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Operating Agent for the Gas Engine Collaborative Task

in the

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Agent:
ETH Zürich
Institute for Energy Technology
Aerothermochemistry and Combustion Systems Laboratory (LAV)
ML J39, Sonneggstrasse 3
CH-8092 Zürich, Switzerland
www.lav.ethz.ch

Author:
Dr. Yuri M. Wright, LAV, ETH Zürich, wright@lav.mavt.ethz.ch
Prof. Konstantinos Boulouchos, LAV, ETH Zürich, boulouchos@lav.mavt.ethz.ch

SFOE head of domain: Carina Alles, Carina.Alles@bfe.admin.ch
SFOE programme manager: Stephan Renz, renz.btr@swissonline.ch
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The author of this report bears the entire responsibility for the content and for the conclusions drawn therefrom.

Swiss Federal Office of Energy SFOE
Mühlestrasse 4, CH-3063 Ittigen; postal address: CH-3003 Bern
Phone +41 58 462 56 11 · Fax +41 58 463 25 00 · contact@bfe.admin.ch · www.bfe.admin.ch

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Project goals

Within this project, all activities relating to the Gas Engine Collaborative Task – within the Technology Collaboration Programme "clean and efficient combustion" of the International Energy Agency – are coordinated, including: further development of the task w.r.t. collaboration between members; improving visibility of the Task; IEA reporting; organization of gas engine sessions and work-shops at the TLM.

Summary

Since the establishment of the Gas Engine Collaborative Task (GECT) at the 35th IEA Task Leader Meeting (TLM) in San Francisco, the main goal of the task is to establish and improve collaborations among task member and to coordinate all reporting activities at the task level for subsequent consolidation via the Executive Committee (ExCo) of the TCP to the end use working party (EUWP) and finally IEA headquarters.

The GECT is focussed on gaseous fuels, which may stem from conventional exploration, newly developed techniques or from sourced from biomass conversion. Combustion of natural gas in lieu of liquid fossil fuels is highly attractive for a number of reasons: An abundance of supply due to shale gas exploration lead to low fuel prices makes it particularly suitable for power generation, freight transportation and other applications with high running vs. investment costs. Environmentally, the low C/H ratio (1 to 4 versus roughly 1 to 2 for longer-chain liquid fuels) results in an immediate reduction in CO_2 of 25% reduction compared to oil based fuels (and up to 50% compared coal). Furthermore, combustion of natural gas enables ultralow NOx and soot emissions due to lean pre-mixed combustion in IC engines in conjunction with very high efficiencies. From an energy security perspective, local availability leads to considerably reduced dependence on liquid fuels sourced primarily by OPEC.

Combustion of natural gas in IC engines is a rapidly developing field, due to straightforward implementation using broadly established engine components. Nonetheless a number of challenges remain, for which considerable research efforts are underway. These include in particular the development of novel and conventional ignition systems, higher engine efficiency and the reduction of unburnt hydrocarbon emissions. The task seeks to bundle these research efforts and provide a platform for international exchange between academia and industrial R&D. The GECT is among a total of 12 collaborative tasks in the “clean and efficient combustion” Technology Collaboration Programme (TCP) of the International Energy Agency (IEA). The combustion TCP itself seeks to address increasing concerns with respect to A) local pollution levels and B) rising levels of CO_2 in the atmosphere worldwide by improving the efficiency of combustion devices while simultaneously lowering emissions.

Work undertaken and findings obtained

The **39th Task Leader Meeting** was held **in Baiona**, Spain, for which a total of eight presentations could be secured in the GECT session:

- Kahila, Keskinen, Kaario, Vuorinen, Ahmad, Aryal, Ranta and Larmi (Aalto University, Finland): ” Computational and Experimental Gas Engine Combustion Research 2017 in Aalto University”
- Pochet, Jeanmart & Dias (UC Louvain, Belgium), Contino (Vrije University, Belgium), Truedson and Foucher (Université d’Orleans, France): “Investigation of a carbon-free fuels in HCCI engine: The case of hydrogen-ammonia blends”
- Bardis, Benekos, Bolla, Frouzakis, Giannakopoulos, Koch, Kotzagianni, Kyrtatos, Xu, Schneider, Wright & Boulouchos (ETH Zurich): “Pre-chamber ignition for lean-burn gas engines”

