ANNUAL REPORT
FOR THE YEAR 2012

OF THE

INTERNATIONAL ENERGY AGENCY IMPLEMENTING AGREEMENT FOR ENERGY CONSERVATION AND EMISSIONS REDUCTION IN COMBUSTION

prepared by the
Executive Committee Secretariat

for
Dennis Siebers, Agreement Operating Agent
Sandia National Laboratories - California

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IN COMBUSTION IMPLEMENTING AGREEMENT

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EXECUTIVE ABSTRACT

The purpose of the IEA Implementing Agreement on Energy Conservation and Emissions Reduction in Combustion program is to improve fundamental and applied combustion technology which is developed to provide predictive design capabilities for internal combustion engines, furnaces, and gas turbines. This document summarizes the progress made in this agreement year.

Since 1978, IEA cooperative research by program participants has focused on developing experimental and computational tools to aid combustion research and on developing advanced laser-optical diagnostic tools that permit time- and space-resolved measurements of combustion phenomena for achieving this end. The Agreement's Annex structure has been planned to improve the modeling and simulation processes as well as the instrumentation required for the supporting experimental activities. In order to stimulate additional multi nation collaborations the Annex structure was revised in the 2011 agreement year to enable a more deliberate focus on such collaborative activities. The opportunity for invididual contributions was retained to satisfy the desires of those members who wished to contribute in that manner.

The Annex structure to be followed going forward is given below

Annex 1	Individual Contributor Tasks
	Area 1 Advanced Piston Engine Technology
	Area 2 Advanced Furnace Technology
	Area 3 Fundamentals
	Area 4 Advanced Gas Turbine Technology
Annex 2	Sprays in Combustion (Collaborative Task)
Annex 3	Homogeneous Charge Compression Ignition (Collaborative Task)
Annex 4	Advanced Hydrogen Fueled Internal Combustion Engines (Collaborative Task)
Annex 5	Alternative Fuels (Collaborative Task)
Annex 6	Nanoparticle Diagnostics (Collaborative Task)
Annex 7	Hydrogen Enriched Lean Premixed Combustion for Ultra-Low Emission Gas Turbine Combustors (Collaborative Task)
Annex 8	Supporting Activities

YEAR 2012 ACTIVITIES OF THE EXECUTIVE COMMITTEE

Chair: Prof, Choongsik Bae, Korea

Vice Chair: Mr. Gurpreet Singh, United States

The Executive Committee (ExCo) of the International Energy Agency's (IEA) Program of Research, Development and Demonstration on Energy Conservation and Emissions Reduction in Combustion coordinates the cooperative efforts undertaken by participating institutions. The Committee met twice during the business year. The first meeting took place in April at IEA headquarters in Paris. The second took place following the Agreement's Thirty-fourth Task Leaders Meeting in October on Jeju Island, Korea.

Actions taken by the Executive Committee this year include:

Task Leaders Meeting: The Thirty-fourth Leaders Meeting, sponsored by the Executive Committee was held at the Hyatt Regency Hotel on Jeju Island, Korea in October. Principal Investigators, Executive Committee members, and invited guests gathered to hear papers presented on the Agreement's research. Fifty-two members of the Combustion Research Community attended and twenty-nine papers were presented on the Agreement's ongoing Collaborative Task activities

Executive Committee Meetings: Minutes of the Executive Committee's meetings of April and October have been published and distributed to IEA Headquarters and to ExCo members. The Proceedings of the Thirty-fourth Task Leaders Meeting were published and distributed to IEA Headquarters and Executive Committee members for distribution to participants. The Agreement's Annual Reports and 30 Year Anniversary Report are available on the public web site.

Future Meetings: The Executive Committee scheduled its next meetings for April 2013 at IEA Headquarters, Paris and July 2013 in the United States The July meeting will be held immediately following the 35th Task Leaders meeting and at the same location.

Highlights from Recent ExCo Meetings

Paris France --- April 17, 2012

The Executive Committee:

Welcomed Anders Johansson as the new ExCo member from Sweden replacing Berrnt Gustafsson who is retiring

Endorsed a study of possible modifications to the Agreement's Public Website and Annual Report format

Encouraged the migration of Individual Contribution Tasks from Annex 1 to Collaborative tasks in other Annexes

Confirmed February 19, 2013 in Portugal as the date and location of the Agreement's 2013 Strategy Meeting

Confirmed April 23, 2013 as the date of the Agreement's next ExCo meeting at IEA Headquarters in Paris, subject to meeting room availability

Jeju, Korea --- October 11, 2012

Reconfirmed February 19, 2013 in Portugal as the date and location of the Agreement's 2013 Strategy Meeting

Reconfirmed April 23, 2013 as the date of the Agreement's next ExCo meeting at IEA Headquarters in Paris, subject to meeting room availability

Confirmed the greater San Francisco, California area as the location for the 2013 Task Leaders Meeting to be hosted by the United States.

Elected Gurpreet Singh of the United States as the chair and Dr. Marie Bysveen of Norway as the Vice Chair of the Executive Committee for the Agreement year 2012-2013. Their appointment becomes effective at the conclusion of the October 2012 ExCo Meeting.

SUMMARY OF RESEARCH ACTIVITIES FOR A PROGRAM OF APPLIED RESEARCH, DEVELOPMENT, AND DEMONSTRATION IN ENERGY CONSERVATION AND EMISSIONS REDUCTION IN COMBUSTION

Introduction

The Implementing Agreement for A Program of Applied Research, Development, and Demonstration in Energy Conservation and Emissions Reduction in Combustion requires that the Executive Committee define and adopt detailed specifications for each research task undertaken within the program.

For most of its existence the Agreement consisted of a single Annex comprised largely of individual/single investigator tasks. Although this model worked well, the Executive Committee recognized that more attention should be paid to multi-nation/multi-investigator collaborative tasks. As the result of a series of strategic planning meetings six broad areas were identified for collaborative task development. In the spring of 2011 this culminated in an expansion of the number of Annexes within the Agreement such that each of these collaborative research areas were designated as a separate Annex. At the same time the original concept of single contributor tasks was retained for those investigators who preferred to contribute in that manner.

Moving forward, the Agreement will be comprised of multiple Annexes with Annex 1 being reserved for single contributor tasks, Annexes 2 through 7 being multi-nation collaborative tasks and Annex 8 being supporting activities

Briefly the focus of the individual Annexes is summarized below:

Annex 1 --- Individual Contributor Tasks

This Annex has been planned to improve fundamental and applied combustion technology which is developed to provide predictive design capabilities for internal combustion engines, furnaces, and gas turbines. The Annex is divided into the following Areas:

Area 1: Advanced Piston Engine Technology
The objective of the cooperative work in this Area is the development of combustion technology, both analytical and experimental, that will provide improved models for advanced internal-combustion piston engines, namely lean homogeneous-charge, stratified-charge, and diesel engines. The research will contribute primarily to technology common to these engine concepts and will provide data bases and descriptive and predictive system codes, in addition to practical demonstrations

Area 2: Advanced Furnace Technology
The objective of the cooperative work in this Area is the development of combustion technology, both analytical and experimental, that will provide models for furnaces and

boilers. The research will provide a data base and descriptive and predictive system codes, as well as practical demonstrations.

Area 3: Fundamentals
The objective of the cooperative work in this Area is to conduct theoretical investigations of the fundamental physical phenomena relevant to the combustion process as is called for in Areas 1, 2 and 4, and to support the development of new diagnostic techniques for application in the future.

Area 4: Advanced Gas Turbine Technology
This Area covers work related to the development of combustor and gas turbine modeling and verification, to the study of emissions formation and control mechanisms, and to practical studies in fuel injection and fuel/air mixing.

Annex 2: Sprays in Combustion

Spray investigations aim at a deeper understanding of the complex interrelated aerodynamic and thermodynamic mechanisms involved in transient & steady spray combustion, which are responsible for the tradeoffs among energy conversion efficiency, nitrogen oxides and soot emissions in advanced engines and combustors. Tasks in the context of spray propagation involve a wide set of investigations on atomization, fuel-air mixing and combustion under high temperature and high pressure, as encountered in advanced diesel engines, gas turbines – and to some extent also boilers

Annex 3: Homogeneous Charge Compression Ignition

The combustion process in the HCCI engine is mainly driven by the chemical kinetics. Thus the chemical properties of the fuel are of outmost importance. Many small molecule fuels like methane and methanol have relatively simple and well controllable combustion process but it has been shown that many fuels experience a two-stage ignition process with a time period between the two stages without significant heat release.

The intent of this Annex is to look into the interaction between HCCI and fuels. It will include activities for both the gasoline and diesel type of fuels and HCCI with fully premixed charge and direct injection.

Annex 4: Advanced Hydrogen Fueled Internal Combustion Engines

This Annex focuses on research concerning the use of hydrogen as a fuel in internal combustion engines. Both engines fueled by pure hydrogen as well as by hydrogen blends are within the Annex scope. Experimental and computational work is included. In fact, it is of special interest to the Annex to coordinate the interaction between these two types of investigations.

Annex 5: Alternative Fuels

The present day engine combustion technology has been fully developed for crude oil based traditional liquid fuels: gasoline and diesel fuel.

The aim of the Annex is develop optimum combustion of future fuels and thereby significantly reduce engine out emissions together with noticeable increase in engine efficiency. The development of combustion techniques focuses especially on synthetic and renewable fuels. This Annex concentrates mainly on road transportation. There is a potential of engine out emission reduction by 70% to 90 % or even more. Dedicated fuels need new combustion technology to meet optimal emission reduction.

Annex 6: Nanoparticle Diagnostics

This Annex focuses on research concerning the measurement of nanoparticles produced by combustion. The development of diagnostics to characterize the physical or chemical characteristics of the nanoparticles, and demonstration of the application of these diagnostics, are within the scope of this Annex. The development may include experimental, numerical, or both approaches to the research. Demonstration may be in-flame studies of nanoparticle formation and oxidation, or post-flame measurements of nanoparticle emissions.

Annex 7: Hydrogen Enriched Lean Premixed Combustion for Ultra Low Emission Gas Turbine Combustors

In response to national policies gas turbine manufacturers have set the goal to adapt their large gas turbines for CO2-mitigated power generation, whereby up to 90% of the carbon contained in the fired fossil fuel is captured and stored as CO2. In order to mitigate CO2 emissions Zero Emission Power Plant concepts are being explored on a global scale. Gas turbine based configurations are playing a significant role in these scenarios. Following up on the previously conducted collaborative effort on “Hydrogen enriched Lean Premixed Combustion for Ultra-Low Emission Gas Turbine Combustors” it is proposed to widen the future collaborative task activities to gas turbine combustion issues linked to respective Zero Emission Power Plant concepts.

Annex 8: Supporting Activities

The objective of the work in this area is to provide administrative support services and information dissemination as called for by the work in Annexes 1 - 7.

In addition from time to time the Executive Committee may request that a Special Session of invited speakers focused on a research area or Policy Matter of current interest be added to the Program for an upcoming Task Leaders Meeting

Additional information on any of the work areas of the Agreement may be obtained by contacting:

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How to Join the Agreement

Participation in IEA Combustion is based on mutual benefit to the Implementing Agreement and the interested newcomer.

If there is interest in joining the Implementing Agreement please contact the IEA Combustion ExCo Secretary, Dr. Robert Gallagher (Bobgall@aol.com). The Secretary will provide you with details on the Implementing Agreement and invite you to attend an ExCo Meeting as an Observer. By attending you will become familiar with the Implementing Agreement's current and future research areas. Assuming mutual interest, the next step would be to make a formal presentation to the ExCo at its next regularly scheduled meeting identifying the research areas in which you would propose to contribute. Prior to this ExCo presentation you would also be welcome to attend the next Task Leaders meeting as an Observer and, if you wished to, make a presentation related to a combustion related research topic in which you were currently engaged.

Contracting Parties to IEA Combustion Agreement are usually governments. Therefore, for interested parties it is necessary to seek support from their government to join the Implementing Agreement. The government will later appoint a Delegate and an Alternate to represent the Contracting Party in the ExCo.

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Summary of Accomplishments for the 2012 Agreement Year

Introduction

In the summary which follows the reader will find highlights from the Research conducted by Agreement Participants during the past year. If further detail is of interest the leaders identified for each of the Tasks should be contacted directly.

