Yearly Report CCGEx

2019

Competence Center for Gas Exchange
Charging for the Future!

CCGEx at KTH Royal Institute of Technology

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Summary

The Competence Center for Gas Exchange (CCGEx) at KTH is a joint effort of the Departments of Machine Design (ITM School), Mechanics (SCI School), and Aeronautical and Vehicle Engineering (SCI School) at KTH, the Swedish Energy Agency (STEM) and the industrial partners. CCGEx was initiated officially 1st of January 2011 and entered during 2018 in its third period (2018-2021). The current document represents the 2019 yearly report.

The research within CCGEx is organized for the 2018-2021 period, under three research areas: the integrated COLD side (i-COLD), integrated HOTside (i-HOT), and integrated SYstem Studies (i-SYS). The i-SYS research area includes also active research with respect to engine aftertreatment. All CCGEx projects and research activities are organized within these three research areas. These are financed and supported by the Swedish Energy Agency, KTH, Scania, Volvo Car, Volvo GTT, and BorgWarner Turbo Systems. Noteworthy, during 2018 BorgWarner Turbo Systems (BWTS) Engineering GmbH, Kirchheimbolanden, Germany became a full partner for CCGEx. One must note that BWTS has been a collaborator of CCGEx since 2015. Moreover, during 2018, Wärtsilä joined also as collaborating partner committed to support and invest in the current and future research within CCGEx.

The purpose with the Center's activities is to build a deeper knowledge of the gas exchange processes and turbocharging, and thereby lay the foundation for a future, more efficient gas exchange system. The research efforts are directed towards making the power train system more efficient and environment-friendly thus to increase fuel efficiency without losing performance, to lower emissions of hazardous substances and to manage sound generation and attenuation in the engine gas handling system. The center has a key role in Sweden for educating expert engineers and scientists who are currently creating future technologies to enable sustainable transports.

The focus on three particular research areas has increased the possibility for a joint academy and industry view regarding the challenges which industry is currently facing, and what the designed projects within each area aim to answer and deliver. The area focus has also facilitated for the industry and academy to jointly identify and provide "in-kind" contributions, which take the projects forward and provide possibilities that go far beyond those that the academy itself possesses.

Concerning the academic results obtained during 2019 within CCGEx, one can mention that three (3) PhD students graduated with a PhD degree. CCGEx published 17 peer-reviewed publications in 2019, among which 5 journal articles. CCGEx students and faculty have been an important presence to international and national conferences, meetings, and symposia of relevance to automotive industry and related research.

A new CCGEx Postdoctoral student (Stefan Sack) was recruited and started during the month of January 2019 as part of the integrated cold-side research area (i-COLD). Thus, he was added to the five (5) PhD students already recruited during 2018. As an Associated Project with the Center, another post-doc (Shyang Maw Lim) joined in February 2019, project which is financed by Horizon 2020 as part of the EU consortium directed on Green-Vehicles initiative VISION-xEV.

The program essentially is fully funded, with a positive outlook regarding its future.

Background and Introduction

The Competence Center for Gas Exchange (CCGEx[1]), was initially initiated in 2006 as CICERO, being the third competence center in the field of internal combustion engine technology in Sweden. In 2013, the Swedish Energy Agency decided on a new financing period 2014–2017 for the competence centers under the Swedish Combustion Engine Consortium (SICEC[2]), related to internal combustion engine technology. For the Competence Center for Gas Exchange at KTH (CICERO 2006-2009, CCGEx 2010-2013), the 2018-2021 period meant that the Center entered its third financing round. The purpose of this document is to present a report on the activities within CCGEx for the year 2019.

Sweden has a strong and dynamic automotive industry, which continuously advances and develops its products so that is at the forefront among international competitors when it comes to environmental and energy related requirements. The current trend, with even stricter emission requirements (focused on e.g. minimizing CO_2 emissions, noise, particles), maximizing power-train efficiency, increasing the proportion of biofuels, hybridization and electrification - means that the Swedish automotive industry is facing big challenges, in the form of requirements for higher efficient power-train systems, tighter optimizations with reduced emissions, as well as a strong international competition.

