ERWEITERUNG UND VALIDIERUNG DER CRFD (COMPUTATIONAL REACTIVE FLUID DYNAMICS)-SIMULATION FÜR NEUE MOTORISCHE BRENNVERFAHREN UND KRAFTSTOFFE

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ZUSAMMENFASSUNG

Dieses Projekt strebt an, bestehende Simulationswerkzeuge zu erweitern um neuartigen Brennverfahren und unterschiedlichen Kraftstoffeigenschaften Rechnung tragen zu können und präzise Vorhersagen zu ermöglichen. Zu diesem Zwecke werden in Zusammenarbeit mit anderen nationalen und internationalen Forschungsvorhaben wertvolle Synergien genutzt. Die Problematik wird dabei von vier Seiten angegangen: Jeweils paarweise ein experimenteller Teil zur Bereitstellung der Validierungdaten und parallel dazu die Simulations-Code Entwicklungsarbeit. Die zweite „Achse“ besteht in der gezielten Ausnutzung der jeweiligen Vorteile von motorischen Versuchsträgern (welche die Validierung an technisch relevanten Verbrennungvorgängen erlaubt anhand globaler Grössen wie bspw. Zylinderdruck) und von ‚generischen‘ Experimenten an optisch zugänglichen Verbrennungskammern und Einhubtriebwerken (welche zusätzlich wertvolle, örtlich aufgelöste Informationen liefern für die Submodellvalidierung und –kalibrierung).

In 2008 konnte am LAV ein MTU 396 Einzylinder heavy duty Forschungsmotor erfolgreich in Betrieb genommen werden welcher einen flexiblen Austausch der Instrumentierung zulässt (schnelle Entnahmesonde, Mehrwellenpyrometrie, Ionenstrom-Sonden etc.). Der bestehende Conditional Moment Closure code wurde mittels Daten eines vorher ausgemessenen heavy-duty Motors für einen weiten Bereich von Betriebsbedingungen erfolgreich weiter-validiert anhand von Druckverläufen, Brennraten und NO_x Emissionen, dies für konventionellen Dieselkraftstoff. Letztere Untersuchung wurde zur Publikation eingereicht für den SAE World Congress im April 2009.

Erste Modifikationen für die Inbetriebnahme des Einhubtriebwerkes im ‚dual-fuel‘-Betrieb, d.h. mit homogener Grundladung und Zündung mittels Dieselpilot sind erfolgt und eine umfangreiche Literaturstudie zu diesem Brennverfahren weitgehend abgeschlossen. Aufgrund von Rekrutierungsschwierigkeiten konnten auf der Seite der Kraftstoffvariationen noch keine Messungen durchgeführt werden, alle vorbereitenden Arbeiten sind weitestgehend abgeschlossen und die Infrastruktur und Messausrüstung steht ebenfalls bereit; Evaluationen und Interviews mit potentiellen Kandidaten erfolgen laufend.

Im nächsten Jahr wird der Schwerpunkt der Arbeit an der Generierung experimenteller Daten an den verschiedenen Versuchsträgern liegen, wobei die Simulation begleitend ausgebaut wird.

Projektziele

Computational reactive fluid dynamic (CRFD) has become an indispensable tool in the development of technical products. The long term goal is to partially replace expensive measurement campaigns with cost- and time-effective simulation. This is motivated on the one hand by the enormous cost reduction potential and on the other hand by 'time to market' considerations. The latter is becoming a major issue as the development of highly flexible fuel injection systems has lead to an increase in the degrees of freedom by several orders of magnitude in the last decades and efficient testing of all possible combinations s becoming more and more difficult. Hence **this project aims at further developing CRFD tools allowing for improved predictions** and hence offering a) the potential **to substitute** some of the **expensive engine testing and** b) **further gain insight into the combustion processes**. To this end an existing CRFD code which models combustion and turbulence-chemistry interaction with Conditional Moment Closure (CMC) and is capable of detailed chemistry will be extensively validated by means of experimental data. **Further developments/improvements** to the sub-models and extensions **of the code for the treatment of new 'state-of-the-art' combustion concepts and emission predictions will be implemented** wherever required.