Annex 1 – Individual Contributor Tasks

There were no individual contributor tasks this year

Annex 2 - Sprays

The following activities were undertaken within the Sprays Task during the past year

> Christopher Powell (Argonne National Laboratory, USA)
> X-Ray Diagnostics for Fuel Injection and Sprays
>
> Youngchui Ra (Engine Research Center, University of Wisconsin-Madison, USA)
> Numerical simulation of multi-component spray combustion
>
> Armin Wehrfritz, Ville Vuorinen, Ossi Kaario, and Martti Larmi
> A High Resolution Study of Non-Reacting Fuel Sprays using Large Eddy Simulations

Highlights from the work included the following:

Dr. Christopher Powell of Argonne National Laboratory, United States presented results on the use of X-Ray Diagnostics to understand automotive spray structures.

> Line of sight fuel distributions were compared with models. Measurements show *average* fuel distributions allowing a test of spray models.
>
> Measurement of Diesel Sprays were done in collaboration with Sandia's Engine Combustion Network
>
> 3D density distributions were calculated using a model-based approach
>
> There was good agreement between CFD and measurements
>
> The importance of cavitation in the fuel injection process was illustrated

Dr. Youngchul Ra of The Engine Research Center, University of Wisconsin-Madison, United States presented results on the Numerical Simulation of Multi-Component Spray Combustion

Given that there are too many components in real automotive fuels to model, surrogate mixture models known as Discrete Multi-Component fuel models (DMC) to represent the real fuel are required

A procedure for automation of the fuel modelling process was developed

Reduced mechanisms for surrogate components for chemical classes led to a MulriChem mechanism

The modelling used a combination of the DMC spray model with MultiChem chemistry

The use of multi-component fuel models enabled realistic and accurate modelling of automotive fuel sprays

Automation of the modelling process made the method practical

Drs. Armin Wehrfritz, Ville Vuorinen, Ossi Kaario, and Prof. Martti Larmi, of Aalto University, Finland conducted a High Resolution Study of Non-Reacting Fuel Sprays using Large-Eddy Simulation

A fully transient, 3D numerical computation of non-reacting fuel sprays using the open source CFD code OpenFOAM was undertaken

Lagrangian Particle Trracking (LPT) was used to model the liquid phase

Two different droplet breakup models were used

The Experimental Test Case was specified by the Sandia Engine Combustion Network

Significant differences in predicted droplet diameter between the two droplet breakup models were observed

Modificationof the breakup model parameters are indicated with respect to high ambient/injection pressure fuel sprays

Future oirk will include improvements of the near nozzle liquid-to-gas phase momentum transfer and initial conditions

Combustion simulation will be undertaken using the Flamelet Generated Manifold (FGM) approach

Annex 3 - Homogeneous Charge Compression Ignition (HCCI)

The intent of this IEA task is to look into the interaction between HCCI and fuels. It will be activities for both the gasoline and diesel type of fuels and HCCI with fully premixed charge and direct injection. In the latter case a gradual stratification will result with later and later fuel injection.

The following activities were undertaken within the HCCI Task during the past year

Bengt Johansson (Lund University, Sweden)
1.6A.01 ”HCCI fuels with Partially Premixed Combustion”

Mark Musculus (Sandia National Laboratory, US)
”Optical Diagnostics of Combustion Propagation in Dual-Fuel Partially-Premixed Low-Temperature Combustion ”

Yasuo Moriyoshi (Chiba Univ. Japan)
1.6A.05 Transient Operation of a blowdown supercharged HCCI gasoline engine

Atsumu Tezaki, (University of Toyama, Japan)
1.6A.13 ” Chemical Mechanism of Compression Ignition Analyzed through Detection of Transient Species ”

Christine Rousselle (Univ. Orleans-CNRS, France)
1.6A.14 ” Effect of minor species on auto ignition delay in HCCI combustion ”
Choongsik Bae (KAIST, Korea)

1.6A.08 ” Effect of Injector Configurations on Spray and Combustion in a Gasoline Direct Injection Compression Ignition Engine at Low Load Operation ”
James Szybist (Oak Ridge National Laboratory, USA)
1.6A.15 ” A Comparison of Two Methods for High Load Expansion of HCCI: Boosted Lean HCCI vs. Naturally Aspirated Stoichiometric Spark-Assisted HCCI ”

Eiji Tomita, (Okayama University, Japan)
1.6A.06 ” Combustion characteristics of biogas in a dual fuel engine ignited with a pilot diesel fuel ”

Gerardo Valentino (CNR, Italy)
1.6A.10 ” Optical Investigation of Combustion Process of Diesel/Gasoline/Butanol Blends in a Common Rail CI Engine ”

The numbers higher than 10 are new for the attendees giving the first presentation in Korea 2012.

Highlights from the work included the following:

Prof. Bengt Johansson from Lund University Sweden presented a study on the PPC type of combustion at low loads with high-octane fuels. In previous IEA meeting the PPC concept has been presented. It was concluded that up to 57% indicated efficiency could be reached with PPC using high-octane fuels like gasoline at mid to high loads.

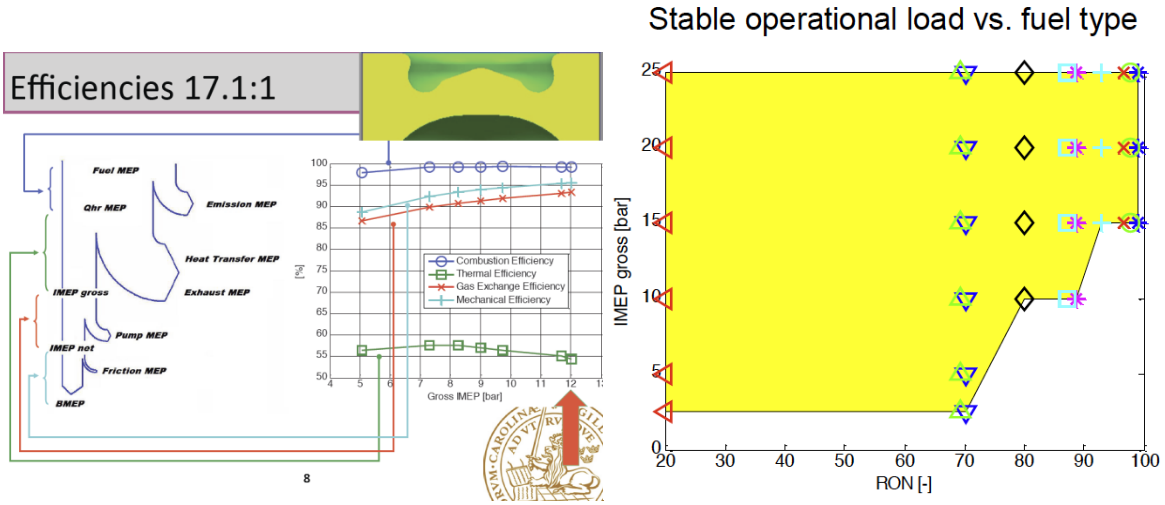


Figure 1: Fuel efficiency and operating range with PPC using gasoline with changing octane number.

To overcome the issue with PPC combustion using high-octane fuels at part load engine modifications similar to those found effective with classical HCCI. One of the best is to apply negative valve overlap, NVO and by this trap hot residual gas. The higher temperature enabled operation down to idle or 1-1.5 bar IMEP. At these loads diesel fuel in much easier to ignite and is hence preferable but also 87 RON gasoline could be used with high amounts of NVO. Soot was noted to much lower with gasoline than with diesel fuel, approaching levels that would be emission compliant without a DPF.

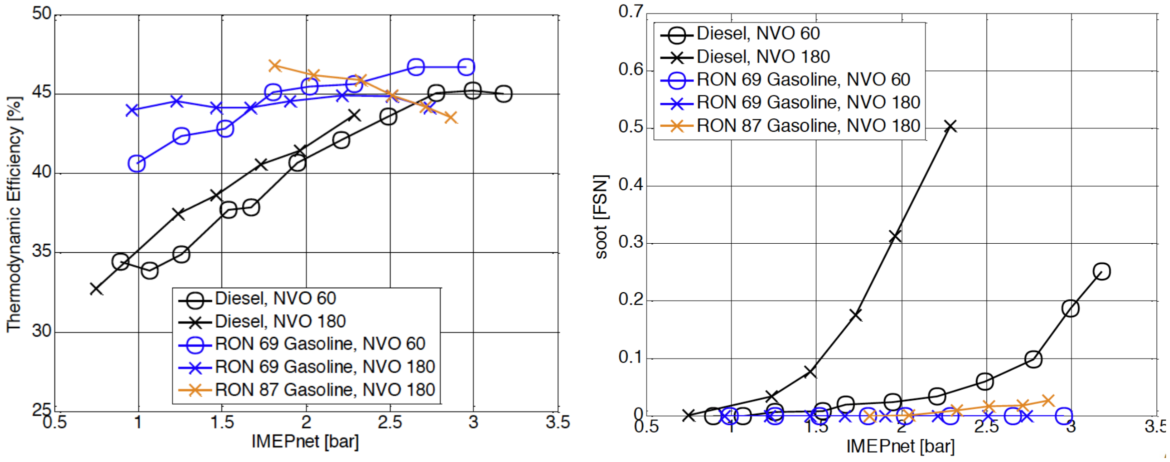


Figure 2: Efficiency and soot as a function of load with diesel fuel, low octane gasoline

and conventional pump gasoline RON 87.

Mark Musculus Sandia Nat. Labs, USA presented optical diagnostics of low temperature combustion with the RCCI concept. It was noted that the burn rate was a minimum with a fuel injection at -50. Earlier injection generated a very homogeneous charge with HCCI like combustion and a late injection (-15) gave too much stratification with rich zones burning fast. Studies with laser ignition some 10 CAD before start of combustion (i.e. auto ignition) showed some presence of flame propagation but the reactions associated with this were weak.

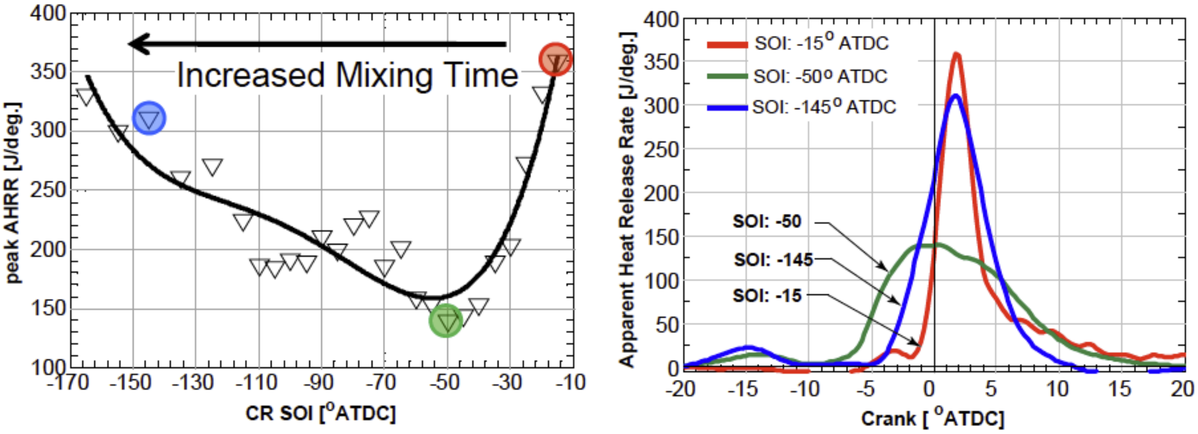
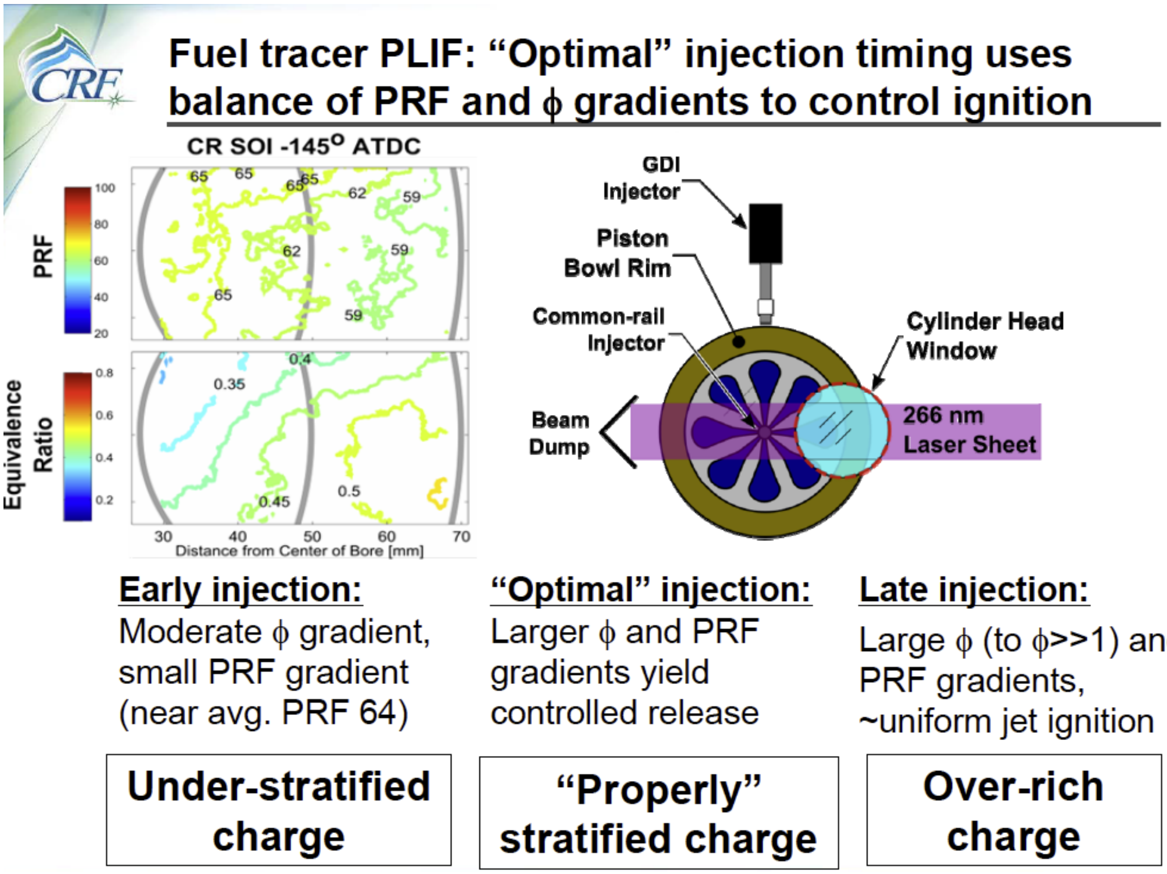