- Chu, Kang & Min (Seoul National University, Korea): “Potential of Propane/Diesel Dual-fuel PCI with Low Compression Ratio for High Load Expansion”

- Moriyoshi, Kubayama & Matsumoto (Chiba University, Japan): “Application of Low Temperature Plasma Ignition to a Gas Engine”

- Oh (Korea Institute of Machinery and Materials, Korea): “Advanced research on the ultra-lean burn LPG direct injection engine and its application”

- Srna, Bombach & Jansohn (PSI, Switzerland), Bruneaux (IFPen, France), Herrmann (FHNW, Switzerland), Boulouchos (ETH Zurich, Switzerland): “Experimental study of pilot-fuel ignition mechanisms under dual-fuel engine relevant conditions”

- Tsujimura (AIST, Fukushima Renewable Energy Institute, Japan): “R&D on stationary engines using renewable and carbon-free hydrogen”

Considerable effort was undertaken during the panel sessions to further elaborate a **new task template** initiated by Paul Miles, Gilles Bruneaux and further members of the ExCo. The main goal was **to** clearly **identify** the **mission and global context of the work undertaken** towards highlighting the task **impact on energy use, emissions, economic growth and energy security** (4E). A table listing topical areas and task member involvement details the efforts undertaken at the various institutions worldwide. The developed task summary further documents linkages to other work packages and TCPs and lists major achievements of the past two years. All task summaries were discussed lively during the **“wrap-up and conclusions” sessions** on the last day and **lead to an iterative improvement of the template**. Following the TCP, further refinement of the statements were carried out between the operating agent and various task member and a revised task summary was provided to Paul Miles (ExCo) on July 24th 2018 following the TLM. These efforts serve to summarize concisely each task and provide vital information for later task and TCP assessment purposes to the EUWP. The template will be updated on an annual basis and serves as input also for TCP reporting purposes.

A **strategic planning workshop** took place from Feb. 11th – 15th 2018 **in Oréans**, France to discuss issues raised by IEA concerning the 2016 Request for Extension, following which the TCP was granted only two years to respond to IEA requests and address the concerns raised. The moderated workshop with participation from most task member countries from EU and USA elaborated a **new task vision, a clear mission statement and a list of objectives for the period up to 2024**. Subsequent input requested by the chairs and TCP agent was and a **consolidated Request for Extension** was provided to IEA. Mid-September, the TCP RfE was approved by the EUWP, followed by **final approval by CERT in April 2019, granting the TCP an extension over five years**.

The **40th Task Leader Meeting** was held **in Fréjus**, France in June 2018. Various changes to the programme were introduced compared to previous TLMs, in particular concerning the format of the task sessions: In lieu of former numerous 15 min presentation and Q&A, the task sessions could be freely organized in an attempt to promote more interaction between participants. While some tasks opted for short introductions to the contributed posters in lieu of conventional presentations followed by Q&A to deepen the opportunity for exchange, the Gas Engine Collaborative Task featured two invited talks from academia (Dr. Christos Frouzakis, ETH Zurich: “Direct numerical simulation of prechamber ignition”) and industry (Dr. Andreas Schmid, Winterthur Gas and Diesel, Switzerland). The choice of two comprehensive invited talks in the GECT session was targeted at initiating a discussion on how to bridge the gap between the predominantly fundamental work carried out in the combustion TCP and the industrial requirements for product development. This topic constitutes one of the key challenges of the TCP as a whole in view of visibility and impact of its achievements in the broader IEA context and goals.