To ensure maximum benefits in terms of applicability and relevance, the project is tackled from two sides, namely engine based work and more fundamental development based on measurements and validation by means of 'generic' test rigs. The approach is further strengthened by employing a 'pair' of work packages consisting of one experimental work package and a parallel modelling/validation package. E.g. in work package 1 (AP1), a heavy duty single cylinder engine is used to generate an extensive data-base for a broad range of operating conditions which is used to assess and validate the developments in the framework of work package 3 (AP3) for engine configurations. In work package 2 (AP2), experiments are performed for two optically accessible set-ups: In AP2a for the LAV-ETH high pressure high temperature combustion vessel (HTDZ) and in AP2b for a single shot machine featuring a free floating piston. In work package 4 (AP4) validation and code development will be carried out in the two sub-packages AP4a and AP4b based on the corresponding measurements from AP2a and AP2b. Work package 5 (AP5), finally, contains publication activities and PhD thesis preparation.

All work packages are running parallel to other projects which ensures optimal leverage of the BfE funding: AP1 and AP3 are synchronised to the **Swiss Competence Center Energy and Mobility (CCEM)** project **"CELaDE"**; AP2a and AP4a with the **Forschungs-Vereinigung Verbrennungskraftmaschinen (FVV)** project **"Future Fuels Diesel"** and AP2b and AP4b with the **FVV project "Piloteinspritzung"**.

For the reporting period 2008, the project goals of the individual work packages are as follows (wherever applicable, more detailed information from the respective CCEM/FVV projects is provided):

AP1:	• Single Cylinder engine fully instrumented	9 / 2007
	• Complete results with ion-sensors and sampling valves, incl. heat release rate	9 / 2008
AP2a	• Modifications/re-design of the single stroke machine	12 / 2008
	• Feasibility/accuracy study of the envisioned measurement techniques for the reference fuel at one defined thermodynamic state	12 / 2007
AP2b	• Data-set acquisition and development of first laminar burn speed correlation	9 / 2008
AP3:	• Sensitivity of combustion models with respect to NO_x predictions	3 / 2008
	• Model for heat release rate finished	9 / 2008
AP4a	• Work package scheduled to start after 7 PM, i.e. 1st February 2009	N/A
AP4b	• Work package scheduled to start after 9 PM, i.e. 1st April 2009	N/A
AP5:	• Documentation / publications	on-going

Durchgeführte Arbeiten und erreichte Ergebnisse

In **AP1**, an MTU 396 single cylinder heavy duty engine is used for the acquisition of a large experimental data-set to be used for model validation purposes. In terms of the original CCEM project plan, the project is roughly 12 month behind schedule. This is predominantly due to unforeseeable difficulties with various sub-components (lubrication oil conditioning system, engine control system) and substantial adjustments required relating to the test rig infrastructure: The large engine displacement made adaptations in the high pressure air supply line necessary, in particular also due to the requirement of the pneumatically driven starter motor as well as with regard to the novel variable heating of the intake system (installation provided by the ETH central “technischer Dienst”). Since the start of the BfE funding on the other hand, the project is progressing as planned with the engine being commissioned and undergoing the compulsory break-in programme before full load testing can be commenced. A schematic overview of the complete test rig and the necessary infrastructure is given in figure 1 below.