The road to taking on these challenges is via a transition to a more knowledge and calculation-based way of working, less dependent on prototype testing and solutions based on trial and error. This calls for a strong need to identify, understand, and in an innovative way work with the underlying physical processes used in the systems and components required by future highly efficient powertrain concepts involving the internal combustion engine and different levels of hybridization / electrification.

CCGEx promotes research on advancing the gas exchange and turbocharging technologies, heat-transfer quantification for smart thermal-management solutions; thus, to enable knowledge-based and efficient design of next generation clean propulsion systems for vehicle applications. The companies part of the Swedish automotive industry have been early adopters of turbocharging technology and are exceptionally knowledgeable in this field from an international perspective. The significance of this field of research is increasing as the new internal combustion systems require high EGR-percentages and boost pressures. Moreover, turbocharging is a mature and key technology in the future modern hybrid power-train systems with variable valves' opening and closing times as well as cylinder deactivation/activation. One must note that such technologies, e.g. intake/exhaust valve systems with variable opening and closing times, as well as lifters, are becoming more and more prevalent. To remain competitive, it is important that the industry is continuously attracting valuable competences in the field. This includes expert knowledge as well as researchers with relevant skills.

Gas Exchange processes and *Turbocharging* research fields are specific to the Competence Center for Gas Exchange (CCGEx) and exclusive for KTH – not covered by any of the other competence centers within SICEC. Moreover, in 2018 after about 3 years of collaboration, BorgWarner Turbo Systems (BWTS) became a full partner for CCGEx, joining Scania, Volvo Car, and Volvo GTT.

[1] https://www.ccgex.kth.se/
[2] http://sicec.se/

The purpose of CCGEx is to perform academic research of highest quality in the field of Gas Exchange processes and Turbocharging with relevance to the modern power train systems used in the automotive industry. CCGEx has proved expertise on quantifying and understanding physical phenomena associated with gas exchange processes and turbocharging (turbulent flows, heat-transfer, thermodynamics, compressible flows, multiphase flows, acoustics, NVH) as well as on using and developing advanced methods and approaches for this purpose (high-fidelity simulations including LES and advanced data post-processing techniques; Dynamic System Simulations; Gas-dynamics & gas-stand experiments; Flow measurements & optical laser diagnostics; Predictive simulations & optimization for virtual design; Gas-stand testing & instrumentation). The research is carried out in close collaboration with the Swedish Automotive Industry (Volvo Car, Volvo GTT, Scania), BorgWarner Turbo Systems (BWTS), and Wärtsilä; thereby effectively contributing with transfer of knowledge and technology to an efficient, sustainable and competitive transport system based on efficient alternative fuels adapted to engine systems combined with electrification.

By making use of advanced methods for analyses, measurements and synthesis, the physical understanding of basic relevant phenomena is set to increase. With such built knowledge, CCGEx researchers can identify new technical possibilities and solutions in gas exchange, EGR systems, turbocharging and after treatment systems.

Long-term vision, mission and strategy

The vision[3] with CCGEx is to make possible the change from extensive physical testing to innovative virtual development using predictive simulation tools developed on physics-based understanding of phenomena.

Within CCGEx, *a multidisciplinary and integrated research is promoted*, which combines dedicated competences, expertise and facilities in *gas dynamics*, *acoustics*, and *engine technology*. It is based on extensive knowledge of fluid mechanics, turbocharging and combustion engine technology and includes both fundamental and applied experiments and simulations. The starting point for the formulation of research projects are challenges with the current propulsion systems for automotive applications.

The overall goal is to enable knowledge based and efficient design of next generation clean propulsion systems with focus on advanced gas exchange and turbocharging technologies.

