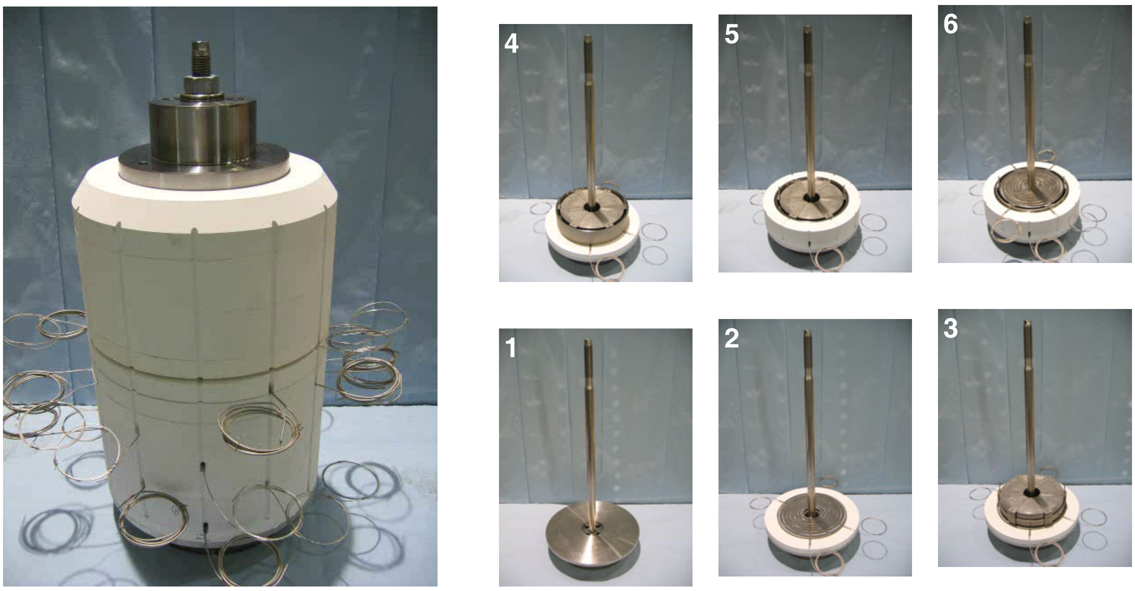

Fig. 9: Finally assembled regenerator core

Figure 9 shows the erection stages of the first flow cells package and the final assembly of the regenerator core with the corresponding heat conductor cables.

The logistics refers not only to the manufacturing of the major components (see fig. 6), but also to the organization of all accessories, such as gaskets, plates, rods, sleeves, cup springs, screws and so on. In addition, also the standard two-stroke marine diesel engine (WCH) elements and ordinary parts had to be provided. The transport, respectively the delivery had to be arranged in a way to have the whole set of all necessary components here before the start of the assembly.

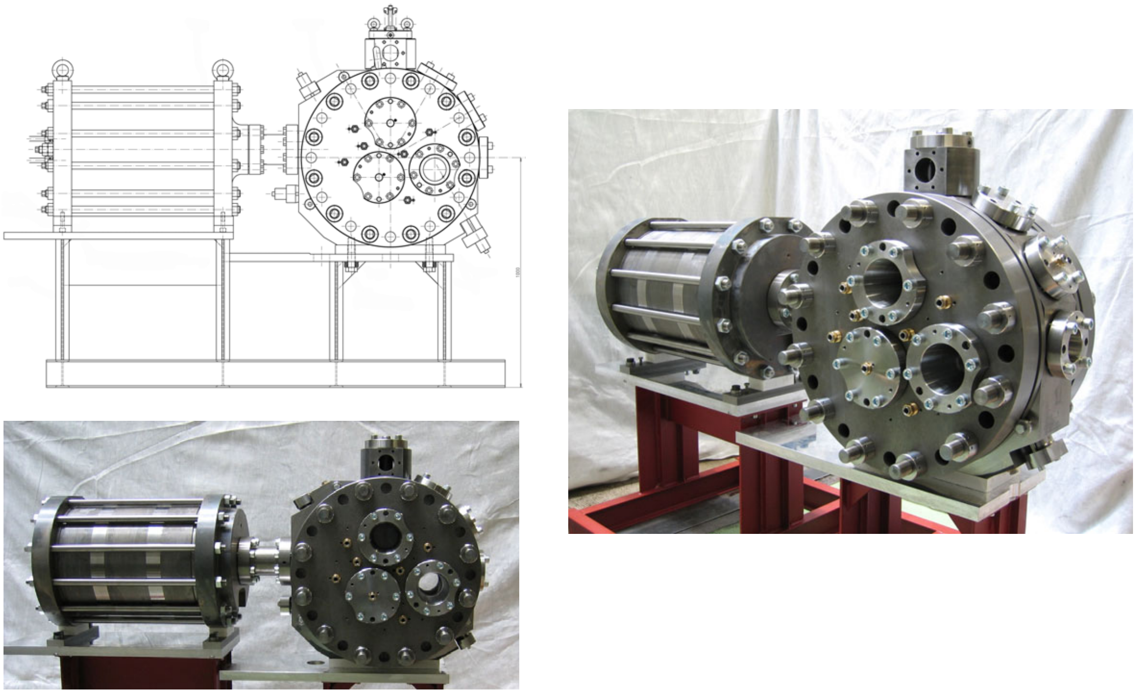

Fig. 10: Entire spray/combustion chamber facility

Finally, the regenerator cover has been connected to the spray/combustion chamber, to complete the setup of the entire test facility. Figure 10 gives an impression of the whole setup, whereas unfortunately the dimensions are not very well recognizable. The system has the extent of 2x1x1.5m and the weight is about 3 tons.