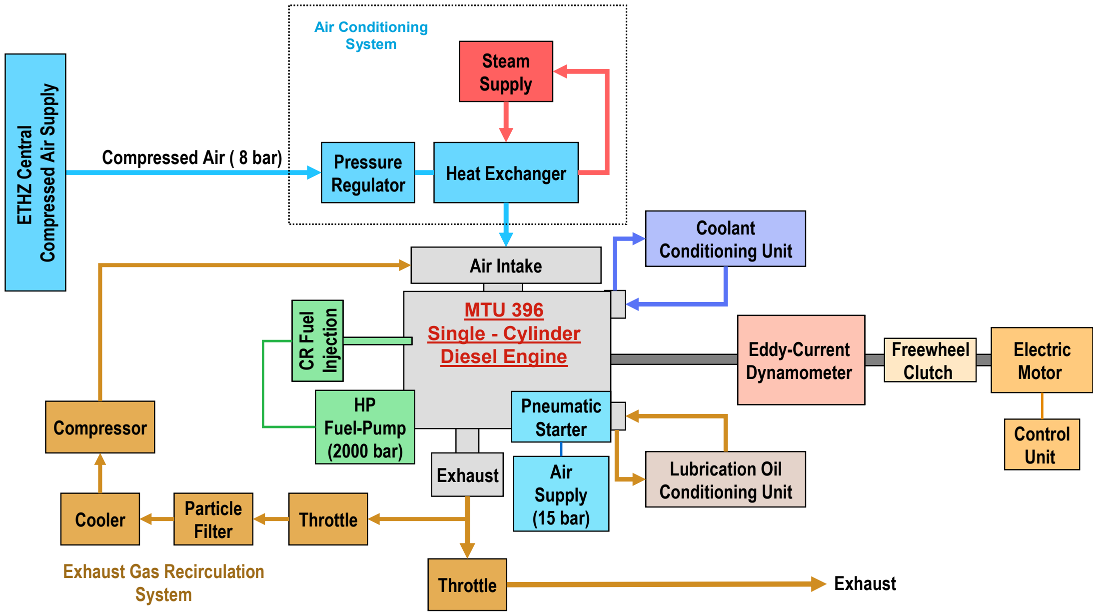

FIGURE 1 – MTU 396 SINGLE CYLINDER HEAVY DUTY ENGINE: SCHEMATIC OVERVIEW

Two complete cylinder heads are available for the engine hence, in a first step, the available, conventional plunger-type fuel injection system is used during the running-in phase whilst, in parallel, the second cylinder head is adapted to accommodate the common-rail fuel injector as shown in figure 2 below. A section plot illustrating in more detail the modifications can be found in the appendix in figure 8.

Additionally, one of the two exhaust valves has been deactivated and a replacement insert is being machined. This approach allows for time- and cost-effective exchange of the experimental techniques resulting in low engine down time. A broad range of instrumentation will be applied including a fast sampling valve to characterise in-cylinder emission data, endoscopes (for soot pyrometry), ion current sensors or an additional pressure transducer for calibration purposes etc.

FIGURE 2 – MTU 396 SINGLE CYLINDER HEAVY DUTY ENGINE: MODIFIED CYLINDER HEAD WITH COMMON-RAIL FUEL INJECTOR AND ADAPTOR

In **AP2a** the preparatory modifications of the single stroke machine are mainly completed and the experimental equipment assembled. Due to recruiting problems, no measurements could unfortunately be performed so far.

An in-depth literature review for dual fuel engine operation, e.g. premixed lean gas with Diesel pilots has been carried out in the first project months of **AP2b**.

Due to the delay of work package 1, no experimental data for the MTU 396 single cylinder engine was available which could be used for model validation in **AP3**. Based on the first, highly encouraging results of the CMC code applied to a full engine configuration documented in [1], additional validation by means of heat release rate and NO_x emissions was performed for a wide range of operating conditions on a high quality measurement data-set from a heavy-duty engine which was recorded in the framework of [2]. The variations include changes in the engine load, the engine RPM, injection timings and injection pressure. The main engine data and the operating points investigated are summarised in Table 2 and Table 3 in the appendix. The operating points investigated have been selected based on the European Steady Cycle test [3] conditions, for which an overview is given in figure 3.

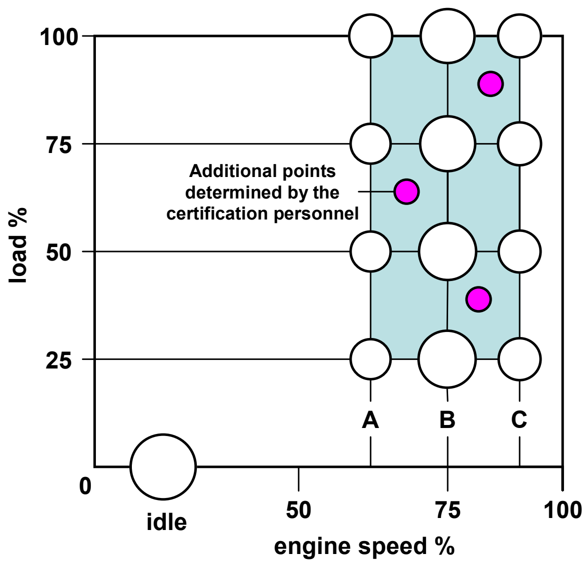

FIGURE 3 – EUROPEAN STEADY CYCLE TEST MAP, SOURCE [4]