Organization

The Center is a combined effort between KTH, the Swedish Energy Agency, the Swedish automotive companies (i.e. Scania CV, Volvo Car, and Volvo GTT), the turbocharging manufacturer BorgWarner Turbo Systems Engineering GmbH in Germany, and Wärtsilä in Finland.

The involved departments at KTH during 2019 are the Department of Machine Design (MFM, Internal Combustion Engines), Department of Mechanics (Mek, Computational and experimental fluid mechanics), and Department of Aeronautical and Vehicle Engineering (MWL, The Marcus Wallenberg Laboratory for Sound and Vibration Research). The complementary and consistent views within the

[3] https://www.ccgex.kth.se/aboutccgex/ccgex-vision-1.644867

organization as well as the set-up of the working environment promote cooperation across group boundaries and with industry.

The Center is organizationally placed at the Industrial Engineering and Management (ITM) School. The Board[4] of CCGEx is composed of representatives of all research groups involved in the Center. CCGEx is headed by a director and two deputy directors with the help of the Research Management group. Presently, the Research Management group (LG)[5] consists of director, deputy-directors, representatives of the CICERO and ICE Labs, student representative and young faculty and researchers actively involved the Center's activities.

The Research Management Team is advised by the Scientific Council (VR), formed of faculty at KTH (professors from the involved departments), and by the Industry Reference Group (specialized personnel from CCGEx's industry partners). Both the Scientific Council and the Industry Reference Group are acting as consultative bodies for the management team and will ensure the scientific level and relevance of the Centre's research areas and projects.

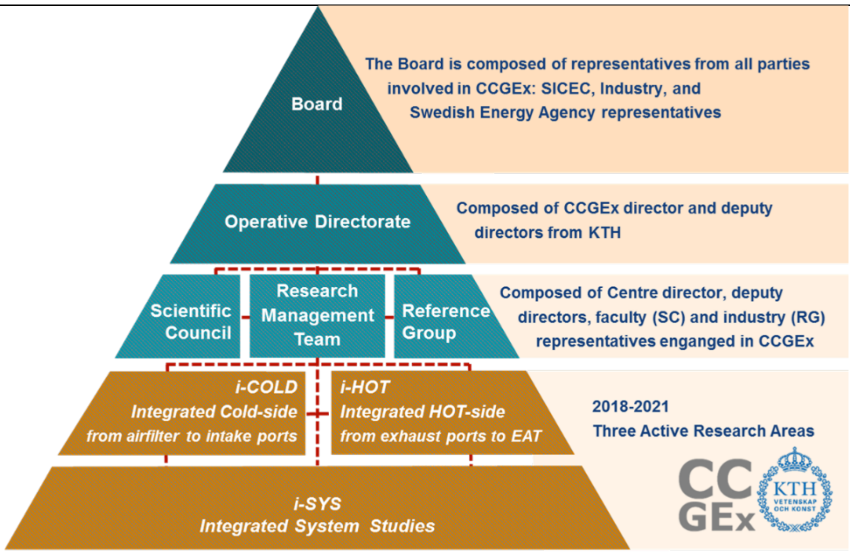

Figure 1: CCGEx Organization 2018-2021.

As shown in the diagram above (Fig. 1), there are three research areas active in the Center, namely: "Integrated Cold-side – iCOLD", "Integrated HOTside - iHOT", and "Integrated System Studies – iSYS".

Most of the research[6] within CCGEx is conducted by Doctoral students[7] (including two Industry PhD students, as for 2019) under faculty guidance and supervision and with support from the industrial partners. At the end of their studies these will earn a Licentiate and / or a Doctoral Degree. Post-doctoral students and Researchers were/are also involved in Center's research activities but in a smaller number (see also *Table 5*).

