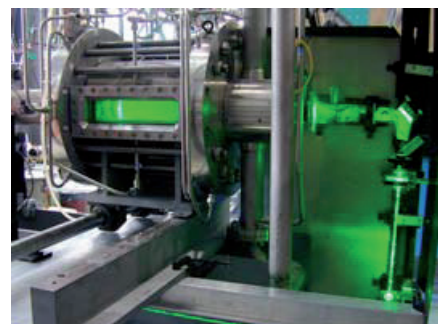
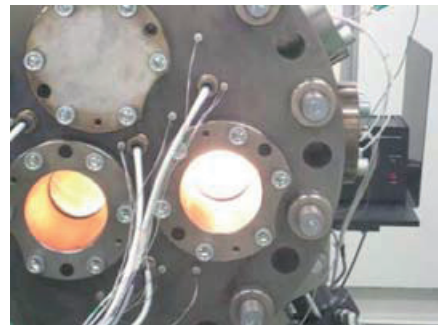


Tagung

Verbrennungsforschung in der Schweiz

28. Oktober 2009

Semper Sternwarte in Zürich



Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Energie BFE

PAUL SCHERRER INSTITUT
PSI

ETH LAV

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Programm

08:30	<i>Registrierung & Kaffee</i>
09:00	Begrüssung
09:15	Eidgenössische Energieforschungskommission CORE G.A. Lustgarten, CORE-Mitglied
09:30	IEA Verbrennungsforschung St. Renz & S. Hermle, Bundesamt für Energie (BFE), Bern
Forschungsprojekte aus Industrie und Hochschulen	
09:45	Thermoacoustic Modeling of a Gas Turbine Combustor using Transfer Functions measured at Full Engine Pressure B. Schuermans; Alstom (Schweiz) AG, Baden
10:10	Gas Turbine Combustion with Flue Gas Recirculation: Operating Limits & Emission Characteristics T. Griffin, Fachhochschule Nordwestschweiz, Brugg-Windisch
10:35	<i>Kaffeepause –Poster - Networking</i>
11:00	Lean Premixed Combustion of Syngas at Gas Turbine Relevant Conditions S. Daniele, Paul Scherrer Institute (PSI), Villigen
11:25	Methane and Propane Fueled Catalytic Microreactors S. Karagiannidis, Paul Scherrer Institute (PSI), Villigen
11:50	Hydrogen-Methane Blends for Fuelling Passenger Cars P. Dimopoulos, EMPA, Dübendorf
12:15	<i>Mittagessen – Poster - Networking</i>
14:00	Recent developments in the marine industry and their impact on combustion research for large marine diesel engines G. Weisser, Wärtsilä Schweiz AG, Winterthur
14:25	Lattice Boltzmann Simulations of Reactive Flows with Applications to Combustion S. Chikatamarla, Laboratorium für Aerothermochemie und Verbrennungssysteme, ETHZ, Zürich
14:50	Influences of Alternative Fuels GTL, RME & ROR on Combustion and Emissions of a Modern HD-Diesel Engine J. Czerwinski, AFHB Berner Fachhochschule, Nidau
15:15	<i>Kaffeepause – Poster – Networking</i>
15:40	Neues Mess- und Auswertesystem für die Motorindizierung und ECU-Applikation im Fahrzeug H. Jenny, Elektronik und Software, Kistler AG, Winterthur
16:05	Vom phänomenologischen Russbildmodell zum virtuellen Russ-Sensor P. Obrecht, Laboratorium für Aerothermochemie und Verbrennungssysteme, ETHZ, Zürich
Forschungsziele der Industrie und Herausforderungen	
16:30	Herausforderungen für Industriedieselmotoren: Aktuelle Entwicklungsarbeiten für Stufe 3b und 4a A. Pfeifer, Liebherr Machines Bulle SA, Bulle
16:45	Heavy duty Dieselverbrennung für Euro VI und die Zukunft W. Gstrein, Fiat Powertrain Technologies, Arborn
17:00	Zusammenfassung, Verabschiedung

Abstracts

„Verbrennungsforschung in der Schweiz“

28. Oktober 2009 – ETH Zürich, Semper Sternwarte

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IEA Verbrennungsforschung

Implementing Agreement Energy Conservation and Emissions Reduction in Combustion

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Renz St., Leiter Forschungsprogramm Verbrennung, Bundesamt für Energie

ABSTRACT

Das hohe Niveau der Verbrennungsforschung in den wichtigen Industrienationen erfordert die Orientierung an den internationalen Zielen und Ergebnissen sowie die Zusammenarbeit mit Forschungsinstitutionen und Industriepartnern aus anderen Ländern. In zahlreichen vom BFE unterstützten Projekten besteht eine Vernetzung mit europäischen aber auch internationalen Hochschulen und Industriepartnern.

Ein wichtiger Informationsaustausch und die Gelegenheit, die Schwerpunkte der Verbrennungsforschung international mitzugestalten, erfolgt durch die Mitarbeit in Arbeitsgruppen der Internationalen Energieagentur (IEA) [1]. Für die Verbrennung relevant sind das Implementing Agreement *Energy Conservation and Emissions Reduction in Combustion* (IEA Combustion) [2], das Implementing Agreement *Advanced Motor Fuels* [3] und die *Working Party for Fossil Fuels* (WPFF) [4], in denen das BFE vertreten ist. Durch die Mitarbeit in den Leitungsgremien (Executive Committees) sowie in Projekten (Tasks) findet ein regelmässiger Informationsaustausch statt.

Ziel des *IEA IA Combustion* ist, die Entwicklung von Verbrennungstechnologien mit vermindertem Treibstoffverbrauch und geringeren Partikelemissionen für industrielle Anwendungen voranzutreiben. Die Forschungsschwerpunkte umfassen: (1) Die Verbesserung der Effizienz und der Treibstoffflexibilität von Verbrennungsmotoren für Autos und Lastwagen; (2) Die Reduktion des Luftüberschusses in Feuerungen zur Erhöhung des Wirkungsgrads bei minimalen Emissionen; (3) Kontrollmechanismen der Treibstoffeinspritzung und Gemischbildung sowie der Entstehung der Emissionen in Brennkammern von Gasturbinen und (4) Untersuchungen von grundlegenden physikalischen Phänomenen im Verbrennungsprozess. Als eine der Haupterfolge ist die Entwicklung von robusten diagnostischen Fähigkeiten zu werten, wie z.B. Laser induced fluorescence, verbesserte Computational fluid dynamics und Chemical kinetics codes. Die Forschungsthemen werden in sogenannten Collaborative Tasks bearbeitet. Aktuell werden in 6 Tasks die Themen Hydrogen Internal Combustion Engines, Homogeneous Charge Compression Ignition, Gas Turbines, Alternative Fuels und Nanoparticle Diagnostics bearbeitet. Weitere Collaborative Tasks wie Energy Security und Soot Formation werden diskutiert. Die Zusammenarbeit mit dem Advanced Motor Fuels Agreement der IEA im Bereich der synthetischen und erneuerbaren Brennstoffe wird geprüft.

Erfreulich war die grosse Beteiligung der Schweizer Forscher am diesjährigen Task Leaders Meeting des IEA Combustion mit insgesamt 5 Beiträgen zu den Themen Sprays, Nanoparticles, Alternative Fuels und Gas Turbines. Zudem wird der Collaborative Task Gas Turbines von P. Jahnson vom Paul Scherrer Institut geleitet.

Die Mitarbeit der Schweiz sichert eine Vertretung der Interessen im Bereich Verbrennung, eine Mitwirkung bei der Festlegung zukünftiger Schwerpunkte, die Vermittlung schweizerischer Forschungsergebnisse, die Bekanntmachung der Firmen aus der Schweiz sowie die Weitergabe der Informationen über internationale Aktivitäten an Interessierte in der Schweiz.

Die *WPFF der IEA* [4] leitet unter anderem die Implementing Agreements *Greenhouse Gas R&D Programme*, *Enhanced Oil Recovery* und das *IEA Clean Coal Centre* und richtet ihre Berichte und Empfehlungen an das IEA Governing Board. Die Reduktion der CO₂-Emissionen ist aktuell das zentrale Anliegen der WPFF. Als Massnahmen sollen Wirkungsgradverbesserungen in der Energieumwandlung und Eliminationsverfahren (Carbon Capture and Storage, CCS) an den Förderstellen und bei grossen Kraftwerken angegangen werden.

[1] International Energy Agency (IEA) <http://www.iea.org>

[2] International Energy Agency (IEA) Implementing Agreement *Energy Conservation and Emissions Reduction in Combustion* <http://ieacombustion.com/default.aspx/>

[3] International Energy Agency (IEA), Implementing Agreement on *Advanced Motor Fuels* <http://www.iea-amf.vtt.fi/>

[4] **WPFF** Working Party for Fossil Fuels der IEA <http://www.iea.org>

Gas Turbine Combustion with Flue Gas Recirculation: Operating Limits and Emissions Characteristics

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ABSTRACT

Carbon Capture and Storage (CCS) solutions are currently being assessed in order to address appropriately the climate change challenge. Post-combustion CO₂ capture is one of the technologies proposed for both coal-fired and natural gas-fired power plants. In Natural Gas Combined Cycle (NGCC), the flue gas is treated after the Heat Recovery Steam Generator (HRSG) in a so-called post-combustion CO₂ capture module, in which CO₂ is absorbed through use of solvents. The size of systems required for the capture of CO₂ scales with both the volumetric flow to be treated together with the CO₂ concentration contained in the flue gas. Flue Gas Recirculation (FGR) is proposed as a means to increase CO₂ concentration in the flue gas together with a net reduction of volumetric flow to be treated by the CO₂ capture module. One of the limiting factors of this technology is the vitiation of air within the gas turbine combustor and the associated reduction in oxygen concentration. This paper analyses the influence of air vitiation upon methane and simulated natural gas combustion in a generic premix lean burner, which simulates the second combustor of a reheat gas turbine. Tests are carried out under representative temperature levels and at elevated pressure. Variation of inlet oxidizer composition is simulated with the addition of nitrogen and carbon dioxide to the inlet air. It is observed that CO emission increases with oxygen depletion at a fixed residence time, signaling a reduction of combustion reactivity. In addition, NO_x emissions are shown to be sensitive to oxygen depletion. The effect of hydrogen addition to improve reactivity was tested by adding up to 20% (by volume) hydrogen to the fuel. The use of Catalytic Partial Oxidation (CPO) as an in-situ method to produce hydrogen via methane reforming has been investigated. The combustion stability limits of the resulting syngas/methane or syngas/natural gas mixtures were also measured. Hydrogen addition helps to improve the reactivity of the flame counteracting the negative impact of FGR on combustion stability.

Lean Premixed Combustion of Syngas at Gas Turbine Relevant Conditions

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ABSTRACT

Lean premixed combustion is considered the state-of-the art technology applied in stationary gas turbines for highly efficient, low-emission power generation using natural gas.

Due to the increased interest in the integration of power generation with gasification processes, to CO₂ mitigation issues and use of solid fuels, fundamental combustion properties of upcoming new synthetic fuels (syngas) must be investigated.

Despite of the quantity of current research activity involving syngas, a deficit exists for lean premixed combustion experiments at gas turbine relevant conditions. More specifically, there is very little high-pressure / high-temperature data for turbulent, lean premixed syngas flames available. Changes in flame characteristics at elevated pressure and temperature (operational window, flame position, flame structure, turbulent flame speeds) necessitate such studies.

By means of an experimental investigation, this work presents some of the challenges a modern low NO_x gas turbine has to face when fired with syngas.

A description of the operational window in terms of lean blow out and flashback limits is provided at gas turbine relevant conditions. The focus of the paper is also on the turbulent flame speed (S_T). With the experimental approach taken (flame surface area derived from laser induced fluorescence data (OH-LIF)) S_T values can be calculated based on a mass continuity approach and thus represent global consumption rates.

Data are presented for various gas mixtures with the aim of covering a wide spectrum of “real life” fuel compositions, going from pure CH₄ and co-firing of syngas and natural gas up to diluted hydrogen.

As expected, the results highlight the strongly elevated values of turbulent flame speed for high hydrogen containing fuel gas mixtures. Compared with flame speed data for pure CH₄ the ratio ($S_T^{Syn}/S_T^{CH_4}$) can take up values in the order of 10. For ultra-lean conditions high burning velocities can be maintained with increased H₂ content in the fuel mixture.

In a fully fuel flexible scenario, firing GT engines in premixed mode with natural gas, syngas and eventually H₂-rich fuels, will require to account for changes in the burning velocity of an order of magnitude.

Methane and Propane-Fueled Catalytic Microreactors

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ABSTRACT

Small-scale, hydrocarbon-fueled thermochemical devices have received increased attention in portable power generation due to their superior power density compared to Li-ion batteries. Catalytic processes are well-suited for small-scale hydrocarbon combustion. The pure heterogeneous and the coupled hetero-/homogeneous combustion of fuel-lean propane/air mixtures over platinum have been investigated at pressures $1 \text{ bar} \leq p \leq 7 \text{ bar}$. Experiments were performed in an optically accessible catalytic channel-flow reactor involving 1-D Raman measurements of major gas-phase species concentrations across the reactor boundary layer and planar laser induced fluorescence (LIF) of the OH radical. A global catalytic reaction step valid over a pressure–temperature–equivalence ratio parameter range relevant to small-scale power generation has been established, which revealed a $\sim p^{+0.75}$ dependence of the catalytic reactivity on pressure. The global catalytic step was coupled to a detailed gas-phase reaction mechanism in order to simulate homogeneous ignition in the channel-flow reactor, with the measured gas-phase ignition distances reproduced within 10% at pressures $p \leq 5 \text{ bar}$.

The steady hetero-/homogeneous combustion of lean propane-air and methane-air mixtures in a platinum-coated, catalytic, channel-flow microreactor has been investigated at pressures of 1 and 5 bar, channel heights 1.0 and 0.3 mm, and wall thermal conductivities 2 and 16 W/mK. Stability limits were assessed as a function of fuel, inlet velocity, and imposed external heat losses. A full-elliptic, 2-D numerical model was employed with detailed gas-phase reaction schemes for both fuels, a detailed heterogeneous reaction scheme for CH₄, and the recently developed global reaction step for C₃H₈. Comparisons between the stable regimes of CH₄ and C₃H₈ revealed a strong impact of the fuel molecular transport properties on combustion stability and maximum allowable mass throughput. The higher diffusive transport of methane was critical in maintaining reactor stability over a wider range of inlet velocities and external heat losses compared to propane, despite the higher catalytic and gas-phase reactivity of the latter. Gas-phase chemistry had a strong impact on the blowout limits at channel heights as low as 0.3 mm. The stable combustion regimes of both methane and propane increased substantially at 5 bar compared to the same mass throughput at 1 bar, owing to a positive $p^{+0.47}$ and $p^{+0.75}$ dependencies on pressure of methane and propane catalytic reactivity respectively.

Transient simulations were finally performed for methane-fueled microreactors made of Pt-coated ceramic and metallic walls. A 2-D model for the flow domain was used with detailed catalytic and gas-phase chemical reaction mechanisms. The effect of solid material properties on the ignition and steady-state microreactor times has been assessed. An increase in inlet pressure from 1 to 5 bar induced a $\sim 50\%$ reduction in both characteristic times owing to the enhancement of catalytic reactivity with rising pressure. Reactors with low wall thermal conductivity exhibited shorter ignition and steady-state times compared to metallic ones due to the creation of spatially localized hot spots that promoted catalytic ignition.

Hydrogen-natural gas blends fuelling passenger car engines: Combustion, emissions and well-to-wheels assessment

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ABSTRACT

In this project a state of the art passenger car natural-gas engine was optimised for hydrogen natural-gas mixtures and high exhaust gas recirculation (EGR) rates in the major part of the engine map. The investigations involved stoichiometric combustion. With optimal combinations of spark timing and EGR rate the achievements are efficiency increase with substantially lower engine-out NO_x while total unburned hydrocarbons and CO-engine-out emissions are only modestly affected. The efficiency is increased by 3% in the low load and by more than 5% in the medium load domain. Increasing hydrogen content of the fuel accelerates combustion leading to the efficiency improvements. Combustion analysis showed that the increasing burning rates mainly affected the initial combustion phase (duration for 5% mass fraction burned). Nevertheless, increase of the hydrogen fraction in the fuel over a certain threshold did not result in any efficiency increase in the medium loads. Loss analysis identified high wall heat losses as the main reason. Dedicated combustion chamber design may be able to avoid these losses and lead to additional efficiency benefits. Well-to-wheel analysis revealed paths for the production of the fuel blends still having overall energy requirements slightly higher than a diesel benchmark vehicle but reducing by roughly 7% overall greenhouse gas emissions.

Recent Developments in the Marine Industry and their Impact on Combustion Research for Large Marine Diesel Engines

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ABSTRACT

The International Maritime Organisation (IMO) has reviewed the emissions regulation for seagoing vessels (MARPOL Annex VI), specifying Tier II and Tier III levels for nitric oxide emissions as well as next steps in limiting the sulphur content of the fuels used or equivalent reduction of sulphur oxide and particulate matter emissions. In addition, various national or regional fuel quality or emissions control related regulations have been introduced over the last few years.

In combination with continuing market trends, e.g. with respect to the fuel supply, this results in considerably wider requirements towards future marine engines: On the one hand, they need to be able to deal with an increasing variety of fuels, without impairing performance and reliability. On the other hand, achieving compliance with the increasingly stringent emissions standards requires a considerably more delicate optimization, specifically also in terms of combustion.

Therefore, it is essential that the combustion related processes in large marine two-stroke diesel engines are well understood. Firstly, to enable the more extensive utilization of simulation methods in the development of those engines for supporting and partly substituting the costly optimization tests. Secondly, to enable the development of combustion control concepts on that basis.

For this purpose, a specifically designed experimental setup has been developed in collaboration with ETH Zürich and the PSI in the context of the HERCULES research program, co-funded by the EU and Swiss authorities. It simulates the combustion system of a large two-stroke marine diesel engine in terms of physical dimensions, operating conditions and geometrical arrangement, thereby allowing the investigation of the spray and combustion processes via appropriately designed windows for optical access using high-speed imaging techniques.

The setup has been thoroughly tested and validated against the design specification and its potential for studying spray and combustion processes at conditions relevant to large marine diesel engine combustion has been clearly confirmed. It is now used both for establishing reference data for spray propagation at those conditions for the validation of simulation models and for evaluating measurement technologies in terms of their applicability for further extending this validation database. Moreover, the setup has even been used for preliminary assessments of new key injection component designs and their effect on spray phenomena, and thus integrated in the product development process.

Lattice Boltzmann Simulations of Reactive Flows with Applications to Combustion

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ABSTRACT

The lattice Boltzmann method (LBM) is a kinetic-theory approach to computational fluid dynamics, with applications ranging from high Reynolds number flows to flows at a micron scale, porous media, multi-phase and reactive flows. The LB method solves numerically a fully discrete kinetic equation for populations designed to reproduce the Navier-Stokes equations in the hydrodynamic limit. The LBM has many inherent advantages like easy handling of complex geometries such as porous media, easy to implement, excellent parallel performance enabling it to handle large and complex engineering problems. However, the LBM was until now constrained in application due to its numerical instabilities. We use here a novel entropic lattice Boltzmann method which alleviates this obstacle by restoring entropy (Boltzmann H theorem), and rendering the method non-linearly stable. Numerous entropic LB models capable of simulating multi-component mixtures and reactive flows were developed in the recent past. We present here in brief these mixture models and show applications for reactive flows. The lattice Boltzmann method is also combined with a novel model reduction technique known as Method of Invariant Manifolds (MIM). The MIM is used to reduce the number of species, the reactions involved and hence the computational costs involved in a combustion reaction of Hydrogen and air. Combining these models reduction techniques with fast and efficient solvers like the lattice Boltzmann method promises a new alternative to affordable and reliable combustion simulations.

Influences of Alternative Fuels GTL, RME & ROR on Combustion and Emissions of a Modern HD-Diesel Engine

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Kasper Markus, *Matter Engineering AG, Wohlen, CH*

KEYWORDS

Alternative fuels, biofuels, Diesel-injection, Diesel-combustion, Diesel-emissions, (Nano) Particulates, Particle Analysis.

ABSTRACT

Due to the limited energy resources as well as due to increasing CO₂-emissions the importance of alternative- and biogene fuels is continuously increasing.

Investigations of the engine operation were performed on a latest technology Liebherr engine for construction machines. It was operated using crude rapeseed oil (ROR), rapeseed oil methyl ester (RME), synthetic Gas-To-Liquid fuel (GTL) and diesel (as reference fuel). The combustion diagnostics, the performance of the injection system as well as the pollutant emissions, including unlimited nanoparticles were assessed.

The most important findings can be summarized as follows :

Fuel injection

- Both, RME and ROR shortened the injection delay which was due to a quicker increase of injection pressure and a faster needle lift,
- the highest maximum injection pressure was observed with ROR (1610 bar), followed by RME (1580 bar), Diesel (1450 bar) and GTL (1410 bar),
- As compared to diesel, GTL exhibited no significant differences of hydraulic behavior.

Combustion

- Usually, GTL caused a shorter ignition delay, but it burned slower, so that 50% of heat release took place at the same CA-position, as for Diesel. In addition, GTL provoked a lower rate of pressure raise and reduced the maximum combustion pressure. These effects were particularly pronounced at lower and medium loads.
- At higher engine load ROR and RME started to burn earlier and at a higher rate, than Diesel and GTL. Therefore, 50% of the heat release followed with ROR and RME 1-2 °CA earlier which had consequences for the NO_x emissions.

Limited emissions and energy consumption

GTL lowered generally all emission components – as compared to standard Diesel fuel. In addition, the energy consumption with GTL was equal or slightly lower.

RME lowered CO and HC emissions and increased NO_x emissions at all operating points. It lowered PM at higher engine loads and increased PM at lower engine loads. RME had no effect on specific energy consumption.

ROR lowered CO, HC and PM at all operating points by at least 50% or more. In the high-load-operation ROR reduced the specific energy consumption (approx. 2%) and increased NO_x (up to approx.5%).

At low-load-operating points (1500 rpm/10%) ROR did not affect CO and NO_x, but increased PM emissions and energy consumption.

Nanoparticle emissions

- GTL and diesel nanoparticle emissions were identical,
- Both RME and ROR moved the particle size distribution spectra to smaller sizes and increased the nuclei mode due to spontaneous condensate formation,
- Both RME and ROR caused lower particle emissions at high load and higher emissions at low load,
- The use of ROR resulted in a particularly high portion of condensates (SOF) at low load and idling.

Neues Mess- und Auswertesystem für die Motorindizierung und ECU-Applikation

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ABSTRACT

Mit dem mobilen Indiziersystem „KiBox“ hat die Kistler Instrumente AG ein neues Mess- und Analysesystem entwickelt, das speziell für die Zylinderdruckindizierung im Fahrzeug konzipiert wurde. Neben einem innovativem Datenerfassungskonzept und der einfachen Einbindung in das Applikationssystem INCA zeichnet es sich durch eine Vielzahl über den Stand der Technik hinausgehende Eigenschaften aus.

Die Indizierung im Fahrzeug stellt besondere Anforderungen an die Datenerfassung. Zum einen soll aus Rationalisierungsgründen der motorseitige Kurbelwinkelgeber verwendet werden und zum anderen müssen der hochtransiente Motorbetrieb sowie die naturgemäss vorhandenen Signalstörungen beachtet werden. Zentral bei mehrkanaligen Datenerfassungssystemen ist, dass die analogen Signale simultan und möglichst verzögerungsfrei bzw. phasentreu erfasst werden. Im vorliegenden Fall sind es die Zylinderdrücke, die Einspritz- und Zündimpulse sowie der Kurbelwinkel. Nur so sind korrekte Vergleichsbetrachtungen und Berechnungen möglich. Schon kleinste Signallaufzeitunterschiede von zwei bis drei Mikrosekunden können die Ergebnisqualität erheblich beeinflussen. Das Prinzip der zeitdiskreten Abtastung erfüllt die Anforderungen, die an ein modernes Indiziersystem gestellt werden, ideal. Es erlaubt die Korrektur der unterschiedlichen Messsignalverzögerungen, die Signalfilterung im Zeitbereich und die Transformation von Messsignalen in den Winkelbereich. Die hohe Drehzahldynamik und geforderten Genauigkeiten bedingen jedoch sehr hohe Abtastraten und damit extreme Datenmengen. Der rasante Technologiefortschritt bei Computer- und Schnittstellenbausteinen ermöglichte es uns, mit diesem Verfahren ein kompaktes Indiziersystem für Fahrzeuganwendungen zu realisieren.

Als Ausblick wird ein System- und Integrationskonzept für die wirtschaftliche Russbestimmung mit der so genannten Zweifarben-Methode (Dreifarben-Pyrometrie) vorgestellt. Eine so konzipierte „SootBox“ könnte die klassischen Indizierkennwerte der „KiBox“ mit Russkennzahl und maximalen Verbrennungstemperatur pro Zylinder und Arbeitsspiel optimal ergänzen und zusätzlichen Kundennutzen generieren.

Vom phänomenologischen Russbildemodell zum virtuellen Russ-Sensor

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ABSTRACT

Partikel-Emissionen haben unbestritten einen schädlichen Einfluss auf die menschliche Gesundheit, Russpartikel sind lungengängig, können in den Blutkreislauf eindringen, die angelagerten polyzyklischen Aromaten sind krebserregend. Die Wirkungsmechanismen der Partikel auf die menschliche Gesundheit sind nicht restlos geklärt und nach wie vor Gegenstand der Forschung.

Die Grenzwerte für den Partikelaustritt von Dieselmotoren sind deshalb in den letzten Jahren massiv verschärft worden und werden in Zukunft weiterhin verschärft. Diese Vorschriften stellen für die Motorenhersteller eine grosse Herausforderung dar, durch geeignete Massnahmen die Grenzwerte wenn möglich ohne grosse Verbrauchs- und Kostennachteile einzuhalten.

Durch Minimieren der Partikel-Rohemissionen können die Abbrand-/Regenerations-Intervalle des Partikelfilters verlängert und dadurch der durch den Partikelfilter verursachte Mehrverbrauch wesentlich reduziert werden. Die Dieselverbrennung mit dem Ziel die Partikel- und NO_x-Rohemissionen ohne Verbrauchs- und Kostennachteile zu optimieren, stellt somit auf der Forschungsseite nach wie vor grosse Herausforderungen. Einerseits erfordert eine Berechnung der Partikelbildung unter Berücksichtigen der vollen Reaktionskinetik einen sehr grossen Rechenaufwand, andererseits werden Modelle zur Abschätzung der Russ-Emissionen für die rechnerische Optimierung von Motorauslegungen mittels gängiger schneller Simulationsprogramme (GT-Power z.Bsp.) benötigt. Da zudem kein in der Serie einsetzbarer Russ-Sensor für Regelungszwecke zur Verfügung steht, besteht ein Bedarf mittels geeigneter Modelle die momentane Russ-Emission des Motors aus leicht zu erfassenden Grössen wie Temperaturen, Last, stöchiometrisches Luft/Brennstoff-Verhältnis etc. zu berechnen, diese in einem „schnellen“ Modell - einem virtuellen Russ-Sensor – zu verarbeiten und die so abgeschätzte Russ-Emission für Regelungszwecke einzusetzen.

Die Erforschung und Modellierung der Russbildung in der Dieselverbrennung bildet seit mehreren Jahren einen Schwerpunkt der Forschungsarbeiten am LAV der ETH Zürich.

So hat R. Schubiger in seiner Dissertation (Diss. ETH No. 14445, 2001) ein Drei-Wellenlängen-Pyrometer entwickelt, mittels dessen im Zylinder in Echtzeit die Russ-Temperatur und ein Mass für die momentane Russ-Dichte (KL-Faktor) und deren zeitlicher Verlauf gemessen werden können. Im Rahmen eines KTI-Projekts wurde daraus in Zusammenarbeit mit der Firma Kistler in Winterthur ein miniaturisiertes, verschmutzungsunempfindliches Pyrometer entwickelt, welches demnächst in den Verkauf gelangen wird.

Zur Entwicklung schneller Russbildemodelle wurden ebenfalls mehrere Beiträge geleistet. Das von M. Wart (Diss. ETH No. 16357, 2005) entwickelte Zeit-aufgelöste phänomenologische Russbildemodell wurde mittlerweile erfolgreich in das Prozessrechnungsprogramm GT-Power implementiert, ist aber als wegen des immer noch relativ hohen Rechenaufwands, ca. 5.5 s pro Arbeitsspiel, als virtueller Sensor nicht geeignet. In der Folge hat P. Kirchen (Diss. ETH No. 18088, 2008) das Modell im Rahmen eines FVV-Projekts zu einem virtuellen Russ-Sensor (Rechenzeit ca. 10ms pro Arbeitsspiel) weiterentwickelt. Letzteres berechnet die Russ-Emission aus zyklustypischen Mittelwerten (Drücke, Temperaturen, Stöchiometrie) und zeitigt für stationäre Betriebszustände eine sehr gute Übereinstimmung der gemessenen mit den berechneten Werten. In einem FVV-Folgeprojekt wird dieses Modell weiterentwickelt und erweitert, sodass auch unter transienten Betriebsbedingungen die Russ-Emissionen mit ausreichender Genauigkeit wiedergegeben werden.

Herausforderungen für Industriedieselmotoren: Aktuelle Entwicklungsarbeiten für Stufe IIIB und IV

Pfeifer A.

Entwicklungsleiter Dieselmotoren, Liebherr Machines Bulle S.A.

ABSTRACT

Emissionsgesetzgebung und steigende Kundenerwartung bedingen eine deutlich höhere Komplexität der nächsten Generation von Baumaschinenmotoren.

Vergleicht man beispielsweise die Gradienten der Emissionsgrenzwerte für NO_x und PM über dem Modelljahr für On-Highway-Nutzfahrzeugmotoren und für Off-Highway Dieselmotoren, so zeigt sich eine deutlich raschere Verringerung für die Off-Highway-Motoren, die mittlerweile dazu führt, dass sich die Emissionsniveaus von Nutzfahrzeugen und Industriebmotoren im Jahr 2014 vollständig angenähert haben werden. Obwohl dieselben Technologien wie für ähnlich grosse Nutzfahrzeug-Motoren zur Emissionserfüllung eingesetzt werden (komplexen Luft- und AGR-Systeme, Common Rail Einspritzung und der erste flächendeckende Einsatz von Abgasnachbehandlung), liegen die besonderen Herausforderungen in der Meisterung der deutlich schwierigeren Randbedingungen beim Industriedieselmotor. Vor allem die unterschiedlichen Einbausituationen ein- und desselben Motors in unterschiedliche Geräte bedeuten unterschiedliche Luftführungen und Anordnungen von Aufladegruppen, die deutlichen Einfluss auf das Emissionsniveau des Motors haben. So ist bei der Emissions-Grundabstimmung dieses Verhalten ebenso wie die deutlich längere Lebensdauer-Anforderung frühzeitig zu berücksichtigen.

Die Verdopplung der Motorsensorik und –aktuatorik im Vergleich zur aktuellen Situation am Stufe IIIa-Motor bietet zwar umfassende Möglichkeiten zur Emissionsdrifterkennung und –kompensation, stellen aber eine grosse Herausforderung in Bezug auf Dauerhaltbarkeit und Diagnose im Feld dar.

Der weltweite Einsatz von Grossgeräten bedeutet zusätzlich, dass eine robuste Lösung trotz stark wechselnder Kraftstoffqualitäten gefunden werden muss.

Exemplarisch werden einzelne Fragen herausgegriffen und die bei Liebherr für die nächste Emissionsstufe IIIB / Tier4 interim und nachfolgend Stufe IV / Tier 4 final entwickelten Lösungen vorgestellt.

Heavy Duty Diesel Verbrennung für „Euro VI und die Zukunft“

Gstrein W.

FPT Powertrain Technologies, IVECO Motorenforschung AG

ABSTRACT

Der Titel „Heavy Duty Diesel Verbrennung für Euro VI und die Zukunft“ bezieht sich primär auf die Abstimmung von Motoren für effizienten Gütertransport im LKW- Fernverkehr.

Für die Verbrennungsoptimierung stellen sich folgende Fragen:

- Welche sind weitere mögliche Fortschritte in der Verbrennung ?
- Was bringt die Zukunft für Rahmenbedingungen ?
- Wie kann der HD- Dieselmotor konkurrieren ?

Welches die zukünftig optimale Antriebstechnologie sein wird, ist heute noch schwer zu beurteilen.

Die wichtigsten Neuerungen für Euro VI sind das gegenüber Euro V weiter um 4/5 abgesenkte Stickoxidlimit und ein scharfer Partikelemissionsgrenzwert, erstmals eine Anzahlbeschränkung auch auf europäischer Ebene.

Das neue Stickoxidlimit soll das mit Russfiltertechnologie einhergegangene erhöhte Verhältnis von NO₂ / NO entschärfen. Eine maximale Ausnutzung der schon für Euro V angewandten Technologie der selektiven katalytischen Reduktion (SCR) wird notwendig. EGR kann zusätzlich zur Optimierung der Betriebskosten genutzt werden.

Das Partikelanzahllimit erfordert hochwirksame Russfilter (geschlossene Russfilter oder „wall flow filter“). Für die nächste Stufe nach Euro VI werden vor allem Massnahmen zur CO₂- Reduktion erwartet. Die Verbrennung muss diesen Anforderungen gerecht werden und evtl. auch für neue Kraftstoff-Formulierungen angepasst werden.

Eine weitere Optimierung der Verbrennung selbst stösst an technologische Grenzen. Die Möglichkeiten zur Beeinflussung der Prozessgaseigenschaften sind für die Fahrzeuganwendung gering und beschränken sich auf Abgasrückführung, Luftverhältnis und Kühlung. Eine Isolierung der Brennräume scheitert an der Verfügbarkeit geeigneter Materialien. Die Optimierung der Verbrennung selbst beschränkt sich hauptsächlich auf die Einstellung des verbrauchsoptimalen Spritzbeginns, eine schnelle Verbrennung und einen schnellen Ausbrand. Vor- und Nacheinspritzungen werden zur Reduktion von Geräusch und Russ eingesetzt. Alternative Brennverfahren spielen beim Heavy Duty Dieselmotor eine untergeordnete Rolle, da die Anwendung auf die Teillast beschränkt bleibt. Eine positive Beeinflussung der Verbrennungsführung durch Gemischbildung und Wandinteraktionen im Brennraum wird angestrebt, um im Zylinder möglichst wenig Schadstoffe zu erzeugen. Durch Verringerung des Zylinderwandkontaktes der Verbrennung und dem damit einhergehenden Russeintrag in das Schmieröl wird das Ölwechselintervall erhöht. Die verfügbare Einspritztechnologie ist bereits sehr hoch entwickelt und lässt im Moment kaum mehr Wünsche offen.

Zusammenfassend muss ein kostenoptimiertes Gesamtsystem aus Aufladung, Einspritzung, Verbrennung und Abgasnachbehandlung gefunden werden, um die Anforderungen kostenoptimal erfüllen zu können.

Posterausstellung

„Verbrennungsforschung in der Schweiz“

28. Oktober 2009 – ETH Zürich, Semper Sternwarte

Poster-Nr.	Titel	Autor
1	PDF Modeling of Spray Combustion: Turbulence Interactions, Combustion and Emission	Anand G., Zoller B., Jenny P. Institut für Fluidodynamik ETH Zürich
2	Direct numerical simulation of autoignition in a premixed turbulent co-flowing jet	Kerkemeier S., Frouzakis C.E., Fischer P., Mastorakos E., Tomboulides A.G., Boulouchos K. Institut für Energietechnik Laboratorium für Aerothermochemie und Verbrennungssysteme ETH Zürich
3	Linear and non-linear evolution of propagating lean hydrogen-air premixed flames	Altantzis C., Frouzakis C.E., Tomboulides A.G., Boulouchos K. Institut für Energietechnik Laboratorium für Aerothermochemie und Verbrennungssysteme ETH Zürich
4	Large Engine Combustion Research	Wilhelm P., Kyrtatos P. Institut für Energietechnik Laboratorium für Aerothermochemie und Verbrennungssysteme ETH Zürich
5	Combustion of Methane-Hydrogen Blends in Internal Combustion Engines	Dimopoulos P., Eggenschwiler K., Winkler A. EMPA Dübendorf
6	Advanced CFD for ‚real-world‘ problems	Vandersickel A., Sharifian L., Schlatter S., Egli R., Wright Y.M., Boulouchos K. Institut für Energietechnik Laboratorium für Aerothermochemie und Verbrennungssysteme ETH Zürich
7	Optical Diagnostics in Engine Research	Mitakos D., Schmid A., Schneider B. Institut für Energietechnik Laboratorium für Aerothermochemie und Verbrennungssysteme ETH Zürich
8	Hydrogen combustion at high pressures and preheats for gas-turbine applications	Ghermay Y., Mantzaras I., Bombach R. Paul Scherrer Institut
9	Lattice Boltzmann simulation of transport phenomena in catalytic microreactors and fuel cell systems	Prasianakis N., Mantzaras I. Paul Scherrer Institut
10	Engine Emission Modeling Using a Mixed Physics and Regression Approach	Benz M. Inst.f. Dynamische Systeme und Regelungstechnik ETH Zürich



Symposium on Combustion Technology

October 28, 2009

A View of the Public Energy Research in Switzerland

George Lustgarten
Federal Energy Research Commission (CORE)



Agenda

- Current Energy Policy Goals
- Structure and Governance of the Energy Research in Switzerland
- Value of Combustion Research from a National Perspective



Our Challenge: Stop Climate Warming

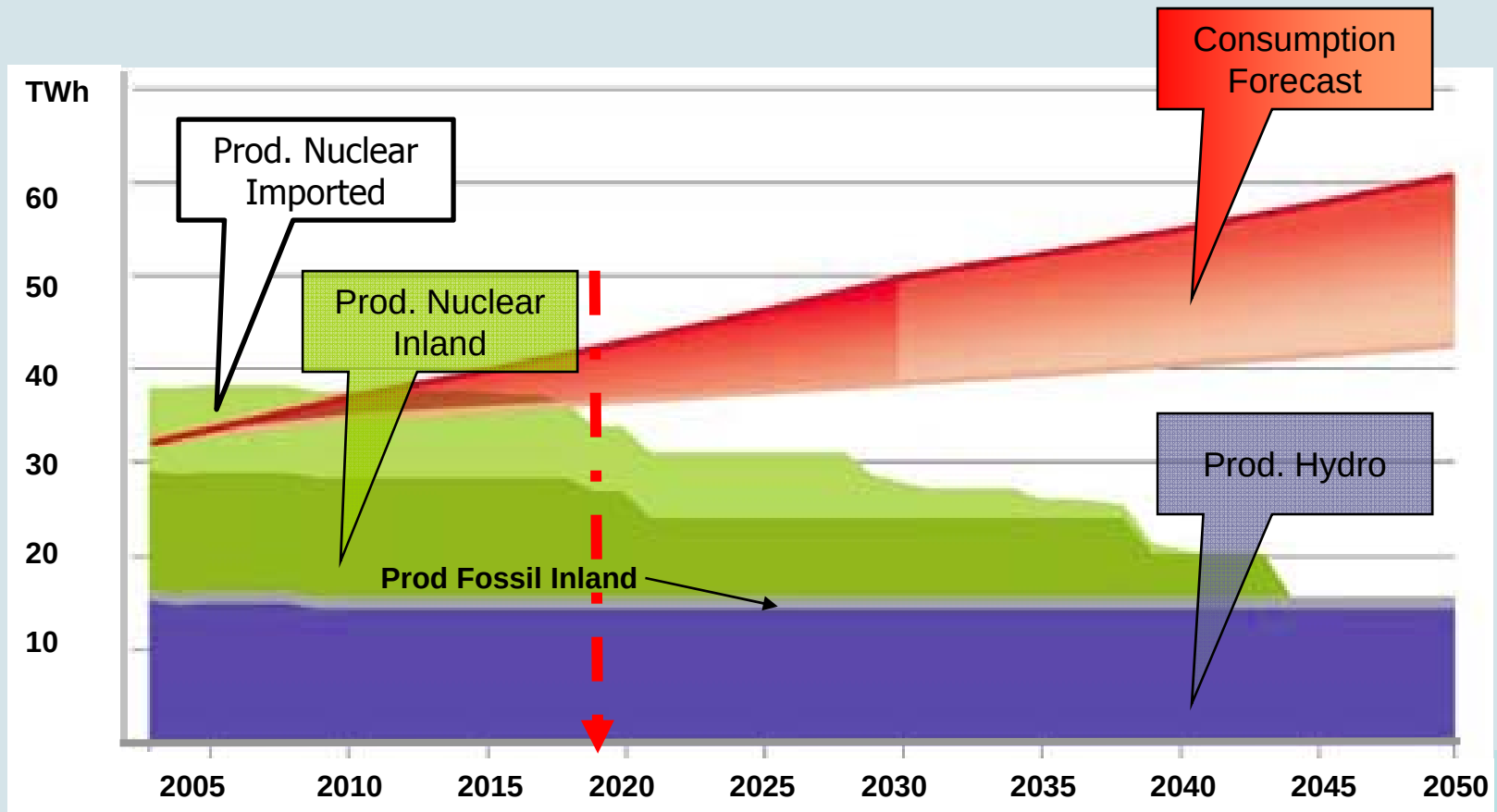


The Volume of the Swiss Glaciers in the Alps Lost 12% During the Last 10 Years





The Swiss Electric Energy Scenario: The Challenge Ahead

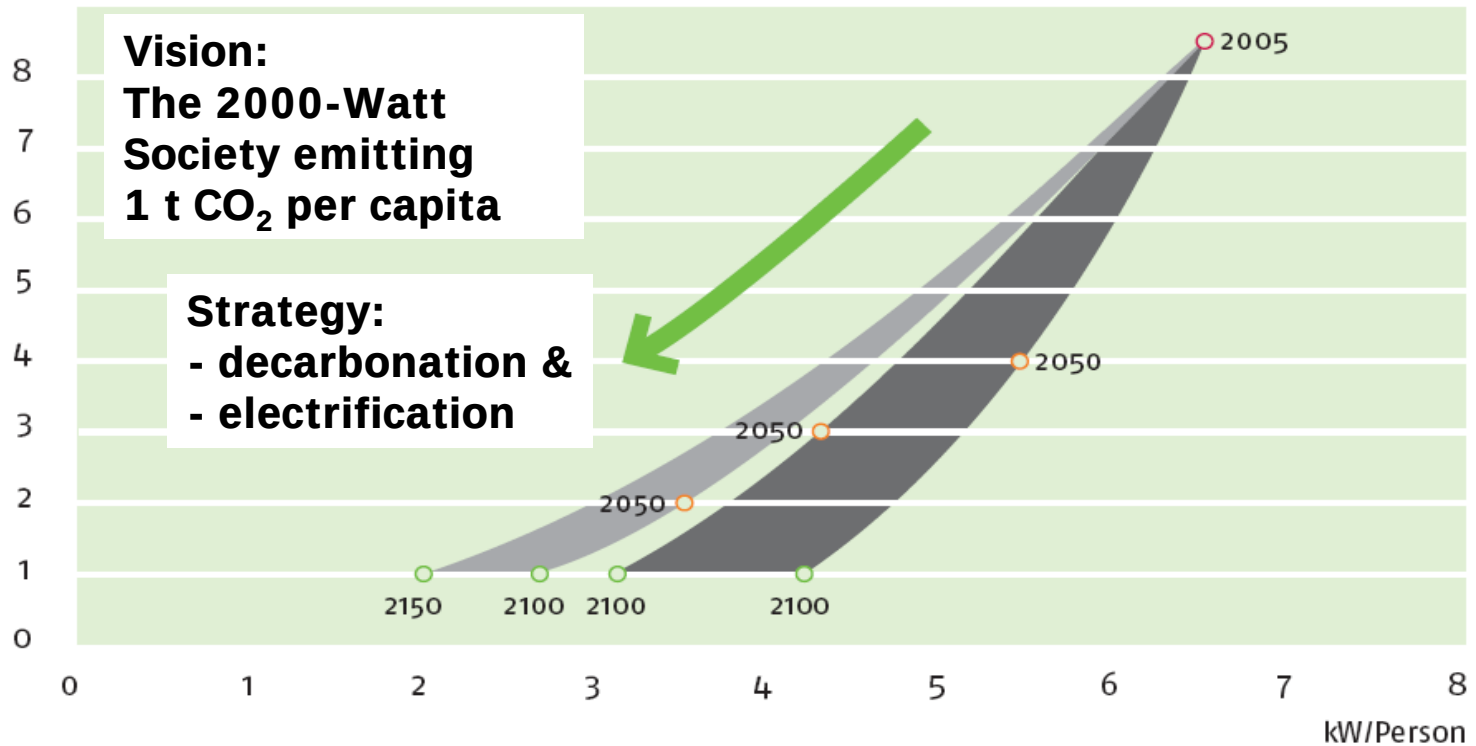




Towards the Eng Game: Decarbonization and Sustainability

The Swiss Scenarios

To CO₂/Pers. and Year



- Vision «2000-Watt-Gesellschaft» (z.B. novatlantis)
- «Dekarbonisierung» (z.B. Strategie ESC/ETH Zürich)



Along the way in 2050

Legislation

- **CO2 Taxation on Fossil Fuels from 01.01.2008 Onwards**
- **Voluntary Climate Toll (“Klima Rappen”) 01.10.2005-End 2012 to Fund Decarbonization**

Market Development

- **Short Term Objectives Until 2020**
 - **Reduce Share of Fossil Energy by 20%**
 - **Increase Contribution of Renewable Sources by 50%**

Incentives

- **Mid Term Objectives Until 2050**
 - **Heating of Buildings w/o Fossil Energy**
 - **Triple Contribution of Biomass**
 - **Reduce Average Consumption of Automotive Fleet to 3L/100km**



Agenda

- Current Energy Policy Goals
- Structure and Governance of the Energy Research in Switzerland
- Value of Combustion Research from a National Perspective



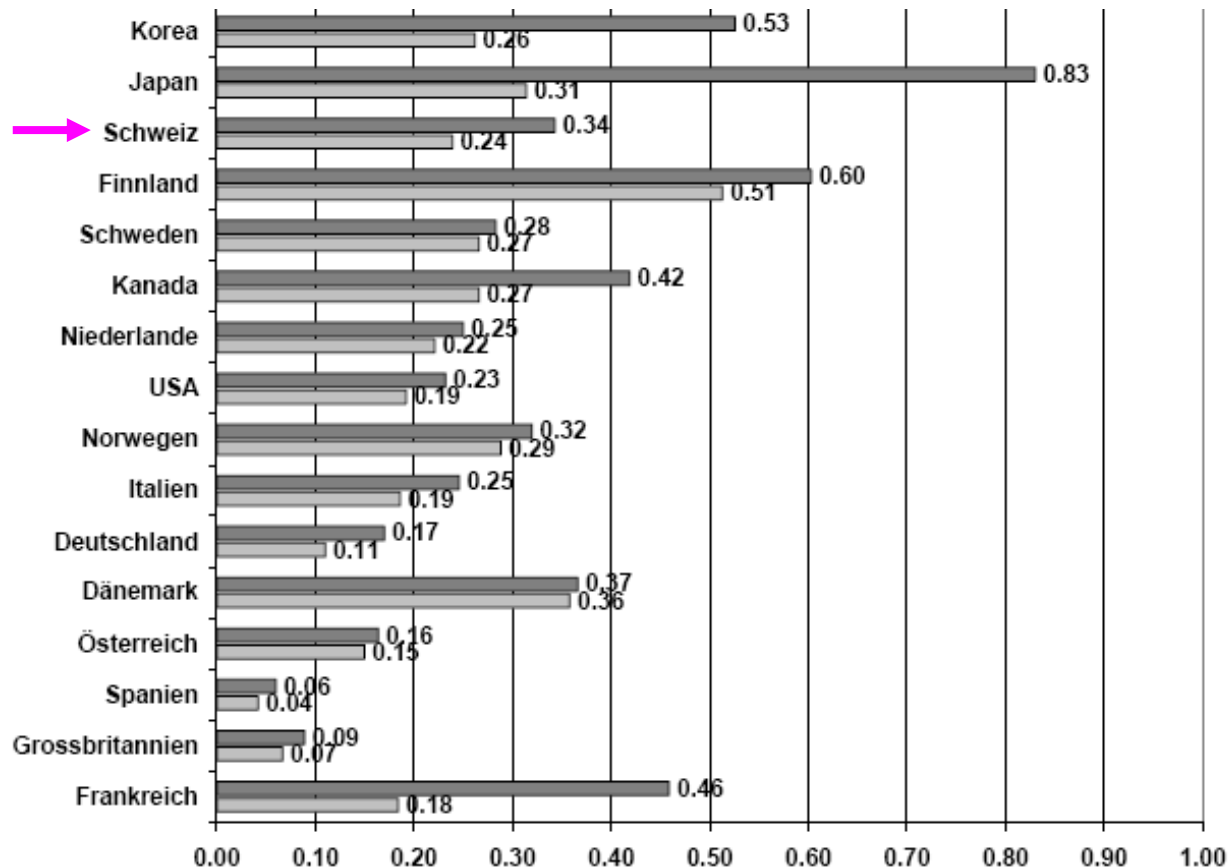
Switzerland in The International Context

Energy Research in 0/00 of GDP

Upper Bar: Total

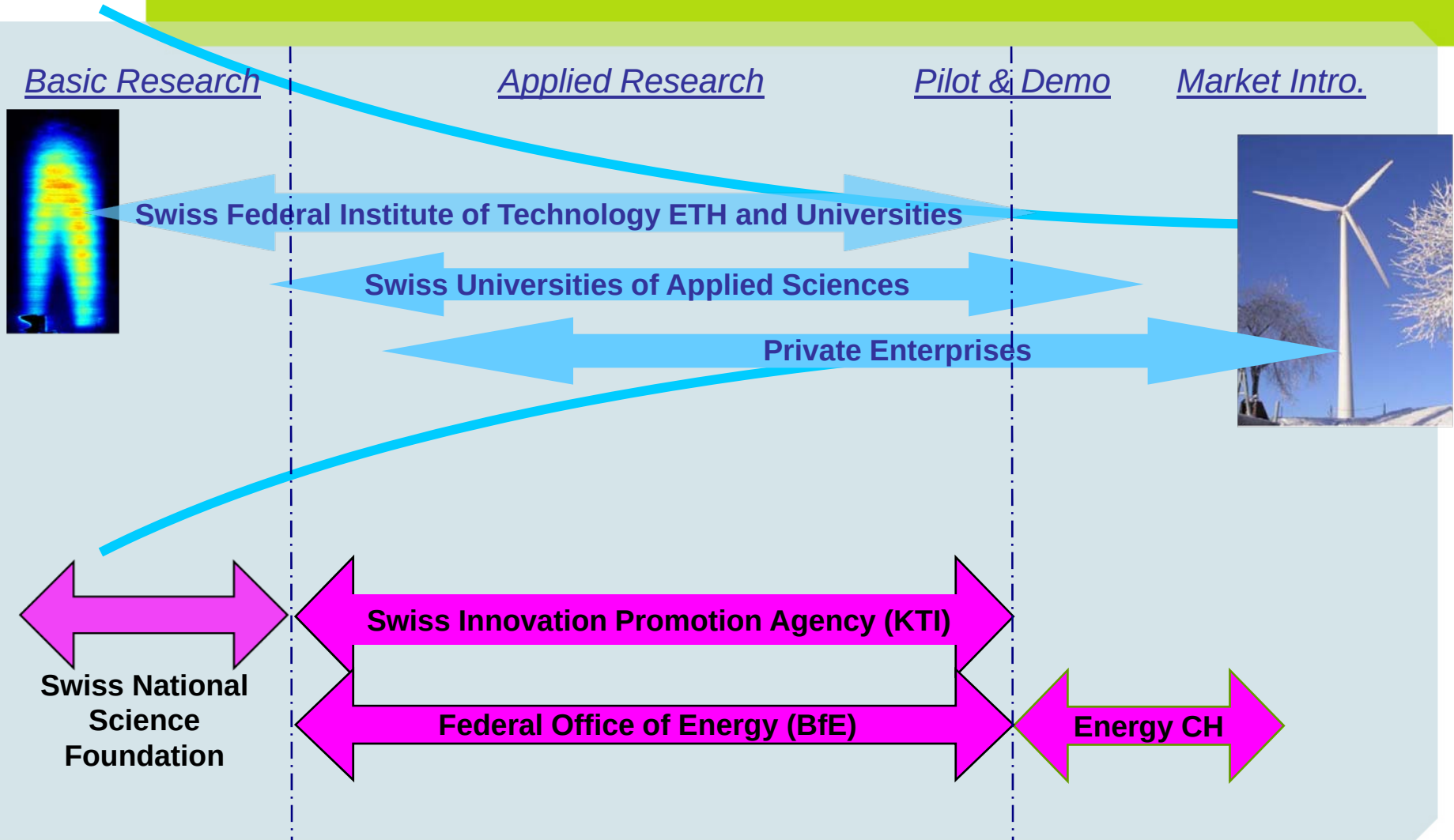
Lower Bar: Non Nuclear

Source: IEA



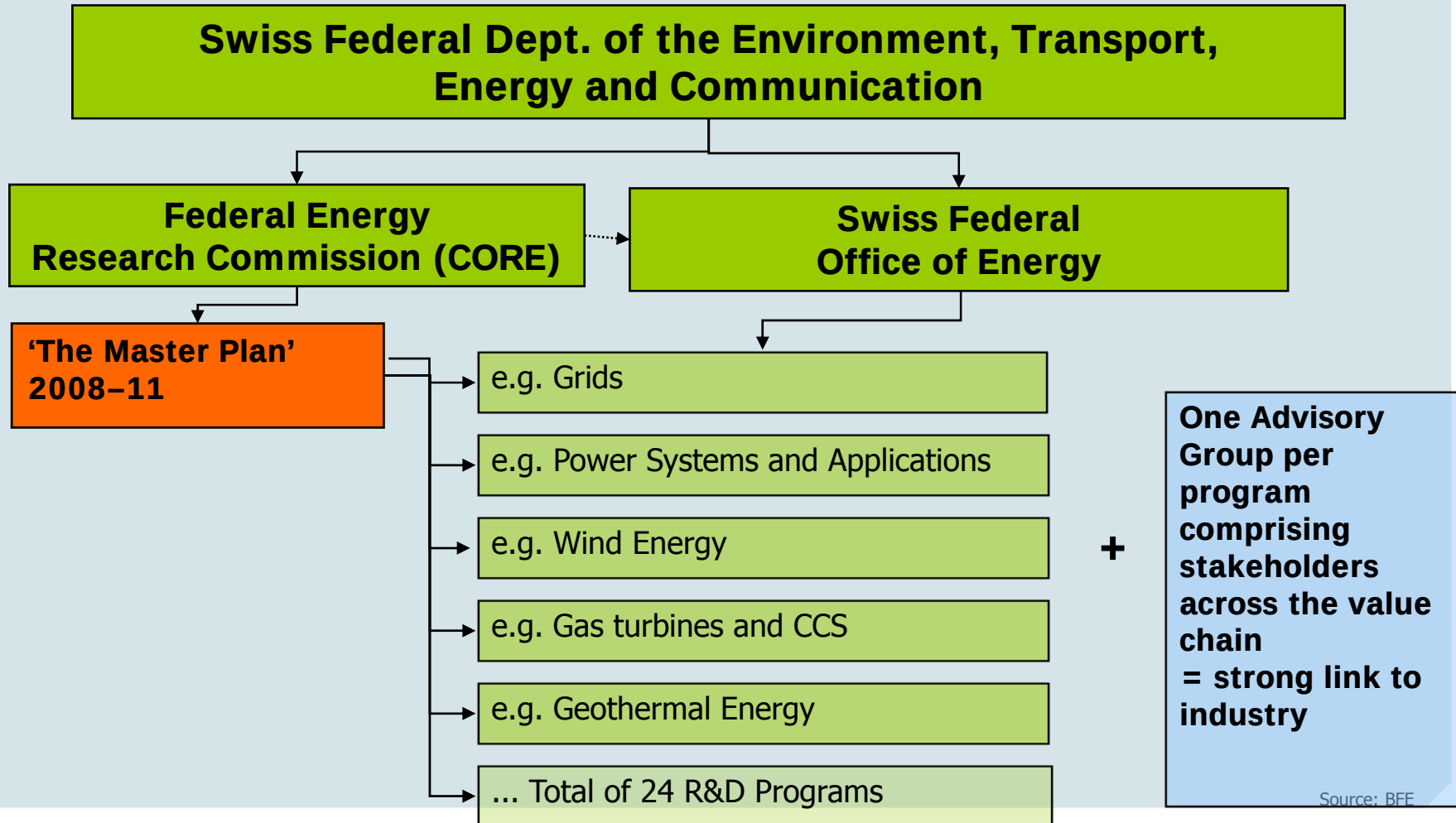


A view of the Swiss Innovation Funnel





Organization of Public Energy Research



Source: BFE



Program Governance

Master Plan

Updated Every 4 Years



**Application
Driven Strategic
Goals (4 Areas)**



24 Focus Areas Covering Efficiency, Renewables and Nuclear Energy



Application Driven Strategic Objectives



Energy Systems: Decarbonization

- Combined Power Plants
- CCS
- Biogenic Fuels



Processes: Sustainability & Efficiency

- CHP
- Waste Heat Utilization



Buildings: Towards Zero Energy

- Heating w. Biomass
- Heat Pumps & Combustion Engines



Mobility: Reduce Share of Fossil Fuels

- High Efficiency ICE
- Range Extender
- Alternative fuels



Comprehensive and Consensus-Based R&D Program – Portfolio

Renewable Energy

- Biomass
- Wood
- Hydrogen
- Geothermal Energy
- Wind Energy
- Photovoltaic
- Solar-thermal
- Industrial Solar Energy Utilization
- Hydroelectric Power

Nuclear

- Regulatory Safety Research
- Nuclear Technology and Safety
- Fusion

Energy Efficiency

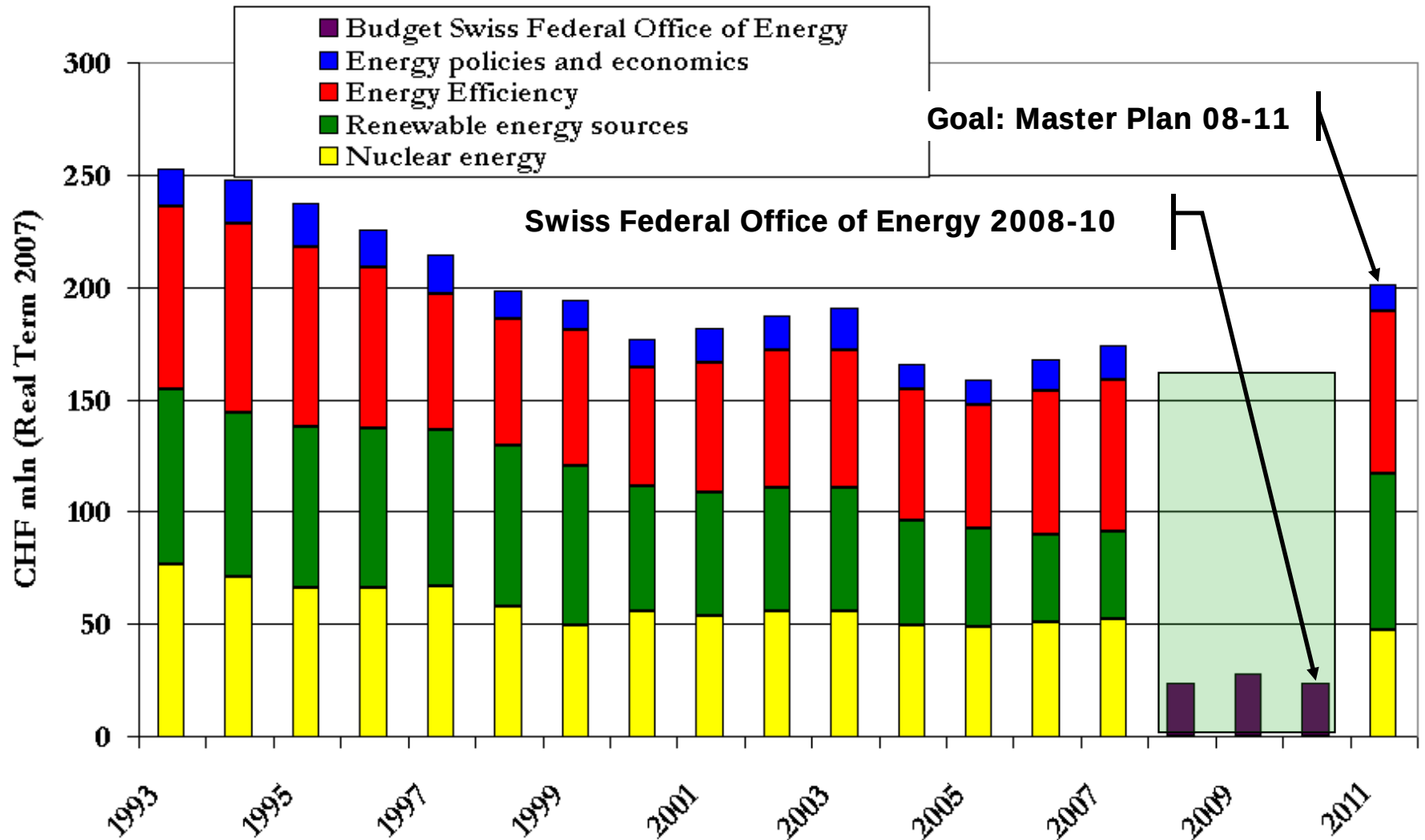
- Buildings
- Traffic
- Accumulators
- Grids
- Process Engineering
- Electricity technologies and applications
- Fuel Cells
- Heat Pumps/Combined Heat and Power
- Gas Turbines / Carbon Capture and Storage
- **Combustion**

Support Functions

- Knowledge and Technology Transfer
- Coordination
- Energy Economics and Policy

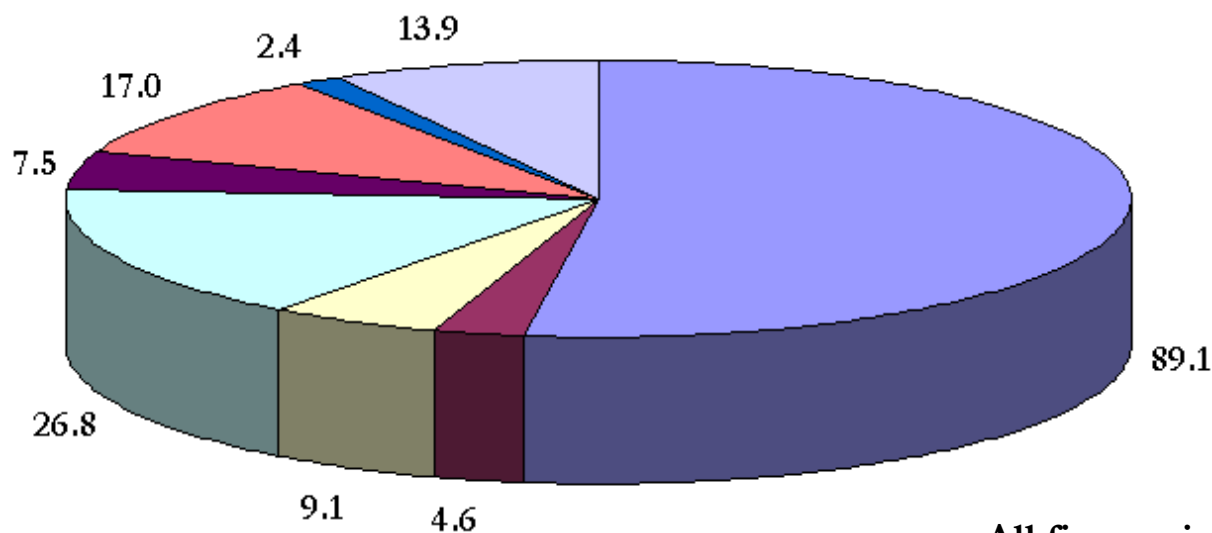
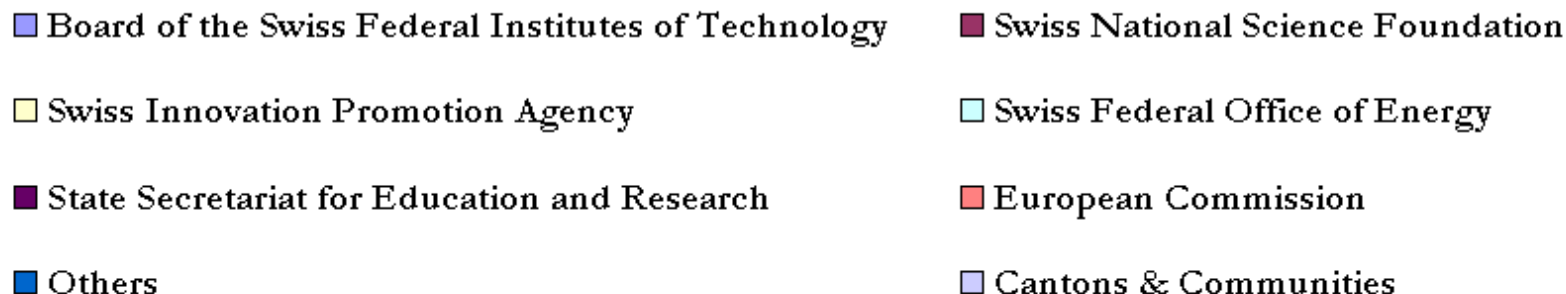


Public Funding History





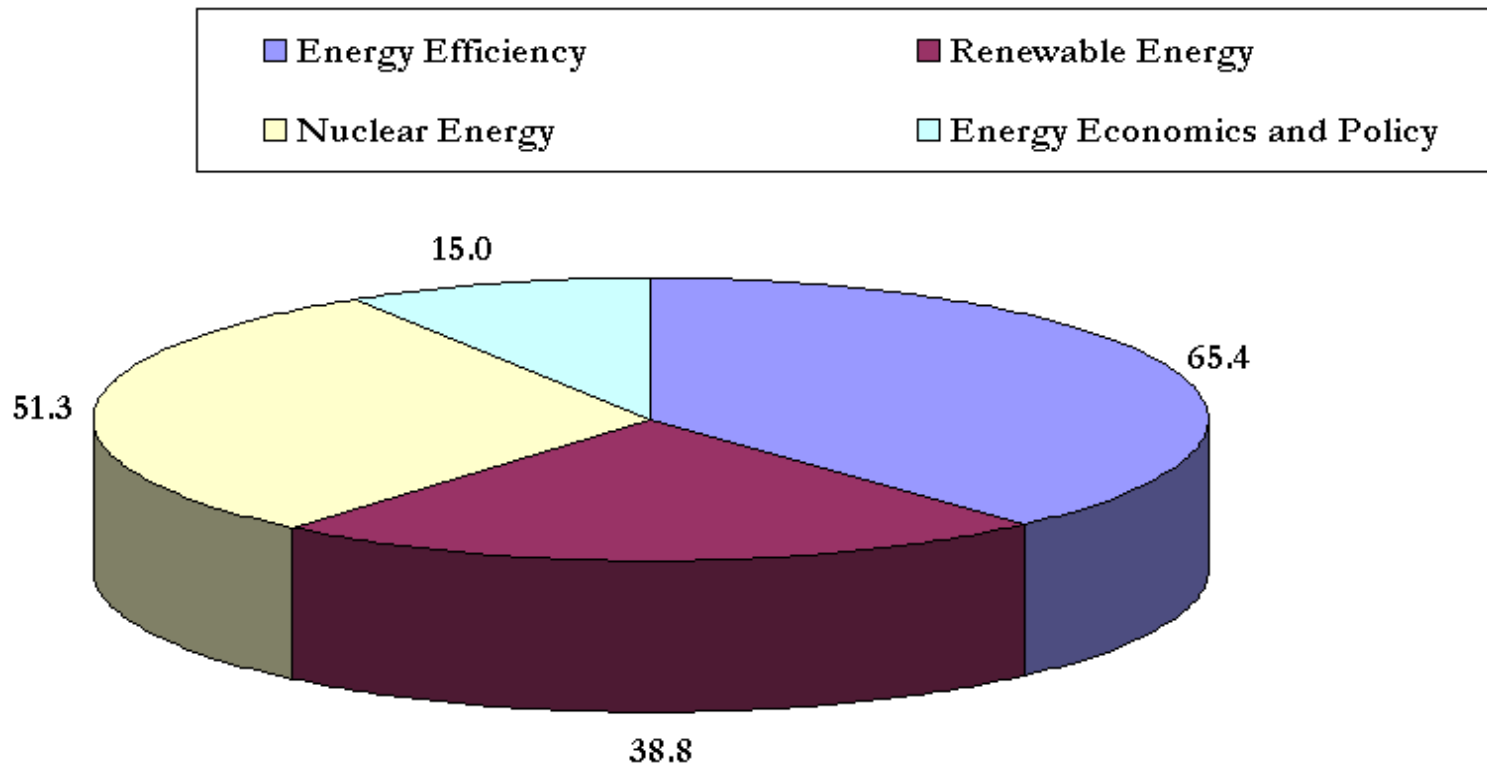
Sources of Public Funds (Average 2006 / 2007)



All figures in CHF mln
Total of **CHF 170.5 mln**



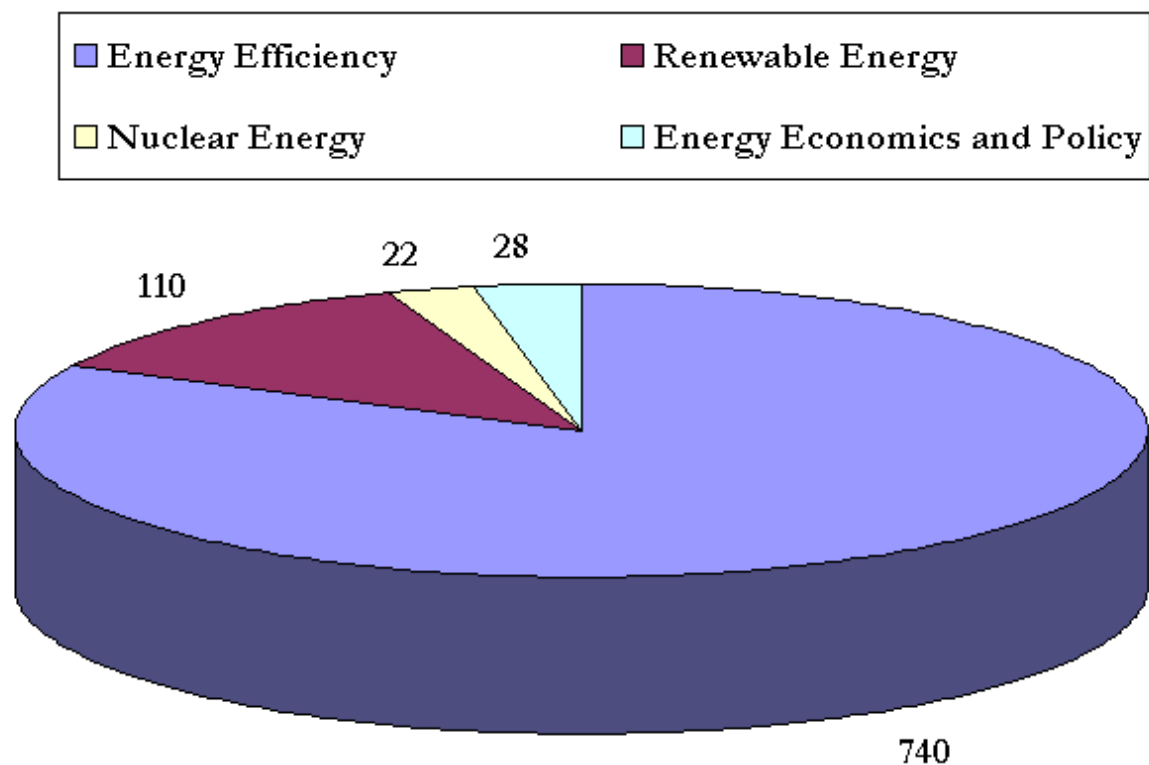
... And Usage of Public Funds (Average 2006 / 2007)



All figures in CHF mln
Total of CHF 170.5 mln



Rough Estimates of Privately Funded R&D

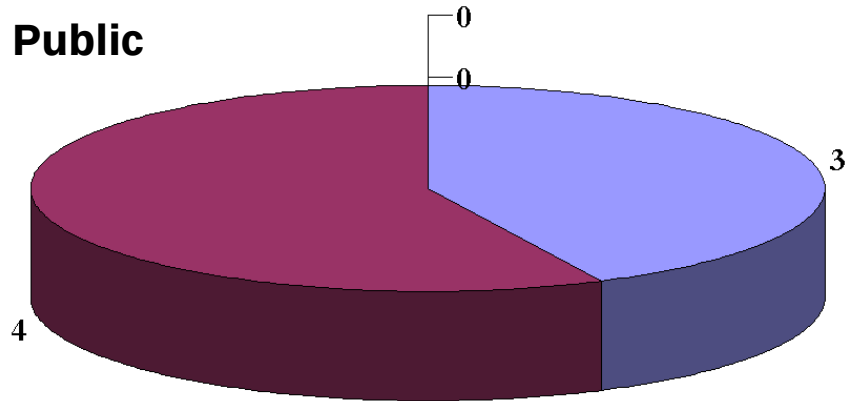


All figures in CHF mln
Total of CHF 900 mln



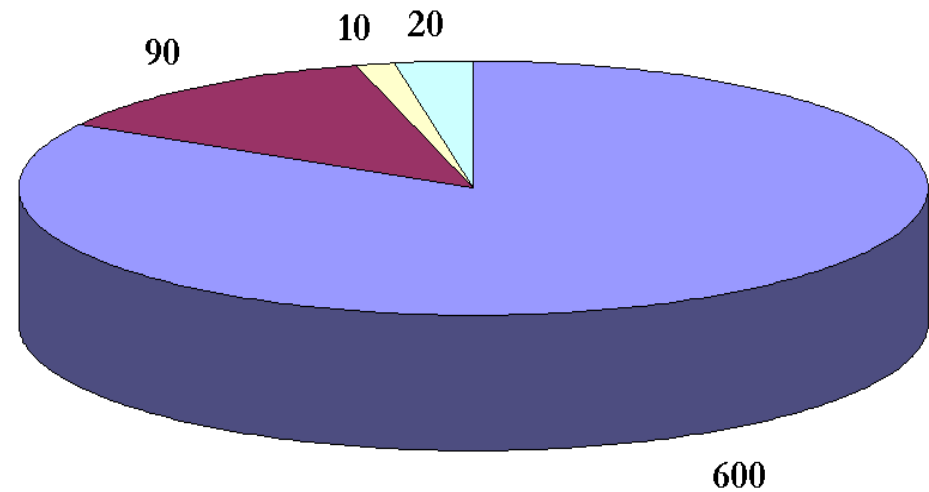
Funds for Pilot and Demonstration Projects

Public



All Figures in CHF Mill.

Private (Estimated)



- Energy Efficiency
- Renewable Energy
- Nuclear Energy
- Energy Economics and Policy



Agenda

- Current Energy Policy Goals
- Structure and Governance of the Energy Research in Switzerland
- Value of Combustion Research from a National Perspective



Focus Area Combustion

Importance of the Swiss Combustion Research

- **Key Energy Conversion Process**
 - ≈ 75 % of Usable Energy Generated by Fossil & Biogenic Fuels
- **High Economical Value**
 - 5000 People Employed
 - 2 Mia. CHF Sales
 - R&D of Global Players Headquartered in CH (Wartsila, Alstom, ABB, IVECO, Liebherr,..)
- **World Class Centers of Competency**
 - Swiss Federal Institutes of Technology (ETH in Zurich and Lausanne)
 - Paul Scherrer Institute, EMPA
 - Swiss Universities of Applied Sciences
- **Key Technology for the Main Focus Areas**
 - Energy Generation, Processes, Buildings and Mobility



Conclusions



**We Have Witnessed During the 90s
the IT Revolution.**

**We are Now Witnessing the ET
(Energy Technologies) Revolution,
and this Revolution is Going to be
“Green”**

**Thomas L. Friedman
Journalist and Pulitzer Prize Winner**



Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Renfermant les Eemples RRE
Gallies Gälländ die Tüüringie GEFEM
Büroho Bundesrat der Eüüringie RRE
Swiss Federal Office of Energy SFOE

IEA Verbrennungsforschung

Bundesamt für Energie



Stephan Renz & Sandra Hermle

Tagung Verbrennungsforschung in der Schweiz

28.10.2009



Inhalte



Internationale Energie Agentur – kurze Einführung

Implementing Agreement Combustion- im Detail:

- Geschichte
- Organisation
- Collaborative Tasks
- Teilnahme von Forschenden aus der Schweiz
- Beispiele für Tasks



IEA Combustion

2



International Energy Agency



- Internationale Organisation; Beratung Energiepolitik für 28 Mitgliedsländer
- Gründung während der Ölkrise 1973-74 -> damalige Aufgabe: Koordinative Massnahmen im Falle von Lieferengpässen
- Heutige Aufgabenbereiche: Energiesicherheit, Ökonomische Entwicklung, Umweltschutz -> aktuelle Themen: Klimawandel, Marktreform, Zusammenarbeit im Bereich Energietechnologie, Verbreitung von Erkenntnissen
- Unterstützung von über 40 intern. Kooperationsabkommen -> F&E, Einsatz und Verbreitung von Energietechnologien
- OECD Mitgliedsländer/ Nicht Mitgliedsländer, internationale Organisationen

Implementing Agreements:

- grösste Herausforderung in Energiepolitik: kosteneffizient die Themen Versorgungssicherheit und Klimawandel anzugehen
- um diese internat. Anstrengungen zu fördern Gründung von IA (rechtsgültige Verträge)
- seit mehr als 30 Jahren: Fundament in der Förderung neuer oder verbesserter Energietechnologien



Etwas Geschichte.....IA Combustion



Gründung: 1977, ausgelöst durch Ölkrise; Grossbritannien, Schweden, USA

Ziel: Informationsaustausch von forschungsrelevanten Informationen zu Verbrennungsprozessen -> Verbesserung der Verbrennungseffizienz, Nutzung von alternativen Treibstoffen

Mitgliedsländer heute: Belgien, Deutschland, Finnland, Grossbritannien, Italien, Japan, Kanada, Norwegen, Schweden, Schweiz, Südkorea, USA

Organisation:

- Collaborative Tasks
- Executive Committee





Collaborative Tasks - Überblick



6 Collaborative Tasks: Chair, Technical Oversight Committee

Annahme durch ExCo

Aktuelle Collaborative Tasks:

- Gas turbines
- Sprays
- HCCI Fuels
- Advanced hydrogen fueled internal combustion engines
- Alternative fuels
- Nanoparticle diagnostics

In Diskussion:

- Soot Formation
- Energy Security

IEA Combustion

5



Collaborative Tasks – im Detail



Gas turbines

- Ziel: Minderung CO₂-Ausstoss -> Carbon Capture
- Themen: neue brennbare Gase und Sauerstoffträger -> magere, vorgemischte VB
alternative Verbrennungskonzepte -> flammenlose VB, katalytisch unterstützte VB
➤ Datenbank: VB-Eigenschaften -> Plausibilität numerische Modelle
- Interessierte Länder: CH, CND, D, S, UK, USA
- Ansprechpartner: [P. Jansohn, PSI \(Schweiz\)](#)

Sprays

- Ziel: Effizienzsteigerung und Emissionsreduktion -> Spray Physik verstehen,
Zusammenarbeit experimentelle & numerische Forschung verstärken
- Themen: Evaporating sprays, fuel spray modeling, in-cylinder flow fields
- Interessierte Länder: CH, FIN, I, J, UK
- Ansprechpartner: [M. Larmi, Helsinki University of Technology \(Finnland\)](#)
[Y. Moriyoshi, Chiba University \(Japan\)](#)

IEA Combustion

6



Collaborative Tasks – im Detail



HCCI Fuels

- Ziel: Interaktion HCCI – Brennstoff besser verstehen
- Themen: Zündungscharakteristiken von dieselähnlichen Brennstoffen, Charakterisierung der Selbstzündungseigenschaften von Diesel mit hoher Verdünnung, Brennstoffaspekte mit komplett vorgemischter Zylinderfüllung (DME + Erdgas, Dieseline)
- Interessierte Länder: J, N, S, UK, USA
- Ansprechpartner: [B. Johansson, Lund University \(S\)](#)

H₂ICE

- Ziel: Effizienzsteigerung, Emissionsreduktion, Minimierung unerwünschter VB
- Themen: Einfluss von H₂ als Additiv, Erhöhung EGR dank H₂-Bemischung, Untersuchung der Gemischbildung
- Interessierte Länder: B, CH, CND, D, J, ROK, USA
- Ansprechpartner: [C. Bae, KAIST \(ROK\)](#),
[S. Kaiser, Sandia National Laboratories \(USA\)](#)



7



Collaborative Tasks – im Detail



Alternative Fuels

- Ziel: Entwicklung einer „optimalen“ Verbrennung für zukünftige Brennstoffe, erfüllen zukünftiger Emissionsstandards mit oder ohne Abgasnachbehandlung
- Themen: Flexible Ventilsteuerung und Einspritzung, Düsenwinkel, Einspritzdruck, Abgasrückführung, Brennkammergeometrie, Kompressionsverhältnis
- Kraftstoffe: synthetische Dieselmotorkraftstoffe (FT-Diesel, DME etc.)
- Interessierte Länder: B, CH, FIN, I, J, ROK, S
- Ansprechpartner: [M. Larmi, Helsinki University of Technology \(Finland\)](#)

Nanoparticle Diagnostics

- Ziel: Messung und Charakterisierung von Nanopartikeln
- Themen: Optische Diagnostik mittels Pyrometrie, LII, Lichtstreuung, Elektronenmikroskopie, akustische Techniken, Bestimmung der volatilen Fraktion von Feinstaub
- Interessierte Länder: CND, I, UK
- Ansprechpartner: [D. Greenhalgh, Heriot-Watt University \(UK\)](#),
[G. Smallwood, National Research Council \(Canada\)](#)



8



Motivation

- Ziele der Schweizer Energieforschung decken sich mit den Zielen der IEA
 - Reduktion Schadstoffemissionen
 - Erhöhung Systemwirkungsgrad
 - Reduktion CO₂- Emissionen
 - Networking und internationale Zusammenarbeit
- ✓ IEA ist eine gute Plattform für den internationalen Austausch
- ✓ IEA Implementing Agreement on Combustion fördert die Zusammenarbeit in ausgewählten Themen
- ✓ Die Gruppe ist überschaubar und Kontakte und Diskussionen sind möglich
- ✓ Das BFE will das Engagement in der IEA verstärken und unterstützt die Mitarbeit



a) *Emissions characterisation of urban transit buses: fuel and technologies alternatives (IEA AMF Projekt)*

- Emissionen und Effizienz als Kriterien für Zulassung und Beiträge für Busse im öffentlichen Verkehr
- Umfangreiche Studie über verschiedene Brennstoffe, Technologien und Einsatzgebiete (Fahrzykle) von Bussen
- Well to Wheel Betrachtung



b) *Towards a global reaction model for future „designer fuels“ (LAV ETHZ)*

- Untersuchung verschiedener Brennstoffe und Brennverfahren
- Einflussfaktoren, Kennzahlen
- Kinetik ist relevant für Zündverhalten und Wärmeabgabe im Brennprozess

c) *Studies on reaction kinetics of combustion and emission formation (J. Vandooren, Uni Louvain, Belgien)*

- Messanordnung für verschiedene Brennstoffe und theoretische Modelle für die Berechnung
- Verschiedene Species werden untersucht so auch NH₃ (Oxidationsprozess)



Beispiele Tasks: Alternativ Fuels (2/2)



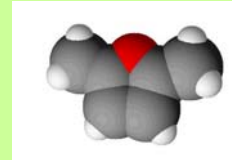
d) Critical evaluation of substitution of natural gas by biogas (F. Behrent TU Berlin)

- Zukunft: Vorwiegend direkte Biogasnutzung anstatt Einspeisung ins Erdgasnetz
- Heute (D): 855 TWh Erdgas und 22.4 TWh Biogas davon 5 % ins Erdgasnetz
- Potential für Biogas bis 2030: 10 mal mehr! (240 TWh)
- kann nicht eingespeist werden: Biogas zu wenig CH_4 zu viel CO_2
- die direkte Nutzung muss verbessert und ausgedehnt werden
-> Entwicklung optimierter Verbrennungssysteme hat Priorität



e) DME as alternativ fuel for CI engine and vehicle – progress in China (H. Zhen, Uni Shanghai)

- DME (Dimethyl Ether $\text{C}_2\text{H}_6\text{O}$) wird in China als Alternative zu LPG und Diesel angesehen. Gewinnung vorwiegend aus Kohle.
- gute Verbrennungseigenschaften aber keine Schmierung und aggressiv gegen Gummi
- In Shanghai Versuchsflotte (Busse) im Einsatz
- neueste Entwicklung: DMF (Dimethyl Furan $\text{C}_6\text{H}_8\text{O}$)

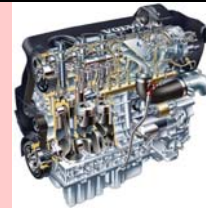


Beispiele Tasks: HCCI Fuels



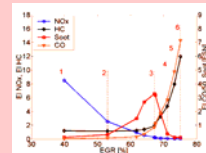
a) PPC for high fuel efficiency engine operation (B. Johnsson, Lund Uni, Schweden)

- Untersuchung von PPC (Partially Premixed Combustion) an versch. Versuchsmotoren (Volvo D5). Bis zu 56 % therm. Wirkungsgrad
- Untersuchung Einfluss der AGR
- Problem: zu geringe Brennstoffnutzung (91%)



b) Research into the fuel properties for HCCI (H. Xu, Uni Birmingham)

- Untersuchung der Faktoren, welche die Wärmefreigabe beeinflussen
- Entwicklung einer zweistufigen Zündung



c) Effect of cetane number on HCCI combustion efficiency and emission (Nat. Research Council Canada; Shell Canada)

- Brennstoffindustrie -> Diesel für traditionelle Dieselmotoren
- Zusammensetzung und Gemische für HCCI ändern
- Untersuchung mit Variation diverser Faktoren (CN, EGR, AFR, Blends etc.)