Following a sensitivity study of the results with respect to CFD mesh dependence and CMC grid resolution/various dimensionality reduction strategies, calculations have been performed for all operating conditions listed in Table 3 in the appendix. As can be seen from figure 4, figure 5 and figure 6 below, good agreement is reported with respect to the pressure traces and the heat release rates for the majority of investigated operating conditions.

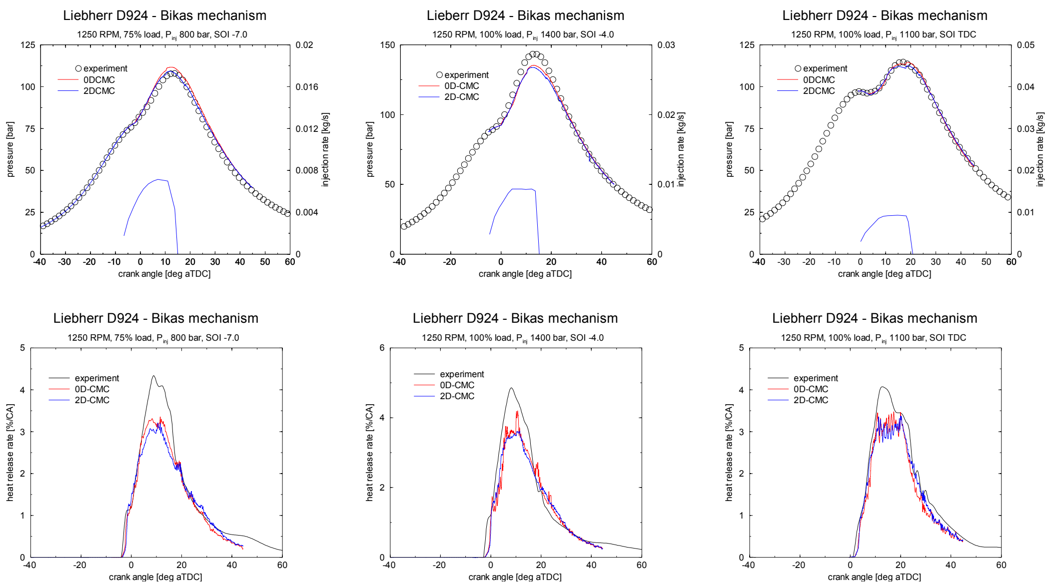

FIGURE 4 – PRESSURE TRACES (UPPER ROW, WITH SUPERIMPOSED FUEL INJECTION RATES) AND HEAT RELEASE RATES (LOWER ROW) FOR 0D- AND 2D-CMC APPROACHES COMPARED TO THE EXPERIMENTAL DATA OF THE LIEBHERR D924 DIESEL ENGINE FOR HIGH LOAD OPERATING CONDITIONS