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[4] https://www.ccgex.kth.se/aboutccgex/organisation/board-1.266926
[5] https://www.ccgex.kth.se/aboutccgex/organisation/management-group-1.374280
[6] https://www.ccgex.kth.se/aboutccgex/research-ccgex
[7] https://www.ccgex.kth.se/aboutccgex/current-phd-students-and-postdocs-1.267893

The main advisors/supervisors for the conducted projects are Associate Professors and Professors part of LG and/or VR. The pursued projects within CCGEx are using the broad expertise available within the Center and therefore it is aimed that as many projects as possible will involve an assistant supervisor with a complementary profile other than that of the main supervisor. At the same time, it is important that within each research area, one can early and continuously seek the possibility of working together and involve industry partners, thus being able to utilize the expertise and resources of all the participants within the Center. There is a strong collaboration with the identified industry working groups (reference groups), which are linked to the three CCGEx active research areas and individual projects. These working groups have regular meetings (usually on-line meetings, approximately 6 weeks apart) to discuss the division of labor and project results, as well as new research and project ideas.

In addition to the research activities funded through CCGEx, during 2019 the Center was able to attract and foster several associated projects and complementary activities, funded from extramural funding (e.g. FFI, CSC, EU). Within Center's activities and functions during 2019, the following persons were engaged:

Table 1: CCGEx Board

Sören Udd	SICEC Ordförande
Sofia Ritzén	KTH
Daniel Söderberg	KTH
Jonas Holmborn	SCANIA CV
Eva Iverfeldt	SCANIA CV
Carolin Wang - Hansen	Volvo Car Corporation
Håkan Persson	Volvo Car Corporation
Johan Wallesten	VOLVO GTT (until 03/2019)
Angela Johnsson	VOLVO GTT
Johan Engström	VOLVO GTT (since 03/2019)
Anders Johansson	Swedish Energy Agency
Sofia Andersson	Swedish Energy Agency

Table 2: CCGEx Directorate

Director	Mihai Mihaescu / Mekanik (since 07/2019)
Director	Anders C. Erlandsson / MFM (until 06/2019)
Deputy Director	Mihai Mihaescu / Mekanik (until 06/2019)
Deputy Director	Anders C. Erlandsson / MFM (since 07/2019)
Deputy Director	Mats Åbom / MWL

Table 3: Management Group

Mihai Mihaescu	Mek, CCGEx Director
Anders Christiansen Erlandsson	MFM, CCGEx Deputy Director
Mats Åbom	MWL, CCGEx Deputy Director
Christophe Duwig	Mek (until 09/2019)
Lisa Prahl Wittberg	Mek (since 10/2019)
Mikael Karlsson	MWL
Emelie Trigell	Mek (PhD Stud. Representative, since 02/2019)
Shyang Maw Lim	Mek (PhD Stud. Representative, until 01/2019)

Christer Spiegelberg	MFM (until 06/2019)
Michael Liverts	Mek /CICERO Lab (since 11/2019)
Hanna Bernemyr	MFM (since 09/2019)

Table 4: CCGEx Scientific Council

Anders Christiansen Erlandsson	MFM
Mihai Mihaescu	Mek
Mats Åbom	MWL
Hans Boden	MWL
Andreas Cronhjort	MFM
Jens Fransson	Mek/CICERO Lab
Laszlo Fuchs	Mek