Figure 3: Maximum burn rate with early (-145) intermediate (-50) or late (-15) fuel injection.



Fuel tracer PLIF: “Optimal” injection timing uses balance of PRF and ϕ gradients to control ignition

Early injection:
Moderate ϕ gradient, small PRF gradient (near avg. PRF 64)

“Optimal” injection:
Larger ϕ and PRF gradients yield controlled release

Late injection:
Large ϕ (to ϕ>>1) and PRF gradients, ~uniform jet ignition

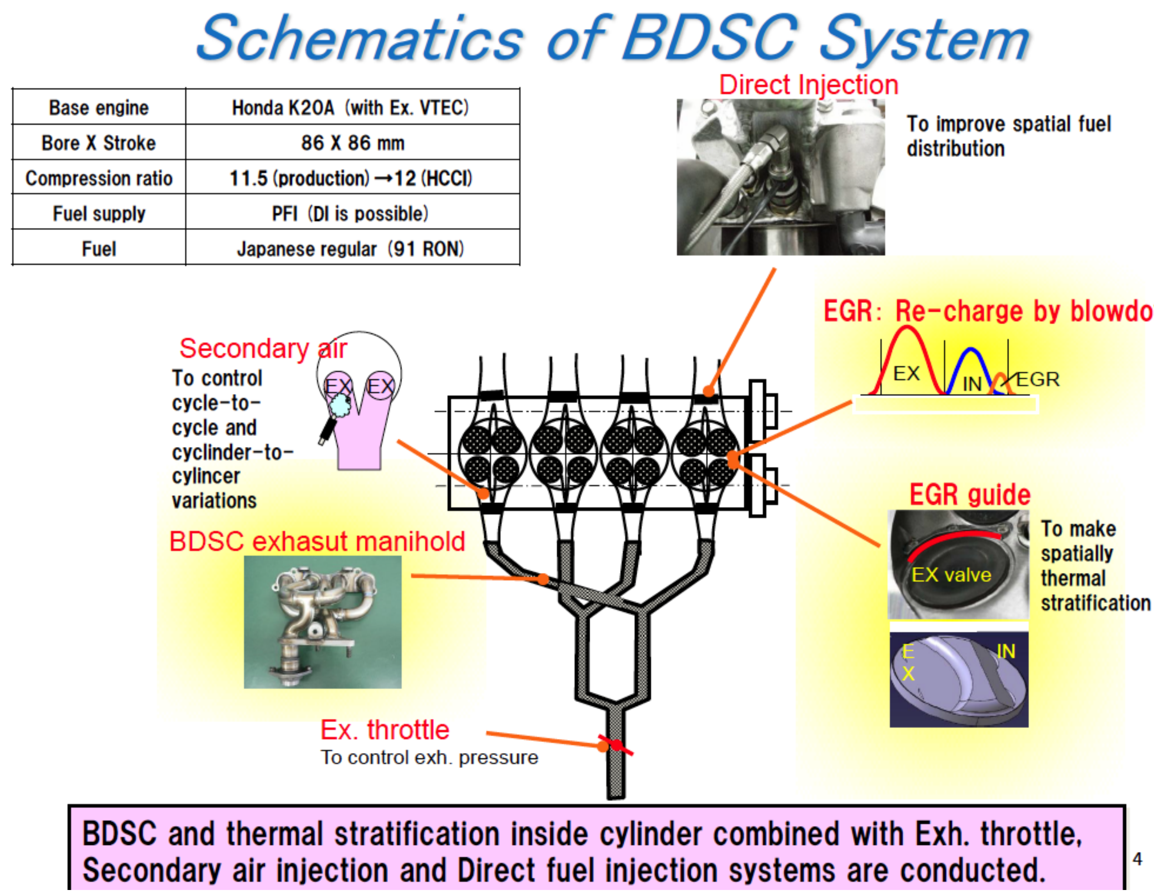
Under-stratified charge

“Properly” stratified charge

Over-rich charge

Figure 4: LIF measurements of fi and octane number in the three zones as indicated above.

Prof. Moriyoshi from Ciba University, Japan showed the latest progression with the blowdown supercharged HCCI system. The project has been reported within IEA since the start of the HCCI collaborative task. The concept is to use a normal naturally aspirated engine and run it with a stoichiometric mixture thus getting the same power density as normal SI engines. If this had been done in HCCI mode combustion without dilution the combustion would be very violent. To get the necessary dilution the cylinder will be half filled with burned gas. If this would be done during normal gas exchange the volumetric efficiency would be around 50% reducing the attainable load. With blowdown superchange the normal gas exchange process is completed trapping a full amount of fuel and air. The necessary dilution is then feed to the cylinder by opening the exhaust valve after normal inlet valve closing. At this time of the cycle the exhaust blow-down is occurring in the “pairing cylinder” giving a much higher pressure in the exhaust manifold. This higher pressure is used to boost the pressure level in the cylinder and hence supercharge the cylinder without any supercharger or turbo. The principle is shown in the figure below.



Schematics of BDSC System

Base engine	Honda K20A (with Ex. VTEC)
Bore X Stroke	86 X 86 mm
Compression ratio	11.5 (production) →12 (HCCI)
Fuel supply	PFI (DI is possible)
Fuel	Japanese regular (91 RON)

Direct Injection
To improve spatial fuel distribution

EGR: Re-charge by blowdown

Secondary air
To control cycle-to-cycle and cyclinder-to-cylincer variations

BDSC exhasut manihold

EGR guide
To make spatially thermal stratification

Ex. throttle
To control exh. pressure

BDSC and thermal stratification inside cylinder combined with Exh. throttle, Secondary air injection and Direct fuel injection systems are conducted.

Figure 5: Concept of blowdown superchange HCCI using exhausts from cylinder 4 to give back to cylinder 1 and the same way with cylinders 2 and 3.

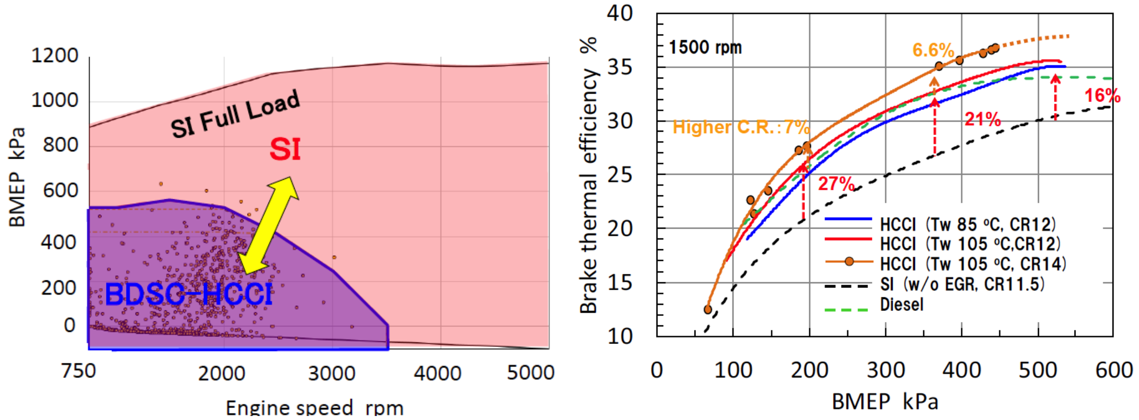
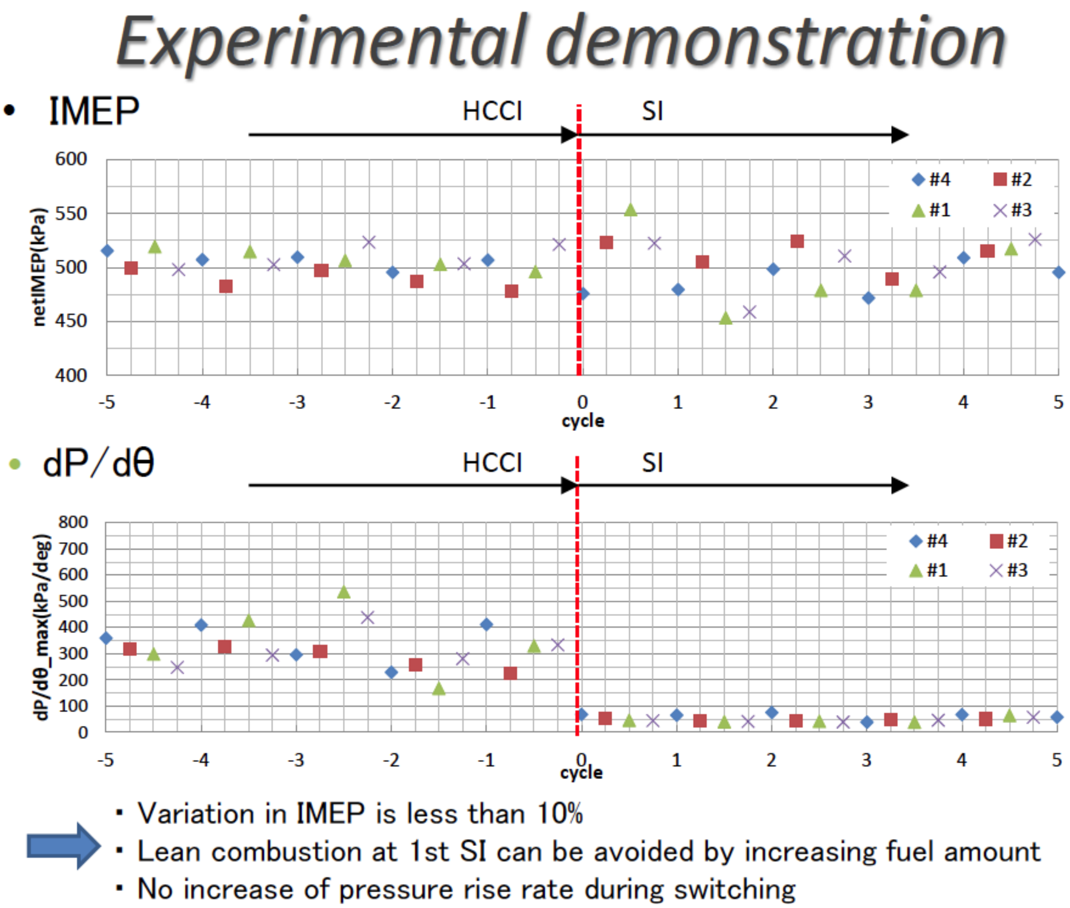


Figure 6: Attainable loads of BD-HCCI and the operating point of the Japanese test cycle (dots). Also shown is the fuel efficiency in comparison to standard SI and diesel engine of similar performance. Note that BD-HCCI beats the DI diesel.