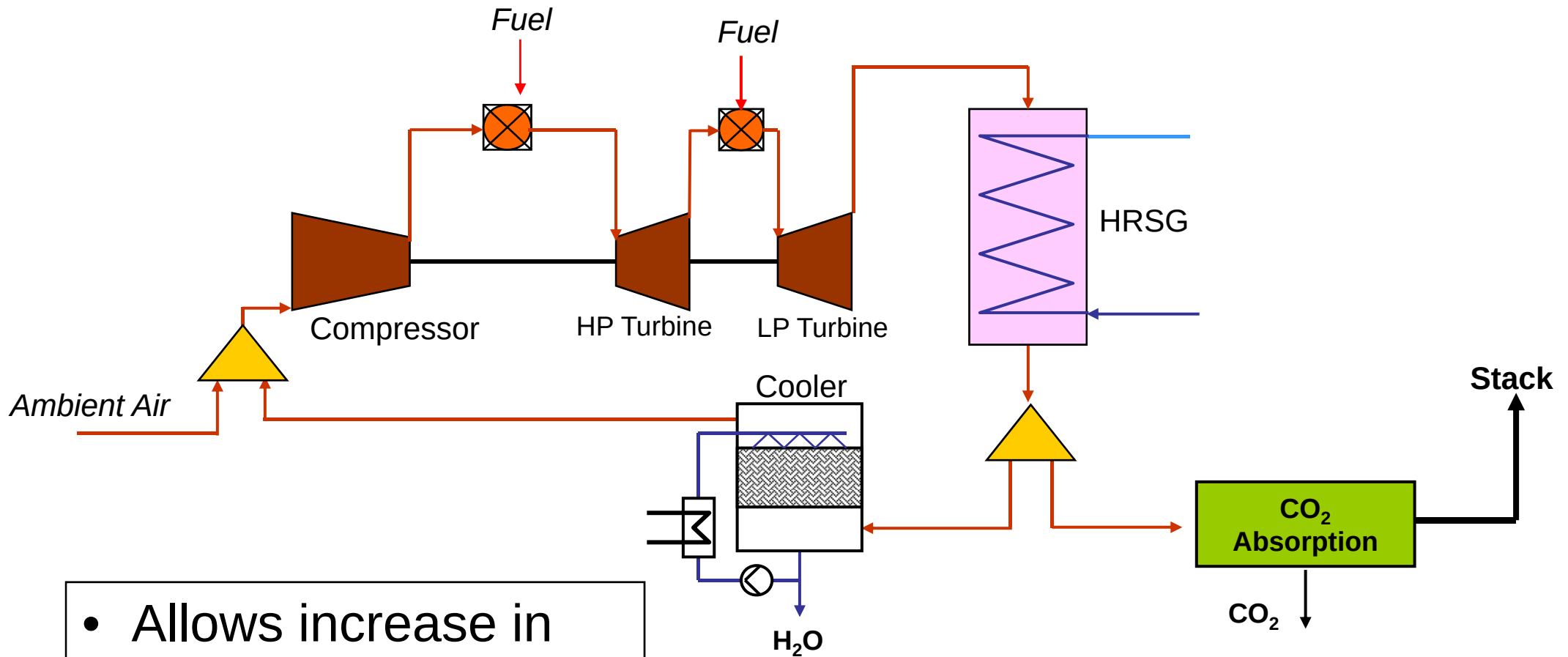
Gas Turbine Combustion with Flue Gas Recirculation

Dieter Winkler, Pascal Müller, Simon Reimer, Timothy Griffin
Fachhochschule Nordwestschweiz
Institute of Thermo- and Fluid-Engineering

Zurich, 28 October 2009

Flue Gas Recirculation

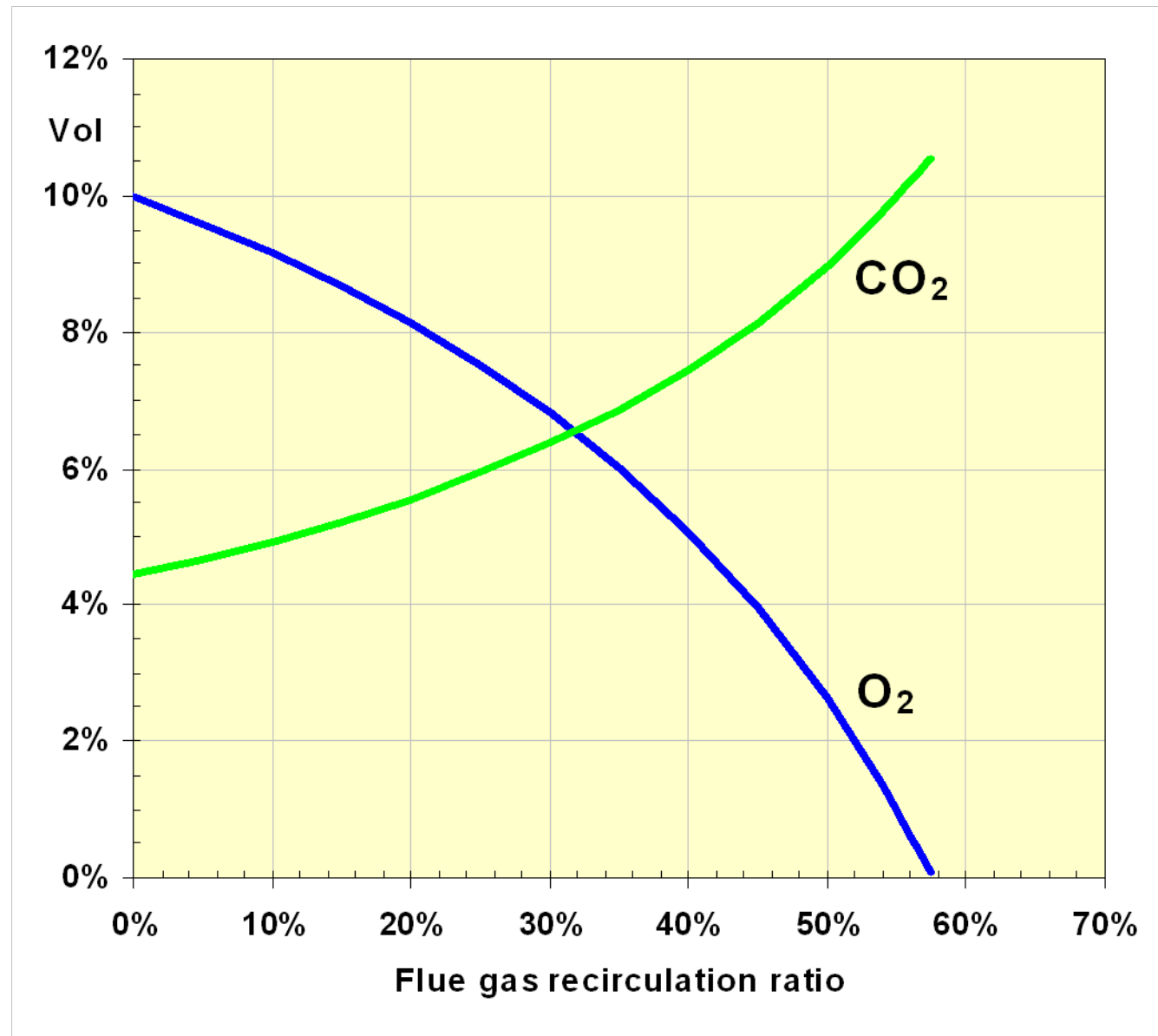
Generic Re-heat GTCC



- Allows increase in CO₂ concentration in exhaust gas

Post Combustion CO₂ Capture

Flue Gas Recirculation



Project goals

1. How much exhaust gas recirculation is possible without extinction of combustion?

a) reduced reactivity: impact of FGR on CO, NOx emissions

2. What is the impact of fuel composition (methane, C2+ content)?

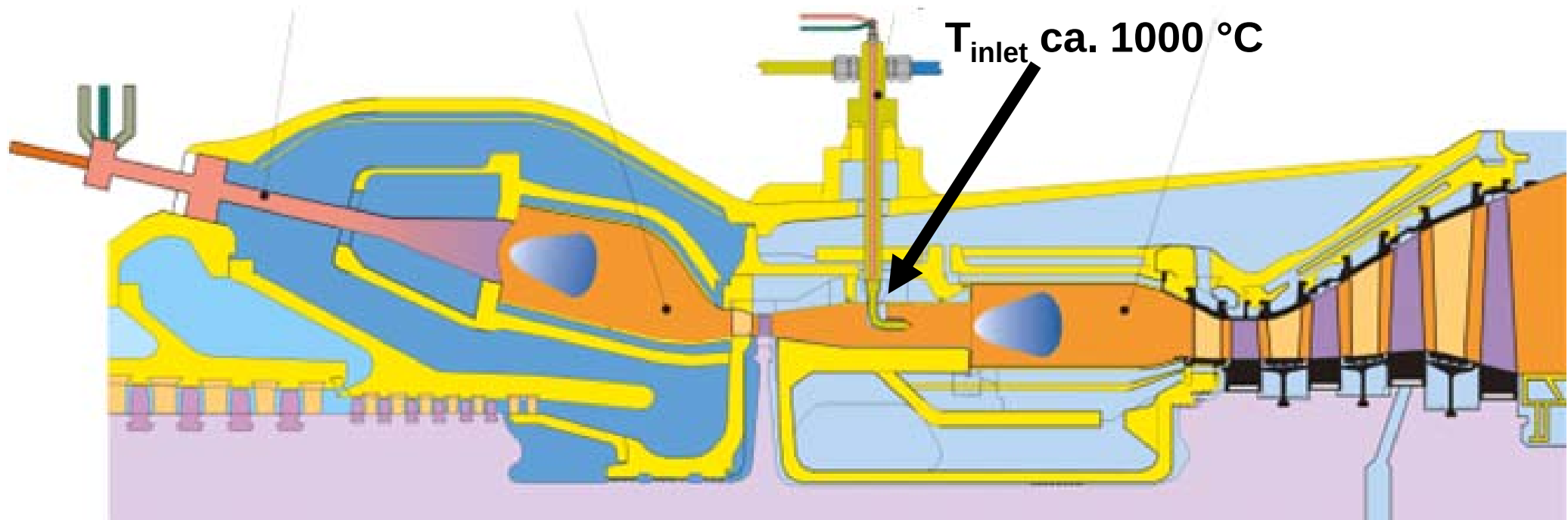
3. Can use of H₂ improve combustion stability?

a) impact of H₂ vs. H₂/CO/N₂

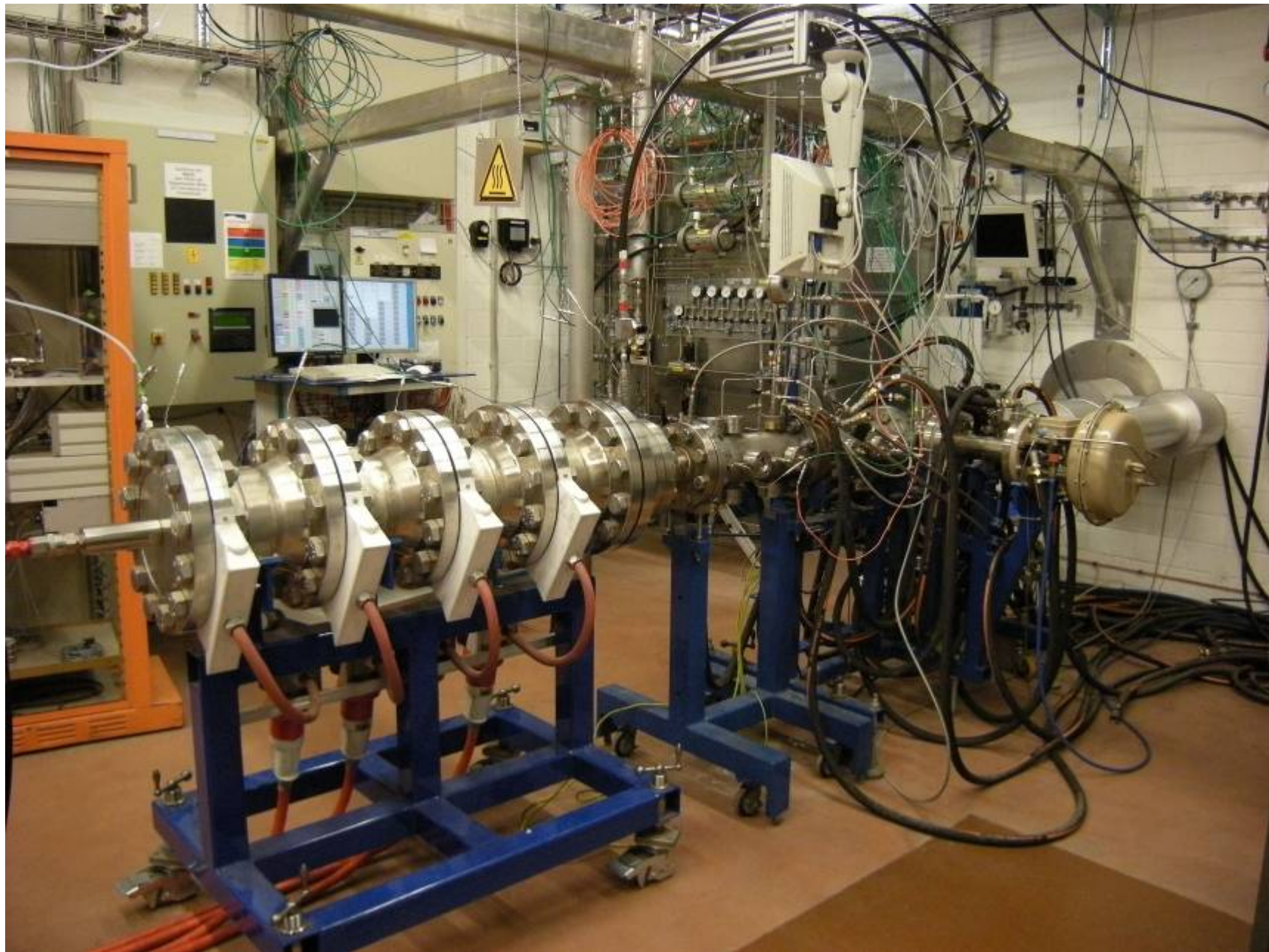
4. *How can H₂ be produced within GT system?*

a) *study of catalytic partial oxidation (CPO)*

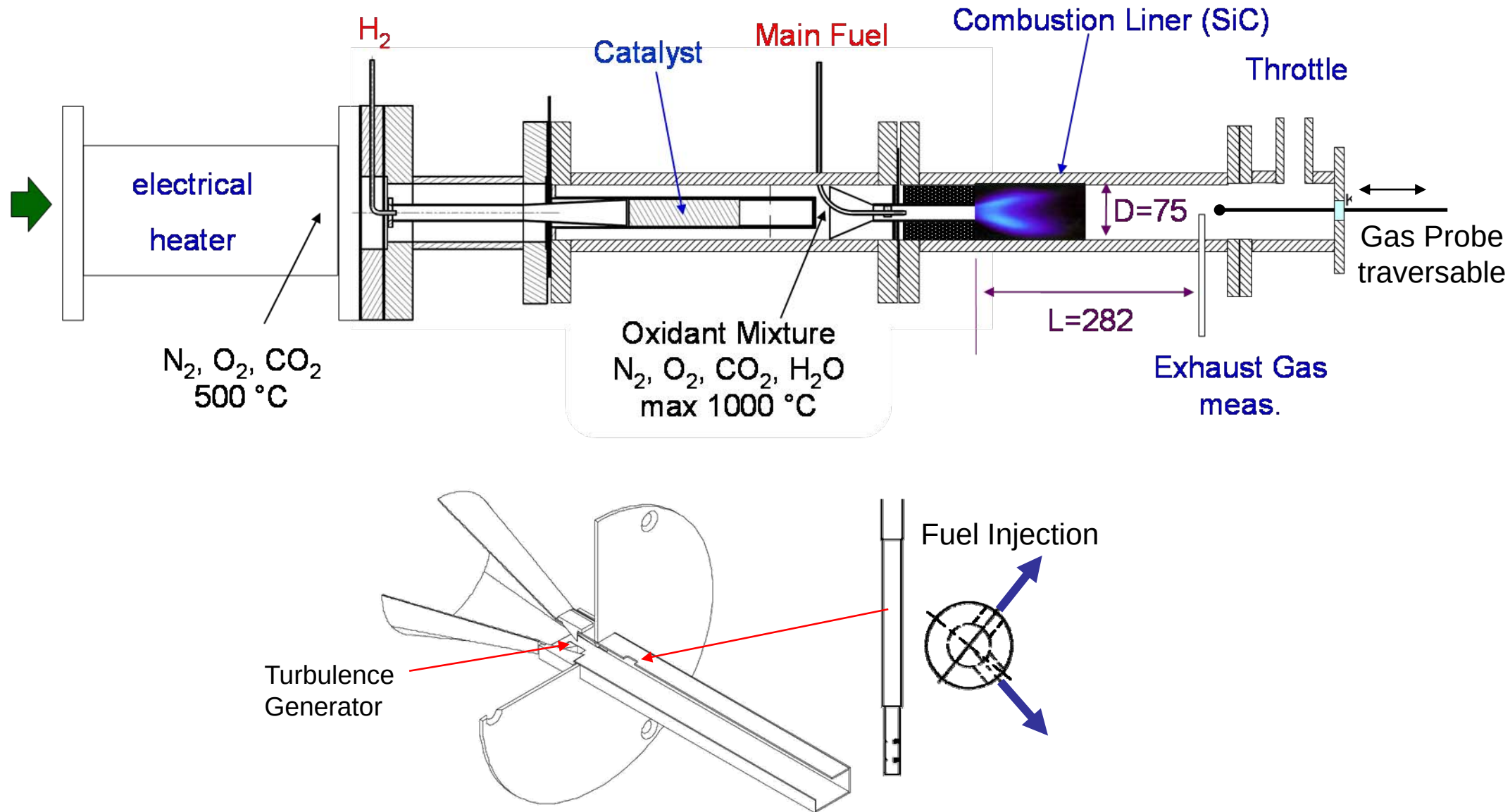
Sequential Combustion



Lab Scale High Pressure Rig

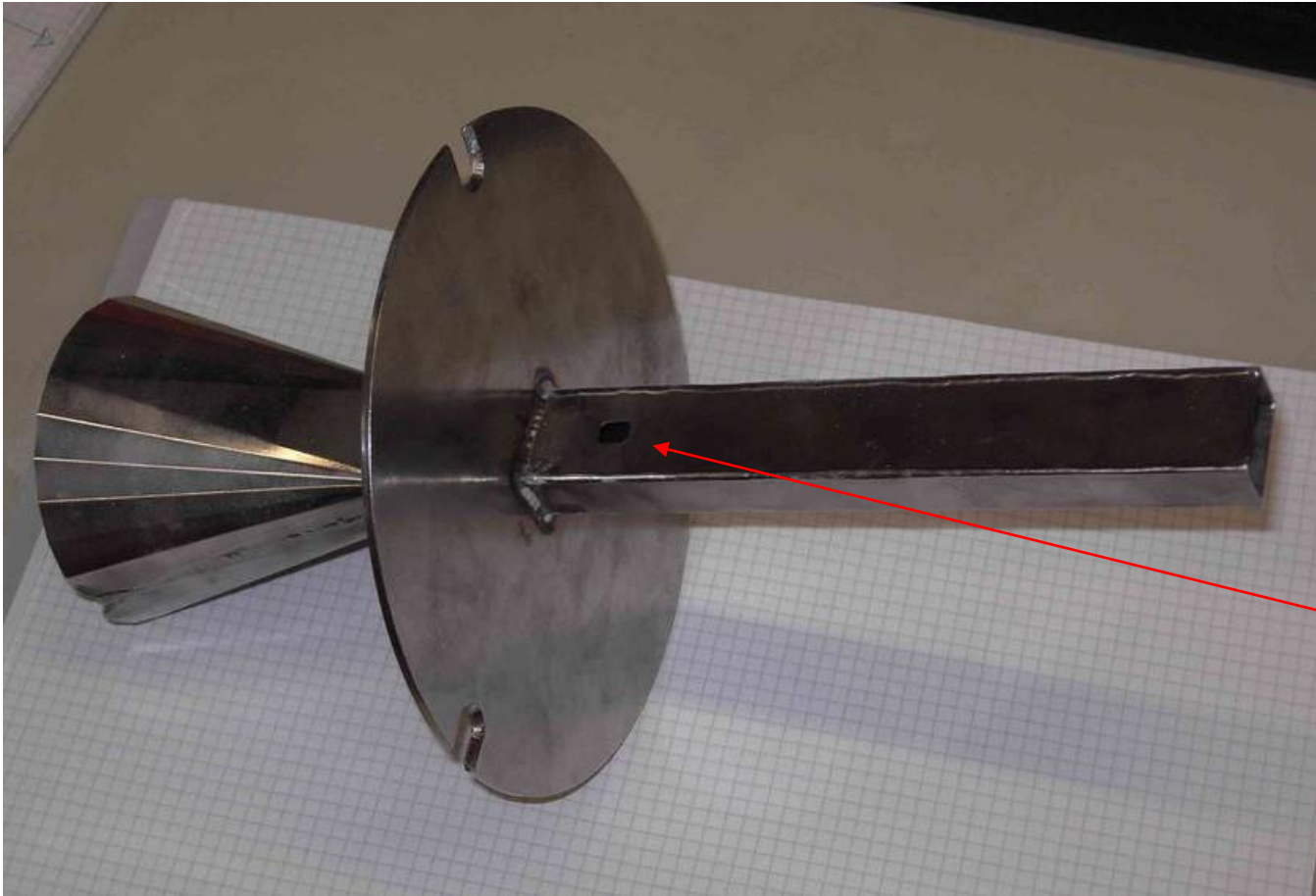


Experimental Simulation of Flue Gas Recirculation



Burner Components

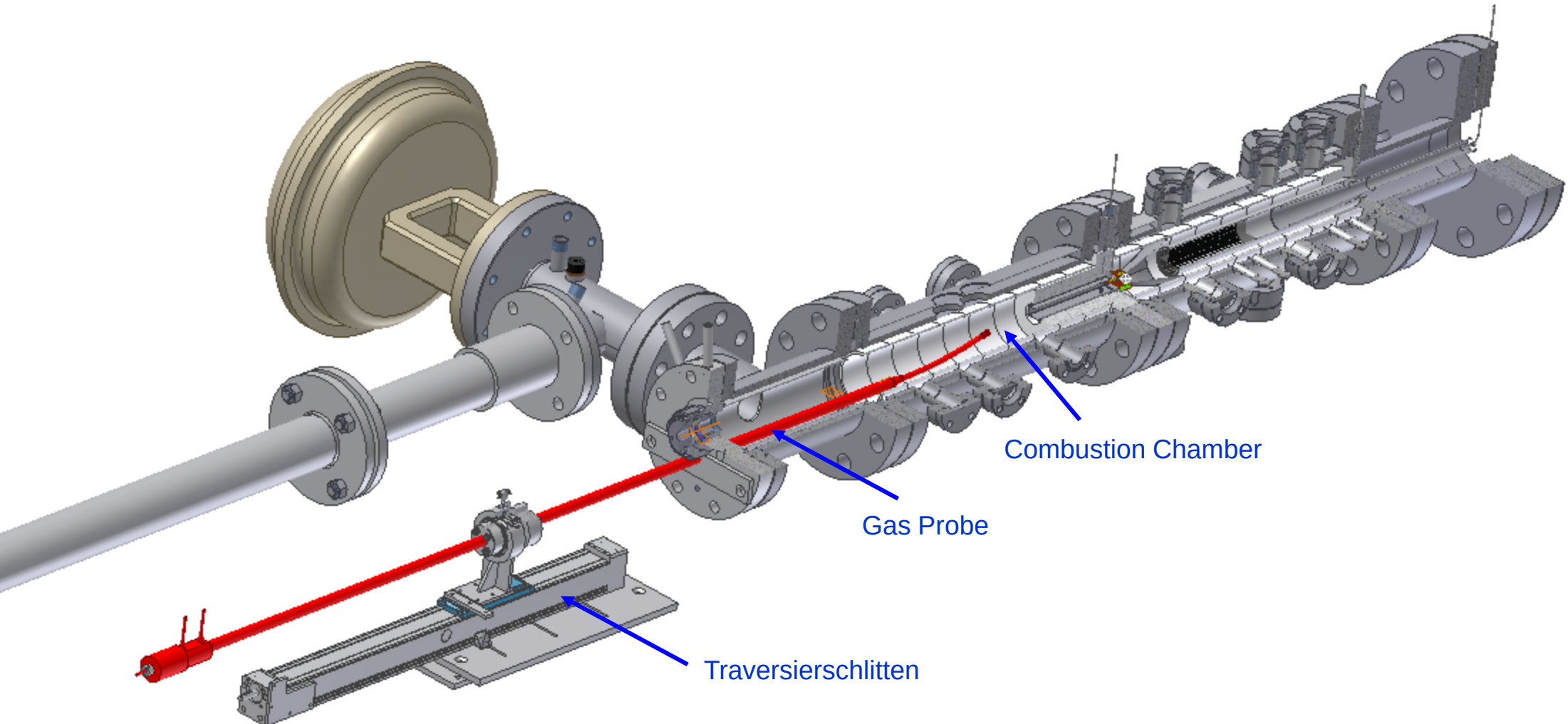
Mixing Tube



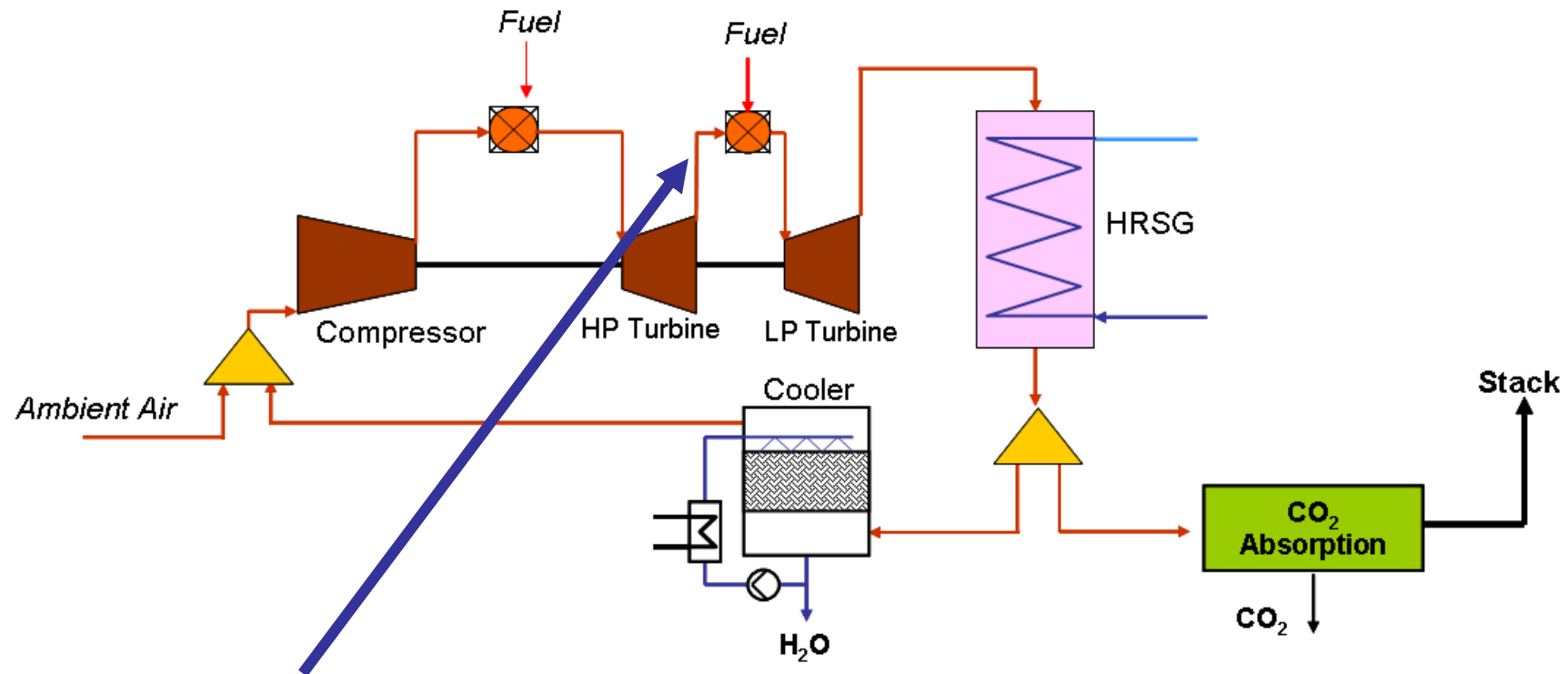
Fuel Injector



Traversable Gas Probe



Combustion Test Conditions



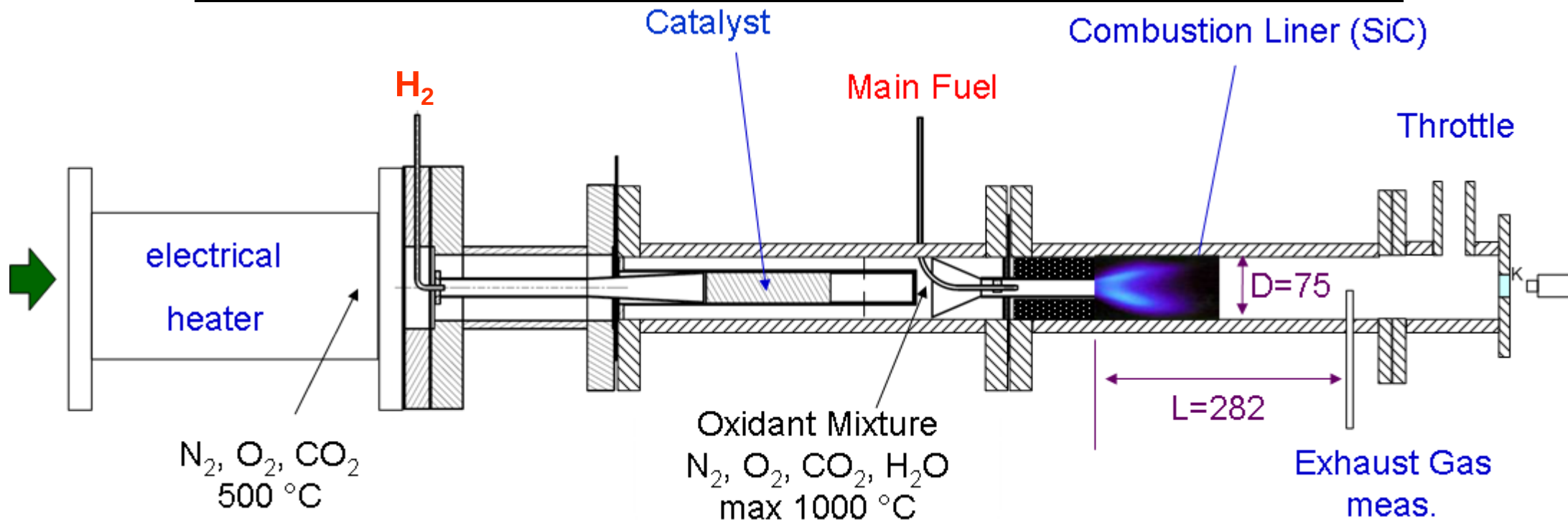
Reference oxidant concentrations at re-heat burner inlet

Case		1 (No FGR)	2 (Med.)	3 (High)	4 (Very High)
N ₂	mol%	76.3	77.8	78.7	79.4
O ₂	mol%	15.2	10.2	7.5	5.8
CO ₂	mol%	2.5	5.3	6.7	7.6
H ₂ O	mol%	6.0	6.8	7.1	7.2

Combustion Test Conditions

Test Parameter Variations

a	Recirculation ratio	no, medium, high, very high	
b	Pressure	8	bar, abs
c	Oxidant Inlet temperature	900, 1000	°C
d	Nominal inlet velocity	100, 200	m/s
	Residence time (resulting)	15 - 30	ms
	For each combination of a-d Adiabatic combustion temperature	1850 ... LBO	K



How were tests performed? I

1. Oxidant Composition, Temperature Velocity Fixed at Inlet

a) corresponds to given FGR rate and O_2 content at nominal T_{ad}

2. Fuel Concentration Varied at Fixed Oxidant Conditions

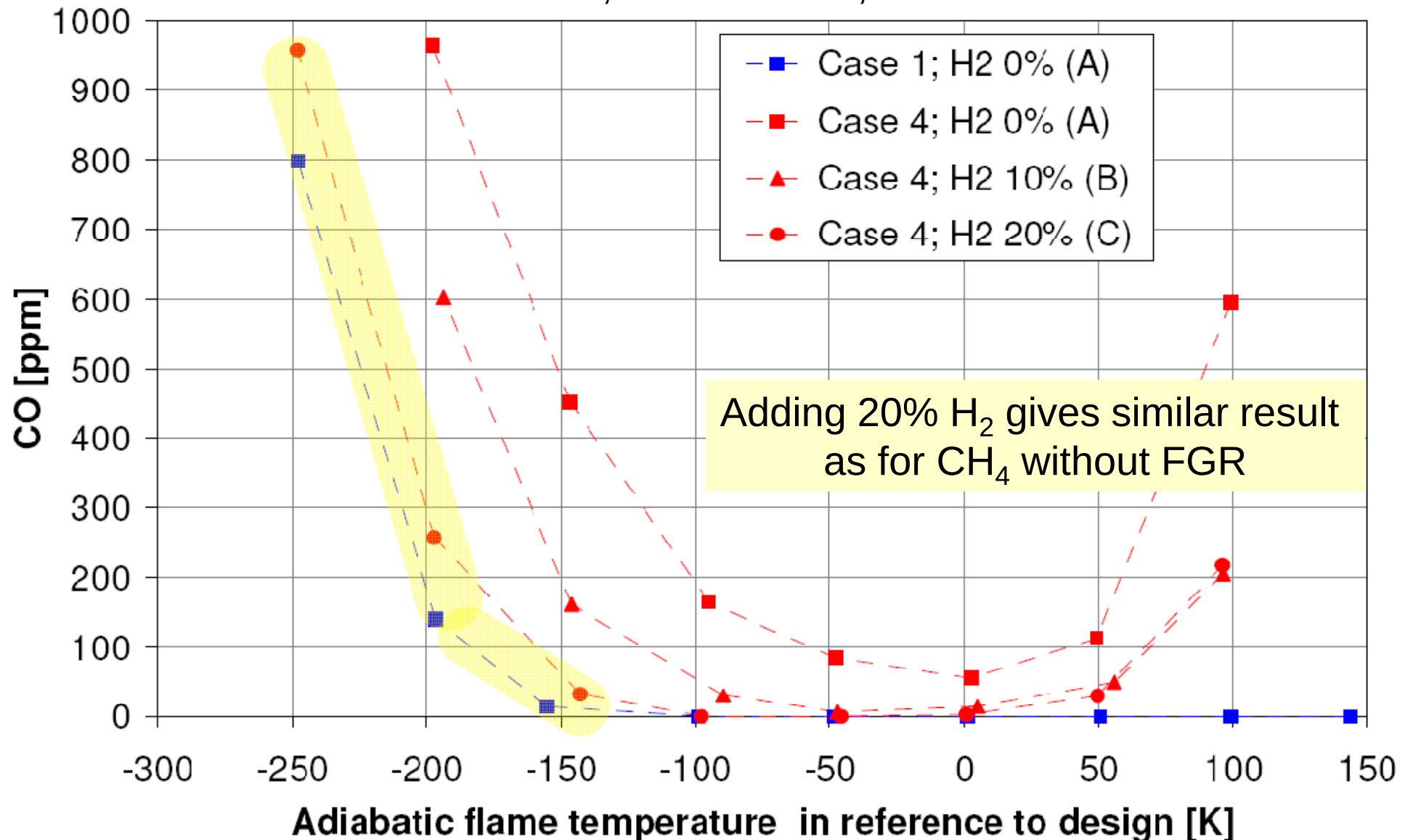
a) more O_2 in exhaust at leaner conditions, less at richer conditions

b) emissions (CO, NOx) vs. flame temperature recorded
(down to lean blow out)

3. Change of Oxidant Composition (new FGR Rate) and Temperature and Repeat Test (2).

Impact of H₂ addition to methane

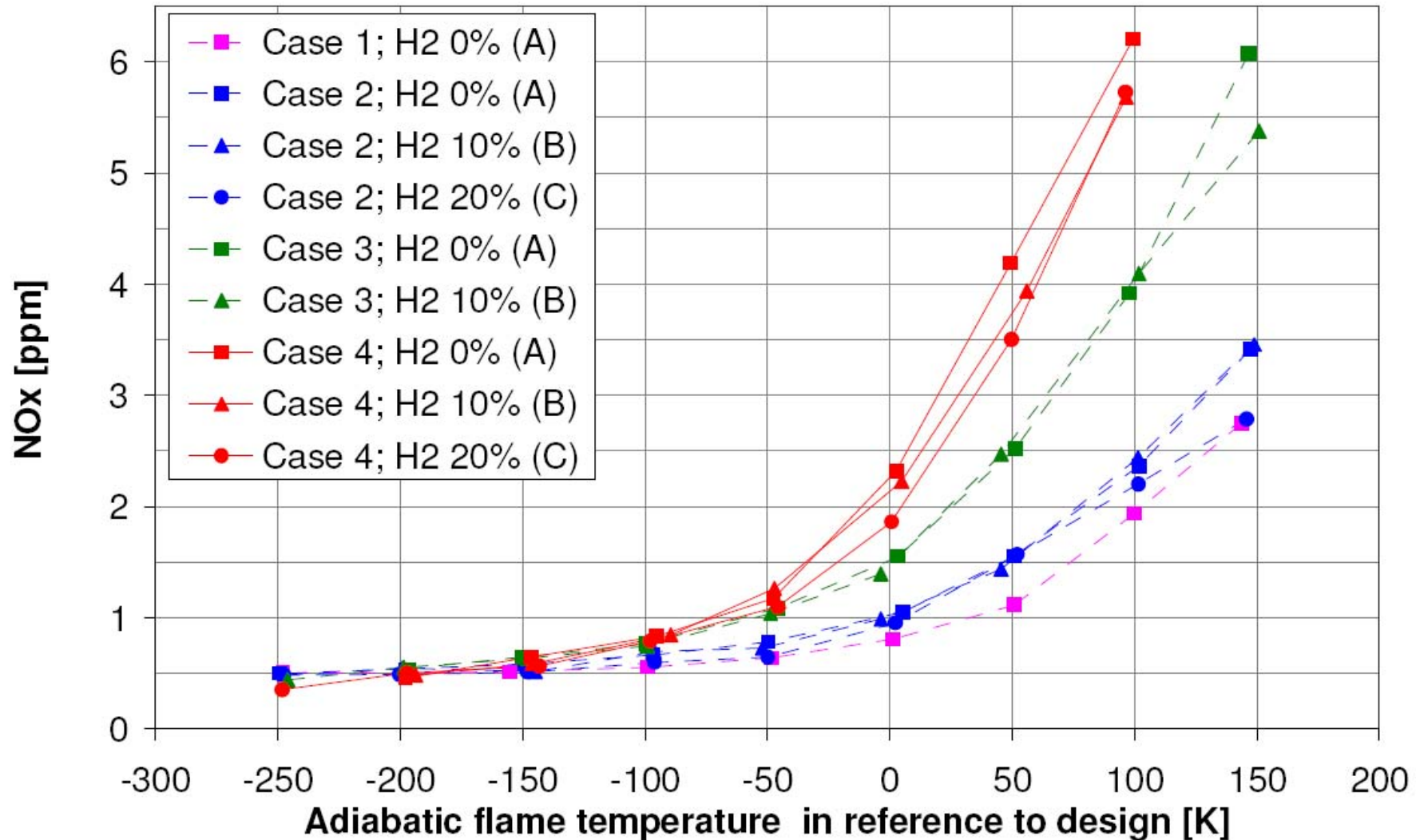
8 bar, 1000 °C inlet, 200 m/s



Impact of Recirculation and H₂ on NO_x

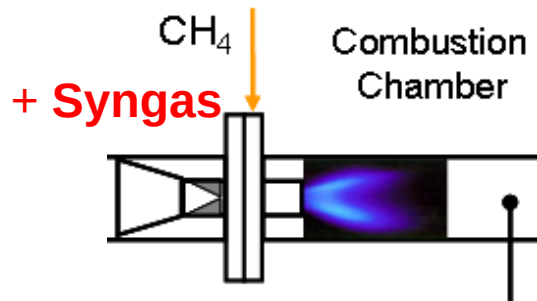
NO_x emissions

8 bar, 1000 °C inlet, 200 m/s



Fuel Compositions

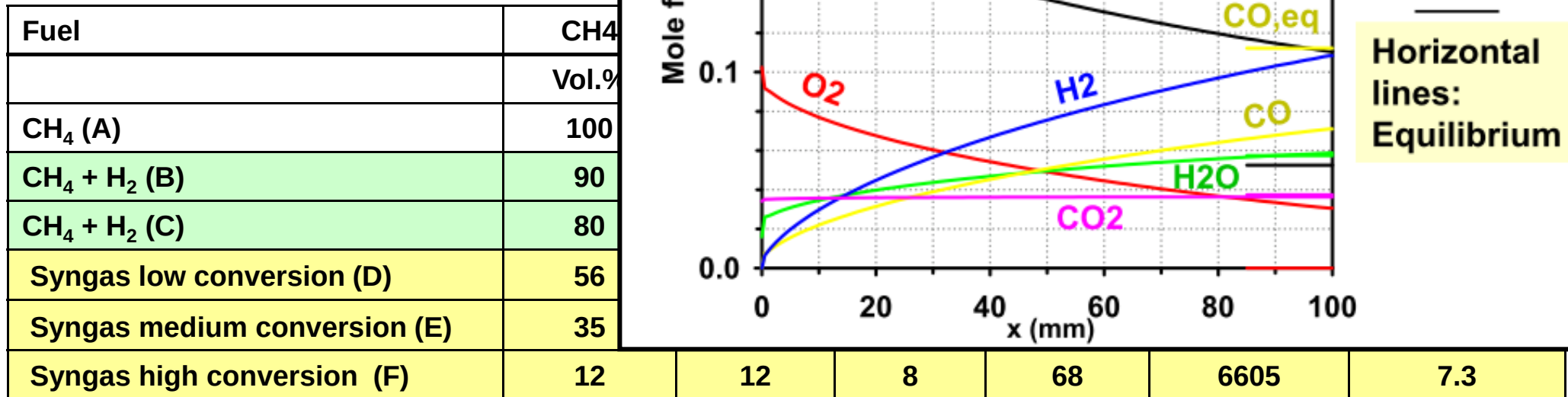
Test configuration



Simulation PSI (4 different cases)

CPO (+/- bypass)

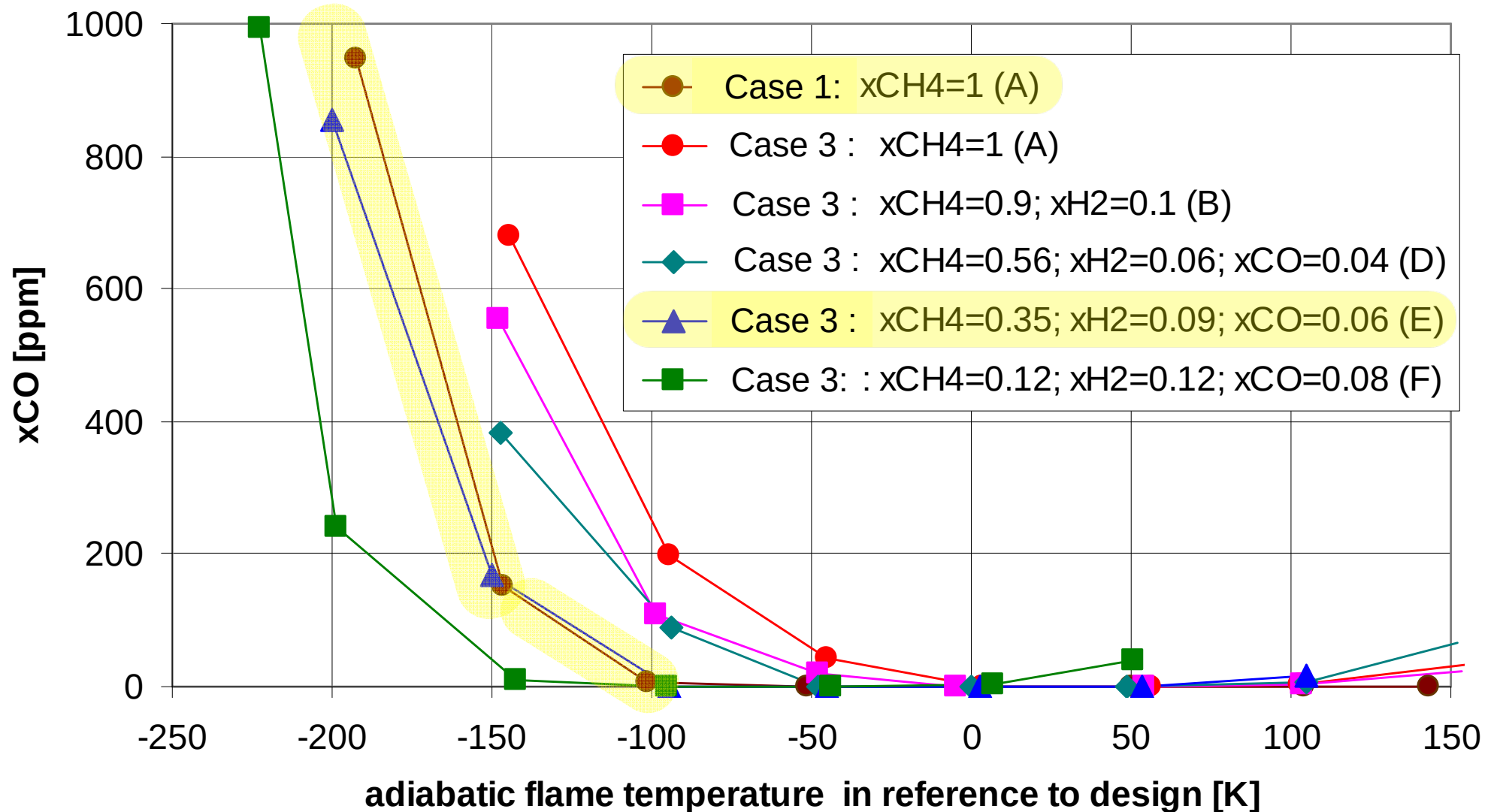
Test conditions



FGR with syngas stabilization

Results CO-emissions

8 bar, 1000 °C inlet, 200 m/s



How were tests performed?

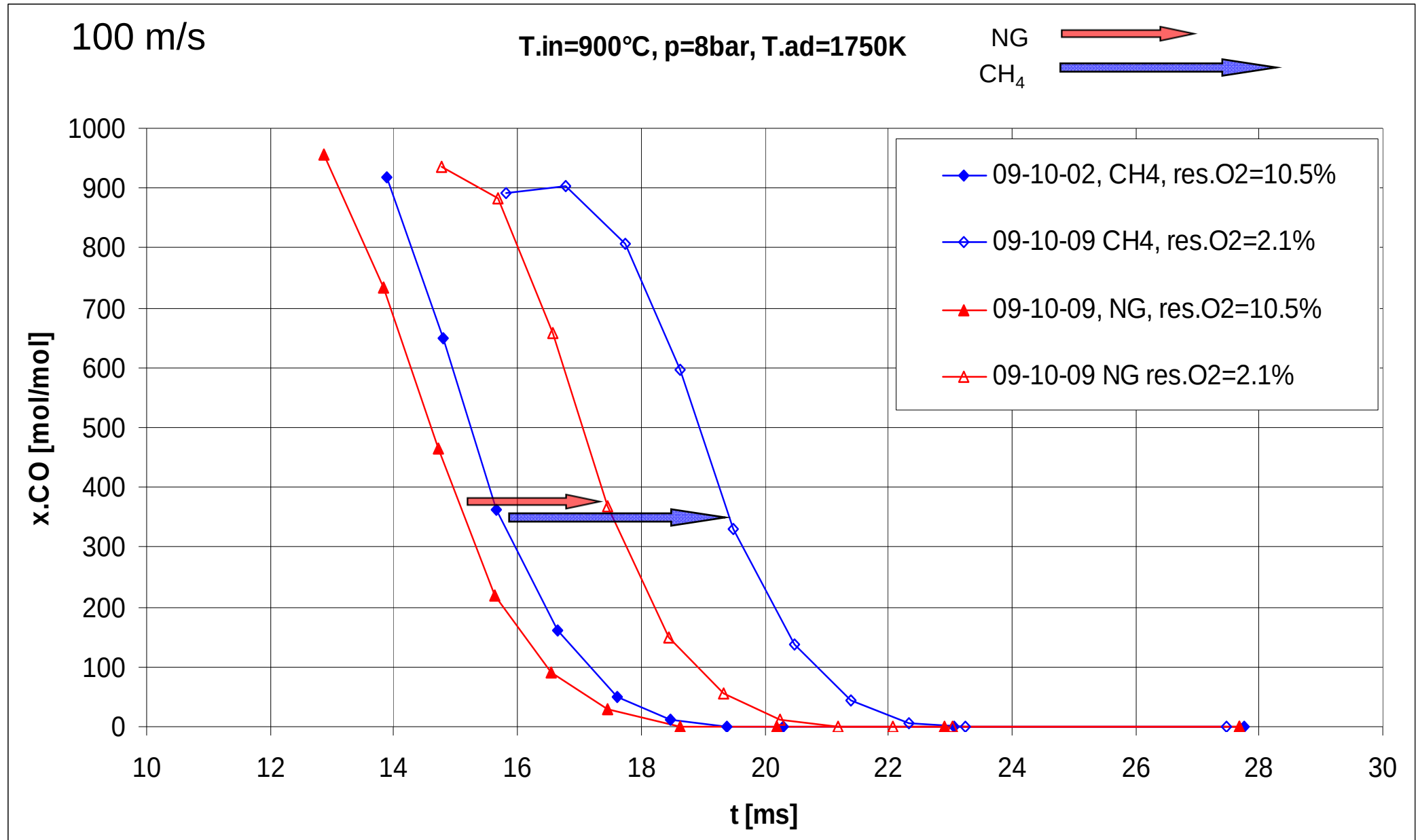
II

Combustion stabilized at nominal flame temperature with fixed oxidant composition

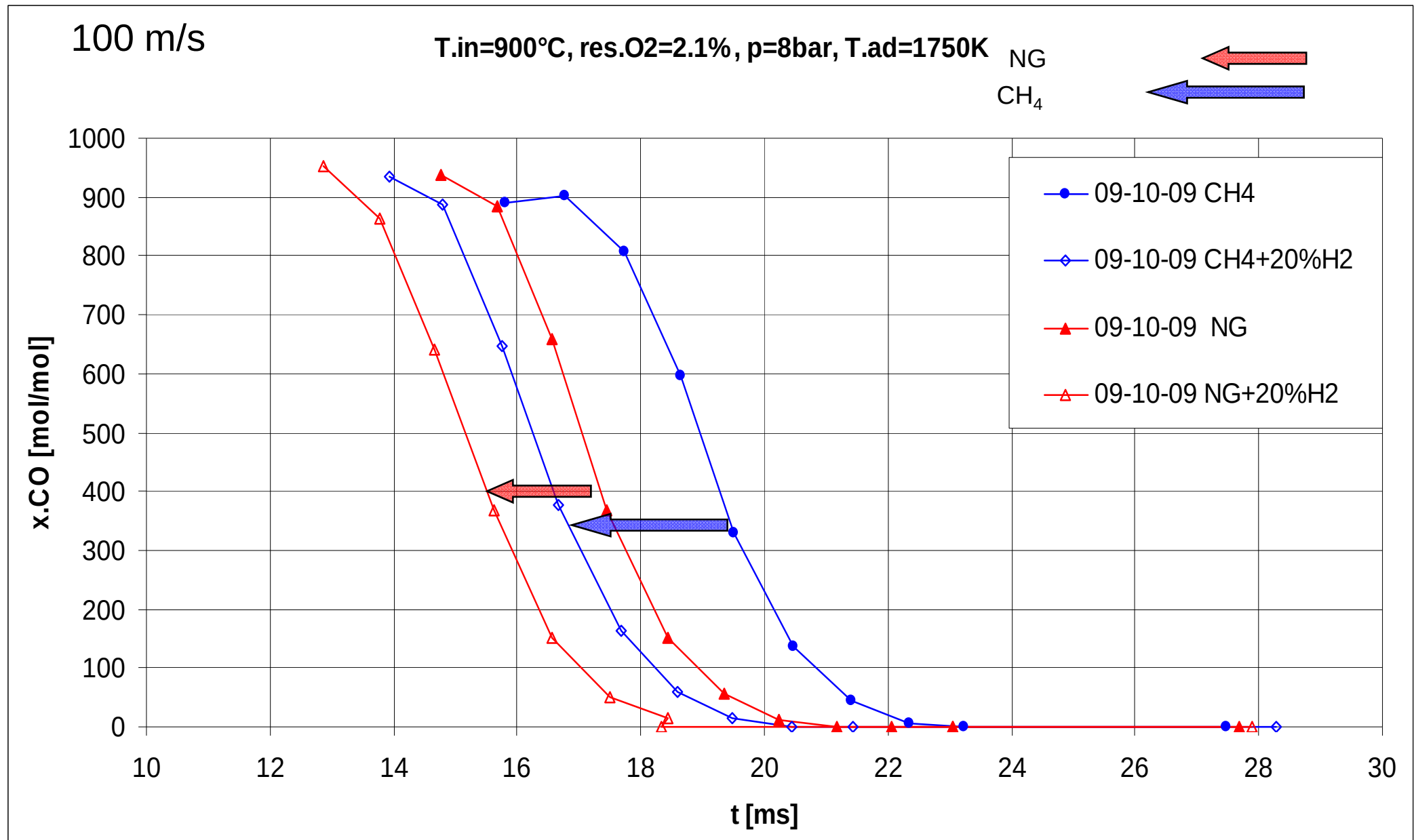
- a) CO concentration profile of flame front measured with axial probe.
- b) oxidant concentration reduced (FGR simulated)
- c) flame front moves downstream
- d) hydrogen (or syngas) added to fuel mixture until flame front moves upstream to original location.

How much H₂ (vol %) is required to attain the same flame position when O₂ content is decreased?

Influence of Oxidant at High Inlet Temperature

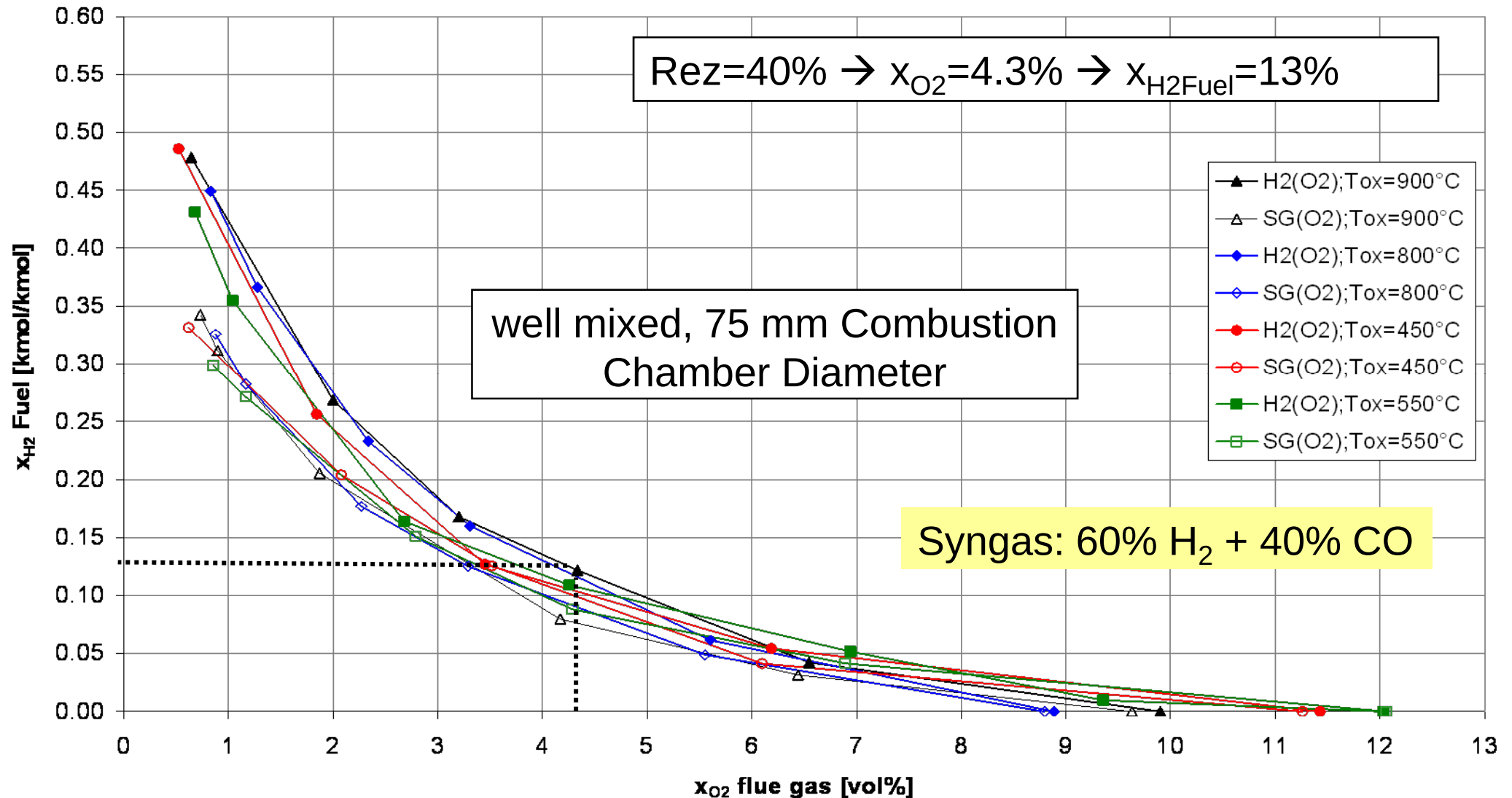


Influence of H₂ at High Inlet Temperature



FGR with syngas stabilization: Swiss Natural Gas Results (90.7% Methane, 4.5% Ethane, 1.3% C3+)

$p=8\text{bar}$, $T_{ad}=1750\text{K}$, $x_{CO}=\text{const.}=100\text{ppm}$



Conclusion I

FGR without H₂ stabilization

- Lean stability effected by FGR,
high CO levels when T_{ad} reduced by 50 K.

FGR with H₂ stabilization in fuel

- Better flame stability
- 20% H₂ at very high FGR yields same stability (CO)
as for CH₄ without FGR

Impact on NO_x Emissions

- NO_x increase with lower inlet O₂ content (for well mixed gases)
- H₂ addition has low impact on NO_x emissions

Conclusion II

FGR with syngas addition to methane

- Partial Conversion of CH_4 to syngas leads to same flame stability as CH_4 combustion without FGR
- lower volumetric concentrations of H_2 required as compared to adding H_2 alone
- inlet temperature plays minor role in required amount of H_2 for stabilization: main parameter is exit O_2 concentration (FGR rate)
- 13% H_2 compensates for 40% FGR rate (4.3 % O_2 in exhaust)

C2+ content in fuel reduces the effects of FGR on flame stability

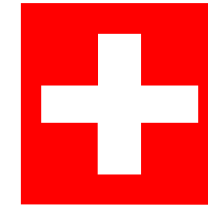
- Natural gas composition should play a significant role

Next steps

- 1. Design of CPO reactor given boundary conditions of a GT fuel delivery system**
- 2. Pilot Tests with CPO reactors at expected conditions**
- 3. Tests with various ethane-methane compositions to simulate natural gas combustion with FGR.**

Acknowledgements:

- Swiss Commission for Technology and Innovation (KTI)



- Bundesamt für Energie (BFE)

- Alstom (Switzerland)



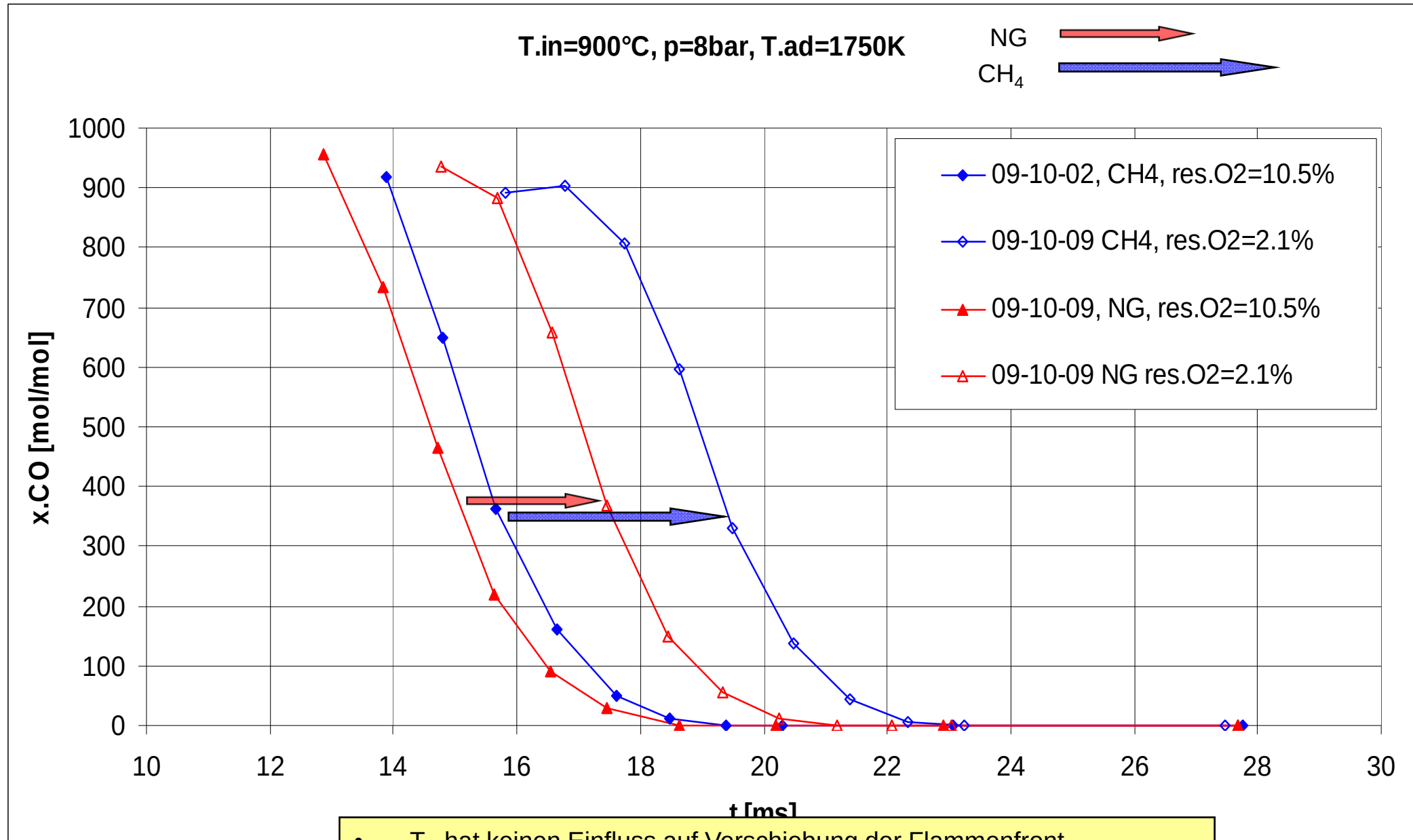
- Swisselectric Research



- Paul Scherrer Institute

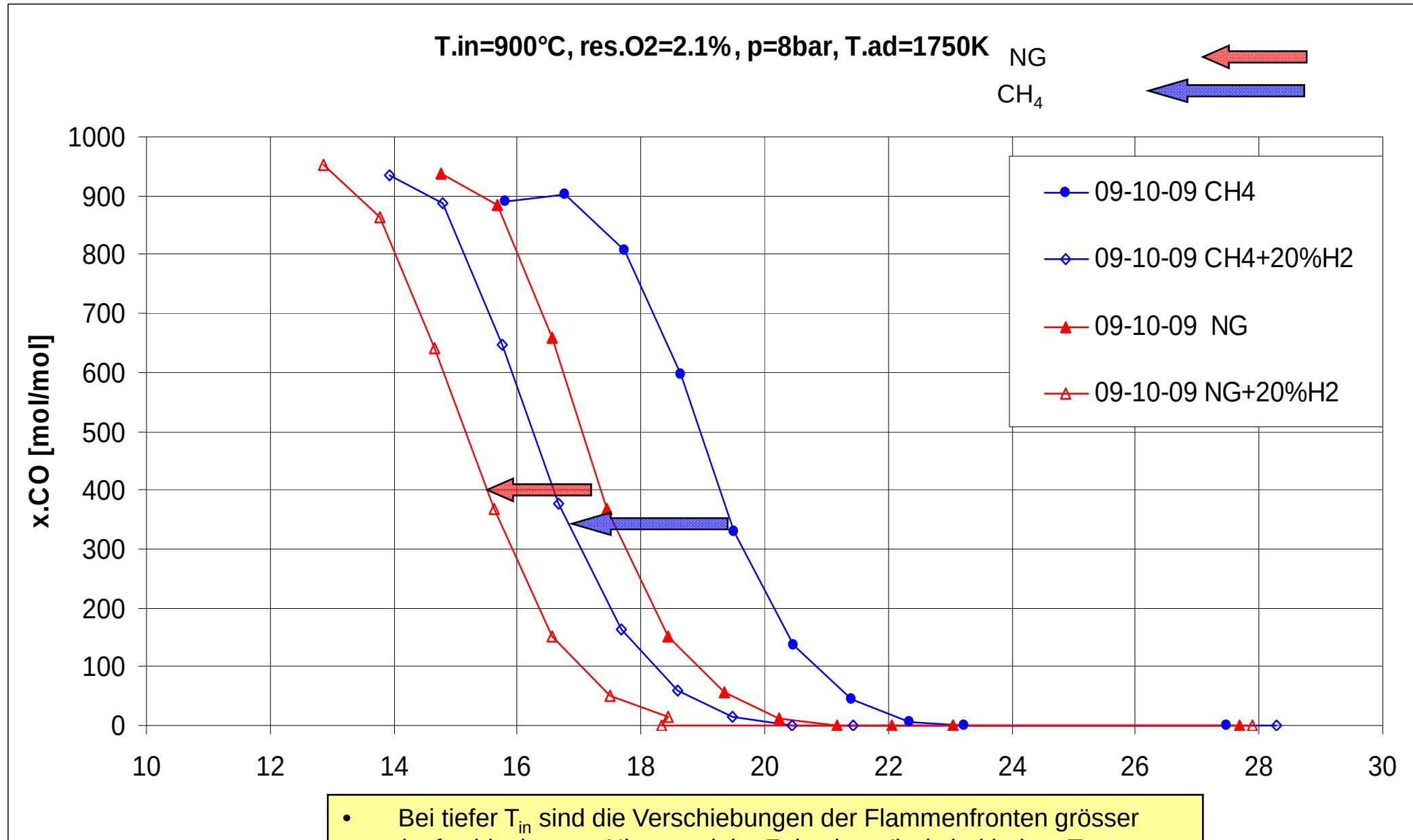


Influence of Oxidant at High Inlet Temperature



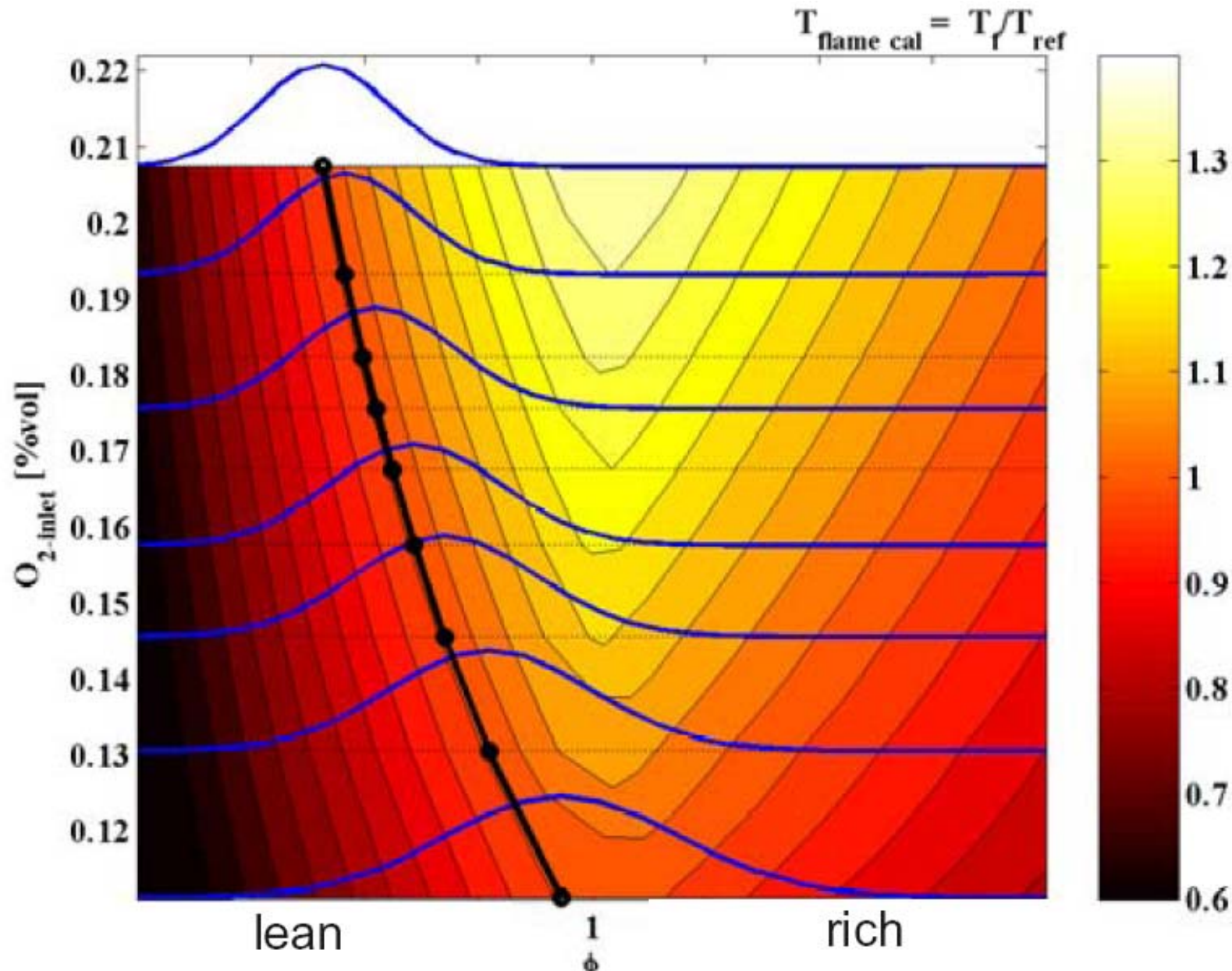
- T_{in} hat keinen Einfluss auf Verschiebung der Flammenfront.
- CH₄ Flammen sind empfindlicher auf wenig O₂ als NG Flammen

Influence of H₂ at High Inlet Temperature

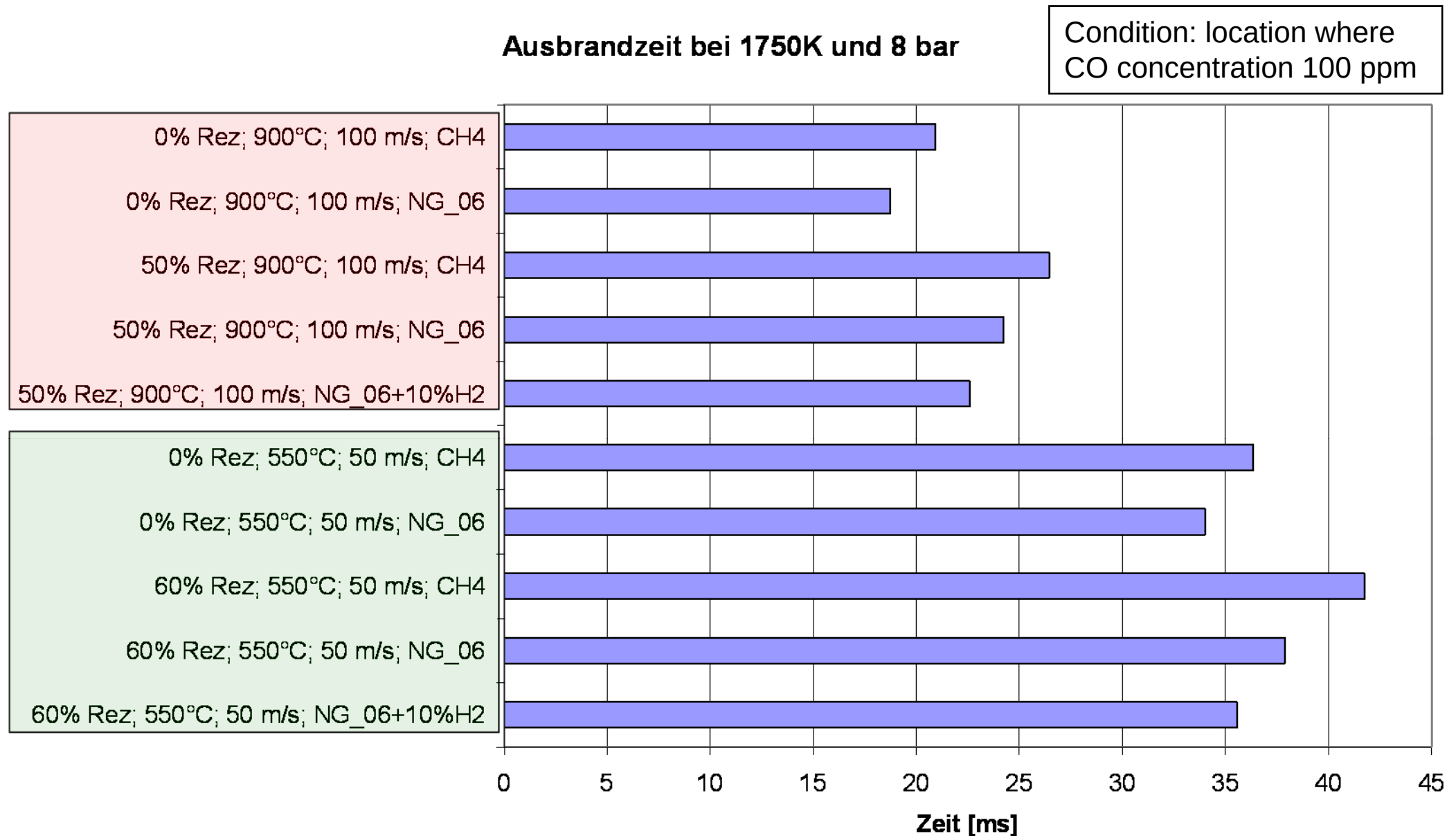


- Bei tiefer T_{in} sind die Verschiebungen der Flammenfronten grösser (auf schlechterem Niveau, siehe Zeitachsen!) als bei hohen T_{in}
- CH₄ Flammen sind empfindlicher auf H₂ als NG Flammen

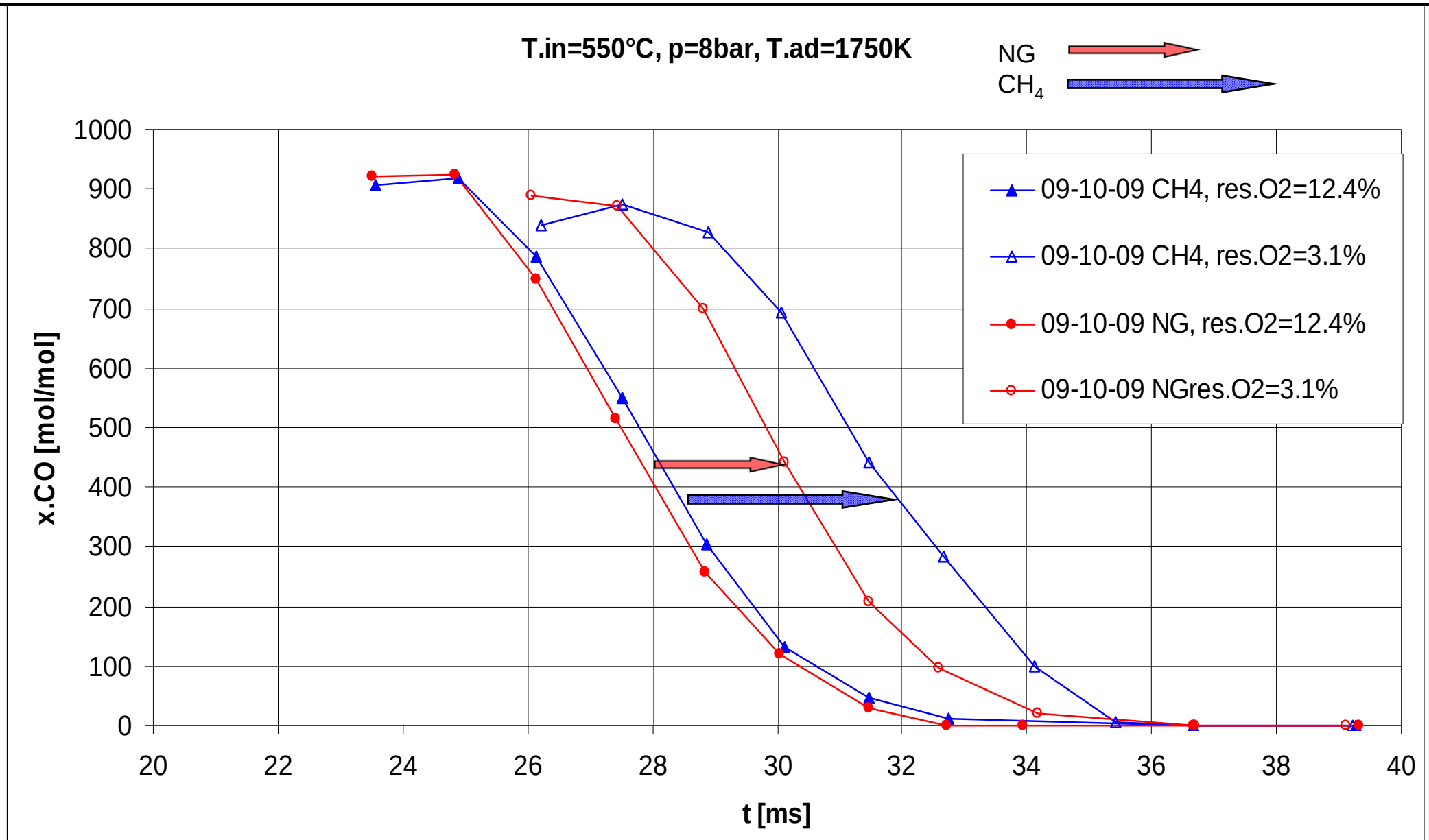
Influence of FGR on flame temperatures



Measurements: Time Required for Burnout in Combustor



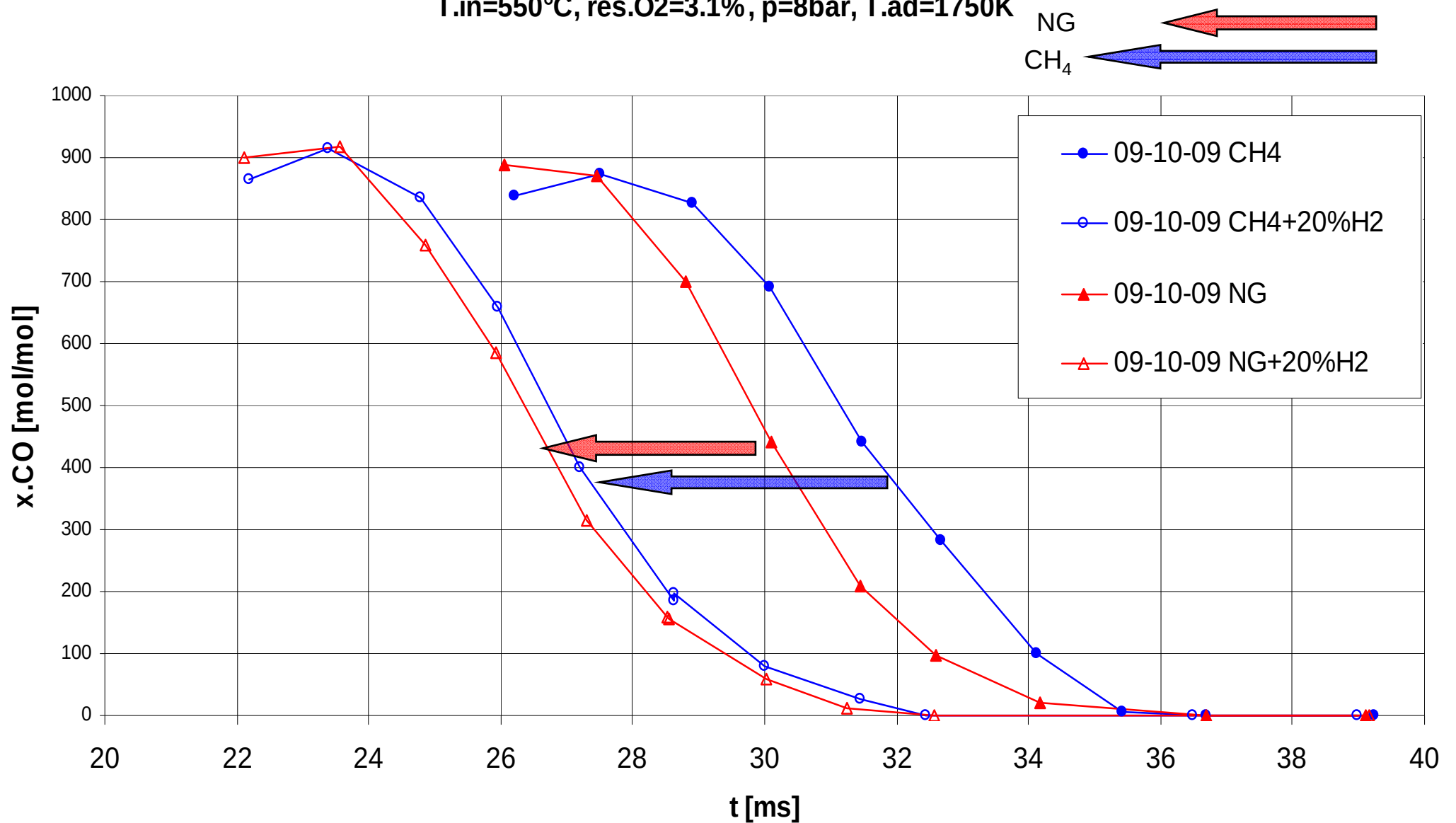
Influence of Oxidant at Low Inlet Temperature



Swiss Natural Gas
(90.7% Methane, 4.5% Ethane, 1.3% C₃+)

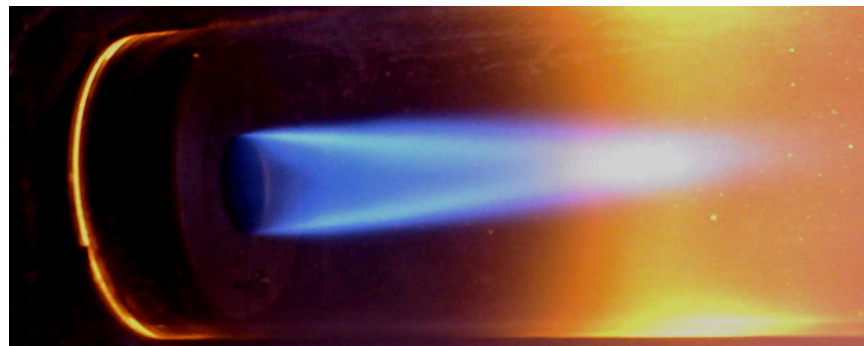
Influence of H₂ at Low Inlet Temperature

T.in=550°C, res.O2=3.1%, p=8bar, T.ad=1750K



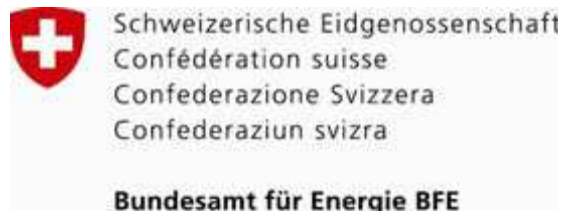
Swiss Natural Gas
(90.7% Methane, 4.5% Ethane, 1.3% C3+)

Lean Premixed Combustion of Syngas at Gas Turbine Relevant Conditions



S. Daniele, P. Jansohn, K. Boulouchos

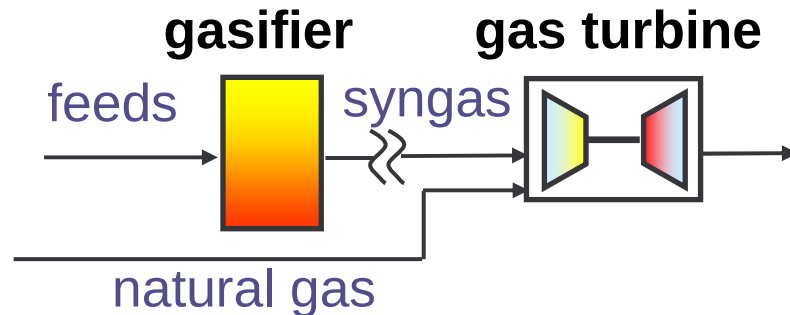
Financial support:



ALSTOM

Motivation

IGCC: Integrated Gasification Combined Cycle



feeds: coal, oil, biomass,
tars, coke/resid, waste

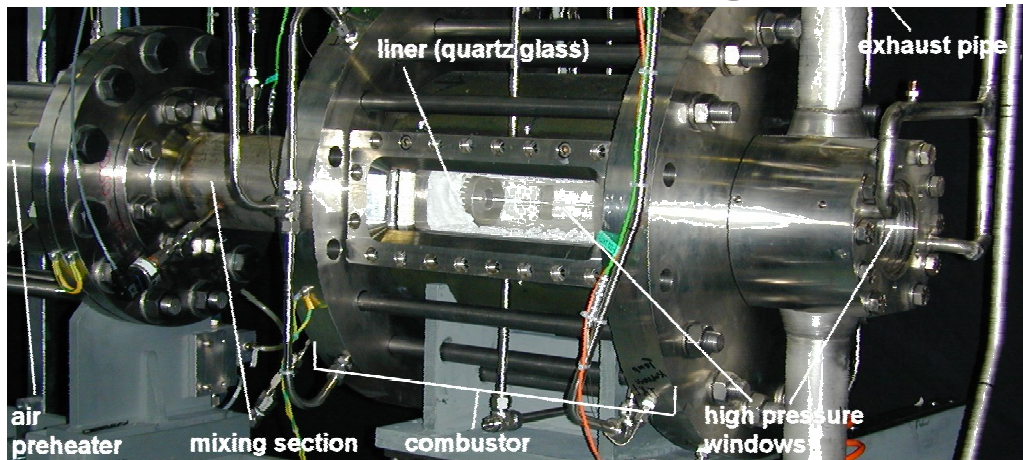
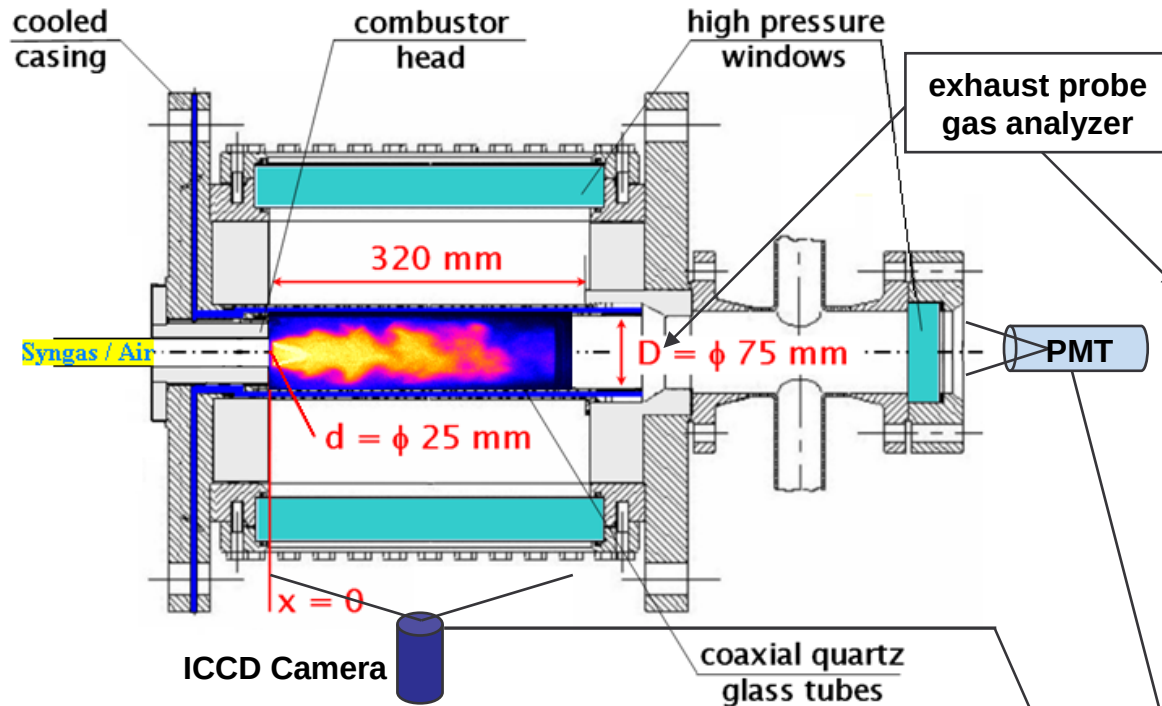
syngas: H_2 , CO , N_2 , CO_2 , H_2O

can we fire with syngas a gas turbine using lean premixed technology?