Table 5: The Research Team

Research Area "i-COLD"	
Mihai Mihaescu	Research Area PI
Mats Åbom	Co-investigator
Lisa Prahl Wittberg	Co-investigator
Asuka Gabriele Pietroniro	Ind. PhD Student, Volvo Car, Mek/MWL
Emelie Trigell	PhD Student, Mek
Stefan Sack	Post-doc, MWL
Research Area "i-HOT"	
Mihai Mihaescu	Research Area PI (until 12/2019)
Michael Liverts	Research Area PI (since 01/2020)
Jens Fransson	Co-investigator
Andreas Cronhjort	Co-investigator
Anders Dahlkild	Co-investigator
Shyang Maw Lim	Post-doc, *Assoc. project*, Mek, (VISION x-EV)
Marcus Winroth	PhD Student, Mek/CICERO Lab (until 08/2019)
Ted Holmberg	PhD Student, MFM
Nicholas Anton	Ind. PhD Student (Scania), MFM (until 07/2019)
Roberto Mosca	PhD Student, Mek
Yushi Murai	PhD Student, Mek/CICERO Lab
Research Area "i-SYS"	
Hanna Bernemyr	Research Area PI (since 09/2019)
Anders Christiansen Erlandsson	Research Area PI (until 08/2019)
Mikael Karlsson	Co-Investigator
Mats Åbom	Co-investigator
Lisa Prahl Wittberg	Co-investigator
Ghulam Mustafa Majal	PhD Stud., MWL/Mek
Zhe Zhang	PhD Stud., *Assoc. project*, MWL (until 07/2019)
Arun Prasath	PhD Stud., MFM
Senthil Mahendar	PhD Stud., MFM
Sandhya Thantla	PhD Stud., *Assoc. project*. WHR, MFM
Beichuan Hong	PhD Stud., MFM
Varun Venkataraman	PhD Stud., MFM
Jianhua Zhou	Post-doc, MWL, until 09/2019

Five new PhD students and one post-doctoral student joined CCGEx during the last six months of 2018. These added to the existent eleven PhD students within the Center (number that includes associated projects and Industrial PhD students). During 2019, two Industry PhD students were active within CCGEx, i.e. Asuka Gabriele Pietroniro with Volvo Car and respectively Nicholas Anton with SCANIA. Nicholas Anton successfully defended his PhD thesis on 16/05/2019 and he is continuing his career with SCANIA.

Measurable Outcomes

CCGEx deliverables and results are measurable through publications, participation in conferences, education and examinations of MSc and PhD students[8], as well as through the involvement of CCGEx faculty within the educational program (undergraduate an graduate). To this, it should be added the knowledge built within the Center, as well as the exchange of information, experience and resources among all partners involved in the Center's activities on both experimental and simulation campaigns. This includes transfer of information, knowledge, data, and resources towards industry partners as well as from CCGEx's industry partners (e.g. in form of in-kind contributions to CCGEx). The following tables (Tables 6 to 9) represent a summary of the most important measurable outcomes delivered by CCGEx during 2019. Three CCGEx doctoral students graduated with a PhD degree during 2019. A total of 17 peer-reviewed articles were published in 2019, among which 5 journal articles (i.e. Journal of Sound and Vibration, Journal of Fluid Mechanics, Int. Journal of Heat and Fluid Flow, Physics of Fluids, Journal of Engineering for Gas Turbines and Power) [9].

Table 6: Doctoral theses (2019)	**3**
Zhe Zhang (MWL, 2019)	*Optimal damping and slow sound in ducts.* Doctoral Thesis KTH Aeronautical and Vehicle Engineering, Stockholm, Sweden. http://www.diva-portal.org/smash/get/diva2:1315635/FULLTEXT01.pdf
Marcus Winroth (Mek/CICERO, 2019)	*Dynamics of Exhaust Valve Flows and Confined Bluff Body Vortex Shedding.* PhD thesis, KTH Mechanics, Stockholm, Sweden. http://www.diva-portal.org/smash/get/diva2:1305613/FULLTEXT01.pdf
Nicholas Anton (MFM/SCANIA, 2019)	*Engine Optimized Turbine Design.* PhD thesis, KTH Internal Combustion Engines, Stockholm, Sweden. http://www.diva-portal.org/smash/get/diva2:1302822/FULLTEXT01.pdf

Table 7: Summary on peer-review publications and conference attendance (2019) **https://www.ccgex.kth.se/publications/journal-conference-papers-1.368301**

Publication type	CCGEx - all papers -	MFM	MWL	Mek	Collaborations MFM/MWL/Mek	Collaborations with industry
Conference publications	12	7	5	0	(1)	(7)
Int. Journal publications	5	0	1	4	(0)	(0)

[8] https://www.ccgex.kth.se/publications/phd-1.265928
[9] https://www.ccgex.kth.se/publications/journal-conference-papers-1.368301