This year the focus was on transient operation of the concept. A problem was that HCCI requires a large A/F as well as G/F and Si needs stoichiometric mixture and low levels of EGR. At the same time the transient should be in one cycle to prevent unstable mixed mode combustion processes. The actuators used were throttles in inlet as well as exhaust and a Honda VTEC valve profile switching system. Also a GDI injection system was used to give the desired fuel amount for each cycle.



Experimental demonstration

- IMEP
- dP/dθ

- Variation in IMEP is less than 10%
- Lean combustion at 1st SI can be avoided by increasing fuel amount
- No increase of pressure rise rate during switching

Figure 7: The IMEP switching from HCCI to SI with the advanced control scheme developed.

Prof. Atsumi Tezaki from Univ. of Toyama Japan presented results from a chemical mechanism of HCCI. The focus of the study was intermediate temperature heat release in an HCCI engine and how the fuel affect this part of combustion. In particular the difference between PRF (n-heptane+ iso-octane) and NTF (n-heptane and toluene).

A fast sampling valve system was used to measure fuel products and intermediate species especially HCHO and H_2O_2 with different fuels. The engine was also run lean enough to suppress the hot ignition giving the chance to measure the composition after first low temperature reactions by exhaust analysis. A simplified model of the experimental results was derived. It gave the same overall tends as the experiments.

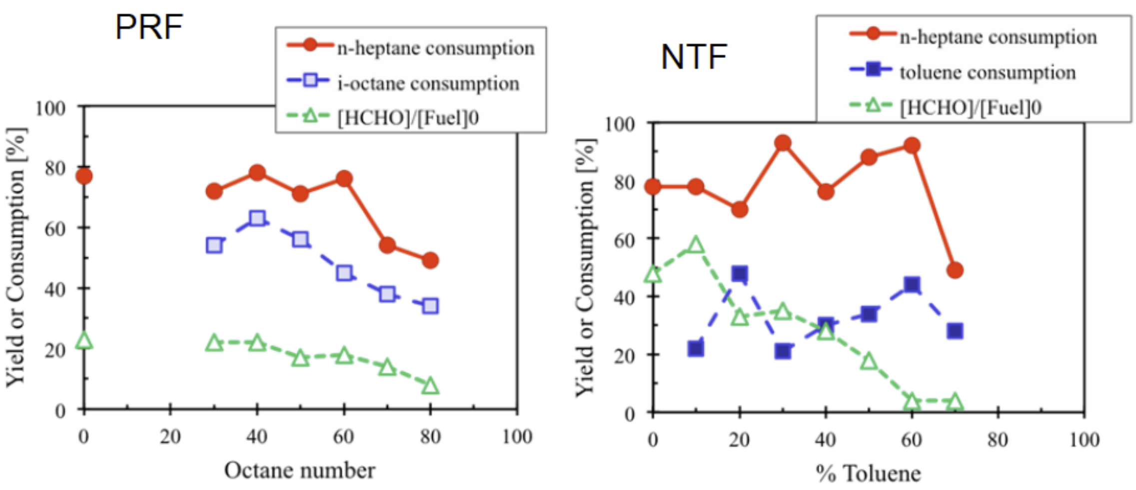


Figure 8: Difference in HCHO yield with toluene and iso-octane

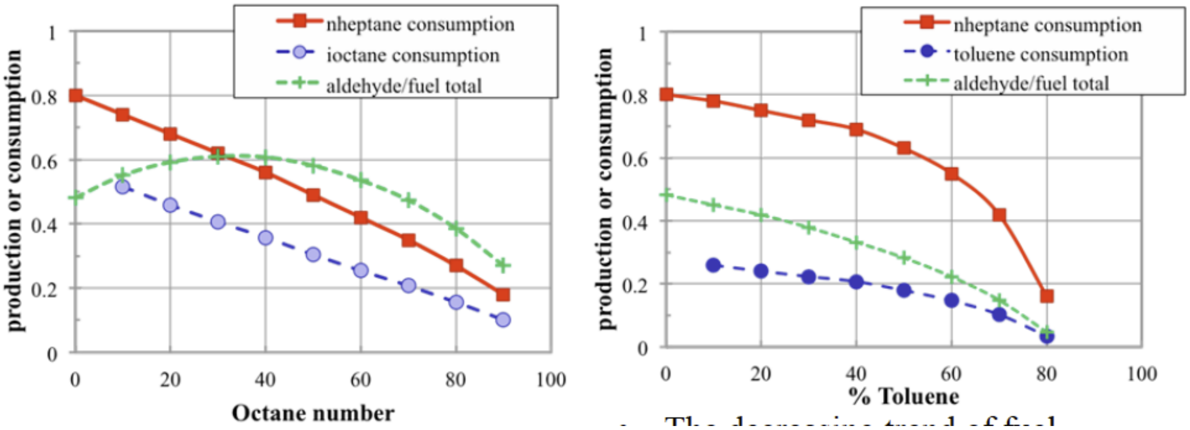


Figure 9: Results of model for the same case as figure above.

Prof. Christine Monaim-Rousselle from Univ. Orleans, France presented the effect of minor spices on the HCCI combustion process.

An HCCI with well mixed charge was operated with a variety of inlet temperature, pressure equivalence ratios and fuel compositions. It was concluded that the HCCI process can be controlled in many ways but most would have drawbacks. Thus the concept of controlling HCCI combustion phasing with ozone was proposed.

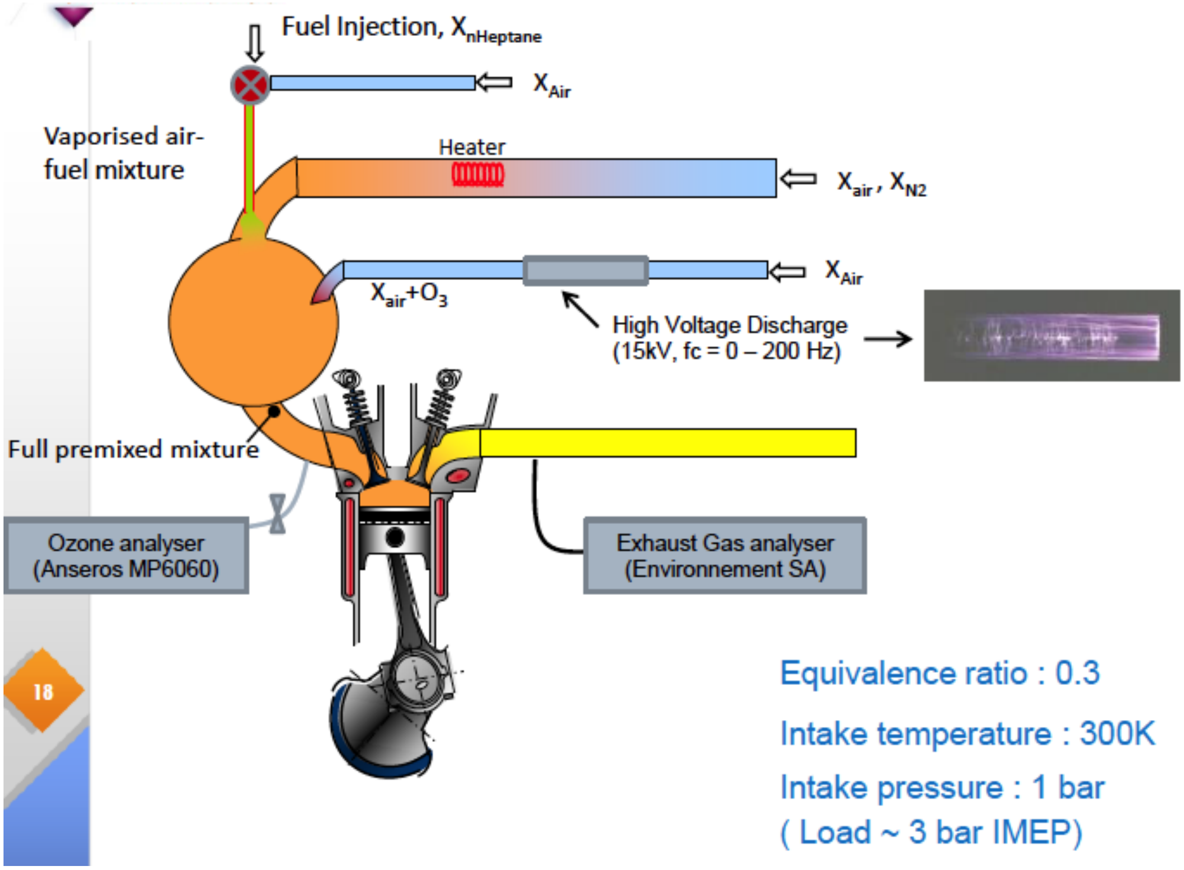
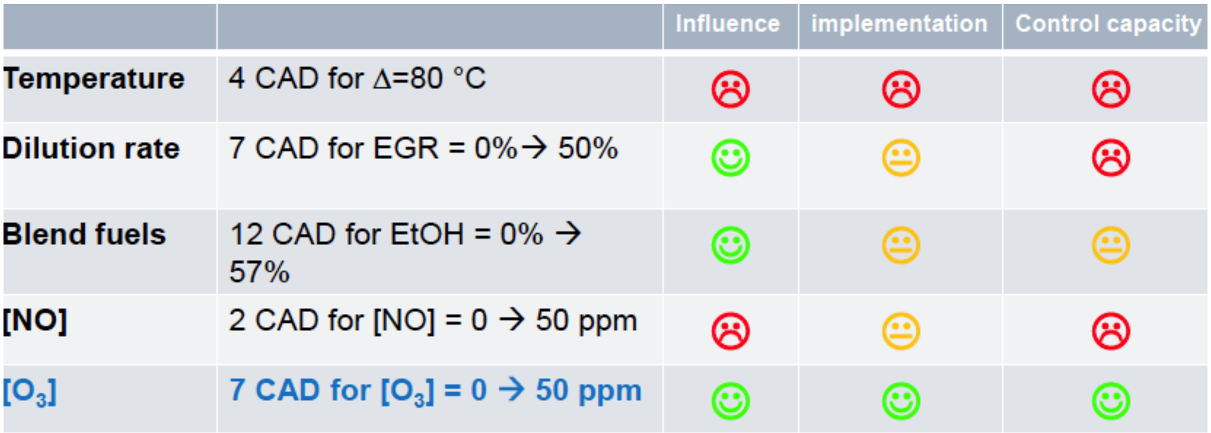


Figure 10: system with ozone generator in the form of low temperature plasma.



		Influence	implementation	Control capacity
Temperature	4 CAD for Δ=80 °C	☹	☹	☹
Dilution rate	7 CAD for EGR = 0%→ 50%	☺	😐	☹
Blend fuels	12 CAD for EtOH = 0% → 57%	☺	😐	😐
[NO]	2 CAD for [NO] = 0 → 50 ppm	☹	😐	☹
[O_3]	**7 CAD for [O_3] = 0 → 50 ppm**	☺	☺	☺

Figure 11: the controllability of inlet temperature, EGR, fuel blending, No and O3.