In addition, also the major necessary **test facility components** have been designed, evaluated or manufactured. Figure 11 shows an overview of the most important components.

The regenerator is coupled to the accumulator system, consisting of two single bottles, which can be filled up to 360 bar. Its specific design is kept very flexible with respect to flow control (regulation valves, fast solenoid valves) and regarding the connection (compressor, condensate drain) possibilities. Further, a separate pressure monitoring as well as individual security valves are included. The connected compressor delivers 500 l/min (300 bar), and, in combination with the accumulator system, also provides the possibility of directly scavenging the combustion chamber.

The latter has been completed with all designed and manufactured components and accessories. The exhaust valve is a special construction according to its additional function as a security valve. The window holders as well as a series of dummies – which can be heated by heating cartridges in order to keep the chamber temperature on a certain level – have been designed, manufactured and mounted. The heating cartridges are located in sleeves (within bores of the dummies) to allow a simpler dismounting in a burst case. In order to perform inert spray investigations (without combustion) a drain nipple connected to a pneumatic high pressure valve has been conceived. Finally, also a hydraulic pre-tension tool to screw down the stud bolts in an elegant way has been build-up.

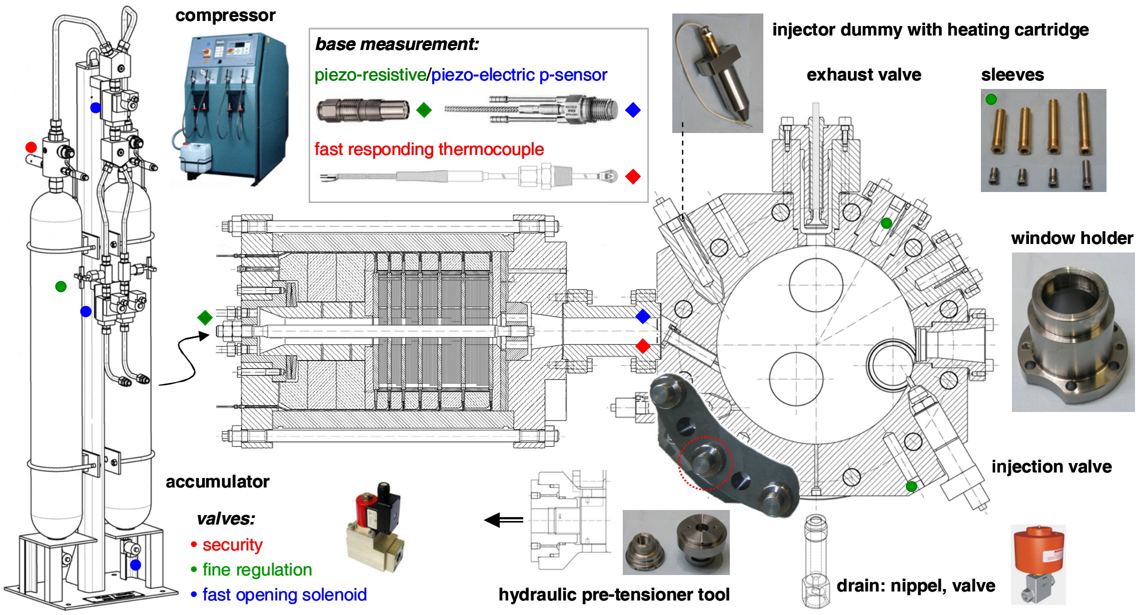

Fig. 11: Periphery, test facility components, tools and accessories

With the purpose of having the spray/combustion chamber soon ready for operation, development and evaluation in lots of different other issues has already been started. A major subproject for example is the design and setup of the entire injection system. On the other hand also the actual laboratory building setup and further test bed facility design is still in progress. Another important point concerns the base measurement system, to acquire the pressure and temperature conditions during operation in the test facility, which has been evaluated and implemented.

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. As in the first year, the collaboration between WCH and ETH was intensive and very fruitful. Numerous aspects of infrastructure and the test rig itself could be solved and the optimal configuration selection of particular importance here was the definition 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 close collaboration with respect to the definition, design and implementation of the controls and operating/data acquisition system of the entire spray/combustion chamber facility.

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, 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 2004 and Outlook 2005

The design and implementation of the large spray/combustion chamber facility within the HERCULES project has made substantial progress within this report year. Based on the design of the first year, extensive Finite-Element investigations have been performed to access the robustness and safety of the apparatus against static and dynamic/transient thermal and mechanical loads, as given by specified limiting operating conditions. They led to design improvements in detail, but confirmed that the original concept and design is appropriate and reasonable. Furthermore an enormous number of components for the combustion chamber itself and its periphery have been defined, commissioned and to a large extent manufactured. The chamber and the regenerator are now assembled together and ready for operation, when the additional infrastructure parts are going to be available. The operation, control and data acquisition system are defined and their manufacturing will be accomplished soon. Furthermore the demanding fuel system has been defined and its construction is in preparation.

During the next project year, implementation of the whole test rig and detailed testing of its functional performance will be carried out. An important step in this direction is the availability of the lab building infrastructure which is already mostly defined. Subsequently measurements with combustion under progressively increasing pressure and temperature conditions are intended. There is justified hope, that at the end of the project, a unique first set of data will be available.

References

[1] ***Website I. P. HERCULES, www.ip-hercules.com***.

[2] ***Website I. P. HERCULES, www.ip-hercules.com***. Category "Structure": Workpackage 2\Task 2.1: Combustion process simulation.