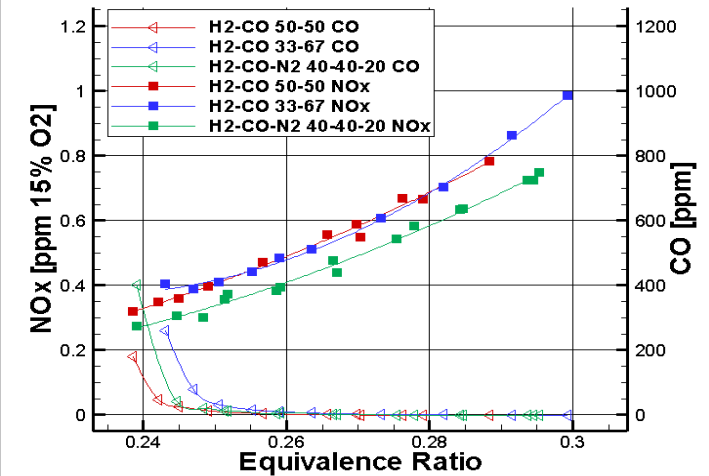
we are investigating on:

Mixture		Vol %	Simulated Process	Experimental conditions	
1	$\text{H}_2\text{-CO-CH}_4$	20-20-60	natural gas co-firing	U_{bulk} [m/s]	40 – 150
2	$\text{H}_2\text{-CO}$	50-50	oil gasification	T_{in} [°C]	150 - 600
3	$\text{H}_2\text{-CO}$	33-67	coal gasification	P [bar]	1 – 20
4	$\text{H}_2\text{-CO-N}_2$	40-40-20	biomass (air blown) gasification	ER	0.20 to 0.70

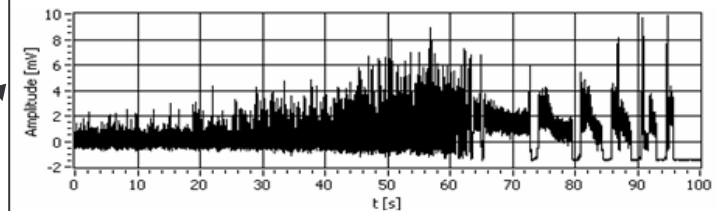
Experimental Setup



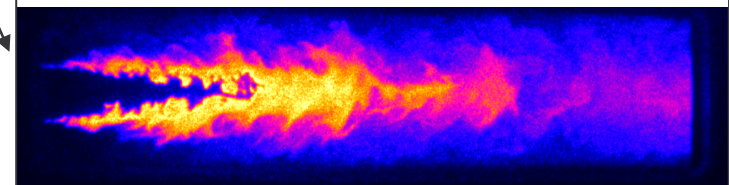
NO_x & CO emissions



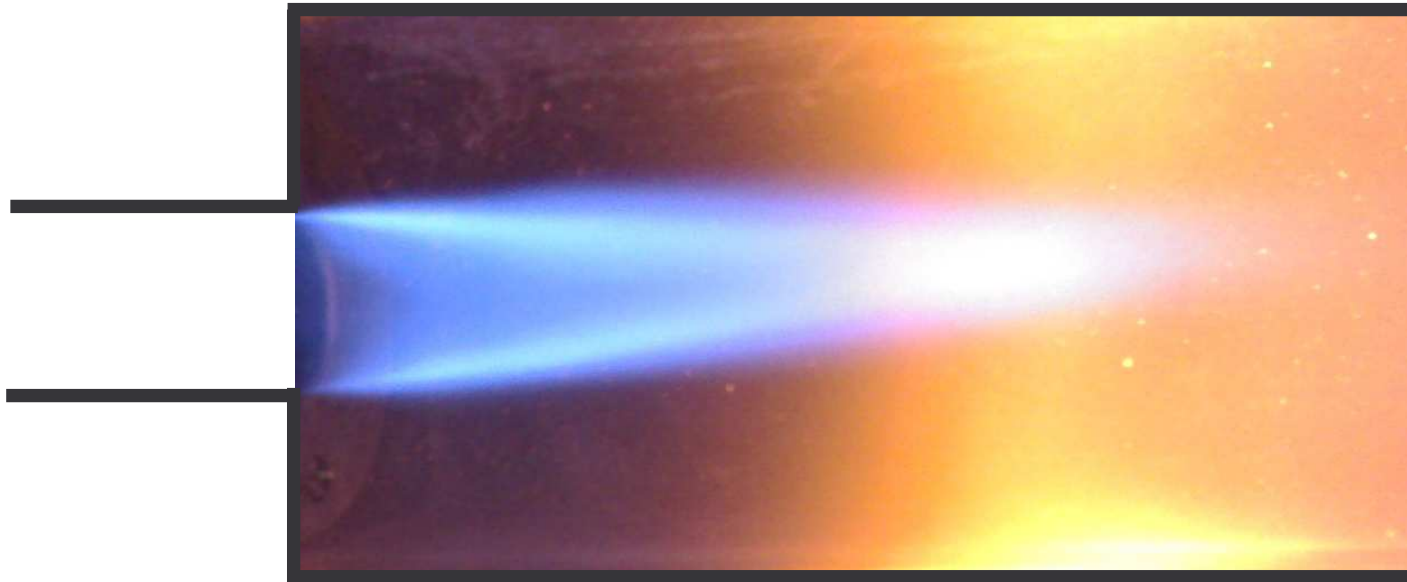
OH time series



OH-PLIF Images

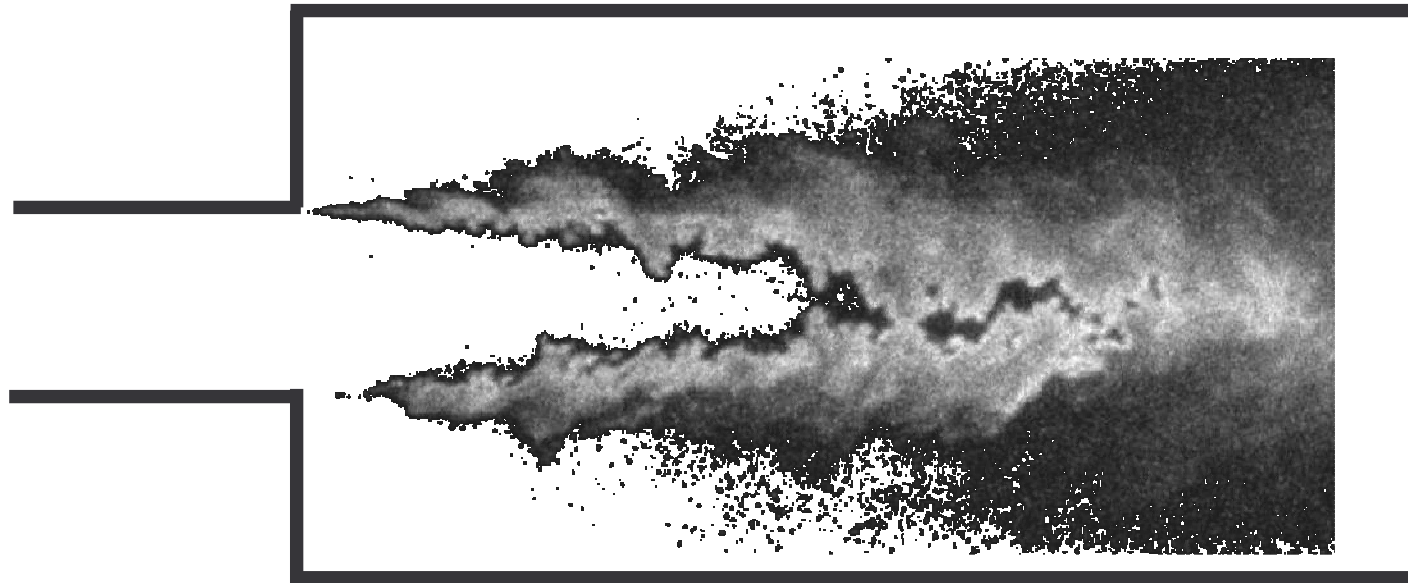


Flame Speed



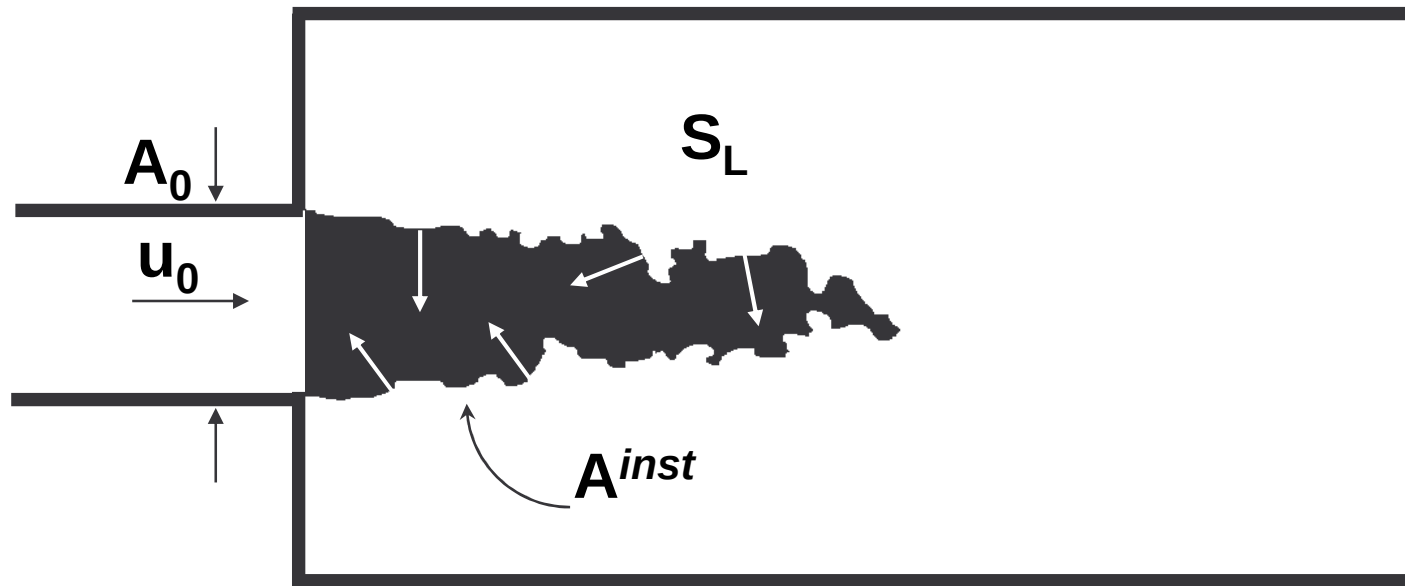
coworker: Mr. D. Erne

Flame Speed



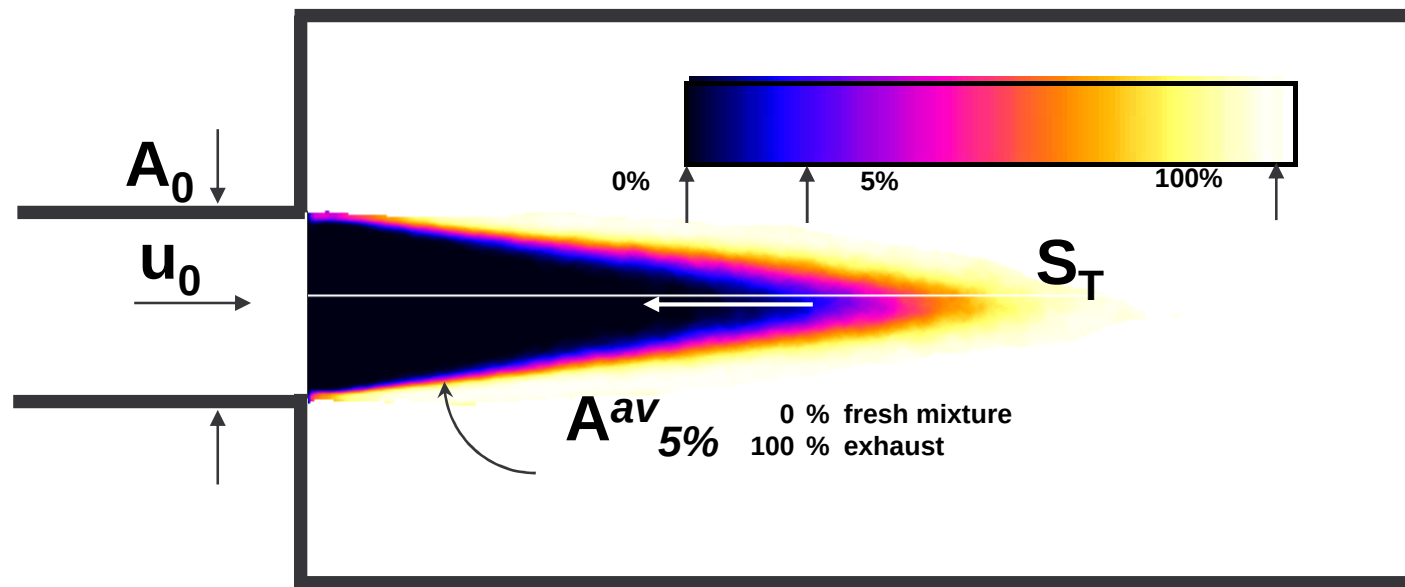
coworkers: Dr. W. Kreutner, Dr. R. Bombach, Dr. A. Denisov

Flame Speed



$$\rho_0 A_0 u_0 = \rho_f A^{inst} S_L$$

Flame Speed



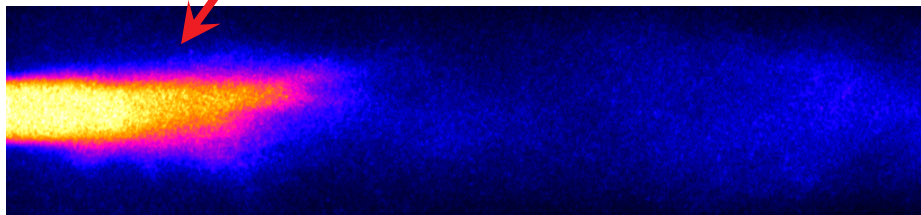
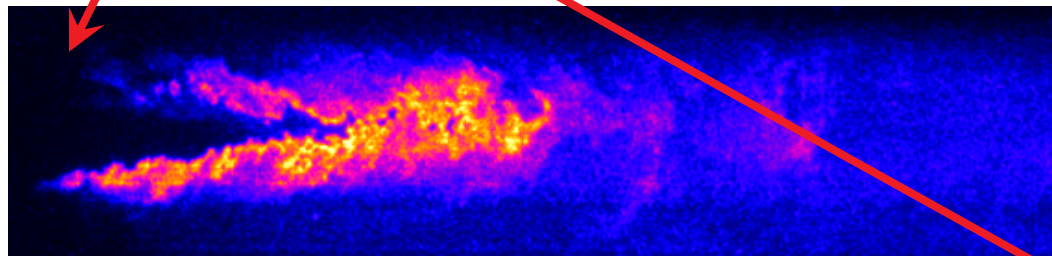
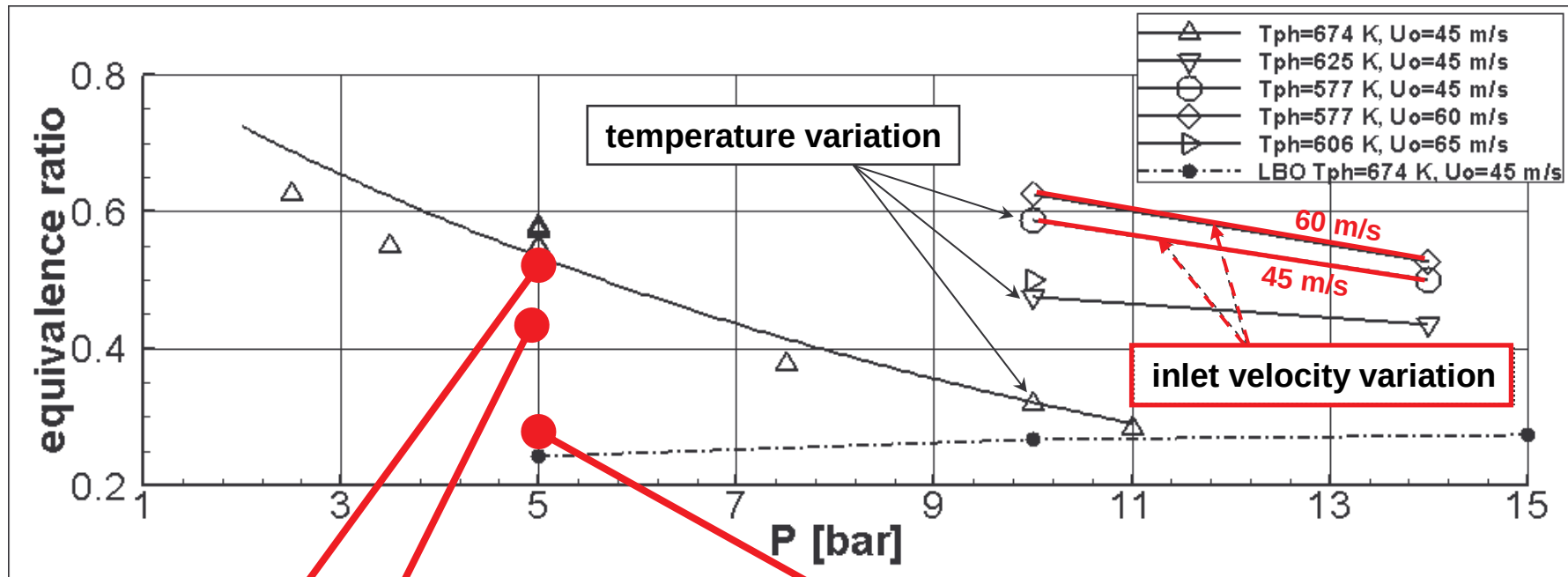
$$\rho_0 A_0 u_0 = \rho_f A^{inst} s_L$$

$$\rho_0 A_0 u_0 = \rho_f A^{av} s_T$$

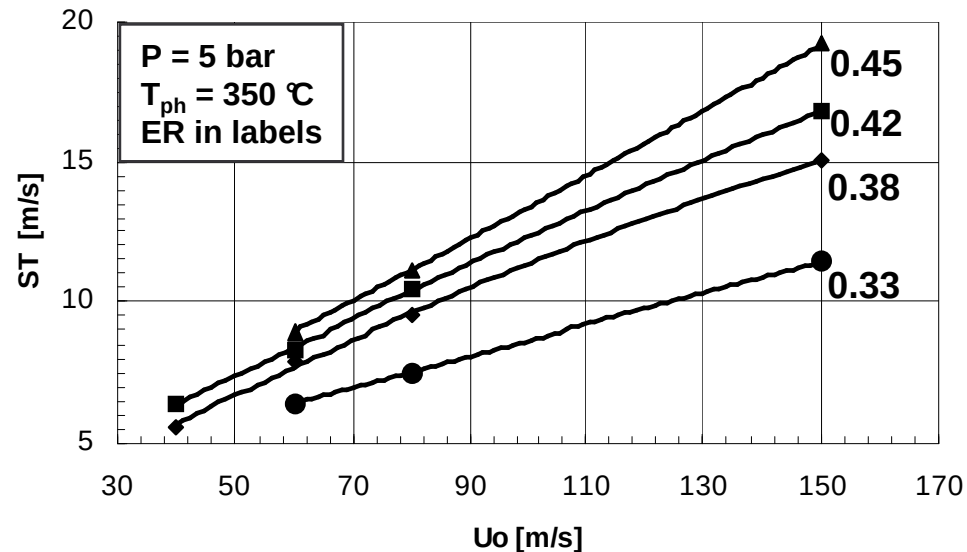
$$s_T = \frac{A_0}{A^{av}} u_0$$

s_T : global consumption
per unit time

Operational Window



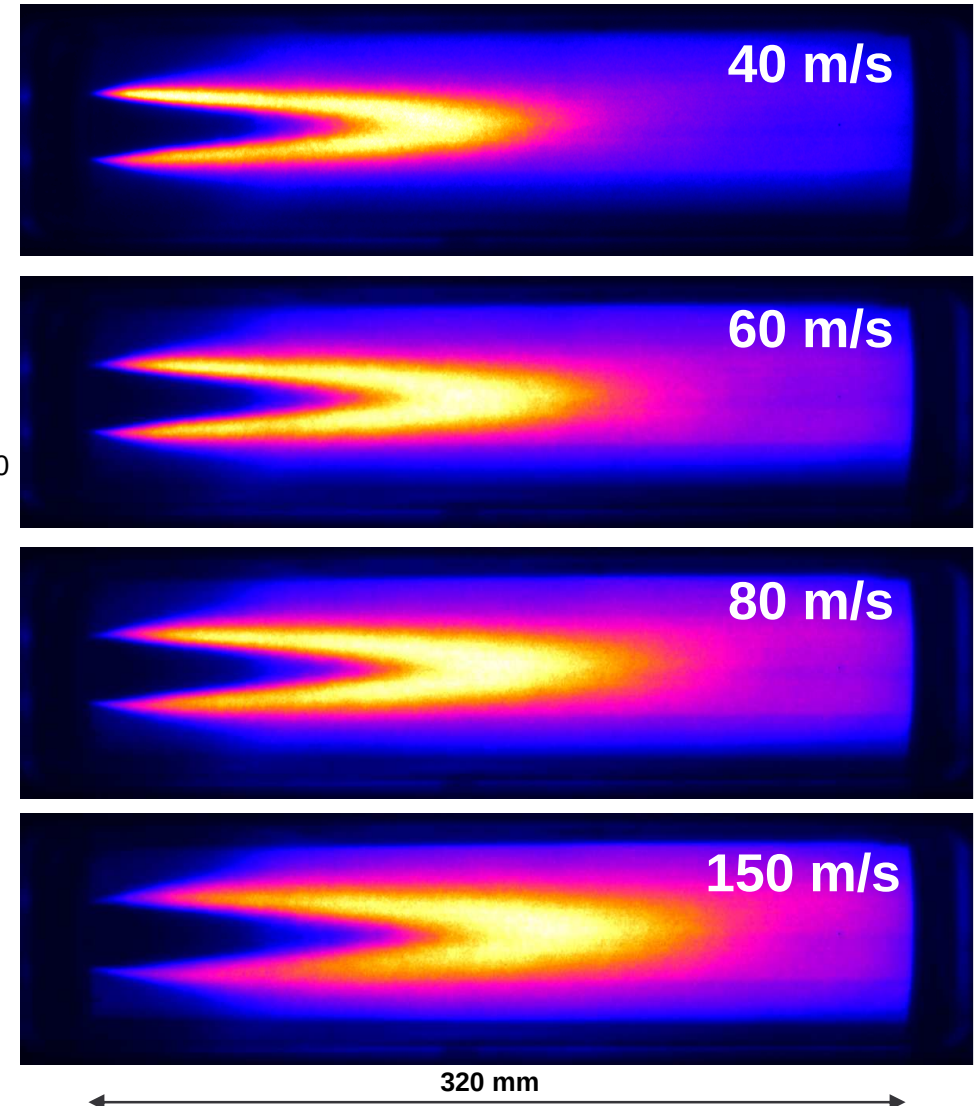
Turbulent Flame Speed – Inlet Velocity Dependence



- S_T increases proportionally to u_0
- Average flame front almost not affected
- Instantaneous flame front must be more corrugated

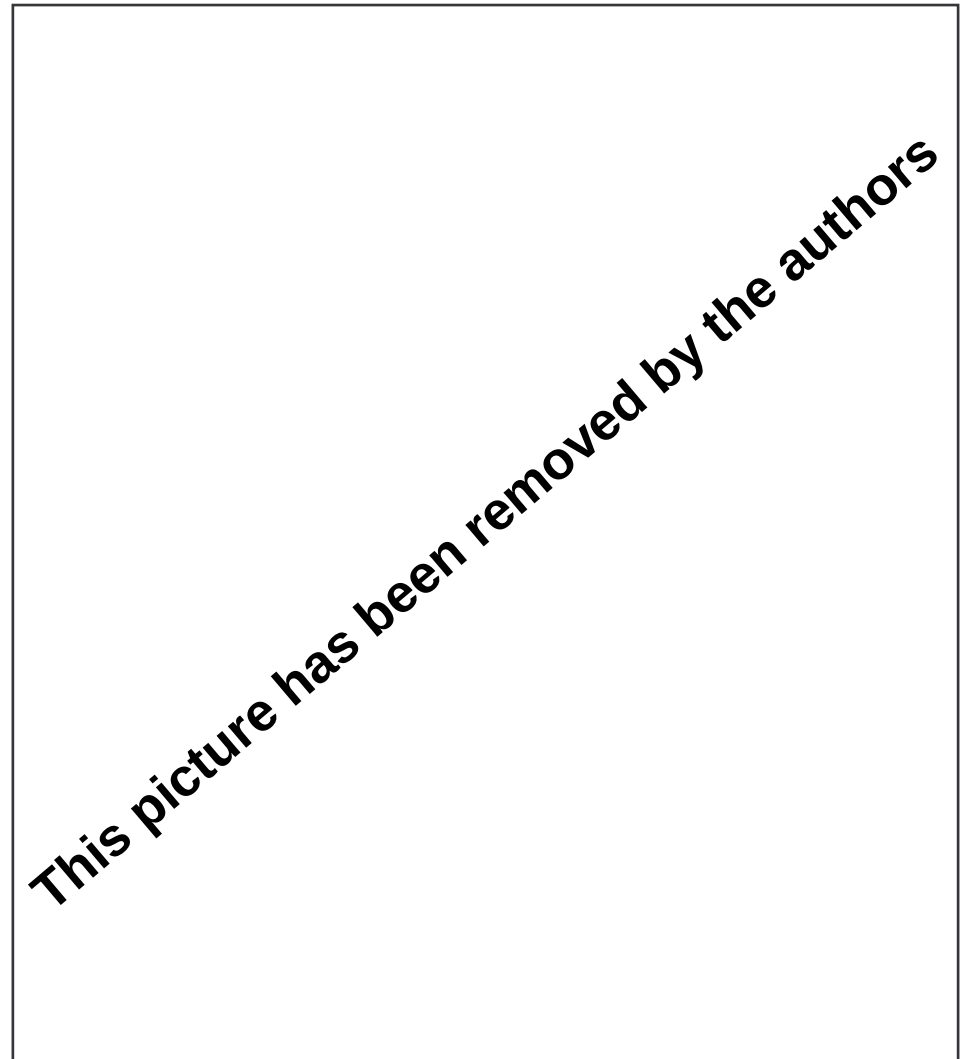
$$s_T = \frac{A_0}{A^{av}} u_0$$

$$s_T = \frac{A^{in}}{A^{av}} s_L$$



Normalized Turbulent Flame Speed

- co-firing NG and air-blown SG (@ 60% - 40%) leads to an increase of S_T/S_L of 15%
- firing pure SG increases dramatically the ratio S_T/S_L depending on the H_2 content
- S_T/S_L values for diluted H_2 can be an order of magnitude higher of the ones of NG



Conclusions

- Flash Back is one of the major issues when firing GTs with high H_2 containing fuels
- Flash Back propensity is not reduced by higher inlet velocities
- Values of normalized S_T increase dramatically with the H_2 content
- For pure H_2 S_T/S_L values can be one order of magnitude higher than the ones of CH_4
- Co-firing of SG and NG requires minor efforts
- Design of a flexible engine capable of operations fueling NG, SG and eventually pure H_2 represents a major challenge

Methane– and Propane–Fueled Catalytic Microreactors

S. Karagiannidis, I. Mantzaras, K. Boulouchos

***Paul Scherrer Institute, Combustion Research Laboratory,
Combustion Fundamentals Group, CH-5232 Villigen-PSI
Aerothermochemistry and Combustion Systems Laboratory,
Swiss Federal Institute of Technology Zurich, CH-8092 Zurich***

Sponsors :

- Paul Scherrer Institute (PSI)
- Swiss Federal Institute of Technology Zurich (ETHZ)
- CCEM-CH “Computational Modeling for Small Scale Converters”

Outline

- **Background – Motivation**

- Catalytic microreactors for portable power generation

- **Method of approach**

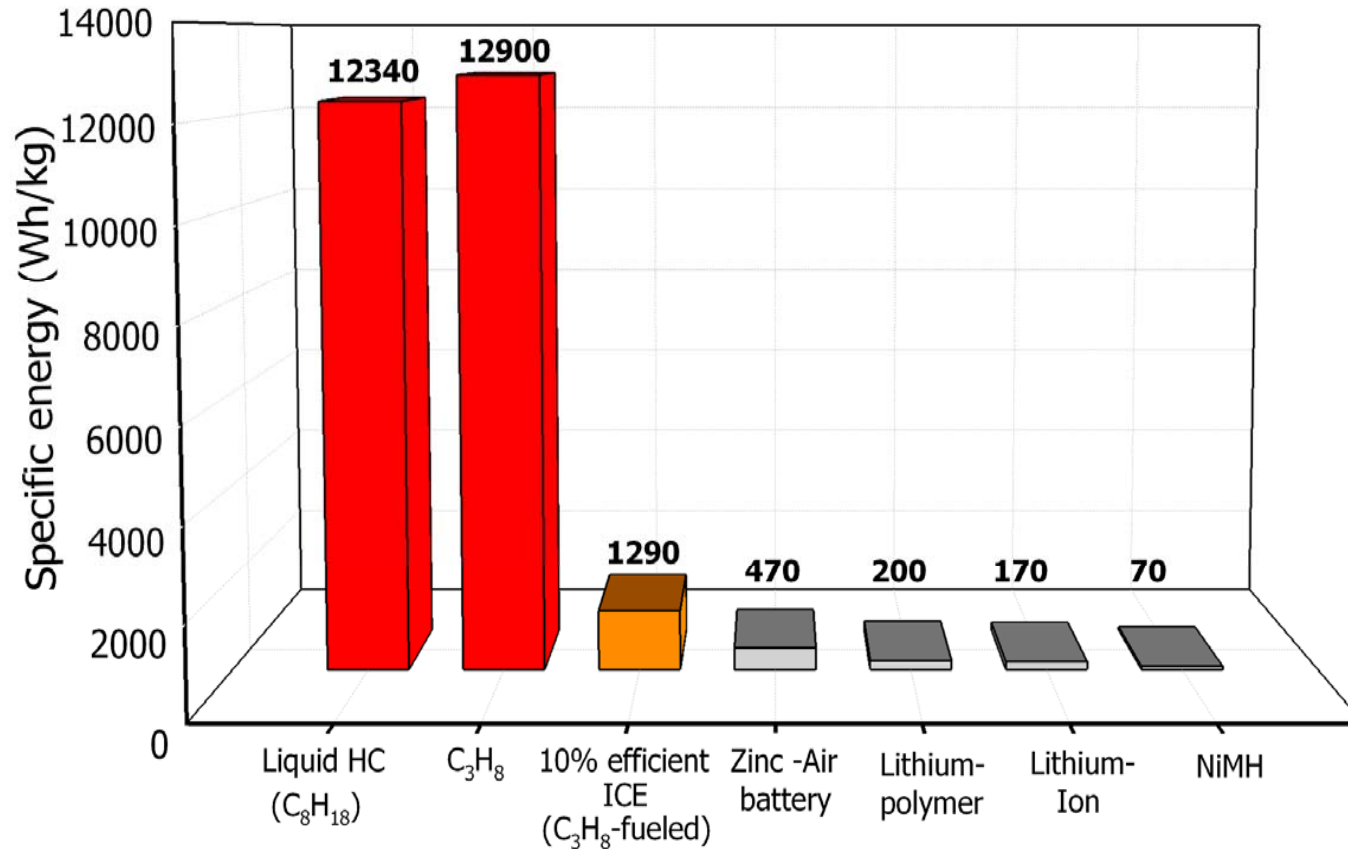
- Optically accessible catalytic reactor
- Numerical model

- **Results**

1. Lean hetero-/homogeneous combustion of propane on platinum
2. Stability maps for hetero-/homogeneous combustion
3. Impact of gas-phase chemistry
4. Effect of pressure
5. Radiation heat transfer

- **Conclusions**

Background – Motivation

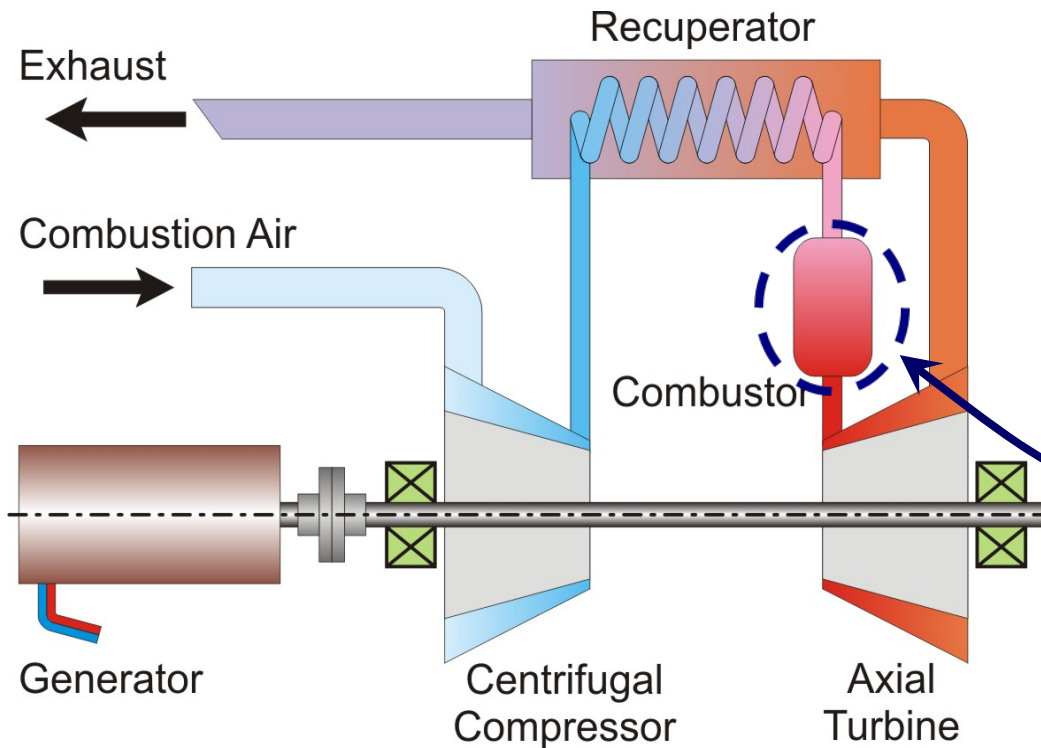


- **Ever increasing need for on-the-go electric power**

Fernandez-Pello., PCI 29, 883-899, 2002

- **Micro IC-engines can cover future needs in portable power generation**

Background – Motivation



- **ETH – INIT project :**
Ultra-high-energy-density converter for portable power
- **GT – based power unit/ catalytic microreactor**

$P_{th} : \geq 1000 \text{ W}$

Target efficiency : $> 10\%$

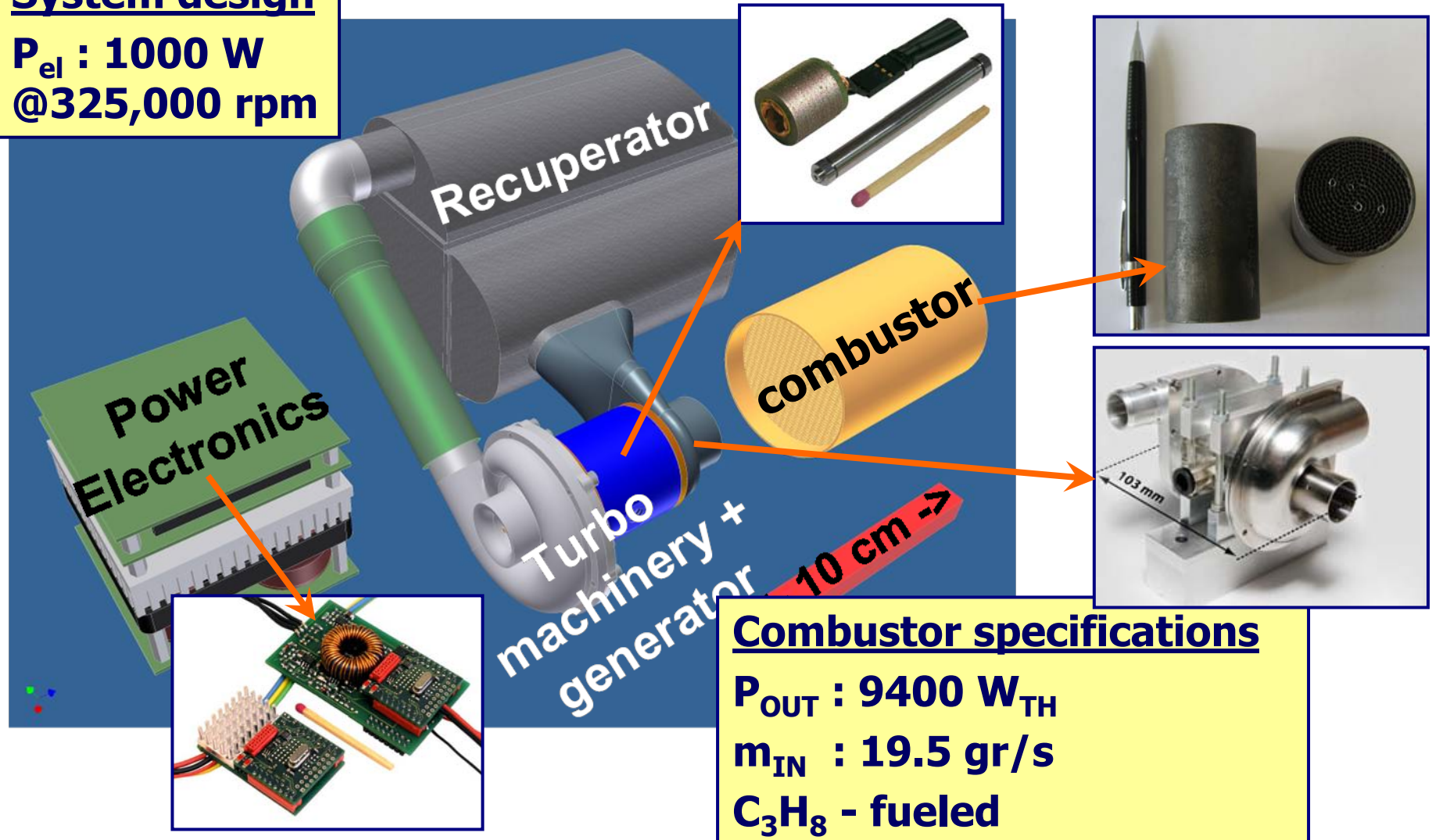
$P_{max} : 5 \text{ bar}$

Turbine Inlet Temperature: 1215 K

Background – Motivation

System design

$P_{el} : 1000 \text{ W}$
@325,000 rpm



Combustor specifications

$P_{OUT} : 9400 \text{ W}_{TH}$

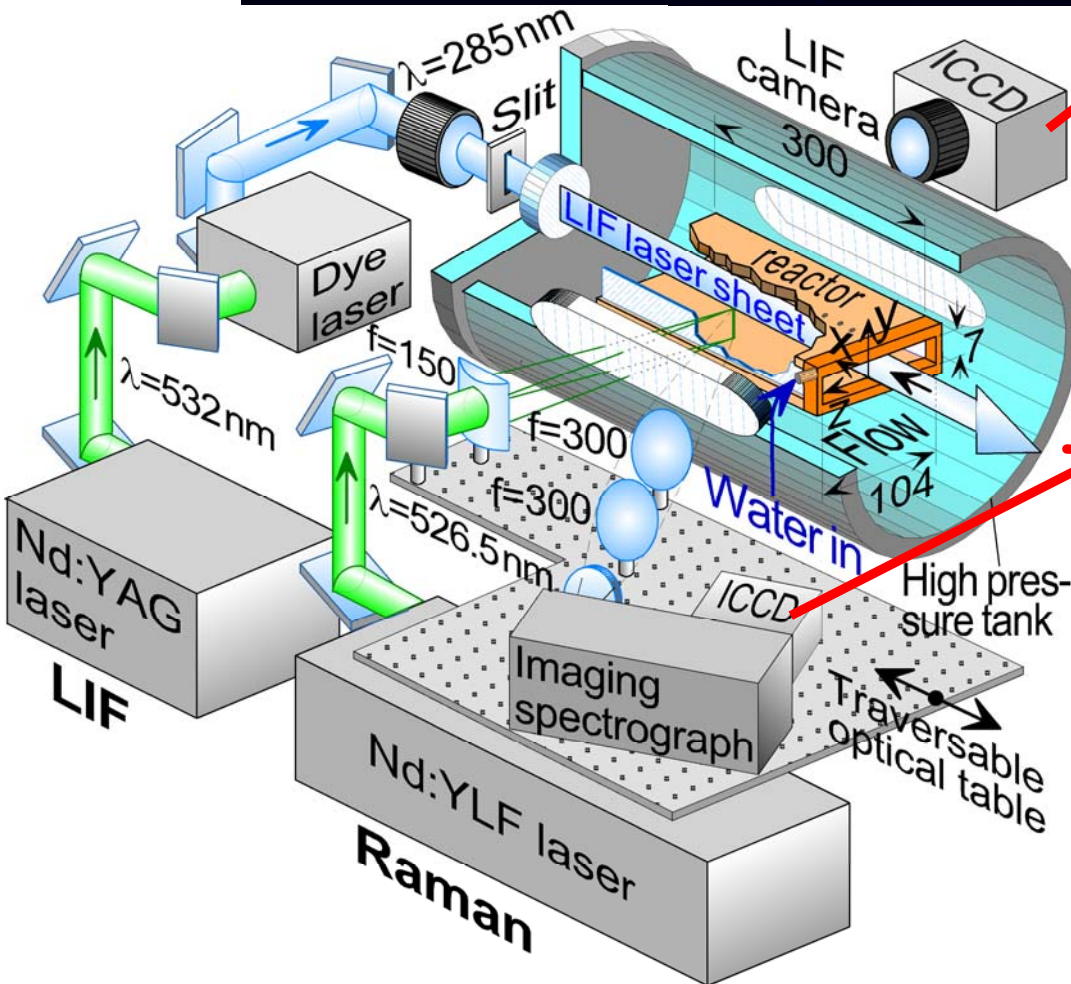
$m_{IN} : 19.5 \text{ gr/s}$

C_3H_8 - fueled

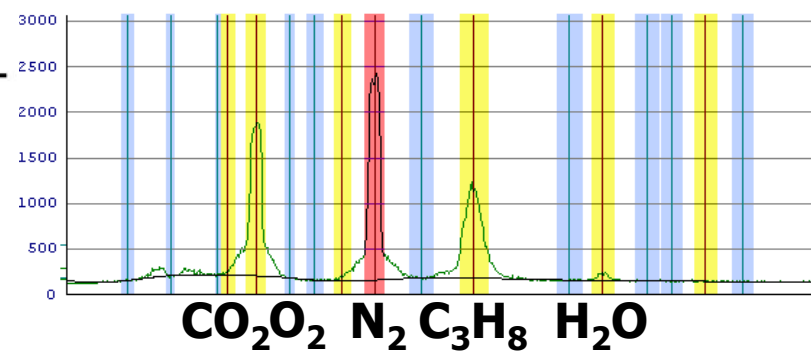
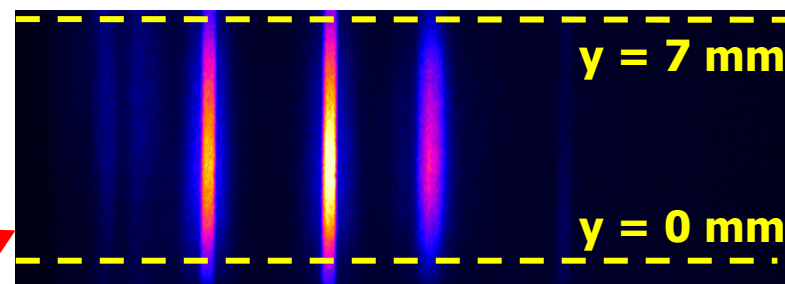
Optically accessible catalytic reactor

$y = 7 \text{ mm}$

$y = 0 \text{ mm}$

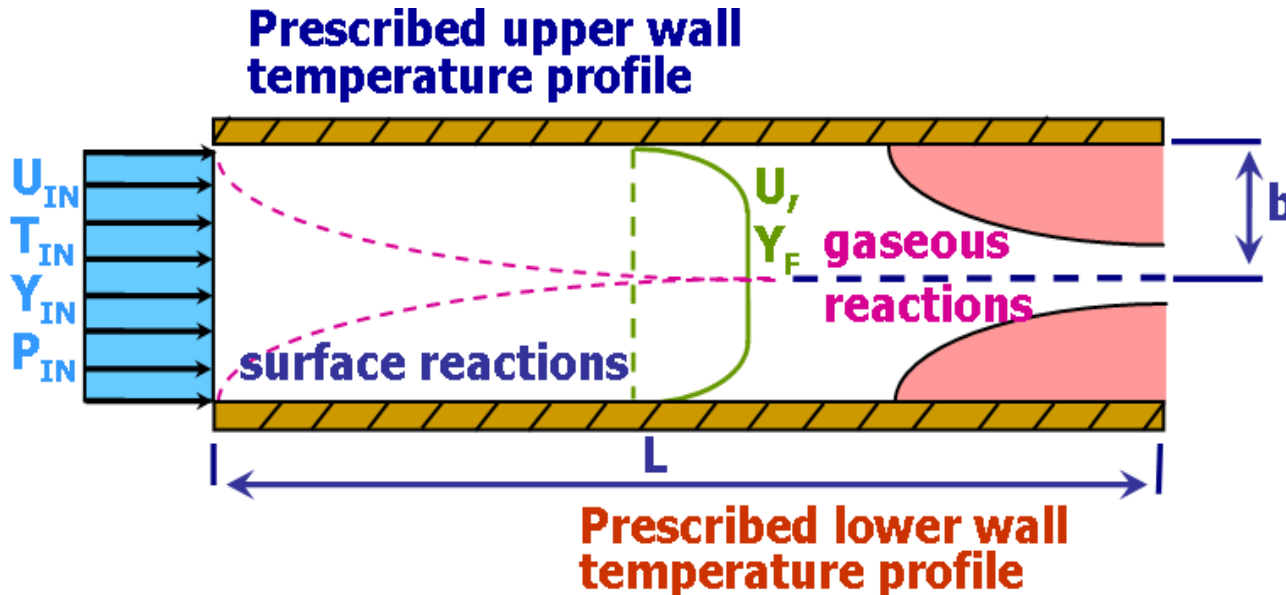


CO_2O_2 N_2 C_3H_8 H_2O



R. Bombach, 2009

Numerical models



Planar geometry

$L_{CH} = 300 \text{ mm}$

$2b_{CH} = 7 \text{ mm}$

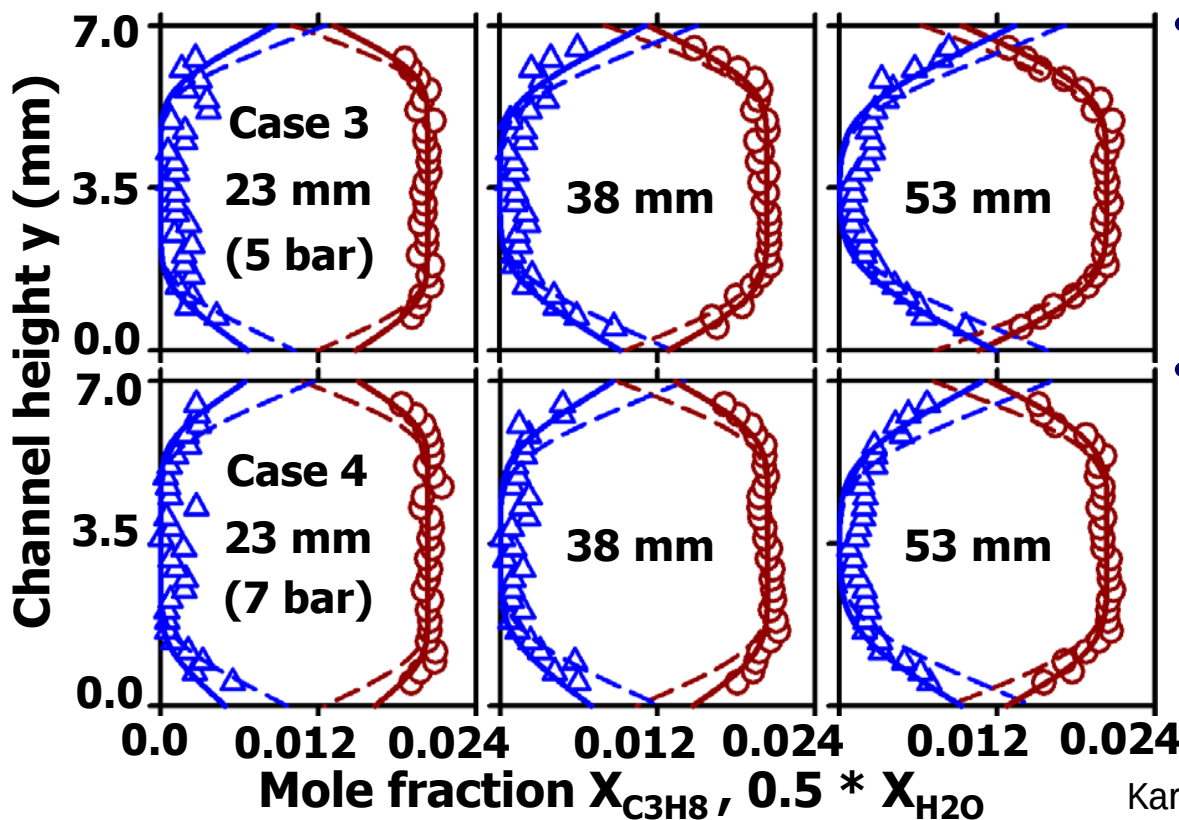
Numerical model for optically accessible reactor

- **2-D full elliptic model** (Mantzaras/Schneider/Karagiannidis 2000-2007)
- **Global catalytic reaction step**
 - Garetto et al. 2004, C_3H_8 on Pt
- **Detailed gas-phase reaction scheme**
 - Qin et al. 2000, optimized C_3 mechanism (70 species, 463 reactions)

Results – Heterogeneous C_3H_8 experiments

Pressure – corrected catalytic reaction step

$$\dot{S}_{C_3H_8} = 93.2 T_W^{1.15} \left(\frac{p}{p_0} \right)^{-n} [C_3H_8]^{1.15} \exp(-71.12/RT_W), n = 0.4 \pm 0.03$$



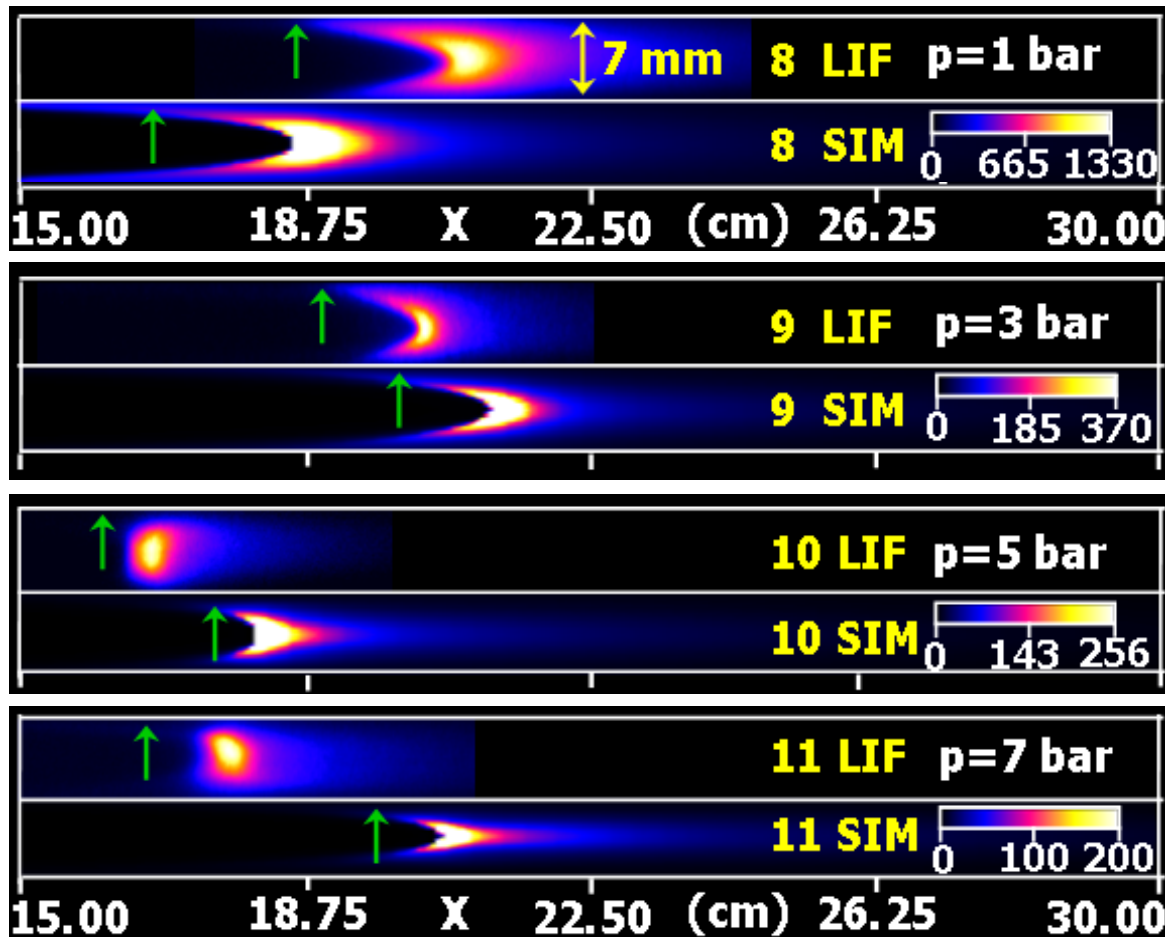
- At elevated pressures, combined effects of increasing C_3H_8 reactivity and O_2 partial pressure need to be accounted for
- Near-wall fuel excess and heterogeneously produced water affect gas-phase ignition

C_3H_8 (○, —)

H_2O (Δ, —)

Karagiannidis et al., PCI 32, 1947-1955, 2009

Results – Homogeneous C_3H_8 ignition

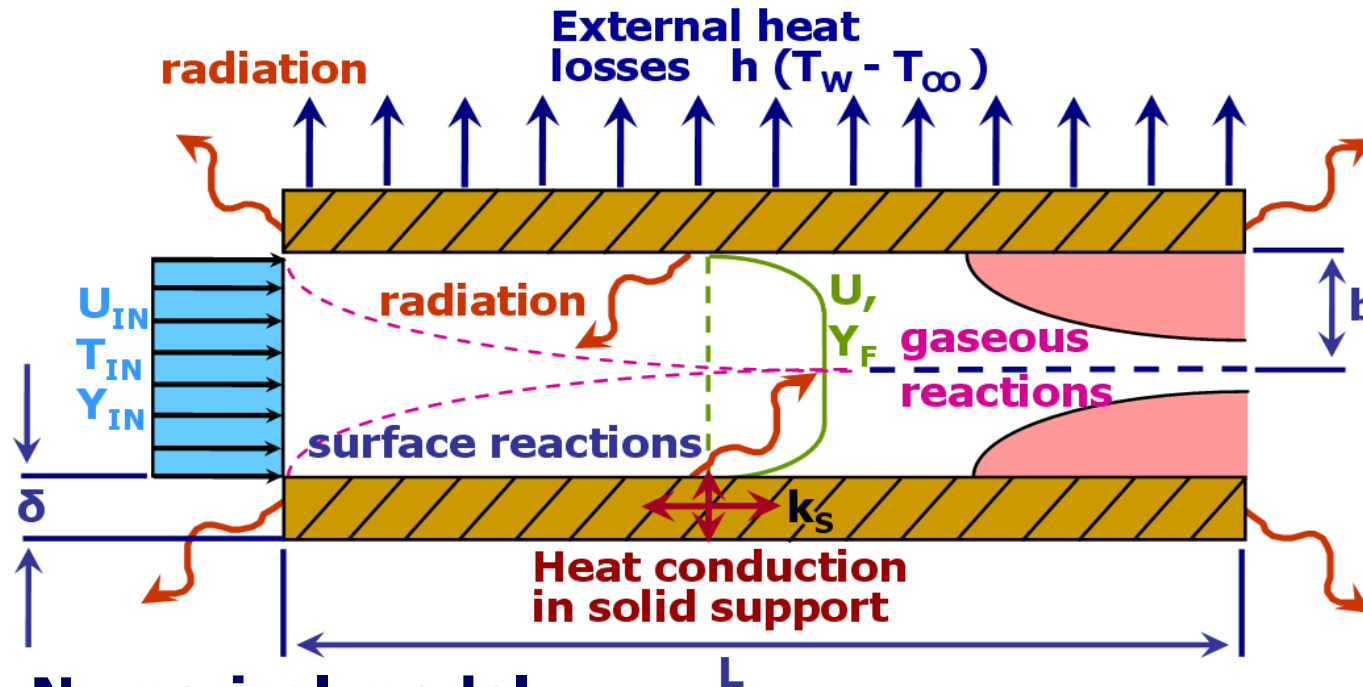


- Measured homogeneous ignition distances reproduced within 10% for $p \leq 5$ bar

- Simulations at $p = 7$ bar overpredict gas-phase ignition distance by $\sim 20\%$

- Green arrows -> homogeneous ignition
- OH levels in ppmv

Method of approach / numerical model



Planar geometry

$$L_{\text{CHANNEL}} = 10 \text{ mm}$$

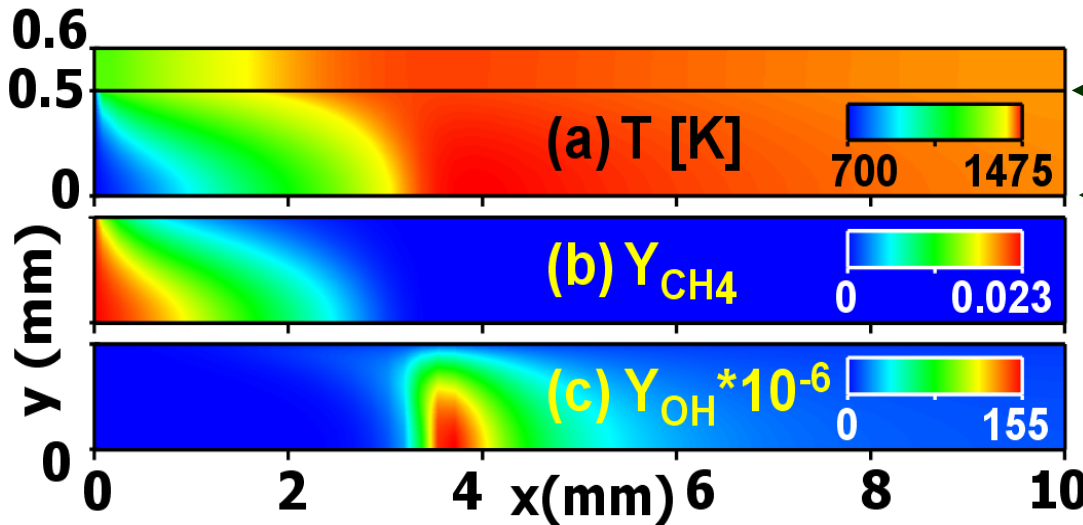
$$2b_{\text{CHANNEL}} = 1 \text{ mm}$$

$$\delta_{\text{CHANNEL}} = 0.1 \text{ mm}$$

Numerical model

- **2D full elliptic, steady model for gas and solid**
(Mantzaras / Schneider 1998-2006)
- **Detailed hetero-/homogeneous reaction schemes**
 - Deutschmann et al. 2000, CH_4 on Pt
 - Warnatz et al., 1996 C1/H/O (Reinke et al. CNF 2005, $1 \text{ bar} \leq p \leq 16 \text{ bar}$)
- **Diffuse-gray net radiation model** ($\epsilon_{\text{INLET}} = \epsilon_{\text{OUTLET}} = \epsilon_{\text{CHANNEL}}$)

Results and discussion



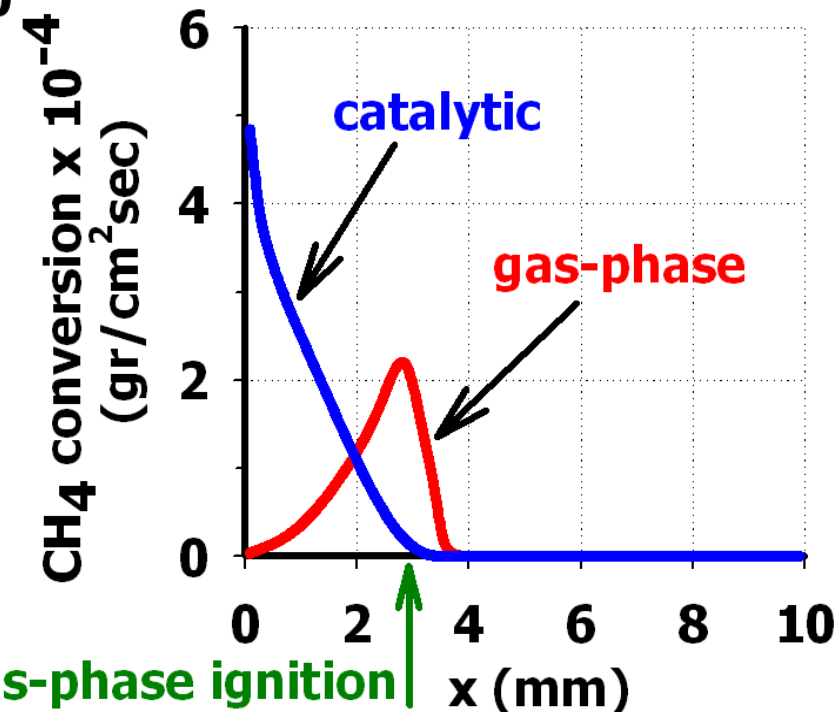
← Gas-solid interface

← Symmetry plane

$\phi = 0.4$, $p = 5$ bar, $U_{IN} = 0.3$ m/s,
 $T_{IN} = 700$ K, $k_S = 2$ W/mK,
 $h = 2$ W/m²K, $\varepsilon = 0.6$

Impact of gas-phase chemistry

- U_{IN} is of order ~ 1 m/s
- Residence time is long enough, favoring gas-phase reactions

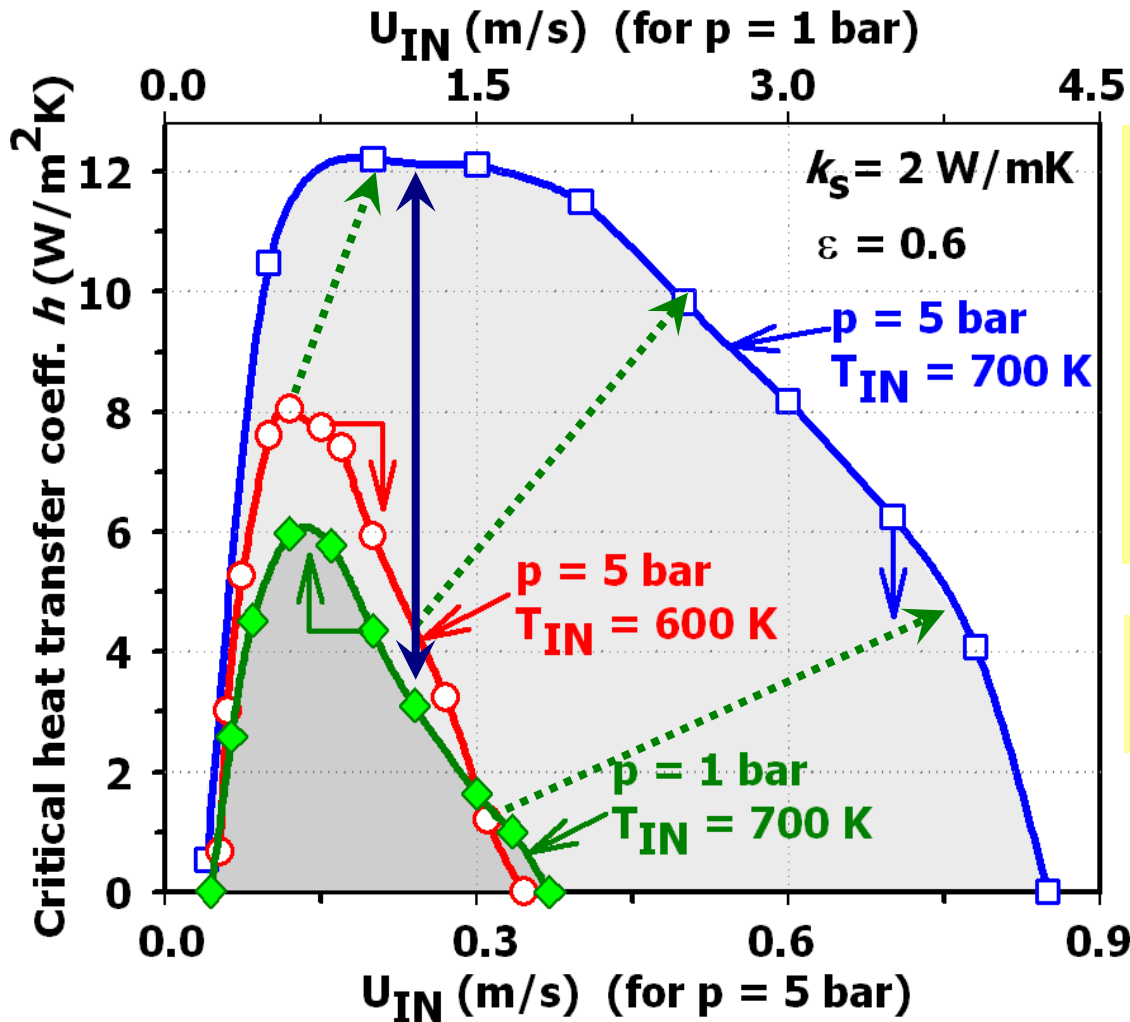


Stability maps

- **Combustion stability diagrams constructed; independent variables:**
 - **External heat transfer coefficient, h**
 - **Inlet velocity, U_{IN}**
 - **Solid thermal conductivity, k_s**
- **Predictions for fixed equivalence ratio ($\phi=0.40$), pressures of 1 and 5 bar, and two different mixture preheats ($T_{IN}= 600$ and 700 K)**
- **Stability limits obtained numerically via one-parameter continuation, until critical extinction heat transfer coefficient was reached**
- **20 processors used for elaborate parametric studies**

Stability maps

Effect of feed pressure p_{IN} and temperature T_{IN} / stability limits



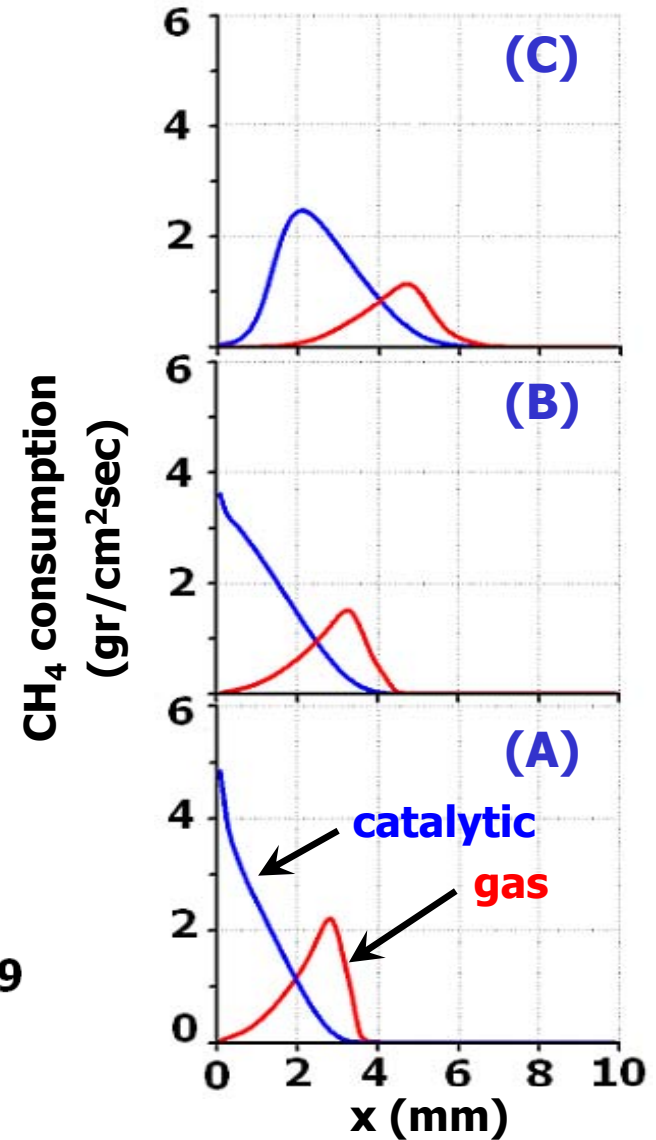
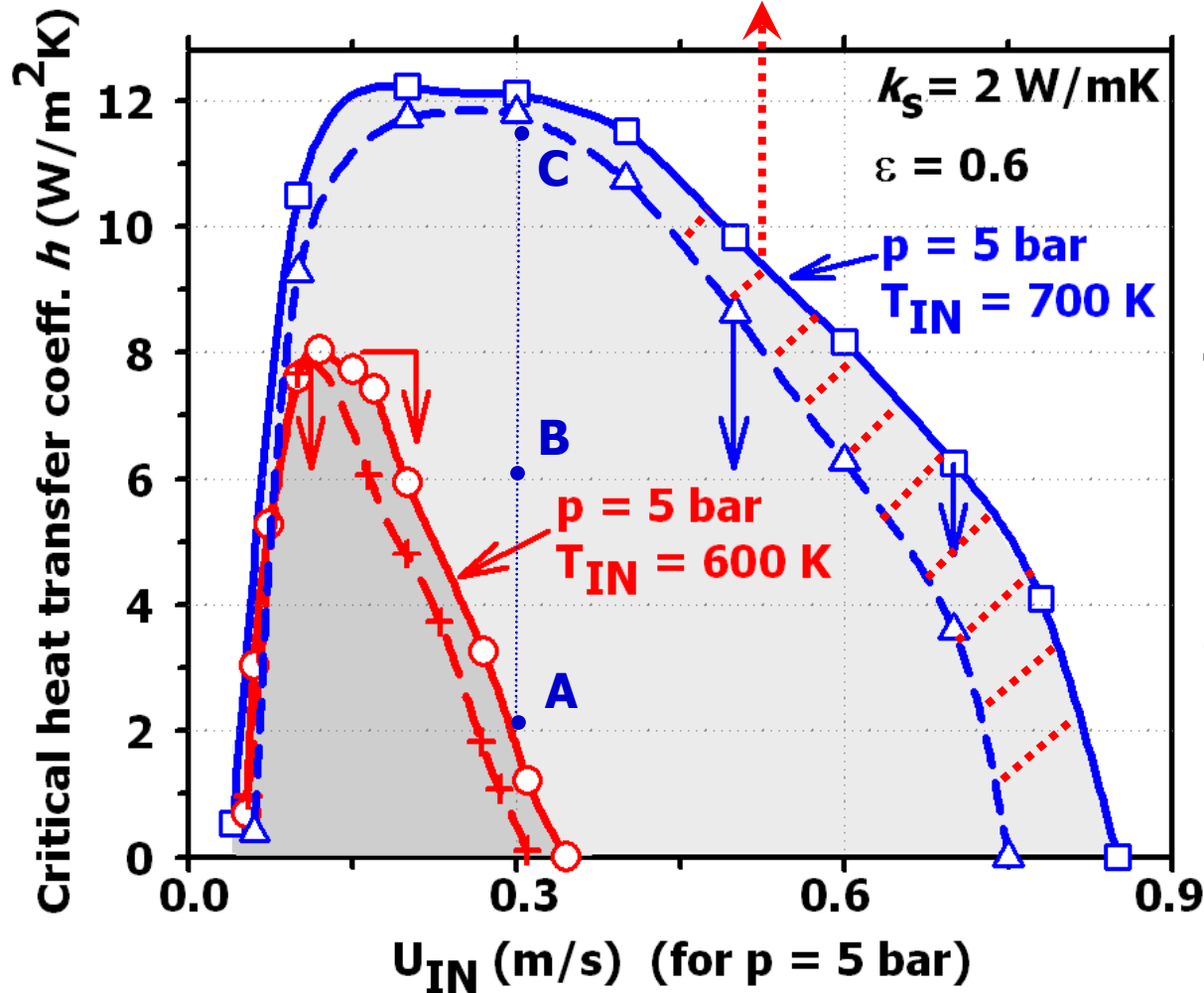
- **Stability limits at 1 bar narrower than 5 bar at $p_{IN} U_{IN} = \text{constant}$;**

- Gas-phase reactivity: $\sim p^{+1.0}$
- Catalytic reactivity: $\sim p^{+0.47}$ (Reinke et al., CNF 2004)

- **Feed preheat necessary for extended stability**

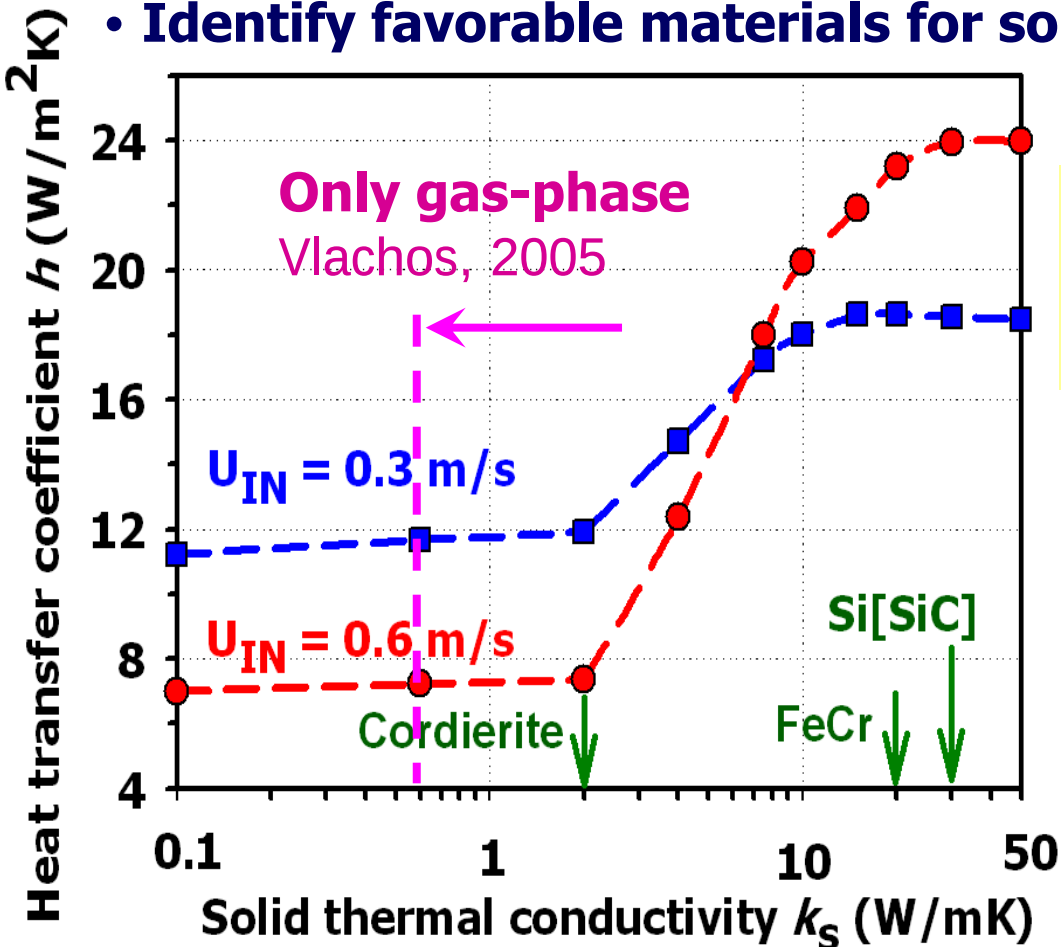
Stability maps / effect of gas-phase chemistry

Gas-phase : strong
impact on blowout limits



Impact of solid thermal conductivity

- Identify favorable materials for solid



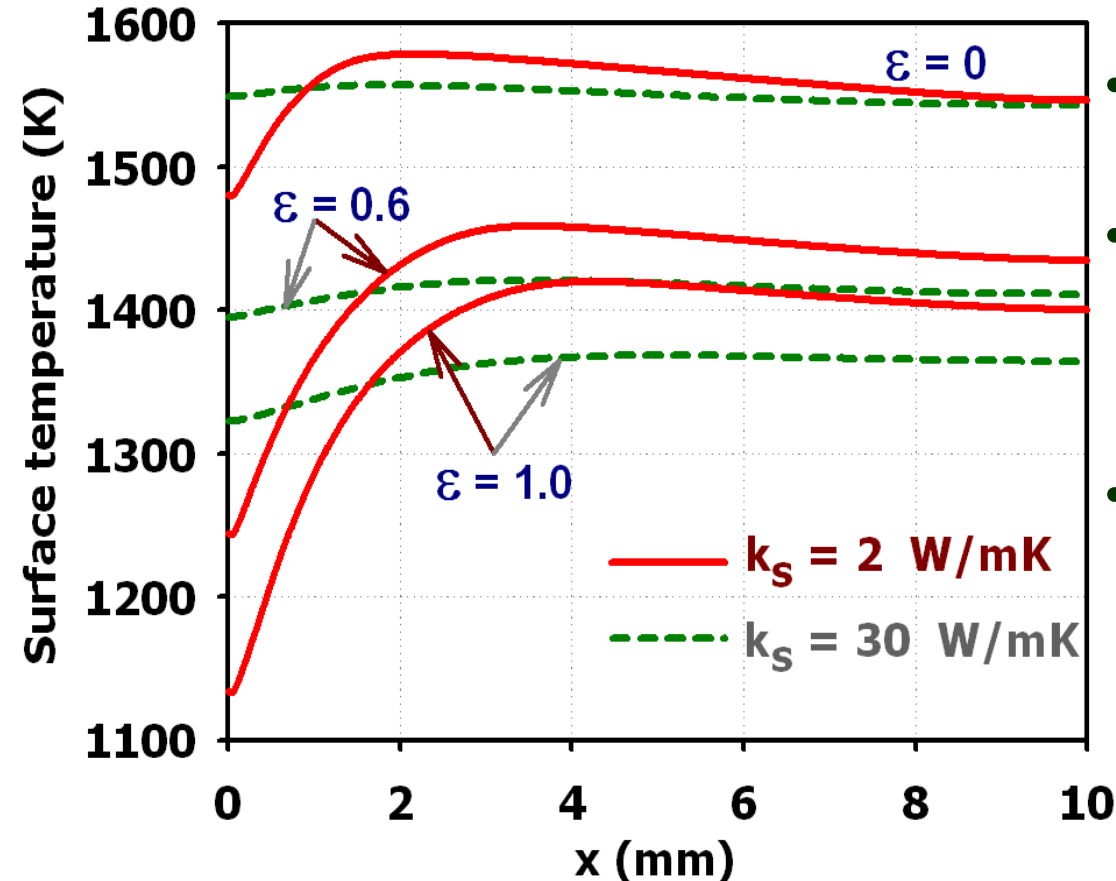
Low thermal conductivity
Low upstream heat transfer
 - Blowout is favored
 - Limits widen at lower U_{IN}

High thermal conductivity
High external heat losses
 - Heat-loss-induced extinction is favored
 - Limits widen at higher U_{IN}

$$\phi = 0.4, p = 5 \text{ bar}, T_{\text{IN}} = 700 \text{ K}, k_s = 2 \text{ W}/\text{mK}, \varepsilon = 0.6$$

Impact of radiation heat transfer

Well-inside the stability envelope:

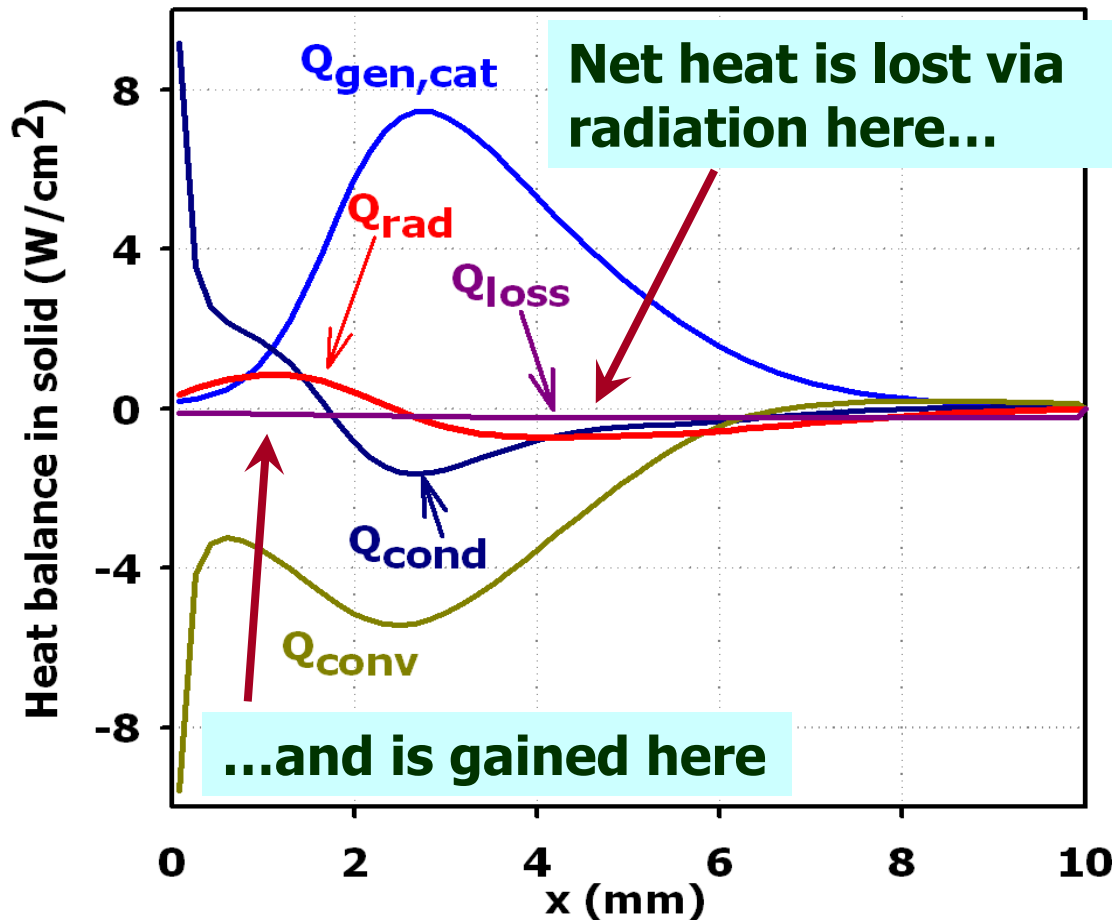


- Radiation is a net heat loss mechanism
- Heat is radiated towards colder channel entry (700K); channel wall temperatures moderated
- Higher k_s less sensitive to impact of radiation

Case A, $\epsilon_{IN} = \epsilon_{OUT} = \epsilon$, $p = 5 \text{ bar}$, $T_{IN} = 700 \text{ K}$, $U_{IN} = 0.3 \text{ m/s}$, $h = 2 \text{ W/m}^2\text{K}$

Impact of radiation heat transfer

Near the stability limit :

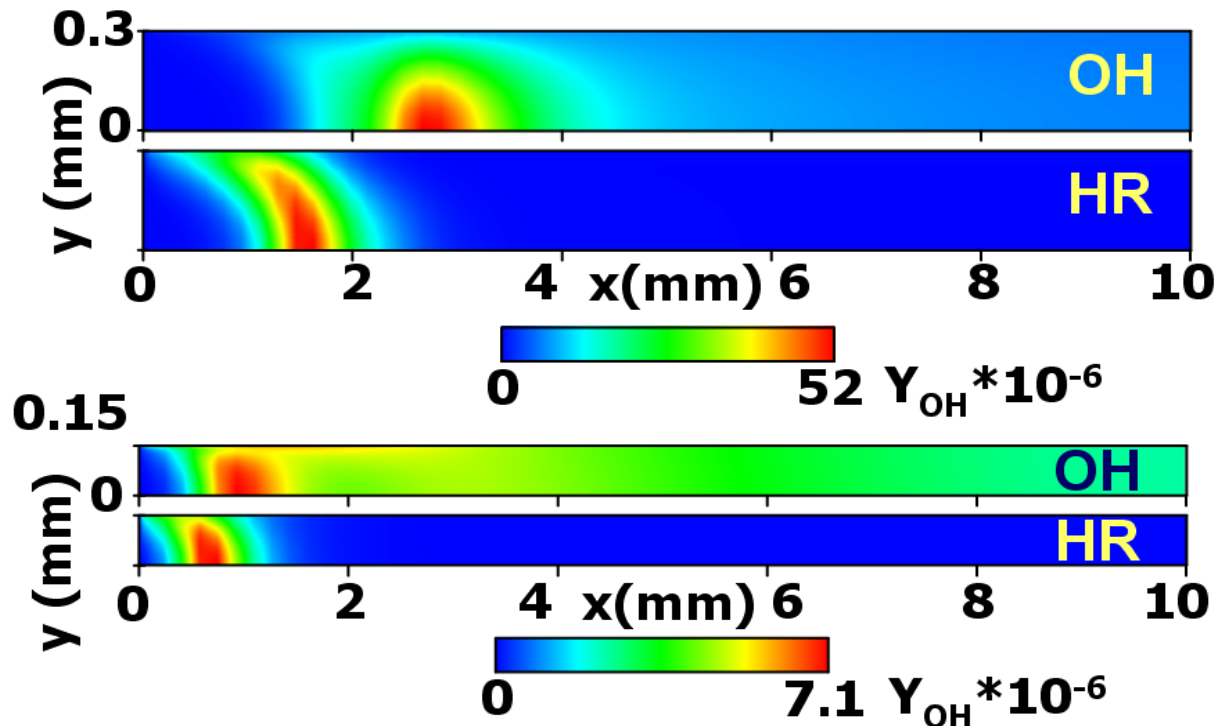


- Heat is transferred from the hotter outlet to the colder inlet section
- Result: stabilizing effect on combustion

$$\varepsilon_{\text{IN}} = \varepsilon_{\text{OUT}} = \varepsilon, \quad P = 1 \text{ bar}, \quad T_{\text{IN}} = 700 \text{ K}, \quad U_{\text{IN}} = 1.2 \text{ m/s}, \quad h = 2 \text{ W}/\text{m}^2\text{K}, \quad k_s = 2 \text{ W}/\text{mK}$$

Channel confinement effect

Channel confinements < 1 mm: gas-phase combustion can be still sustained



Numerical results backed up by future experiments in optically accessible microreactor

**$P=5$ bar, $T_{IN}=700$ K,
 $U_{IN}=0.3$ m/s, $h=2$ W/m²K,
 $\epsilon_{IN}=\epsilon_{OUT}=\epsilon$**

Conclusions

- **Global step catalytic reaction for propane was established, with a $p^{+0.75}$ dependence on pressure ($1 \text{ bar} \leq p \leq 7 \text{ bar}$)**
- **Gas-phase combustion cannot be neglected, even at very small scales of catalytic microreactors**
- **The gas-phase chemical pathway significantly extends the blowout limits and to a lesser extend the heat-loss-induced extinction limits**
- **At a given mass throughput, an increase in pressure extends the stability limits substantially**
- **The widest stability limits are obtained for solid thermal conductivities between 20 and 50 W/mK**
- **Radiation can play an important role by moderating reactor temperatures and by extending the combustion stability limits**



Materials Science & Technology

Hydrogen-Methane Blends for Fuelling Passenger Cars

**Verbrennungsforschung in der Schweiz
Bundesamt für Energie (BFE)
Zürich, 28.10.2010**

P. Dimopoulos Eggenschwiler
Empa, Swiss Federal Laboratories
for Materials Testing and Research

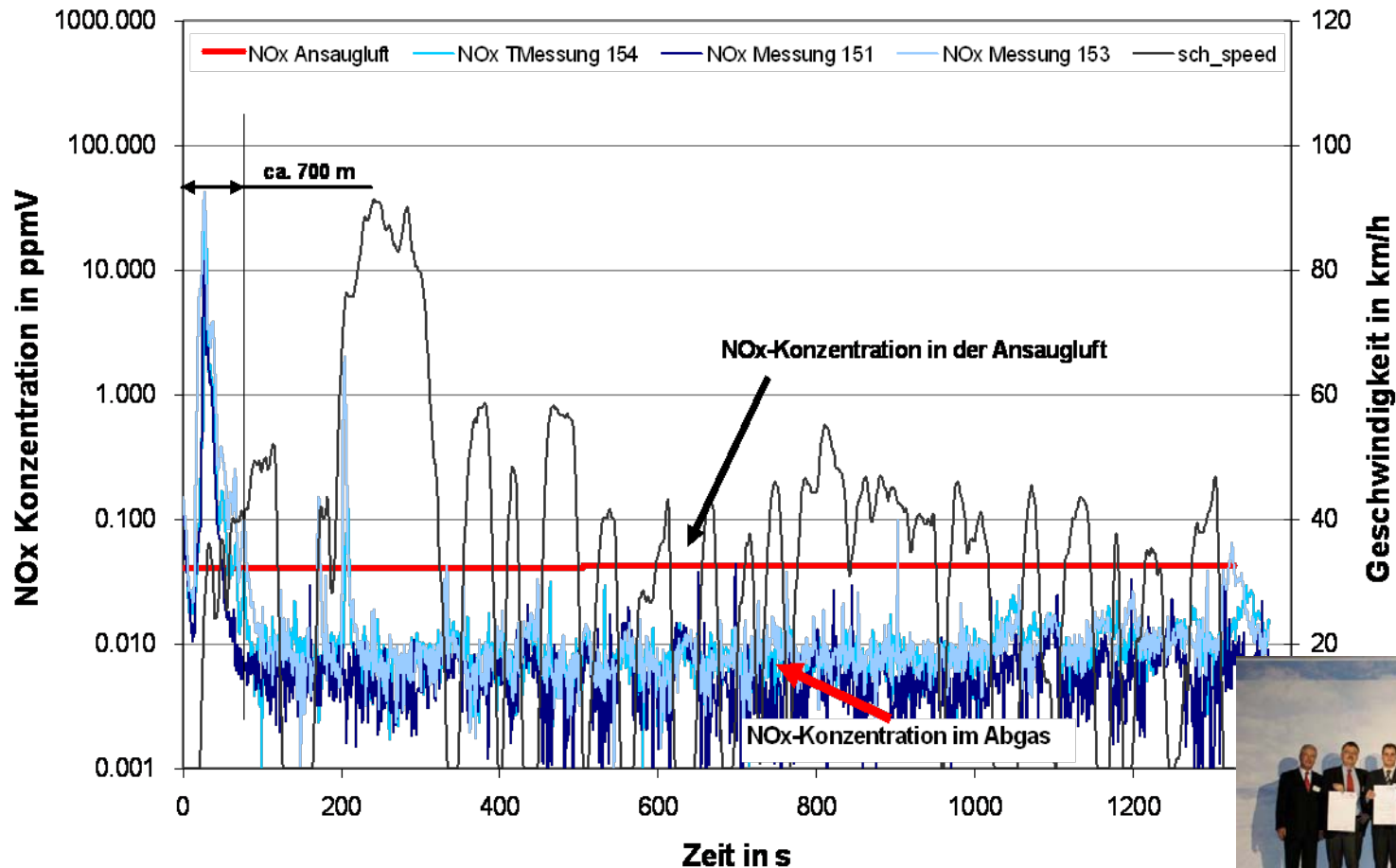
30% less CO₂ comprising with Euro-4/SULEV



- Original Vehicle: VW Polo (MY2000), 1.0lit engine displacement, 4 cylinders, 8 valves, gasoline, $\epsilon=10.7$, EGR, Euro-4
- Clean Engine Vehicle (CEV): Only CNG, $\epsilon=13.5$, Turbocharger with controlled waste gate, cooled EGR
- Stoichiometric, specially developed TWCatalyst



Optimised aftertreatment leading to extremely low NO_x



Blending CNG with H₂: Additional Benefits?