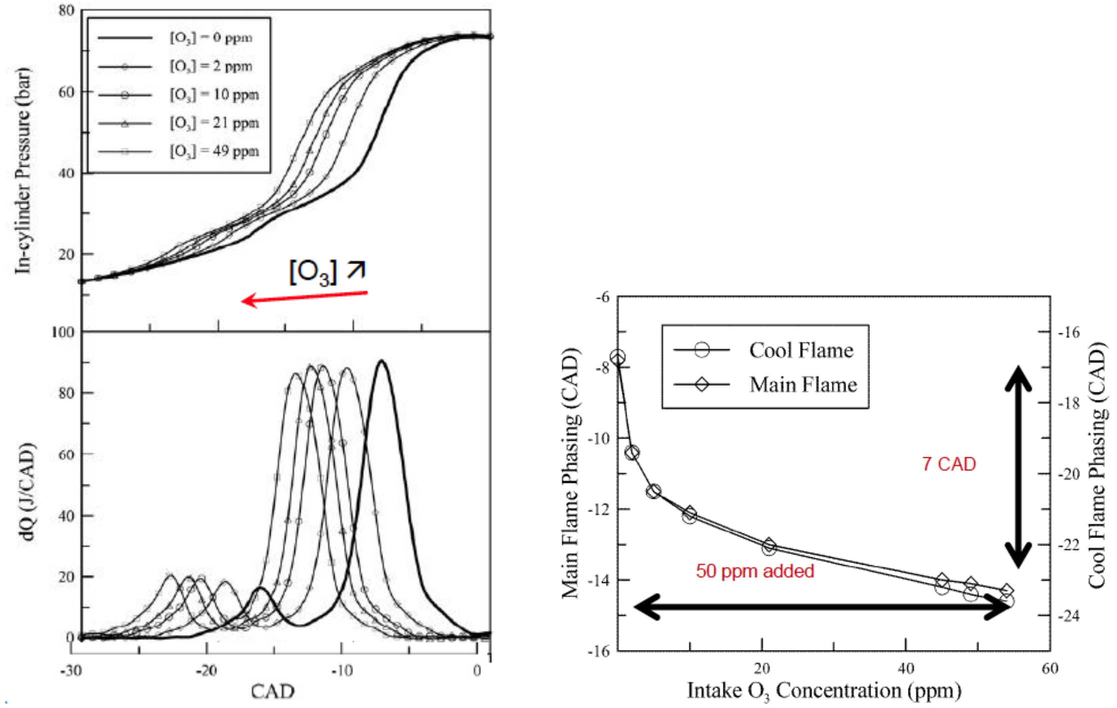


Figure 12: Combustion phasing change with 0-50 ppm of ozone in the inlet.

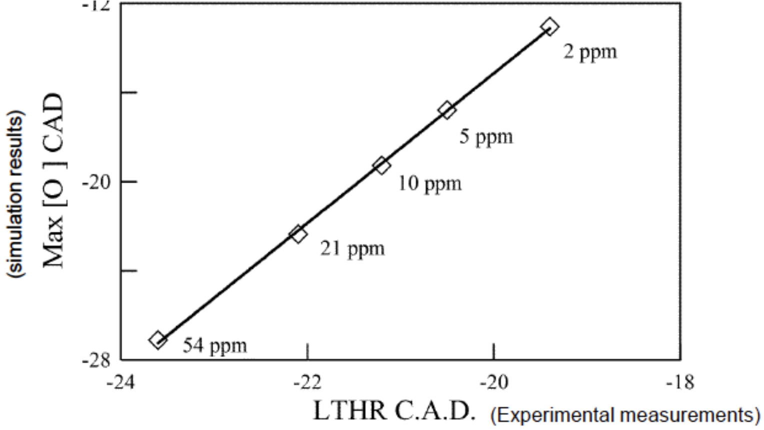
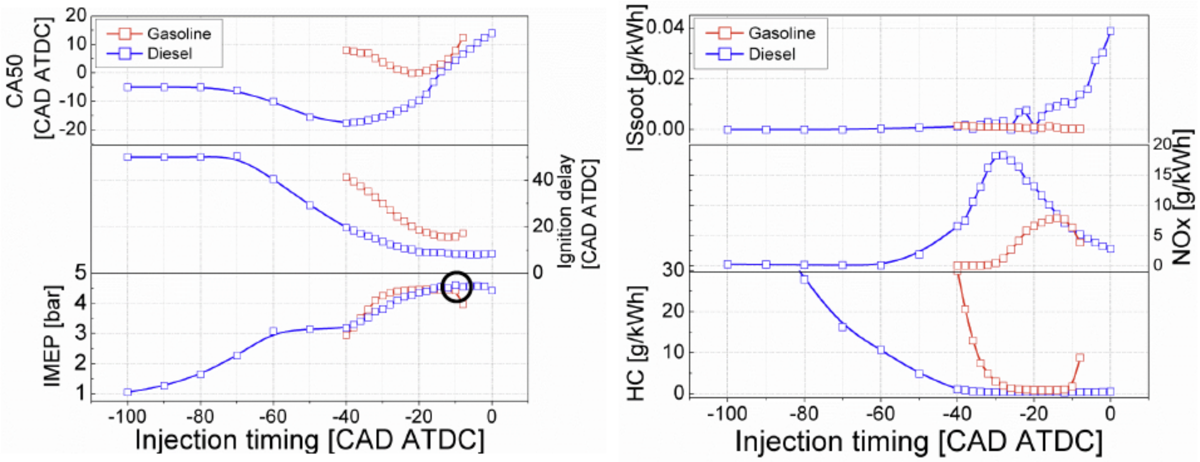


Figure 13: good correlation between simulations in senkin and experimental results.

The results showed a high sensitivity of combustion phasing with only small concentrations of ozone added to the inlet. It was enough to add 50 ppm to change combustion phasing 7 CAD. This concentration of ozone could be produced with minor energy consumption in the ozone generator. Simulations with the chemical kinetics package Semkin showed very good agreement with the experimental findings.

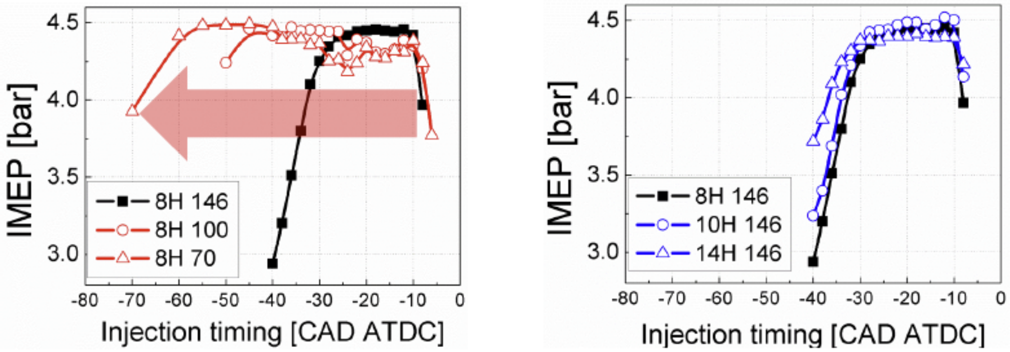
Prof. Choongsik Bae from KAIST Korea was not only an excellent host. He also showed some very interesting results on injector configurations on PCCI combustion in a diesel engine with both gasoline and diesel fuel. The figure below shows that gasoline give much longer ignition delay resulting is retarder combustion, less soot less NOx but higher emissions of HC. The figure below shows the trends with a advanced injection timing.



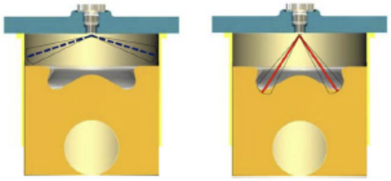
< Engine speed : 1200 rpm, Intake pressure : 1.4 bar, Injection pressure : 400 bar, Injection quantity : 20mg/stroke for gasoline, 20.2 mg/stroke for diesel>

Figure 14: A diesel engine operated with diesel fuel or gasoline.

Test were also shown with a narrow spray angle. The figure below shows that a narrow spary angle is best with early fuel injection but less so with more normal late injection.



<Fuel : Gasoline, Injection pressure : 400 bar, Intake pressure : 1.4 bar>



< Spray trajectory with the injection angle of 146 and 70 at -40 CAD ATDC>

With narrower injection angle,
-Operating range was significantly extended
-IMEP (efficiency) at early injection was comparable to the maximum IMEP from the baseline injector

With larger number of nozzle hole,
-No significant variation in operating range

Figure 15: Tests with narrow spray angle.

Different combination of hole number, spray angle and injection timing were tested. The best trade-off between NOx and fuel consumption was found for 8 holes and 70 degree angle using around -50 injection timing. For all cases gasoline gave shorter liquid spray penetration.

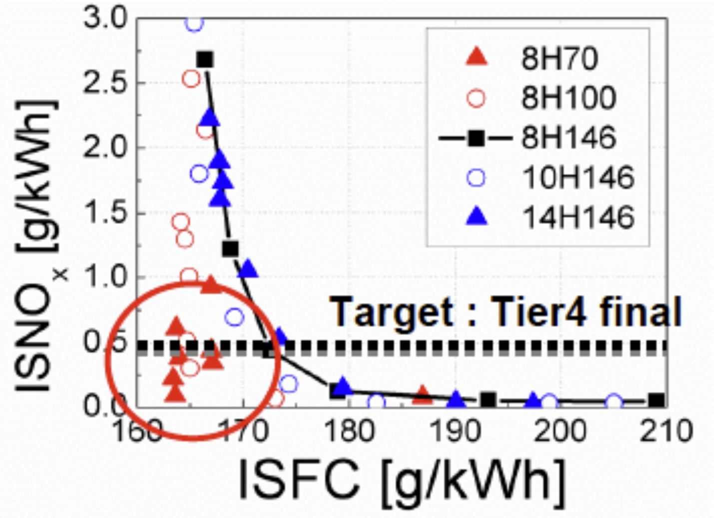


Figure 16: Trade-off between NOx and specific fuel consumption with number of holes and spray angle.

James Szybist from Oak Ridge Nat. Labs., USA presented strategies to extend the high load limit of HCCI. Two methods were compared. Boosted lean HCCI and Naturally aspirated spark assisted HCCI.

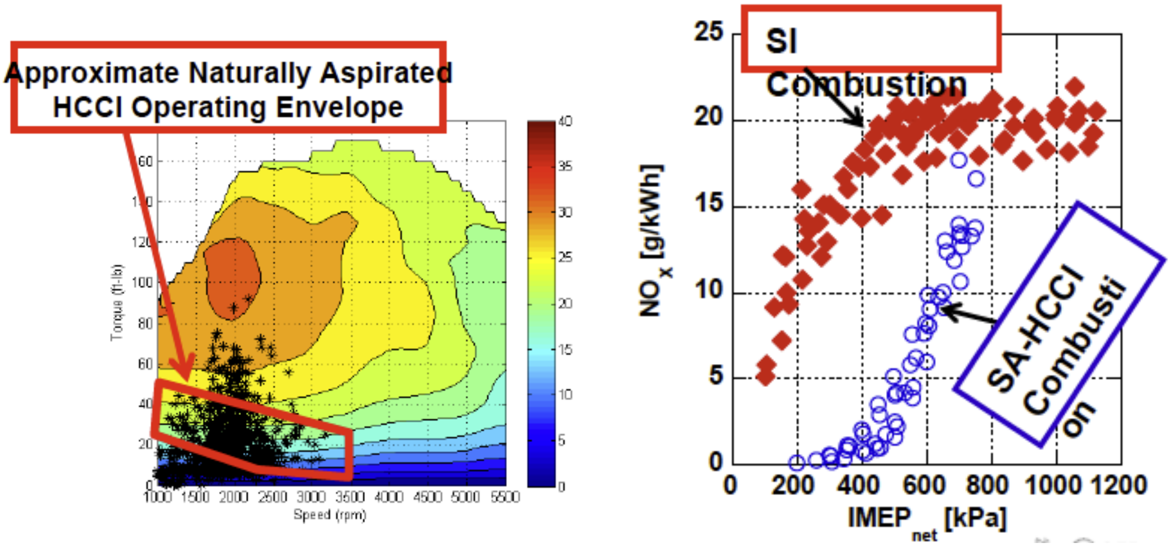


Figure 17: Operating range of HCCI in comparison to load point used in the test cycle (stars). To the right the load range of SACI, limited by NOx.

The figure above shows the needed load range for a transient test cycle and the red box shows the range with HCCI using the conventional negative valve overlap control strategy. To the right in the figure is the NOx as a function of load sown. At 4 bar IMEP the NOx increase sharply but the engine can be operated up to 7 bar in SACI mode. With a TWC this is still a realistic alternative. At 4bar/1500rpm the ISFC was reduced from 274 to 249 g/kWh and at 4bar/2000 rpm it was reduced from 265 to 243 g/kWh. The figure below shows that SACI gives better fuel consumption than SI but boosted lean HCCI gave much better results. The drawback with boosted lean HCCI was higher pressure rise rates and hence more noise. This required a minimum boost pressure of 1.9 bar (abs) at 6.5 bar IMEP. Sensitivity of the combustion process to valve timings was presented and also an investigation on noise level and how it correlates to pressure rise rate or knocking index. It was found that boosted operation was perceived as nosier than what dP/dCAD or RI indicated.