Total	17	7	6	4	(1) out of 17	(7) out of 17

Table 8: Attended conferences and presentations (2019)
- Energimyndighetens stora fordonskonferens, Energirelaterad fordonsforskning, Apr. 1-2, Göteborg. - WCX SAE World Congress, Apr. 21-23, Detroit. - 25th AIAA/CEAS Aeroacoustics, May 20-23, Delft. - InterNoise 2019, June 16-19 Madrid. - ICA Aachen, Sept. 9-13, 2019. - 5th International Symposium on ORC Power Systems, Sept. 9-11, 2019, Athens. - SAE Int. Powertrains, Fuels & Lubricants Meeting, Aug. 26-29, Kyoto. - 14th International Conference on Engines & Vehicles, Sept. 15-19, Capri. - 2019: 20th Annual conf. of Volvo Cars Ind PhD Program (VIPP), Oct. 24, Göteborg. - Acoustical Society of America (ASA) meeting, Dec. 2-6, San Diego.

Table 9: Other important Highlights (2019)
- CCGEx Research Days 2019: October 10-11, 2019, KTH Openlab, Stockholm, 50+ registered participants. - FSG3132 course "Gas Dynamics for ICE" (Nov. 7-8 & Nov. 28-29, 2019, KTH); Level: *doctoral level*, *third cycle course* (16 participants), Course Leader: Mihai Mihaescu.

CCGEx has been positively evaluated during the CCGEx Research Days (10-11 October 2019) by the Internationally Advisory Board (IAB).

The IAB considered the research effort carried out within CCGEx demonstrated "high scientific quality" and "high academic relevance". The research activities were considered "well aligned with the actual necessity to achieve target of interest for Industry". The IAB report emphasized also that there is a "balanced interaction of experiments and simulations", approach that "allowed to obtain significant results that contributed to the enhancement of scientific knowledge on several topics of interest related to the gas exchange processes in ICE."

Prof. Silvia Marelli, University of Genova, Italy
Prof. Martti Larmi, Aalto University, Finland
Internationally Advisory Board (IAB) Report, December 18th 2019

Overview on Research Activities

During 2019, CCGEx research efforts were focused on the three research areas "i-COLD", "i-HOT", and "i-SYS". Substantial efforts from both KTH and industry partners have been dedicated to consolidating and refine the research activities and tasks associated with the projects that started in the second part of 2018.

Research Area: Integrated COLD-side (i-COLD)

Summary: Use advanced experimental and computational techniques with the purpose of predicting and understanding compressor behavior at off-design operating conditions and mitigate the unwanted phenomena for increasing performance and reduce noise.

The project aims for a physics-based understanding of fluid driven instabilities developed with centrifugal compressor at off-design operating conditions with the purpose of controlling /

suppressing the unwanted phenomena. The high-fidelity computational and experimental data are used to develop new ways for predicting the unwanted instabilities and to develop more accurate theoretical predictive models. Among the targeted research directions with the individual projects are: characterize and understand compressor behavior at low mass flow rates and high pressure ratios by assessing the flow structures and the developed flow instabilities; characterize and understand the aerodynamically generated sound in centrifugal compressors; assessment of the impact of upstream and downstream perturbations on compressor performance; identify surge precursors and develop more sensitive methods for surge prediction; develop improved techniques for studying scattering and generation of sound in centrifugal compressors; development of a stability model of the flow in a vaneless diffuser; Assess the impact of casing treatment with a ported-shroud configuration or/and of a non-axisymmetric diffuser on compressor operability and performance.

i-COLD research highlights:

During 2019, experimental compressor noise measurements were initiated in the CICERO Lab (postdoctoral student Stefan Sack working on the project “Compressor Aeroacoustics - Experiments”). The postdoctoral student is analyzing the possibility to use AI-methods for duct acoustics to improve method accuracy. The problem is that for acoustic mode decomposition in ducts knowledge of the wavenumbers and modes shapes are assumed. This is normally based on a simplified assumption of the flow profile, i.e., a uniform plug flow. In practice this is not true which affects both the wavenumbers and mode shapes and thereby our mode decomposition and, e.g., the estimate we make of sound power. In order to create a better method, the idea is to use LNSE to train a neural network to detect acoustic modes. Since we can assume linear acoustics it is possible to create a large set of training data by superposition from essentially one up- and one down-stream test per mode. The first tests of this idea have been for the simplest case with only a propagating plane wave. The results have been presented at some conferences and a manuscript is under review in Journal of Sound and Vibration. The experimental efforts in the CIERO Lab will be complemented in 2020 with experimental measurements on the hot gas-stand at our industrial partners.

It is envisioned that during 2020 the measurements carried out will complement the high-fidelity simulations at off-design compressor operating conditions associated with the two on-going parallel projects i.e. one with focus on Aeroacoustics and noise emission (PhD student Asuka G. Pietroniro); and the second with focus on understanding the impact which upstream and downstream pressure perturbations may have on the developed flow instabilities under off-design operating conditions (PhD student Emelie Trigell). With respect to these simulation projects, it was found that Reynolds averaged Navier-Stockes (RANS) based calculations and associated data analysis are useful in locating noise sources and estimating the emitted acoustic power for a whole compressor map. A computational study targeting the verification of non-reflectiveness of boundary conditions has been completed. The conclusion has been that the solver utilised provides meshing strategies and models that allow for good quality propagation and reasonable low reflection. Thus, one can conduct reliable acoustic analyses with the current computational set-up.

A reasonably good agreement has been found out in terms of compressor performance parameters calculated with the steady-state RANS formulation and the gas-stand experimental data. Unsteady RANS calculations as well as Large Eddy Simulation (LES) calculations are currently on-going for design and off-design operating conditions with and without considering the effect of downstream pressure perturbations. These pressure perturbations are mimicking the pressure waves generated by the intake valves.

Research Area: Integrated HOT-side (i-HOT)

Summary: Holistic approach targeting to reduce/recover the losses in the exhaust system and increase engine's performance. It targets quantification and mitigation of aero- and thermal losses in the exhaust system and understanding the impact of pulsating flow conditions on turbine performance.

The exhaust flow of the gas exchange process is highly 3D, intermittent, and unsteady. It presents features (e.g. secondary flow patterns, flow reversals) that are difficult to analyze using standard tools and methods and therefore not yet fully understood. Significant loses are associated with the developed structures in the exhaust flow and assessing them in an accurate manner it is important. Moreover, turbocharger systems are used for recovering some of the energy of the exhaust gases and their performance is highly dependent on the upstream flow conditions (e.g. exhaust flow homogeneity, energy of the pulsating flow).

All the components in the exhaust system from the exhaust valves, exhaust ports, and turbine are so closely interlinked that they should be considered as one system from the gas exchange point of view. Moreover, any perturbations and changes in the exhaust flow upstream of turbocharger's turbine will change the overall performance of the turbocharger and thus engine performance (strong coupling with the cold - side).

The HOTSIDE project aims to improve understanding of the pulsatile exhaust flow and of its interaction with the radial turbine for a better usage of the exhaust flow energy available to be used (exergy). Both experimental and computational tools (1D & 3D, steady/unsteady) are used for characterizing the pulsatile behavior of the exhaust flow under different exhaust valve strategies. For the assessment of the turbine the approach considers different levels of integration and complexity with the upstream geometry and flow conditions.

i-HOT research highlights:

The experimental efforts within CICERO Lab in the first 6 months of 2019 were focused on assessing the exhaust port flow characteristics and the impact of the exhaust valve opening profile as well as other variables (e.g. engine speed, pressure ratio, radial valve position) on the discharge coefficient. The discharge coefficient has been shown to have a strong dependency on both valve opening speed and pressure ratio. The static measurements overestimate the value of the discharge coefficient, thus indicating that neither the quasi-steady nor the pressure-ratio insensitivity assumption holds. Performed shock-visualization experiments on the flow past the exhaust valve were carried out in the CICERO Lab, using Schlieren photography for different conditions and valve lifts. The flow visualizations indicate shock patterns are present in the exhaust port during the blowdown pulse and that the shock pattern is altered when using a static geometry (typically used during the gas-stand measurements). Marcus Winroth presented these findings as part of his PhD dissertation, successfully defended 05/2019.