- Hydrogen-CNG Blends without EGR (pure experimental)
- Hydrogen-CNG Blends with EGR (DoE Modeling and Experimental)
- Aspects of Well-to Wheel Assessments

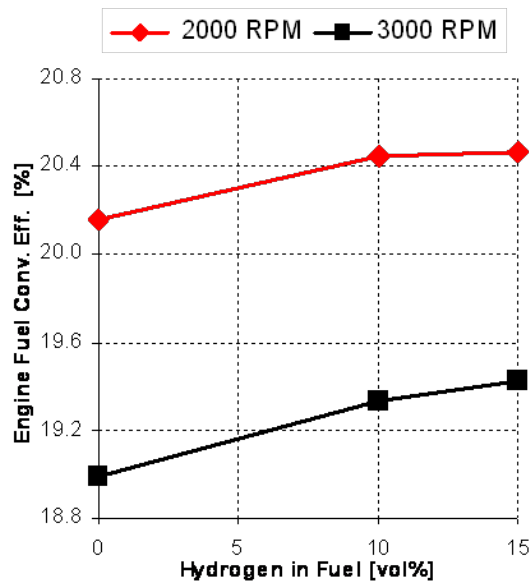
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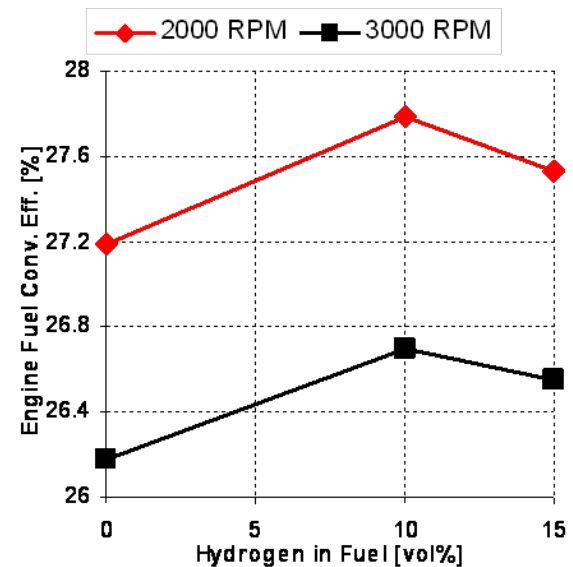
Appropriate Comparison: Fuel Conversion Efficiency

		CH₄	5vol-% H₂	10vol-% H₂	15vol-% H₂
Vol.-Frac. H ₂	[vol%]	0	5	10	15
Vol.-Frac. CH ₄	[vol%]	100	95	90	85
Mass-Frac. H ₂	[mass%]	0	0.705	1.377	2.169
Mass-Frac. CH ₄	[mass%]	100	99.29	98.623	97.831
Energy-subst. H ₂	[%]	0	1.652	3.242	5.053
Stoichiom. Air Ratio		17.19	17.23	17.26	17.284
Low Heating Value	MJ/kg	50.02	50.492	50.964	51.519

Higher Efficiency with increasing H₂,..with diminishing returns

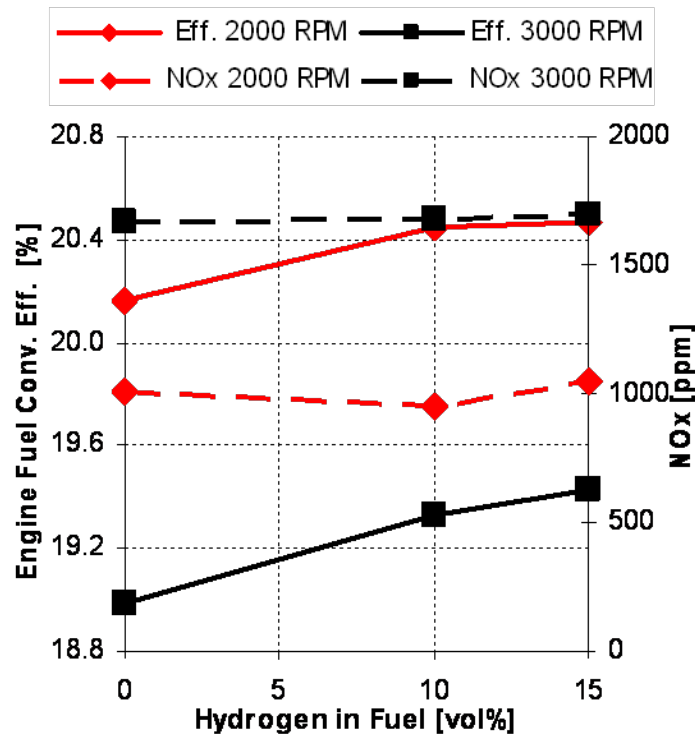


2bar bmep

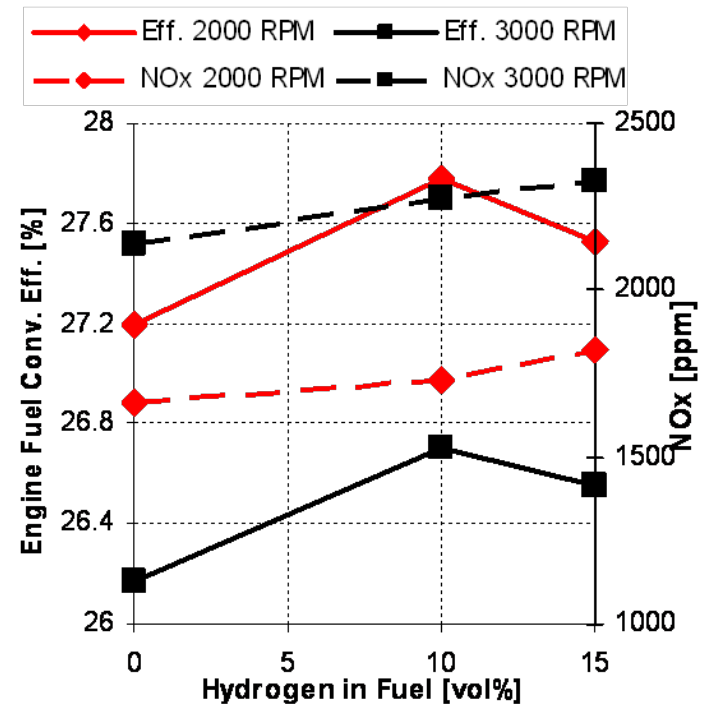


4bar bmep

Higher Efficiency with increasing H₂, also increasing NO_x

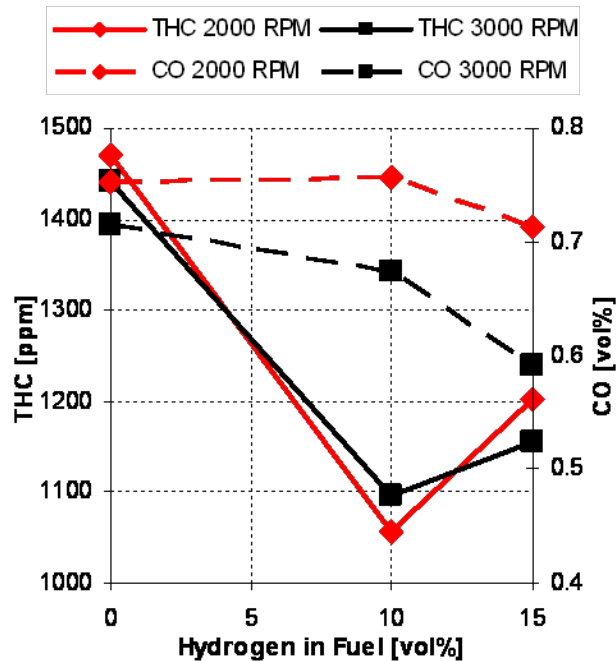


2bar bmep

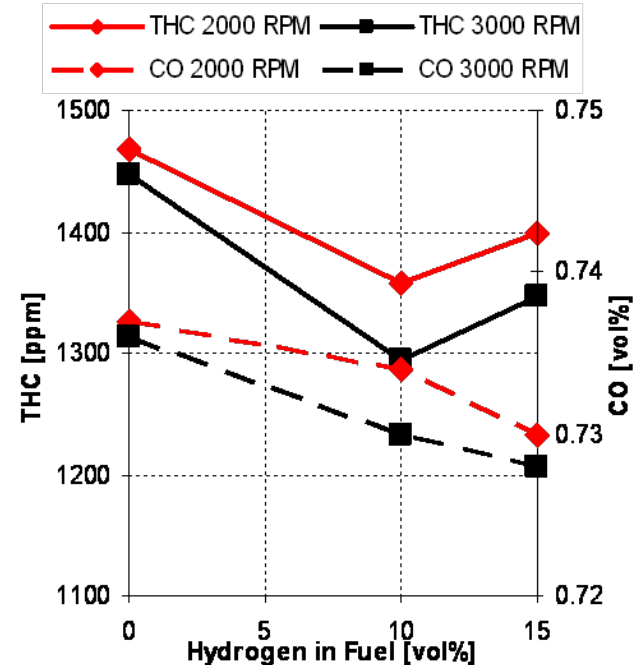


4bar bmep

THC and CO decreasing with more H₂ in the fuel



2bar bmep



4bar bmep

Blending CNG with H₂: Additional Benefits?

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Design of Experiments (DoE) systematic approach for multivariate optimization problems

■ Experimental Parameters

- Control factors (EGR=CO₂ content inlet manifold, ST)
- Response factors (bsfc, NO_x, THC, CO etc)
- Noise factors (Load)

■ Parameter Range

■ Measurement matrix (acc. to model)

■ Measurements

■ Modeling

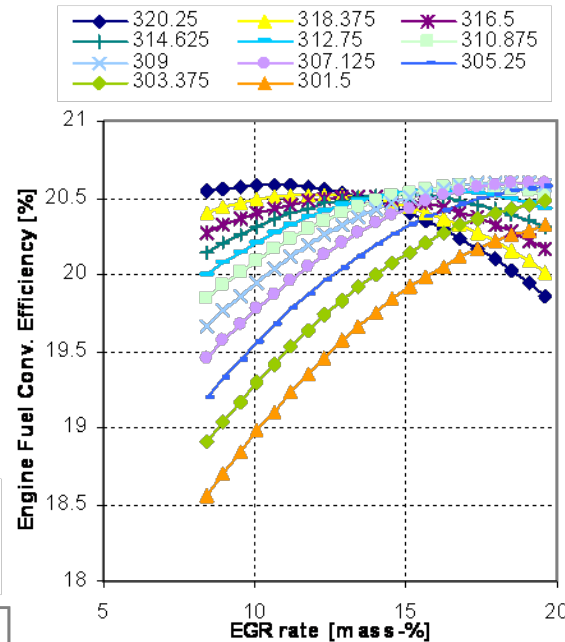
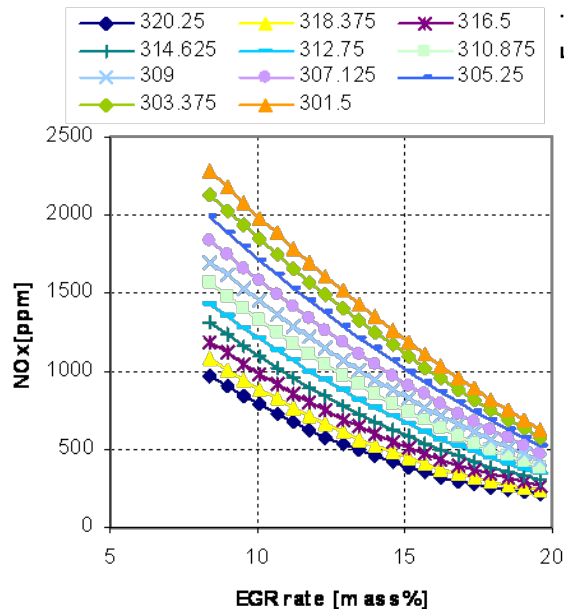
$$\begin{aligned}\eta_f = & \beta_1 + \beta_2 ST + \beta_3 EGR + \beta_4 bmep + \beta_5 ST^2 + \\ & \beta_6 ST \cdot EGR + \beta_7 ST \cdot bmep + \beta_8 EGR^2 + \beta_9 EGR \cdot bmep \\ & + \beta_{10} ST^3 + \beta_{11} ST^2 \cdot EGR + \beta_{12} ST^2 \cdot bmep + \\ & \beta_{13} ST \cdot EGR^2\end{aligned}$$

■ ANOVA for significant terms, model tuning

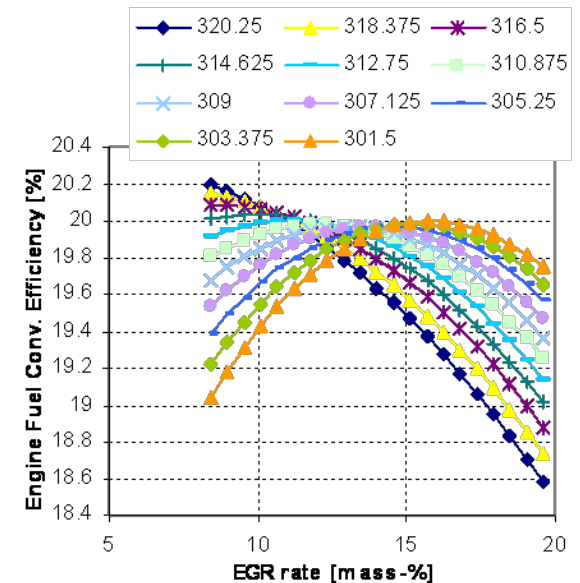
■ Verification

Two Efficiency Optima according to the DoE Predictions

2000 RPM 2bar bmep

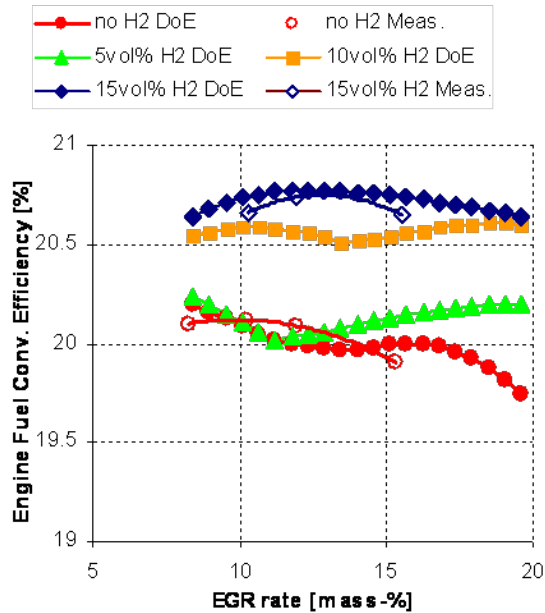


10vol% H₂

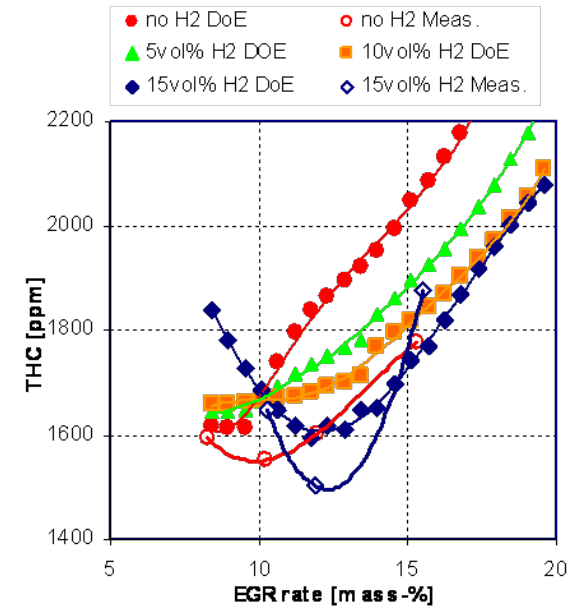
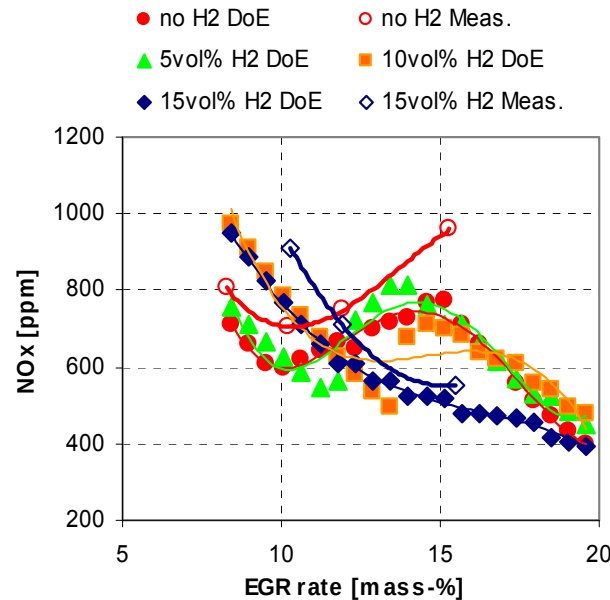


No H₂

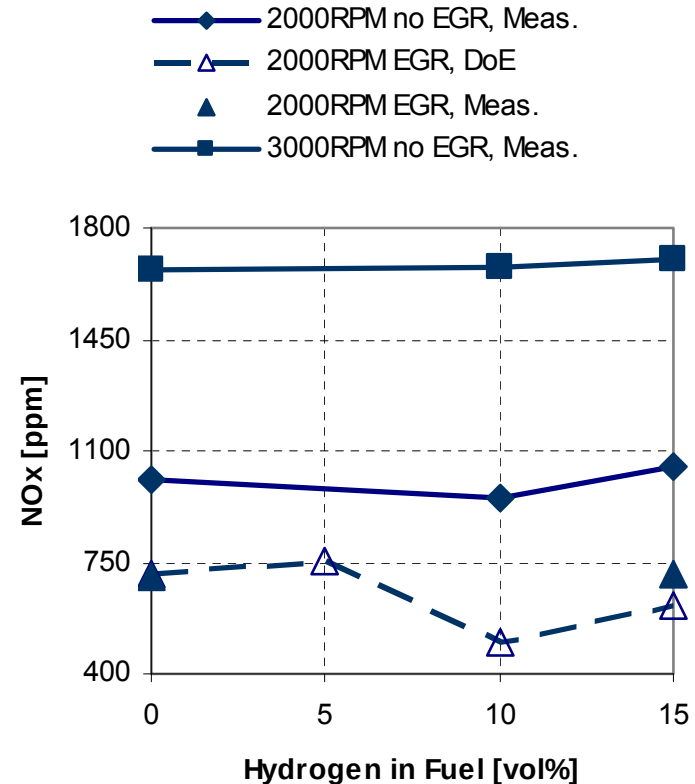
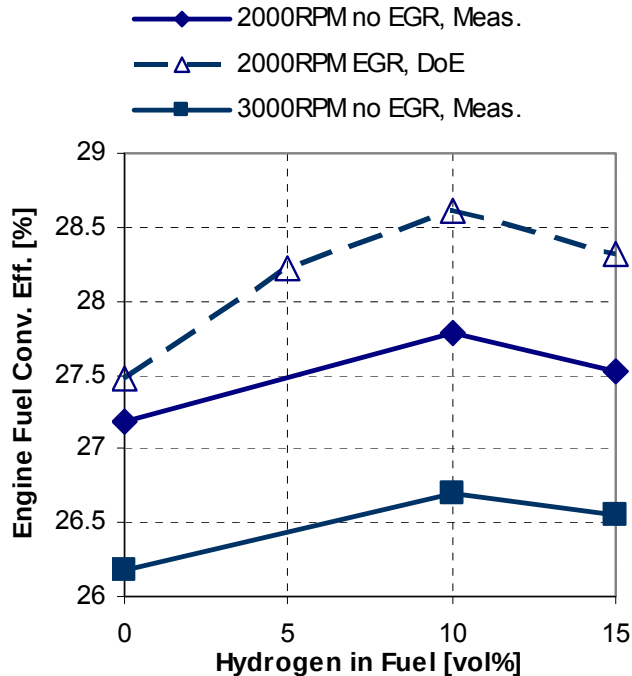
Prediction and verifications are in good agreement



2000 RPM 2bar bmep

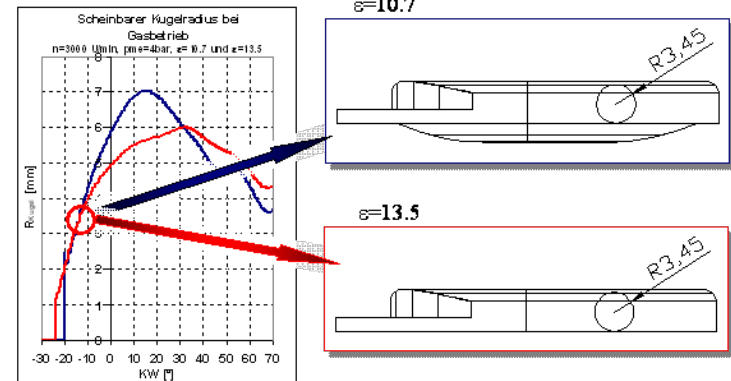
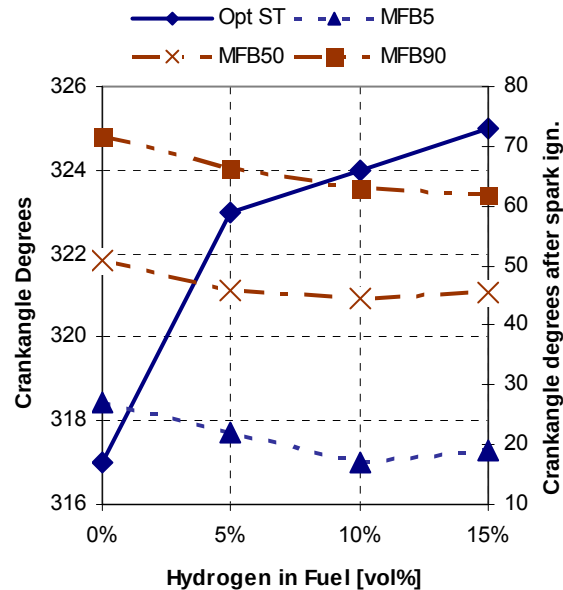


Efficiency increase is 5% while raw NOx can be suppressed by 30%

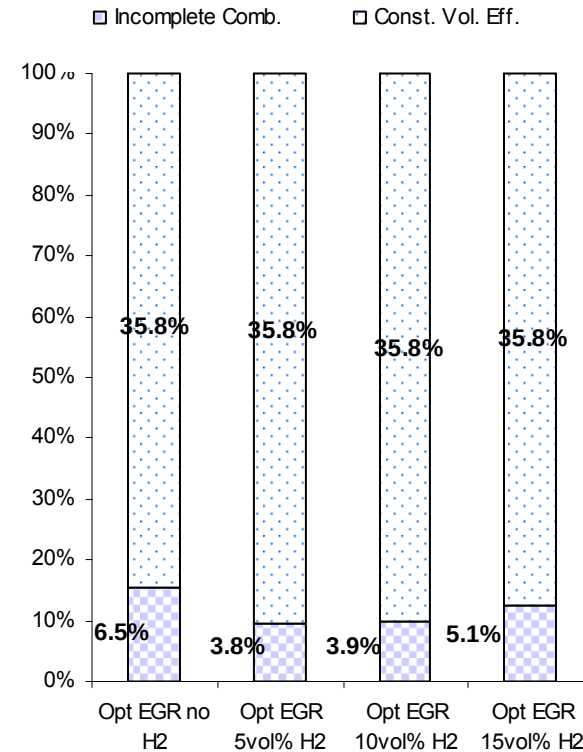
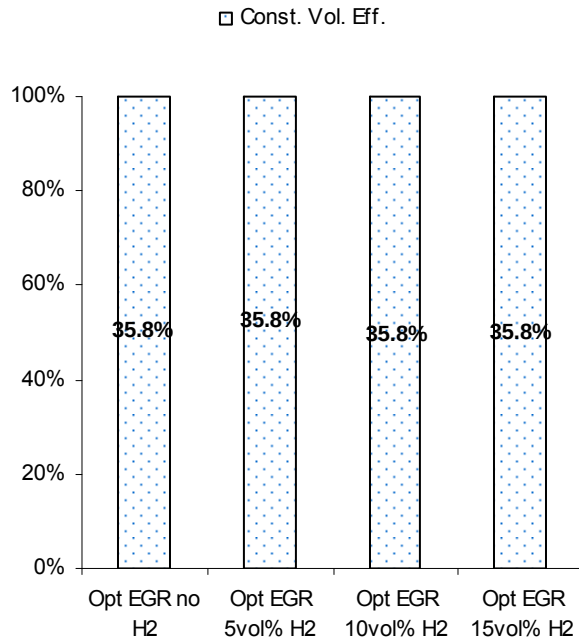


Engine load: 4bar bmep

Hydrogen accelerates combustion, especially the initial combustion phase



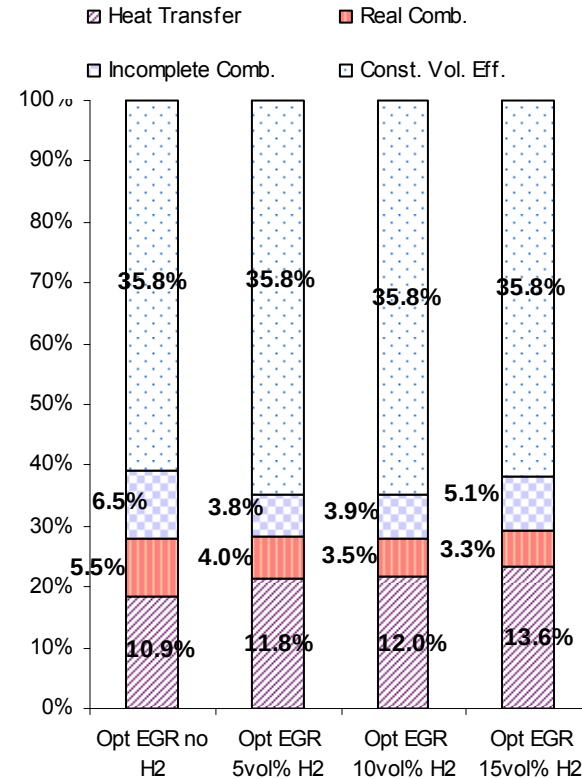
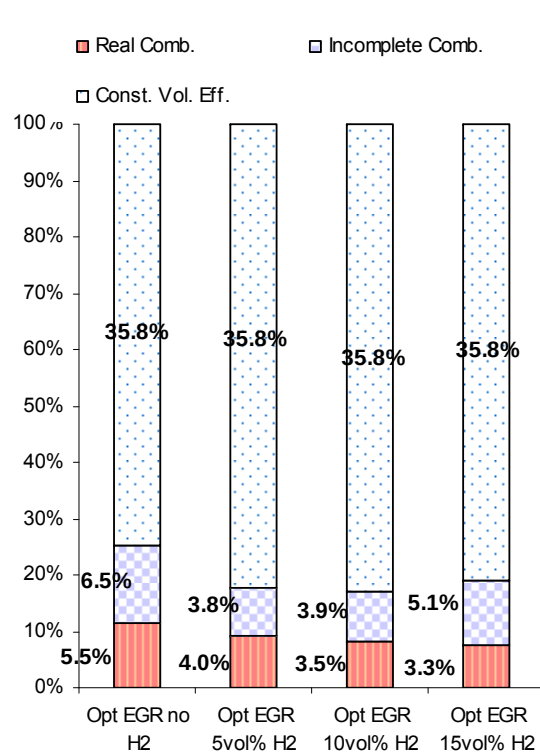
Assumption: Working fluid is air, constant properties



$$\eta_{cv} = 1 - CR^{1-\gamma}$$

- measured HCs
- measured CO
- computed H₂

Hydrogen accelerates combustion .. and increases wall heat losses



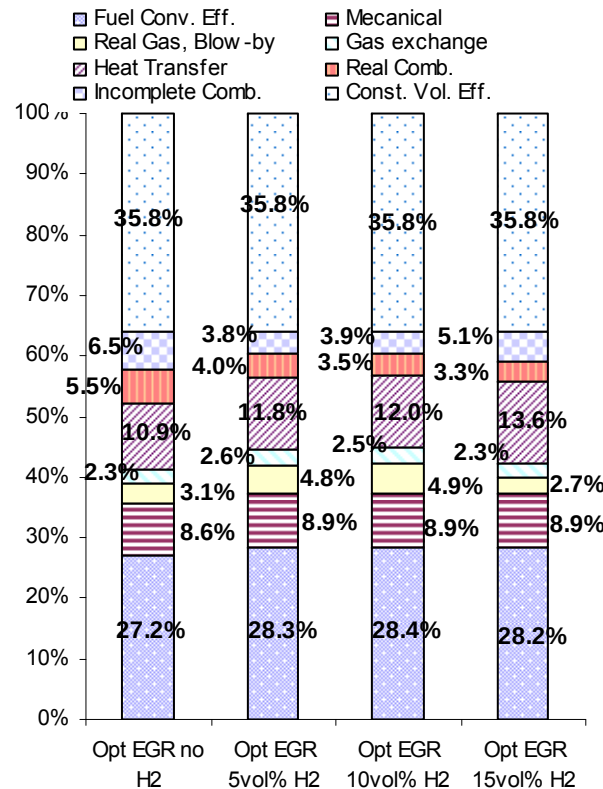
$$CR_{\phi} = \frac{V_c + V_D}{V_{\phi}}$$

$$r_{cv,\phi} = \frac{1 - \frac{1}{CR_{\phi}^{\gamma-1}}}{1 - \frac{1}{CR^{\gamma-1}}}$$

$$\eta_{rc} = \frac{1}{Q_b} \int \frac{dQ_b}{d\phi} \cdot r_{cv,\phi} \cdot d\phi$$

$$\alpha_w \approx s_p^{0.8} \cdot p_{cyl}^{0.8} \cdot B^{-0.2} \cdot T_{cyl}^{-0.53}$$

For reliable loss analysis the precision of in-cylinder pressure measurement and heat release evaluation is crucial



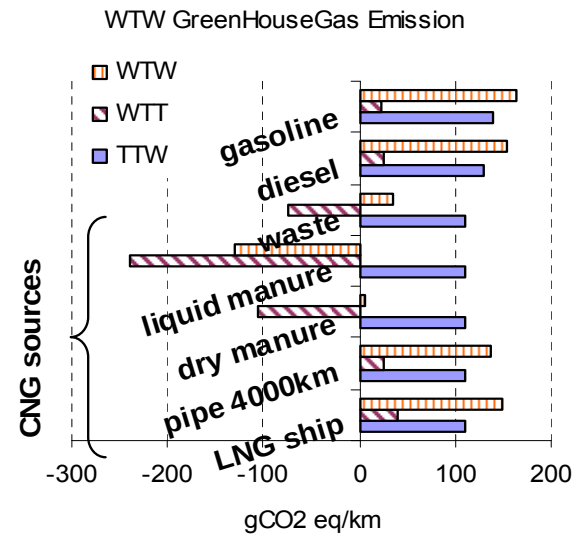
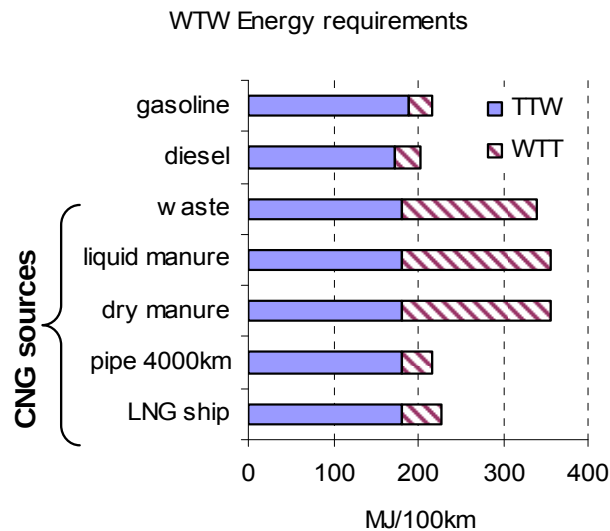
$$p_{mi, gx} = \frac{1}{V_d} \cdot \int_{EVO}^{IVC} p_{cyl} \cdot dV$$

$$p_{mi} = \frac{1}{V_d} \cdot \int p_{cyl} \cdot dV$$

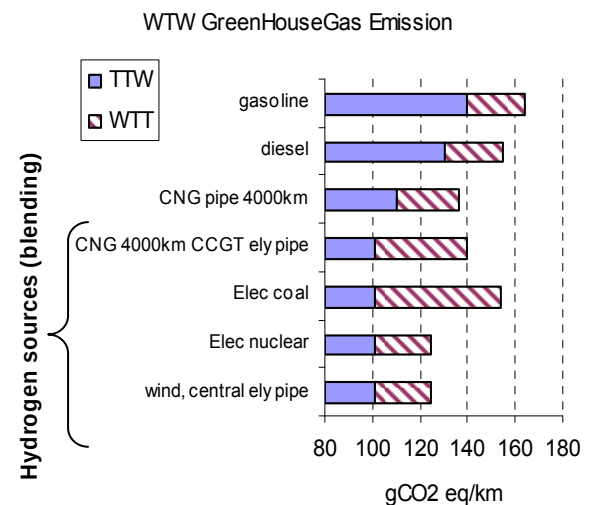
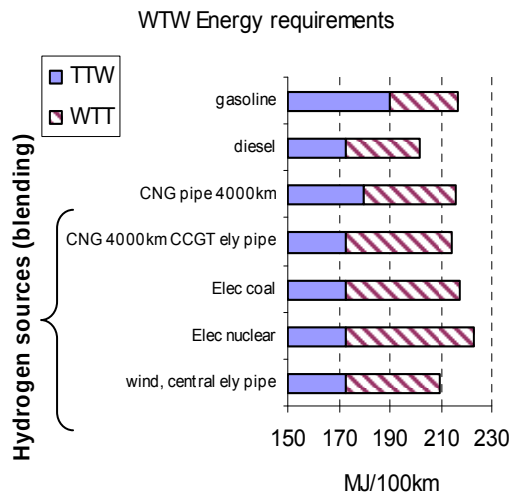
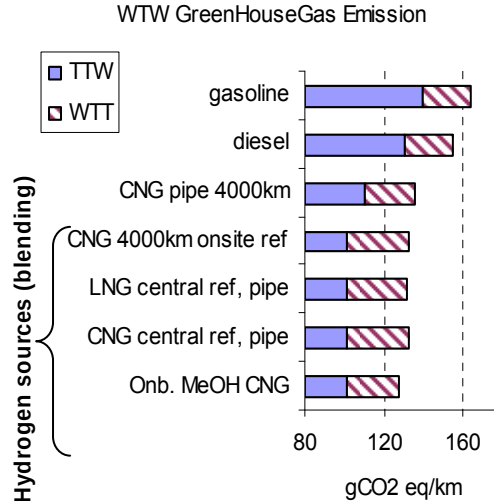
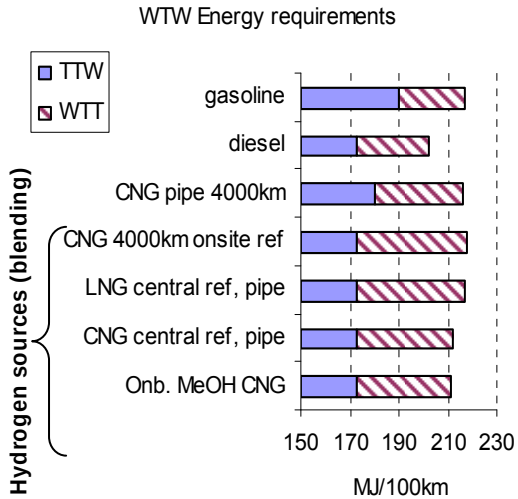
Blending CNG with H₂: Additional Benefits?

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CNGs energy requirements and GHG emissions should be taken into account



There are CNG and H2 production paths resulting in substantial GHG emissions reduction



Conclusions

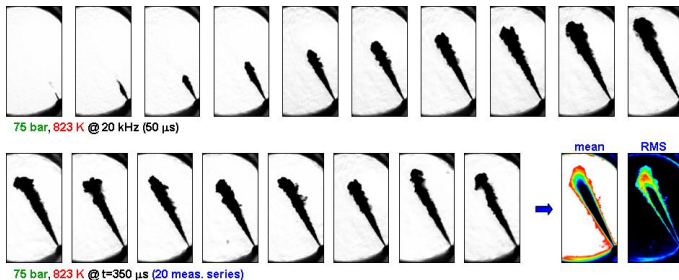
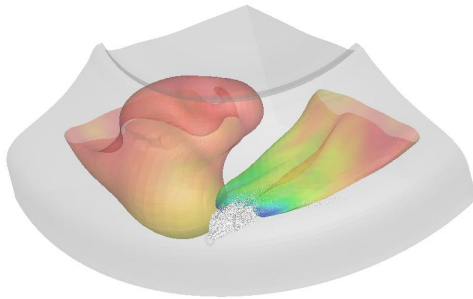
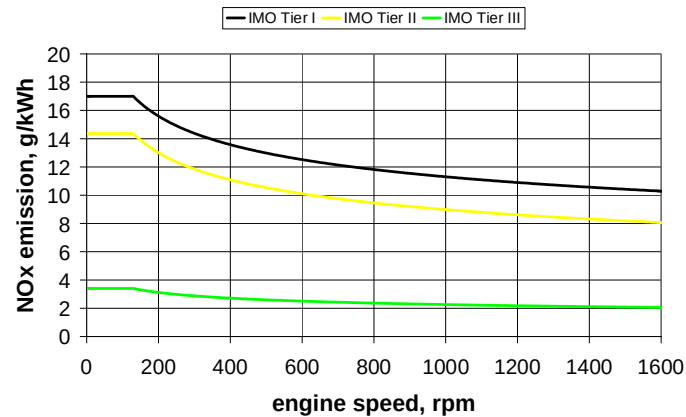
- Hydrogen in CNG increases engine efficiency. Beyond a threshold hydrogen fraction in the fuel, the efficiency gains are diminishing, mainly due to increasing wall heat losses.
- Dedicated combustion chamber design can reduce the wall heat losses.
- Depending on the engine load 2-4% efficiency increase can be attributed to the hydrogen in the fuel and additional 1-2% to EGR.
- The optimal EGR quantity leads to a 40% reduction of engine-out NO_x to a 10% increase of engine out THC, while practically not affecting engine-out CO levels.
- The hydrogen component of the fuel mainly accelerates the initial combustion phase.
- Well-to wheel analysis identifies reforming and electrolytic hydrogen production paths with overall energy requirements higher than diesels, but lower green house gas emissions by almost 10%.

RECENT DEVELOPMENTS IN THE MARINE INDUSTRY AND THEIR IMPACT ON COMBUSTION RESEARCH FOR LARGE MARINE DIESEL ENGINES

**GERMAN WEISSER
WÄRTSILÄ SWITZERLAND LTD
OCTOBER 28, 2009**

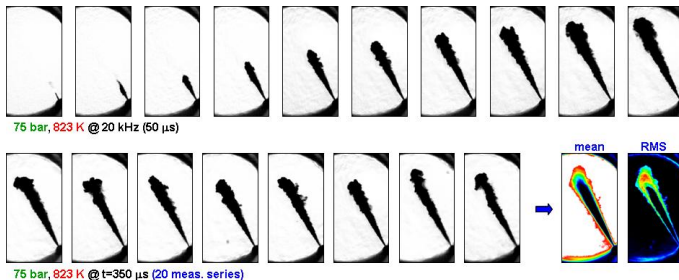
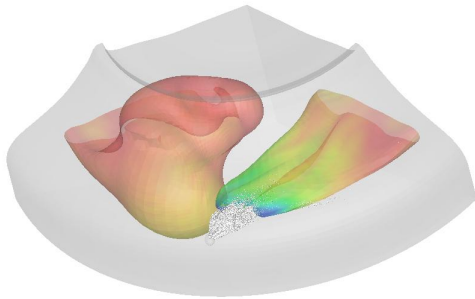
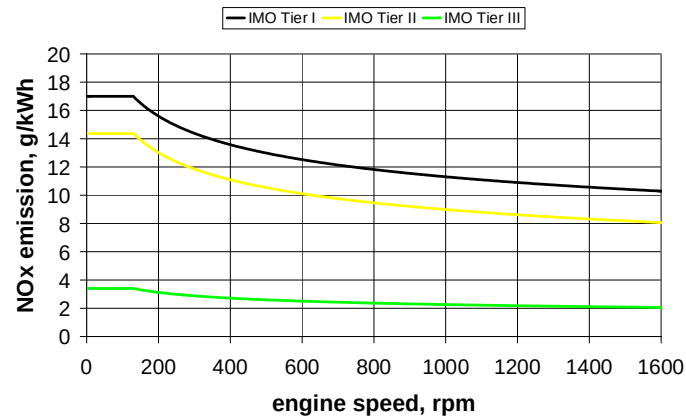


Presentation outline



- Environmental regulations for marine diesel engines
 - International standards
 - National or regional standards
 - Incentive or penalty schemes
- The fuel supply situation
- Consequences for combustion system development
- Experimental combustion research
 - Spray combustion chamber concept
 - Validation against requirements
 - Application and further development
- Conclusions
- Acknowledgment

Presentation outline

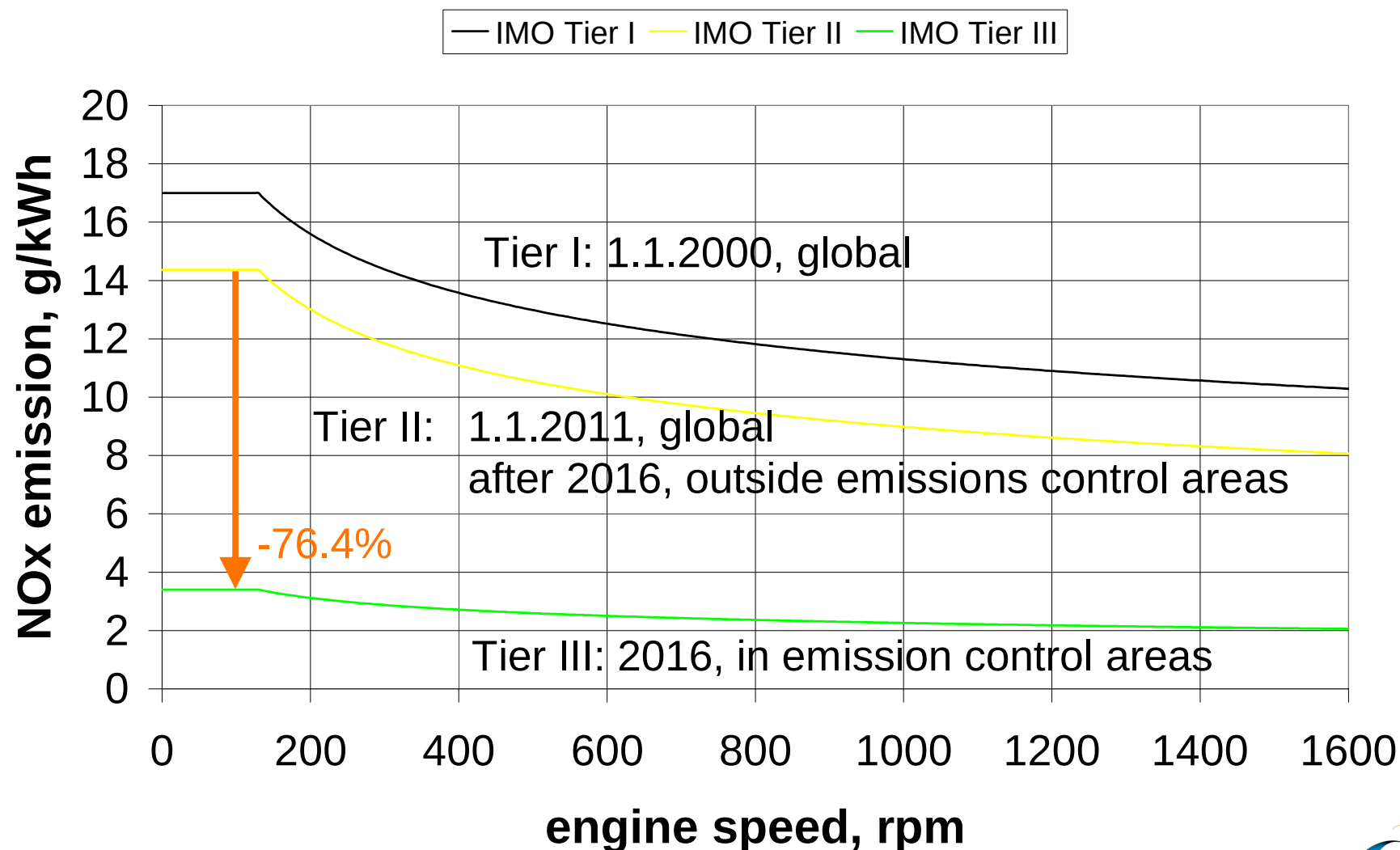


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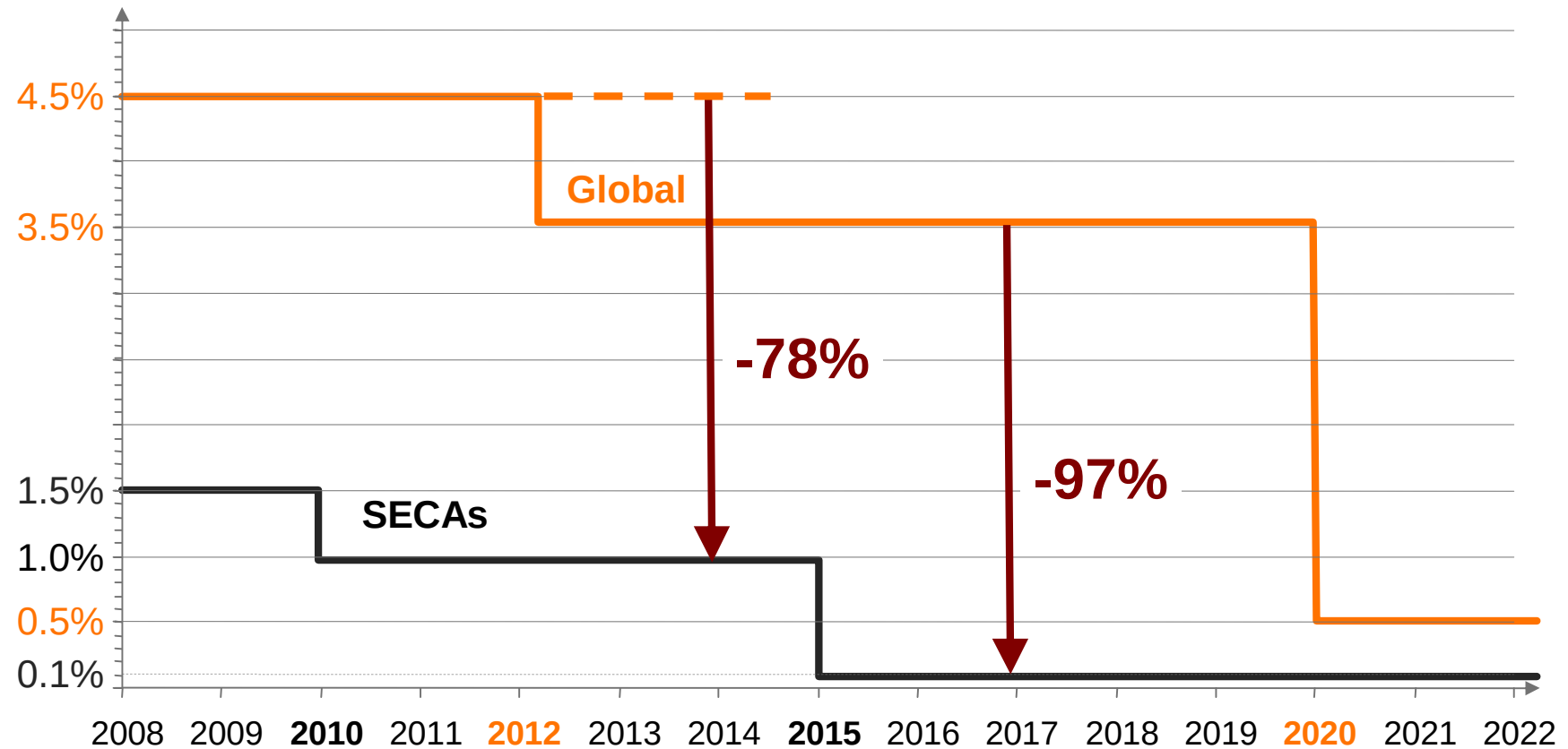
MARPOL Annex VI

- The Annex VI to MARPOL 73/78 to date is the single relevant emissions regulation in force worldwide – it entered into force 2005 and the subsequent review by the IMO was completed 2008 with the following main aspects:
 - NOx emissions for new vessels - three Tier approach
 - NOx emissions for existing (pre-Tier I) engines:
Identification of engines covered, applicable limits and conditions
 - SOx/PM emissions:
To be controlled by means of more stringent fuel requirements – further development of fuel sulphur limits both globally and in SECAs
 - VOC emissions:
Introduction of operational measures for tankers

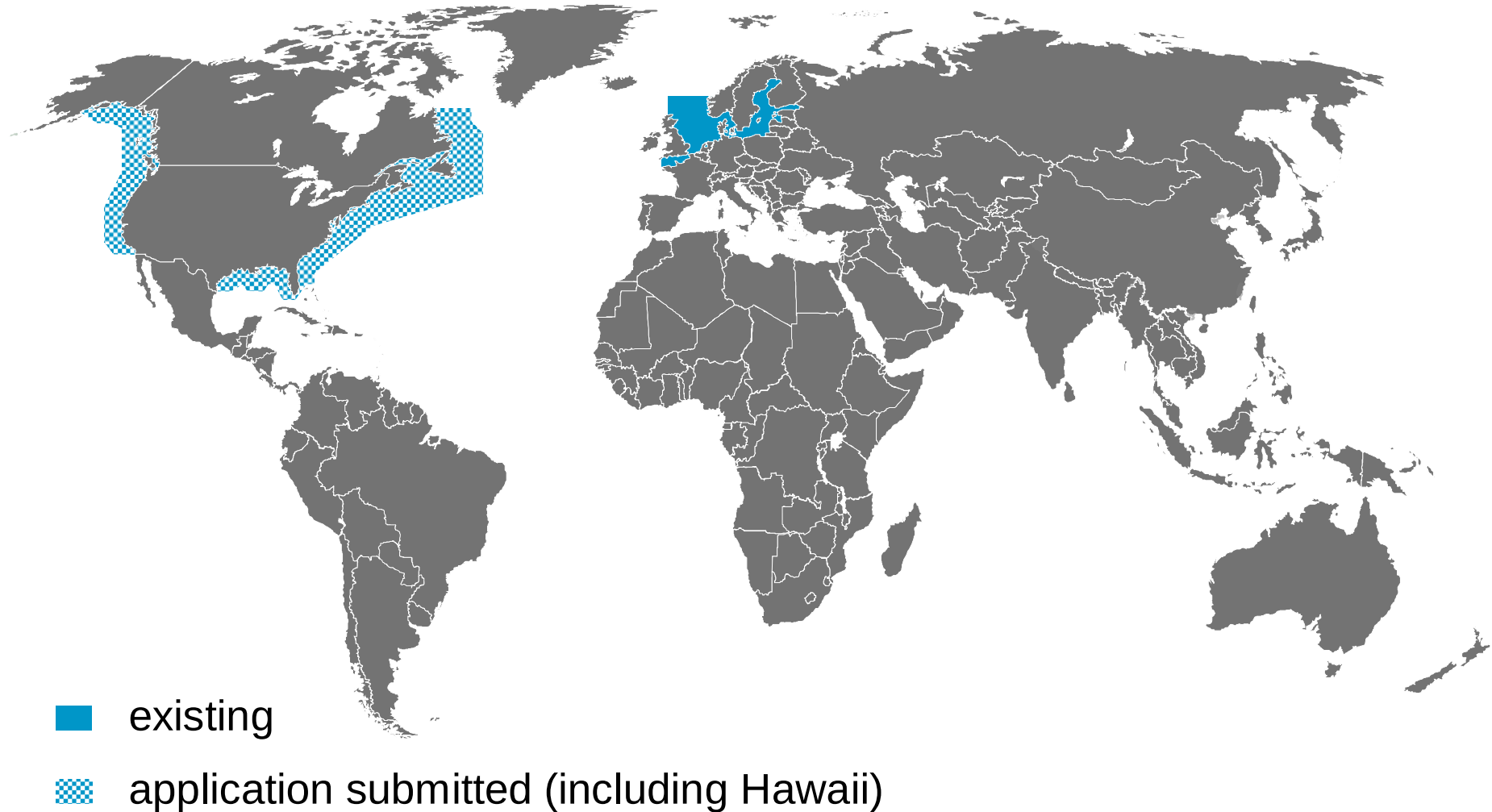
MARPOL Annex VI – NOx emission limits for new vessels



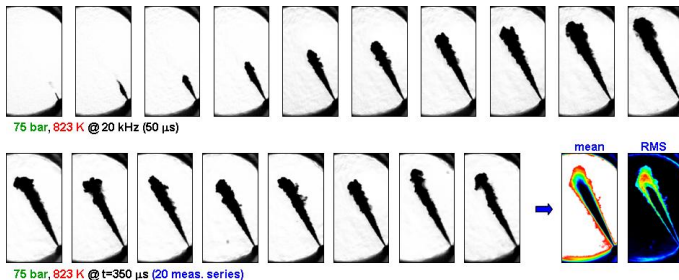
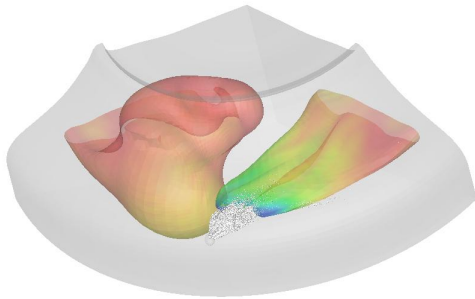
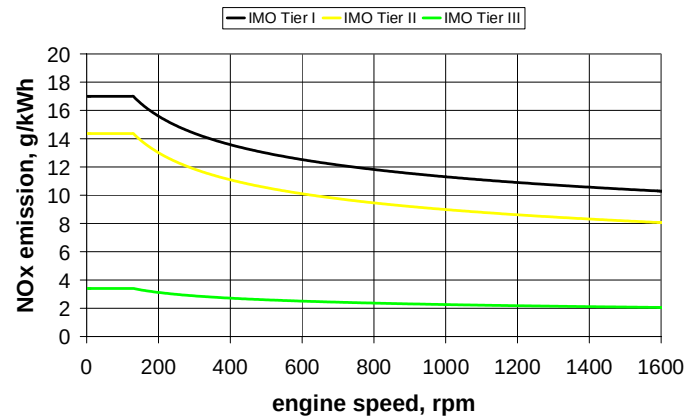
MARPOL Annex VI – Fuel sulphur limit development



MARPOL Annex VI – Emission control area designation



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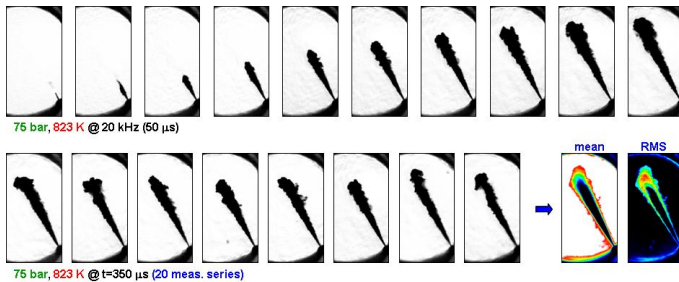
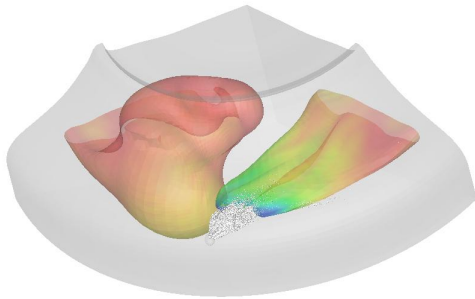
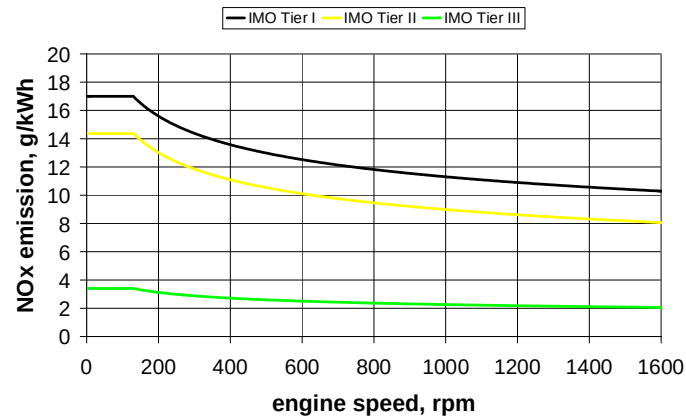
National standards: United States of America

- Revision of present (2004) legislation announced (ANPRM issued end 2007):
 - Targets in correspondence with U.S.A. proposal to IMO:
 - Two-Tier approach wrt NOx emissions for newbuildings
 - Additionally, strict PM and SOx limits for designated areas proposed
 - NOx limits also for existing vessels
 - Final rule publication expected for end 2009
 - Boundary conditions:
 - Lawsuit initiated by Friends of the Earth International against EPA for non-compliance with their own regulation
 - Petition of various environmental interest groups to adopt greenhouse gas (GHG) emissions regulations for ocean-going vessels
 - California preparing separate regulations

Regional / local standards

- European Union:
 - Regulation for propulsion engines on inland waterways vessels:
 - Limiting CO, HC+NO_x and particulate mass emissions
 - Limiting fuel sulphur content to 0.1% by January 2010
 - EU sulphur directive:
 - SECA concept similar to IMO
 - All vessels in EU ports: max. 0.1% (January 2010)
 - Passenger ships connecting EU ports: max. 1.5% (August 2006)
- Alaska:
 - Abolition of visible smoke from vessels cruising in coastal waters
- California:
 - Requirement of switching to low sulphur fuel while operating in coastal waters (24 mile zone)
 - July 2009: 1.5% (MGO) or 0.5% (MDO)
 - January 2012: 0.1% (MGO or MDO)

Presentation outline



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Incentive / penalty schemes

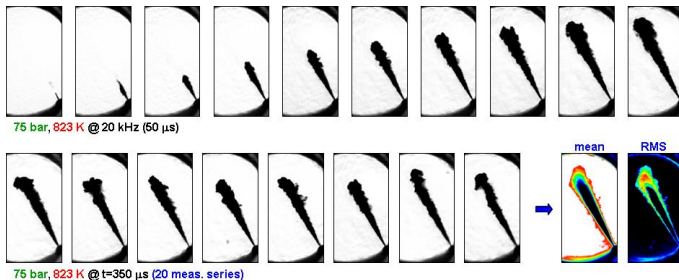
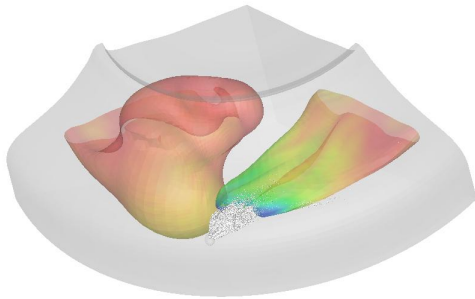
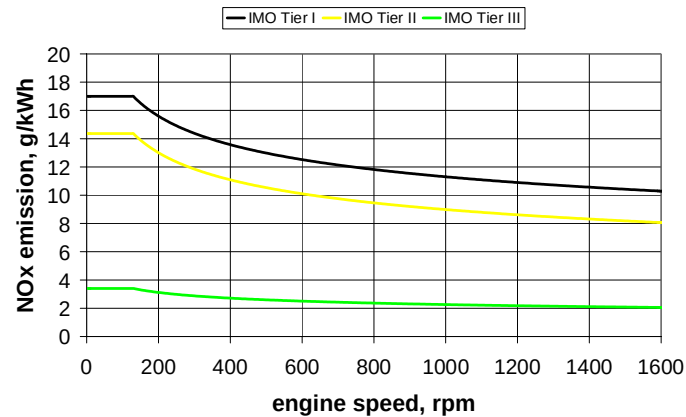
- Norway:
 - Environmentally differentiated tonnage tax system
 - NOx fee for vessels operating in Norwegian waters
- Sweden:
 - Differentiated fairway and harbour fee system
- Voluntary emissions control programs established by classification societies
- Port authorities emissions control programs

Norway

NOx emissions fee in force since January 1, 2007:

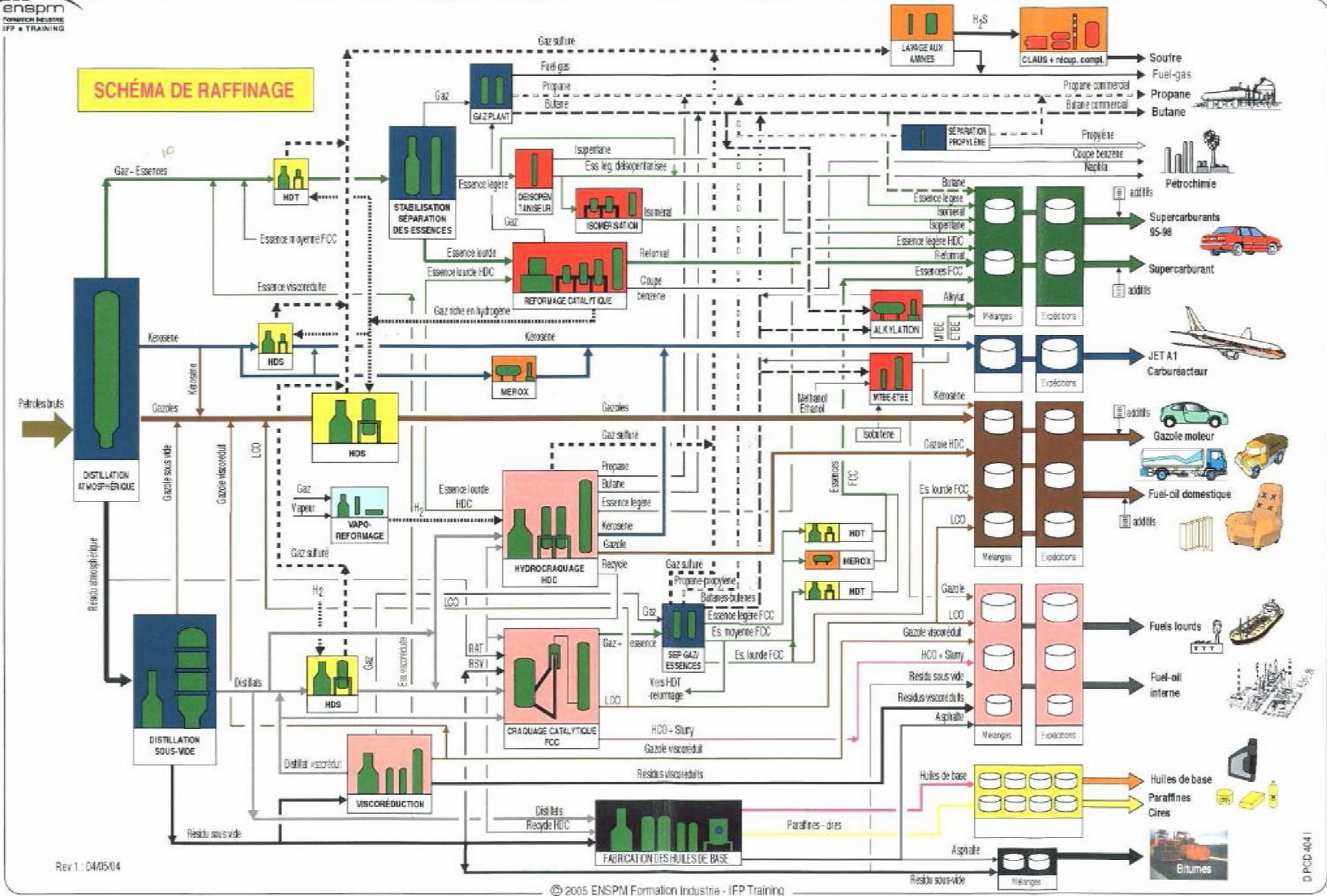
- Initially, the fee is set to 15kr/kg NOx (for engines above 750kW), - most likely to increase up to 50kr/kg NOx towards year 2010.
- The geographical area is limited to "Norwegian waters" as described in the Gothenburg protocol of 1997.
- The fee will have to be paid monthly to "Toll- og avgiftsdirektoratet".
- Fuel consumption and a NOx factor are the basis of the fee calculation.
- For vessels without documentation of emission level (either an EIAPP or an approved emission measurement), a standard NOx factor will be used.

Presentation outline

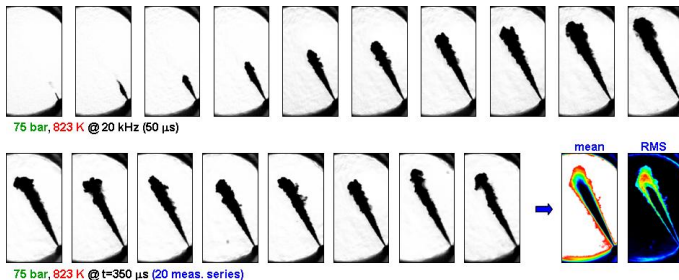
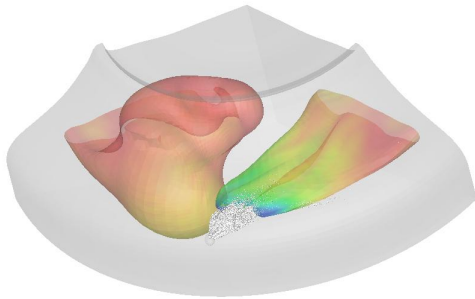
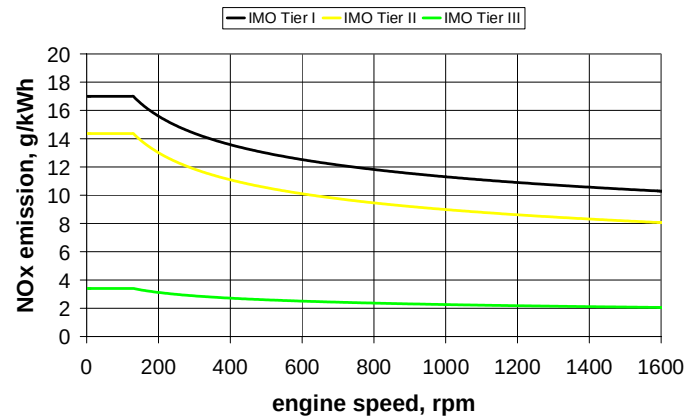


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HFO – Refinery



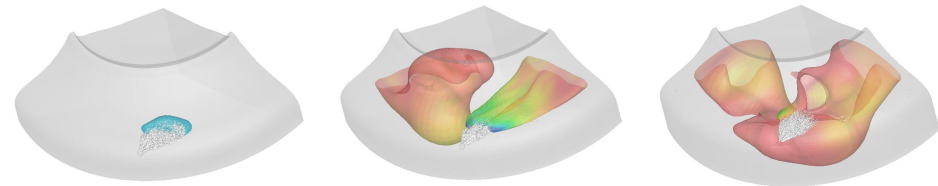
Presentation outline



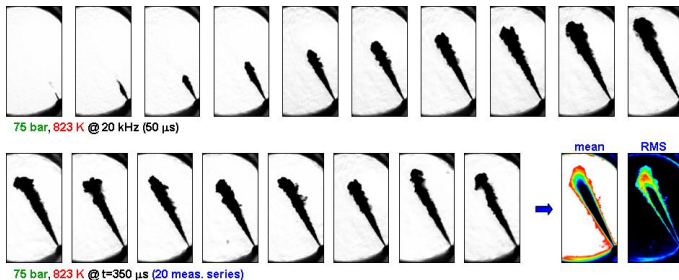
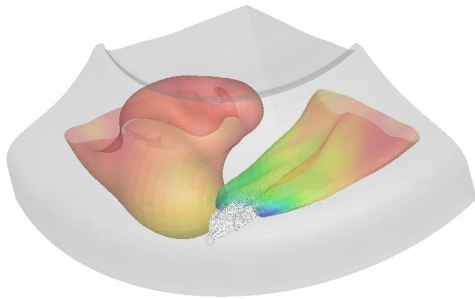
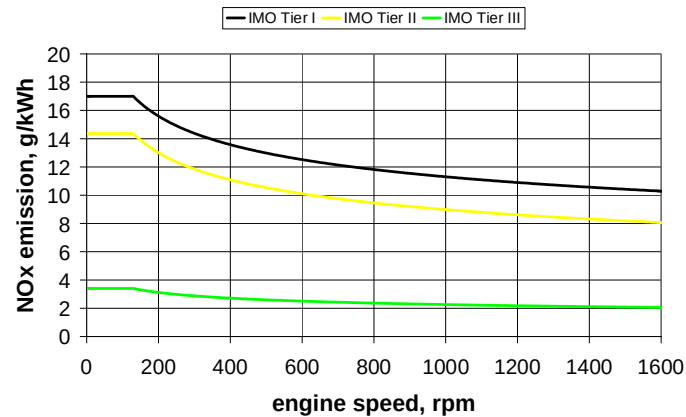
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Consequences for combustion system development

- Engines need to be prepared for burning a large variety of fuels
 - Very low-grade fuels (high-density, high viscosity, ...)
 - Low-sulphur HFO as long as sufficient for ECA requirements
 - Ultra-low sulphur fuels (light qualities) within ECAs or specifically designated areas
- Engines need to be more thoroughly optimized in order to be able to meet the NO_x limits
 - Highly reliable, reproducible injection
 - Efficient control of combustion:
 - spray / swirl interaction
 - spray / spray interactions
 - spray (flame) / wall interaction
- For this purpose, in-depth insight into the fundamental in-cylinder processes (at typical conditions) is indispensable in order to be able to employ CFD simulation in combustion system development



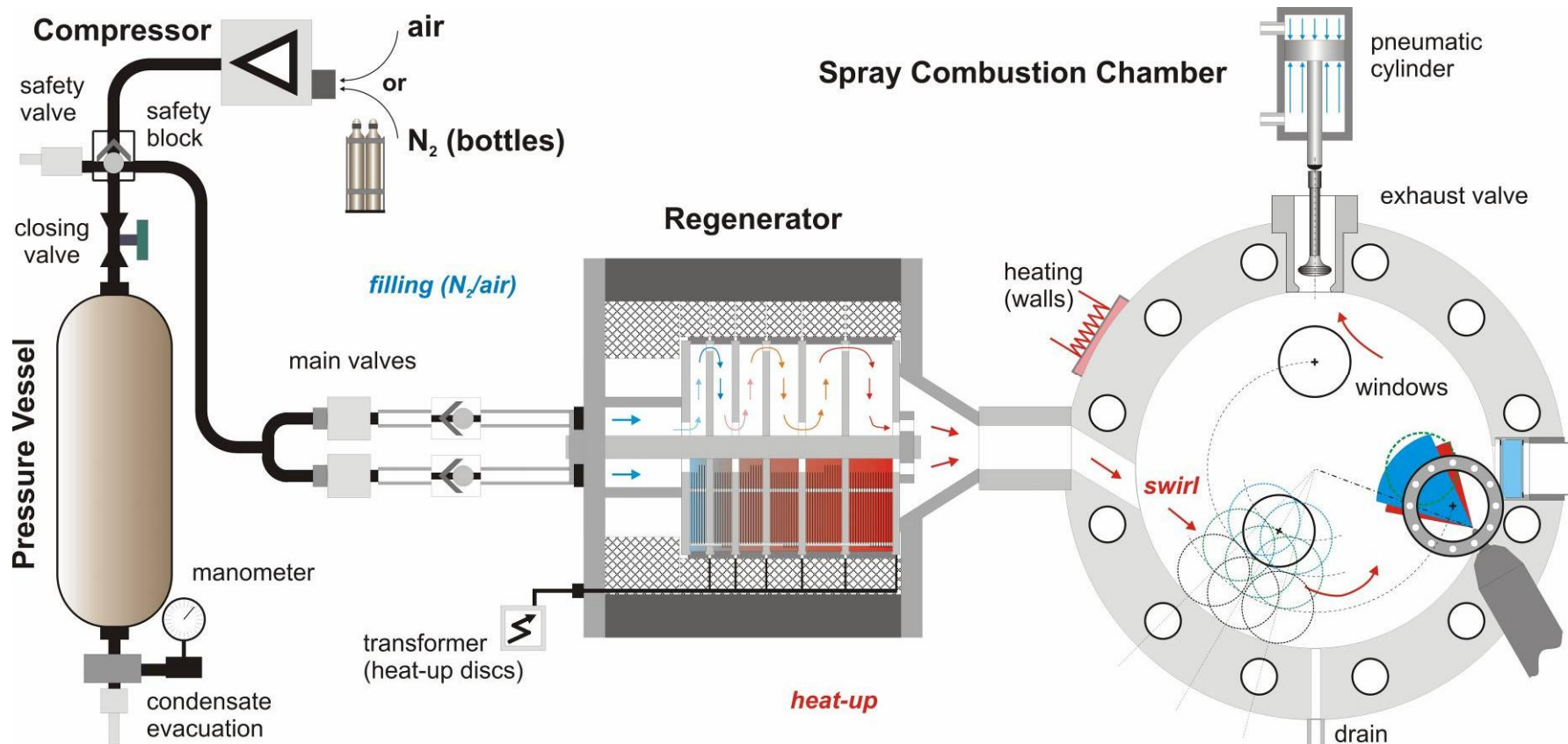
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Principle Test Facility

Setup experimental SCC test facility

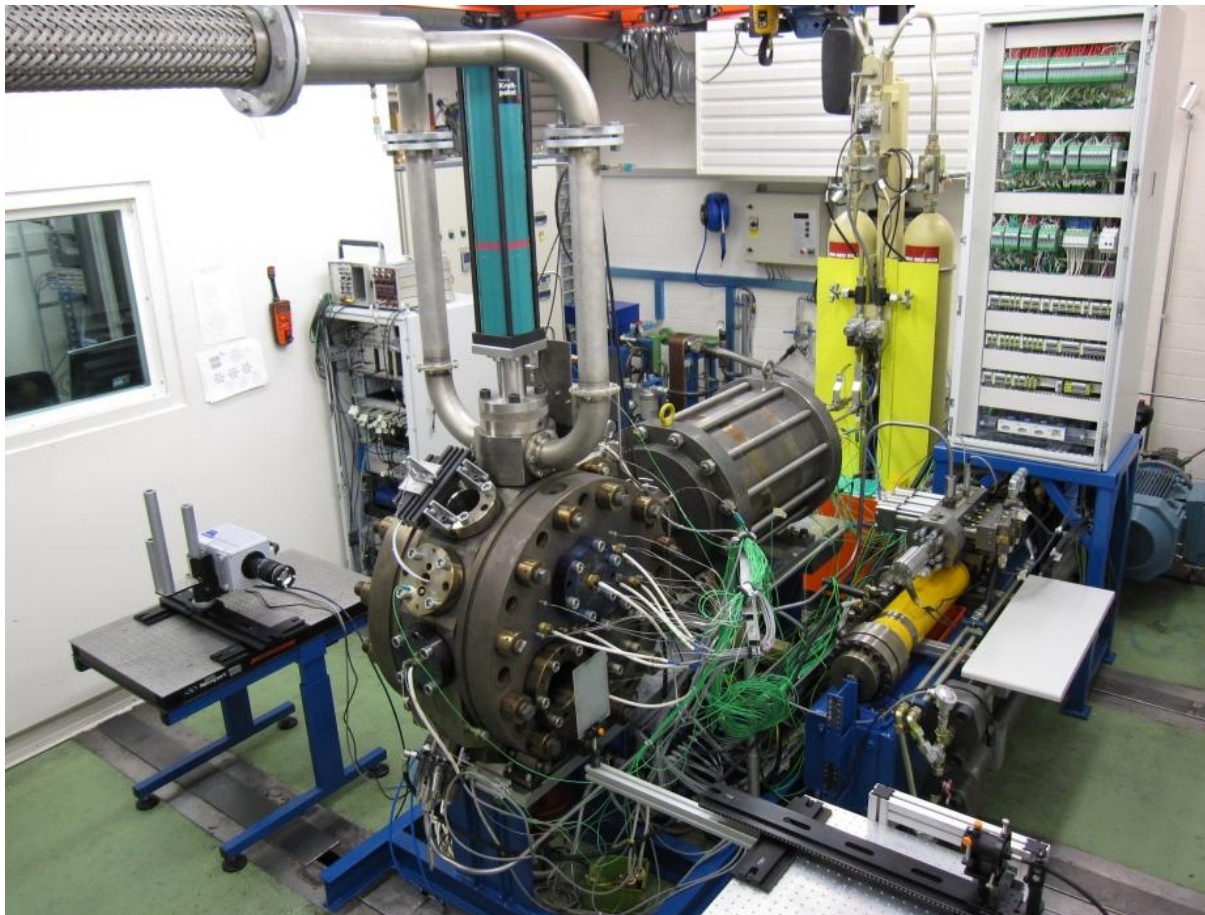


Test Facility Overview

Experimental setup of the spray combustion chamber (SCC)

⇒ *completion of setup*

150 components, ~400 parts (>1000 individual pieces), weight: ≈ 3 t

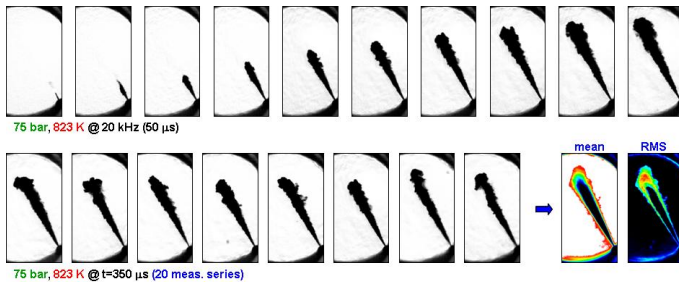
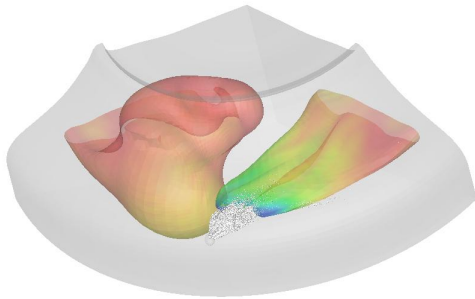
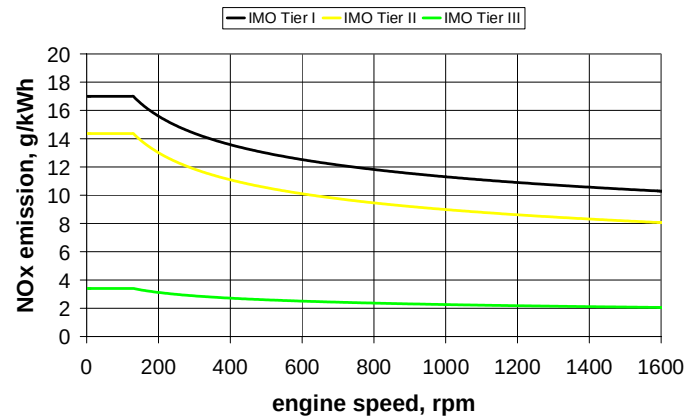


Dimensions!