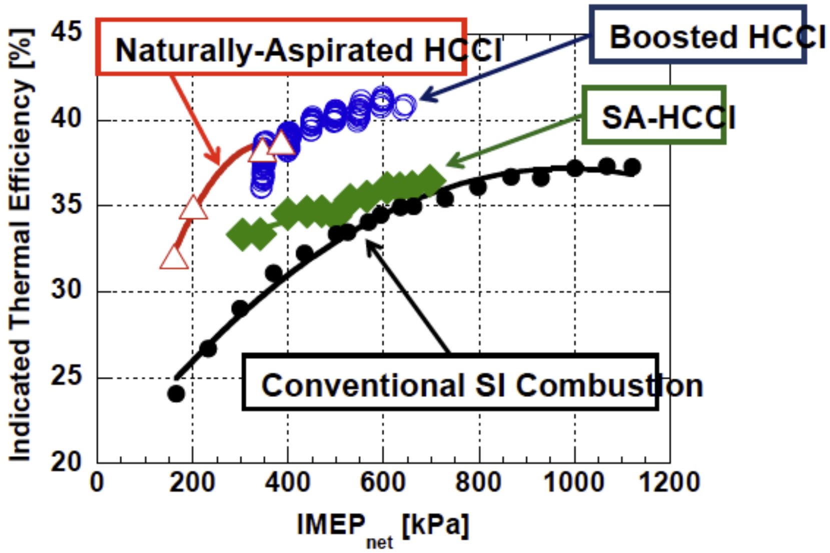


Figure 18: Efficiency with boosted HCCI and SACI in comparison to conventional SI and NA HCCI.

Prof. Eiji Tomita from Okayama University, Japan presented the latest results on his dueal fuel concept. In this presentation he presented biogas ignited with a pilot diesel fuel spray. He used a gas respresentative of biogas containing 58% methane, 35% carbon dioxide and 7% Nitrogen. The PREMIER combustion concept was used as in pervious studies reported with natural gas at IEA. It is based on three stages. The first is auto ignition of the pilot fuel, the second is flame propagation from the sprays and the third and final stage is auto ignition of the gaseous fuel. The process is illustrated in the next figure.

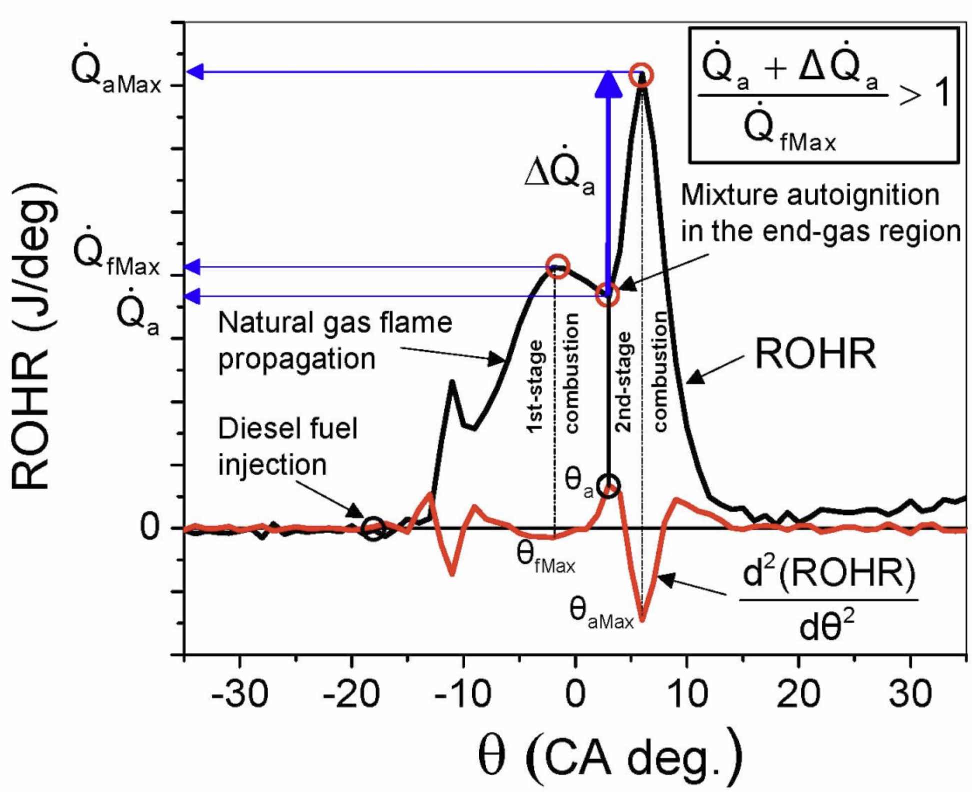
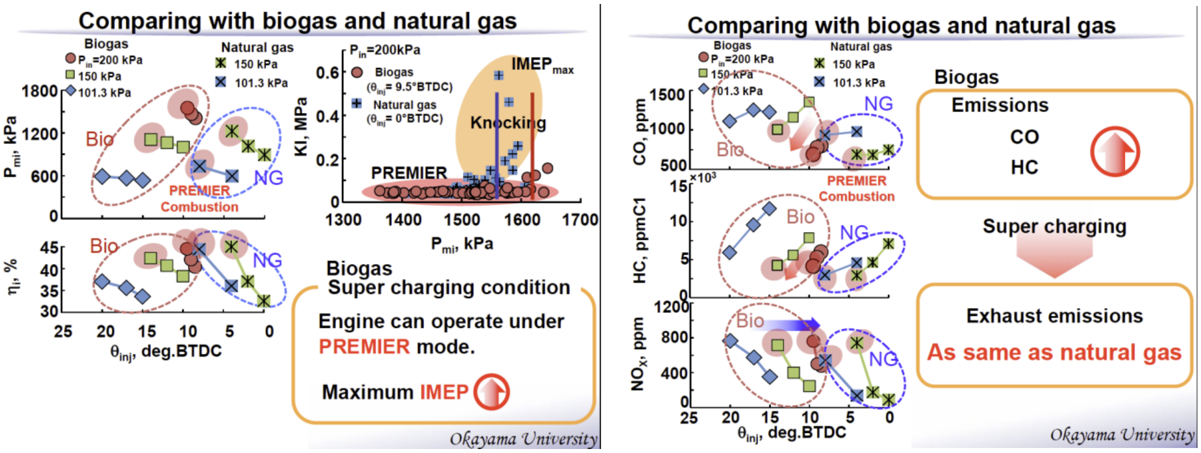


Figure 19: The PREMIER combustion concept.

The figure below shows the results when using biogas. It was possible to operate higher loads with biogas but engine efficiency was not increased very much. It was mainly the higher CO2 content that reduced compression temperature and hence suppressed knock tendency that enabled the higher load.



Comparing with biogas and natural gas

Biogas
Super charging condition

Engine can operate under PREMIER mode.

Maximum IMEP

Okayama University

Comparing with biogas and natural gas

Biogas

Emissions

CO

HC

Super charging

Exhaust emissions

As same as natural gas

Okayama University

Figure 20: Results with biogas in comparison to natural gas.

Gerardo Valentino, Insituto Motori, Italy presented results on mixtures of diesel and butanol under partially premixed conditions. The engine was of passenger car size, 1.25 liter four cylinder with 16:8:1 compression ratio and 7 hole fuel injector. Tests were conducted at 8 bar/2500 rpm. The 52 Cetane diesel fuel was blended with 44 CN butanol. In contradiction to methanol or ethanol the heating value of butanol does not differ much from that of diesel the change was only from 42.5 to 39.7 even though it contain significant amounts of oxygen. The figure below shows that the oxygen in the fuel reduce soot tendency and also gave a longer ignition delay. As a consequence the combustion is more premixed. This also reduced NOx to some extent.

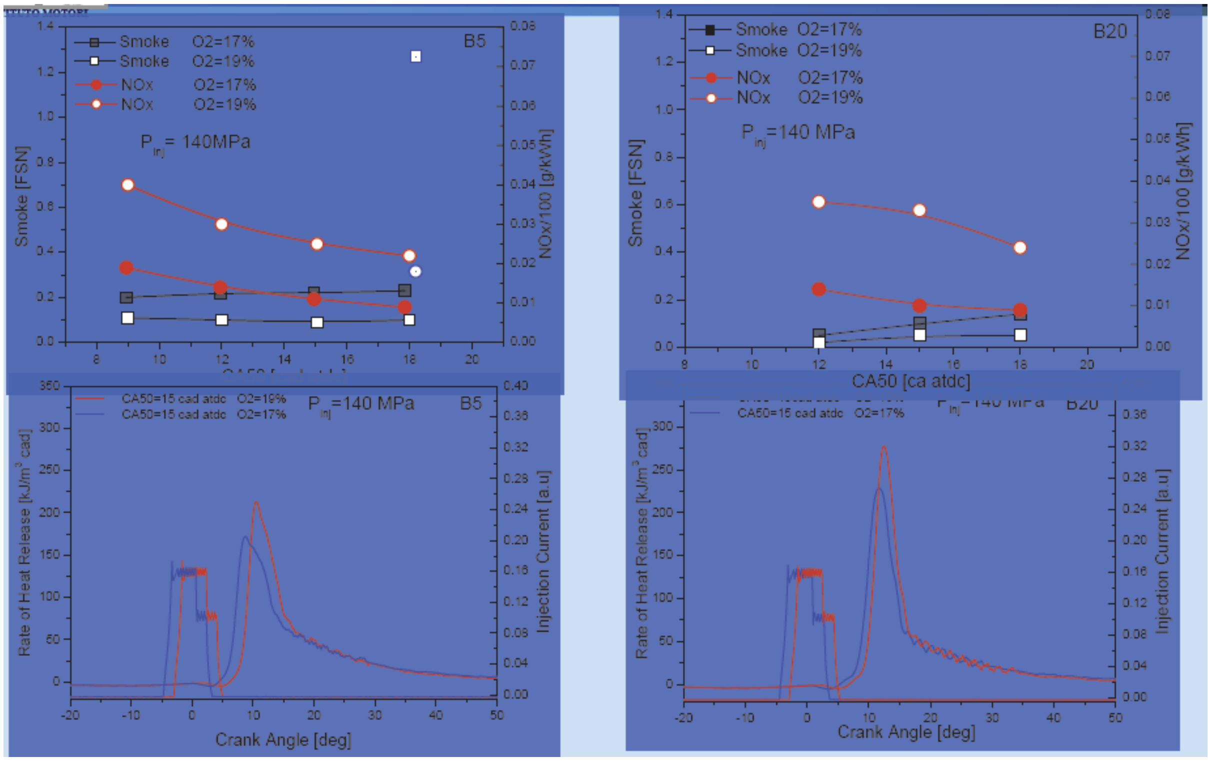


Figure 21: Smoke levels and combustion behavior with conventional diesel fuel (B5) and diesel with 20% butanol (B20)

Annex 4 - Advanced Hydrogen Fueled Internal Combustion Engines

Hydrogen, which is almost unlimited, is one of the most clean energy sources due to its carbon-free emissions. The objective of the H_2ICE task is to increase the fundamental understanding of physical and chemical processes required to control internal combustion engines operating with hydrogen.

The H_2ICE (Hydrogen Internal Combustion Engine) is one of the promising power sources in the future of "the hydrogen economy". However, hydrogen spark ignition (SI) engines have many disadvantages to overcome.

During the past year both H_2ICE SI engines and CI engines that add hydrogen as combustion enhancer were investigated.