A total of six posters and corresponding abstracts were further contributed to the **GECT poster session at the TLM**:

- Ahmed, Kaario & Larmi, Aalto University, Finland: ”An Optical Investigation of Dual Fuel Combustion”

- Masouleh, Keskinen, Kaario, Kahila & Vuorinen, Aalto University, Finland: “Effect of flow and thermal fields on cycle-to-cycle variation in spark ignited gas engine”
- Tsuru & Tajima, Kyushu University, Japan and Pirker, LEC GmbH, Graz, Austria: “Visualization of Combustion in Gas Engines with various micro pilot injection conditions”
- Srna, von Rotz & Bombach, Paul Scherrer Institute, Switzerland, Hermann, University of Applied Sciences FHNW, Switzerland, Boulouchos, ETH Switzerland and Bruneaux, IFPEN TE, France: “Advanced Optical Diagnostics for Dual-Fuel Gas-Engine Combustion Research”
- Lhuilier, Brequigny, Mounaïm-Rouselle, Université Orléans, France and Contino, Vrije University, Belgium: “Experimental stud on the performance and emissions of an ammonia/hydrogen fuelled spark-ignition engine”
- Hermann, University of Applied Sciences FHNW, Switzerland, Schneider & Boulouchos, ETH Switzerland: “Flex-OeCoS – Flexible Optical engine for Combustion or Sensing”

Considerable effort was further undertaken during the **break-out sessions at the TLM to elaborate the task template**. The main goal was to identify more clearly the TCP mission, the global context of the work undertaken towards highlighting the impact on **E**nergy use, **E**missions, **E**conomic growth and **E**nergy security (**4E**) and to finalize input for the Request for Extension in summer. Efforts were also dedicated at identifying an unanimously approved statement on **how to acknowledge IEA during dissemination of results**.

On June 18th 2018 the **second joint IEA and ERCOFTAC workshop on ”Gas engine combustion fundamentals”** was organized at ETH. A total of 63 participants attended the event from a total of nine countries: Austria (2), Finland (3), France, Germany (10), Italy (2), Switzerland (39) and the United Kingdom (4) plus two overseas participant from Korea and Canada; five of the participants present are actively involved in the Gas Engine collaborative task of the IEA combustion TCP. 45 participants were from Universities or national research institutions; the remaining 28 from industry: engine, turbocharger, ignition and fuel injection systems manufacturers, as well as consulting and software companies. ERCOFTAC funding was provided to four student participants from Germany; Finland and the United Kingdom (2) to cover their travel expenses. Following the successful establishment of the first workshop in 2016, this second workshop in 2018 was also considered a success, clearly motivating development of the workshop into a biennial series. The list of talks and scientific report provided to ERCOFTAC can be found in the appendix.

Participation to the **IEA DG-EN workshop on electrofuels** took place at IEA HQ in Brussels, September 10th, where the role of electrofuels in particular for long-haul freight and aviation was clearly advocated, while “direct use” of electricity for short-haul/light-duty passenger car was favoured by a majority of country representatives on the panel.

National cooperation and results dissemination

A number of research projects underway at various research institutions in Switzerland are listed below. Many of these have actively contributed to the Task Leader Meetings or the Gas Engine Combustion Fundamentals Workshops and thereby promoted wider dissemination of the results achieved beyond the project related journal and conference proceedings.

A **joint project involving the Swiss Innovation Promotion Agency CTI/KTI (17565.1 PFEN-IW) and Liebherr Machines Bulle concerning the development and optimization of pre-chamber combustion has been completed**. The project combined experimental diagnostics of production level as well as optically accessible pre-chambers in a high-pressure, high-temperature combustion vessel and the Rapid Compression Expansion Machine of LAV/ETH and multi-cylinder full metal engine measurements at LMB. The project also funded an external PhD candidate of LAV at LMB, who developed a simulation platform for lean burn natural gas combustion in heavy-duty engines [1-5]. **Dr. Guoqing Xu successfully defended his PhD thesis on September 24th 2018 titled “Combined**

numerical and experimental investigations on unscavenged prechambers for gas engines operated under lean-burn mode" [6]. The 3D-CRFD results have been successfully employed also for the development of phenomenological models [7] by a second PhD candidate (Mr. Konstantinos Bardis). Further dissemination of activities took place at the 4th IAV international Conference on Ignition Systems for Gasoline Engines, Berlin, Germany, Dec. 7/8th, 2018 [8] and the Dessau Gas engine workshop April 11/12th, 2019 [9].