- SCC & regenerator assembly
- injection system (marine)
- laboratory facility, periphery
- control system(s)
- data acquisition
- ...
- commissioning & operation
- validation (base diagnostics)
- initial application
- measurement campaigns
- fuels

Presentation outline



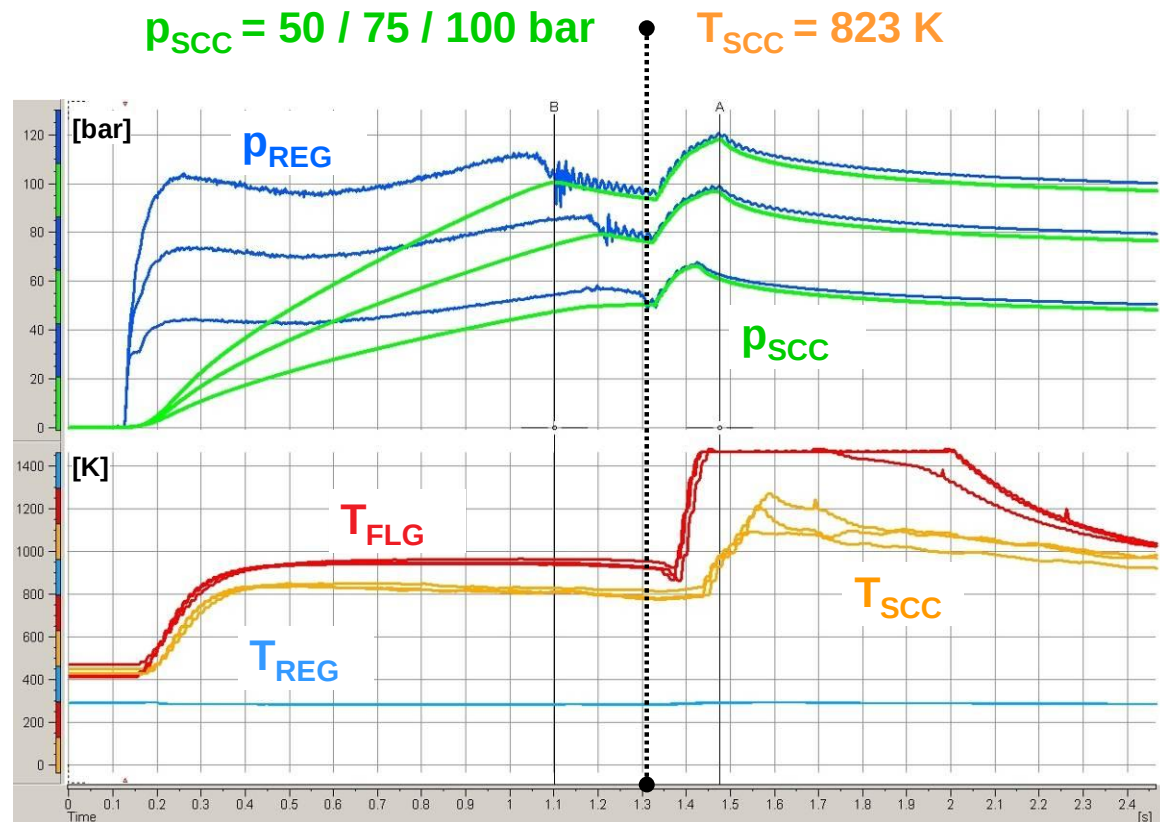
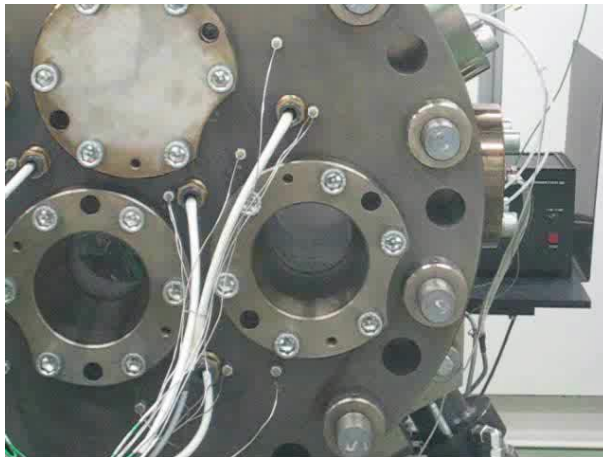
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Operation SCC

Conditions pressure, temperature

1-hole nozzle tip, $t_{\text{fill}} = 0.75$ s, $\delta t_{\text{inj}} = 150 \dots 180$ ms, $\lambda_v \approx 3.0 \dots 4.0$

$p_{\text{SCC}} = 90$ bar, $T_{\text{SCC}} = 900$ K



Validation

Specifications p, T, swirl (u)

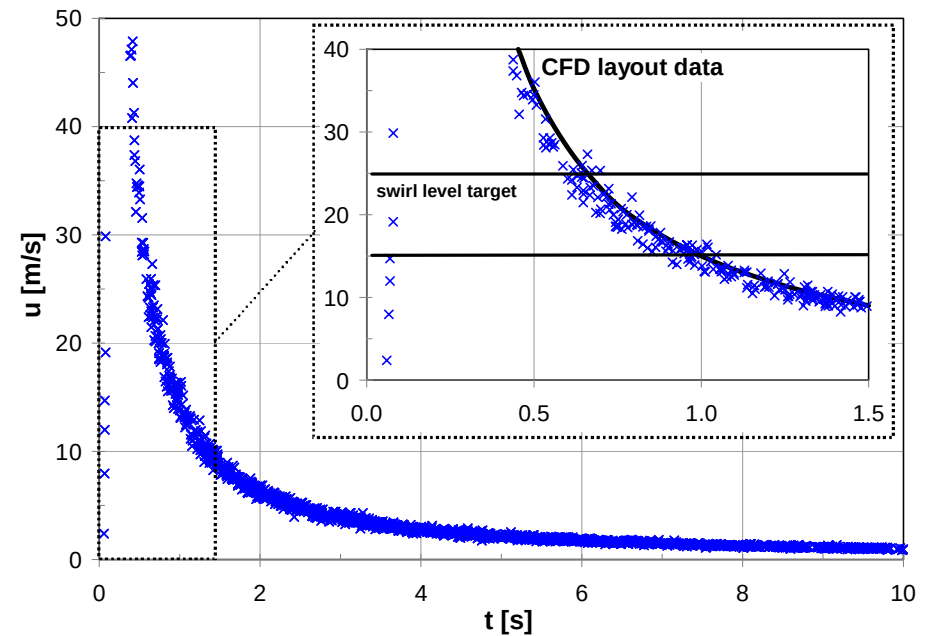
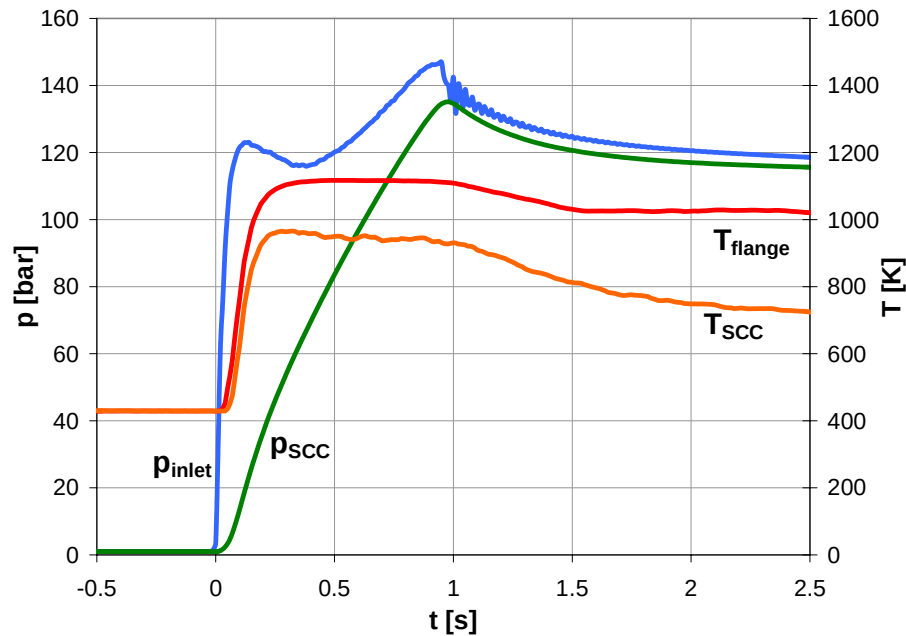
$p_{\text{bottle}}=340\text{bar}$, $t_{\text{fill}}=0.75\text{s}$, $T_{\text{REG}}=930^{\circ}\text{C}$, $T_{\text{SCC}}=190^{\circ}\text{C}$

$p_{\text{SCC}} \approx 100 \dots 130 \text{ bar}$

$T_{\text{SCC}} > 900 \text{ K}$

$u=15 \dots 25 \text{ m/s}$

@ 0.6 ... 1.0 s

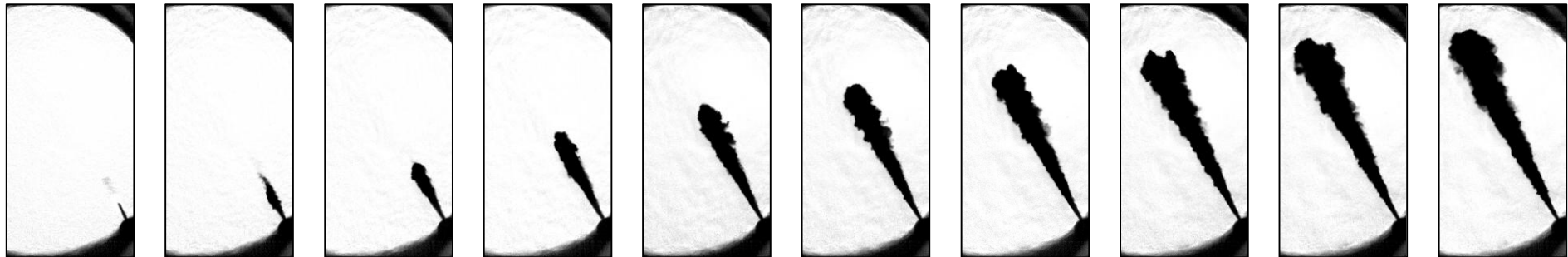


SCC conditions (p_{SCC} , T_{SCC}) $\Rightarrow$ adjusted by p_{bottle} , T_{REG} , t_{fill}

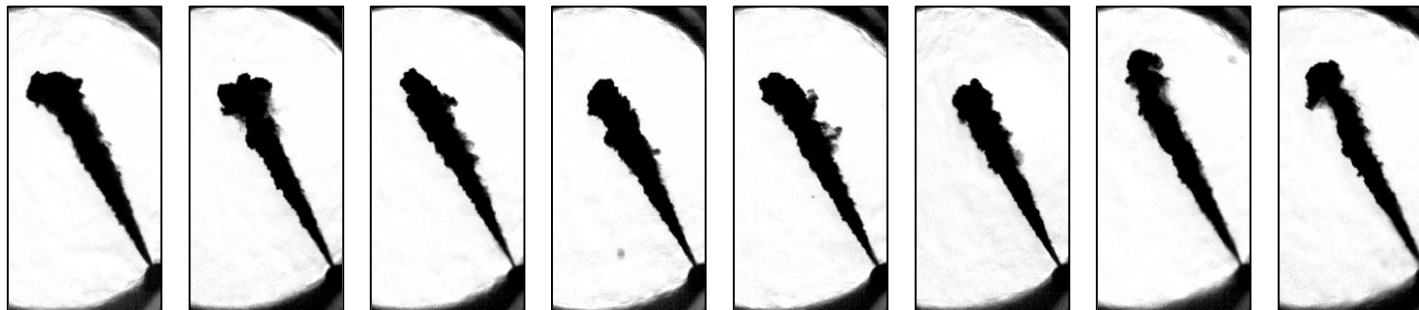
Spray Measurement

non-reactive (N_2)

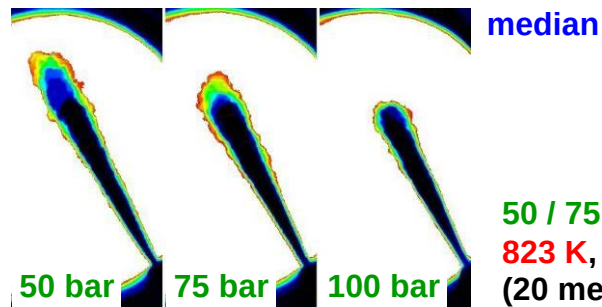
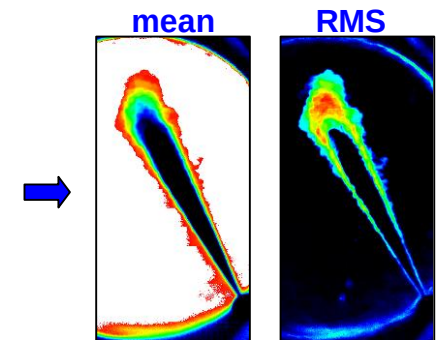
Spray evolution: angle & penetration (liquid phase)



75 bar, 823 K @ 20 kHz (50 μ s)

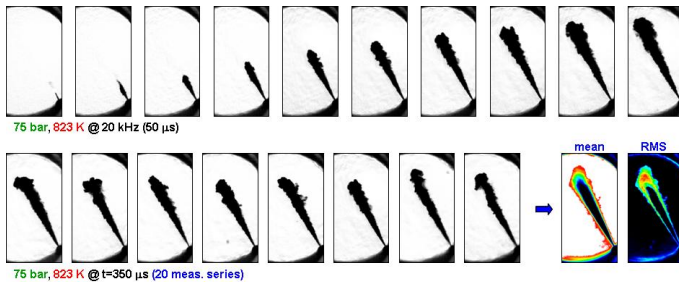
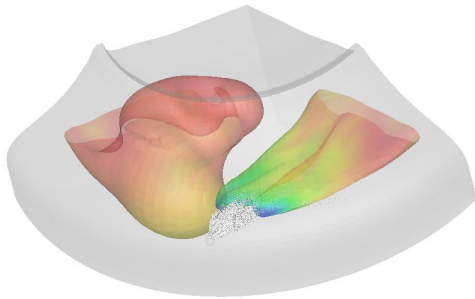
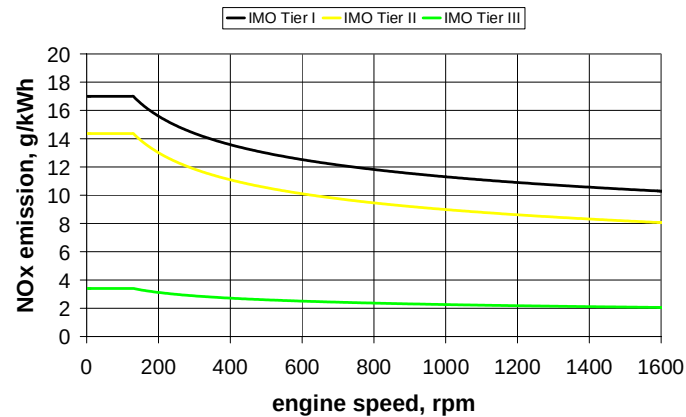


75 bar, 823 K @ t=350 μ s (20 meas. series)



50 / 75 / 100 bar
823 K, t=300 μ s
(20 meas. series)

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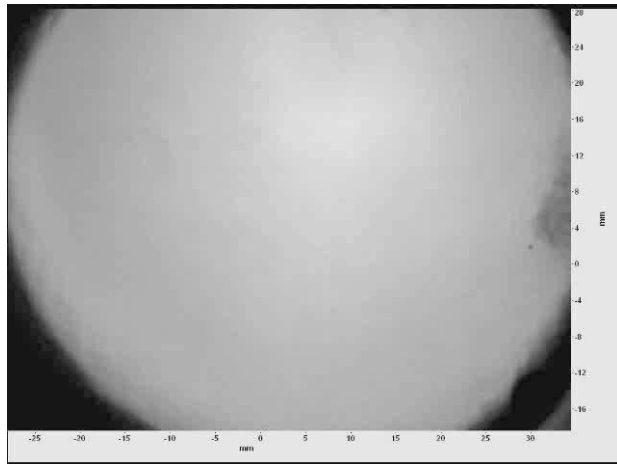
Shadow-Imaging

injection duration 36 ms
movie sequence duration 40 ms

reactive (air)

Illumination

common light source (Arc, QTH)



exposure time: 4 μ s

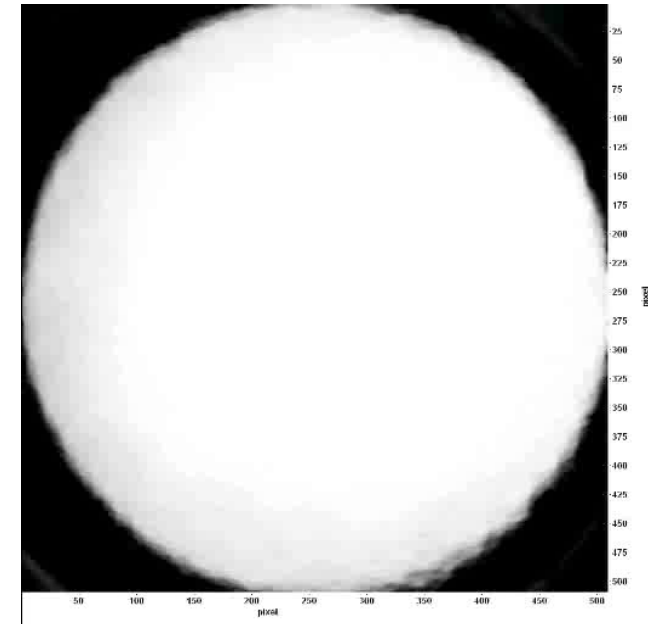
20 kHz (frame/50 μ s)

SCC: 90 bar / 930 K

2-hole
nozzle tip

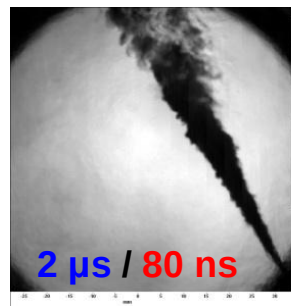
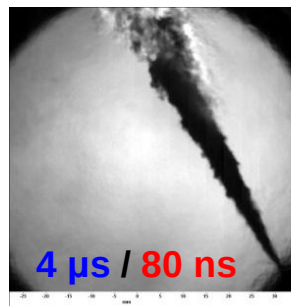
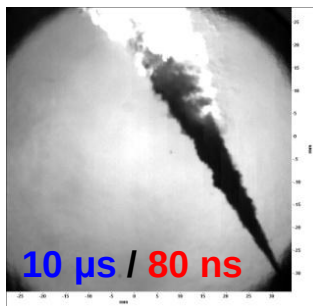
2-hole
nozzle tip

pulsed diode laser



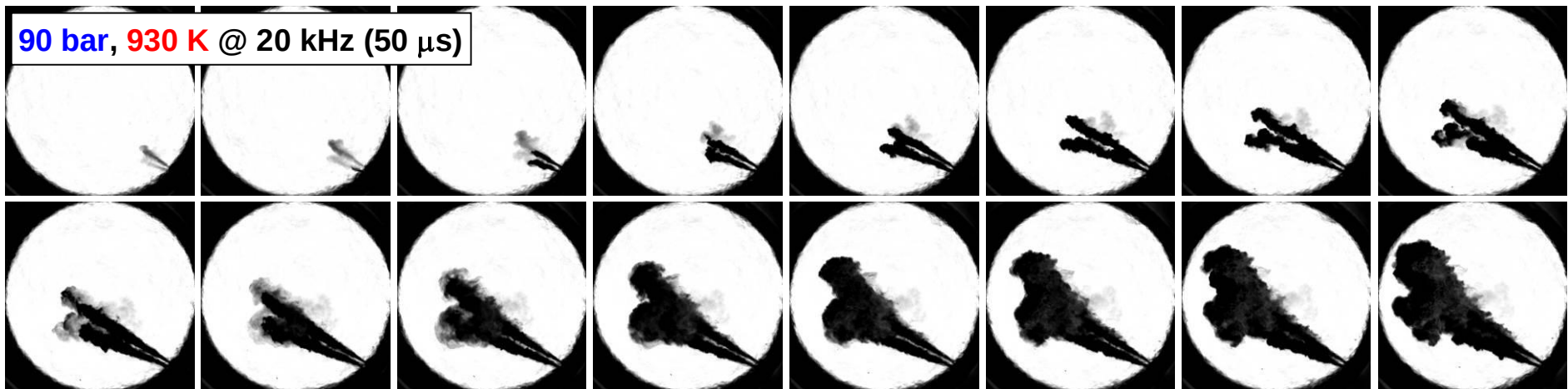
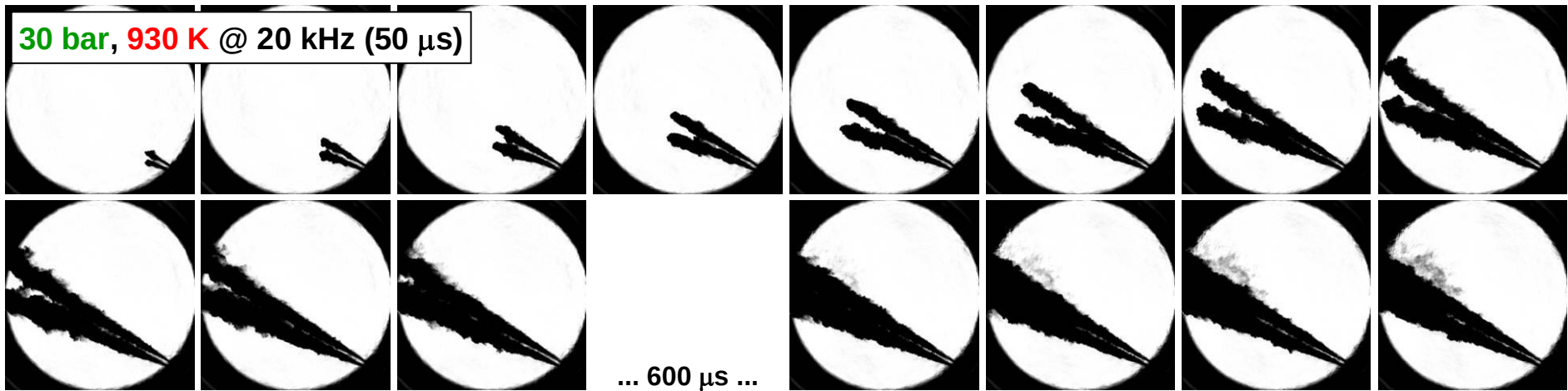
exposure time: 1 μ s / 50 ns laser pulse

Flame light blocking filter (690 nm)



Spray Measurement

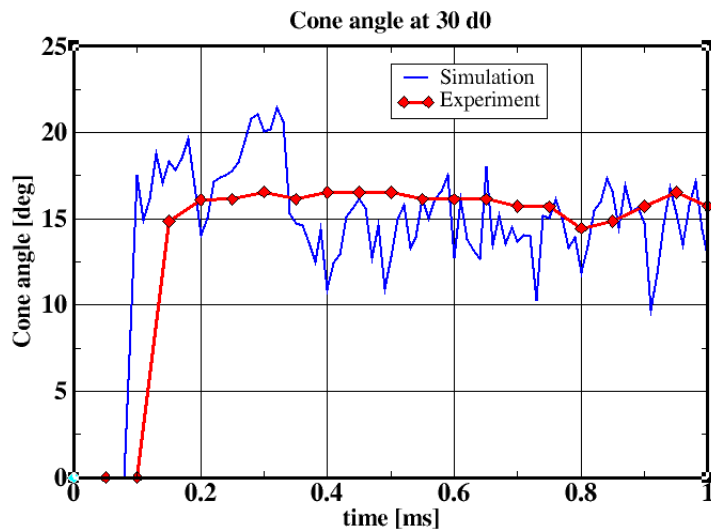
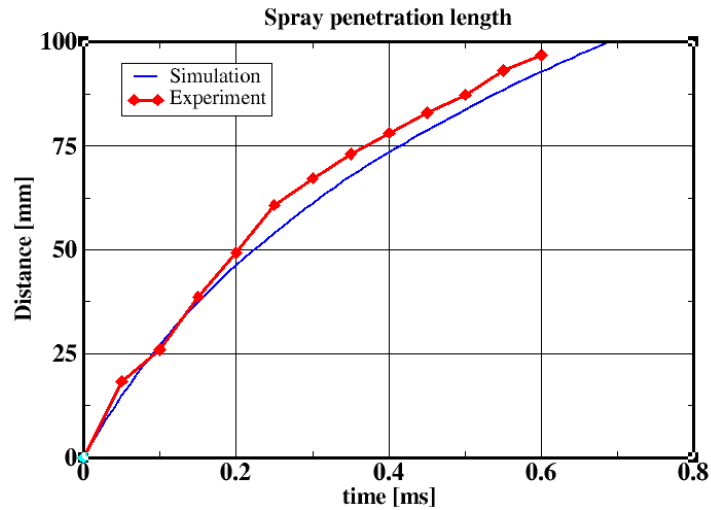
Spray evolution: angle & penetration (liquid phase)



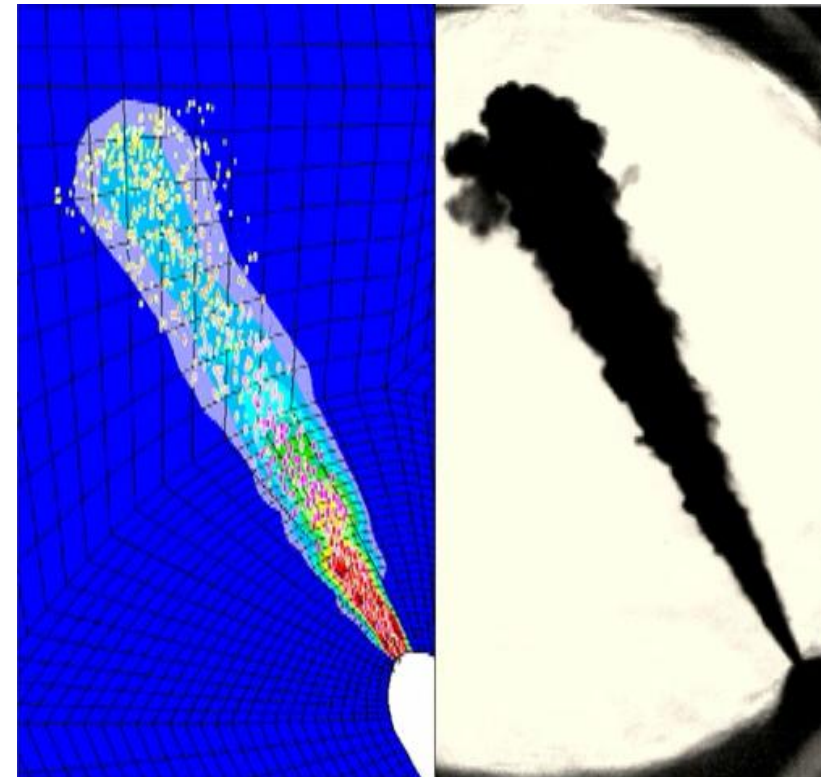
Spray Analysis

*M. Bolla, Y. Wright (ETH) LAV 

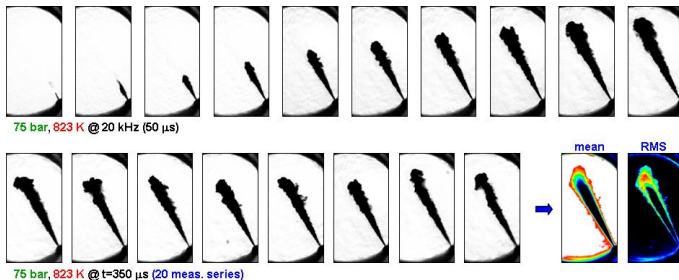
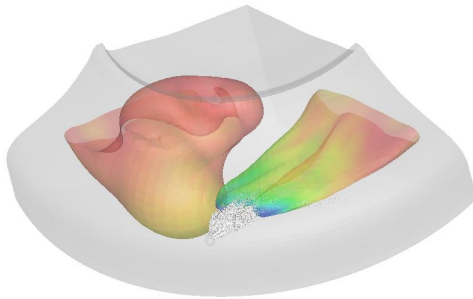
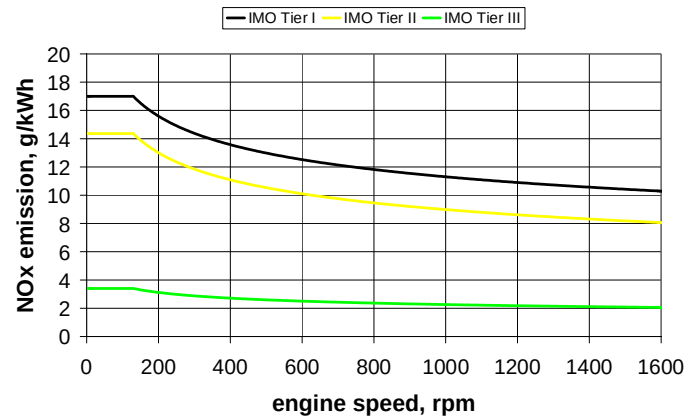
Spray model comparison



... (analysis) work in progress !!!



Presentation outline

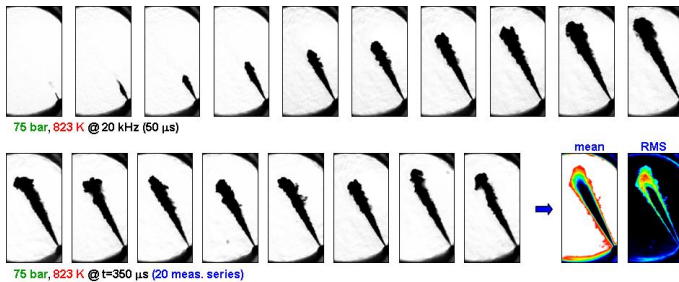
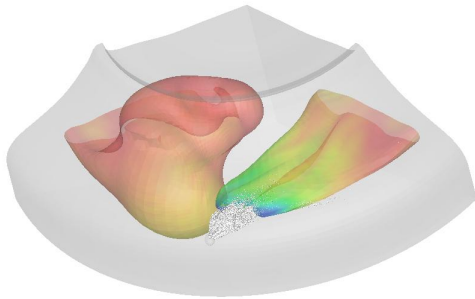
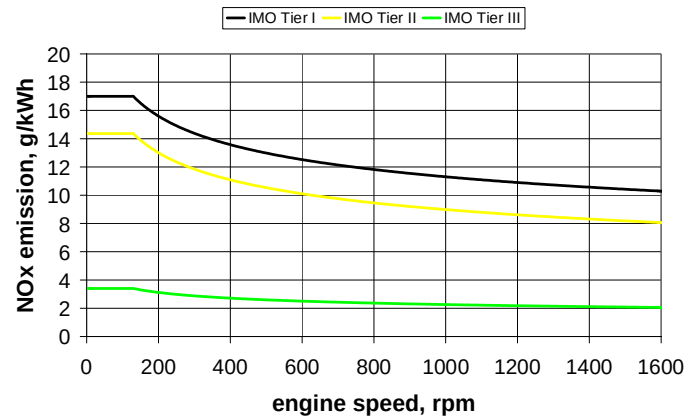


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Conclusions

- The changing requirements resulting from recent developments in the marine industry (environmental regulations as well as fuel quality trends) make the more thorough optimization of combustion on large marine engines indispensable
- For this purpose, appropriate tools are needed, both for supporting the development by means of sufficiently accurate simulations and for experimentally studying the effect of key parameters
- The spray combustion chamber takes a key role in this context – by providing reference data for the validation of simulation tools at relevant conditions and by allowing a direct verification of the effect of some design features
- Continuous further development will ensure that the potential of this device can be fully exploited, both regarding operational parameters and measurement methods

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Acknowledgment

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 - State Secretariat for Education and Research (under EC's fp6)
 - European Commission (fp7)
 - Federal Office of Energy
- Achieving progress in this field requires competent partners:
 - ETH Zürich (IET/LAV – Bolla, von Rotz, Wright, Boulouchos, ...)
 - Paul Scherrer Institute (Bombach, Stettler, Jansohn, ...)
 - Wärtsilä Switzerland (Herrmann, Kyrtatos, Schulz, ...)



Thank you for your interest

German Weisser

Dr. sc. techn.
Head of Engine Performance
Project Manager HERCULES
Research & Development
Wärtsilä 2-stroke Engines

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www.wartsila.com



“Influences of Alternative Fuels GTL, RME & ROR on Combustion and Emissions of a Modern HD-Diesel Engine”

Czerwinski Jan, Zimmerli Yan,
University of Applied Sciences, Biel-Bienne, CH
Heitzer Armin,
Erdöl-Vereinigung, Zürich, CH
Kasper Markus,
Matter Engineering AG, Wohlen, CH



with support of the

Swiss Oil Association

FEV ...

Forschungsfonds

Erdöl

Vereinigung

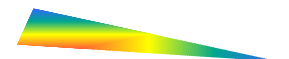
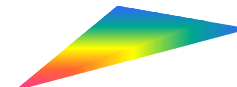
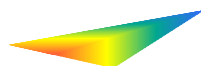
Fuel properties as per EU-standards and further analysis of the test fuels

		Diesel	GTL	RME	ROR
Density at 15°C	g/m	0.842*	0.790*	0.885*	0.925*
Viscosity at 40°C	mm ² /s	2.0 - 4.5	3.5*	4.6*	34.9*
Flash point		above 55°C	101°C	143°C	245°C
Cloud point		max -10°C	-0.5°C	-	-
Filterability CFPP		max -20°C	-1°C	-15	+15°C
Ash	%	max 0.010	0.001	Traces	0.004
Sulfur	ppm	<10	<5.0*	1.3*	2.0 *
Cetane Number		51	79	56	40 - 44
Calorific value	MJ/kg	42.7	43.8	37.2	37.0
C fraction	in %	86.7	85.0	77.5	77.5
H fraction	in %	13.3	15.0	11.8	11.5
O fraction	in %	0	-	10.7	11.0
Air _{min}	kg/kg	14.52	14.91	12.49	12.37
Boiling range 10-90% °C		180 - 340	246 - 342	315 - 360	315 - 360

* measured values

Data of the lube oil used for this study

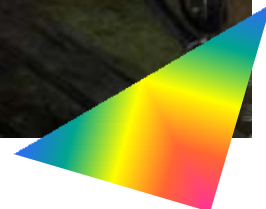
Property	Lubrizol	
Viscosity kin 40°C	104.8	mm ² /s
Viscosity kin 100°C	14.22	mm ² /s
Viscosity index	139	(--)
Density 20°C	-	kg/m ³
Pourpoint	-25	
Total Base Number TBN	13.5	mg KOH/g
Sulfur ashes	18'000	mg/kg
Sulfur	6'500	mg/kg
Mg	< 10	mg/kg
Zn	1'270	mg/kg
Ca	4'730	mg/kg
P	1'160	mg/kg



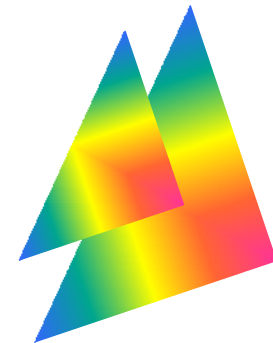
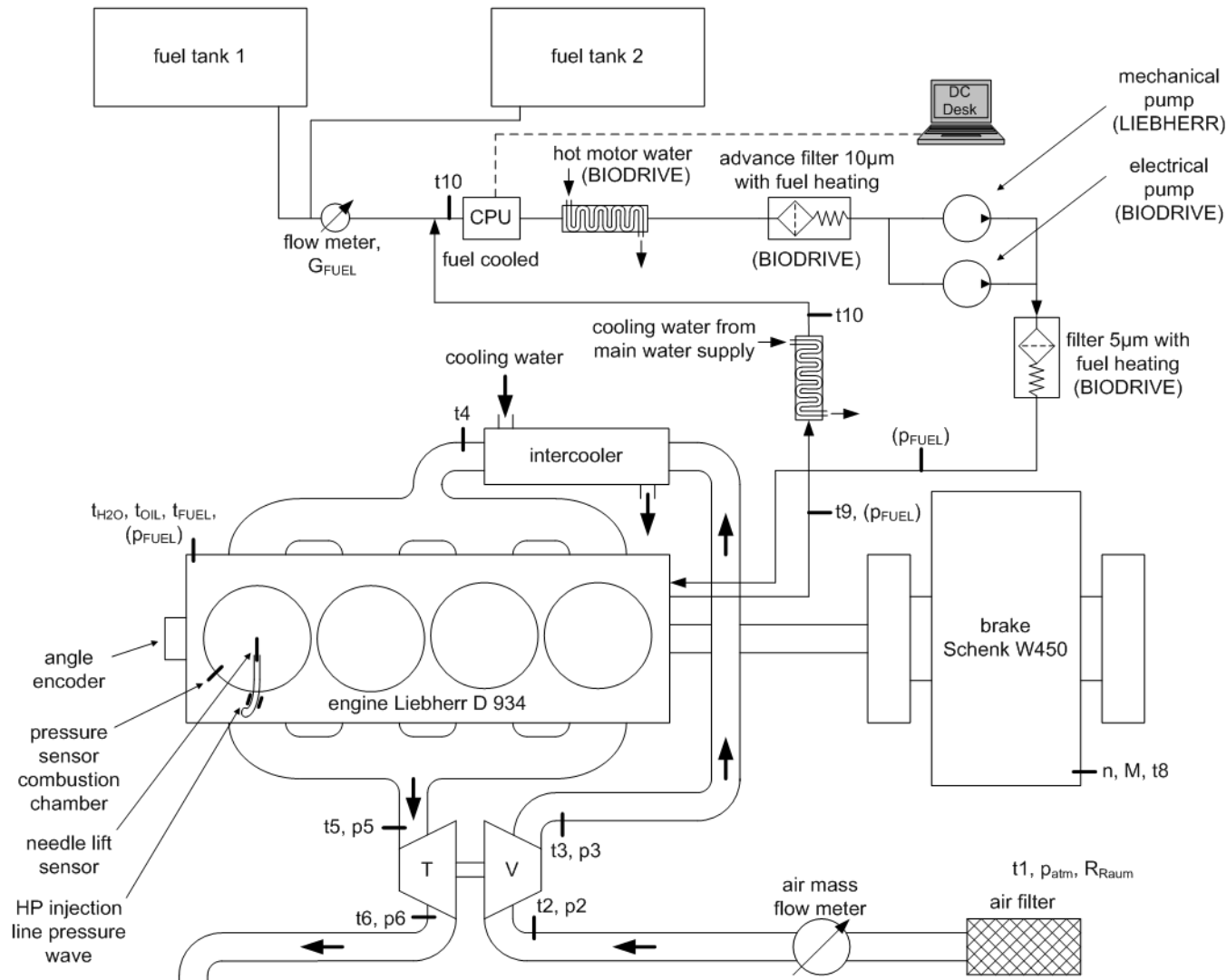


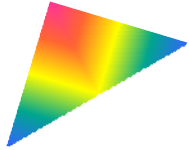
TEST ENGINE

Manufacturer:	Liebherr Machines Bulle S.A., Bulle/Fribourg
Type:	D934 L
Cylinder volume:	7.01 Liters
Rated RPM:	2000 min⁻¹
Rated power:	140 kW
Model:	4 cylinder in-line
Combustion process:	direct injection
Injection pump:	Bosch unit pumps
Supercharging:	Turbocharger with intercooling

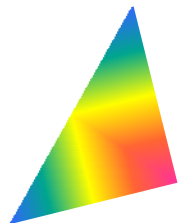
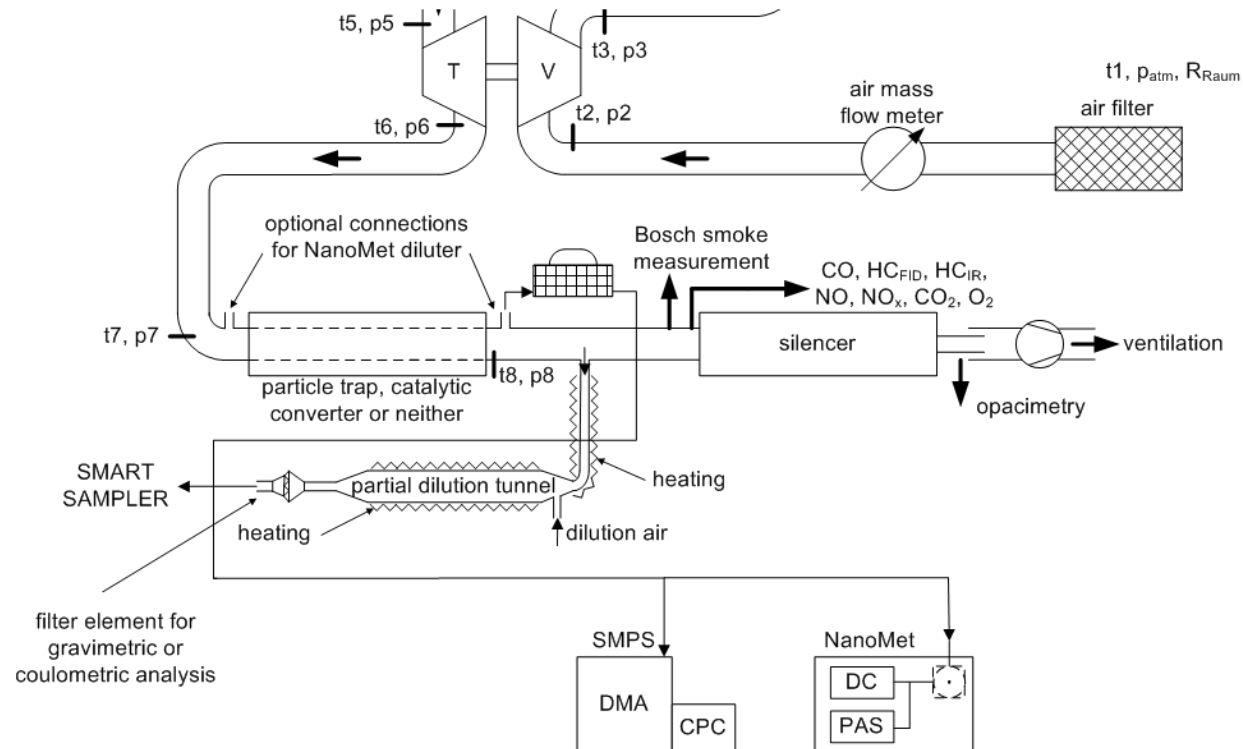


Schematic test bench -1-

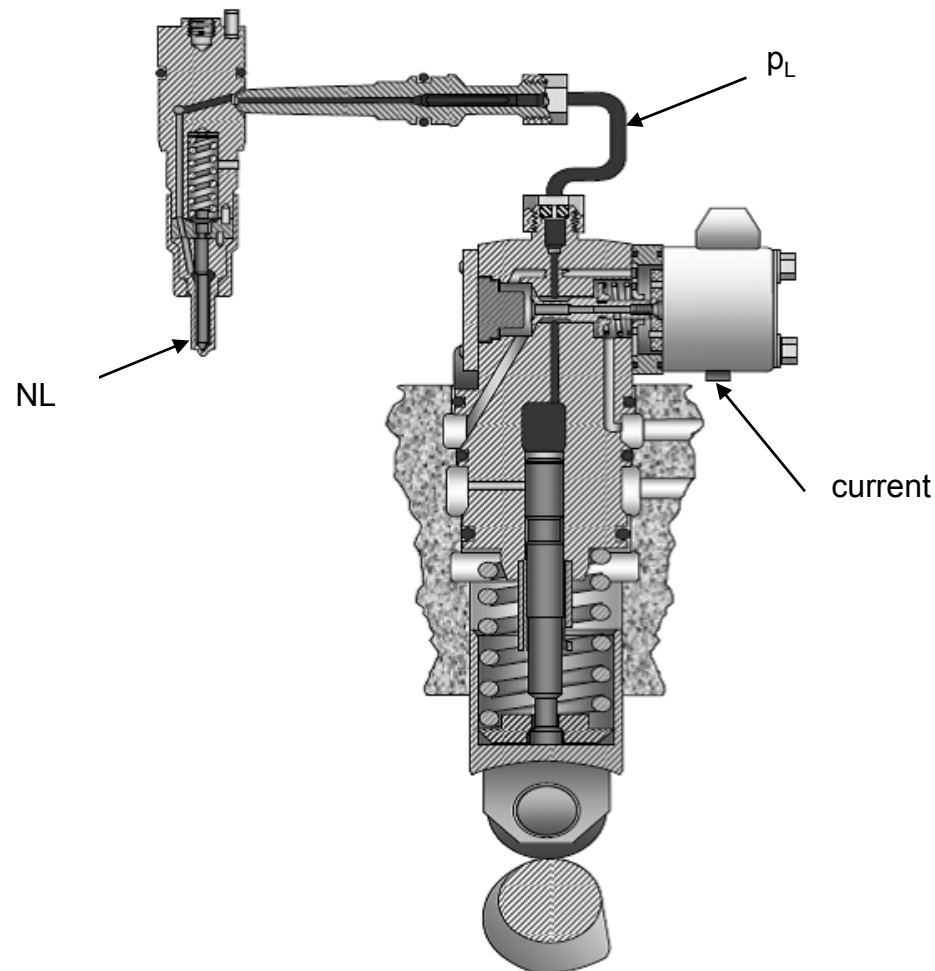


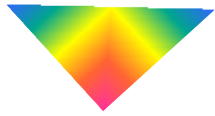


Schematic test bench -2-

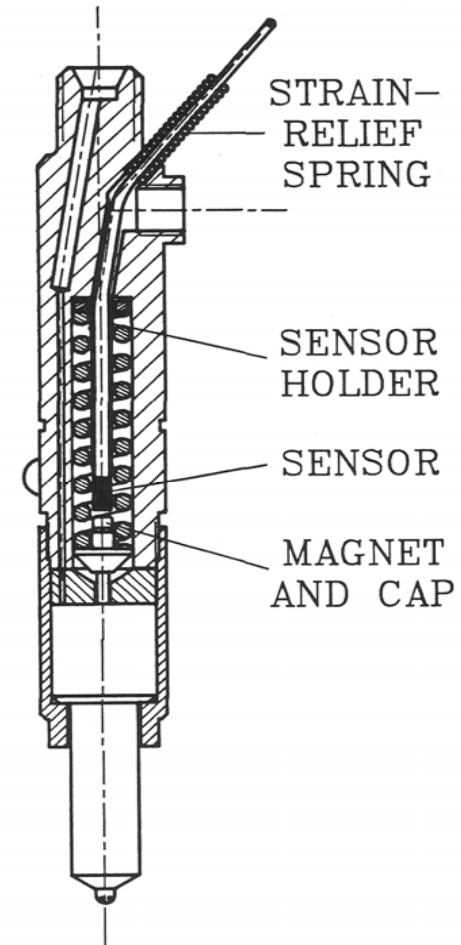
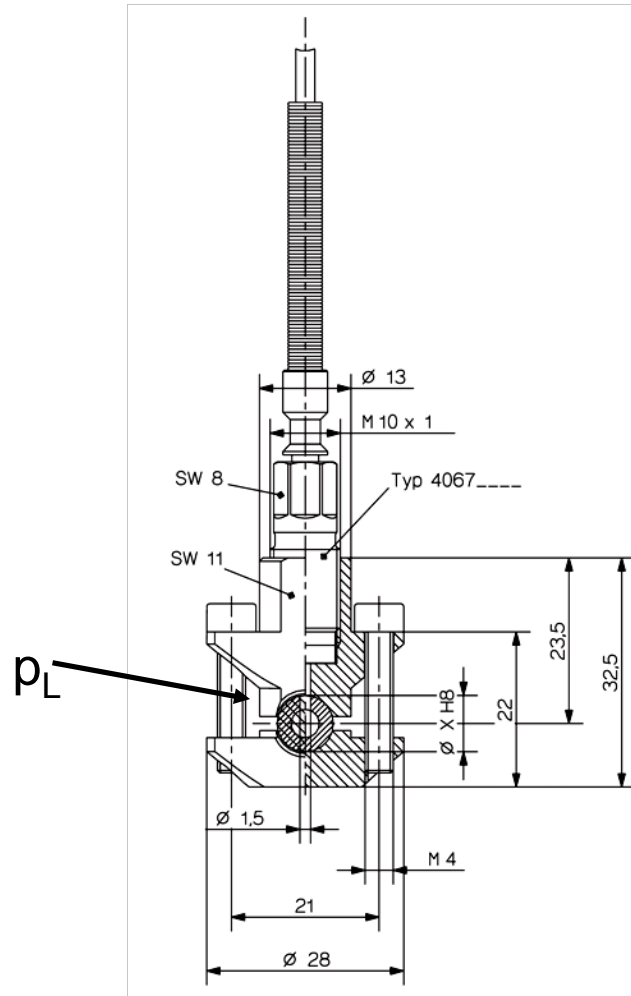


Bosch unit pump and positions of parameter measurements

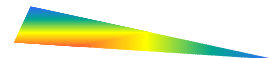
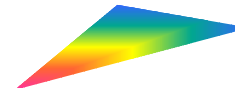
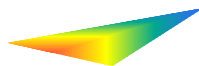
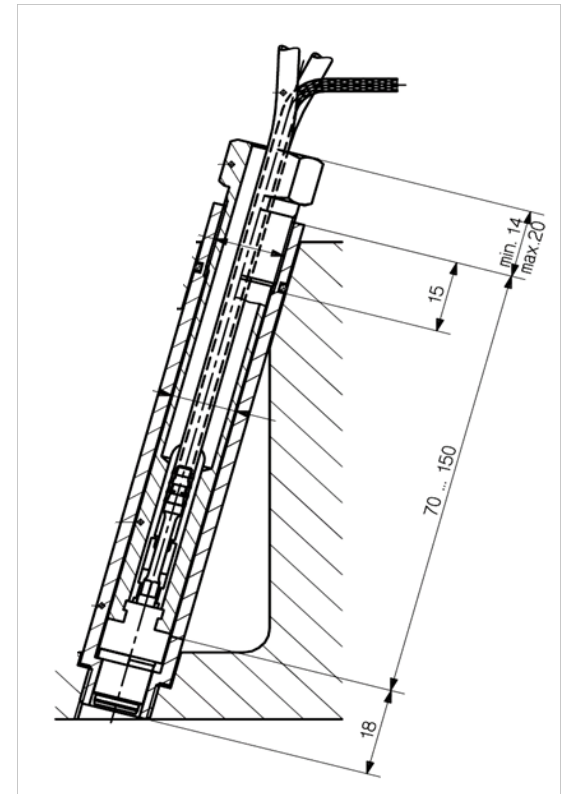
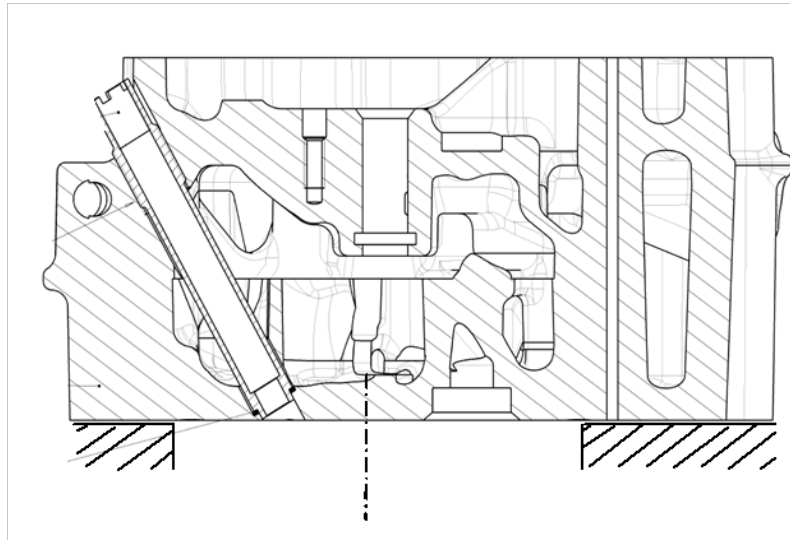




Kistler sensor for high pressure injection line & Wolff needle lift sensor

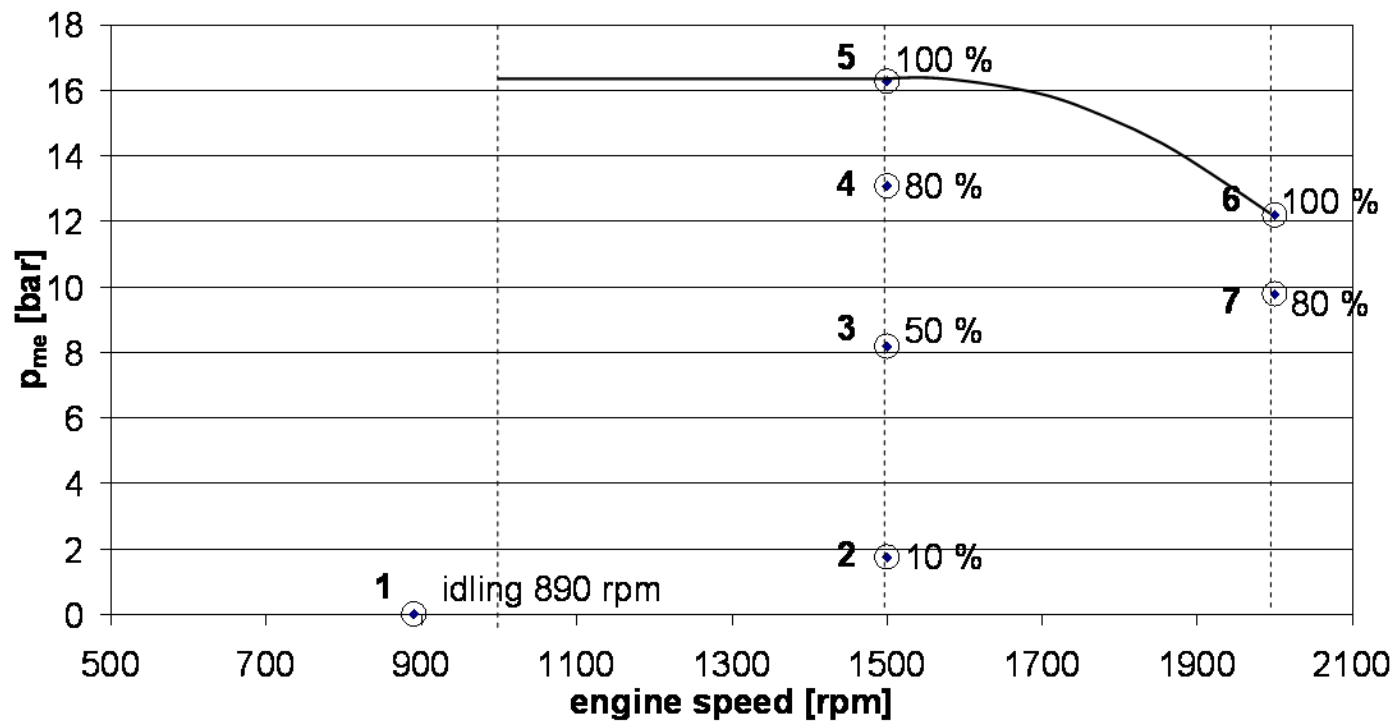


Cylinder head and pressure transducer for pressure indication in combustion chamber (p_i)



Operating points in the test programm

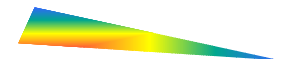
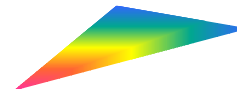
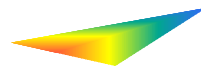
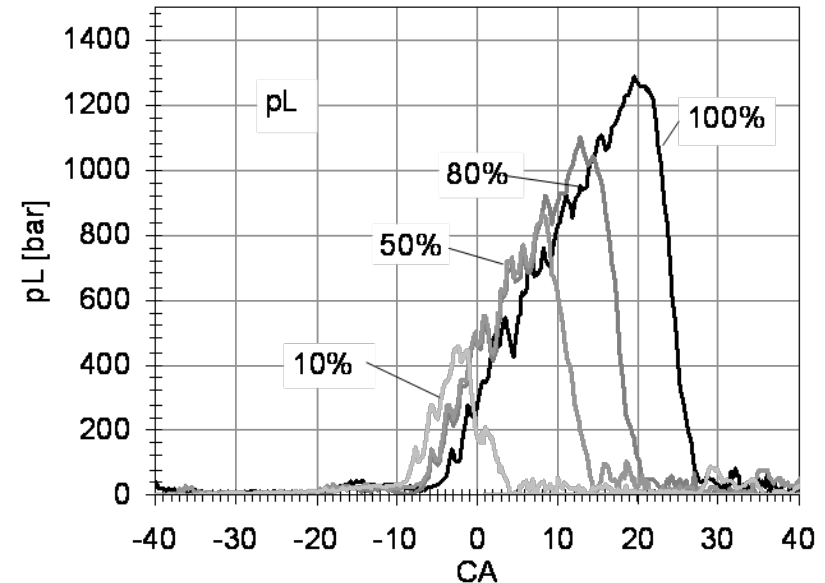
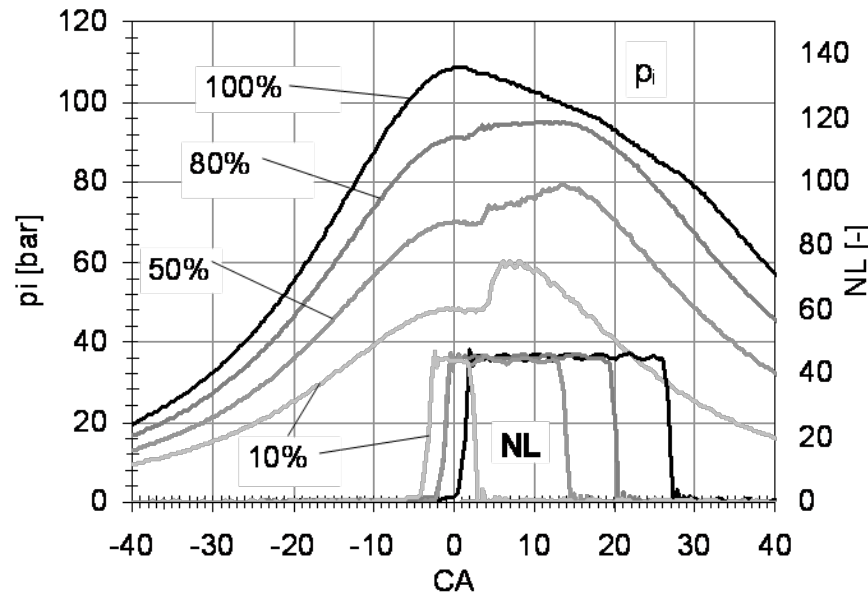
engine LIEBHERR D 934 LA 6



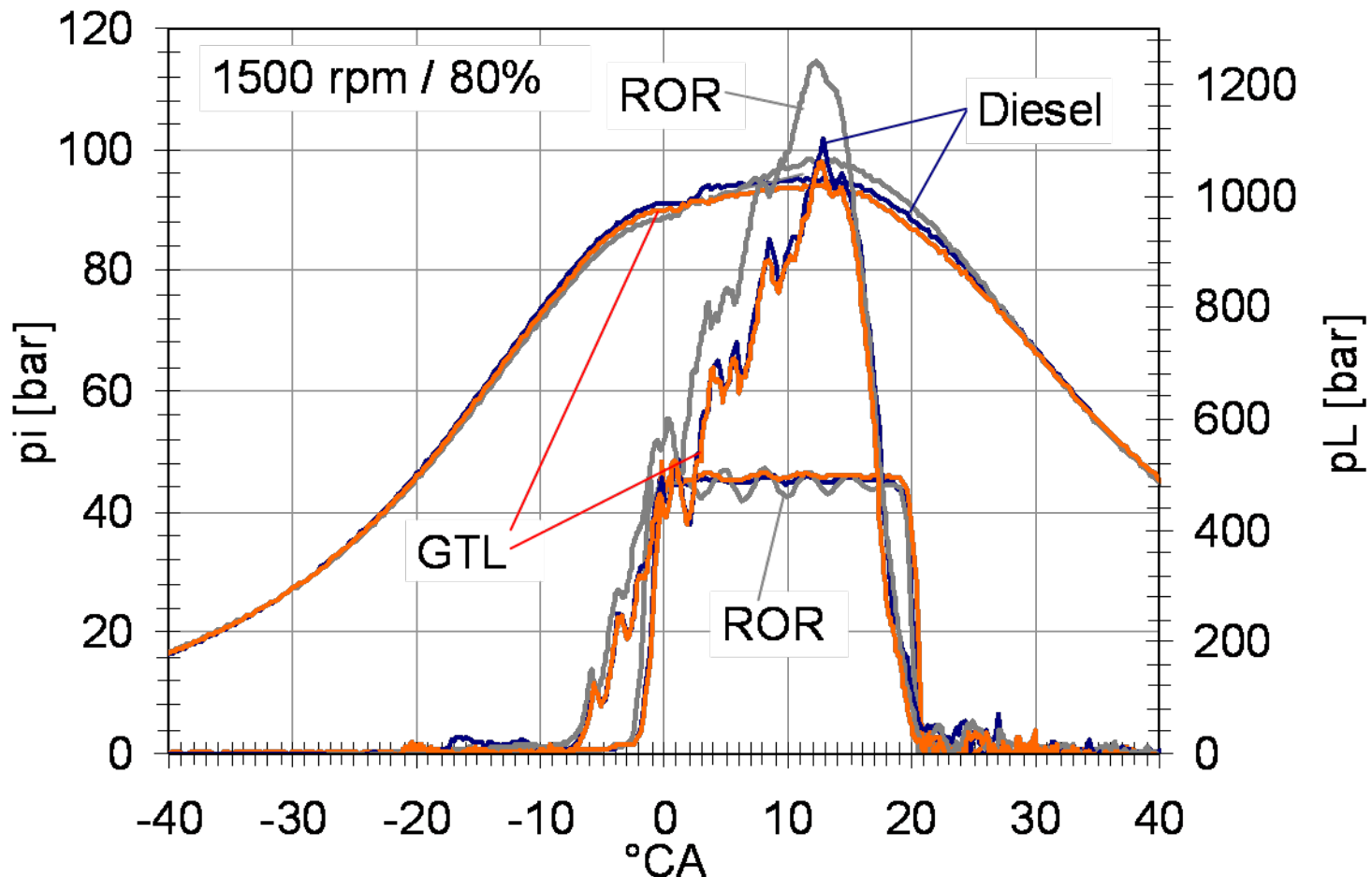


Injection & Combustion

Injection line pressure p_L , needle lift NL and indicated combustion pressure p_i , at constant speed (1500 rpm) and increasing load.



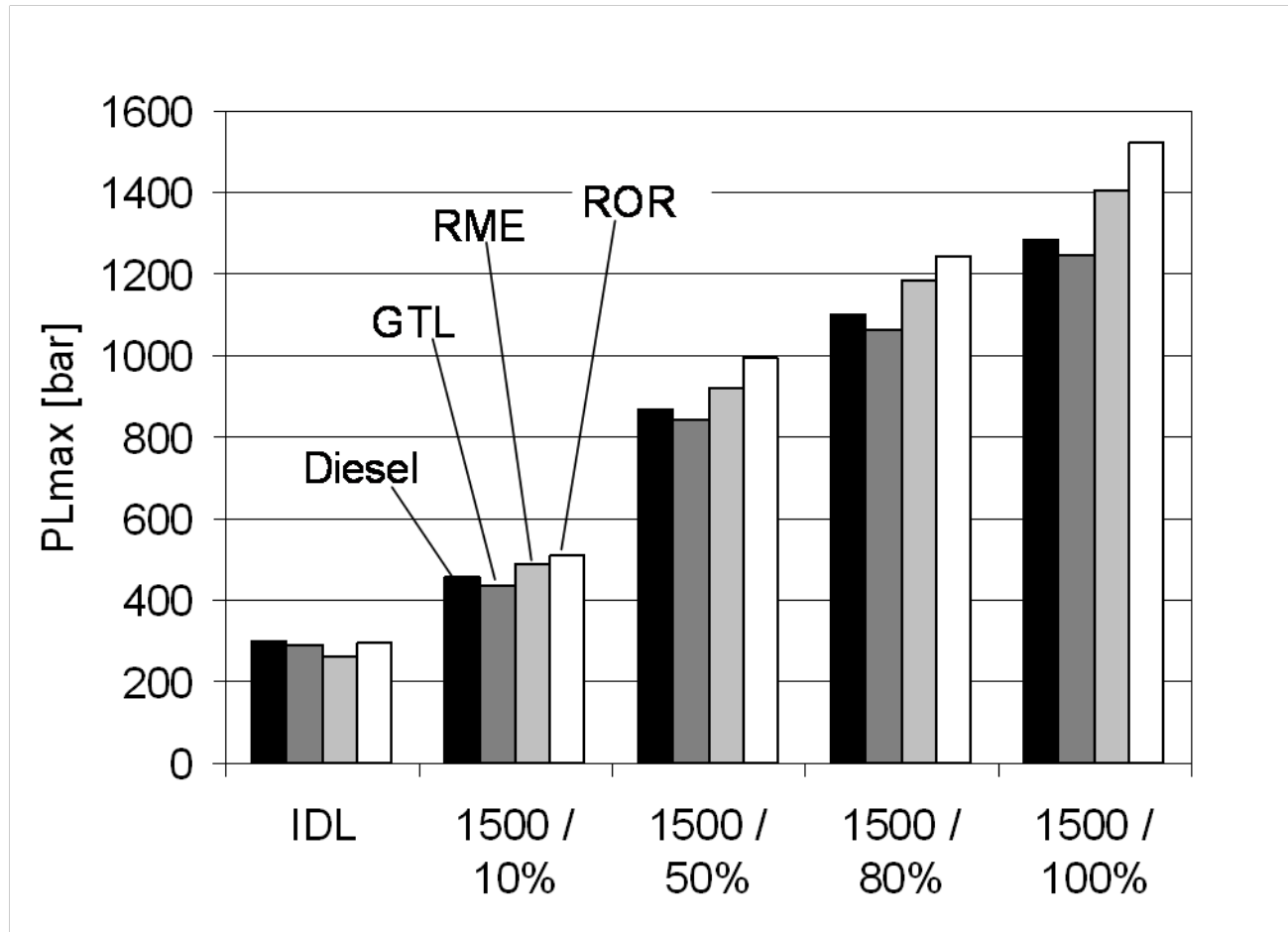
Comparison of indication and injection parameters DIESEL - ROR - GTL

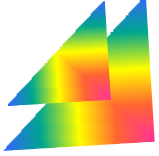


Torque and power at middle speed & FL

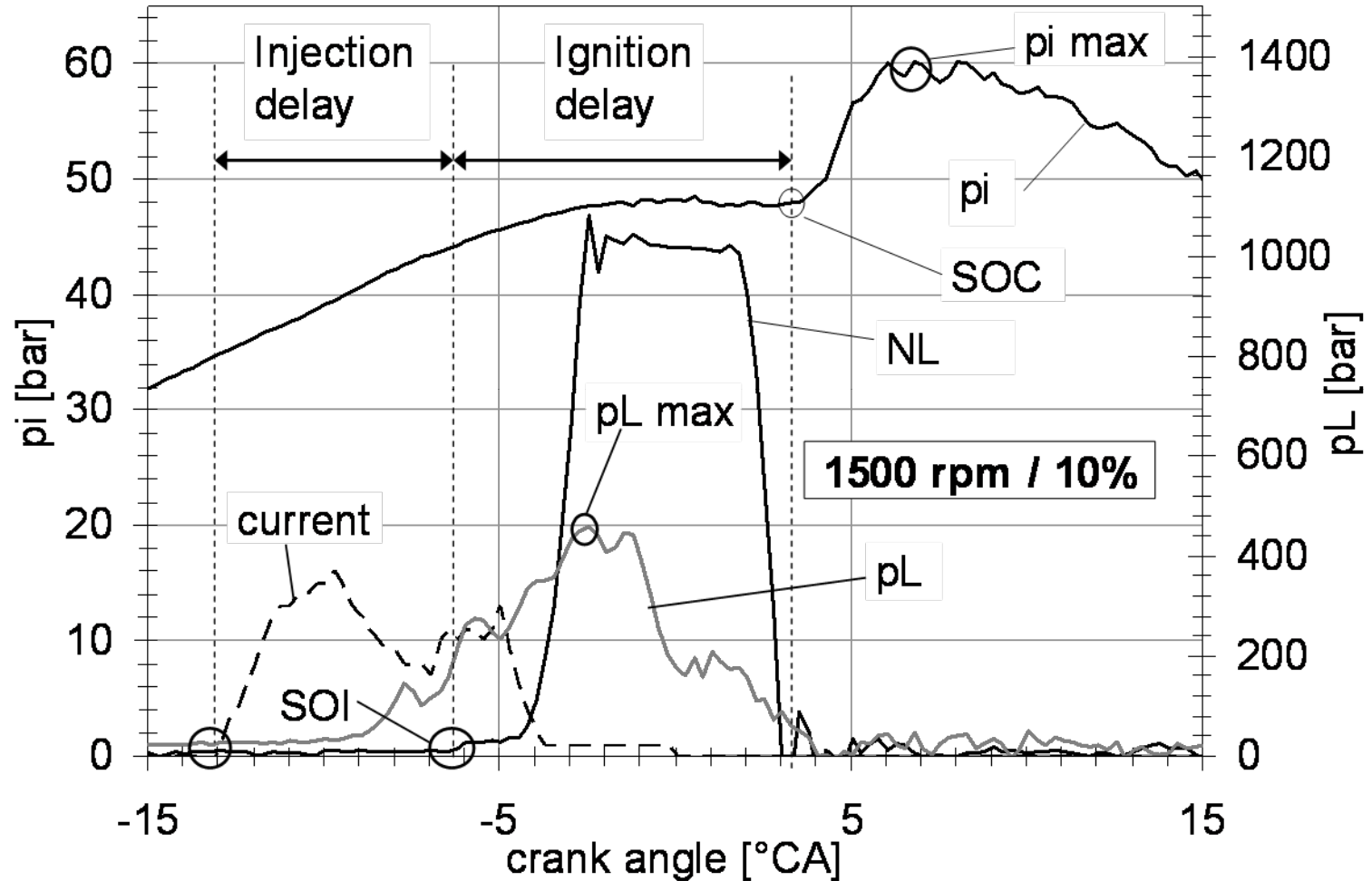
1500 rpm/FL	Diesel	GTL	RME	ROR
M [Nm]	908	890	875	898
Pe [kW]	142.8	139.8	137.6	141.0
% Diesel	100%	98.0	96.4	98.9

Maximum injection pressures with 4 fuels

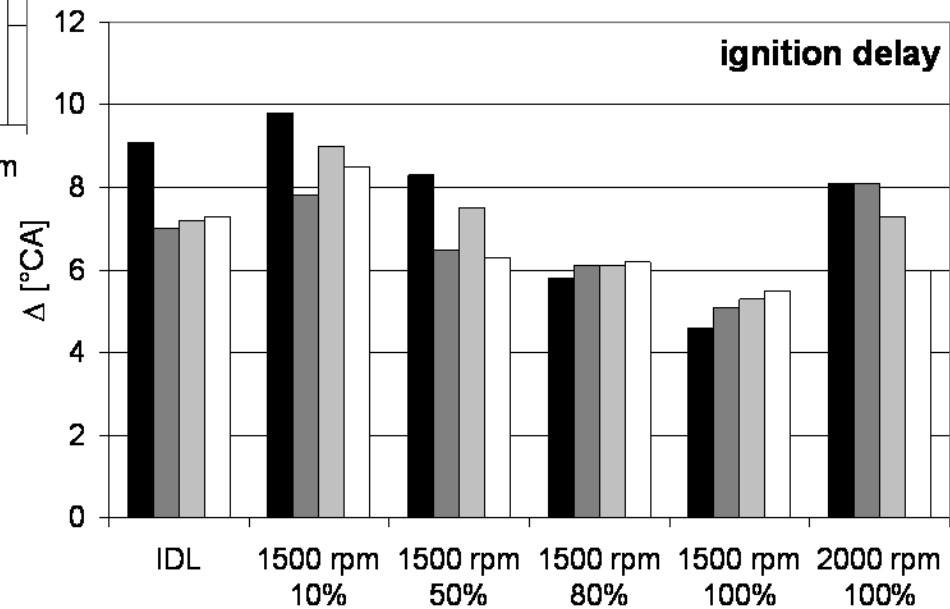
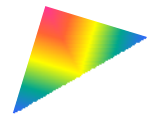
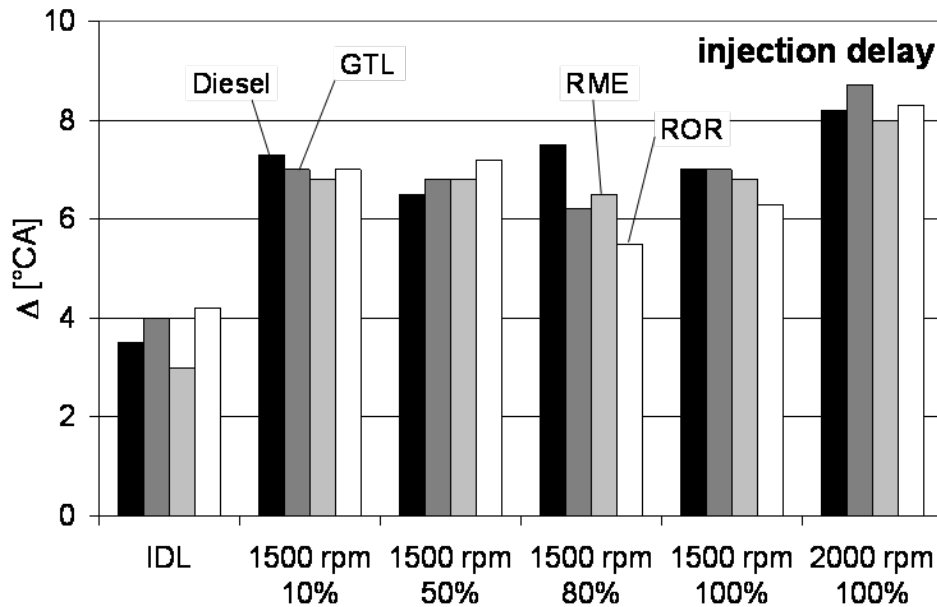
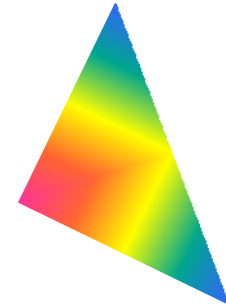


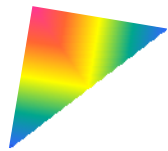


Definition of fuel injection and pressure indication points

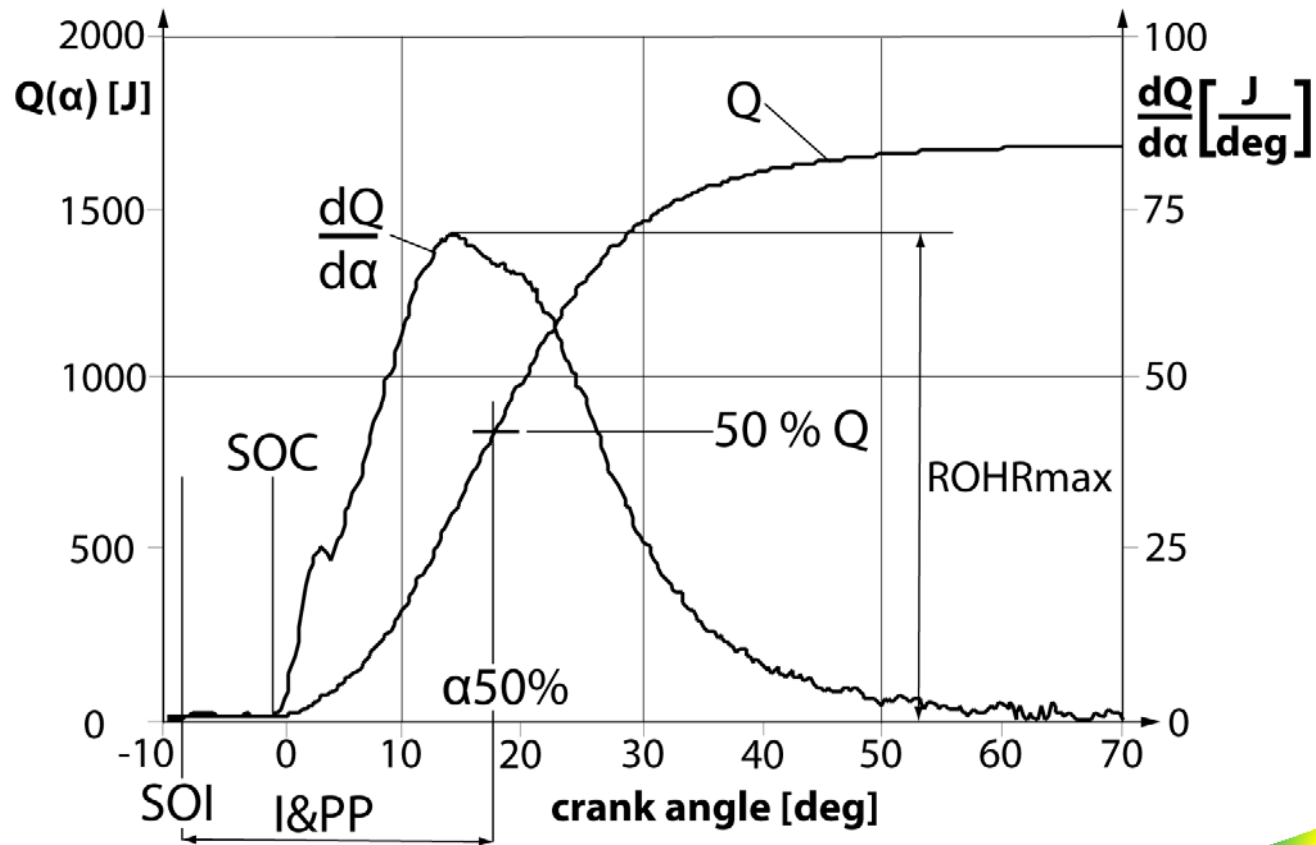


Injection delay and ignition lag for 4 basic fuels





Definition of heat release parameters



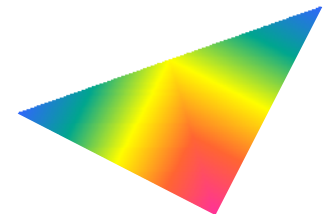
ROHRmax:

maximum rate of heat release

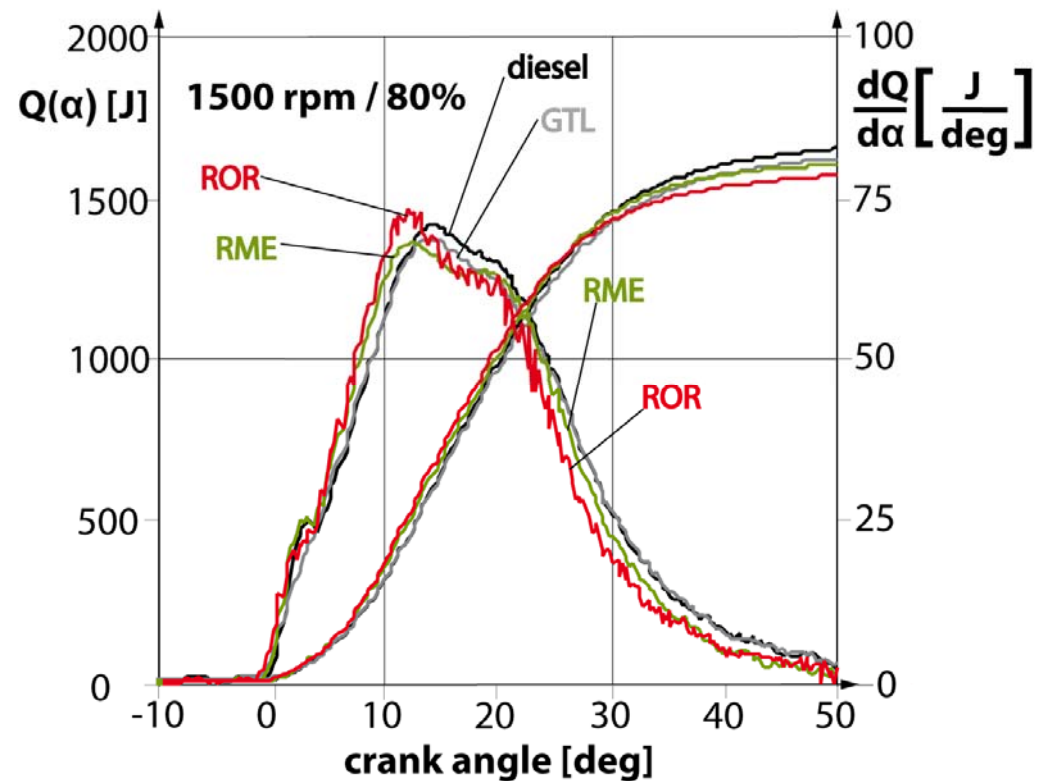
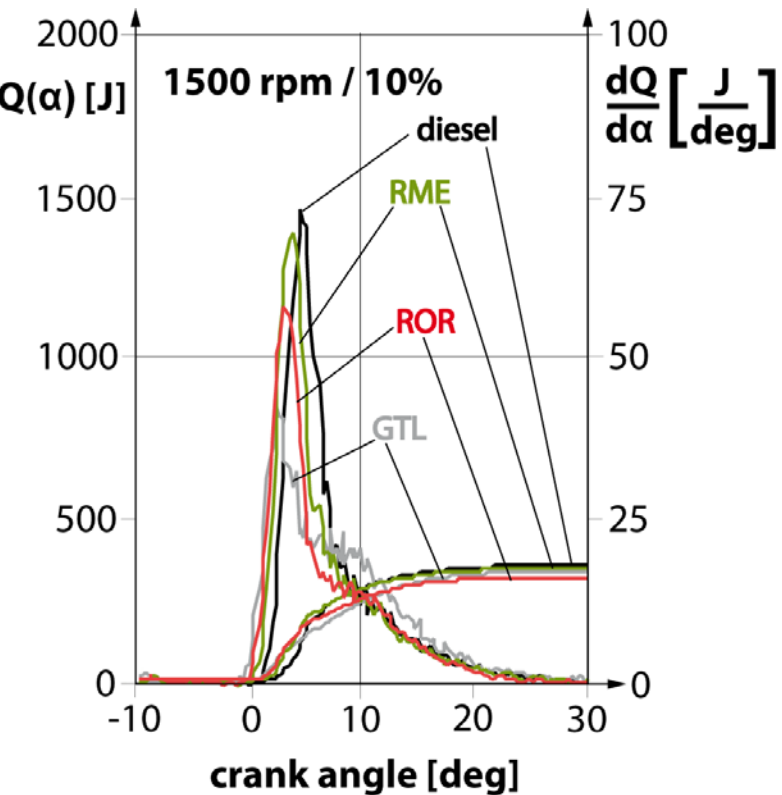
I&PP:

inflammation and premixed phase

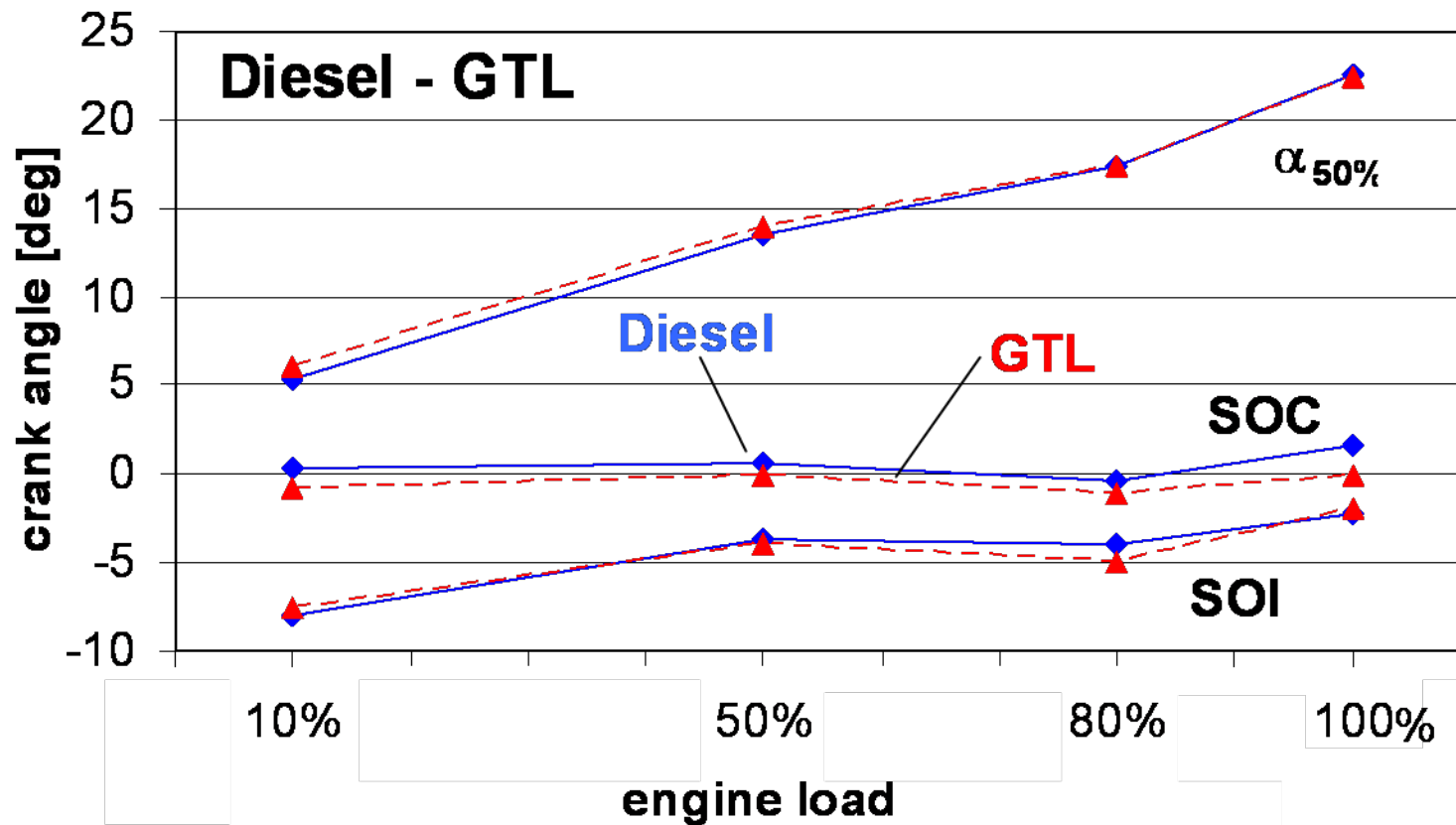
(including mixture preparation and ignition lag)