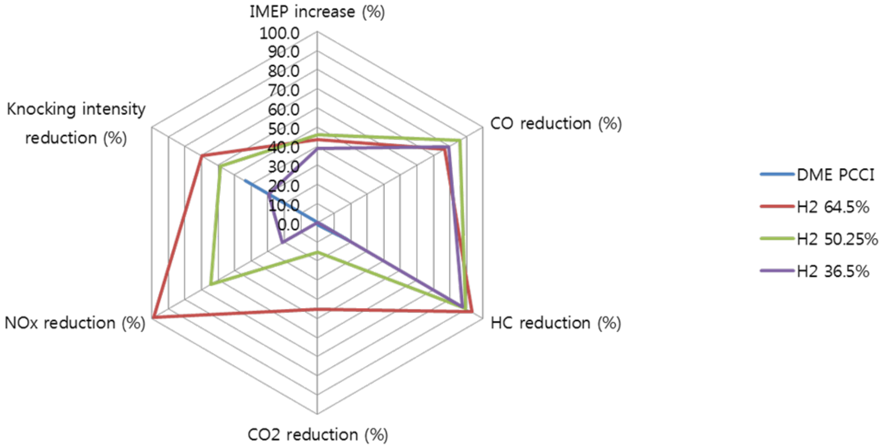
The following activities were undertaken within the Advanced Hydrogen Fueled Internal Combustion Engines Task during the past year:

> Choongsik Bae (Korea Advanced Institute of Science and Technology (KAIST), Republic of Korea)
> Effect of hydrogen and DME injection in homogeneous charge compression ignition engine with DME second injection strategy
>
> Hongsheng Guo, Vahid Hosseini, W. Stuart Neill, Wallace L. Chippior (National Research Council, Canada)
> Effect of Hydrogen Enrichment on Diesel Fuelled HCCI Combustion,
>
> M. K. Roy, N. Kawahara, E. Tomita,(Okayama University, Japan)
> High-Pressure Hydrogen Jet and Combustion Characteristics in a Direct-Injection Hydrogen Engine,

Highlights from the Task included the following:

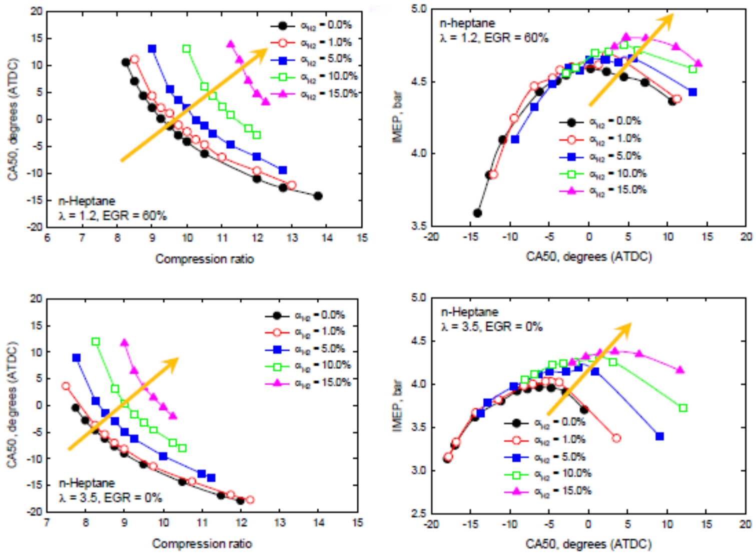
Choongsik Bae from The Korea Advanced Institute of Science and Technology (KAIST) studied the effect of hydrogen addition in DME PCCI combustion.

> Bae operated DME PCCI engine with high ratio of hydrogen addition. Through the IMEP and Exhaust emissions, the fuel injection timing and quantity were optimized. The DME second injection timing of the low NOx and low HC, CO emissions was selected. In this study, when the second DME was injected at -30 CAD ATDC, the NOx emission was maintained lower level without increase of HC and CO emissions. At this point, each DME injection strategy was compared in the point of IMEP increase and HC, CO, NOx, CO_2 reduction. In the graph, larger area means higher IMEP and lower emissions. The DME injection with 5mg of DME second injection shows largest area.



Hongsheng Guo in National Research Council Canada investigated the effect of hydrogen enrichment on combustion and emission characteristics of diesel HCCI combustion.

> H_2 enrichment retarded combustion phasing and reduced combustion duration of diesel HCCI. H_2 enrichment allowed a diesel HCCI engine to operate at a higher compression ratio, and also led to higher power output and fuel conversion efficiency. H_2 enrichment showed more effective at a higher λ without EGR than at a near stoichiometric λ with higher EGR

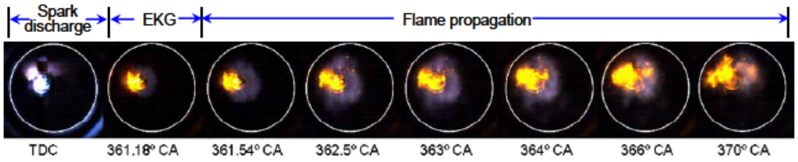


CA 50 **IMEP**

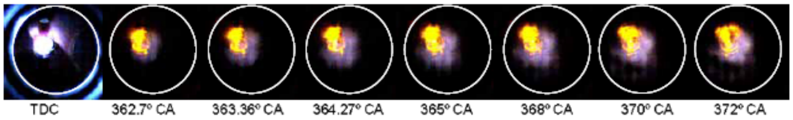
Eiji Tomita from Okayama University investigated high pressure hydrogen jet and combustion characteristics in a direct injection hydrogen engine.

> A high-speed video camera was used to visualize hydrogen jet development at the nozzle exit in a constant volume chamber. The effects of fuel injection pressure and ambient density on the jet overall characteristics were studied. DI hydrogen combustion was studied in an optical research engine. The effects of

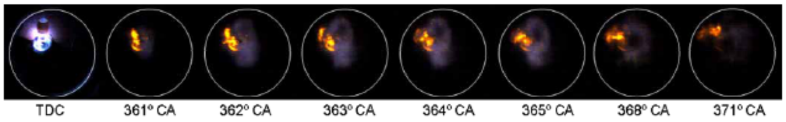
injection pressure and fuel injection timing were studied under different equivalence ratios, and thermodynamic data and high resolution images were recorded.



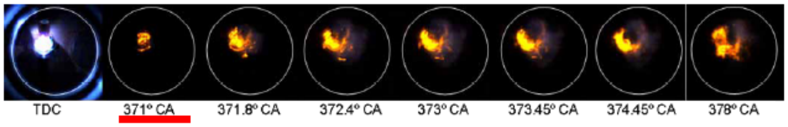
a) Tail Ignition (TI) - SOI = 320.5 °CA ; EOI = TDC



b) Late Ignition (LI) - SOI = 317 °CA ; EOI = 355 °CA



c) Center Ignition (CI) - SOI = 343 °CA ; EOI = 382.5 °CA



d) Head Ignition (HI) - SOI = 355 °CA ; EOI = 394.5 °CA

Annex 5 - Alternative Fuels

Sustainability and the environment are key issues of this Collaborative Task. The research is focused on new and sustainable fuels in combustion, especially on renewable fuels in gas engines, in spark ignition engines, in compression ignition engines and in advanced combustion systems such as HCCI or kinetically controlled combustion.

The improved performance of internal and external combustion devices and emission reduction are goals of the alternative fuel studies. The collaborative task has sub-projects on computational and experimental research. The aim is to increase the understanding of the combustion of alternative fuels and also to promote collaboration between experimental and computational research.

Both simulation and computational methods are essential parts of the collaborative task. In addition to its main focus on engine combustion, the task also links to furnace combustion, gas turbine combustion, general fuel chemistry, combustion properties and emission characteristics of new fuels.

The task chair is Martti Larmi (Aalto University, Finland). Participants include Gerardo Valentino (CNR Istituto Motori, Italy), Ingemar Denbratt (Chalmers University of Technology, Sweden), Véronique Diaz (Université catolique de Louvain, Belgium), Delphine Lupant (Mons University, Belgium) and Choongsik Bae (Korean Advanced Institute of Science and Technology, Korea).

The following activities were undertaken within the Alternative Fuels Task during the past year:

Cheolwoong Park. Tae Young Kim, Yonggyu Lee, Young Choi, Hongsuk Kim, Seungmook Oh, Kemyong Kang (KIMM, Korea)
Combustion and Emission Characteristics of LPG in a Spray-guided Type Direct-Injection Engine

Gerardo Valentino, Felice Corione, and Stefano Iannuzzi (CNR, Italy)
Effects of Diesel-Butanol Blend on Performance and Emissions in a High Speed Diesel Engine under Partially Premixed Combustion

Sunyoup Lee, Jee Hoon Chan, Yonggyu Lee, Seungmook Oh (KIMM, Korea)
Effect of Biodiesel Blending Fuel on Performance of CI Engines

Uen Do Lee (KITECH, Korea)
The Development of a Biomass to Liquid (BTL) Process for Automotive Fuel

Veronique Dias and Herve Jeanmart (Universite Catholique de Louvain,Belgium)
Kinetic Model for C2 Oxygenated Compounds

Seouksu Moon (AIST, Japan)
Strategies to Extend the Use of Biofuels and Develop Clean and Efficient Gas Engines

Highlights from the Task included the following:
Dr. Park of the Korean Institute of Machinery and Materials presented work on the Development of Lean-burn LPDI Engines

Drs. Gerardo Valentino, Felice Corcione, and Stefano Iannuzzi from Instituto Motori, Italy reported on the use of Diesel-Butanol Blends in High Speed Diesel Engines under Partially Premixed Combustion.

Two Concepts were explored:

Retarded start of injection that pushes the ignition around or after TDC to realize a PPC regime

Fuel Blend of Diesel-Butanol (Lower Cetane Number) that exhibits longer ignition delay and is more resistant to auto-ignition

The effect of combustion phasing, boost pressure, oxygen concentration and injection strategy on exhaust emissions was explored in a light duty diesel engine at medium load condition.

The commercial diesel fuel gave reduced smoke emissions setting a high injection pressure and an injection timing that allow to reach a partial premixed combustion.

In the interval of oxygen concentration between 17 to 19 and late injection timings, NOx and smoke emissions were drastically reduced with aslight effect on the fuel consumption.

For a given set of operating conditions, the B20 blend gives a higher ignition delay compared to the diesel fuel, leading to a better mixing before the start of combustion with an improvement of NOx and smoke emissions.

The joint action of the lower cetane number and higher volatility of B20 extending the ignition delay and promoting a better dispersion of fuel vapor within the combustion chamber (higher volatility) allowed to reach very low smoke emissions (0.1FSN) and NOx emissions (1 g/kWh) with minor penalties on fuel consumption (<3.5% if compared to the B5)

Drs. Sunyoup Lee, Jae Hoon Jang, Yonggyu, and Seungnook Oh from The Korean institute of Machinery and Materials presented results from a Study of the Effects of Biodiesel Blending Fuels on the Performance of CI Engines

The goals of the study were to:

Investigate the effect of biodiesel blending fuels on performance and emissions of CI engines

Apply biodiesel blending fuels to low temperature combustion technique as a way to meet the regulation for non-road vehicles

The following conclusions were reached:

Blending biodiesel in diesel decreases IMEP but is beneficial to thermal efficiency at high EGR rate conditions

Higher content of biodiesel promotes more complete oxidation of soot, THC, and CO. This effect becomes remarkable especially in high EGR conditions

As more biodiesel is blended, NOx emission is initially decreased and then increased which is different from what is generally expected.

The soot “hump” got smaller as more biodiesel was blended and almost disappeared for BD100.This means that the LTC regime can be extended to lower EGR rates by using biodiesel blending fuels

Drs. Uen Do Lee, Young Doo Kim, Beom Jong Kim, Ji Hong Moon, Won Yang, Chang Won Yang, Kwang Soo Kim, Jung Woo Lee (KITECH), Myung Won Seo (KIER), and Sangbong Lee (KRICT) reported on The Development of a Biomass to Liquid (BTL) Process for Automotive Fuel

Current Energy Status in Korea

Energy consumption: ~11th biggest energy consumer in the world (240Mtoe),

97% of energy is imported

Crude oil import: ~5th biggest importer (83% of crude oil from Middle East, 2011)

CO_2 emission: ~9th largest emitter in the world

Gasifier and syngas cleaning system

Syngas composition and H_2/CO ratio are suitable for F-T process.

The performance of DFB biomass gasifier was verified with the long-term operation test over 300 hours.

In DFB system, tar reduction and increase of steam conversion rate are the key technologies for increasing gasification efficiency.

Significant amount of H_2S was removed in the wet scrubber, whichdecreases the cleaning load of MeOH absorption system.

COS is not removed with the wet scrubbing

Oxygen content should be carefully monitored in the whole system which is directly connected to safety issues.

Characteristics of BTL Fuel

As a alternative fuel low temperature characteristics, density and lubrication are the main issues.

BTL diesel is almost sulfur free.

It has low aromatic content and high Cetane number.

The mixed fuel of conventional diesel and BTL diesel satisfies the fuel standard except for density criterion.