More fundamental investigations with respect to prechamber simulation with Direct Numerical Simulation are ongoing in the **Swiss Federal Office of Energy project "DNS gas engine"** (grant no. SI/501301-01).

Generation of a dual fuel data-base by LAV/ETH together with project partners from PSI took place in the framework of the **Swiss Federal Office of Energy project "Dual Fuel combustion systems"** (grant no. SI/500970-01). This project co-funded activities in the **Swiss Competence Centre Energy and Mobility (CCEM) projects "ScheDual" [10]** and "**Flex-FI-dual" [11]** which were successfully concluded in 2017 and the FVV project "Diesel auf homogenem Grundgemisch" (for further details on the latter see 'International cooperation' below).

The **CCEM "RENERG" project**, where the Aerotheromchemistry and Combustion Systems Laboratory of ETH Zurich investigated the combustion of natural gas with hydrogen addition in Internal Combustion Engines was successfully concluded and the **final conference took place at EMPA on October 30th, 2017**. A joint paper with EMPA documenting activities to improve the optically accessible Rapid Compression Expansion Machine at ETH to reach engine relevant turbulence levels was presented at the SAE International Conference on Engines and Vehicles in Capri in September 2017 and selected for inclusion in the SAE International Journal of Engines [12]. Engine simulations have been performed in the framework of a PhD thesis for which several papers have been published [2, 13, 14] or are still under review. **Dr. Jann Koch successfully defended his PhD thesis entitled "Simulation of turbulent premixed combustion of hydrogen-methane admixtures in internal combustion engines" on Dec. 17th, 2018**.

International cooperation and results dissemination

A list of research projects underway at various international research institutions relevant to the gas engine collaborative task are given below. Results from many of these projects have been presented at the Task Leader Meetings or the Gas Engine Combustion Fundamentals Workshops and thereby promoted wide dissemination of the results achieved, beyond the project related journal and conference proceedings. A number of collaborations have resulted either directly through joint participation in the combustion TCP or indirectly as a consequence of Gas Engine Collaborative Task relevant interaction with the partner universities.

Projects:

EU H2020 project "GasON": participation of LAV in work package 5 "New non-DI CNG combustion process and on-board gas sensor-concept", close to completion. A total of three papers with ETH involvement were presented at the SAE world congress in Detroit, April 9-11th, 2019 [15-17]. Additional dissemination activities include the 16th Conference „The Working Process of the Internal Combustion Engine" in Graz, Austria, 2017 [3].

FVV project "Diesel auf homogenem Grundgemisch" studying ignition of lean premixed natural gas by means of micro-pilot fuel sprays has been successfully concluded and the **final report was presented at the FVV spring conference March 2019** [18]. A last paper concluding efforts within this project was presented at the SAE World Congress in Detroit, April 9-11th, 2019 [19].

FVV/CORNET Project "Otto wall heat transfer": Funding for a joint project between LAV, ETHZ and Technical University of Darmstadt was secured and the project started on Oct. 1st, 2017. **The**

project investigates flame-wall interaction and heat transfer in gas engines towards improved understanding of the fundamentals of near-wall phenomena. The project is co-funded by the Swiss Federal Office of Energy (grant no. SI/501615-01) and five Swiss and five German SMEs have further committed a letter of intent, highlighting the relevance of the work undertaken and to facilitate/ensure knowhow transfer from fundamentals to application.

A follow-up project proposal for the above **was submitted to FVV/CORNET and the Swiss Federal Office of Energy**: The study **seeks to investigate the universality of the findings** obtained in the current project at low engine speed and load **and extend the study to more engine relevant operating conditions**. If approved, the project will continue the good collaboration with TU Darmstadt, where optical data will be procured for validation of the LES platform. As for the ongoing study, this follow-up application is also supported by five letters of intent from Germany and Switzerland, indicating strong interest from the industrial R&D side.