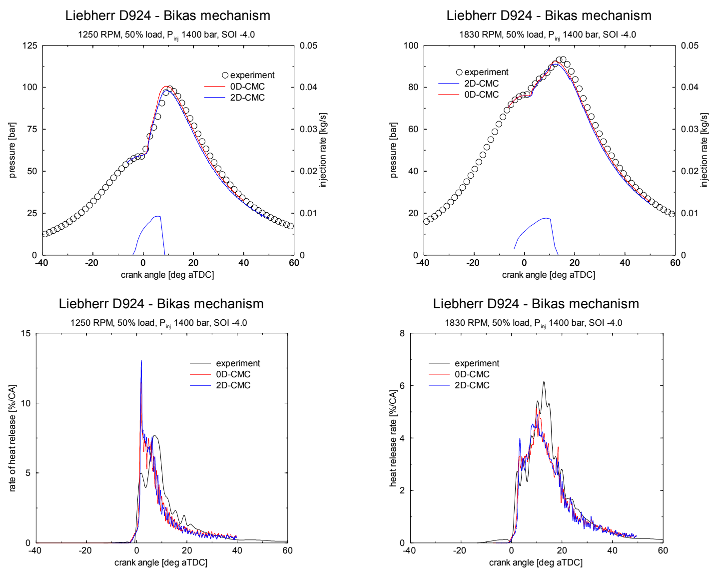

FIGURE 5 – PRESSURE TRACES (UPPER ROW, WITH SUPERIMPOSED FUEL INJECTION RATES) AND HEAT RELEASE RATES (LOWER ROW) FOR 0D- AND 2D-CMC APPROACHES COMPARED TO THE EXPERIMENTAL DATA OF THE LIEBHERR D924 DIESEL ENGINE FOR 50% LOAD OPERATING CONDITIONS

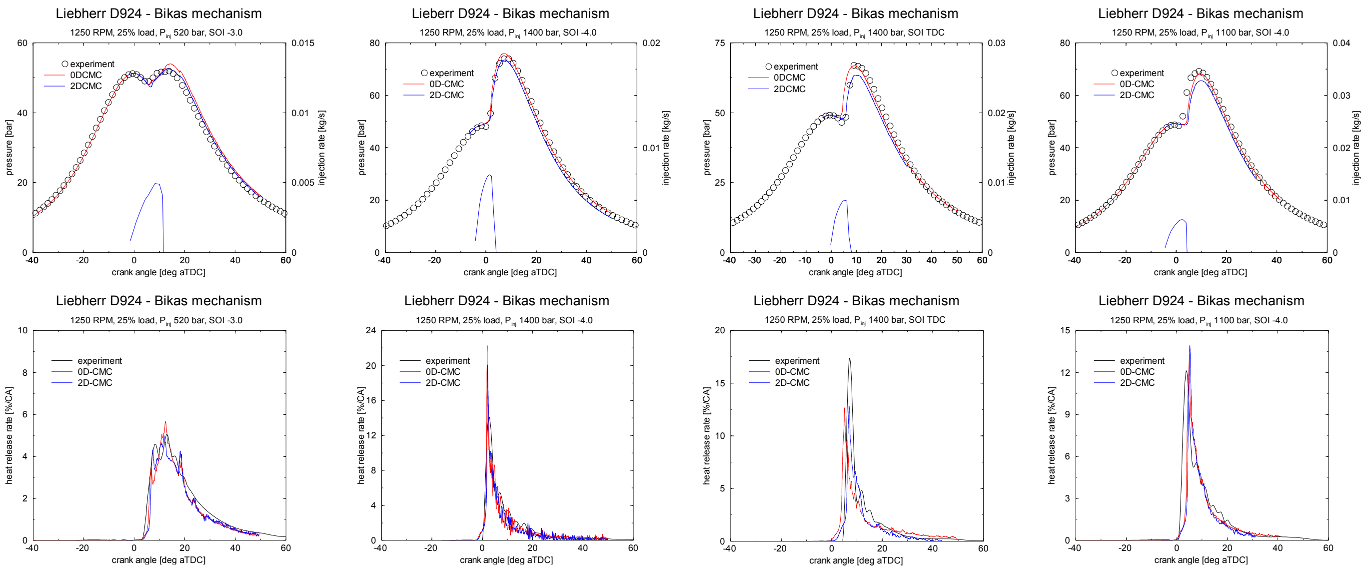

FIGURE 6 – PRESSURE TRACES (UPPER ROW, WITH SUPERIMPOSED FUEL INJECTION RATES) AND HEAT RELEASE RATES (LOWER ROW) FOR 0D- AND 2D-CMC APPROACHES COMPARED TO THE EXPERIMENTAL DATA OF THE LIEBHERR D924 DIESEL ENGINE FOR 25% LOAD OPERATING CONDITIONS

The NO_x predictions are in fair agreement with the experimental data as is shown in figure 7 below. While in absolute values, in some cases significant discrepancies can be observed compared to the experimental values, the trends are relatively well captured: For the 50 percent loads an increase in the engine speed is well predicted. At 25 percent load, two trends are correctly represented, namely the increase in injection pressure for identical injection timing leading to higher engine out NO_x emissions as well as the influence of earlier injection timing for constant injection pressure showing increased NO_x levels. At full load, later injection leads to lower NO_x emissions.