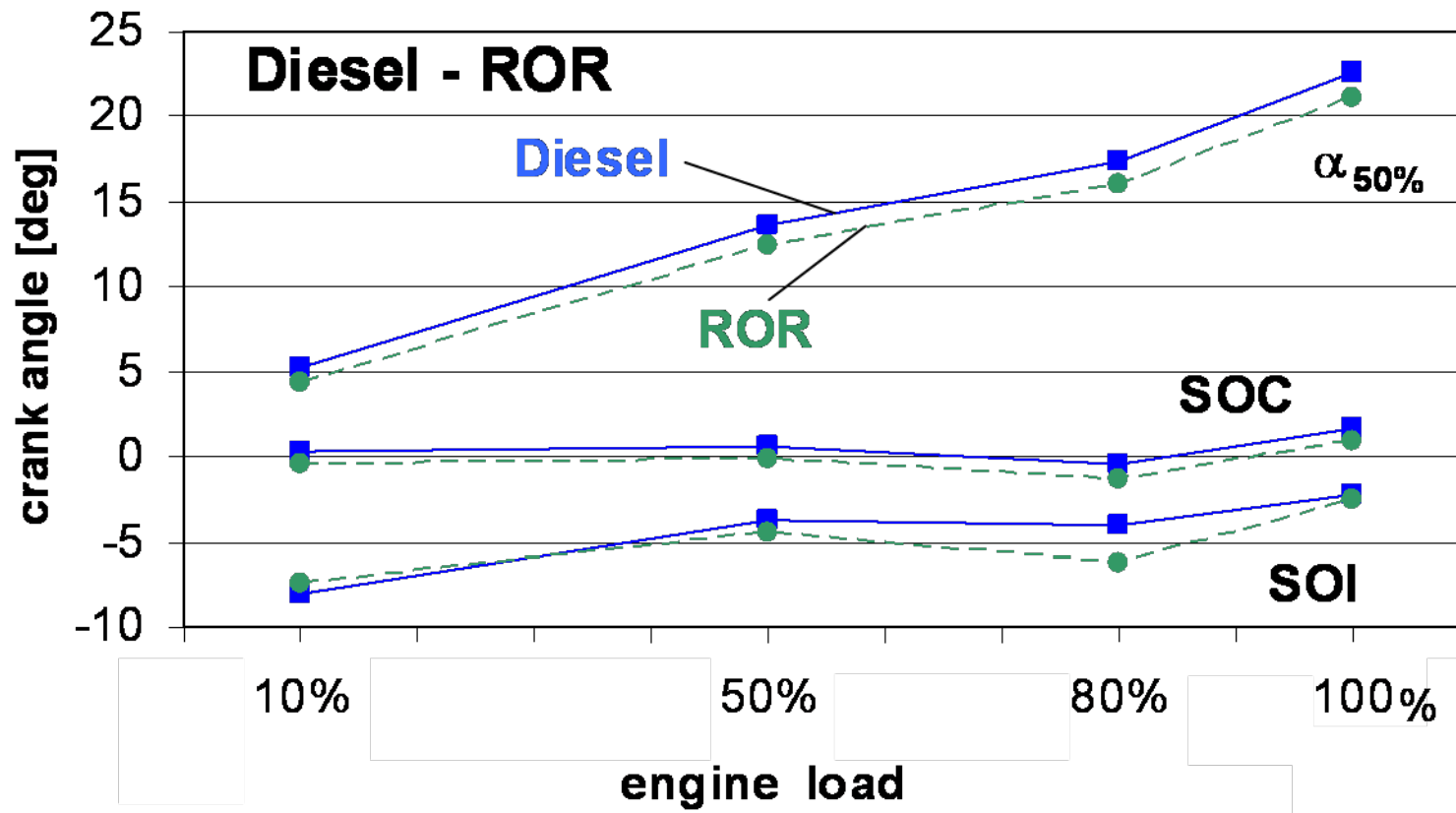
Heat release with 4 basic fuels



Injection and combustion progress with different fuels at 1500 rpm



Injection and combustion progress with different fuels at 1500 rpm

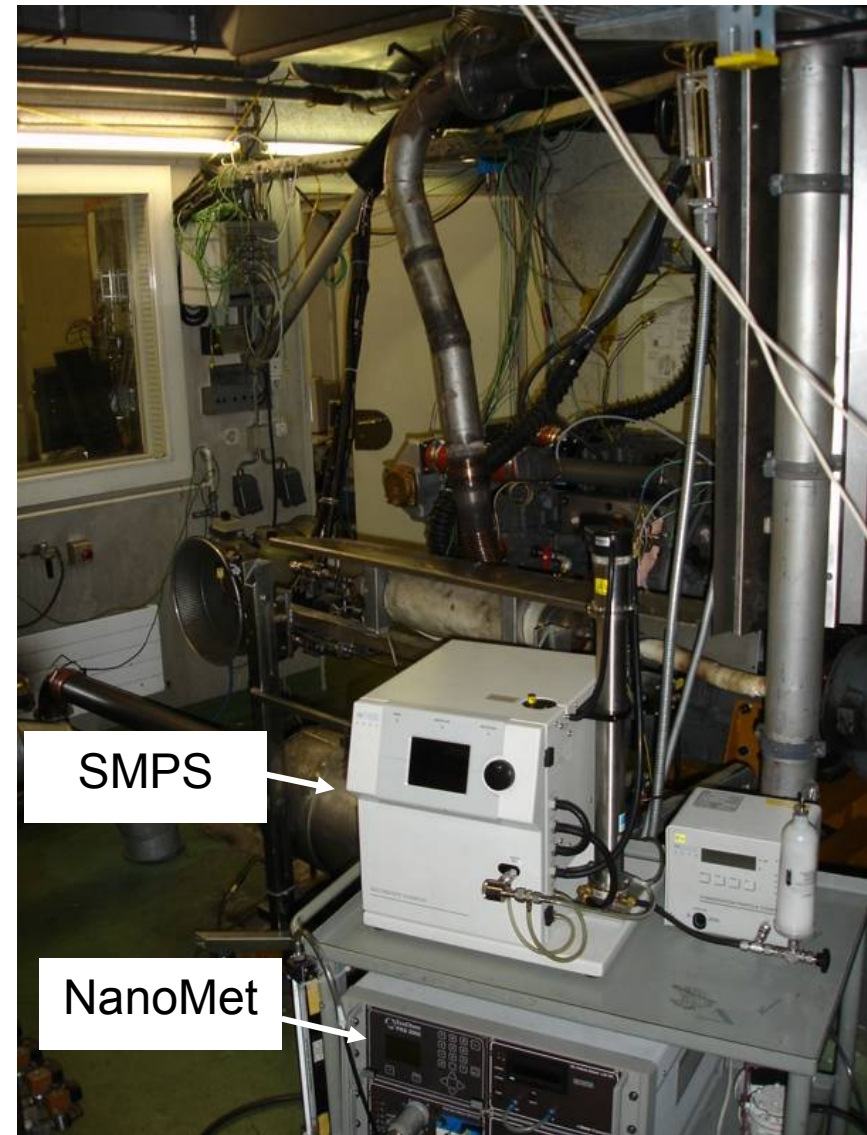




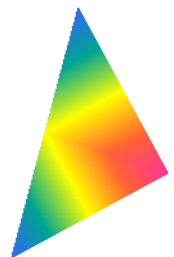
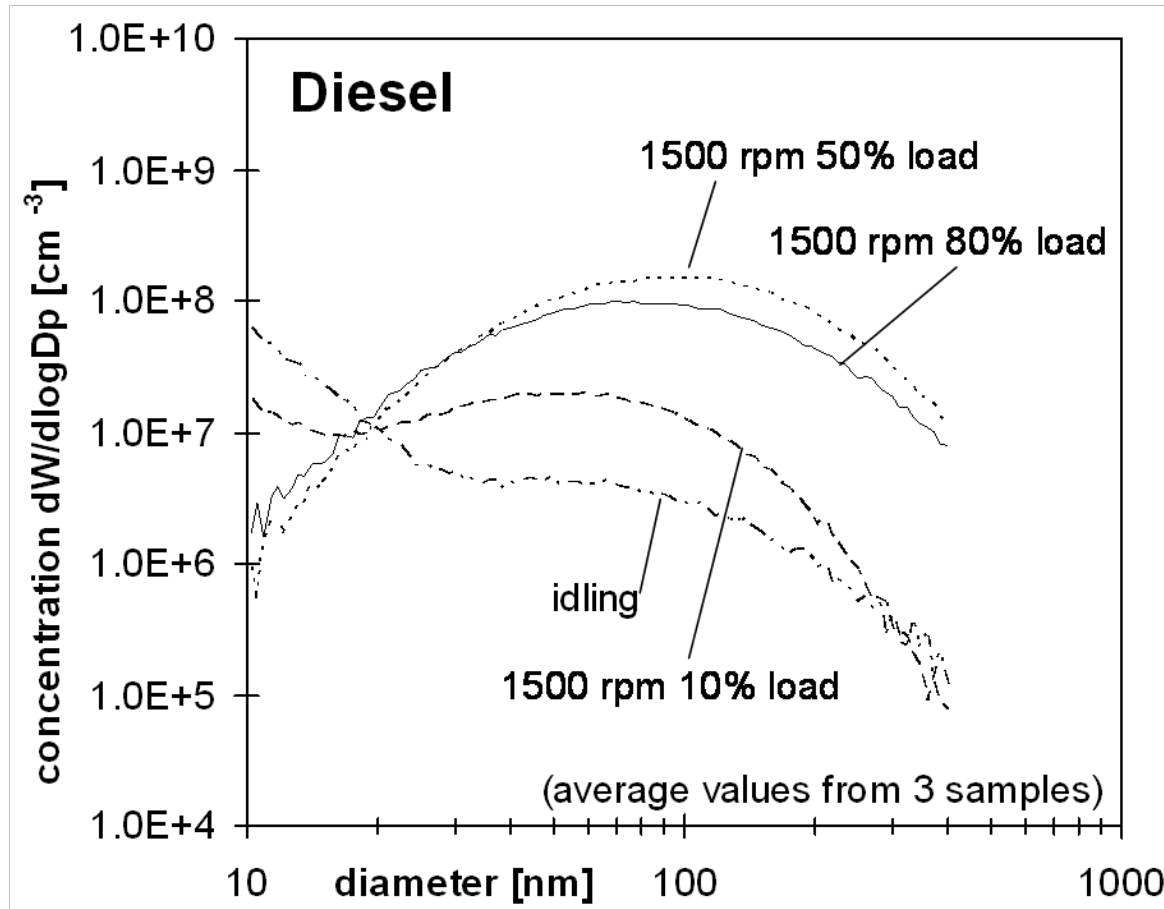
Limited emissions & Nanoparticles

PARTICLE SIZE ANALYSIS

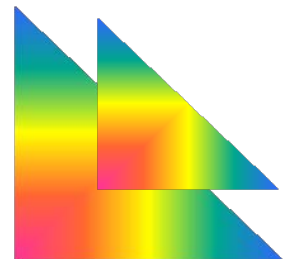
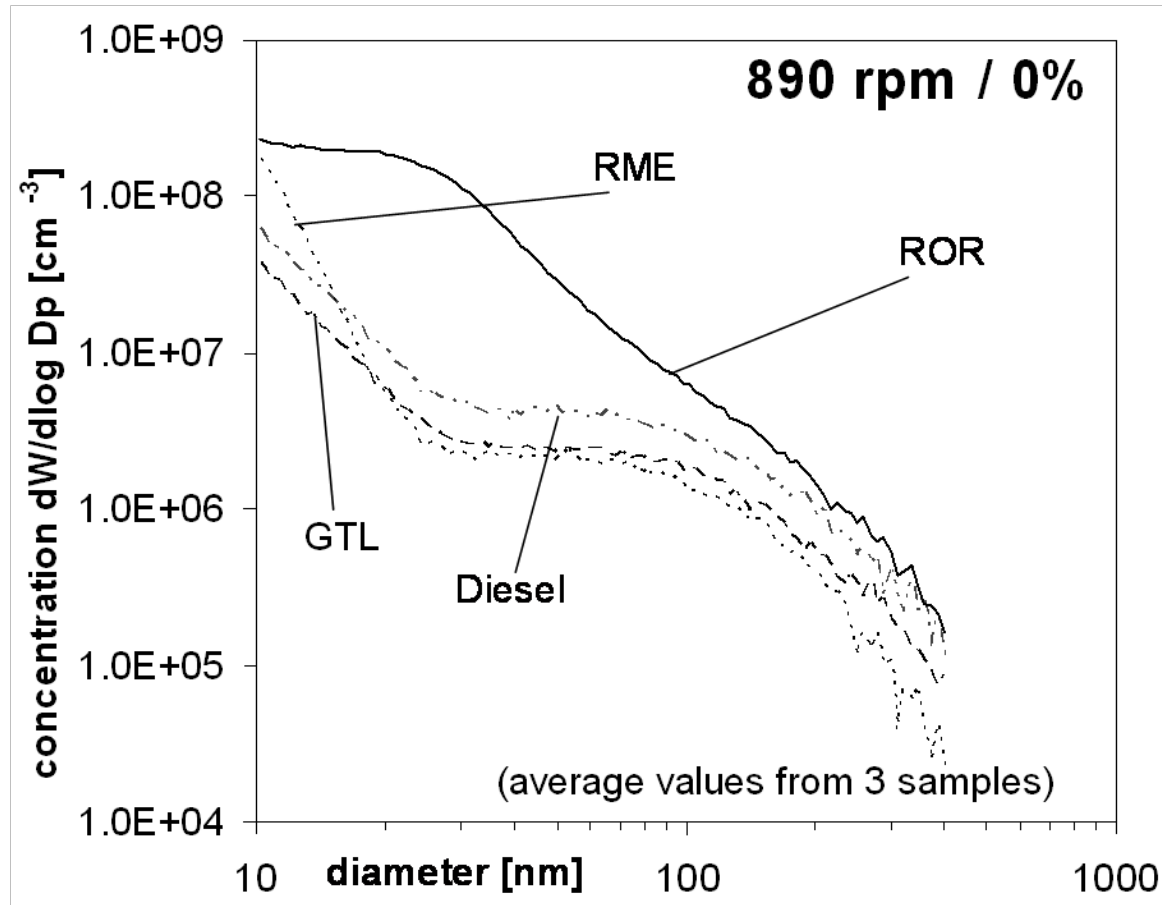
- **SMPS – Scanning Mobility Particle Sizer, TSI**
- **NanoMet – System consisting of:**
 - **PAS – Photoelectric Aerosol Sensor**
 - **DC – Diffusion Charging Sensor**
 - **MD19 tunable minidiluter**



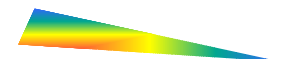
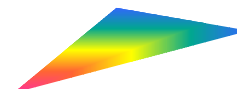
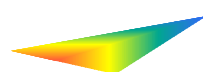
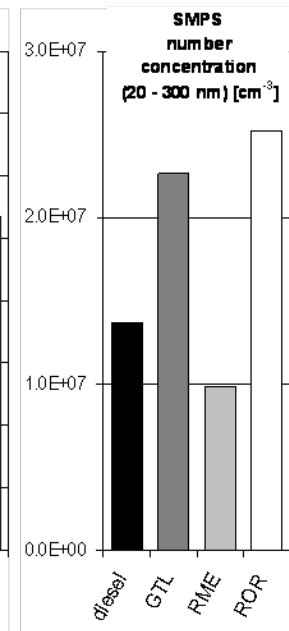
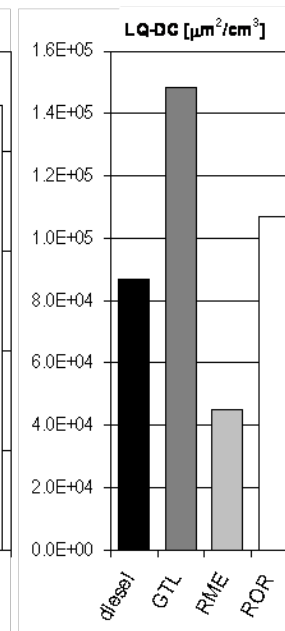
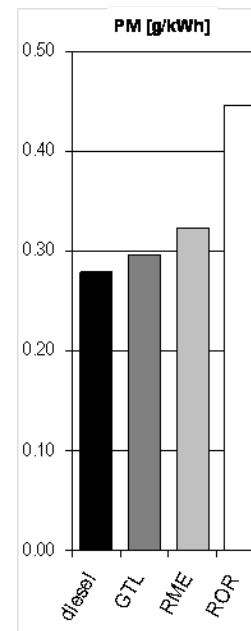
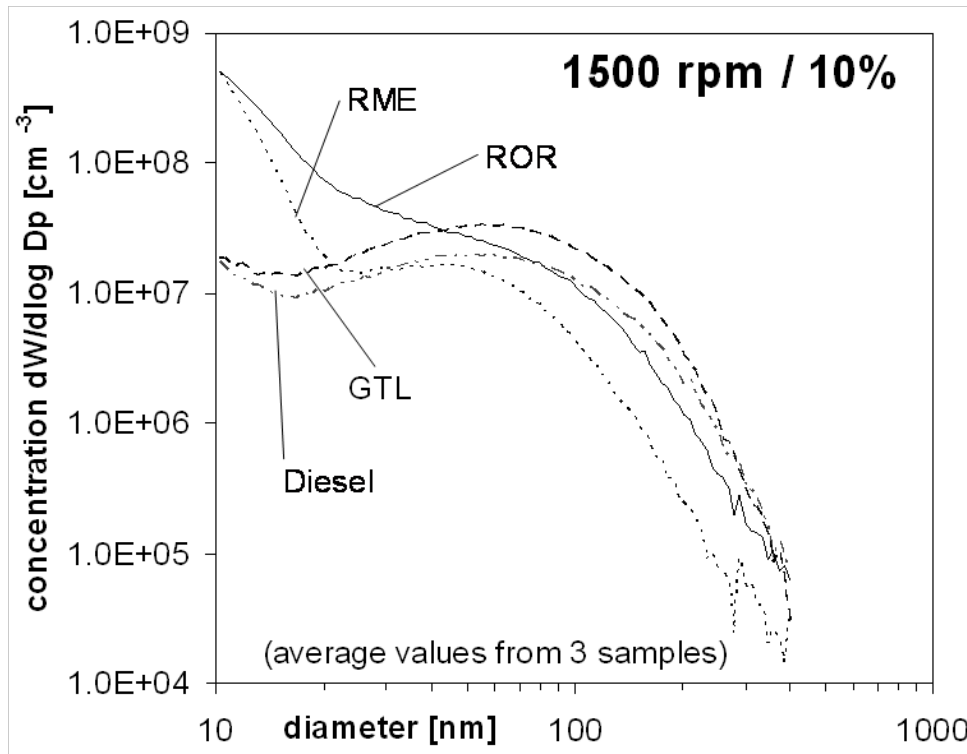
Influence of engine operating conditions on nanoparticle emissions.



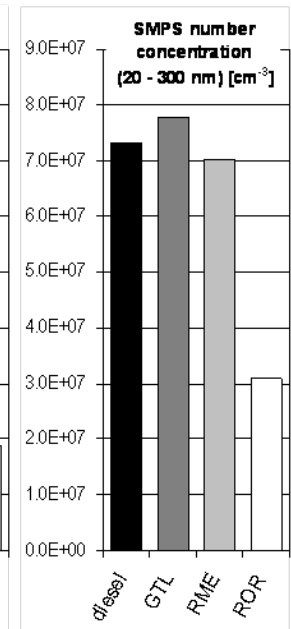
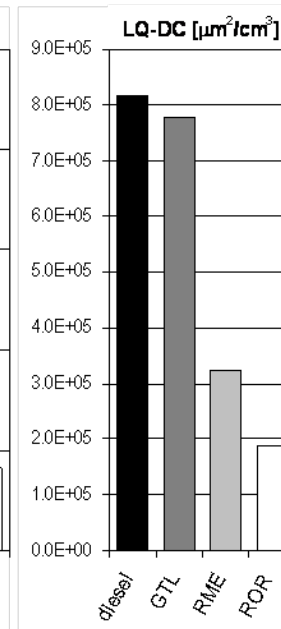
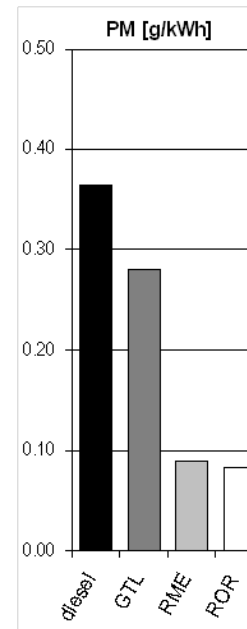
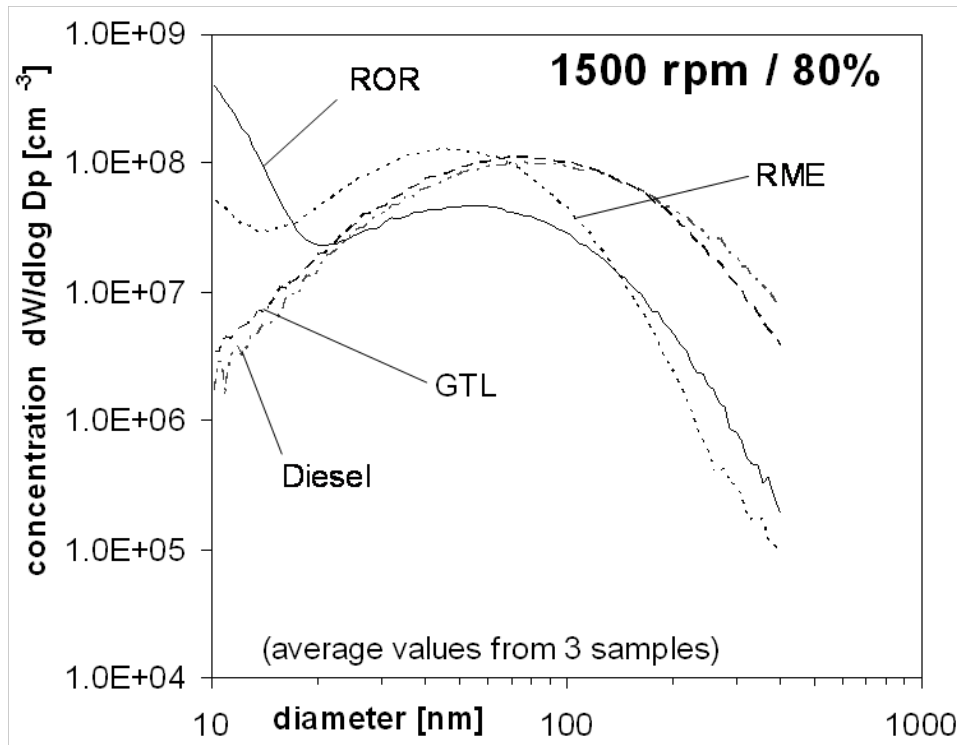
SMPS nanoparticles for different fuels at idling.



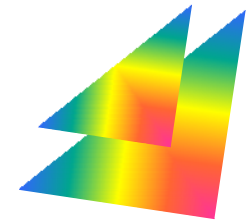
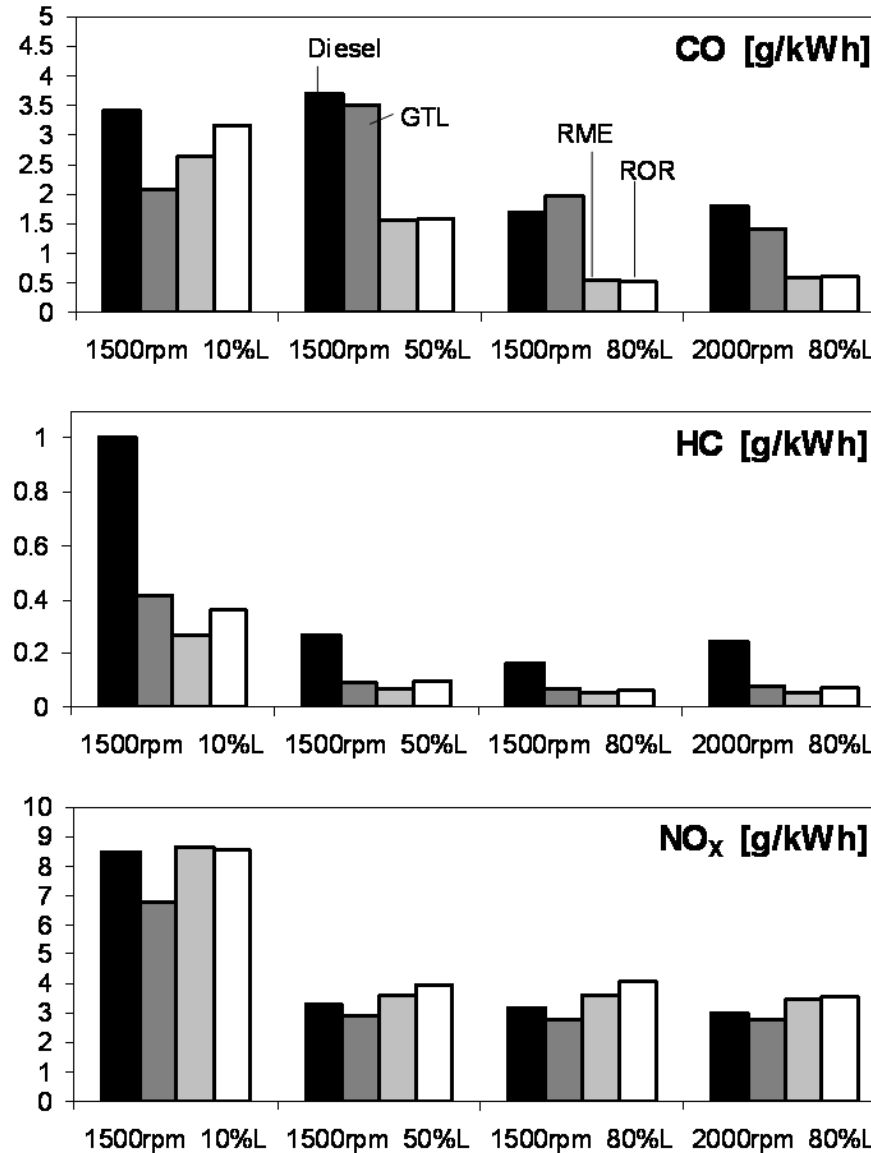
Particle mass and nano-particles; comparison of different fuels at low load



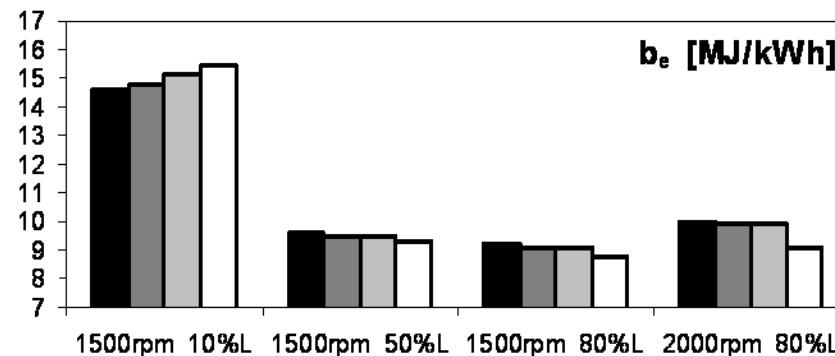
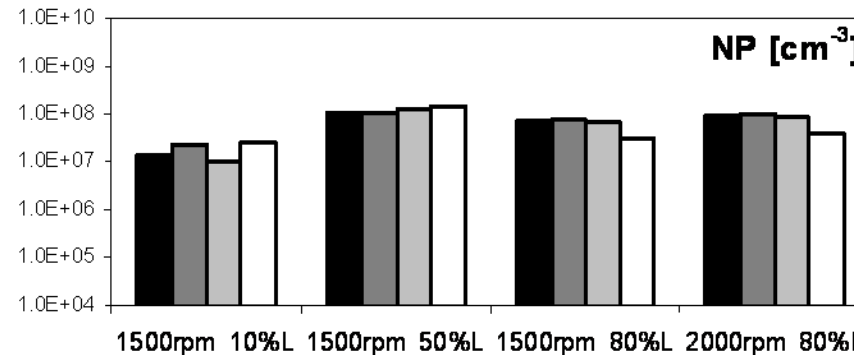
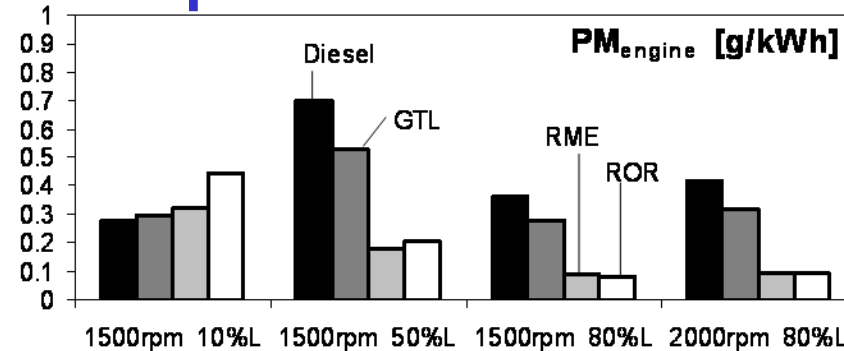
Particle mass and nano-particles; comparison of different fuels at high load



Comparison of gaseous emissions with different fuels



Comparison of particle emissions and specific energy consumption with different fuels





Coulometry

EC & OC

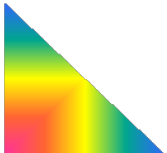
SOF / INSOF

Standard Coulometric Method (SUVA)

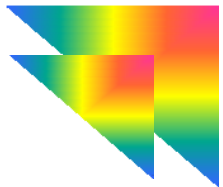
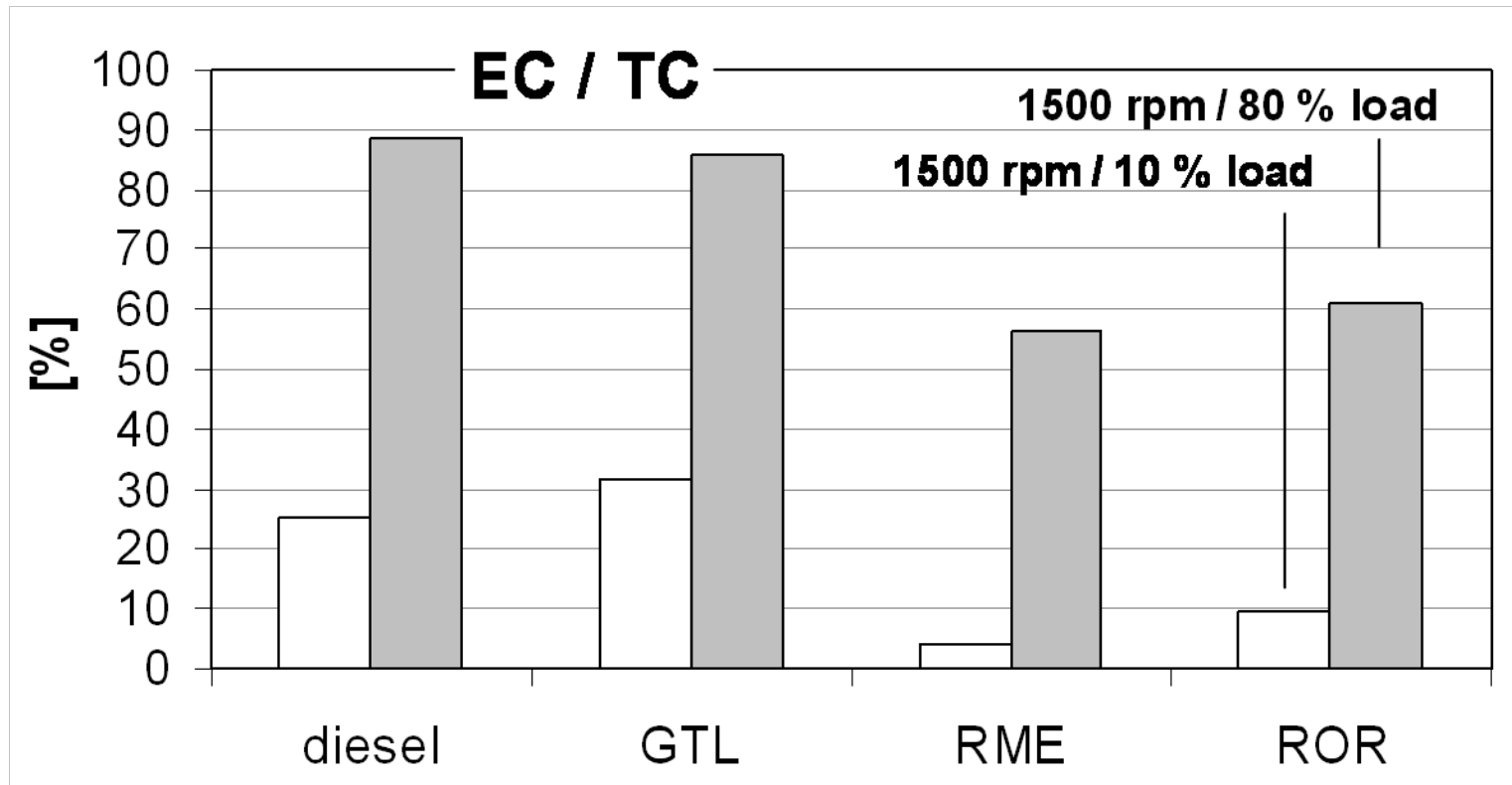
- Thermal extraction of SOF with:

N_2 at 500°C , 8 min. $\longrightarrow$ Oxidation to CO_2 $\longrightarrow$
 $\longrightarrow$ OC

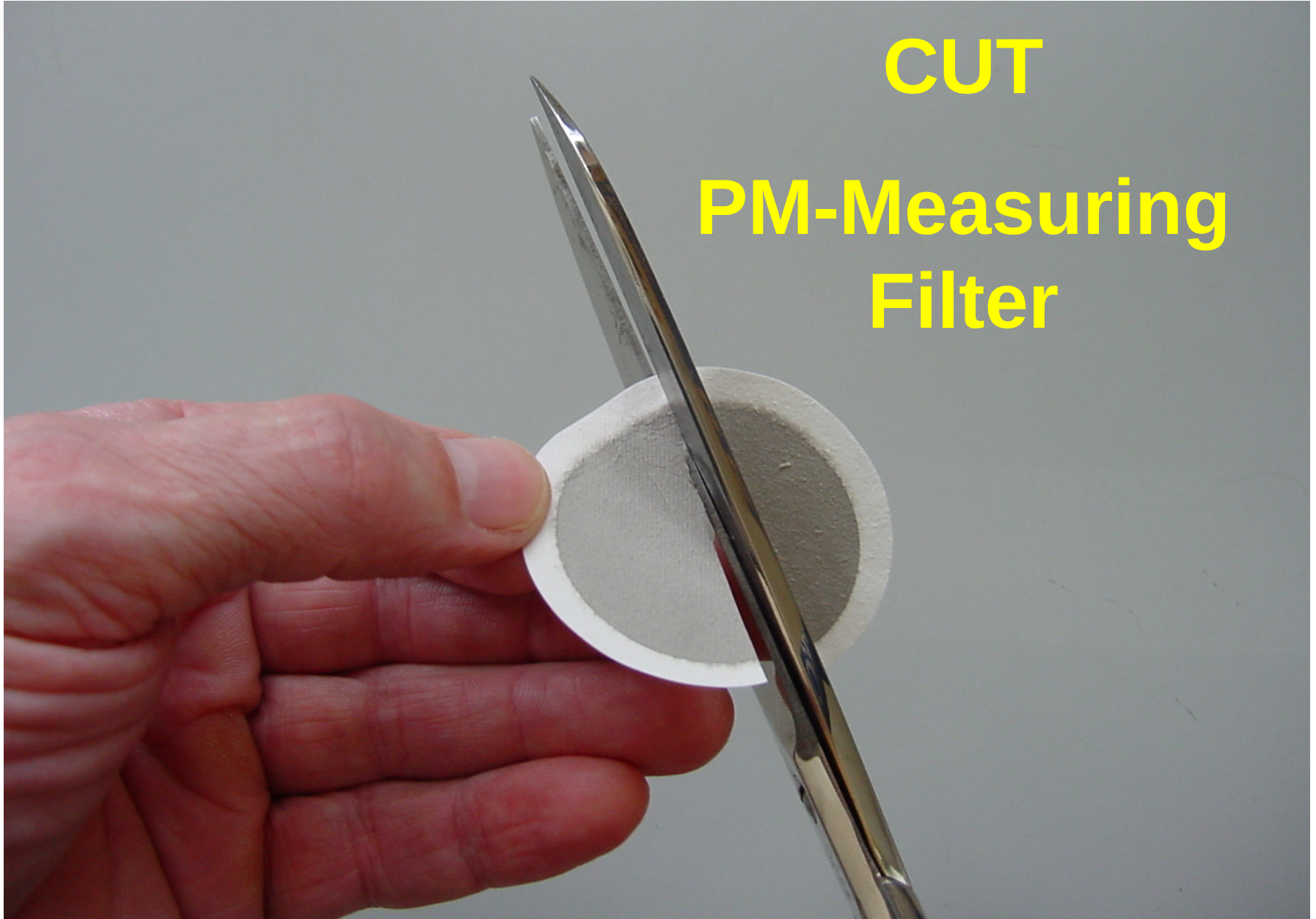
- Residual substance INSOF: oxidation with O_2
at 650°C $\longrightarrow$ CO_2 $\longrightarrow$ EC



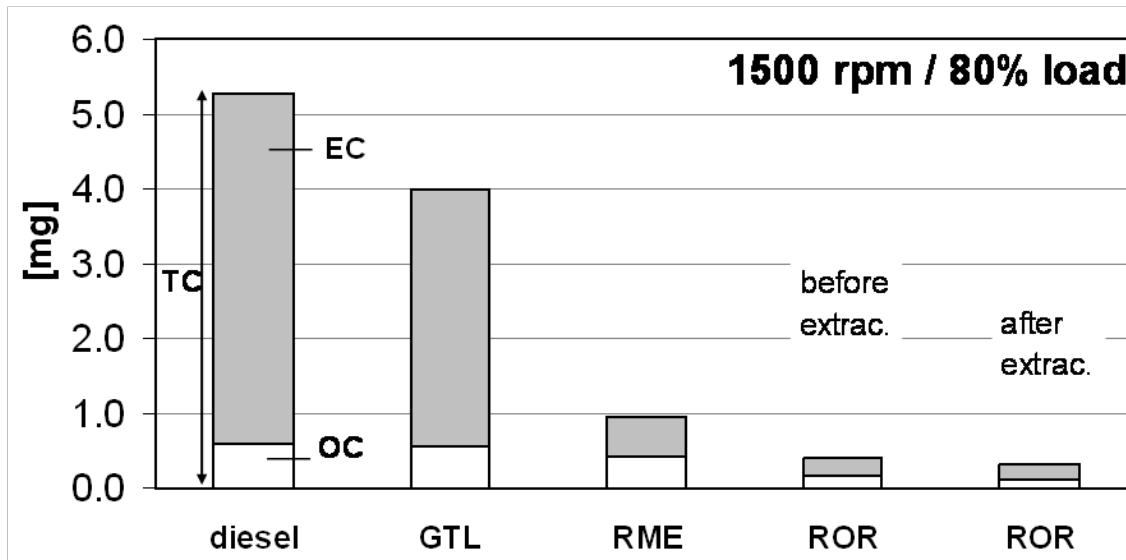
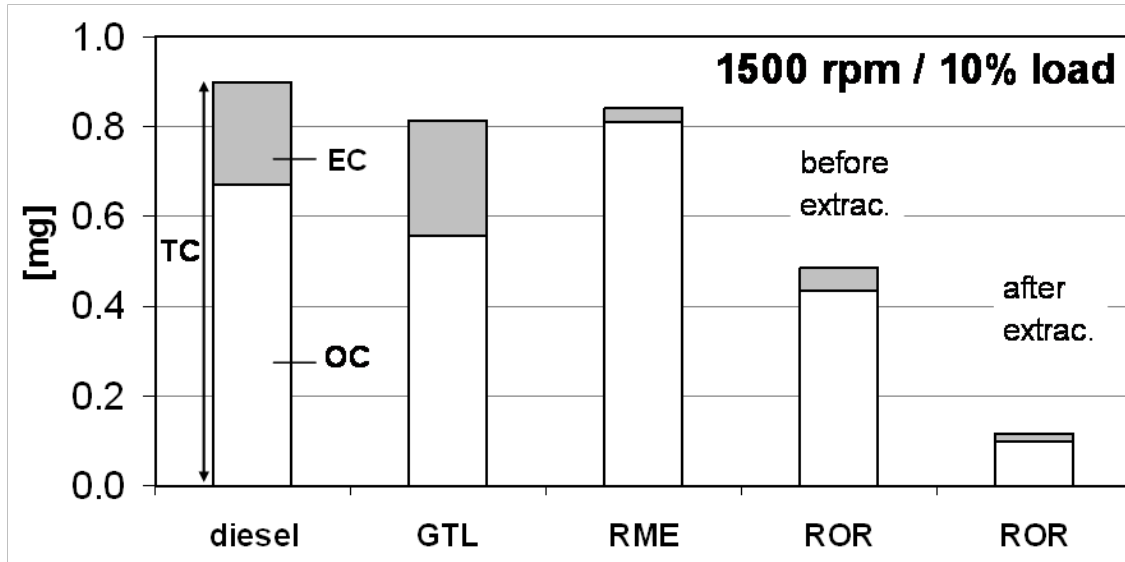
Influences of engine load on EC/TC-ratio for different fuels



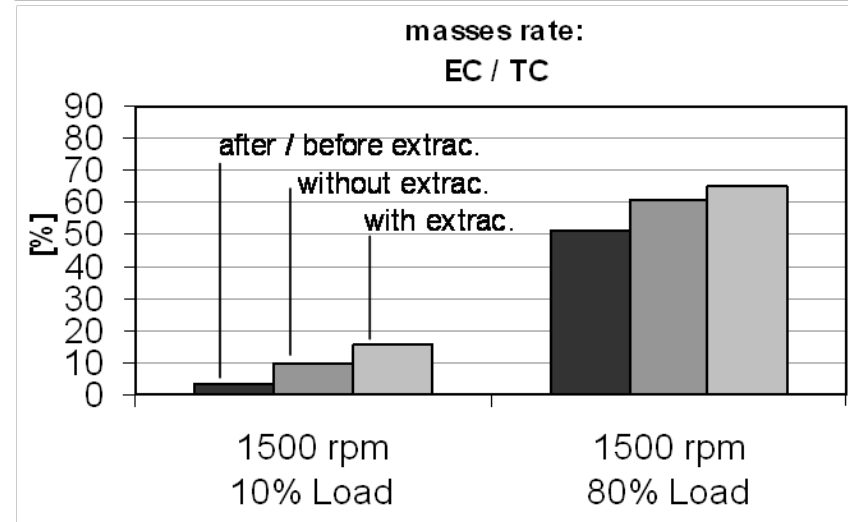
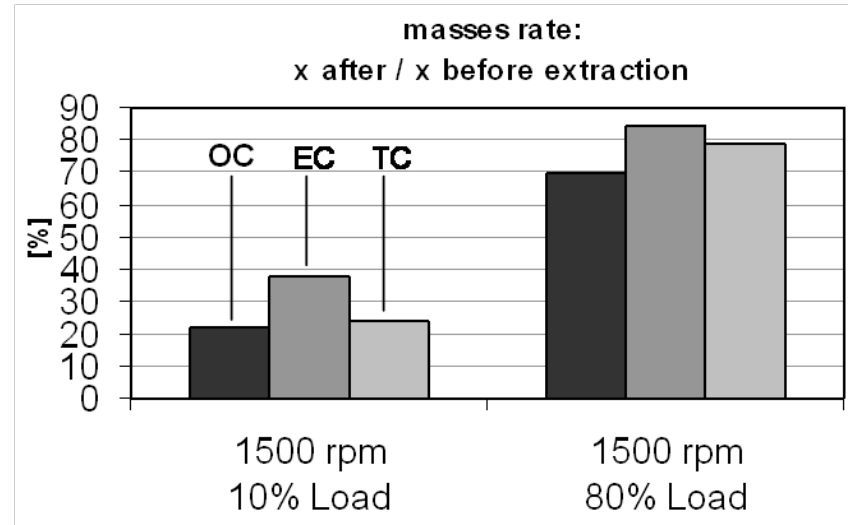
CUT PM-Measuring Filter



OC / EC / TC absolute values for all fuels



Influences of the preliminary solvent extraction on the OC / EC results with ROR



Conclusions (1), SOF/INSOF

The preceeding

solvent extraction

Influences very much the

Coulometric results EC, OC, & TC

Conclusions (2), SOF / INSOF

Charing



- Partial polymerisation of heavy HC's during the thermal extraction of SOF
- Increased supply of carbon for the final
 O_2 - oxidation  increase of EC



General Conclusions

Conclusions - Injection

- RME, ROR injection delay ↓
- RME, ROR max. injection pressure ↑
- GTL $\approx$ Diesel

Conclusions – Combustion (FL)

- RME, ROR

ignition lag ↓

$\alpha_{50\%}$ earlier

NO_x ↑

- GTL $\approx$ Diesel

Conclusions – Emissions (FL)

- RME, ROR

CO, HC, PM ↓
NO_x ↑

} reverse
at part
load

- GTL

lowers all

Conclusions – NP, SOF

- RME, ROR NP counts $\uparrow$ at part load $\downarrow$ at FLNP
sizes $\downarrow$ generally, nuclei mode $\uparrow$
- RME, ROR higher portion of SOF (OC)
at part load & idling
- RME, ROR reduced PM at FL due to EC $\downarrow$
- GTL $\approx$ Diesel



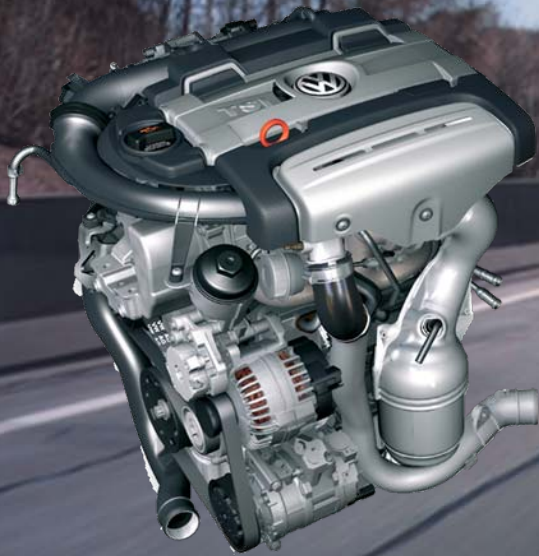
A Mobile Combustion Analysis System

Kistler Group
Heinz Jenny

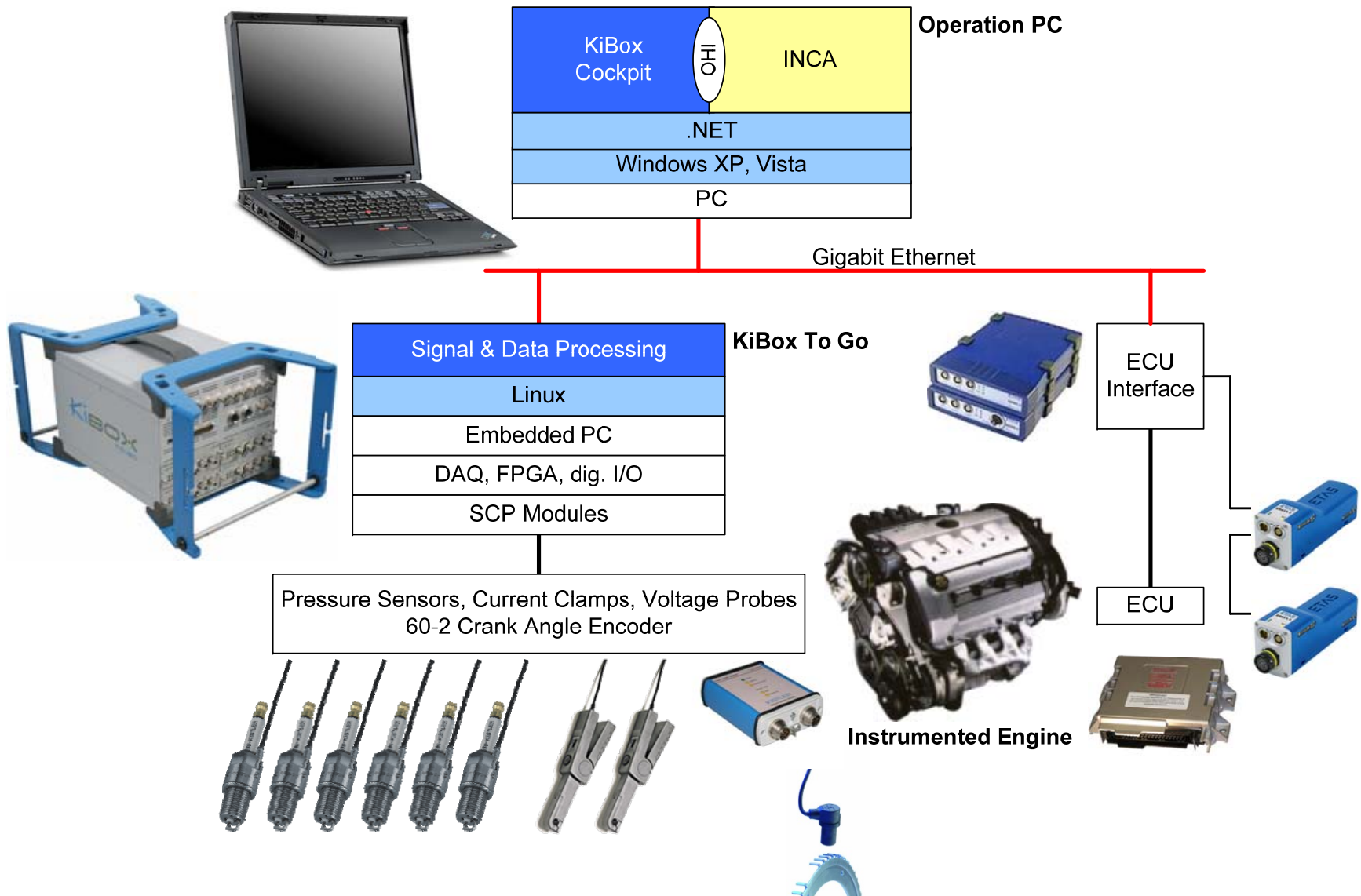
Development Trends and Needs

- Higher complexity: Engine and/or ECU calibration has reached a complexity where car manufacturers are demanding in-vehicle indication systems which are closely cooperating with ECU calibration tools, e.g. INCA.
- Cost reduction: Test stand hours are extremely expensive (instrumented test cells, climate chambers and altitude simulators); system operation by lower skilled personnel.
- System optimization: Engine fine tuning and diagnosis moves from test stand to vehicles on the road; analyzing transient behavior, e.g. real feedback of the powertrain under real conditions.

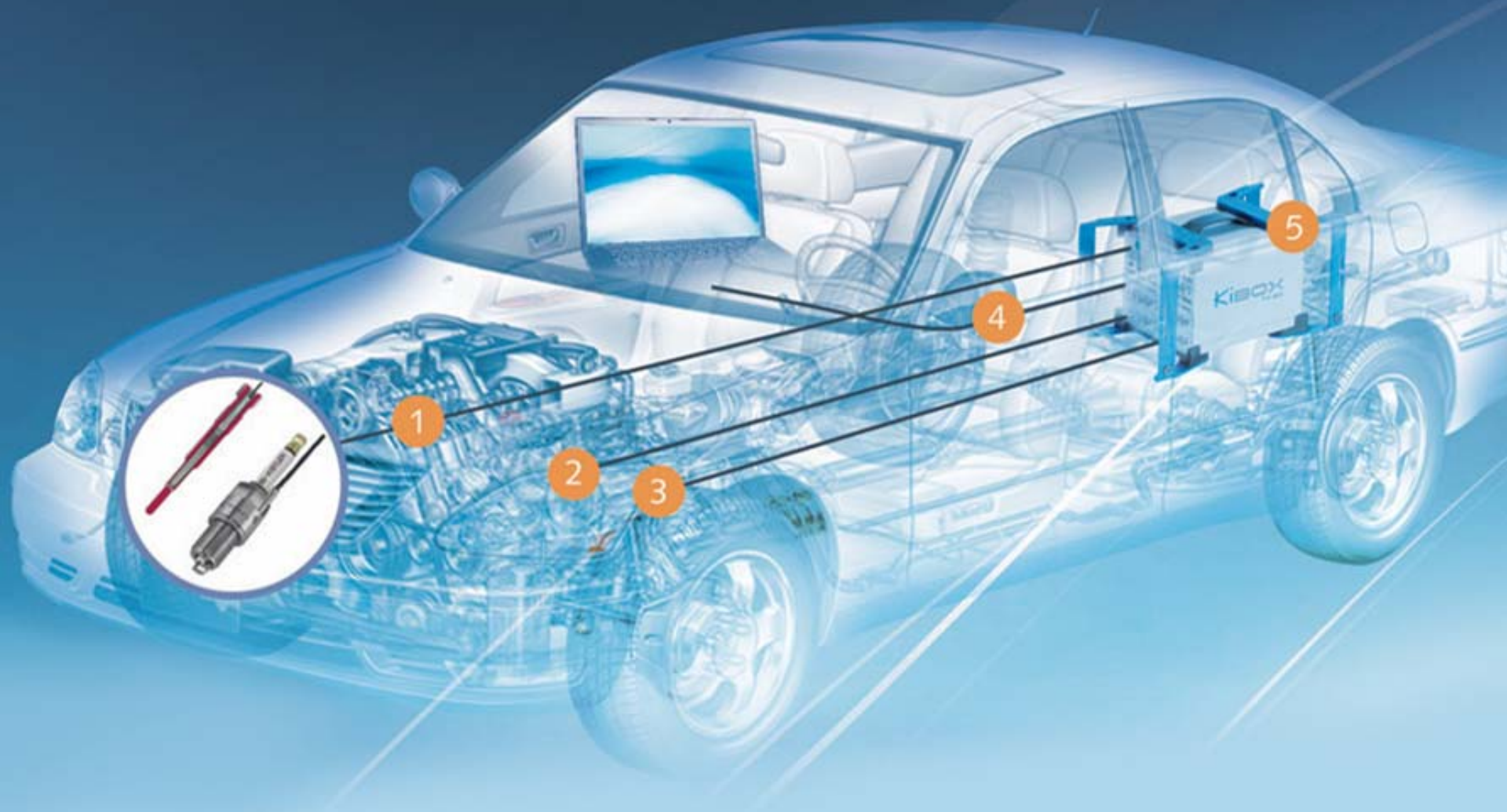
On-The-Road Engine Testing & ECU Calibration



System Overview & Architecture



In-Vehicle System Setup



High Degree of Integration

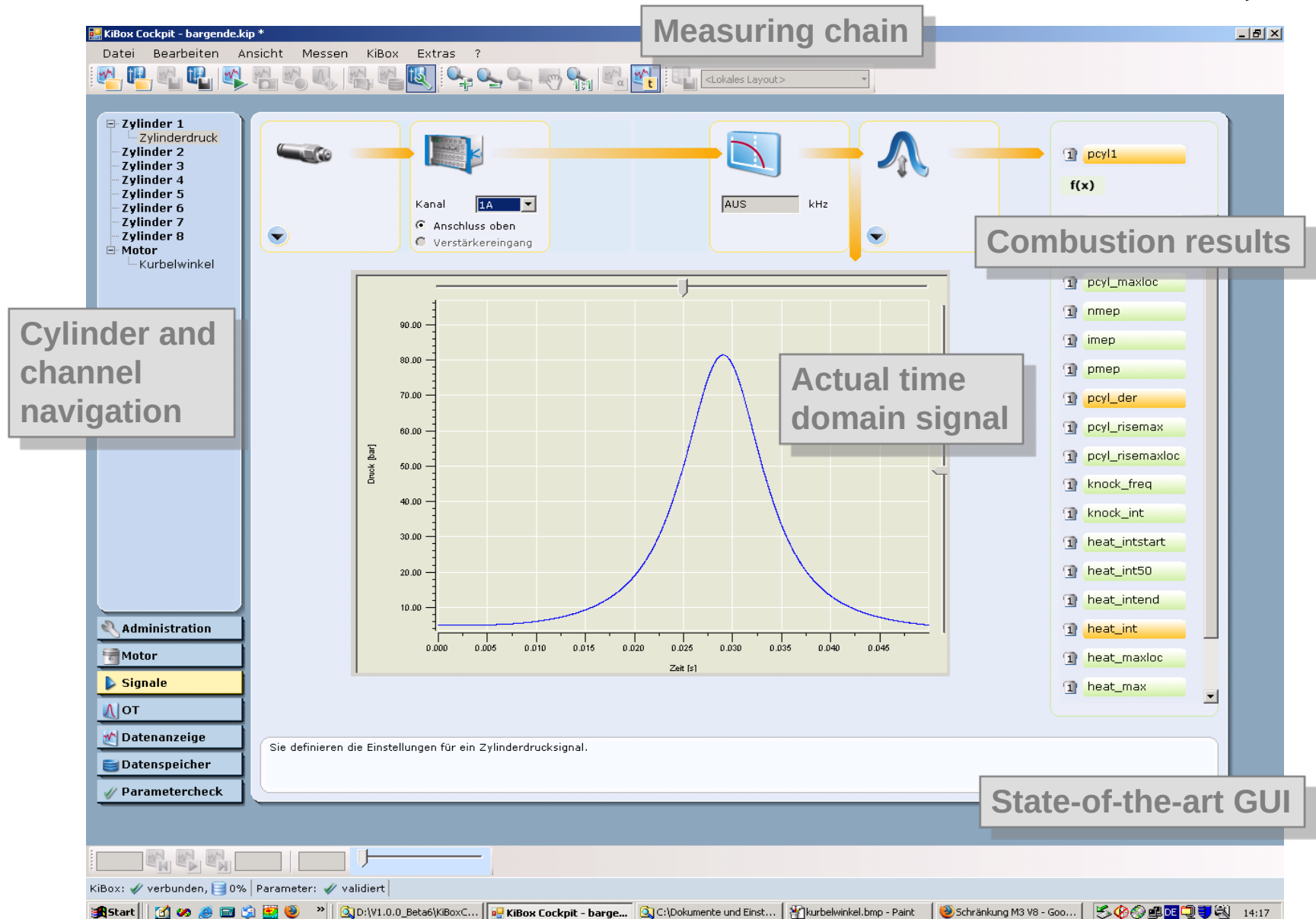


Before KiBox: Two separated systems were required; data have to be merged manually

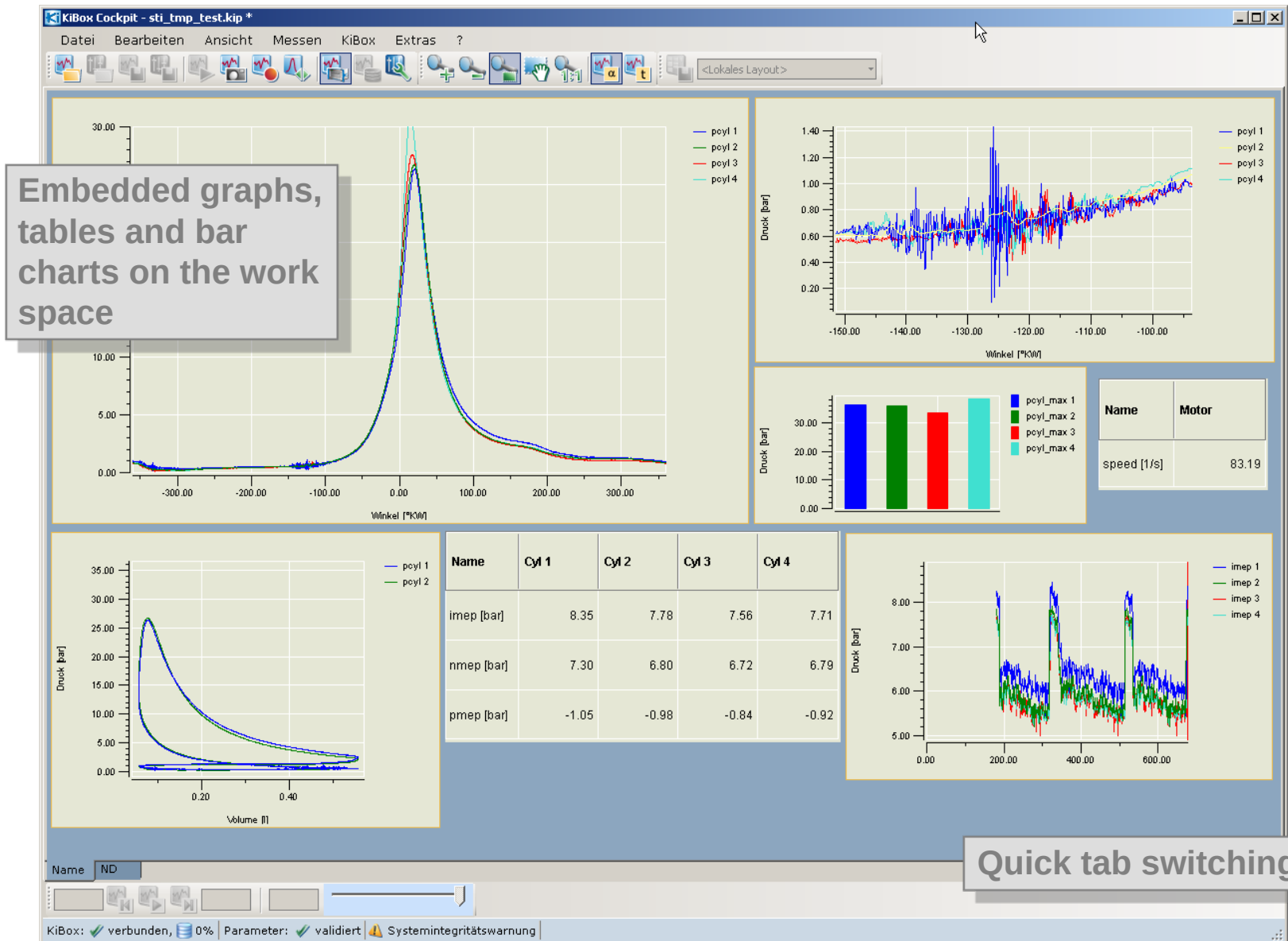
KiBox and INCA – one integrated system: The KiBox generates combustion values while INCA will present synchronously combustion analysis results and ECU values



KiBox Cockpit – Parameter Setup

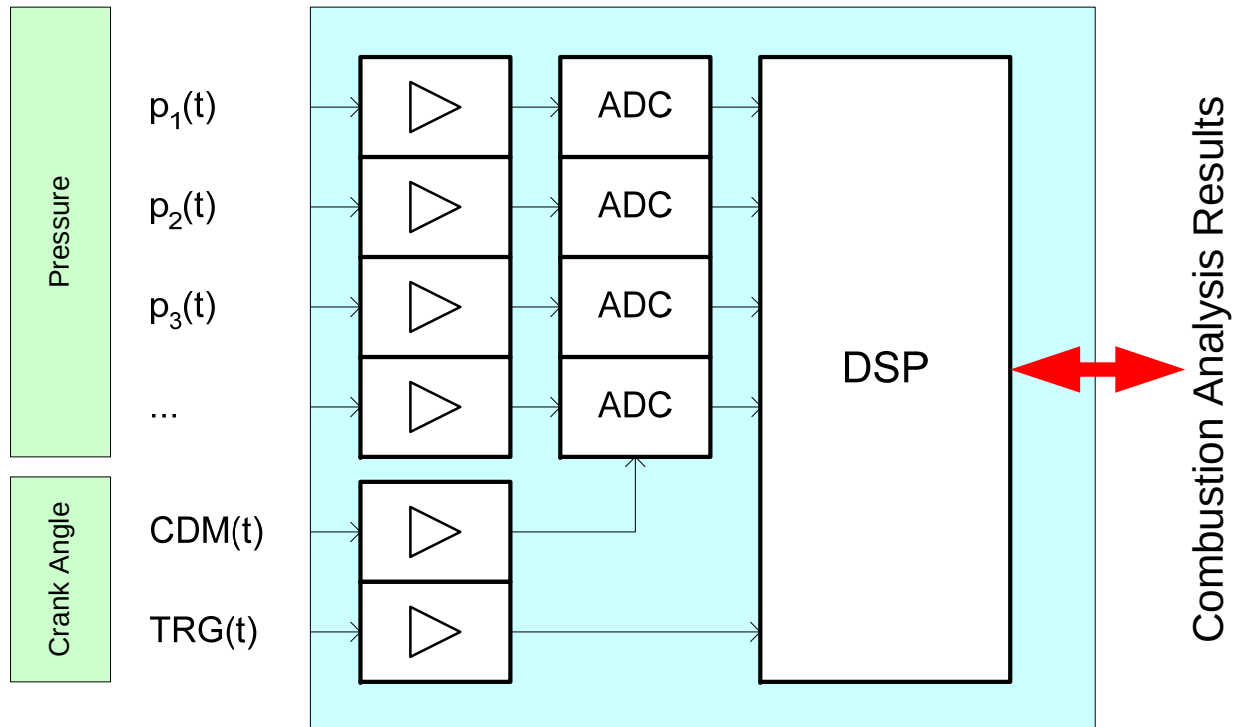


KiBox Cockpit – Online Data Representation

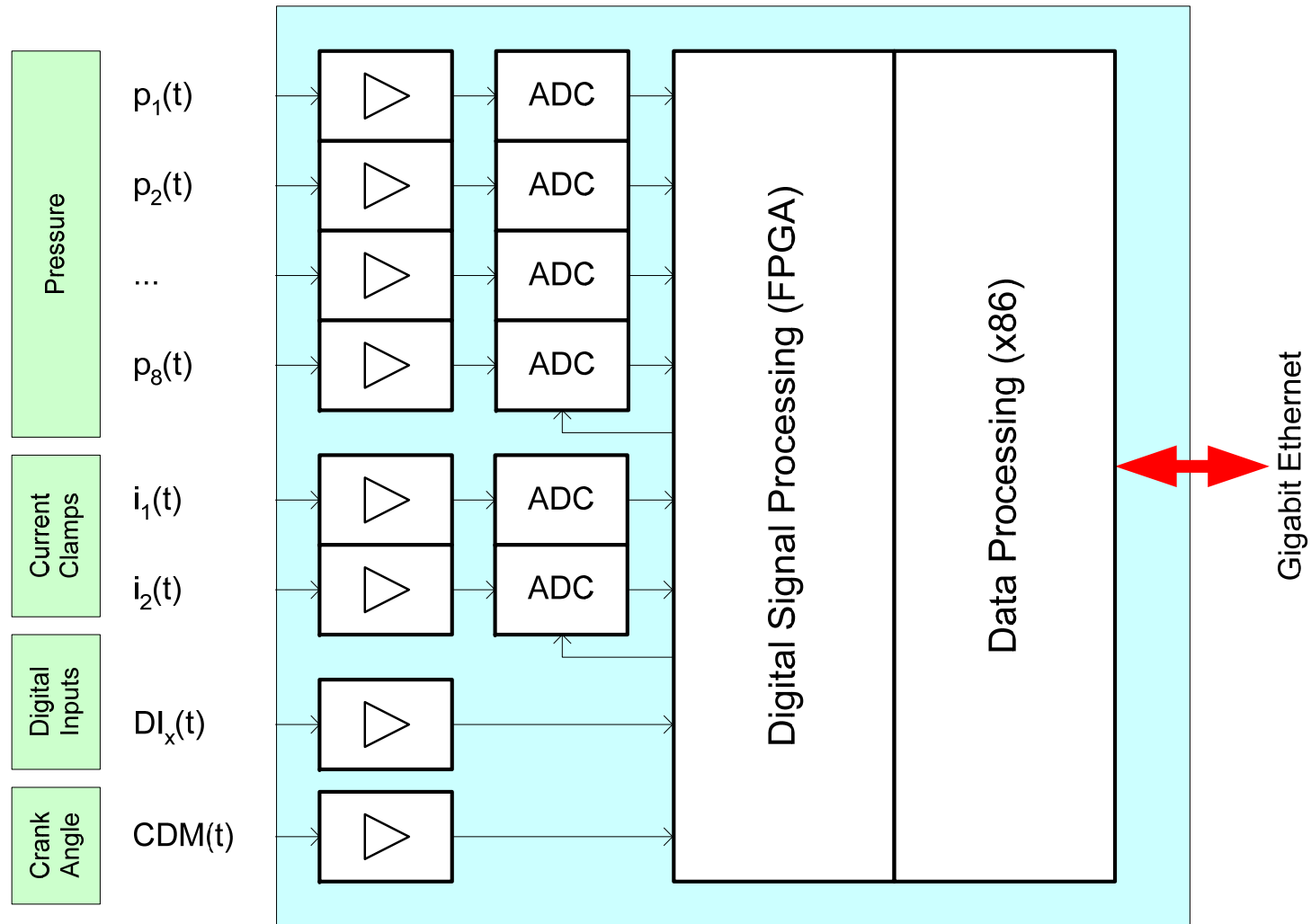


- For in-vehicle combustion analysis usually the cylinder pressure sensors are used together with spark and glow plugs adapters
 - This compromise could cause pipe oscillations
 - This requires low-pass filtering (usually in time domain) – but the Filter group delay causes an angle error
- NOISE and KNOCK calculations naturally require time-domain data (spectrum analysis)
- Thermodynamic calculations, like WORK, HEAT, BURN, etc., are depending on the cylinder volume (which is indirectly determined by the crank angle)
- Achieving the required angle resolution of 0.1°CA as well during high transient engine operation while using onboard crank angle encoders (e.g. 60-2)

Typical Competitors Solution



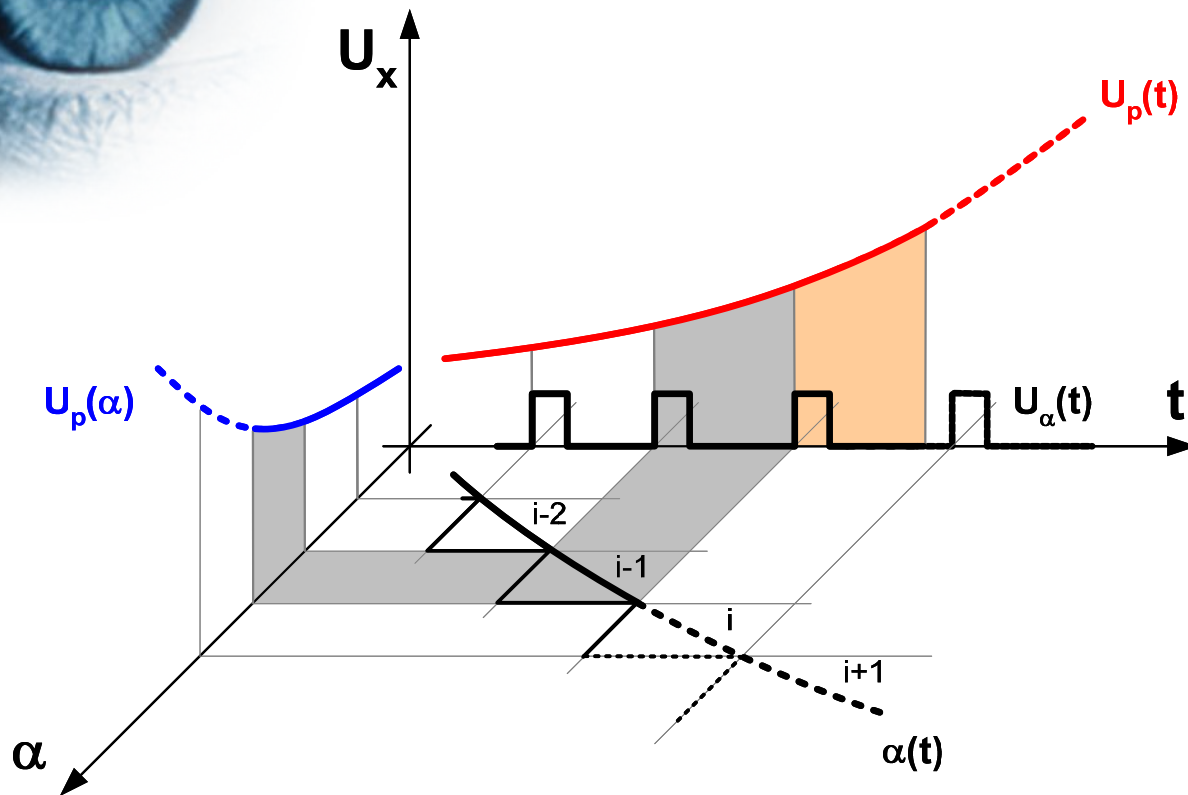
Kistler's Solution



Core Innovation – Crank Smart™



KISTLER
measure. analyze. innovate.



60-2 Crank Degree Marks

$U_\alpha(t)$

$$T_2 = \frac{T_1}{60}$$

$$T_2 = \frac{T_1}{180}$$

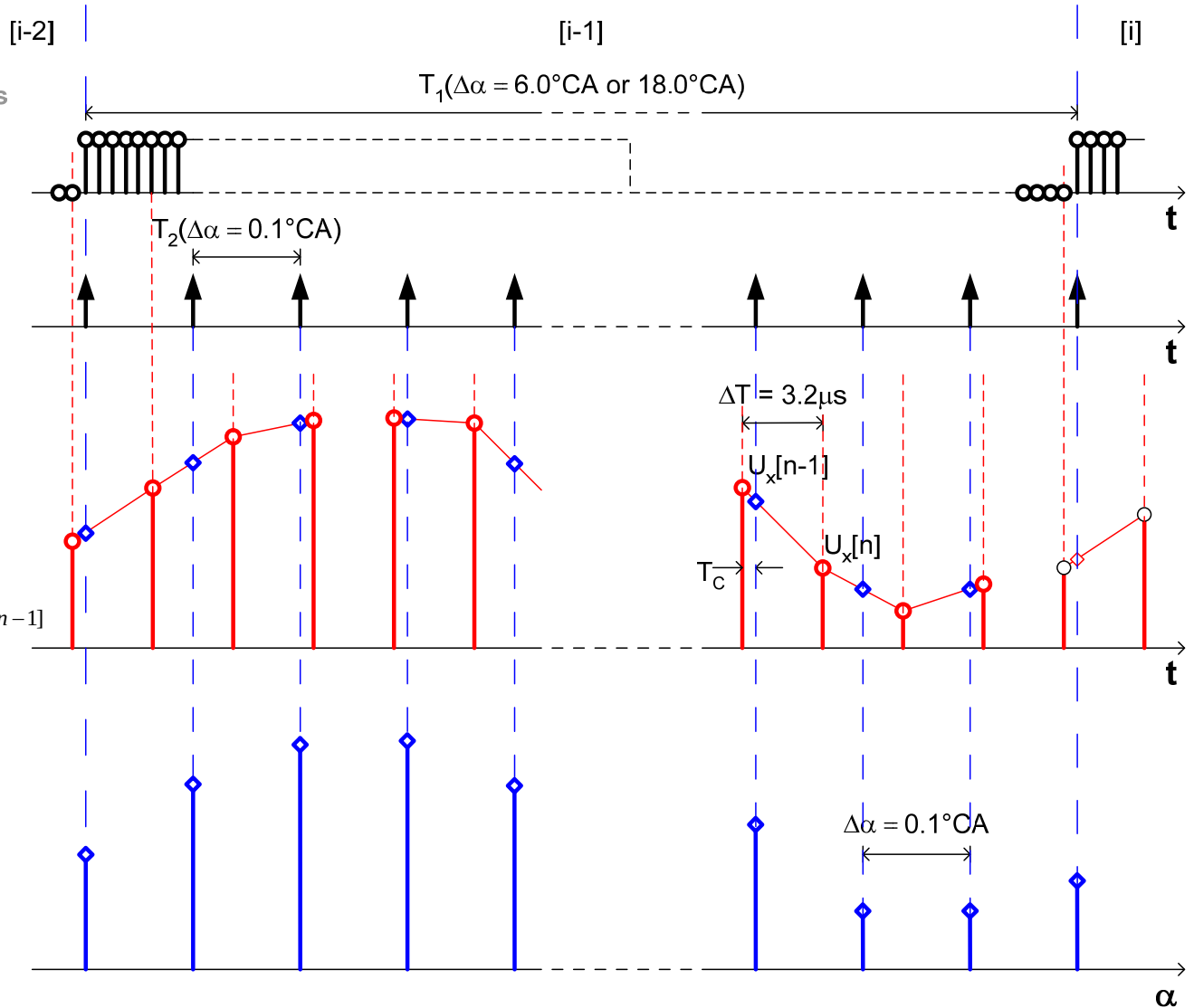
Time Domain Data

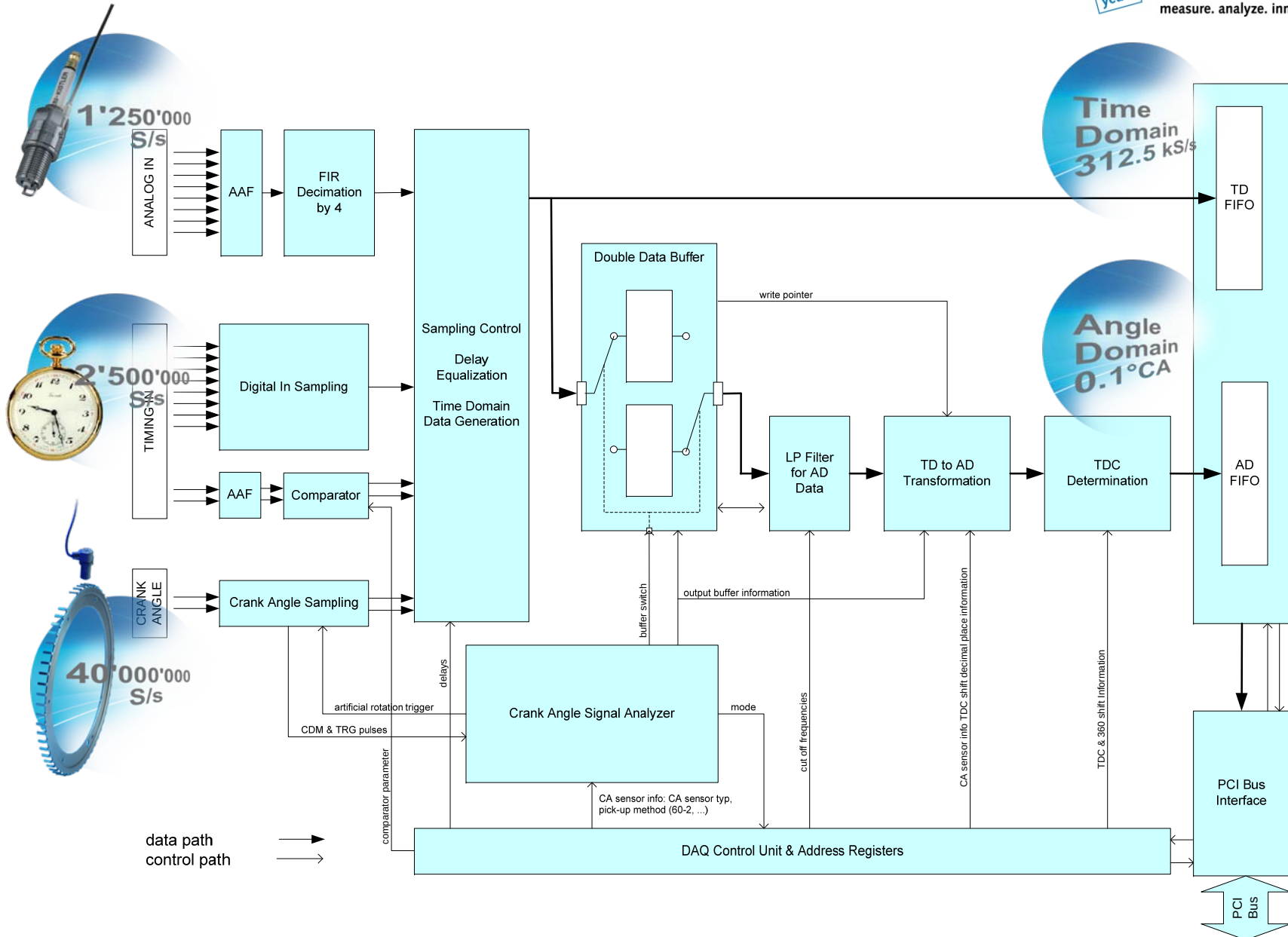
$U_p(t)$

$$U'_x[n] = \frac{U_x[n] - U_x[n-1]}{\Delta T} T_C + U_x[n-1]$$

Angle Domain Data

$U_p(\alpha)$



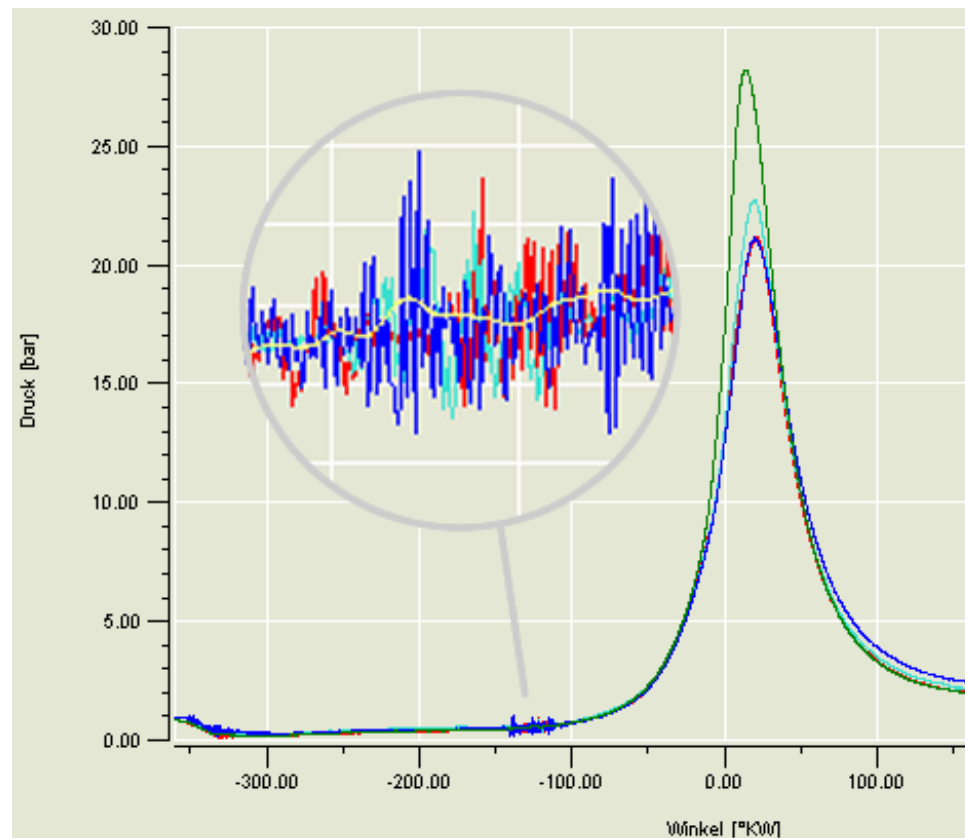


Crank Smart™ – Values

- Robust crank angle and signal interpolation to 0.1°CA works for a variety of sensor systems and trigger wheels
 - Crank degree marks with embedded trigger mark, e.g. 90-1, 60-2, 60-1, 36-2, 36-1, 36+1, 30-1, 30-2 etc.
 - Crank degree marks with additional trigger mark, e.g. 360/1, 720/1
- Wide speed range: 1..15'625 rpm
- Correction of the speed-dependent angle error for inductive sensor systems (Hall pickups do not show this behavior)
- The principle would allows trigger wheel correction (trigger wheel calibration would be required)

Crank Smart™ – Values

- Digital low-pass filtering offers zero group delay over the entire measuring chain for each measuring channel (true phase, no delay)



Combustion Analysis Results

Cylinder pressure $p_{\text{Cyl}}(\alpha)$ and $p_{\text{Cyl}}(t)$

- Mean effective pressure IMEP, PMEP and NMEP
- Peak pressure p_{max} and location $\alpha(p_{\text{max}})$
- Heat release and mass fraction burned
- Pressure gradients $dp/d\alpha$ and dp/dt , peak and its location
- Combustion noise
- Knock diagnosis

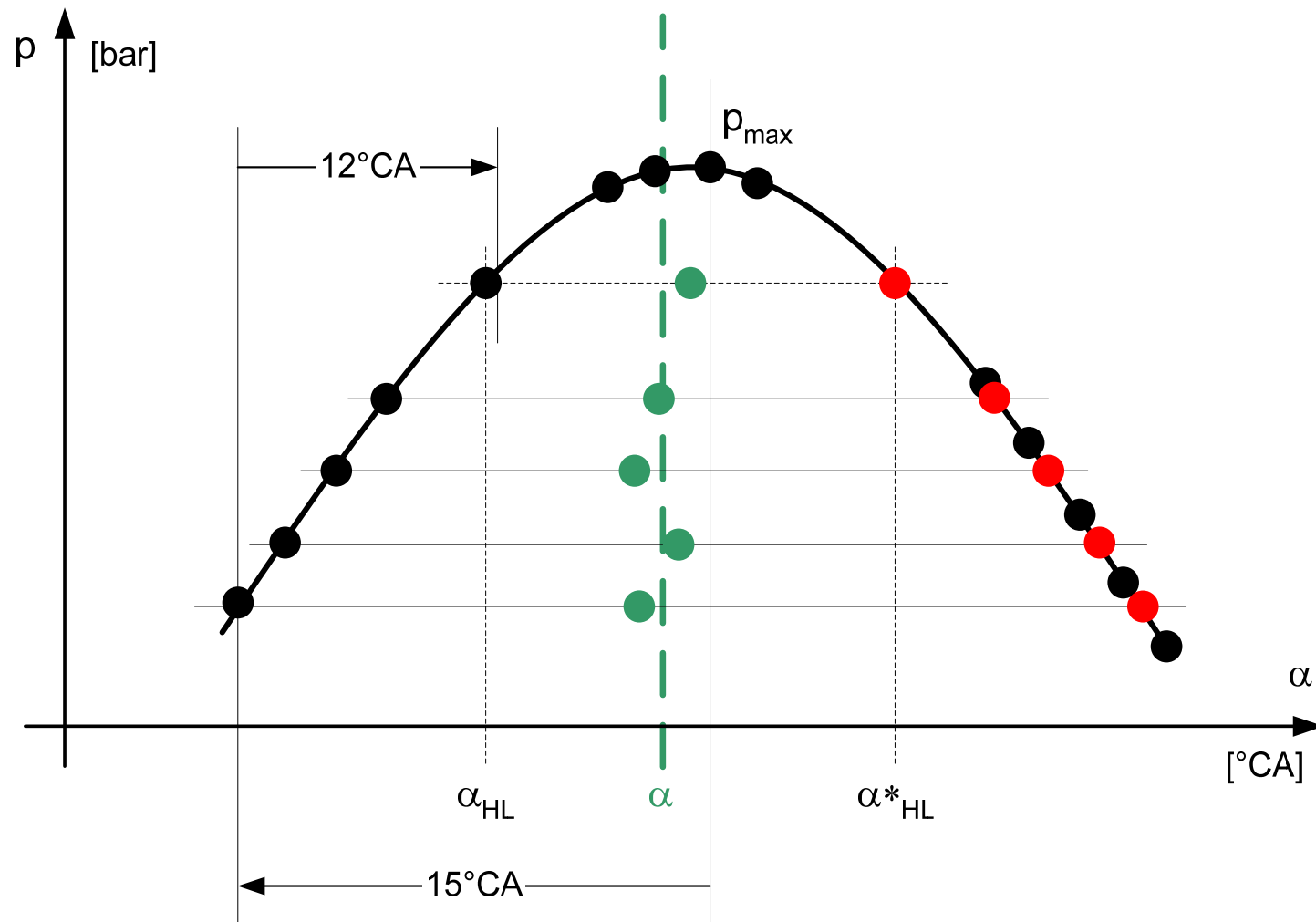
Fuel injection $FI(\alpha)$, $FI(t)$ and ignition $IG(\alpha)$

- Injection begin and end
- Ignition angle

Intake and exhaust pressure $p_{\text{Int}}(\alpha)$ and $p_{\text{Exh}}(t)$

- Gas exchange analysis

Top Dead Center Determination





Power Box, Type 5785A
with UPS and Ethernet switch

Analyzer, Type 2893A
with SCP signal conditioner,
DAQ system, and real-time
data processing



**Crank Angle Adapter,
Type 2619**

First dedicated in-vehicle combustion analyzer:

- Compact design, quick installation and easy setup
- Real-time calculation of combustion analysis results
- CrankSmart™ to use production crank angle sensor (e.g. 60-2)
- High precision data even under transient engine operation
- Time and angle domain data acquisition enables for perfect engine start measurements, true phase filtering (no phase shift)
- Interface to INCA – the high degree of integration secures efficient ECU calibration

Engine Testing & ECU Calibration Perfectly Synchronized.