Collaborations:

- Prof. Epaminondas Mastorakos, University of Cambridge, UK
    - Close collaboration on jet ignition combustion (pre-chamber ignition), resulting in a joint paper presented at the SAE International Conference on Engines and Vehicles in Capri 2017; the paper was later selected for inclusion in the SAE International Journal of Engines [20].
    - Development of a unified Conditional Moment Closure combustion code for single conditioning on I) mixture fraction and II) reaction progress and double conditioning on III) mixture fraction/reaction progress and IV) two mixture fractions.
- Prof. N. Swaminathan, University of Cambridge, UK
    - A joint paper was presented at the SAE International Conference on Engines and Vehicles in Capri 2017 [21], documenting model developments for premixed combustion in engines using validation data from the Swissauto 250cc engine and support for implementation in STAR-CD from Jann Koch and Yuri M. Wright to Cambridge.
- Prof. Ed Richardson, University of Southampton, UK
    - Sharing of experimental data for n-heptane micro pilot dual fuel combustion from [22], resulting in two joint publications: results were first presented at the European Combustion Meeting and later at the SAE Powertrain Fuels and Lubes (PFL) meeting, leading to a joint paper [23].
    - Sharing of experimental data from new measurement campaign for n-heptane and iso-octane.
    - Joint modelling efforts underway to compare Flamelet Generated Manifolds to doubly-conditioned Conditional Moment Closure methods for dual fuel combustion.
- Profs. Martti Larmi and Ville Vuorinen, Aalto University, Finland
    - Following the first engine combustion exchange workshop between Aalto University and LAV held on Dec. 14-15th, 2016 in Aalto, a second workshop with participation of five members from Aalto and six members from LAV on November 9-10th, 2017 was held at ETH Zurich (minutes available upon request).
    - A joint paper on wall heat transfer models has been published successfully in the International Journal of Heat and Fluid Flow [24].
    - A joint paper using the developed model applied to DNS data from ETH for the Imperial College experiment has been published in the International Journal of Heat and Mass Transfer [25].

  - A joint paper has published in Applied Energy [26] examining the effect of flow and thermal fields on cycle-to-cycle variation of combustion in a spark ignited simplified engine configuration using scale-resolving simulation methods.

- Prof. Andreas Dreizler and Dr. Benjamin Böhm, TU Darmstadt, Germany:
  - Participation to the 6th Darmstadt Engine Workshop by Dr. G. Giannakopoulos and J. Koch on October 6th, 2017.
  - Participation to the 7th Darmstadt Engine Workshop by Dr. G. Giannakopoulos with two contributions on October 19th, 2018.
  - An joint paper was accepted to the 5th conference on Large Eddy Simulations of IC engines [27] (LES4ICE) in Paris, 11th/12th December 2019, presenting experimental work carried out at TU Darmstadt in the optical engine and numerical results from LES and DNS carried out at LAV in the “DNS Gasmotor” SFOE project (grant no. SI/501615-01).

- Prof. Leipertz, University of Erlangen, Germany:
  - Dissemination of DNS activities pertaining to (gas) engines took place via an invited talk held at the Engine Combustion meeting in Ludwigsburg, March 16th/17th 2017, for which the proceedings were published in [28].

Conclusions and outlook

Gas engine combustion is a promising and important avenue to pursue in view of lowest-emission, high-efficiency use of fossil and bioderived gases in IC engines. In this project, the operating agent for the Gas Engine Collaborative Task has

a) Provided consolidated input for reporting purposes

b) Participated to strategy meetings and assisted in the development of mission statements and the elaboration of the – finally successful – request for extension

c) Compiled contributions from task members in the form of posters and talks for the annual Task Leader Meetings

Although not formally part of the contractual funding agreement, the following activities carried out within other projects also clearly contributed to the mission and targets of the combustion TCP of the IEA, namely

d) Organization of the biennial workshop on “Gas Engine Combustion fundamentals”, jointly held in the framework of IEA and ERCOFTAC

e) Fundraising, collaboration and reporting in the context of a variety of national and international joint projects (funded by FVV/CORNET, SFOE, CTI/KTI, EU)

f) Dissemination of results in leading journals and conferences

Based on the extension granted for the combustion TCP, a follow-up proposal will be submitted to the Swiss Federal Office of Energy for the period Feb. 2019 – Feb. 2021.

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Appendix

The scientific report to ERCOFTAC on the 2nd workshop on Gas Engine combustion fundamentals, held June 13th, 2018 at ETH Zurich is attached.