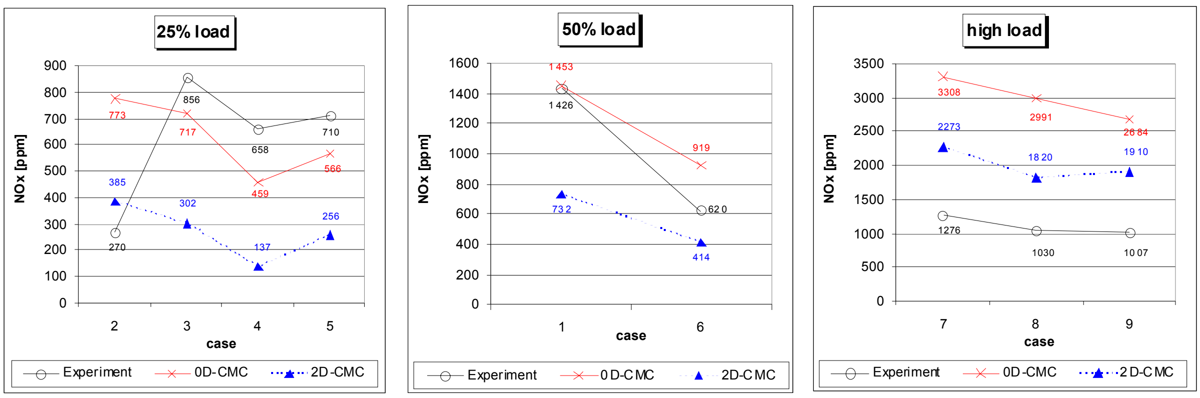

FIGURE 7 – NO_X PREDICTIONS FOR 0D- AND 2D-CMC APPROACHES COMPARED TO THE EXPERIMENTAL DATA OF THE LIEBHERR D924 DIESEL ENGINE FOR A TOTAL OF NINE OPERATING CONDITIONS AT 25%, 50%, 75% AND FULL LOAD

All these results from **AP3**, including the sensitivity study mentioned previously, have been submitted for presentation/publication at the upcoming SAE world congress in 2009 [5] as part of work package 5 (**AP5**).

While these investigations focussed primarily on changes relating to the injection configuration, further validation is necessary to assess the predictive capability of the CMC code with respect to changes in the air path. In particular the influence of slow chemistry effects due EGR will be of primary interest. Furthermore, CMC offers an ideal framework for advanced soot modelling; for the latter a preliminary study has been carried out at LAV in the framework of a Master Thesis [6].

Nationale Zusammenarbeit

AP1 and AP3 are synchronised to the **Swiss Competence Center Energy and Mobility (CCEM) "Clean Efficient Large Diesel Engine (CELaDE)"** project.

Internationale Zusammenarbeit

AP1 and AP3 are in parallel to the AP2a and AP4a are in parallel to projects of the Forschungs-Vereinigung Verbrennungskraftmaschinen (**FVV**), namely AP2a and AP4a to the project **„Future Fuels Diesel"**, AP2b and AP4b to the project **„Piloteinspritzung"**.

Bewertung 2008 und Ausblick 2009

In 2008, substantial progress has been made in **AP1** and the engine is showing first promising results. Early 2009 will bring last changes to the infrastructure, namely the common-rail fuel injection system, the Exhaust Gas Recirculation (EGR) system and a steam supply with heat exchanger for the intake air conditioning. The second cylinder head will undergo the final changes required for the accommodation of the common-rail fuel injector as well as a bore for a cooled pressure transducer. In **AP3**, the first multi-dimensional code demonstration for engines performed in [1] has been extended to a validation study based on pressure traces, heat release rates and NO_x predictions for a broad range of operating conditions of a heavy duty Diesel engine which are summarised in [5]. The next steps will consist of mesh generation for the MTU 396 engine, a grid resolution and spray model sensitivity analysis, followed by first combustion simulations.