50th
years

KISTLER
measure. analyze. innovate.

The Kistler



Vom phänomenologischen Russbildemodell zum virtuellen Russ-Sensor

*Laboratorium für Aerothermochemie und Verbrennungssysteme
ETH Zürich*

Einführung

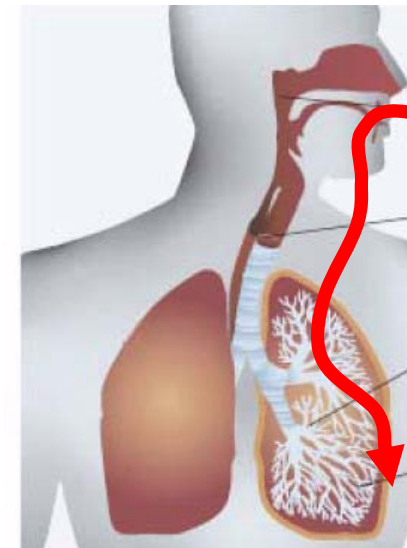
Schädliche Wirkungen von Russ

■ Partikel-Emissionen aus Dieselmotoren haben unbestritten einen Einfluss auf die menschliche Gesundheit:

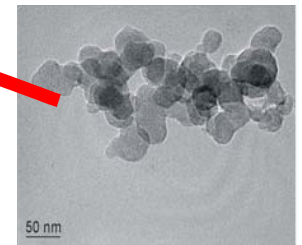
- London, 1952. The Great Fog (vier Tage)¹: **4000-12000** Smog-bezogene Tote
- Harvard Six Cities Studies (1974 – 1988)²: **Erhöhte Mortalität** als Folge der erhöhten Partikel-Konzentration
- Schweiz³: **3700 vorzeitige Todesfälle** pro Jahr, verursacht durch Partikel

■ Einflüsse von Partikeln auf die Gesundheit:

- Entzündungen der Atemwege
- Partikel-Ablagerungen in der Lunge
- Eindringen von Partikeln in den Blutkreislauf
- Krebserregend
- Die Wirkungsmechanismen sind nicht vollständig verstanden



Quelle: (4)



Quelle: (5)

¹ www.metoffice.gov.uk. 2008-08-17

² D. Dockery et al. New England J. Medicine, 329(24):1753-1759, 1993

³ BAFU. Feinstaub macht krank. 2005

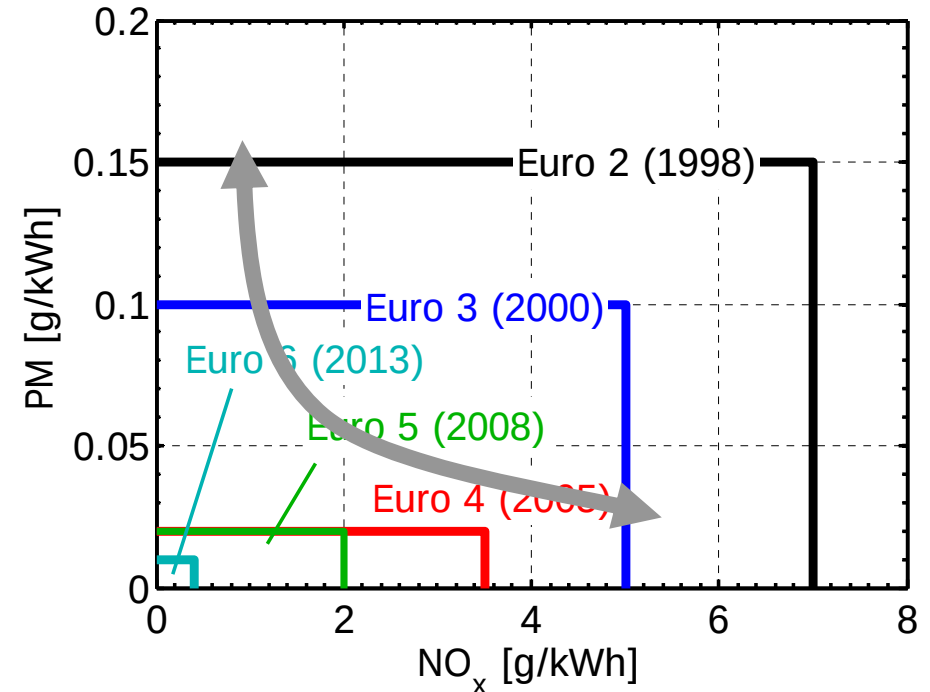
⁴ T. Cerny. ETH Conf. on Comb. Gen. Nanoparticles, 2007

⁵ U. Mathis. ETH Conf. on Comb. Gen. Nanoparticles, 2003

Einführung

- Zunehmend strengere Emissionsgrenzwerte
- Gültige und zukünftige Grenzwerte erfordern Partikelfilter (DPF)
- DPFs verlangen Regeneration
 - ➔ Erhöhter Kraftstoff-Verbrauch!
- Kenntnis der aktuellen Russ-Emission im Betrieb ist wünschenswert für :
 - Regelung des Motors auf minimale Russ -Emission
 - Optimale DPF Regenerations-Strategie
- Zurzeit sind keine für die Serien-Anwendung geeignete Russ - Sensoren verfügbar...

Gesetzgebung und Kontrolle der Emissionen

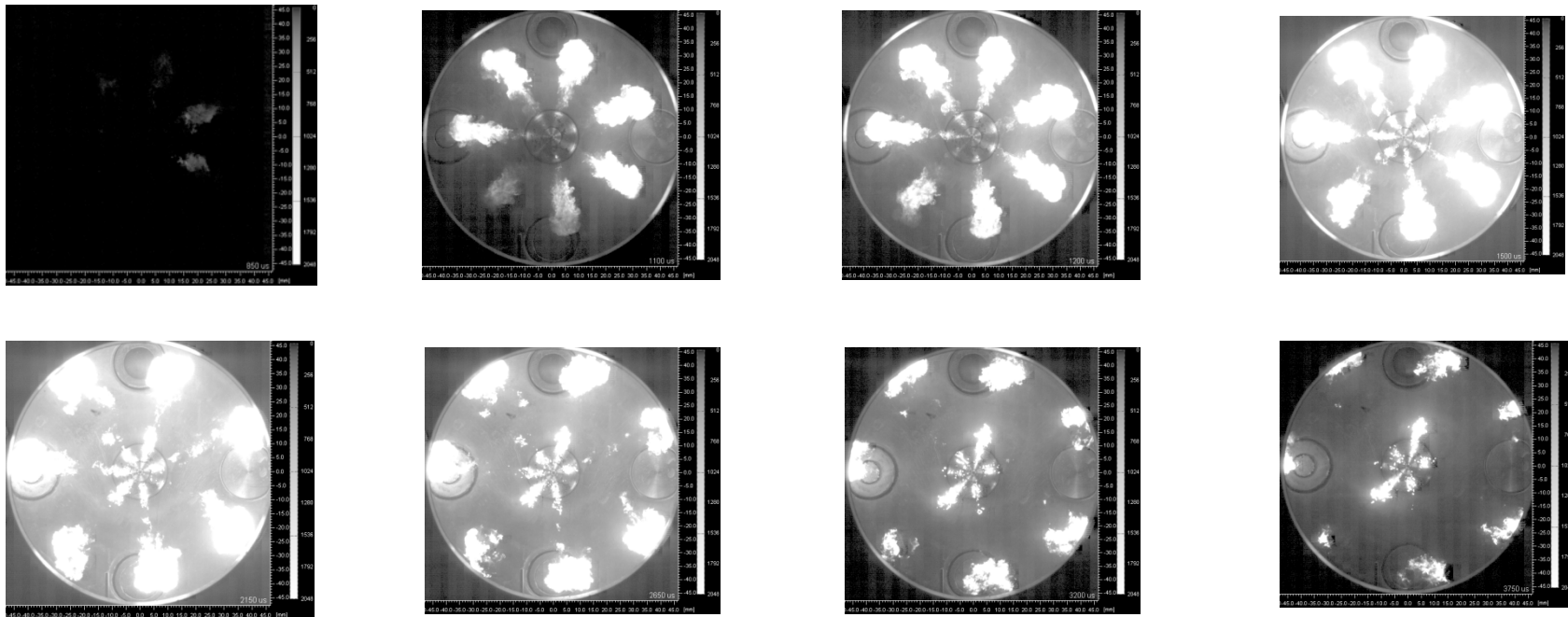


Europäische Emissions-Grenzwerte
für Heavy Duty Dieslemotoren

Verbrennung und Russbildung

Visualisierung

Selbstzündung und Verbrennung in der HTDZ des LAV (Standart-Diesel, CR-Injection 600 bar, Zustand bei Einspritzbeginn 50 bar / 920 K)



Quelle: Dr. B. Schneider, ETHZ/LAV

Verbrennung und Russbildung

■ Russ ist ein Ergebnis von:

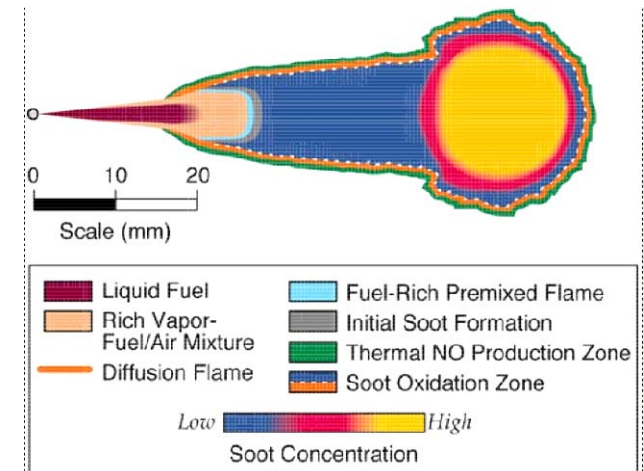
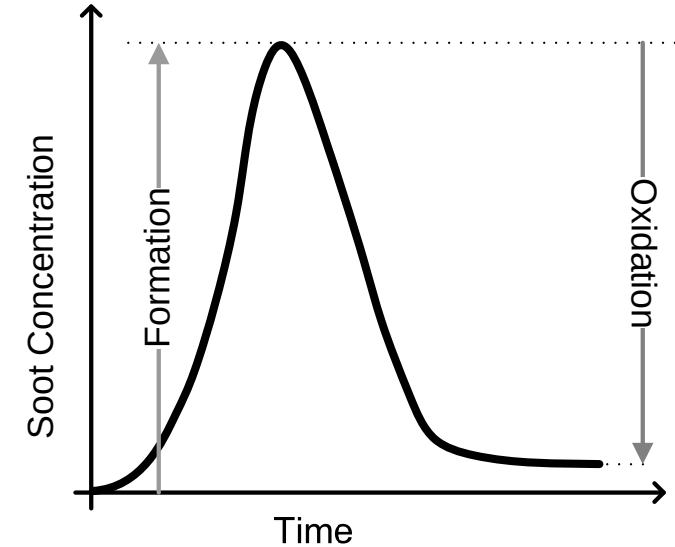
- Formation von Partikeln
 - Pyrolyse des Brennstoffs
 - Formation von PAHs
 - Bildung von Partikeln (Keimbildung)
 - Partikel Koagulation und Agglomeration
- Oxidation der Partikel
 - Gleichzeitig mit der Formation
 - Verlangt genügend hohe Temperaturen und Konzentration von Oxidantien (O_2 , O , OH , ...)

■ Heterogene Diesel verbrennung



Formation und Oxidation sind lokale, von der örtlichen Sauerstoffkonzentration und Temperatur abhängige Phänomene

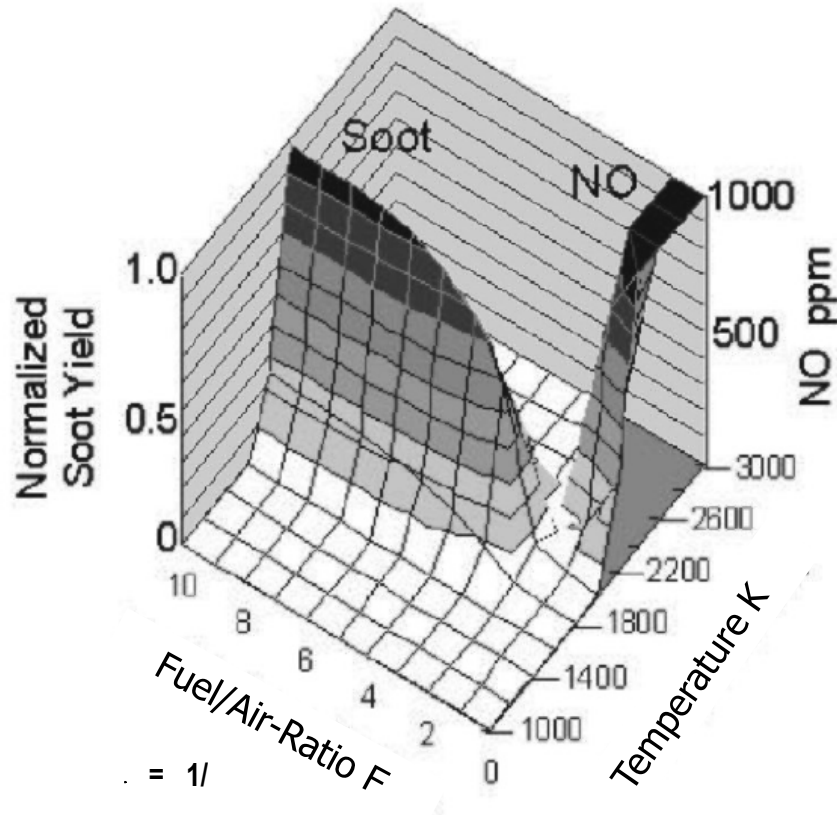
Inhomogene Verbrennung



J. Dec. SAE 970873, 1997

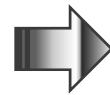
Verbrennung und Russbildung

Einfluss des Luft/Brennstoff-Verhältnis und der Temperatur



■ Russ- und NO- Bildung sind abhängig von:

- Lokale Temperatur im Brennraum
- Lokales Luft/Brennstoff-Verhältnis λ

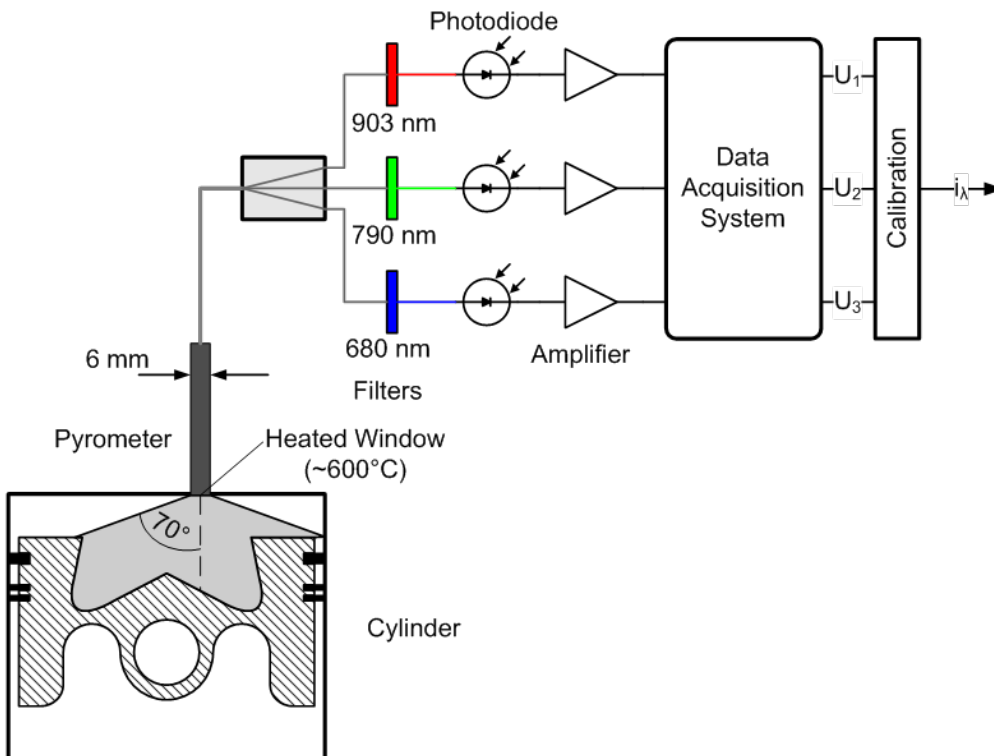


Bei der heterogenen Dieselvebrennung existieren im Brennraum zu jedem Zeitpunkt der Verbrennung sehr unterschiedliche F, T – Bedingungen.

Akihama *et al.* **SAE** 2001-01-0655, 2001

In-Zylinder Pyrometrie

- Mehrfarben-Pyrometrie verwendet das vom Russ emittierte Licht zur Bestimmung von
 - Russtemperatur
 - Russkonzentration/-dichte (KL Faktor)



Russ-Messung mittels Mehrfarben - Pyrometrie

- Erfasst nur heissen "glühenden" Russ
- Erfassung beschränkt durch Optik und Einbaulage
- Zeitaufgelöste Messung

$$\left[1 - \left(\frac{\frac{C_2}{\lambda_1^2 T}}{e^{\frac{C_2}{\lambda_1^2 T_s,1}} - 1} \right) \right]^{\lambda_1^\alpha} = \left[1 - \left(\frac{\frac{C_2}{\lambda_2^2 T}}{e^{\frac{C_2}{\lambda_2^2 T_s,2}} - 1} \right) \right]^{\lambda_2^\alpha}$$

$$T|_{\lambda_1, \lambda_2} = T|_{\lambda_1, \lambda_3} = T|_{\lambda_2, \lambda_3}$$

$$KL = -\lambda^{1.39} \ln \left[1 - \left(\frac{\frac{C_2}{\lambda^2 T}}{e^{\frac{C_2}{\lambda^2 T_s}} - 1} \right) \right]$$

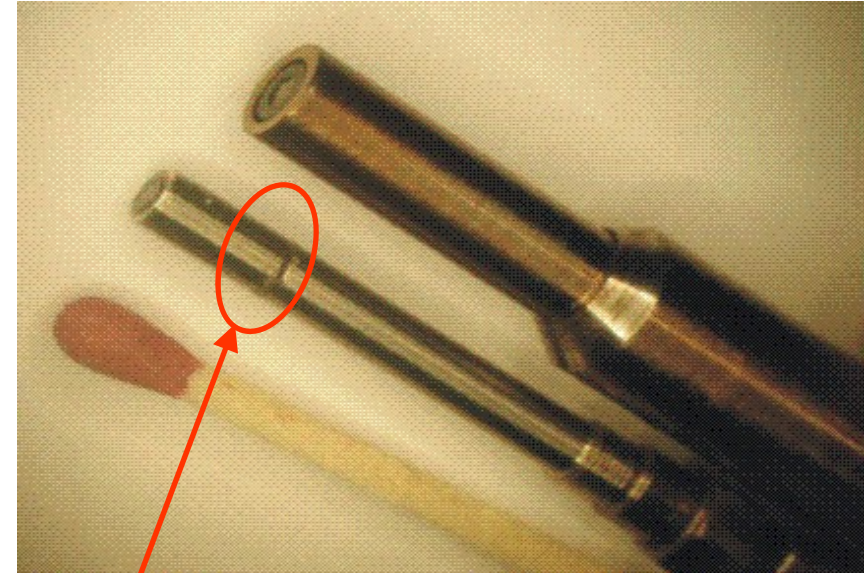
$$KL|_{\lambda_1} = KL|_{\lambda_2} = KL|_{\lambda_3}$$

Hottel and Broughton. *Ind. Eng. Chem.*, 1932. 4(2)

In-Zylinder Pyrometrie

- Erster Prototyp entwickelt am LAV¹
- Weiterentwicklung und Miniaturisierung im Rahmen eines KTI - Projekts mit Kistler AG and Sensoptic²
- Verwendet 3 Wellenlängen für Redundanz (T, KL Verifizierung)
- Auf ~600°C beheizte Optik verhindert Verschmutzung und garantiert Langzeit – Signalstabilität
- Sehr geringe Grösse erlaubt die Anwendung in allen Typen von Dieselmotoren (Glühkerzen-Adapter, zBsp.)

Realisierung eines Mehrfarben-Pyrometers



$d_{\text{Sensor}} = 3\text{mm}$

KISTLER

measure. analyze. innovate.

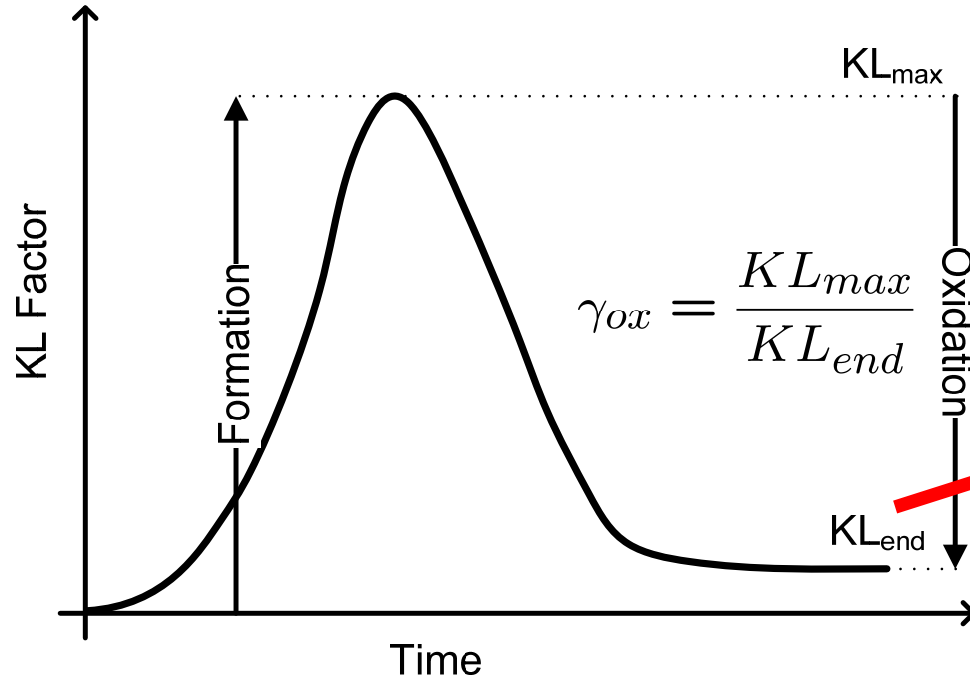
SENSOPTIC

¹ R. Schubiger *et al.* **MTZ**, 2002. 5(63):342-353

² S. Kunte *et al.* **KTI Technical Report**, 2005.

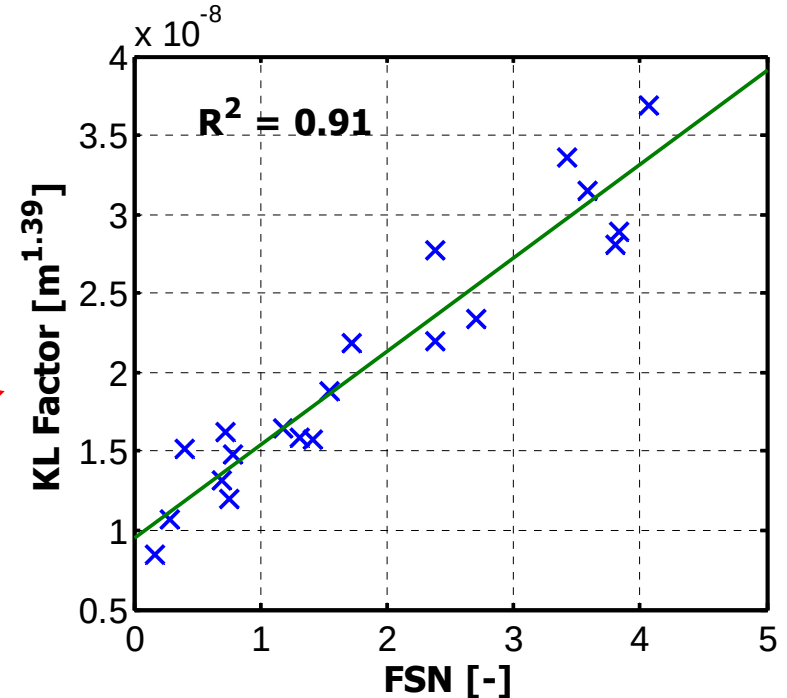
In - Zylinder Pyrometrie

Mehrfarben - Pyrometer , Korrelation mit FSN



- KL_{end} – korreliert mit FSN-Messungen im Auspuff ($R^2 \sim 0.8 \dots 0.9$)

➔ Zyklus-aufgelöste Messung der Russ-Emission

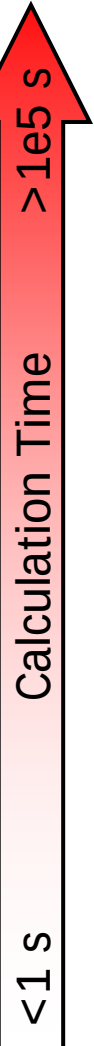


- KL_{max} – Mass für die Russ-Bildung
- γ_{ox} – Mass für die Russ-Oxidation
- ➔ Relative Charakterisierung der Bildungs – und Oxidationsprozesse

Kirchen et al. Proc. Stuttgart Symposium, 2008. 2:129-145

Modellierung der Russbildung

State Of The Art



Calculation Time

<1 s

>1e5 s

- **Detaillierte Modelle:**
 - M. Frenklach *et al.* C&F, 2000 and 1998; M. Kraft *et al.* ETH NPC, 2008.
 - **50-100 species for gas phase chemistry (PAH)**
 - **Surface growth, agglomeration, coagulation (particle tracking)**
- **Phänomenologische Modelle**
 - A. Fusco *et al.* COMODIA, 1994: 571-576. **8-step model**
 - P. Belardini *et al.* SAE 922225, 1992. **4-step model**
 - X. Li *et al.* SAE 952248, 1995. **4-zone model**
 - H. Hiroyasu *et al.* JSME, 1983. 26(214):569-575: **2-step model** (Vorläufer des LAV-Modells)
- **(Semi) Empirische Modelle**
 - S. Wenzel. Ph.D, Otto-von-Guericke Uni. 2006: **Multiplicative function**
 - Brahama *et al.* SAE 2005-01-1122, 2005: **2-step+empirical 23 weights**
 - Auch diese Modelle benötigen Druck- und Brennverlauf

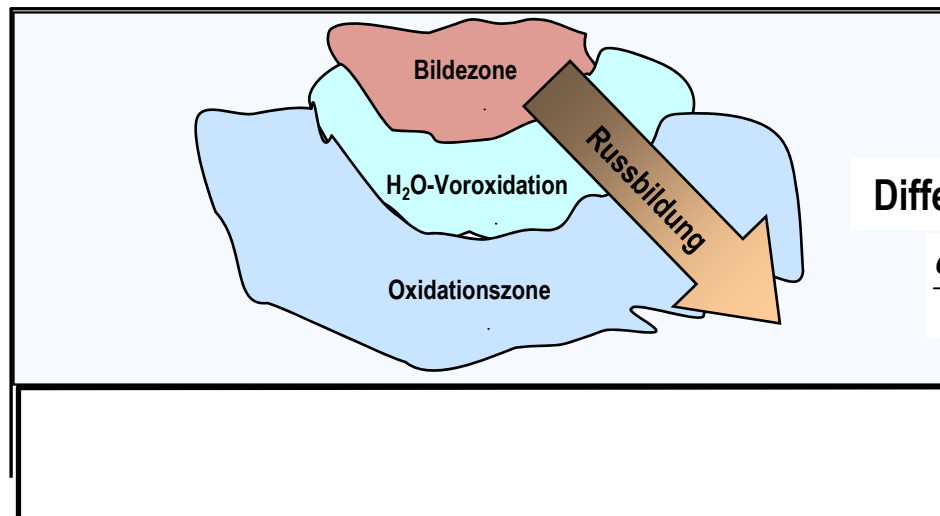
Phänomenologisches Russ-Emissionsmodell LAV

Zeitaufgelöstes Modell

■ Ansatz für ein zeitaufgelöstes phänomenologisches Modell

- Russbildung und -oxidation

- Bildezone: Russbildung unter Sauerstoffmangel
- Voroxidation: Oxidation infolge Wasserbeimischungen (Emulsionen) während der Bildung
- Oxidationszone: Russoxidation unter Sauerstoffüberschuss



Differentialgleichung der Russemission:

$$\frac{dm_{Russ}}{dt} = \frac{dm_{Russ.Bild}}{dt} - \frac{dm_{Russ.Ox}}{dt}$$

Marco Warth: Comparative Investigation of Mathematical Methods for Modeling and Optimization of Common-Rail DI Diesel Engines
Diss. ETH No. 16357, 2007

Phänomenologisches Russ-Emissionsmodell LAV

Zeitaufgelöstes Modell

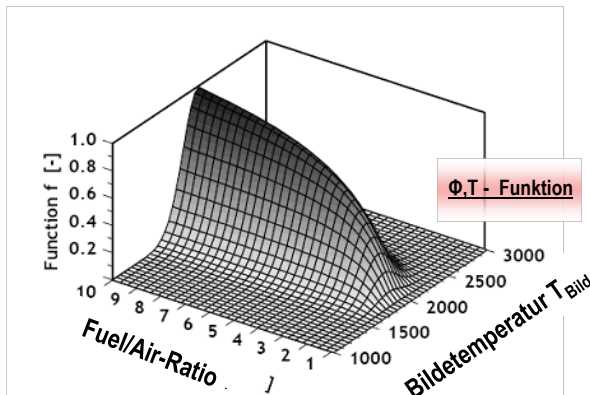
■ Russbildung (Bei gleichzeitiger Voroxidation durch H₂O) 5 Modell-Parameter

$$\frac{dm_{\text{Russ.Bild}}}{dt} = A_{\text{Bild}} \cdot \left. \frac{dm_{\text{Br' stoff}}}{dt} \right|_{\text{Diff}} \cdot \left[\left(\frac{p_{\text{Zyl}}}{p_{\text{Ref}}} \right)^{n_1} \cdot f(T_{\text{Bild}}, \phi_{\text{Bild}}) - A_{\text{Ox.OH}} \cdot \xi_{\text{H}_2\text{O}} \cdot \left(\frac{m_{\text{Russ}}}{m_{\text{Br' stoff}}} \right) \cdot e^{-\frac{T_{\text{A.Ox.OH}} - T_{\lambda=1}}{T_{\lambda=1}}} \right]$$

$\xi_{\text{H}_2\text{O}}$: Wassergehalt des Brennstoffs $\left[\frac{\text{kg}_{\text{H}_2\text{O}}}{\text{kg}_{\text{Br' stoff}}} \right]$

○ Zu bestimmende Modellparameter

○ Zustandsgrößen bzw. Größen aus der thermodynamischen Prozessrechnung



Bildefunktion : $f(T_{\text{Bild}}, \phi_{\text{Bild}})$

Math. Approximation des „Φ-T Diagramms“
erweitert nach M. Warth Diss. ETH No. 16357, 2007

T_{Bild} : Temperatur der Bildezone $\phi_{\text{Bild}} < 1$
 $\phi_{\text{Bild}} = 1 / \phi_{\text{Bild}}$

¹ Akihama, K. et al. „Mechanism of the smokeless rich diesel combustion by reducing temperature“, SAE 2001-01-0655, Warrendale, PA, USA, 2001.

Phänomenologisches Russ-Emissionsmodell LAV

Zeitaufgelöstes Modell

Russoxidation 5 Modell-Parameter

$$\frac{dm_{\text{Russ.Ox}}}{d\phi} = A_{\text{Ox}} \cdot \frac{1}{\tau_{\text{char}}} \cdot (m_{\text{Russ}})^{n_2} \cdot \left(\frac{p_{\text{O}_2}}{p_{\text{O}_2.\text{Ref}}} \right)^{n_3} \cdot e^{-\frac{T_{\text{A.Ox}}}{T_{\text{Ox}}}}$$

 Zu bestimmende Modellparameter

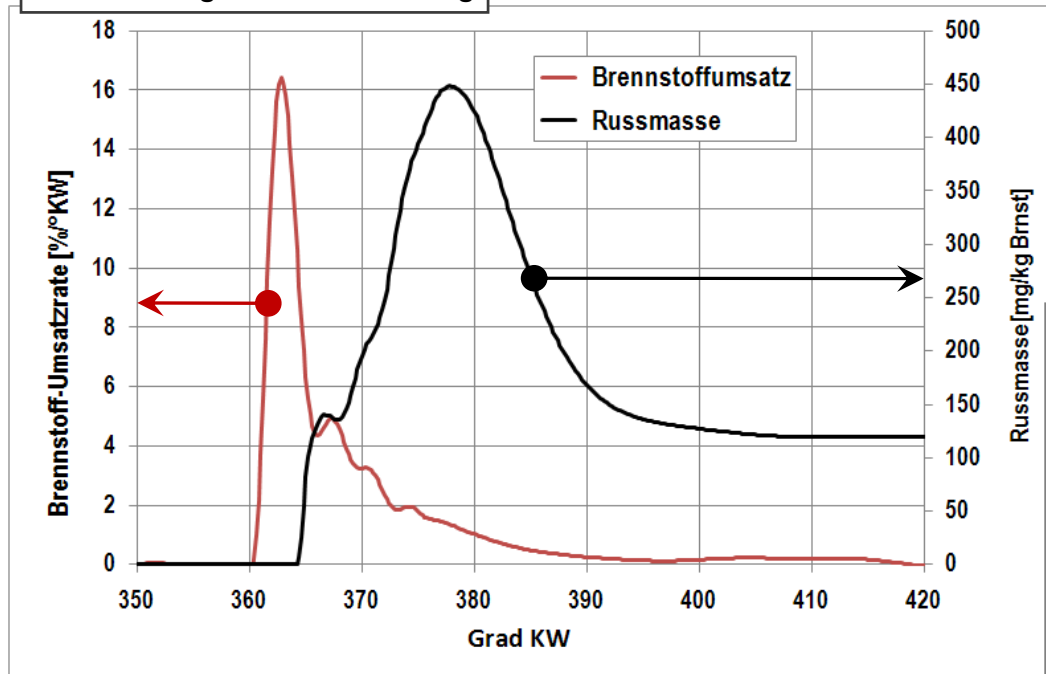
 Zustandsgrößen bzw. Größen aus der thermodynamischen Prozessrechnung

$\frac{1}{\tau_{\text{char}}}$: Charakteristische Mischungszeit	$\frac{dm_{\text{Br}}}{dt}$ $m_{\text{Brnst}} - \text{Dampf}$
T_{Ox} : Temperatur der Oxidationszone	$\text{Oxi} > 1$
p_{O_2} : Sauerstoff-Partialdruck der Oxidationszone	$\text{Oxi} > 1$

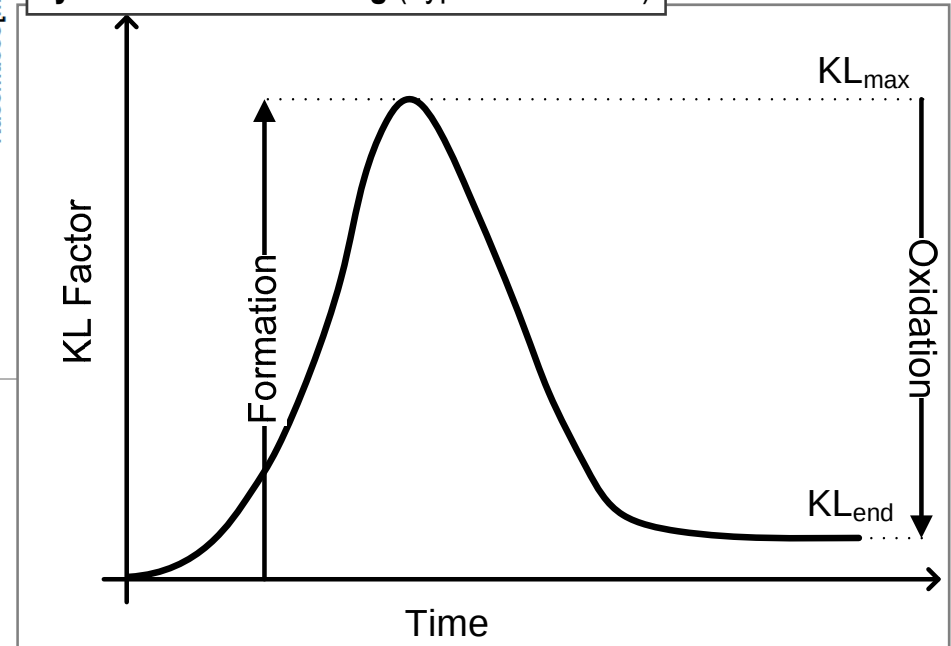
Phänomenologisches Russ-Emissionsmodell LAV

Zeitaufgelöstes Modell

Verbrennung und Russbildung



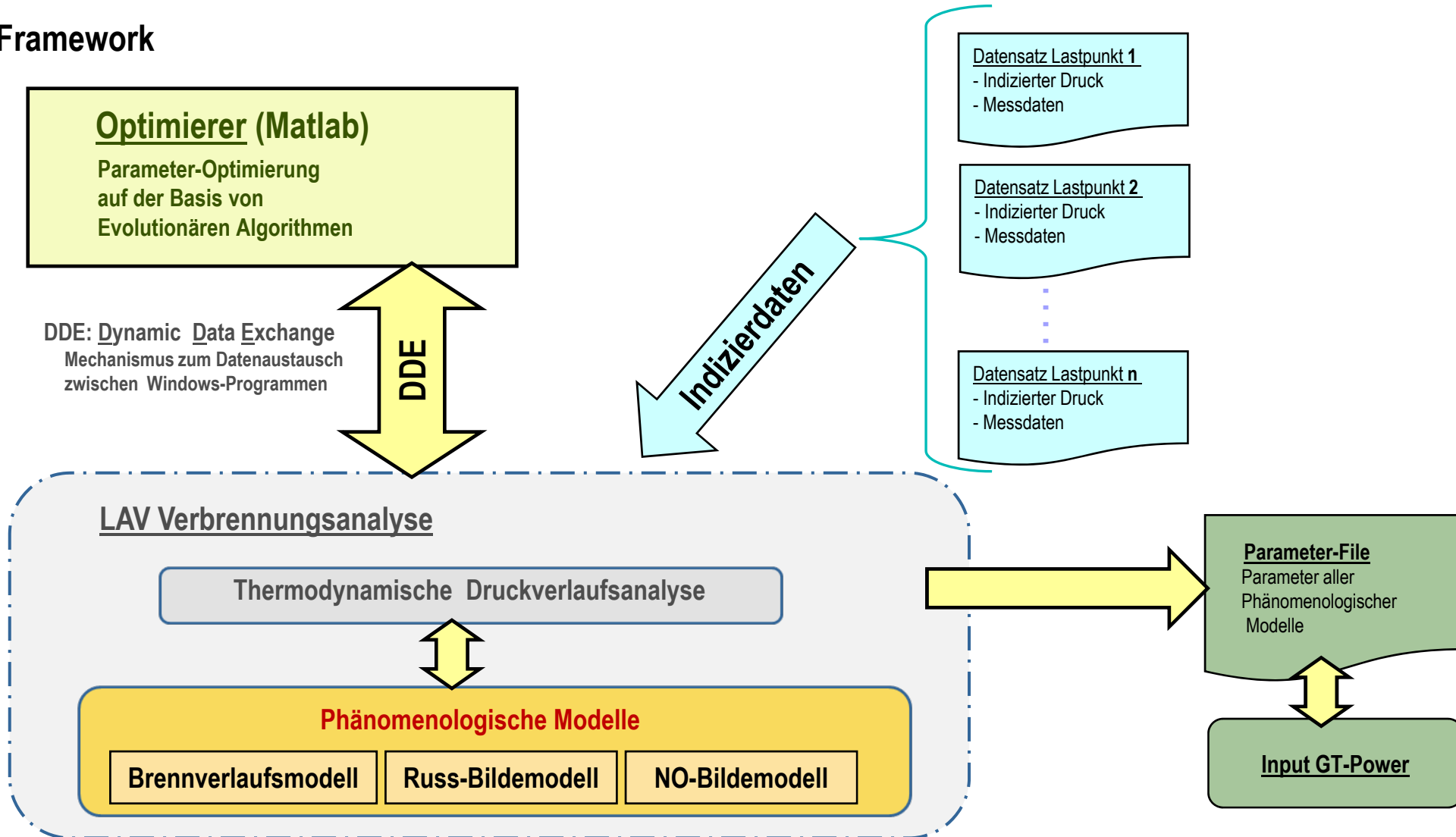
Pyrometrische Messung (Typischer Verlauf)



Phänomenologische Modelle

Parameter-Optimierung

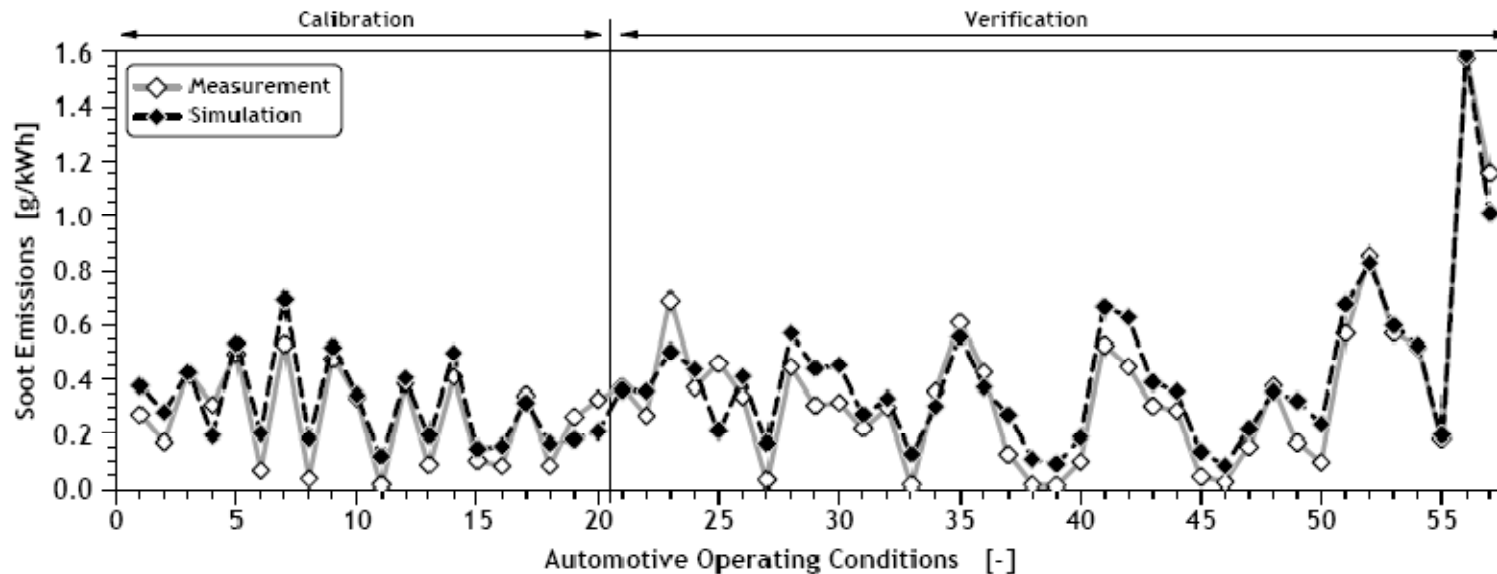
Framework



Phänomenologisches Russ-Emissionsmodell LAV

Zeitaufgelöstes Modell

Modell-Kalibration und -Verifikation: „Automotive“ Diesel



Marco Warth: Comparative Investigation of Mathematical Methods for Modeling and Optimization of Common-Rail DI Diesel Engines
Diss. ETH No. 16357, 2007

Phänomenologisches Russ-Emissionsmodell LAV

Zeitaufgelöstes Modell

❖ Vorteile

- Gute Wiedergabe der Phänomene
- Hohe Qualität der Voraussage der Russ-Emissionen
- Einsatz ausserhalb des Optimierungsbereichs

❖ Nachteile

- Erfordert Zeit-aufgelöste Daten aus einer aufwendigen Mehrzonen-Prozessrechnung , unter anderen
 - Temperaturen verschiedener Zonen
 - Inverse Mischungszeit
 - Brennrate
 - Sauerstoffpartialdruck der Oxidationszone
- Hohe Rechenzeit (zusätzliche Belastung einer Prozessrechnung ca. 5.5 s / Arbeitsspiel)

❖ Eignung

- Erweiterung von Prozessrechenprogrammen (GT-Power z. Bsp.) zur Optimierung von Motorprozessen
- Das Modell ist wegen des grossen Rechenzeitbedarfs für Regelungszwecke als virtueller Sensor nicht geeignet

Mean Value Soot Model (MVSM) Diss. ETHZ Nr. 18088 Patrick Kirchen 2008

Übersicht

■ Bestehendes Zeit-aufgelöstes Modell

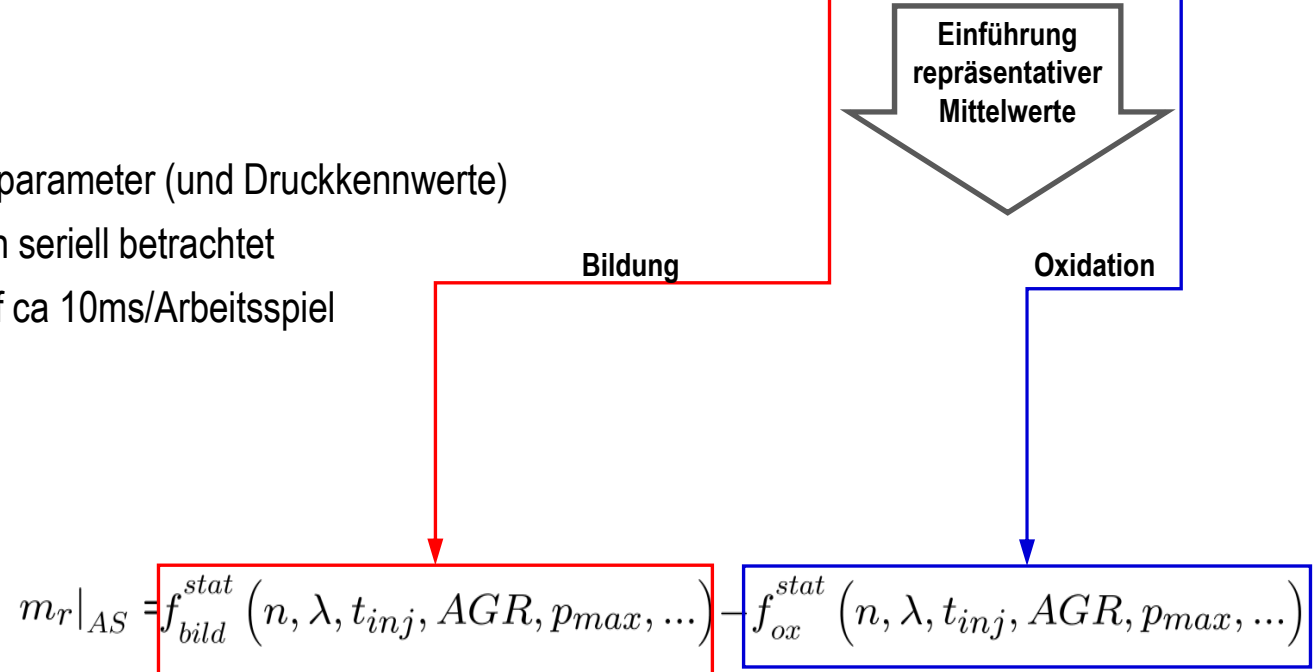
- Kurbelwinkelaufgelöst
- Benötigt Druck- und Einspritzverlauf, sowie aufwendige thermodynamische Analyse
- Rechenzeit ca 5.5 s/Arbeitsspiel

$$\frac{dm_r}{dt} = \frac{dm_{r,bild}}{dt} - \frac{dm_{r,ox}}{dt}$$

$$m_r|_{AS} = \int_{AS} \left(\frac{dm_{r,bild}}{dt} dt \right) - \int_{AS} \left(\frac{dm_{r,ox}}{dt} dt \right)$$

■ Reduzierter Ansatz

- Zyklusaufgelöst
- Berücksichtigt globale Steuerparameter (und Druckkennwerte)
- Bildung und Oxidation werden seriell betrachtet
- Reduktion der Rechenzeit auf ca 10ms/Arbeitsspiel



Mean Value Soot Model(MVSM)

Gesamtrussmasse

Russmasse $m_r = m_{r,bild} - m_{r,ox}$

Russbildung

$$\frac{dm_{r,bild}}{dt} \cdot (\Delta t_{diff})$$

$$\Delta t_{diff} = f(\Delta t_e)$$

Russoxidation

$$\frac{dm_{r,ox}}{dt} \cdot (\Delta t_{ox})$$

$$\Delta t_{ox} = t_{T_{einf.}} - t_{b.diff.}$$

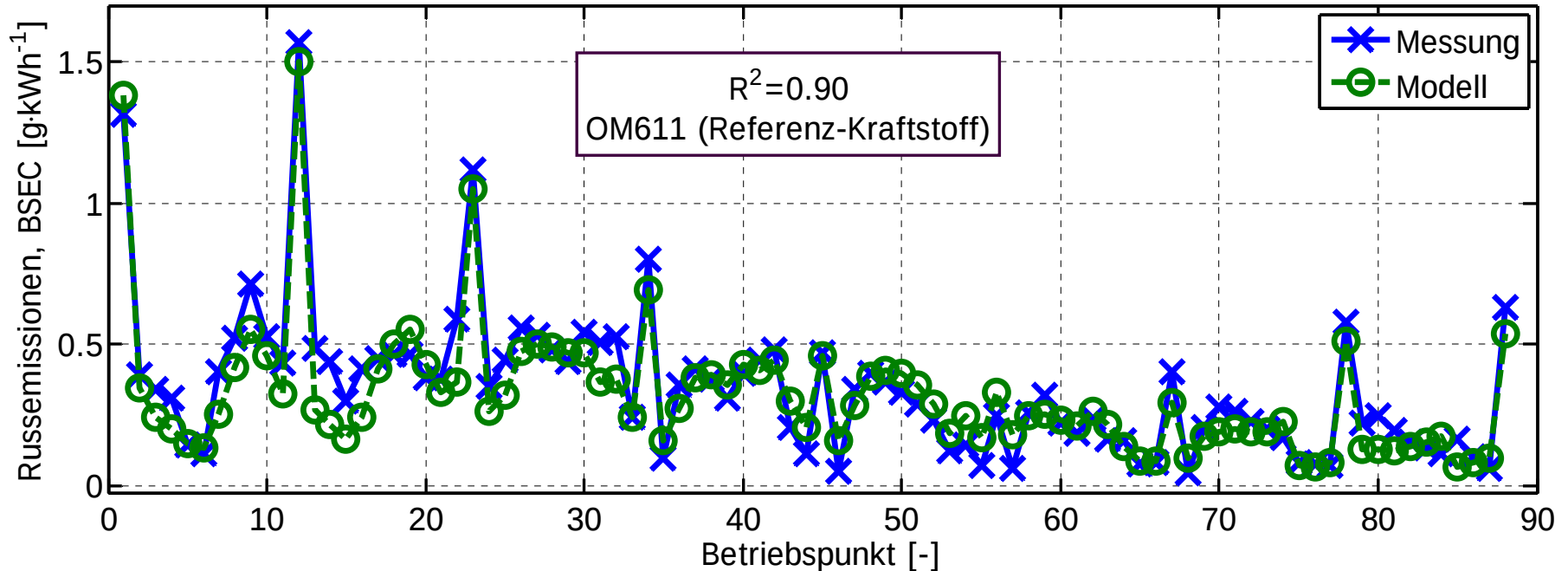
$$f(T_{einf.}, n, \epsilon)$$

$$f(SOI, \xi_{diff})$$

- $m_{r,bild}$ Gebildete Russmasse
- $m_{r,ox}$ Oxidierte Russmasse
- Δt_{diff} Dauer der Diffusionsverbrennung
- Δt_e Einspritzdauer
- Δt_{ox} Zeit für Russoxidation
- $T_{einf.}$ Einfrierungstemperatur
- $t_{T_{einf.}}$ Russ - „Einfrierungszeitpunkt“
- $t_{b.diff.}$ Zeitpunkt zum Beginn der Diffusionsverbrennung
- n Drehzahl
- ξ_{diff} Anteil Diffusionsverbrennung

Mean Value Soot Model (MVSM) Stationärer Betrieb

OM611 – Ref. Kraftstoff

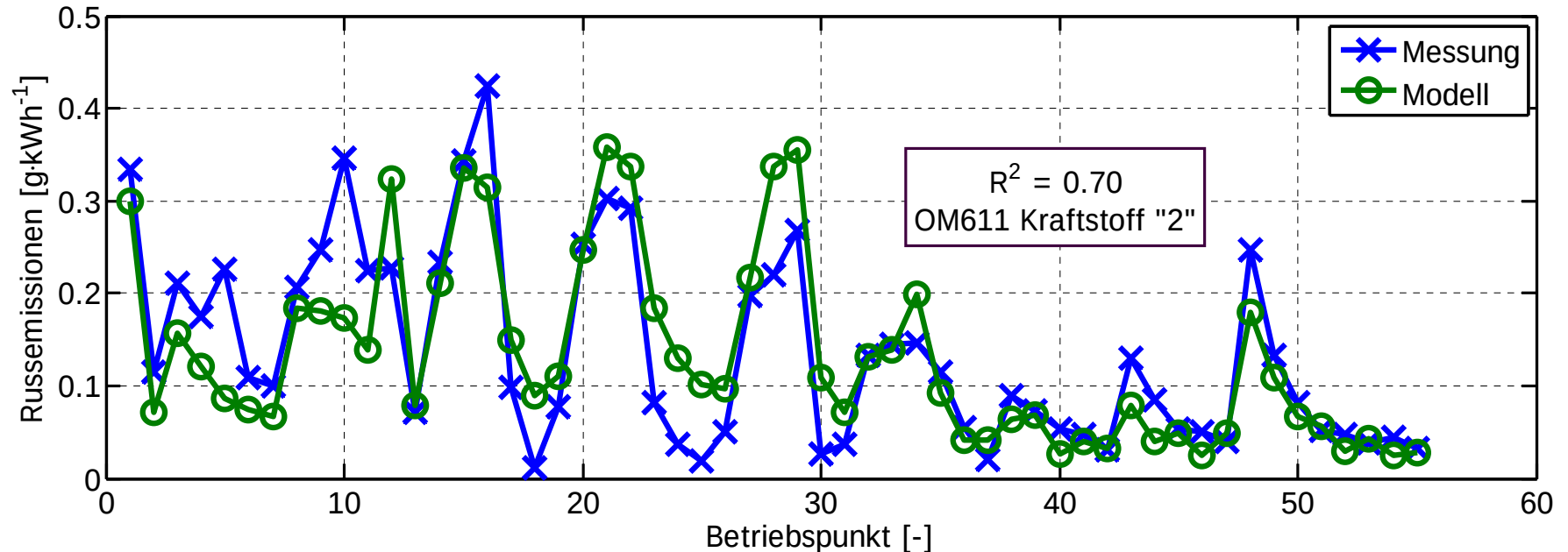
Vergleich Modellrechnung <-> Messungen Referenz-Kraftstoff (Cetanzahl 55, Visk. 2.33 mm²/s, Aromate 18.6%, Siede-Ende 336 °C)

- Parametrierung mit 90 Betriebspunkten
 - Güte der Parametrierung:
 - $R^2 = 0.90$
 - $MSE = 6.5e-3[g \cdot kWh^{-1}]$
 - Alle Parameter variiert

Mean Value Soot Model (MVSM) Stationärer Betrieb

OM611 –Kraftstoff 2

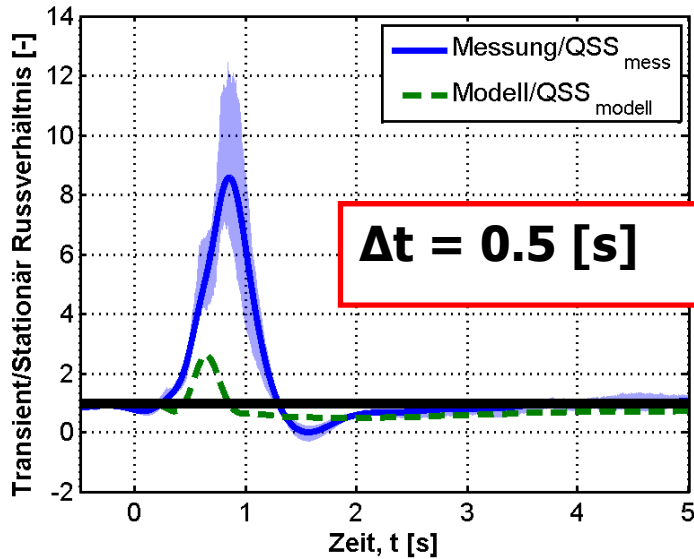
Vergleich Modellrechnung <-> Messungen Kraftstoff 2 (Cetanzahl 43 (55), Visk. 1.07 mm²/s, Aromate 1.9% (18.6%) , Siede-Ende 226 °C (336°C))



- Parametrierung mit 55 Betriebspunkten
 - Güte der Parametrierung:
 - $R^2 = 0.70$
 - $MSE = 3.3e-3$ [g·kWh⁻¹]
- Nur 8 Parameter variiert

Mean Value Soot Model(MVSM) Last-Transiente

OM611 – Ref. Kraftstoff



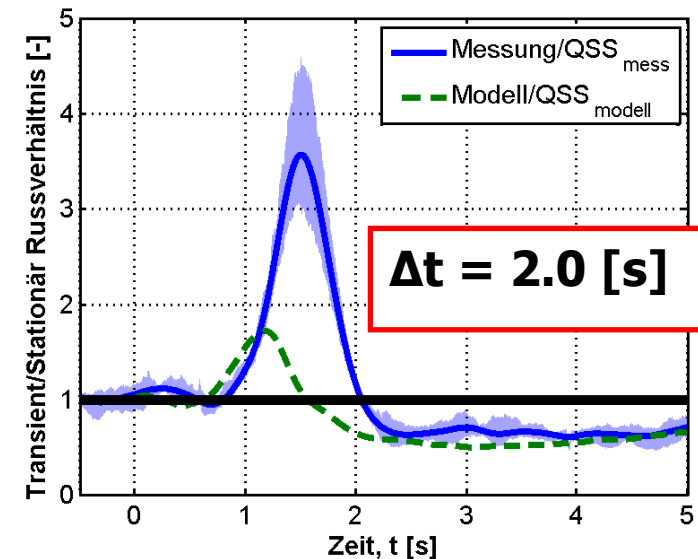
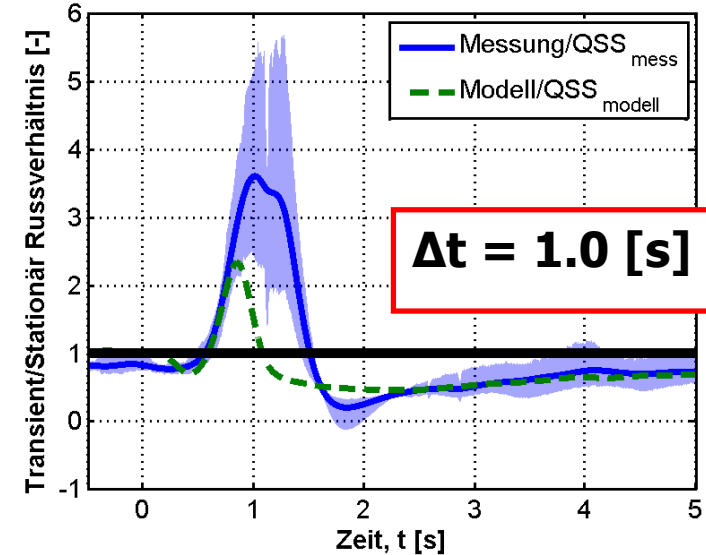
■ Mittelwertmodell:

- Unterschätzt die Erhöhung der Russemissionen
- Reproduziert die Tauchphase nach den Transienten

Die bestimmenden Grössen:

- Temperatur bei Einlass schliessen
- Sauerstoff-Angebot (AGR,

Sind unter Last-Transienten nicht genügend genau bekannt



Mean Value Soot Model (MVSM)

Zusammenfassung und Ausblick

■ Qualitatives Verhalten des Mittelwertmodells

- Im **Stationären Betrieb** wird die Russemission sowohl qualitativ als auch quantitativ gut wiedergegeben.
- Bei den **Last-Transienten** zeigt das Mittelwertmodell die gleichen qualitativen Änderungen (Tendenzen) der Russemissionen wie die Messungen. (Sowohl die kurzfristige Erhöhung, als auch die anschliessenden „Tauchphase“ werden tendenziell richtig wiedergegeben). Emissions-Spitzen werden jedoch deutlich unterschätzt.
- **Kurze Rechenzeit**, ca 10 ms pro Arbeitsspiel (Pentium 4, 3 GHz, Matlab, Windows XP)

■ Ausblick

- Für eine gezielte Verbesserung des Mittelwertmodells in quantitativer Hinsicht, ist eine genaue Erfassung der thermodynamischen In-Zylinder Parameter (Druck → Brennverlauf, thermischer Zustand), sowie die genauere Berücksichtigung der Russbildungs- und -oxidationsprozesse erforderlich.



Nachfolge FVV Vorhaben:
Russgeregelter Dieselmotor

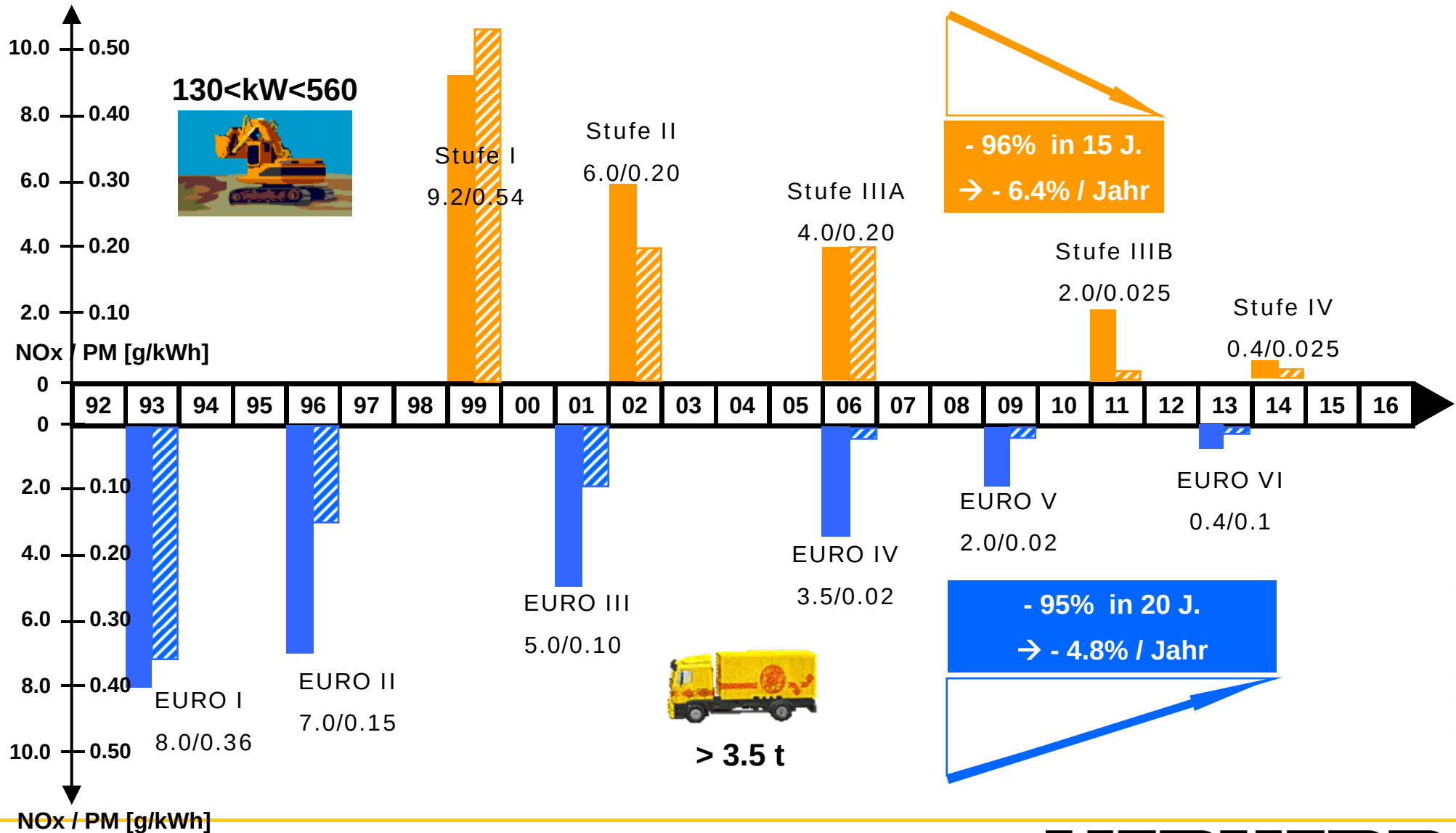
Vielen Dank für Ihre Aufmerksamkeit

Herausforderungen für Industriedieselmotoren

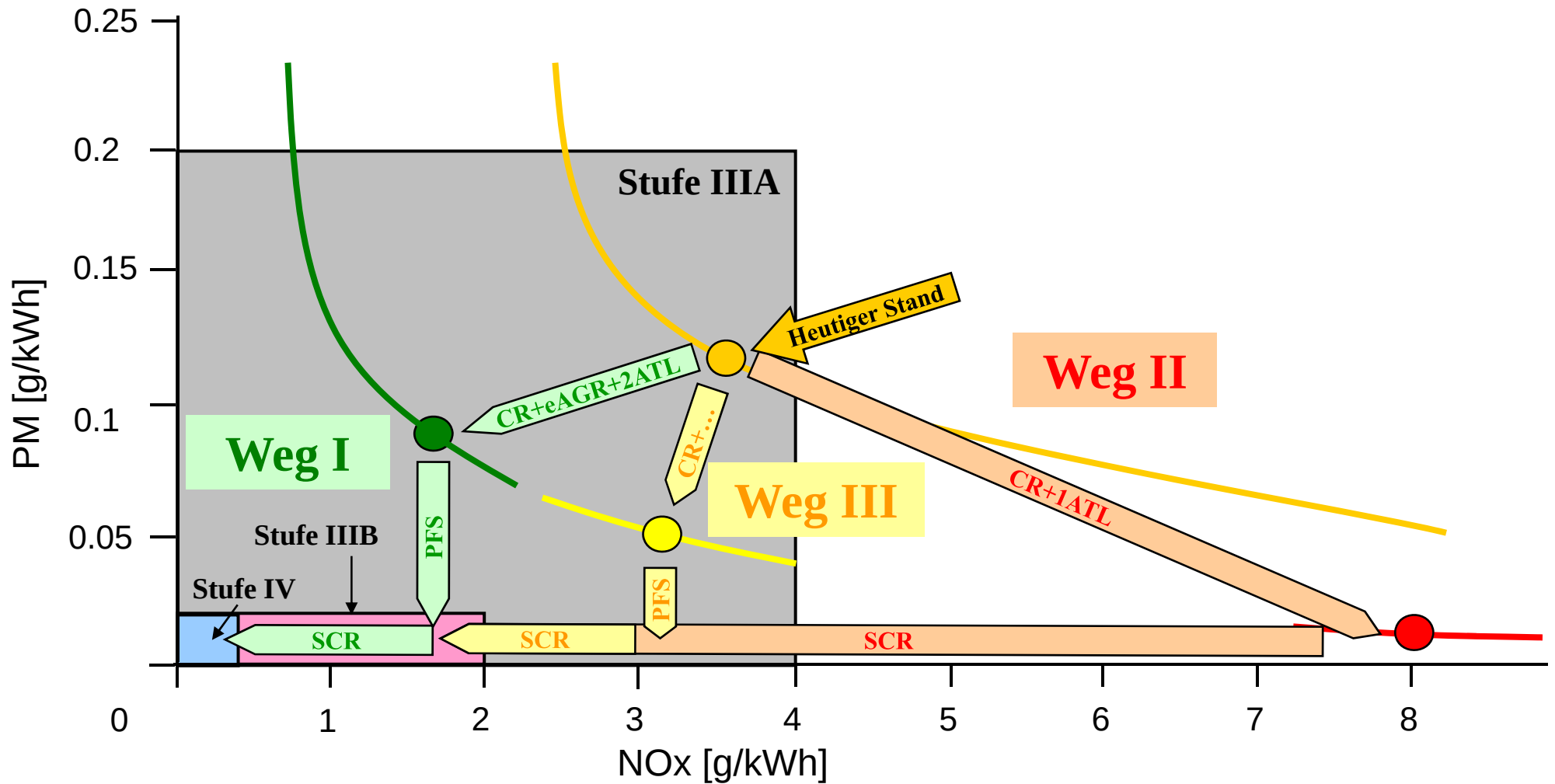
Aktuelle Entwicklungsarbeiten für Stufe IIIb und IV



Zeitliche Entwicklung der Emissionsgesetzgebung: on-Road vs Off-Road

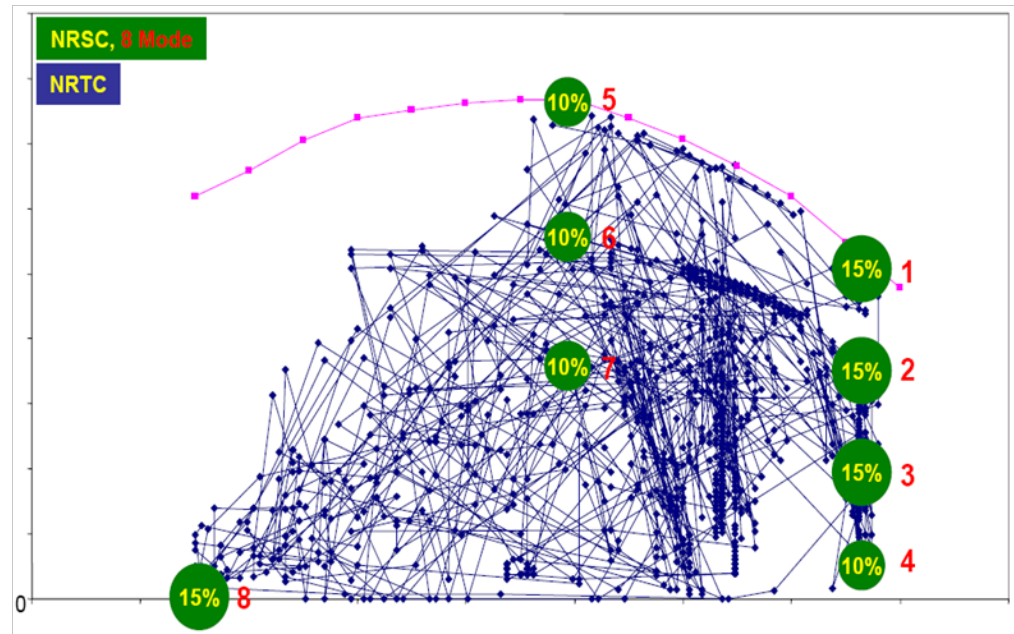


Mögliche Lösungswege zur Emissionsminderung



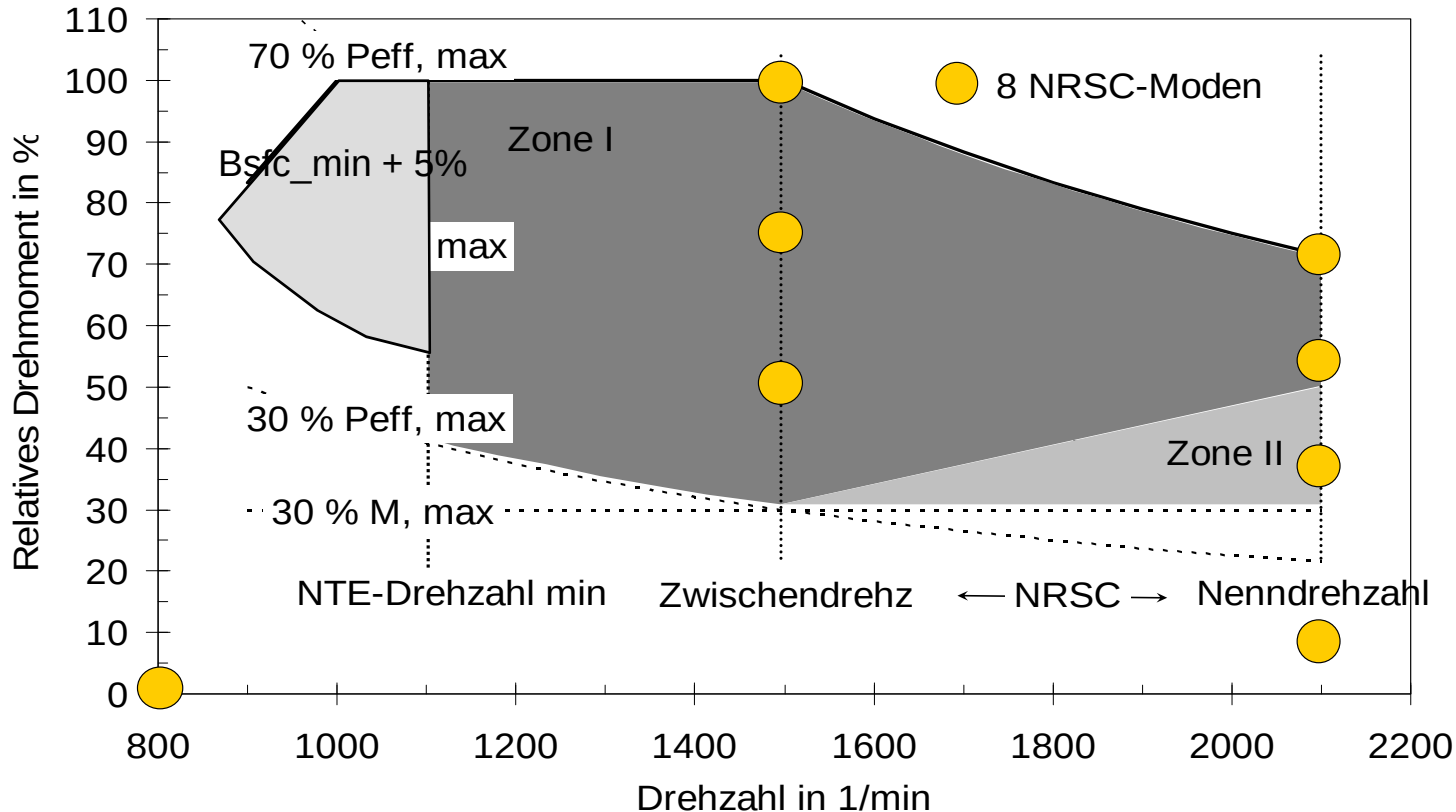
Emissionsgesetzgebung für Off-Highway Motoren: Test Zyklen und Wichtung (EU & USA)

- **NRSC (Non Road Steady Cycle)**
- **NRTC (Non Road Transient Cycle) Neu!**
 - 20 Minuten hochdynamischer Test
 - EU: Gesamtmission = **0.10** × Testergebnis kalt + **0.90** × Testergebnis betriebswarm
 - USA: Gesamtemission = **0.05** × testergebnis kalt + **0.95** × Testergebnis betriebswarm



„Not-To-Exceed“-Bestimmung (*Neu!*)

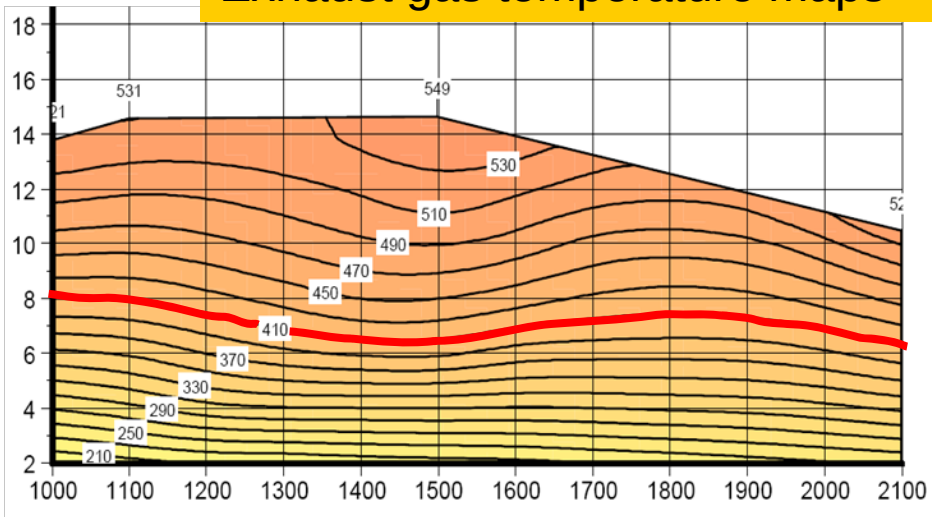
US-Kontrollbereich



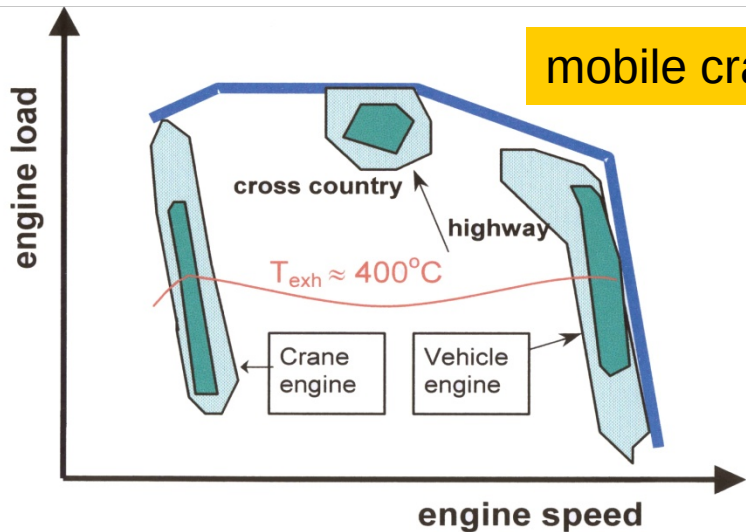
**Erlaubte Schwelle: 125 – 150 % (US)
bzw. 200 % (EU) der Grenzwerte**

Off Highway Applikationen: typische Betriebszyklen

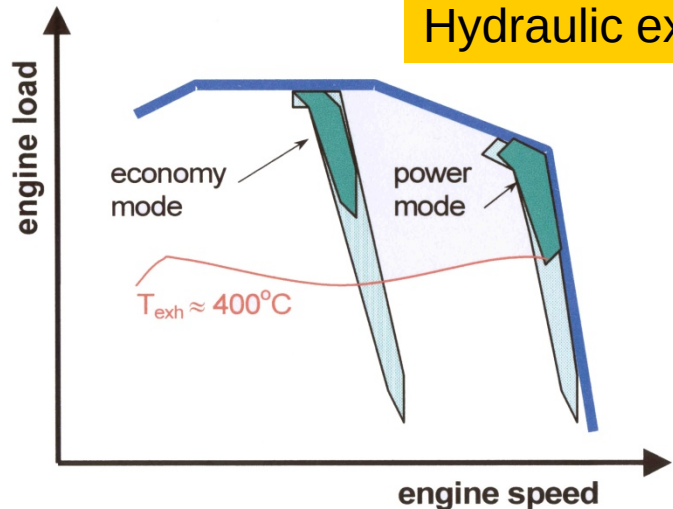
Exhaust gas temperature maps



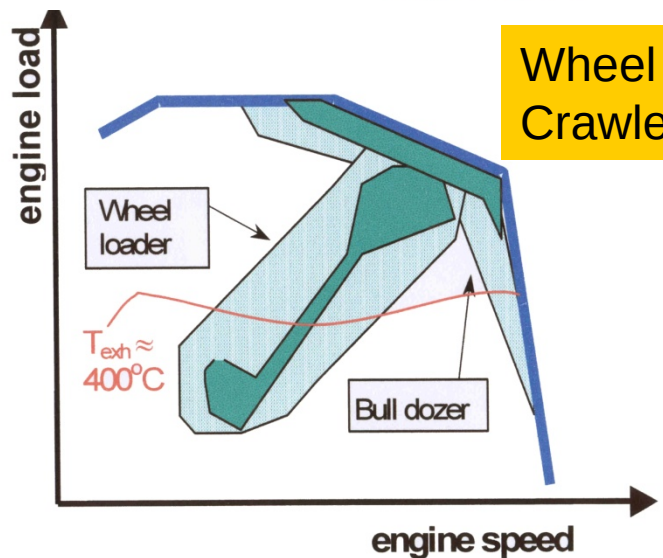
mobile crane



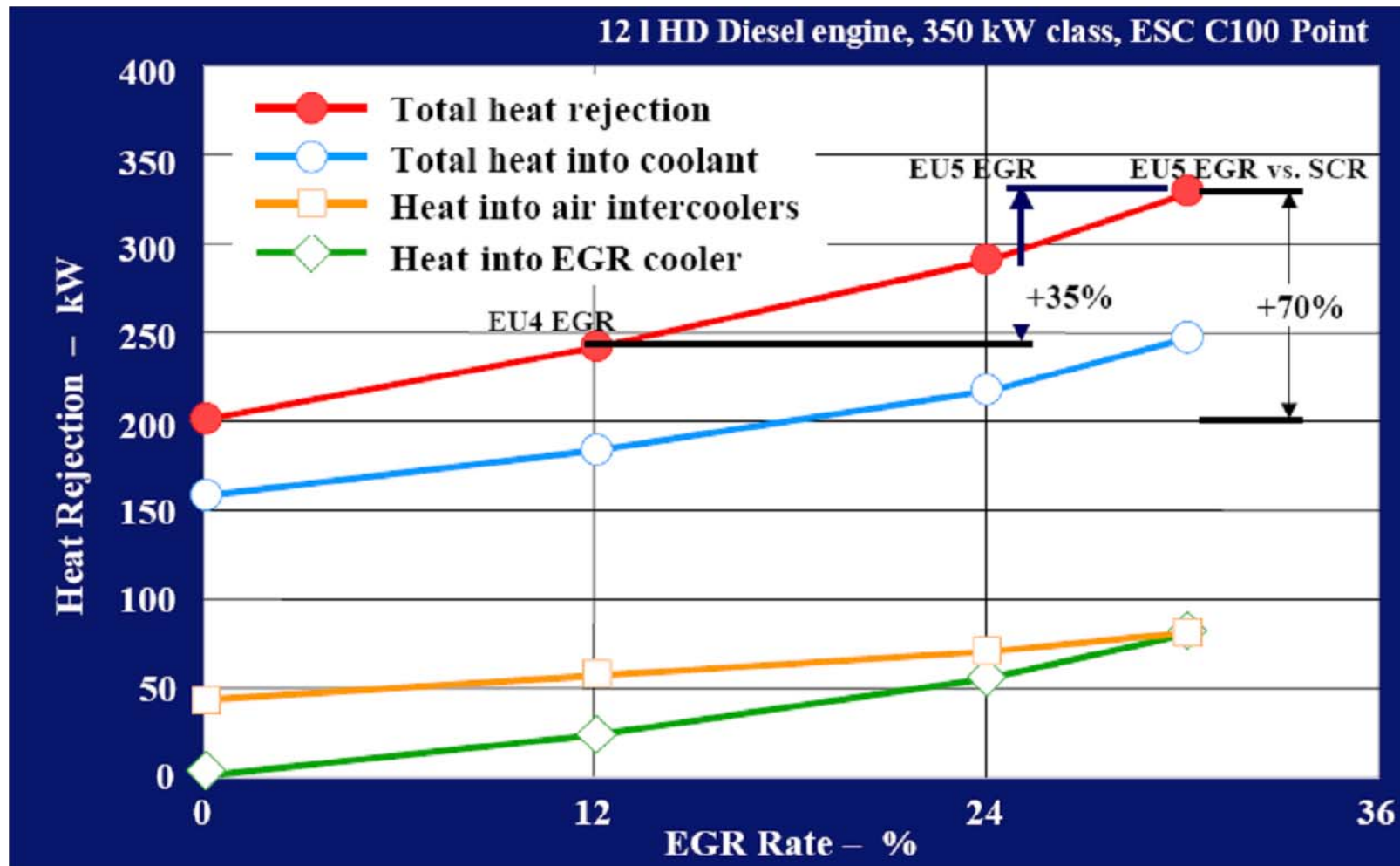
Hydraulic excavator



Wheel loader
Crawler tractor

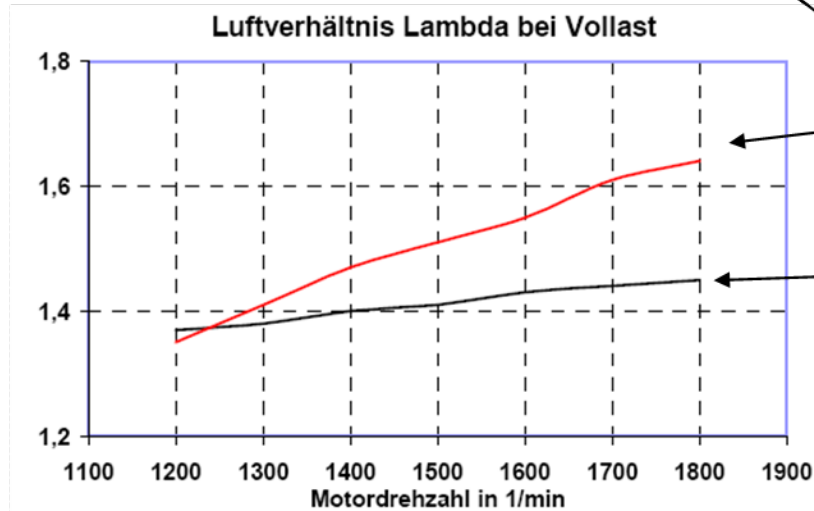
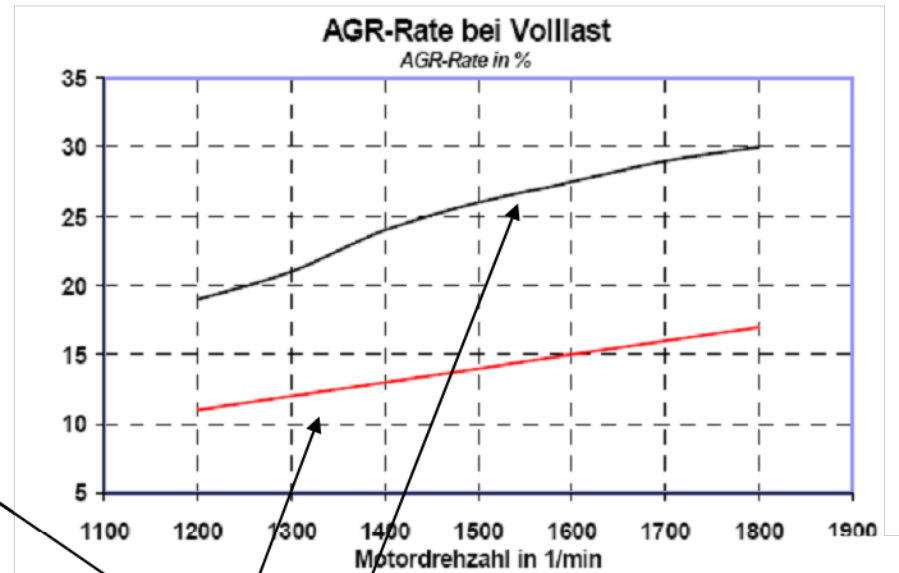
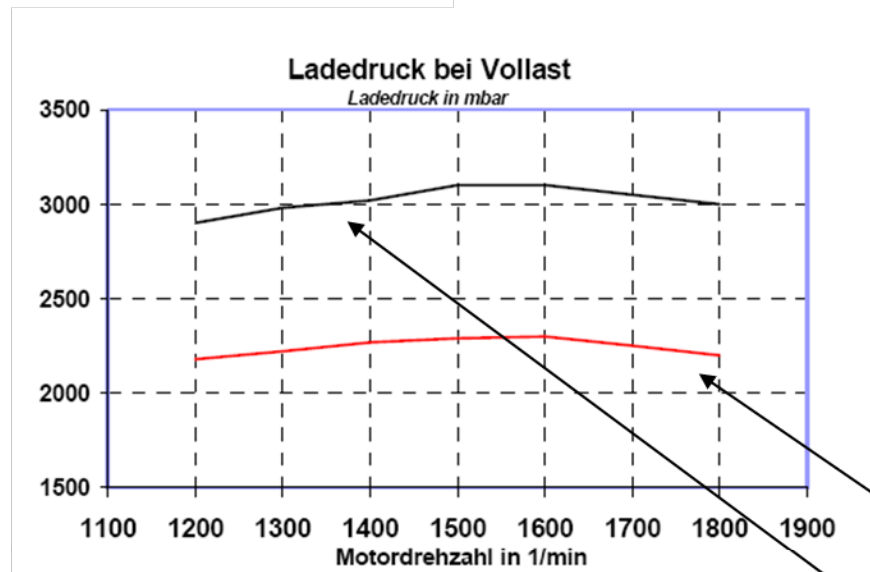