In order to satisfy the fuel standard (density criterion), optimization of BTL diesels near high boiling point (190~350 °C) s necessary

On road test will be conducted with BTL diesel within this year.

Drs, Véronique Dias and Hervé Jeanmart of the Université Catholique de Louvain

(UCL), Belgium reported on the Development of a Kinetic model for C2 Oxygenated Compounds

The following results were achieved:

Ethanol, acetaldehyde, acetic acid and formaldehyde flames were stabilized on a burner to measure mole fraction profiles of all species detected during their combustion.

The UCL kinetic model was completed for these fuels through the addition of the submechanisms for oxygenated species.

Experimental and simulated mole fraction profiles for all species were compared for testing the reliability of the «UCL» mechanism.

The validity range of the model was extended to these oxygenated fuels.

Drs. Seoksu, Taku Tsujimura, and Mitsuharu Oguma from AIST, Japan presented an Overview of Strategies to Extend the Use of Biofuels and Develop Clean and Efficient Gas Engines

The work included:

Strategies to Develop Clean CI Engines
  Standardization of DME Fuel Properties
  Development of Heavy-Duty DME Vehicles
  Spray/Combustion Analysis of DME, GTL, Fischer-Tropsch

Strategies to Extend the Use of Biofuels
  Evaluation of Biofuel Properties
  Establishment of Spray/Combustion Models of Biofuels
  Blend of Biofuels to Conventional Fuels

Strategies to Develop Clean and Efficient Gas Engines
  H2 Engines
  Direct Injection (DI) CNG Engines
  CNG-Diesel Dual-Fuel Engines
  Laser-Induced Plasma Ignition

Annex 6 - Nanoparticle Diagnostics

There was no task Activity during the past year

Annex – 7 Hydrogen Enriched Lean Premixed Combustion for Ultra-Low Emission Gas Turbine Combustors

The objective of the Gas Turbine task is the generation of a data base for combustion properties of hydrogen-rich fuel gases and of hydrocarbon fuels burned in a $O_2/CO_2/H_2O$ atmosphere. Most important conditions to be met are elevated pressure conditions (up to 30bar) relevant for gas turbine operation. The operational envelope studied should also provide information on the flame stability characteristics of such gas turbine combustion systems being operated with quickly changing boundary conditions (pressure, air temperature, flow rates) representative for strong load gradients.

Following up on the previous collaborative efforts on “Hydrogen enriched Lean Premixed Combustion for Ultra-Low Emission Gas Turbine Combustors” the current collaborative task activities on gas turbine combustion issues should be linked to respective Zero Emission Power Plant concepts.

Fast response characteristics and large load gradients need to be additionally dealt with by gas turbine based power plants as such controllable power generation systems will be required to compensate fluctuating electricity production from renewable energy resources (wind, solar).

The following activities were undertaken within the Hydrogen Enriched Lean Premixed Combustion for Ultra-Low Emission Gas Turbine Combustors Task during the past year:

Nonhiko Iki (AIST, Japan)
Basic Research of H_2 Rich Premixed Flames Excited by Oscillated Flow

Peter Jansohn presented by K. Boulouchos (ETH Zurich.Institute of Energy Technology-LAV, Switzerland)
Turbulent Flame Speed of H_2 Rich Premixed Flames at GT Operating Conditions

Dr. Norijhiko Iki from The National Institute of Advanced Industrial Science and Technology, Japan reported on Basic Research of H_2 Rich Premixed Flames Excited by Oscillated Flow

An experimental apparatus has been designed and constructed for combustion oscillation of H2 premixed flame.

Combustion of reformed gas is employed

Steam reforming can increase the thermal efficiency by energy recuperation.

Steam reforming produces hydrogen rich fuel.

The counter measures for combustion pressure fluctuation such as acoustic liner, refinement of flame holder, are successful in natural gas fired gas turbine.

Acoustic characteristics of hydrogen rich flame is important for development of the counter measures for combustion pressure fluctuation in hydrogen rich fuel fired gas turbine.

Drs. Yiu-Chun Lin and Peter Jahnsohn of the Paul Scherer Unstitute in Switzerland reported on A Study of the Turbulent Flame Speed of Hydrogen-Rich Premixed Flames at Gas Turbine Operating Conditions

> Compared to syngas mixtures, flashback occurs at even leaner conditions for H2-rich fuel gases. A significantly reduced operational envelope is observed at elevated pressure (since the lean blow out limits are relatively independent of pressure).
>
> For the H2-rich flames, the profile of flame front generally approaches that of an ideal cone. Accordingly, the conventional approach of evaluating the turbulent flame speed via the flame cone angle may provide a reasonable estimation. Nonetheless, deviations are observed for the syngas and methane flames especially at lean conditions
>
> Compared to the syngas flames, the H_2-rich flames exhibit almost no “ST-bending” effect. This is attributed to the fact that the preferential diffusive-thermal and hydrodynamic instabilities are actually coupled for the lean hydrogen mixtures. The interaction facilitates further wrinkling of the flame surface, which increases ST.
>
> The absence of ST-bending for the H_2-rich flames is also evidenced by the finding that the time scale of the flame front is comparable to that of the turbulence. Thus the flame front is able to respond to the fast turbulence and increase its surface area.

Annex 8 – Administrative Support and Special Topics

At the request of the Executive Committee, a session focused on advances in Combustion Modeling was organized. Five invited speakers made presentations as outlined below.

Prof.Dr. Konstantinos Boulouchos from the Institute of Energy Technology, ETH Zurich made a presentation entitled: Towards an in-depth understanding of reactive flows in IC engines-promising contributions of LES and, potentially, DNS.

IC-Engine Combustion – Grand Challenges

- Further significant reduction of engine-out emissions
- Minimization of CO2-emissoins (specific per work output), e.g.
  - Further increase of overall thermodynamic efficiency
  - Optimize combustion for synthetic/biogenic fuels
- Expand operating limits by overcoming goal conflicts, in particularly related to cyclic variability of engine combustion process (not only in SI-premixed, but also in HCCI/Diesel engines!)

Future Perspectives

- Further progress towards clean, efficient IC engine combustion process must increasingly deal with stochastic, cyclic-varying processes and a quantitative understanding of reactive thermofluidic mechanisms and their interaction.

- Experimental and computational effort will increase even further, as both spatial and temporal resolutions need to be radically finer and simultaneous multiparameter detection methods will become necessary.

- Clean, transparently documented non-intrusive experiments will be indispensable for validation

while

- LES is emerging as the frontier in IC engine CRFD

and

- even accurate reactive DNS will be feasible in the next few years.

However:
It is not all about CPU-hours but also about processing, data mining, understanding, contributing to turbulent combustion models … !

Mark Mussculus, Lyle Pickett, Paul Miles, John Dec, and Joe Oefelein of Sandia National Laboratories. Binh Hu of Cummins, Thierry Lachaux of Alstom, Caroline Genzale of Georgia Tech, Kyle Katke of the Colorago School of Mines, Rolf Reitz of the University of Wosconsin, Mohan Bobba of GE, Clement Chartier of Scania, and Oivind Andersson of Lund University presented: A Conceptual Model for Part\ially Premixed Low-Temperature Combustion

Felice Corcine, G. Valentino, S. Merola, C. Tornatore, S. Ianuzzi, and L, Marchitto if the Instituto Motori made a presentation on: Fuel Blends and Management forMinimizing Exhaust Emissions of Diesel Engines

Introdution

In Europe, from 1992 (EURO 1) to 2009 (EURO 4), soot emissions of passenger cars with direct injection common rail diesel engine moved from 0.14 to 0.025 g/km and HC+NOx moved from 0.97 to 0.30 g/km.

From 2010 (EURO 5), soot and NOx have been reduced to 0.005 and 0.18 g/km, respectively. This result has been reached using the multiple injection strategy and the diesel particulate filter (DPF) at the exhaust.

Probably, from 2014 or 2015 (EURO 6), soot and NOx must be still reduced to 0.0025 and 0.08 g/km, respectively. To meet this stringent EURO 6 emission standard, most vehicle manufacturers, especially

European manufacturers, have opted for the selective catalytic reduction system (SCR) to reduce NOx and DPF to reduce soot

Conclusions

Experimental investigation carried out in a modern automotive direct injection Diesel engine running at different operating conditions and fuelled with blends of diesel-gasoline and diesel-butanolhas been shown. Results have shown that gasoline-diesel and n-butanol-diesel blends are beneficial to optimize the engine performance and minimize emissions than that can be done using the neat diesel fuel.

Compared to diesel fuel, the lower cetanenumber of diesel/gasoline (G40) and diesel/butanol(B40) blends extends the ignition delay, at reduced intake oxygen content, and allows more time for mixing. The higher volatility of blends promotes the dispersion of fuel vapor within the combustion chamber with advantages in mixture preparation. These joint actions bring to almost smokeless combustion with a reduction in NOxemissions at moderate injection pressures and intake oxygen concentrations. The better premixed charge, achieved for B40 and G40, extends the low smoke combustion and NOxreduction to higher engine loads keeping the advantage of moderate injection pressures (100-120 MPa).

B40 and G40 minimize smoke emissions by tuning appropriately the engine parameters like injection pressure, injection timing and O2% at intake but emit, compared to the neat diesel, higher unburned hydrocarbons mainly due to the combined effects of their lower cetane number and higher evaporation heat. This behavior is particularly marked with lower oxygen concentration at intake. In general, both fuel blends give higher CO emissions than neat diesel at reduced O2% at intake.

B40 and G40 blends reduce the combustion noise emission if the injection timing is moved toward the TDC and the combustion attains a complete premixed behavior with a reduced maximum heat release rate.

The observed improvement in emissions for blends is paid in terms of higher specific fuel consumption referred to energy density content. On the contrary, a higher efficiency is achieved with the blends, particularly for the diesel/butanol that may be related to the enhanced oxygen content, which improves combustion.

Finally, a right design and management of fuels with higher resistance to auto-ignition, lower cetane number and higher volatility, enhancing the premixing of fuel and air before combustion, enables the engine to run at high speed and load at near smokeless conditions with low NOx emissions at moderate injection pressures.

Prof. Bengt Johansson of Lund University presented an extensive 112 page overview entitled: Low Tepmperature Combustion: The Path to High Efficiency Combustion Engines. **If a copy is desired, the reader should contact Prof. Johansson directly.** In summary the overview concluded that for Partially Premixed Combustion, PPC

Compression Ignition should use gasoline not diesel

PPC is the most efficient of all processes known !
- Combustion Efficiency >99.8%
- Thermodynamic Efficiency= 55-57%

Load range 0-26 bar IMEP

Low enough emissions
- NOx, HC, and CO below legal limits without catalytic aftertreatment
- PM low enough using ethanol and often gasoline

Prof. Kanh Huh of the Combustion Laboratory. Pohang University of Science and Technology presented: an Analysis of Diesel Combustion by the Conditional Momnet Closure Method (CMC)

Diesel Combustion Characteristics [Lee and Hun, 2012)

Evaporation/combustion timing according to engine speed
- High rpm : Combustion and injection may occur simultaneously
- Low rpm : Most combustion occur after injection and evaporation are complete

Liquid volume fraction negligible

The liquid volume fractions were small enough to consider droplets as point sources in the two-phase formulation, except close to the nozzle exit.

Ignition location

Ignition occurs in rich compositions of the equivalence ratio in the range of 2-4 as observed in Dec[1].

The ignition location corresponds to the most reactive mixture fraction of the given mixture states in the cylinder.

Premixed and nonpremixed combustion controlled by turbulence

After ignition, the peak temperature follows the stoichiometric composition, propagating to lean and rich sides as a diffusion process proportional to CSDR by turbulence.

Summary

The conditional averaging practice provides a promising modeling strategy to resolve turbulence/chemistry coupling in turbulent spray combustion in diesel engines. It is more realistic than arbitrary assumption of a laminar flamelet in LFM.

The spatially integrated version, CMC-ISR, has successfully been applied to both 3D and 0D simulation of different types of diesel engines for both heat release and NOx/PM emissions.

CMC allows realistic low- and high-temperature chemistry for accurate prediction of ignition, NOx and soot emissions. There still is uncertainty in rich PM chemistry and population dynamics.

Extensive DNS study has been performed to establish the regime map and conditional submodels in turbulent spray combustion. Proper spray combustion regime is crucial for appropriate local PDFs and conditional submodels for closure.