The next steps within **AP2a** will consist of a feasibility study for the numerous planned measurement techniques and an evaluation of the respective accuracies. Following the establishment of the appropriate techniques, measurements for several out of in total eight fuel types and detailed post-processing of the data acquired are planned by the end of 2009. The next steps of work package **AP2b** will focus on the development of laminar and turbulent flame speed correlations and the definition of an appropriate air/fuel-ratio range for optimal operation in homogeneous premixed gas situations with Diesel pilots and taking into account in particular also the NO_x emission modelling strategies.

The up-coming calculations in the framework of **AP4a** will focus on an assessment of the fuel spray behaviour, in particular concerning differences in atomisation, droplet break-up and the subsequent mixture formation in order to provide information relating to fuel and temperature stratification for the different fuels. Due to emphasis we need to put on the delayed experiments, AP4 may need to be postponed for quite late within 2009. In **AP4b** 2009 will focus on calibration of the few remaining model constants in the CMC code together with a detailed sensitivity analysis by means of data from one of the in-house optically accessible test rigs. Following this, first investigations may be carried out to assess the applicability of the CMC to Diesel pilot auto-ignition in homogeneous gas environment configurations. The predictive capabilities with respect to the ignition delays for these situations and the identification of potentially required model developments to address the transition of the combustion mode from auto-igniting spots of the Diesel pilots to the establishment of turbulent premixed flame propagation will be of particular interest.

Referenzen

[1] De Paola, G., Mastorakos, E., Wright, Y.M. & Boulouchos, K.: ***Diesel Engine Simulations With Multi-Dimensional Conditional Moment Closure***, *Combustion Sci. and Tech.* **180**, pp. 883-899, 2008

[2] Bertola, A.G.: ***Technologies for Lowest NO_x and Particulate Emissions in DI-Diesel Engine Combustion – Influence of Injection Parameters, EGR and Fuel Composition***, PhD Thesis, ETH Zürich, Switzerland, Diss. ETH No. **15373**, 2003

[3] Directive 1999/96/EC, December 13, 1999

[4] http://www.dieselnet.com, accessed Sept. 2008

[5] Wright, Y.M., De Paola, G., Boulouchos, K. & Mastorakos, E.: ***Multi-dimensional Conditional Moment Closure modelling applied to a heavy-duty common-rail Diesel engine***, *submitted for SAE World Congress 2009, SAE Paper offer number* **09PFL-0833**, 2008

[6] Schlatter, Stéphanie: **Russimulation – von 0D zu 3D mit verschiedenen Verbrennungsmodellen**, MSc Thesis LAV ETH Zurich, 2008

Anhang

ACRONYMS

BfE	Bundesamt für Energie (Swiss Federal Office of Energy)
CCEM	Swiss Competence Centre Energy and Mobility
CMC	Conditional Moment Closure
CR	Common-Rail
C(R)FD	Computational (Reactive) Fluid Dynamics
EGR	Exhaust Gas Recirculation
FVV	Forschungs-Vereinigung Verbrennungskraftmaschinen
LAV	Laboratory for Aerothermochemistry and combustion technology of ETH Zurich
MSc	Master of Science
SAE	Society of Automotive Engineers