Wärmeeintrag der Abgasrückführung ins Motorkühlsystem



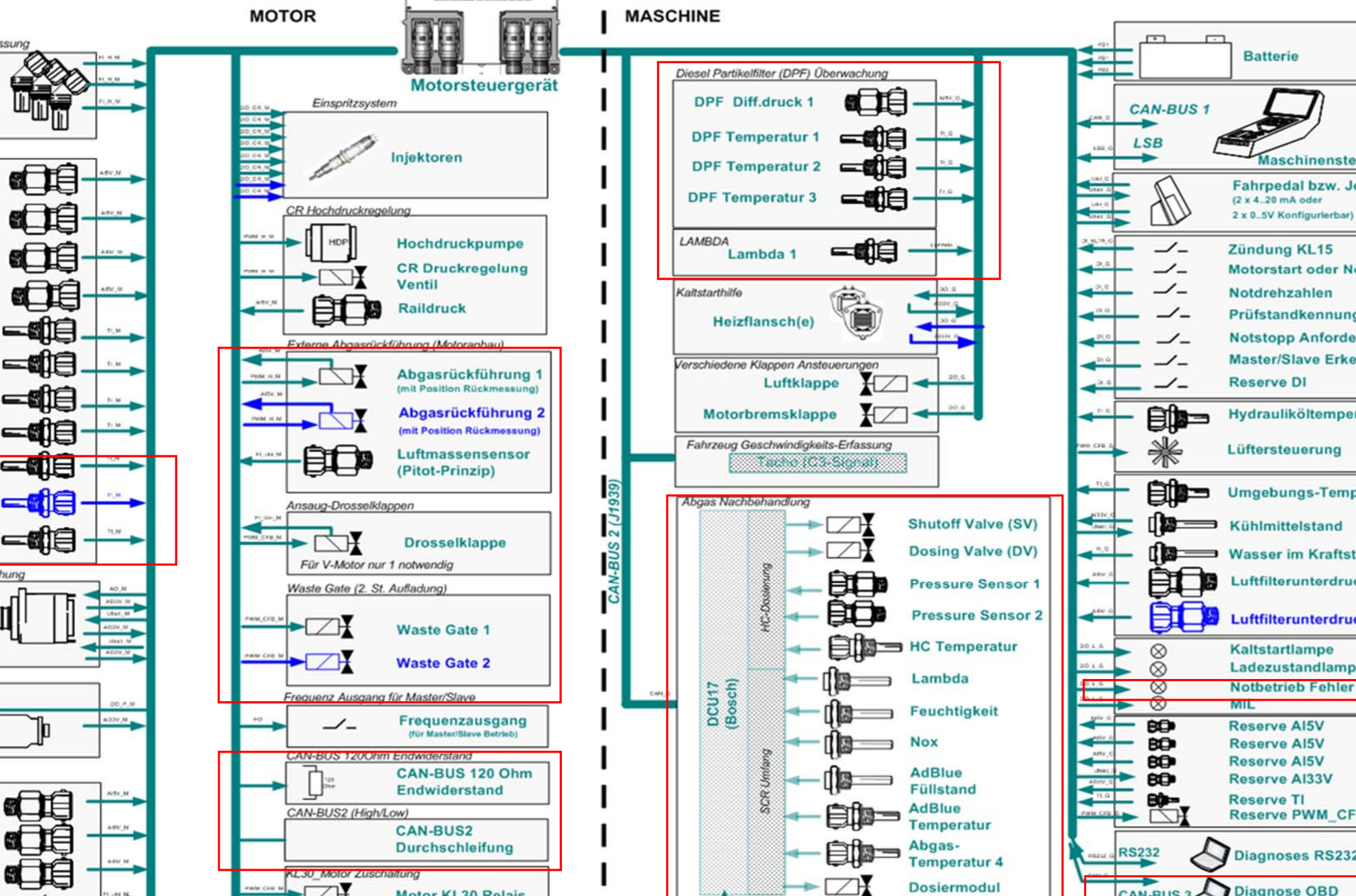
Bei einer AGR-Rate von 24% ergibt sich zusätzlich ein Wärmeeintrag ins Kühlwasser von ca. 15% der Motorleistung

Potential der 2-stufigen Aufladung (Performance & Emissions)

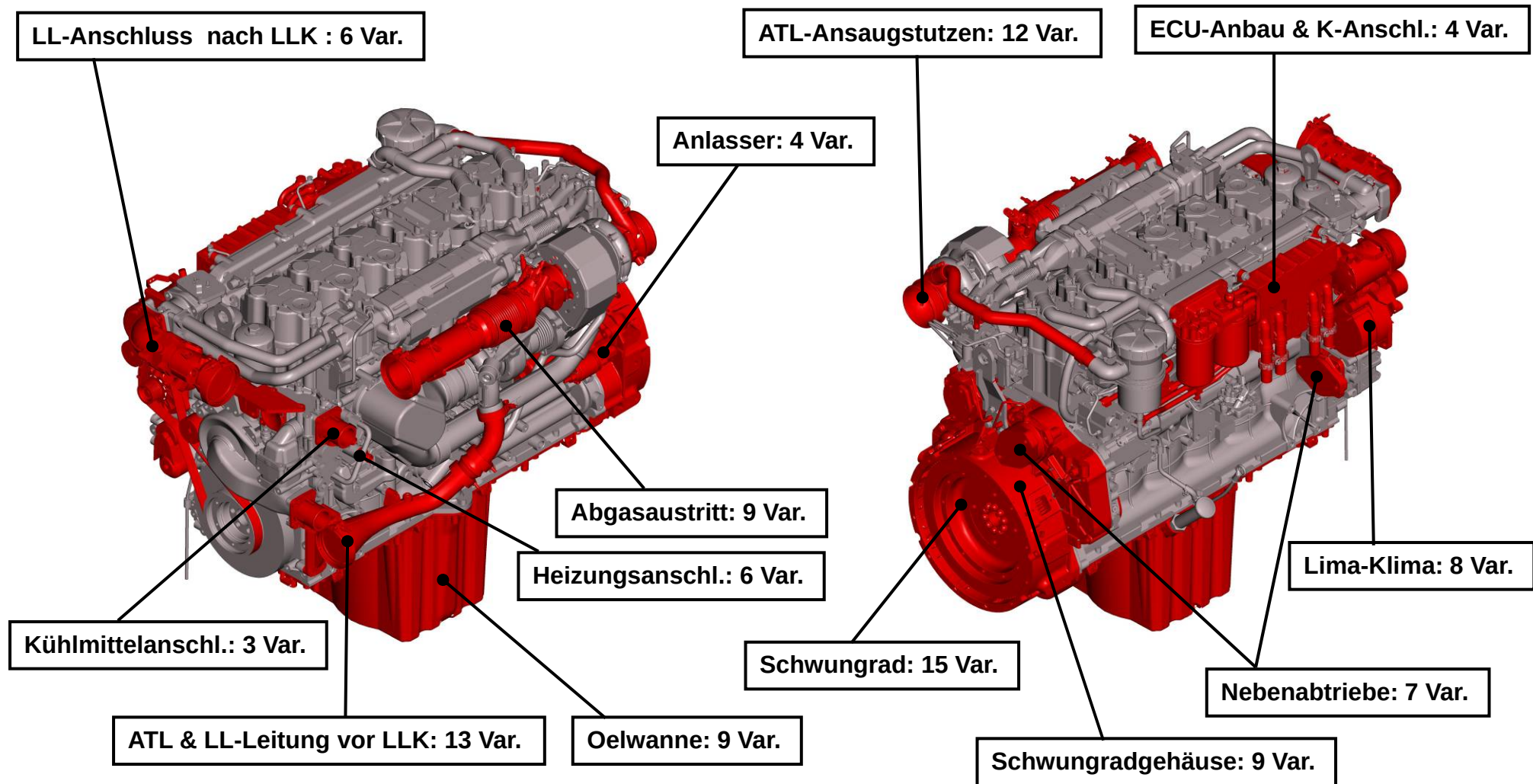


1-Stufig: 5 g/kWh NO_x

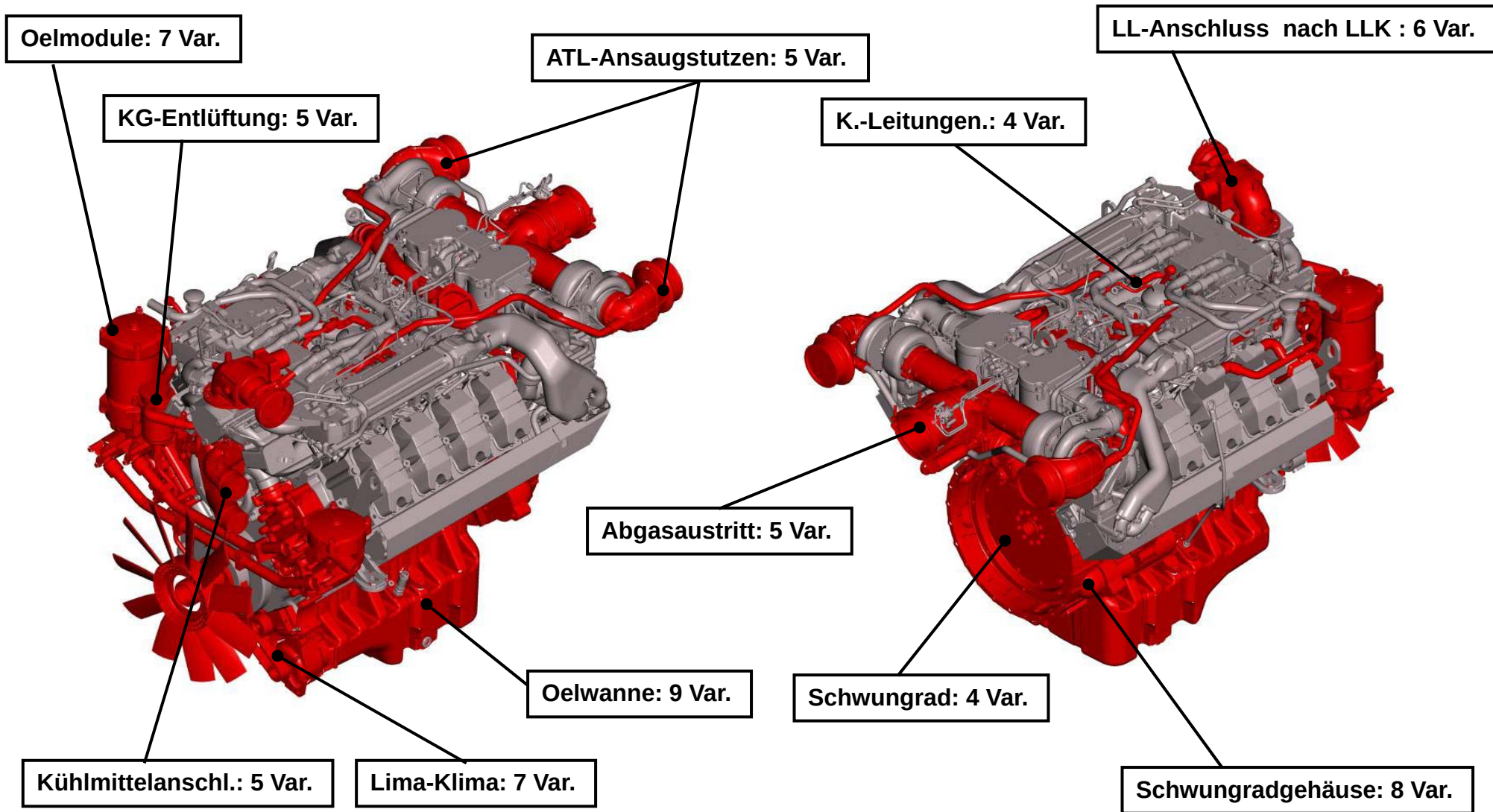
2-Stufig: 2 g/kWh NO_x



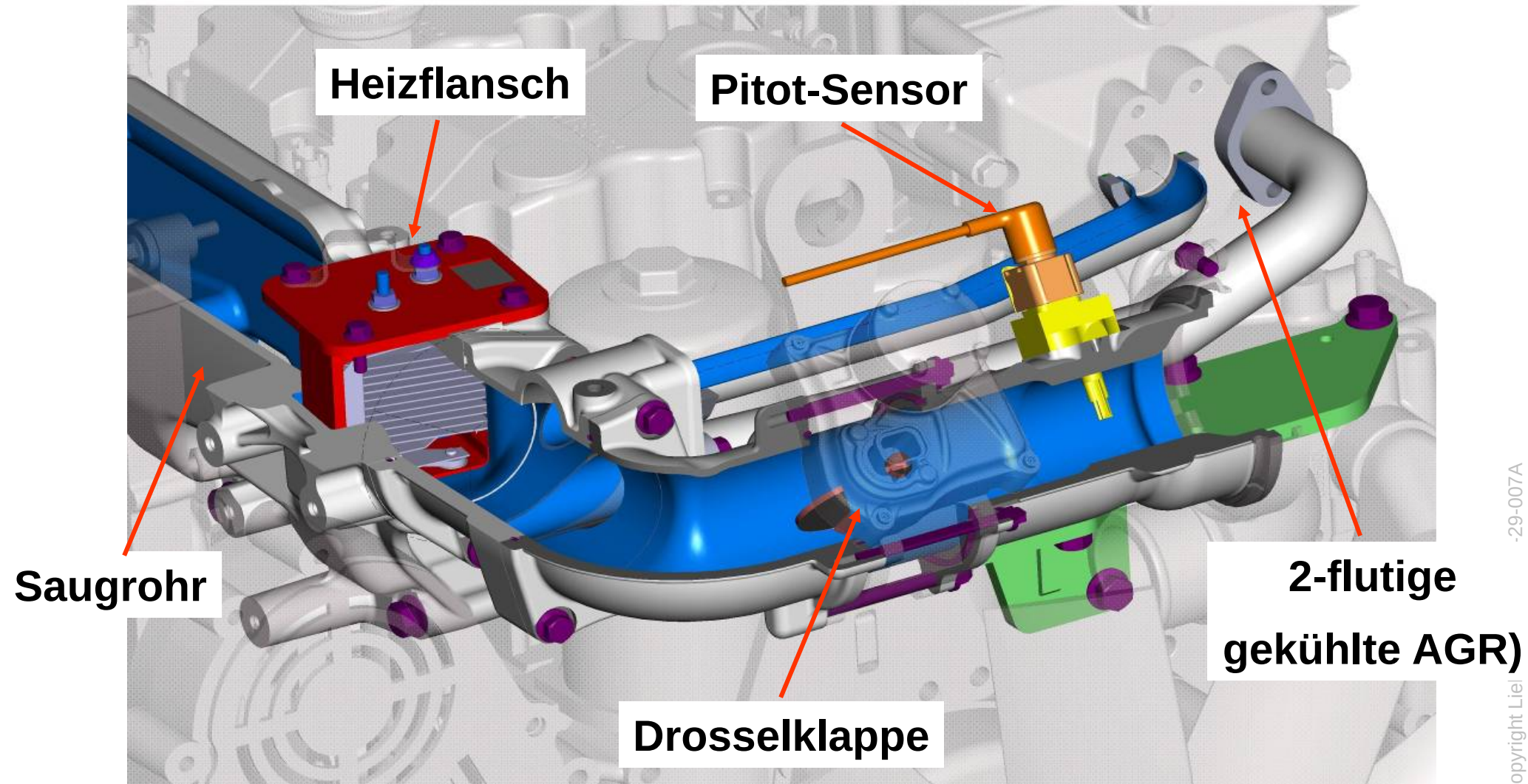
D 934 - D 936 - D 946: Varianten gesamt



D 9508: Varianten



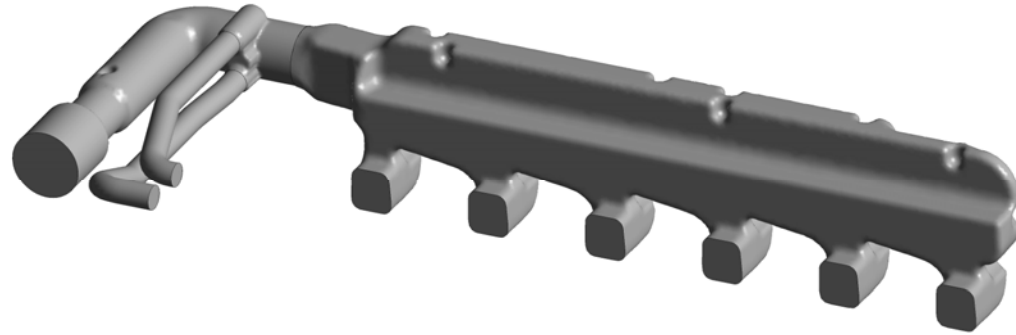
Ladeluft- und AGR-Strecke am Reihenmotor D9xx



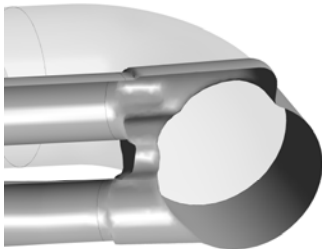
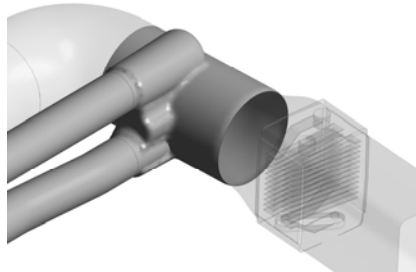
-29-007A

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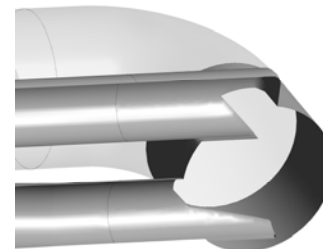
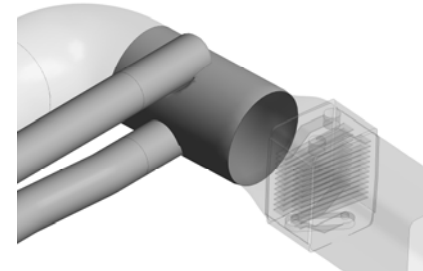
Grundanordnung, zwei exemplarische Varianten



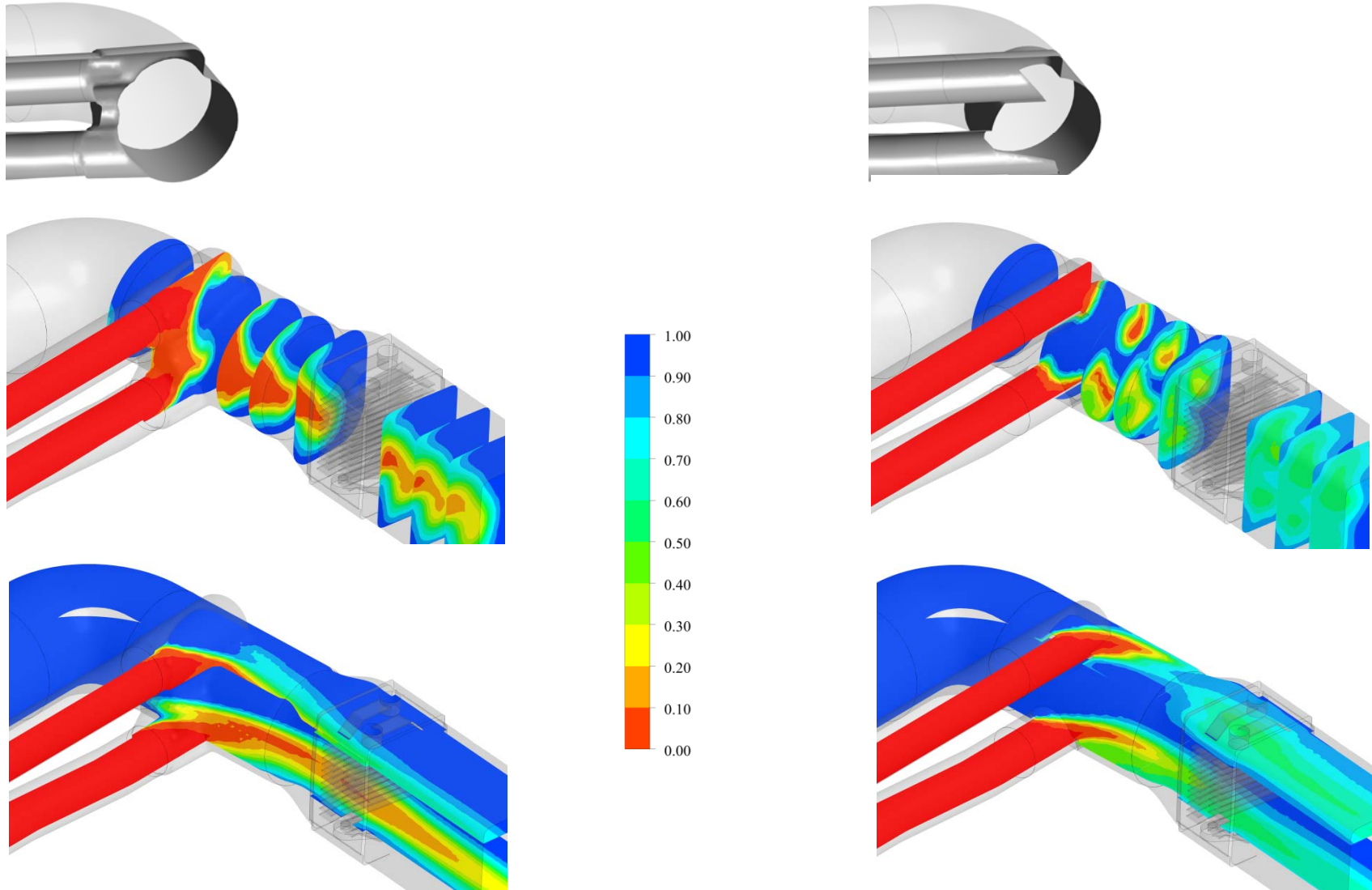
Konfiguration B



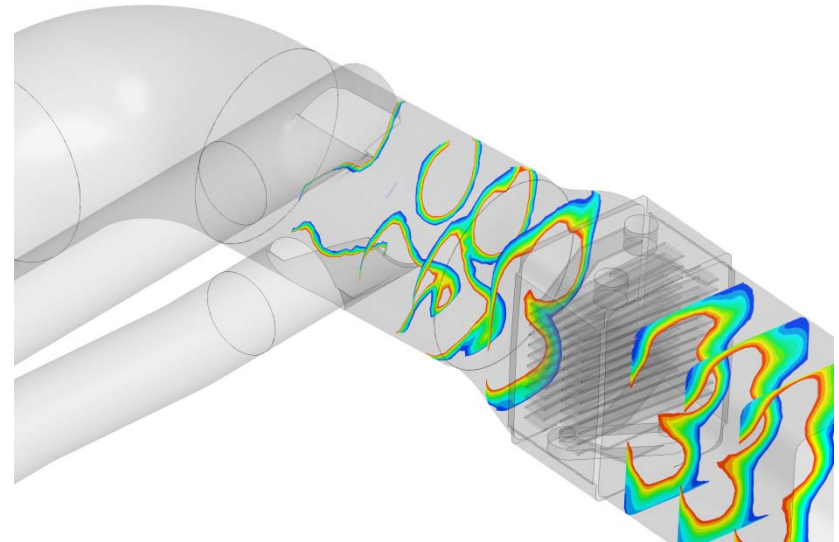
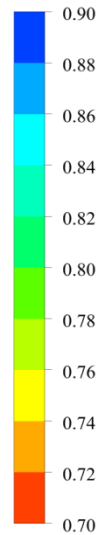
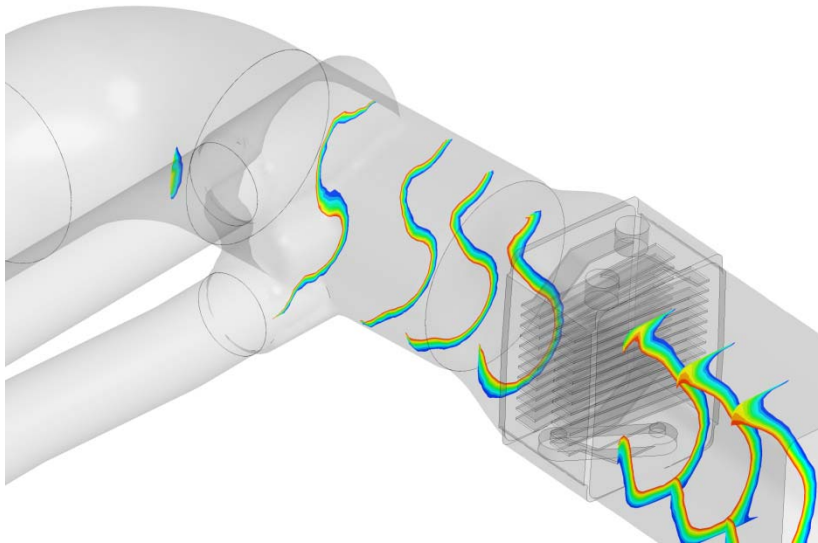
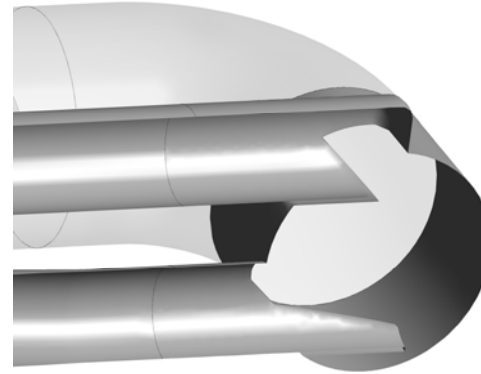
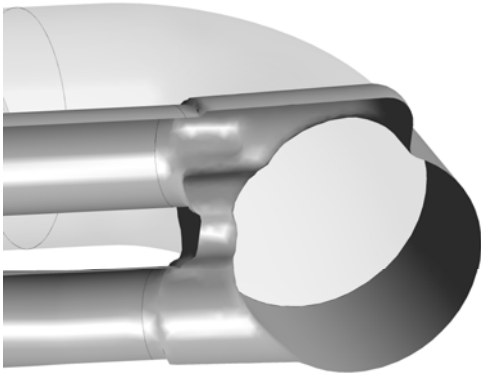
Konfiguration D



Massenanteil Luft gegenüber AGR



Massenanteil Luft – « Zielbereich »



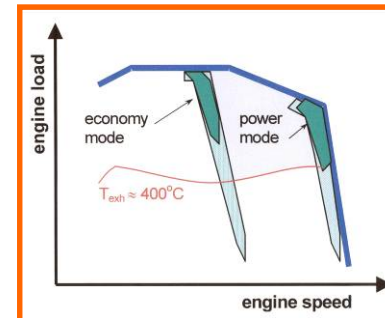
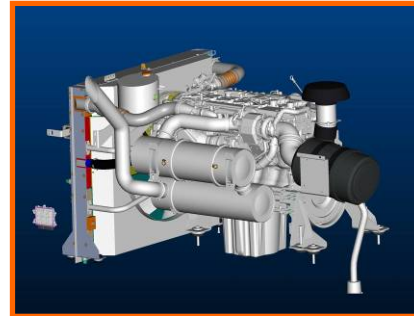
Abgasnachbehandlung: Geräte spez. Applikation (Beispiel)

Grundleistung

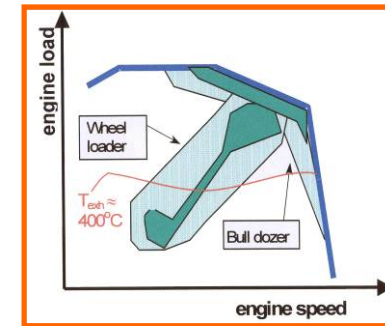
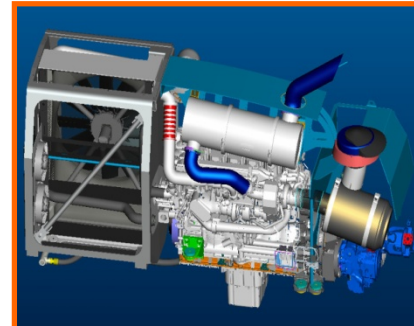
Betriebsleistung

AGN-Einbau

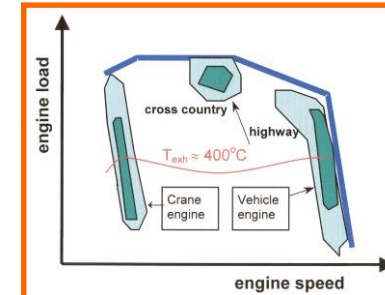
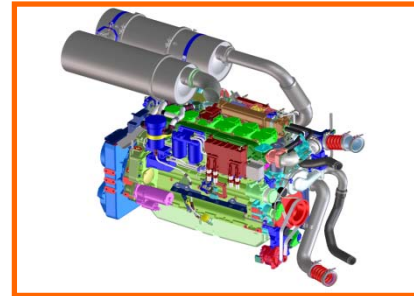
Lastkollektiv



Geräte spez.
Kalibrierung
& Bedatung



Geräte spez.
Kalibrierung
& Bedatung



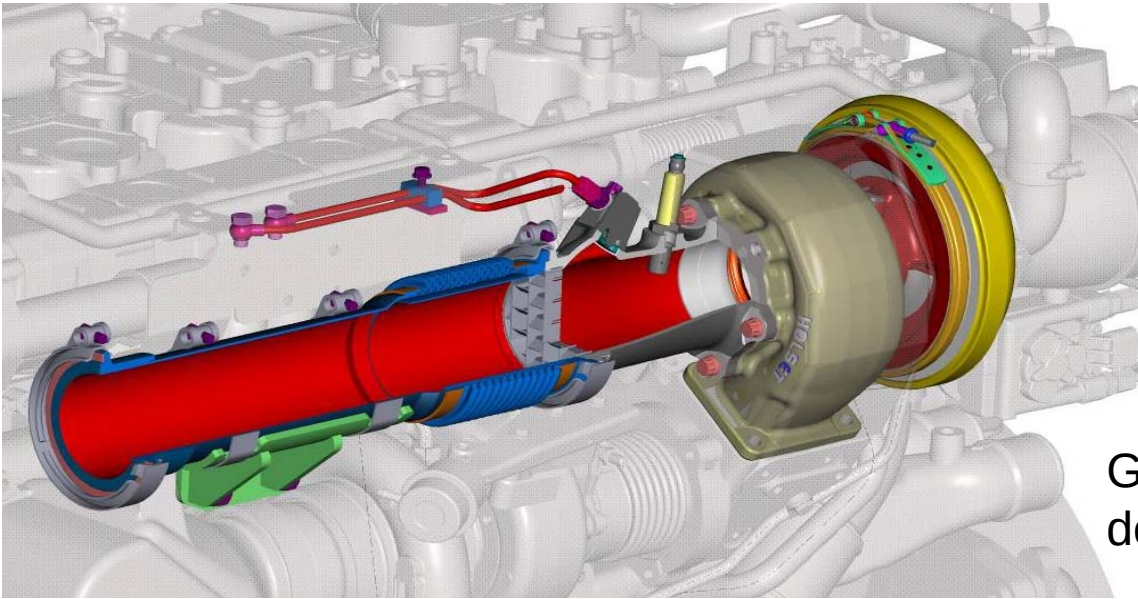
Geräte spez.
Kalibrierung
& Bedatung

D 936

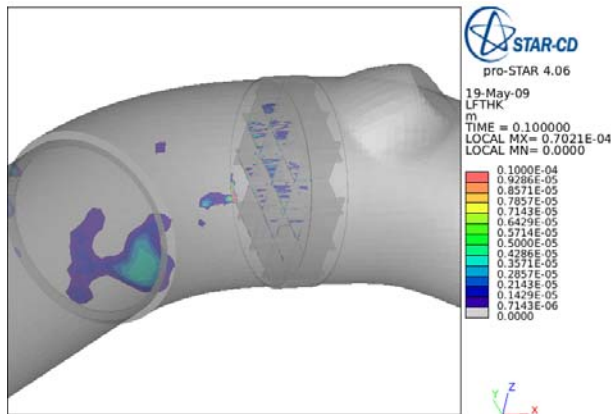
230kW

2000min-1

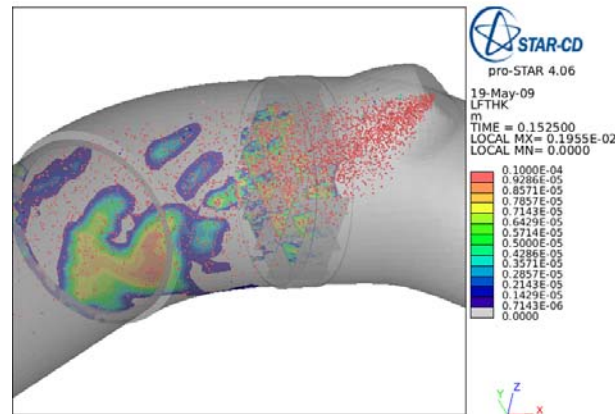
Abgasstrecke mit HC-Doser zur DPF-Regeneration



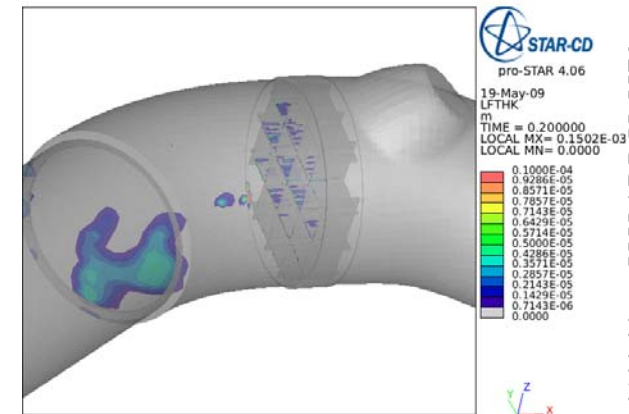
Gemischbildung / Verdampfung
der 2. Einspritzung eines Doppelpulses



Start of injection



End of injection

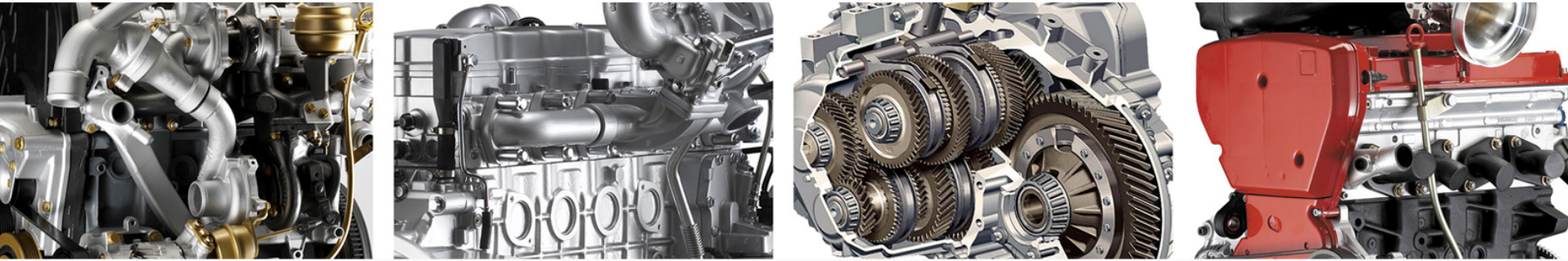


End of 2nd cycle

Regenerations-Strategie / Eskalation für DPF

zunehmende Partikelfilterbeladung →					
Level 0	Level 1	Level 2	Level 3	Level 4	Level 5
Passive Regeneration	Aktive Regeneration				
				Einschränkung Motor	Service
Fahr-Zustand mobil oder stationär			Aktive Regeneration nur im stationären Fahrzeug-Zustand		
	 HEST-Lampe ON bei HC-Dosierung / aktive Regeneration OFF wenn die Abgas-Temp unter Schwellenwert				
		 DPF-Lampe ON konstant	 DPF-Lampe ON blinkend  AWL-Lampe ON konstant	 DPF-Lampe ON blinkend  AWL-Lampe OFF  RSL-Lampe ON	
Möglichkeit zur manuellen Unterdrückung der aktiven Regeneration					
		Möglichkeit / Erfordernis zur manuellen Initiierung der aktiven Regeneration			

Danke für Ihre
Aufmerksamkeit !



"Heavy Duty Diesel Verbrennung für Euro VI und die Zukunft"

Präsentation in Zürich, 28. Oktober 2009

Verfasser: Dr. Wolfgang Gstrein

Funktion: Leiter Vorentwicklung

Heavy Duty Diesel Euro VI Verbrennung: auf Motoren für effizienten Gütertransport im LKW Fernverkehr zugeschnitten

- Welches sind noch mögliche Fortschritte in der Verbrennung?
- Was sind die zukünftigen Rahmenbedingungen?
- Wie kann der Dieselmotor konkurrieren ?



Zukunft: optimales Energiespeicher/wandler Konzept?



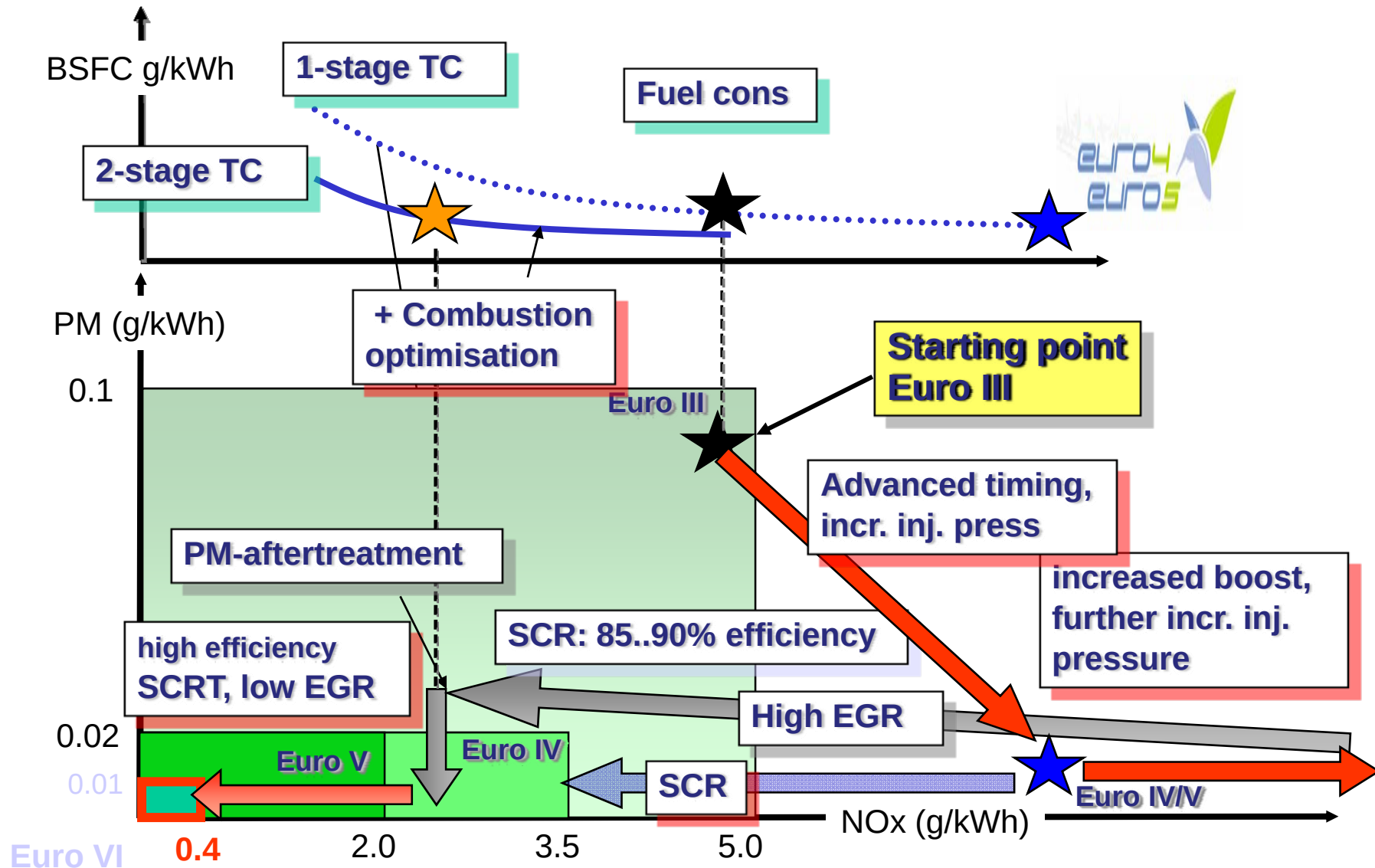
**DESERTE
C**



Dieselmotor:
Beeinflussung,
Ergänzung, Ersatz?

CO₂-
Speichern
(CCS)
Batterie
Hybrid

Emissionslimits , Konzept für Euro VI:

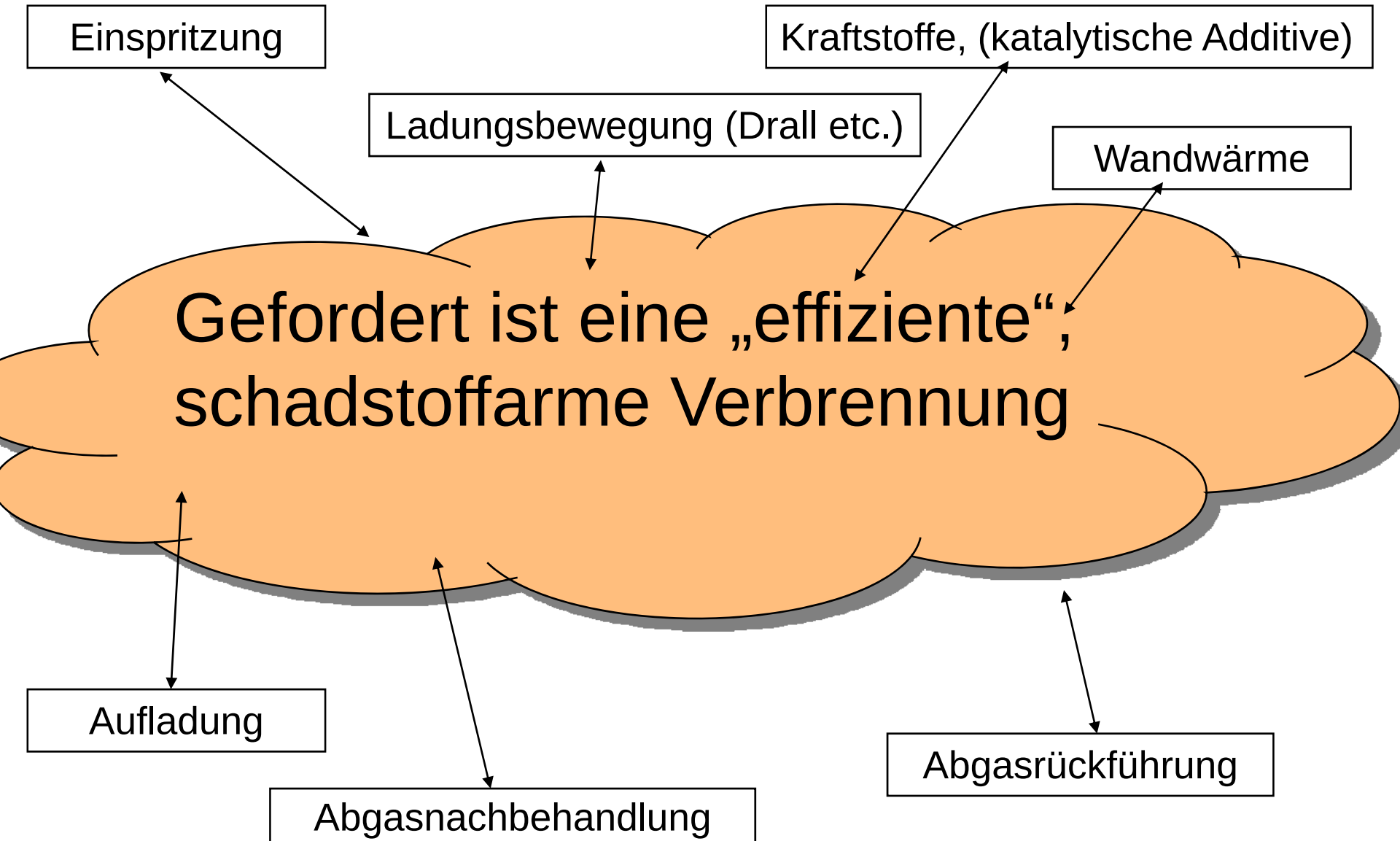


Von Euro V nach Euro VI

- Harmonisierte Emissionstests (ESC, ETC → WHTC mit Kalt- und Heisstestphase, WHSC, NTE, OBD, ISC....)
- Partikelzählung, Limitierung auf $6 \cdot 10^{11}$ #/kWh im WHTC und $8 \cdot 10^{11}$ im WHSC, erfordert „geschlossene Russfilter“ mit äusserst hoher Filterwirkung
→ hohe Investitionen in Mess- und Prüfstandstechnik

Nach Euro VI

- CO₂- Reduktion (bei Dieselkraftstoff mit festem C/H-Verhältnis gleichwertig der Verbrauchsreduktion)
- ?

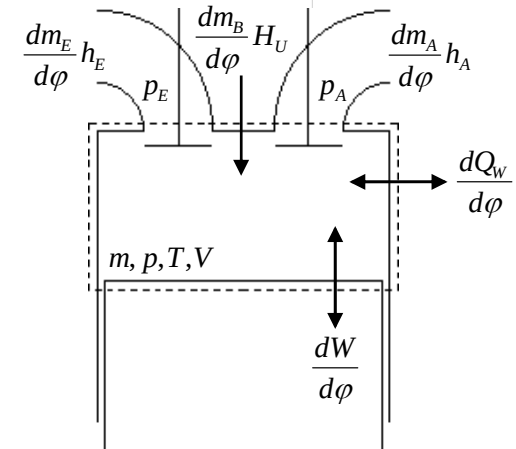
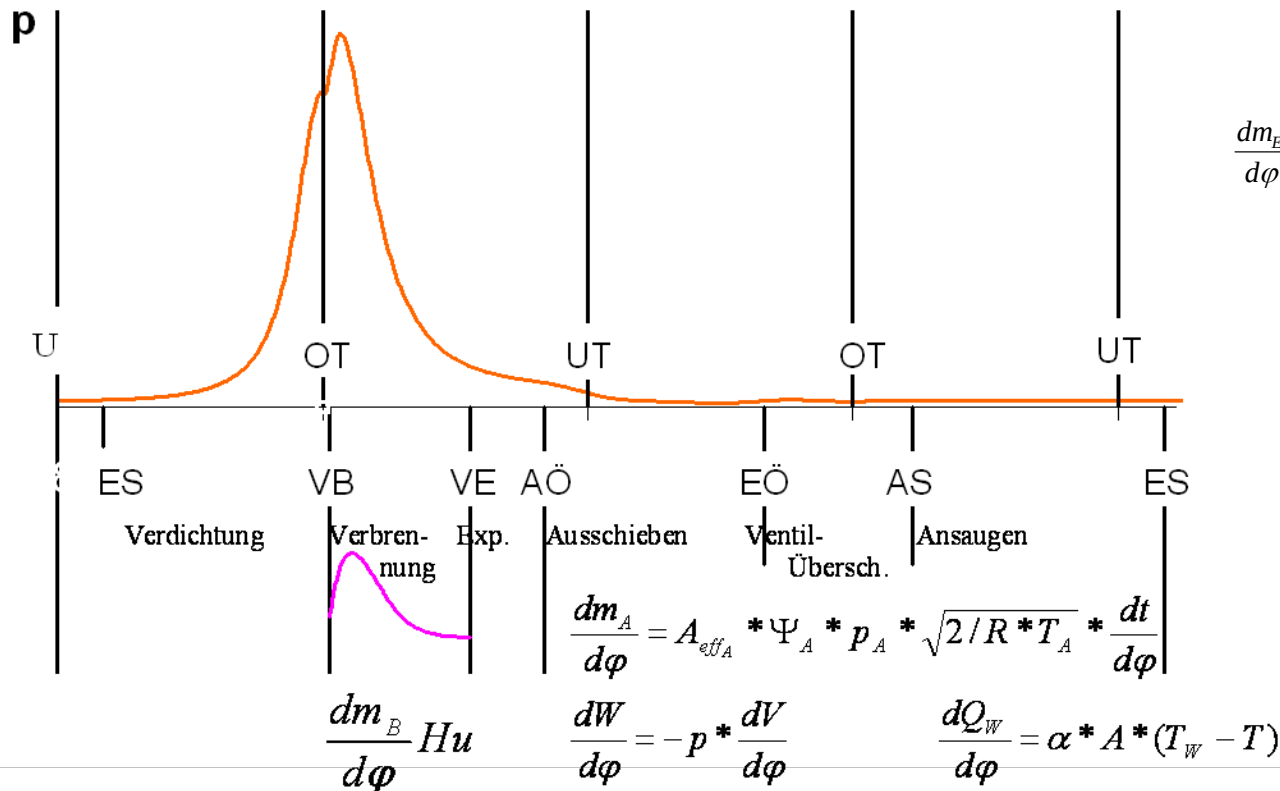


Definition eines Verbrennungswirkungsgrades:

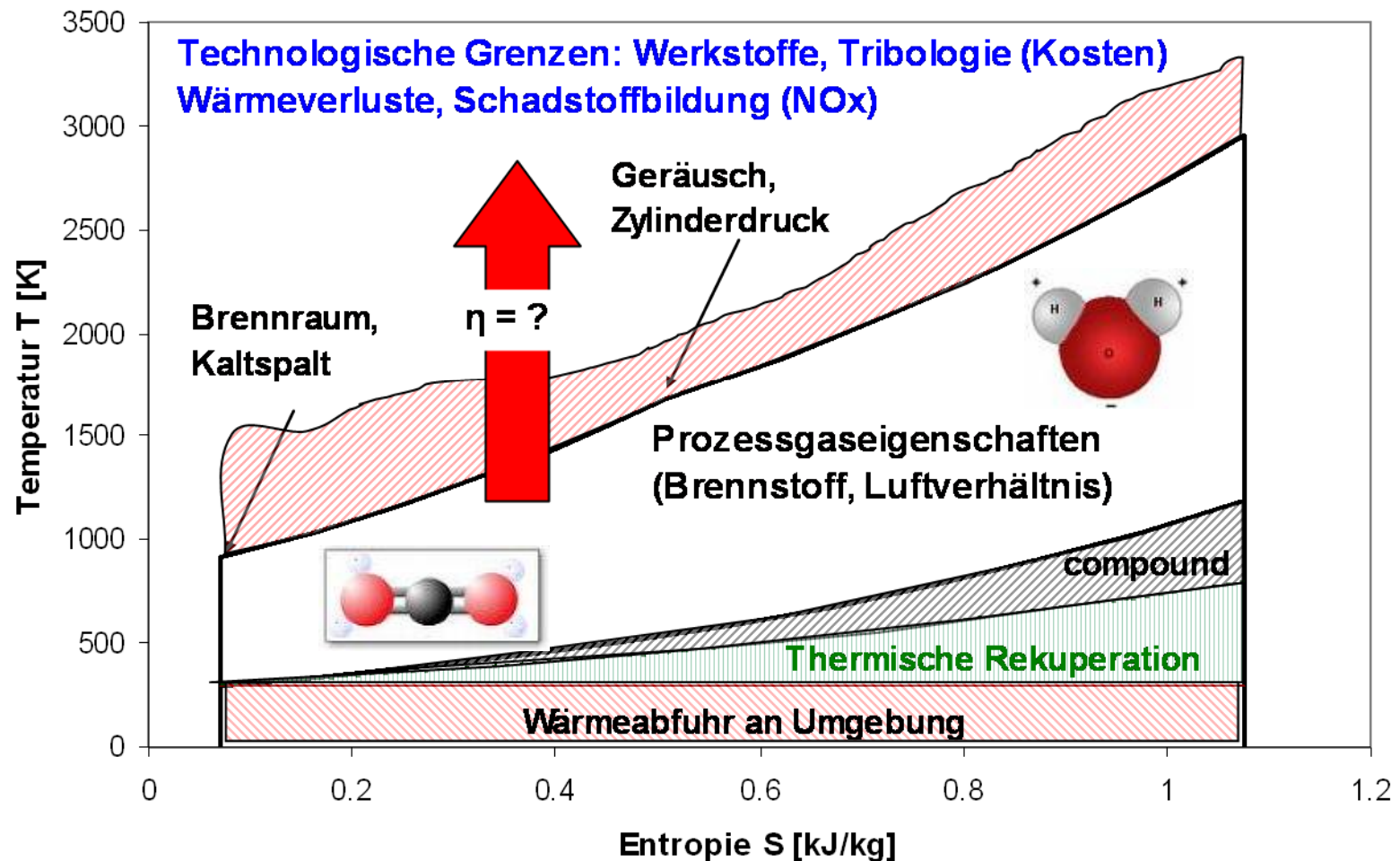
$$\eta_{\text{Verbr}} = \frac{W_{\text{Hochdruck}}}{Q_{\text{Br}} - Q_{\text{Wand}}}$$

Gaseigenschaften (Brennstoff, Luftmenge)
Expansionsverhältnis, Verbrennungsführung

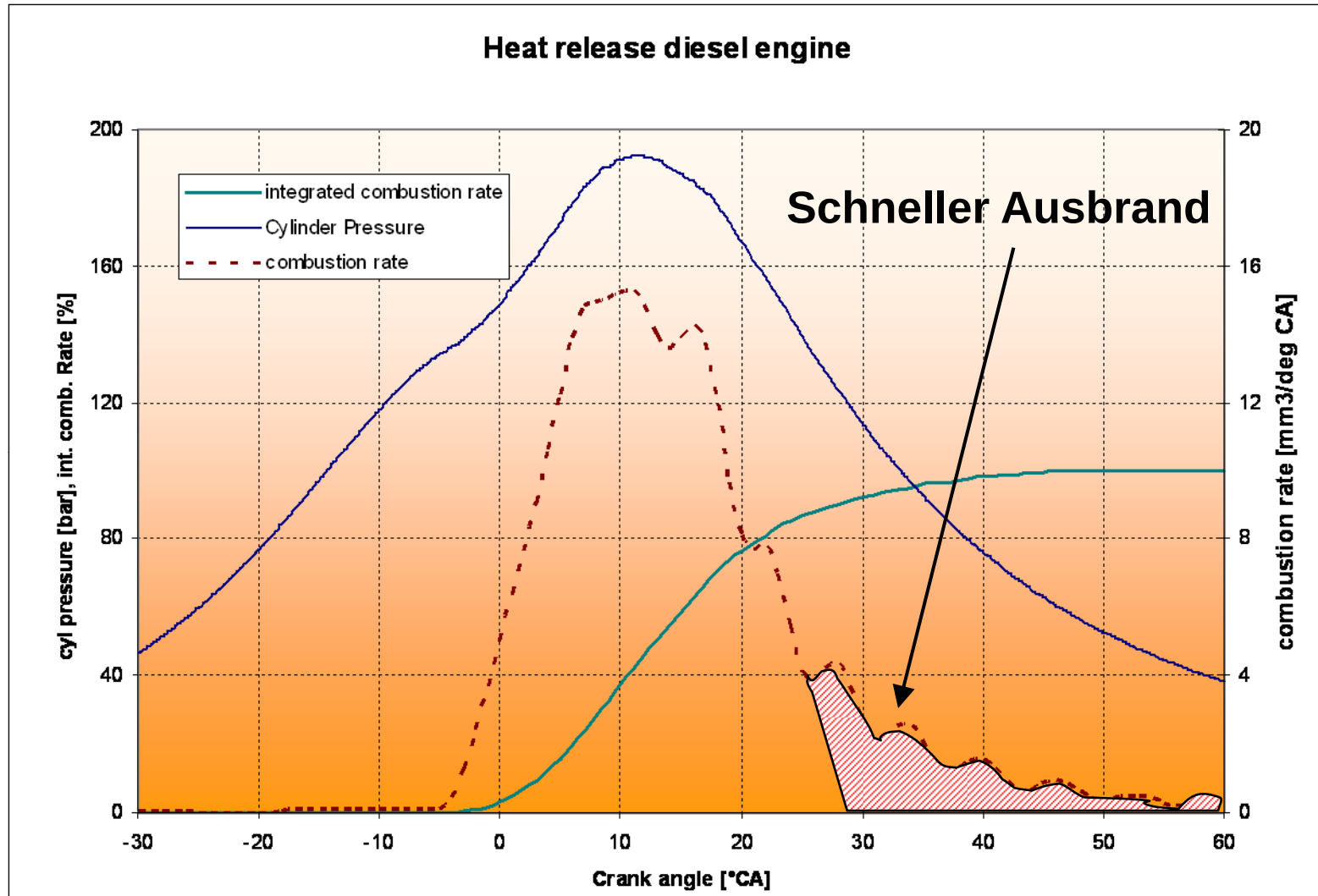
Wärmeübergang = anderes Thema
(Ladungsbewegung, Isolierung)



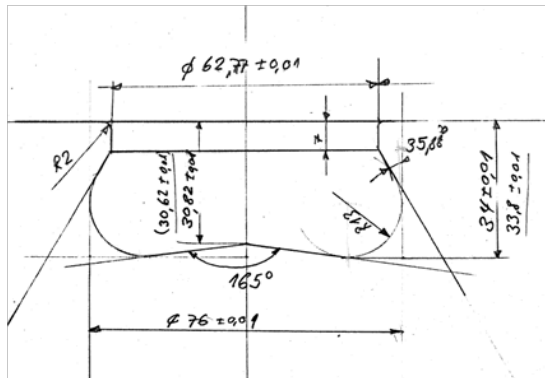
Motorprozess im T, s - Diagramm



- optimaler Spritzbeginn, schnelle Verbrennung, schneller Ausbrand, hierfür: günstige Kraftstoffverteilung mit hohem Einspritzdruck
 - Voreinspritzung für Geräuschreduktion, Nacheinspritzung für Russverringerung und Temperaturmanagement/Aftertreatment
 - Alternative Brennverfahren HCCI, PCCI, Benzin/Diesel- Gemische?
 - Auf Aftertreatmentsystem abgestimmtes NO_2 / Russ- Verhältnis (wegen passiver Russoxidation im Partikelfilter)
 - „Thermomanagement“ des Aftertreatments zur Abgastemperaturerhöhung (Luftverhältnis, Spritzbeginn, Nacheinspritzung)
- Verminderung der Kosten für Aftertreatment



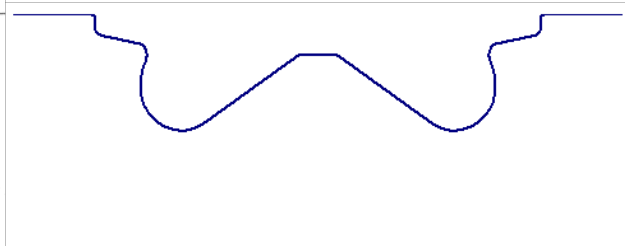
- HD - Euro II



Hand



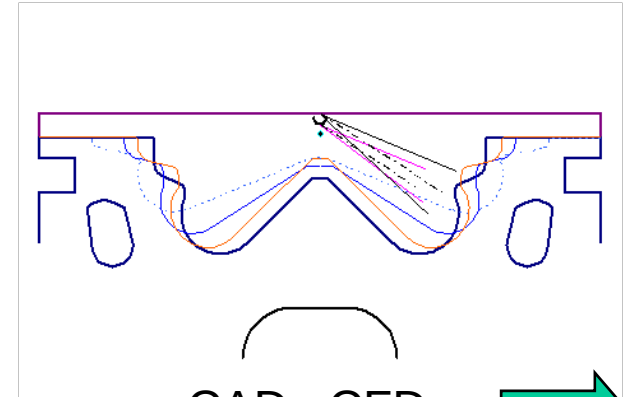
- Euro III/IV/V



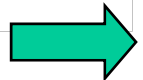
Rechner



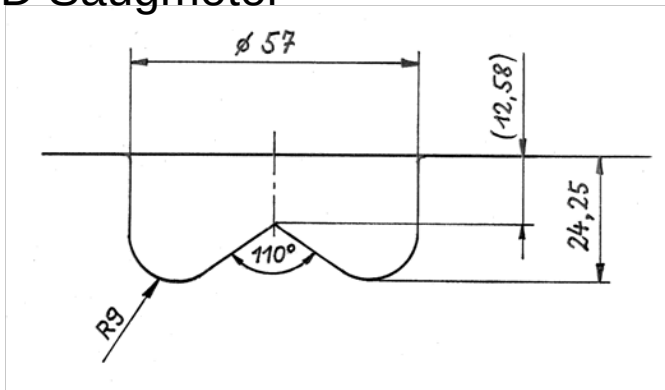
- Euro VI



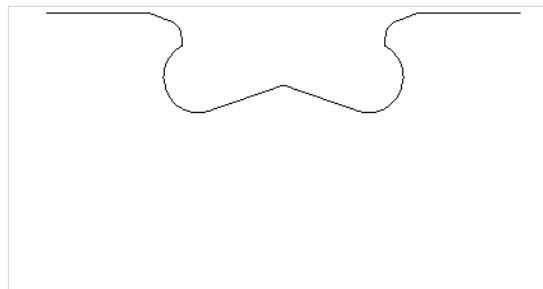
CAD, CFD



LD Saugmotor

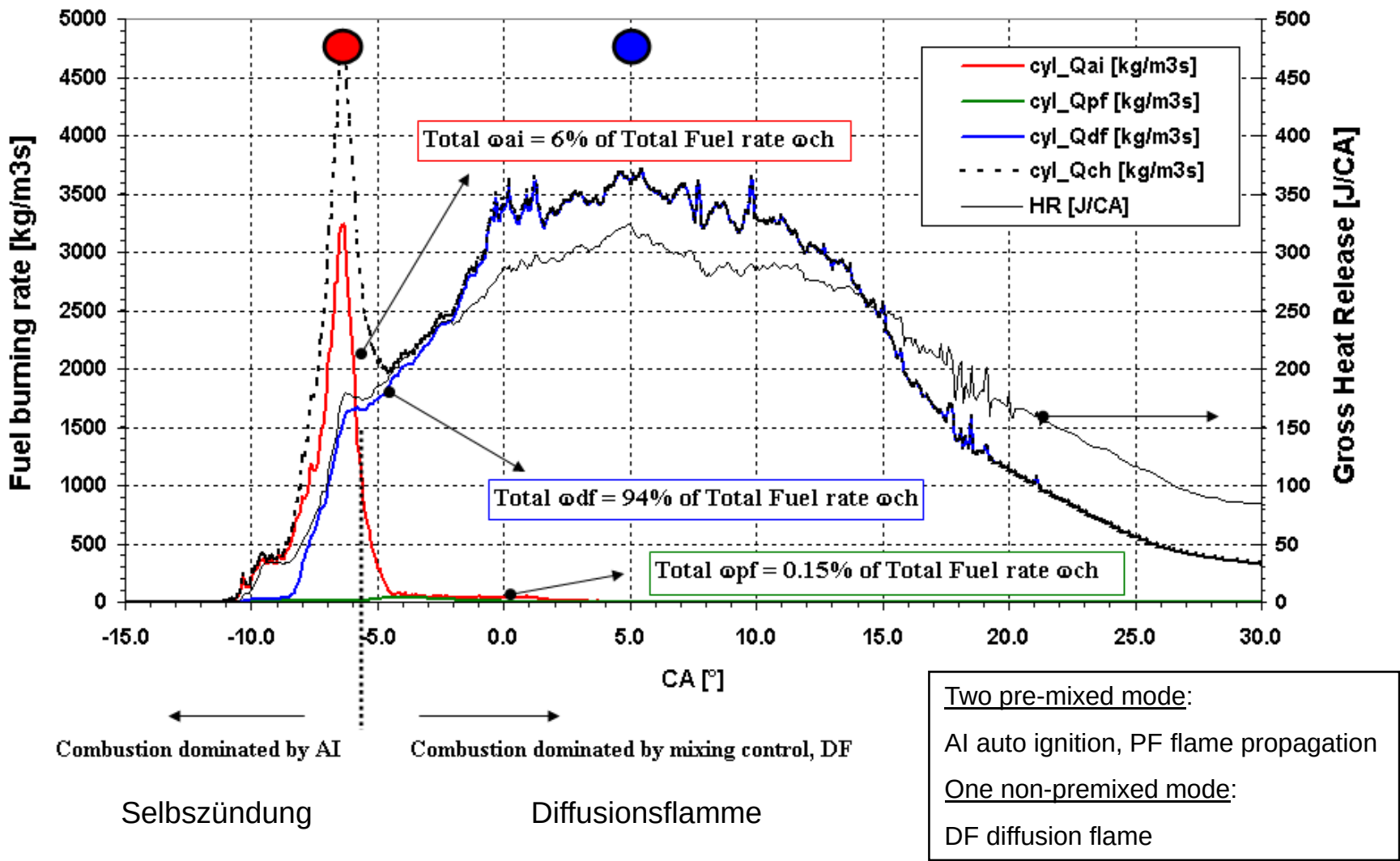


LD Euro 3



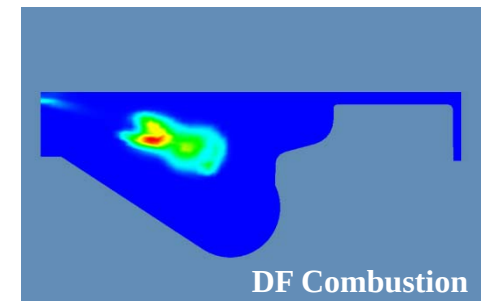
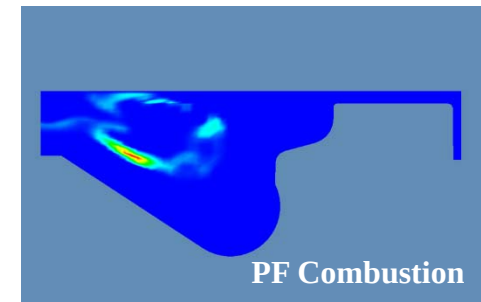
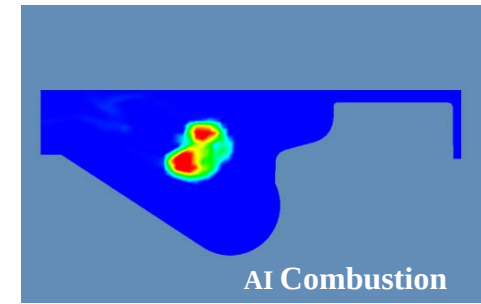
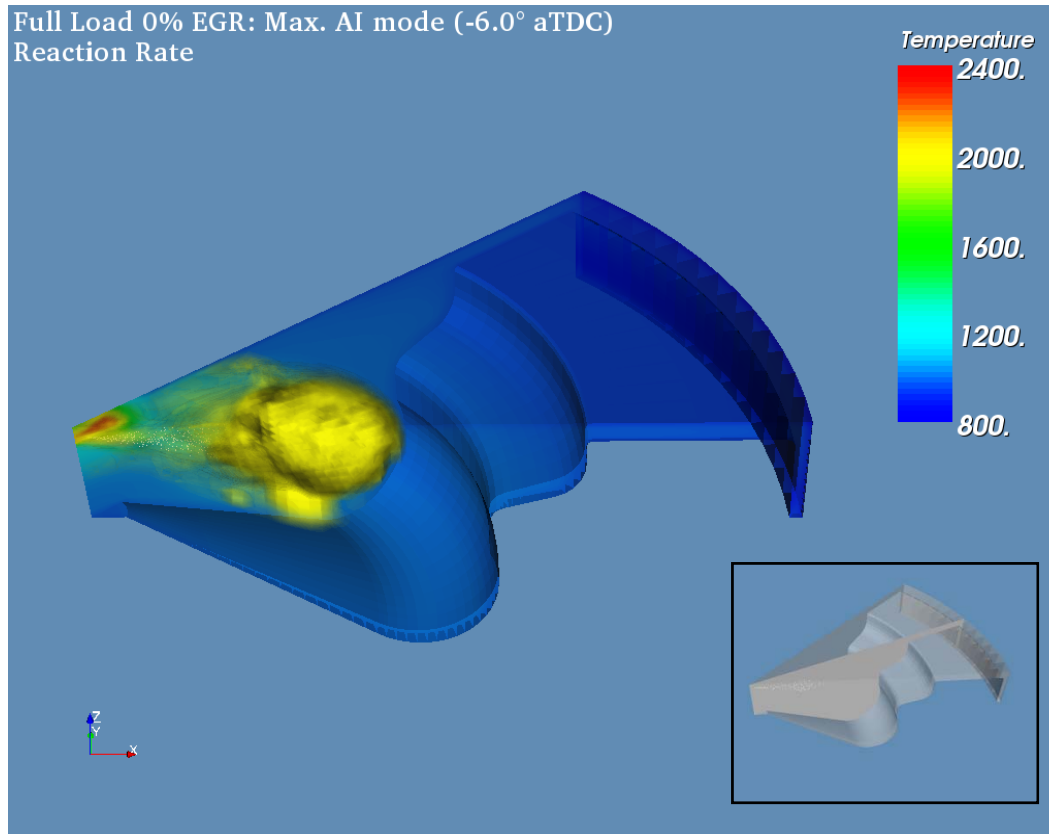
Diesel Vollast- Verbrennung:
Quellterme: ω_{ai} , ω_{pf} , ω_{df}

Diesel Cycle: Full Load 0% EGR



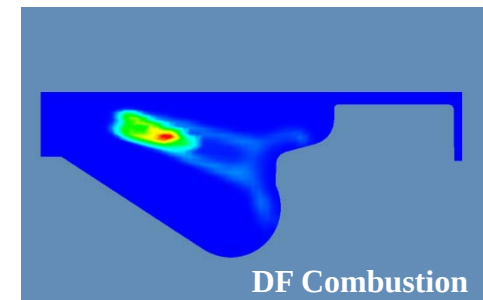
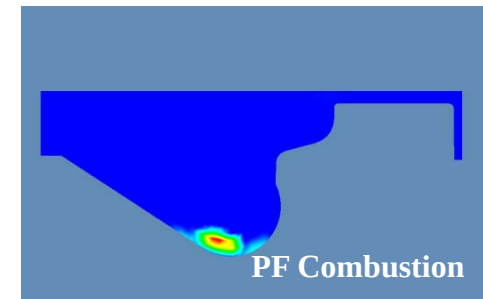
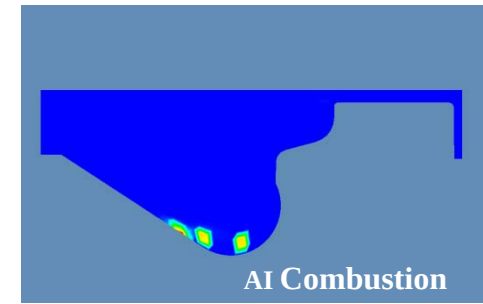
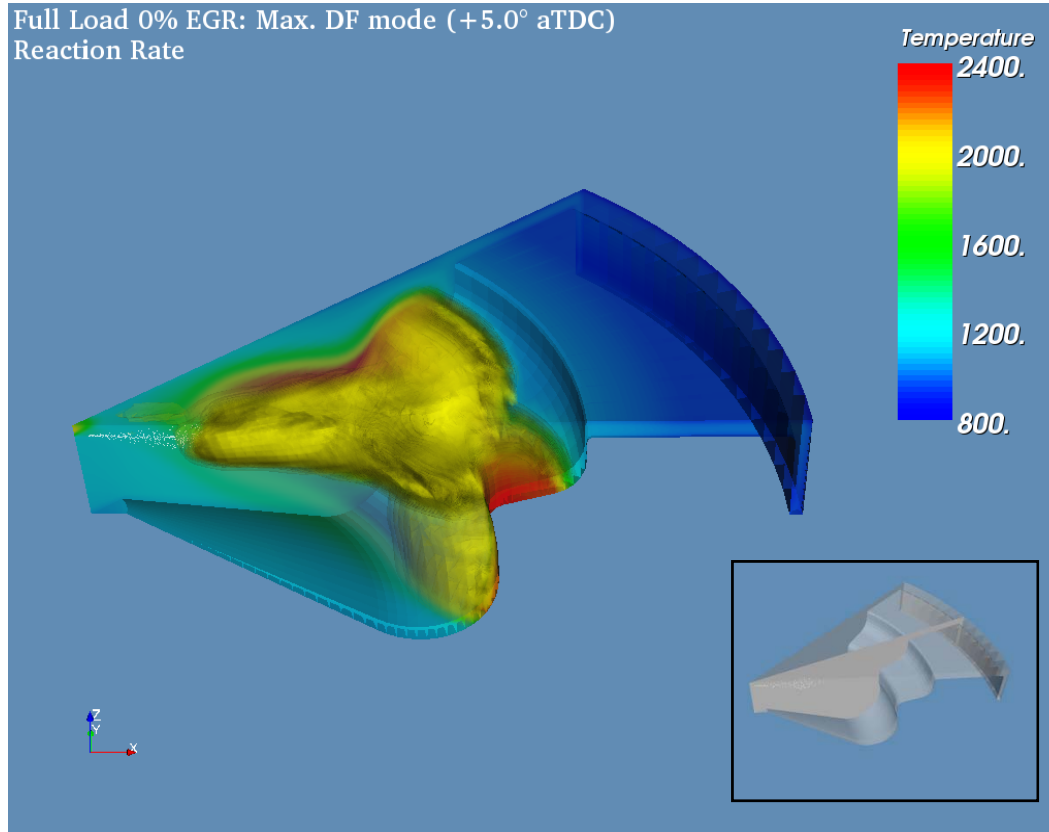
noch kein Wandeinfluss

Full Load 0% EGR: Max. AI mode (-6.0° aTDC)
Reaction Rate



Wandinteraktion der Verbrennung

Full Load 0% EGR: Max. DF mode (+5.0° aTDC)
Reaction Rate



CFD: Teillast HCLI vs. konventionelle Dieselerverbrennung

F1A EU3H 3000 rpm 7.4 bar soih_+1.7° 9.5% EGR

SOI_h = +1.7° EGR = 9.5%

CFD AI is +6.5°

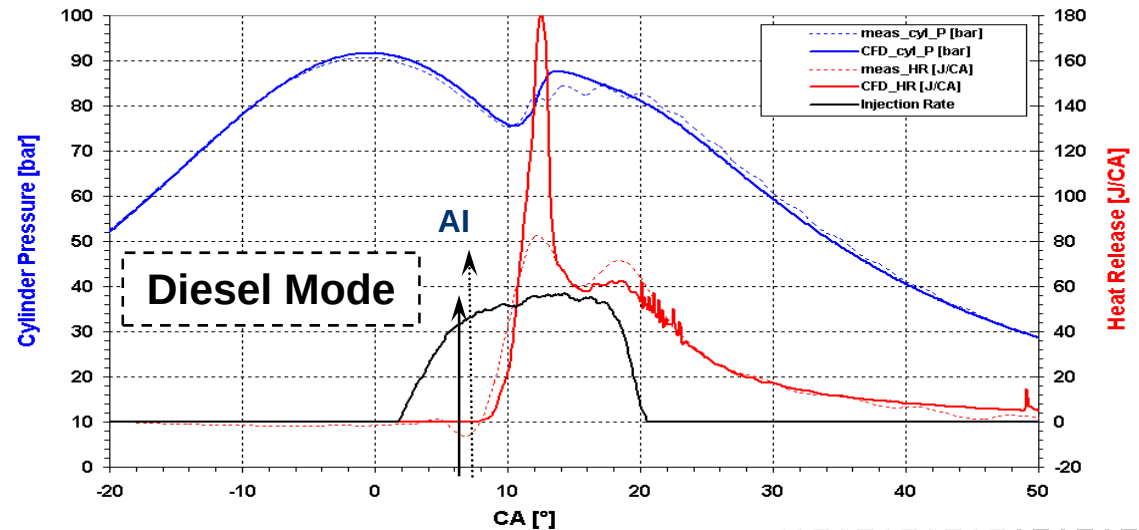
⇒ cyl. P = 83 bar

⇒ cyl T = 908 K

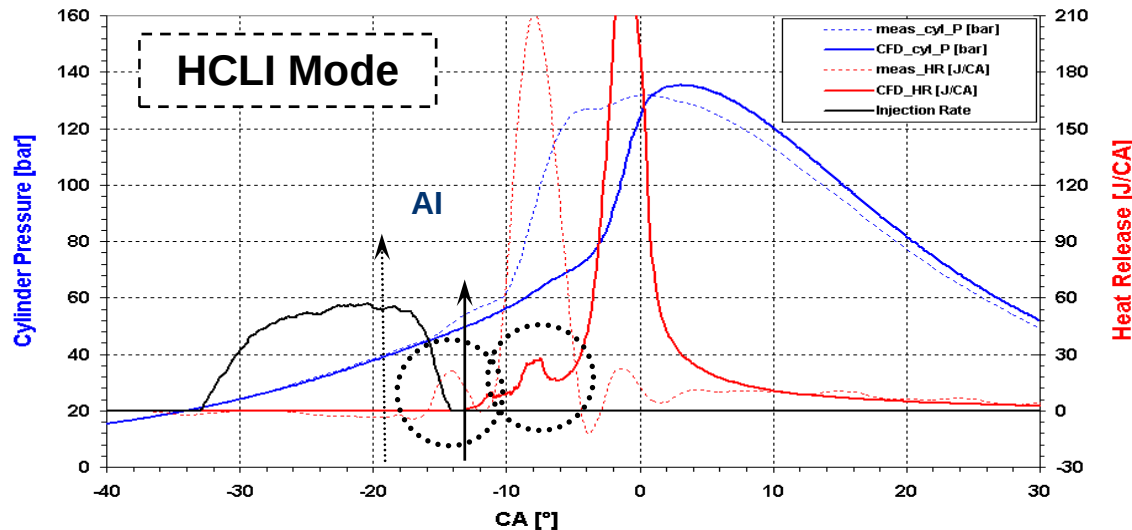
Measured AI (HR) is +7.5°

CFD AI overpredicted by 1°

Good prediction for AI & HR



F1A EU3H 3000 rpm 7.4 bar soih_-33.0° 44% EGR



SOI_h = -33.0° EGR = 44%

CFD AI is -13°

⇒ cyl. P = 47 bar

⇒ cyl T = 810 K

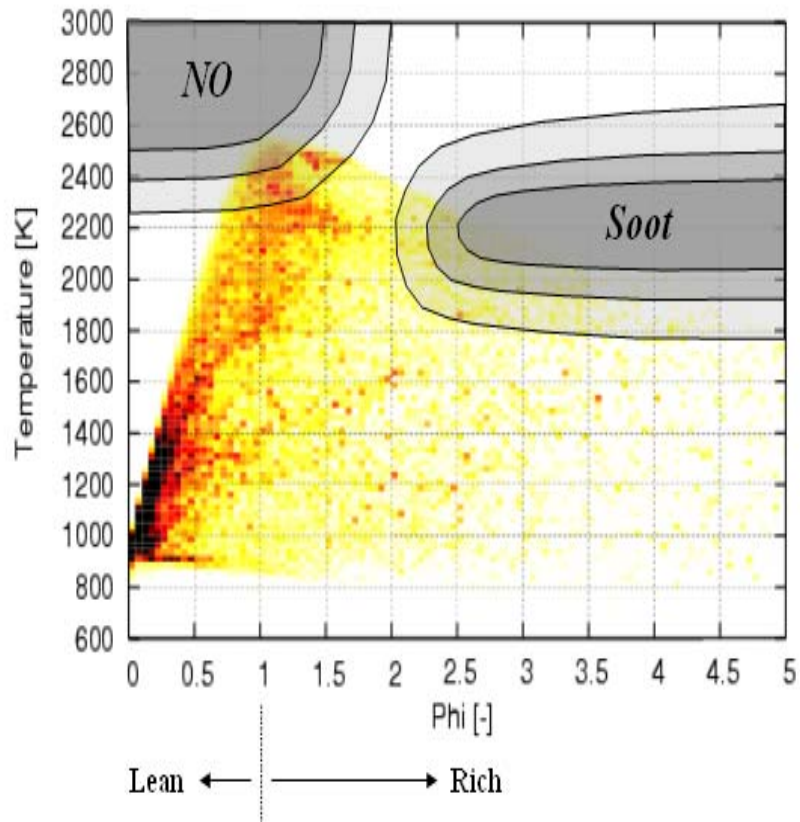
Measured AI (HR) is -19°

CFD AI underpredicted by 6°

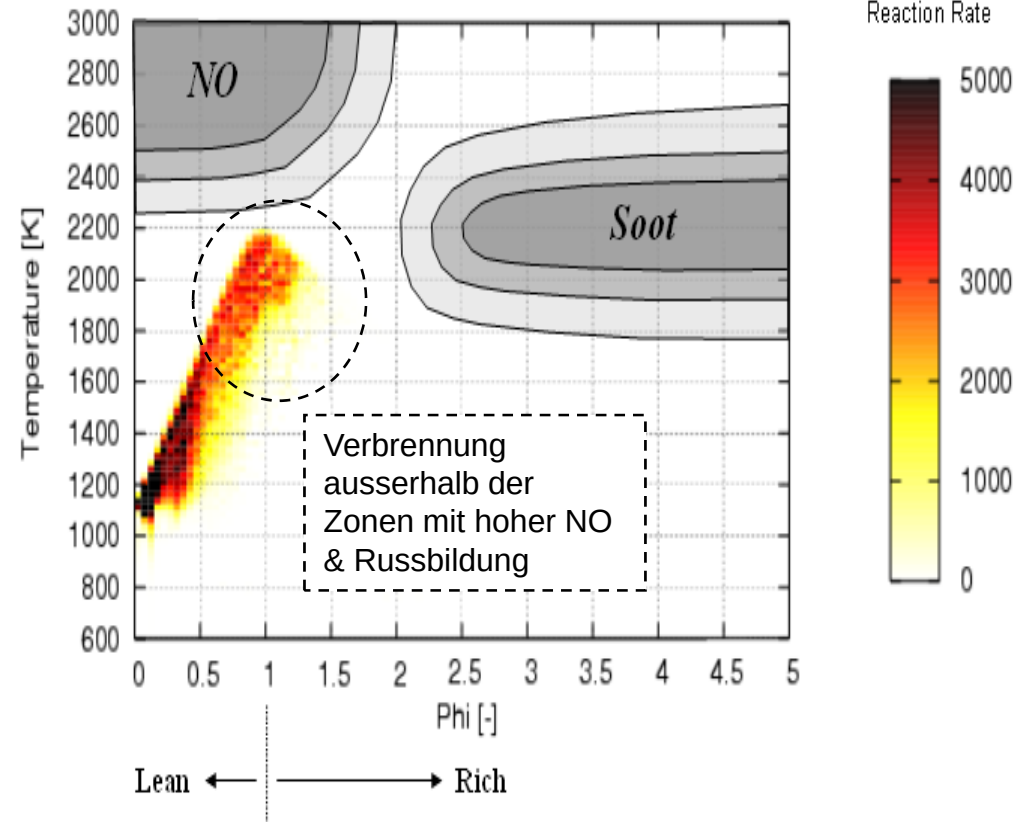
Good prediction of cold flame but AI too much underpredicted. The spray model has big influence on the mixture preparation.

„Globales“ Burke–Schumann Diagramm

10% EGR



HCLI 44% EGR



Die Verbrennungsentwicklung ist weiterhin auf Verbrauchsminimierung und die Verringerung der Schadstoffkomponenten im Zylinder fokussiert.

Ziel ist, ein optimiertes Gesamtsystem aus Aufladung, Einspritzung, Verbrennung und Abgasnachbehandlung zu finden, um die Anforderungen für Euro VI und danach kostenoptimal erfüllen zu können.

„Verbrennungsforschung in der Schweiz“

28. Oktober 2009, ETH Zürich, Semper Sternwarte

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