TABLE 1 – ACRONYMS

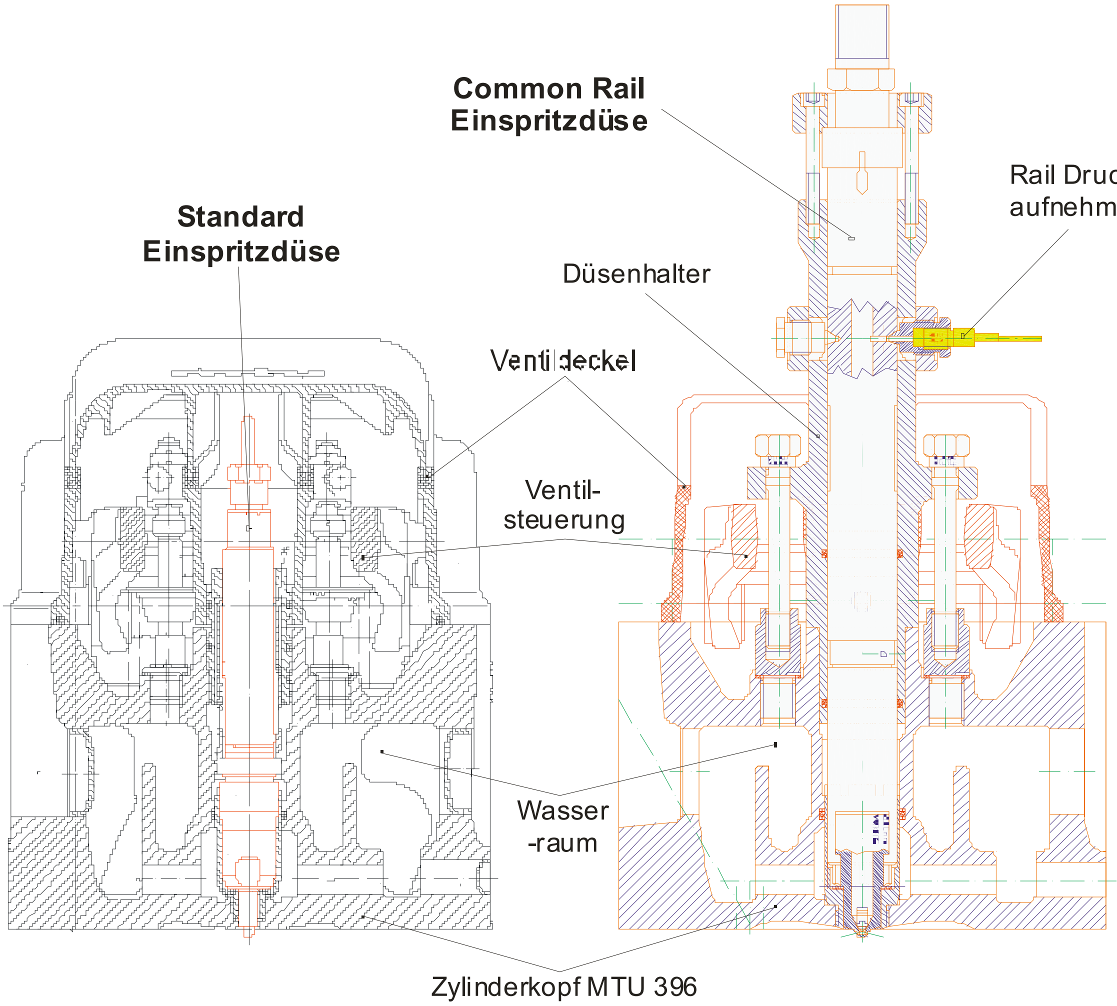

FIGURE 8 – MTU 396 CYLINDER HEAD COMPARISON: CONVENTIONAL FUEL INJECTION SYSTEM (LEFT) AND HEAD MODIFIED FOR COMMON-RAIL FUEL INJECTOR (RIGHT)

AP3 – HEAVY DUTY ENGINE SIMULATIONS

Table 2 and Table 3 summarise the main engine data and operating conditions used for the model validation performed in AP3.

Heavy duty 4-stroke, direct injection, turbocharged, intercooled Diesel engine	
Cylinders	4
Bore	122 mm
Stroke	142 mm
Displacement	6.64 litres
Compression ratio	17.2
Crank radius / connecting rod length ratio	0.3114
Maximum boost pressure ratio	2.6
Maximum power output	183 kW
Engine top speed	2100 RPM
Maximum BMEP	20 bar
Maximum cylinder pressure	160 bar
Swirl (Tippelmann number)	0.65

TABLE 2 – LIEBHERR D924 HEAVY DUTY DIESEL ENGINE: MAIN ENGINE DATA

operating point	load	engine RPM	start of injection [CA aTDC]	injection pressure [bar]
1	50%	1250	-4	1400
2	25%	1250	-3	520
3	25%	1250	-4	1400
4	25%	1250	0	1400
5	25%	1250	-4	1100
6	50%	1830	-4	1400
7	100%	1250	-4	1400
8	75%	1250	-7	800
9	100%	1250	0	1100

TABLE 3 – LIEBHERR D924 HEAVY DUTY DIESEL ENGINE: OPERATING CONDITIONS CORRESPONDING TO A SELECTION OF THE EUROPEAN STEADY CYCLE TEST POINTS