As part of the Industry PhD program with Scania, a bespoke single stage axial turbine stage has been designed from "scratch" and developed into prototype hardware. The influence of axial turbine stage separation performance and efficiency have been assessed in relation to engine efficiency in engine simulations. Sector division performance of a bespoke axial turbine stage has been evaluated in relation to turbine performance and "on-engine" operation using CFD and engine simulations. The CFD and engine simulation results have been verified from engine testing carried out at Scania. Nicholas Anton, Ind. PhD student with Scania successfully defend his PhD thesis on 05/2019.

Turbine performance under adiabatic and diabatic conditions has been assessed for different flow scenarios (continuous and pulsating) using Detached Eddy Simulations-DES calculations. This work is carried out by Roberto Mosca and it is a continuation at a higher level of complexity of Shyang Maw Lim's work (PhD defended 12/2018). The boundary conditions and temperature data were provided by BorgWarner TS and Volvo Cars for engine operating points of interest. An exergy-based model was developed and applied on the DES data. For assessing the effectiveness of the available energy usage in the exhaust system. The effect of the exhaust pulse (e.g. its frequency, amplitude and gradient) on turbine performance and heat transfer is under assessment for different turbine configurations (e.g. single scroll, dual volute). As an example, it was found that a higher pulse amplitude improves turbine performance under pulsating flow conditions. Characterizing the impact of the above-mentioned parameters could help to improve radial turbine efficiency under optimal pulses (or exhaust valve strategies).

As part of the experimental campaign within the CICERO Lab, methods for quantifying with increased level of detail the pulsatile flows in hot exhaust gases are developed. Thus, cold-wire sensors were built for on-engine temperature pulse measurement. The initial experiments suggest that it has a potential to resolve the pulse with ceramic coating applied on the sensors. The experiments were carried out by Yushi Murai and Varun Venkataraman, CCGEx doctoral students that joined the center during this phase. This is another example of cooperation between the different research groups active within CCGEx. Currently, the impact of coating different size of sensors and considering different temperature conditions is under investigation in the shock tube facility and CICERO Lab.

Research Area: Integrated System Studies (i-SYS)

Summary: Increased understanding of the characteristics of gas exchange systems for effective, highly boosted, diluted (EGR) cold combustion with renewable fuels & near zero emissions. The research is aiming at facilitating the transfer to predictive model-based engineering by improved system understanding.

As such the area is relying on a 1-D capable frame work well known to industry, while focusing on developing great lower order models of aggregated detailed data obtained from high-resolved simulations or experiments to better describe reality. Within the area and the projects running, the following topics are treated:

- Combustion process & gas exchange system interactions.
- System efficiency – thermodynamic, mechanical, electrical
- Thermal integration & emissions reduction efficiency
- Component interactions
- Transients system dynamics & control
- New Concept assessment
- Exergy & energy analyses for ICE processes
- Exhaust pulsation flow analysis & modelling

i-SYS research highlights:

The project **"Heavy Duty DISI Gas Exchange Requirements with Renewable Fuels"** – Senthil Mahendar (Started August 2016). Spark Ignition (SI) finds limited application in Heavy Duty (HD) engines since these engines have lower power density and efficiency. Still, SI engines remain an attractive option for HD engines because they provide an inexpensive, low noise, and low emission solution in applications such as city buses and delivery trucks. The objective of this study is to increase the knowledge and establish the limits of utilizing alcohols in HD SI engines.

A literature review was published, which identified gaps and research questions for utilizing alcohol fuels in HD SI engines (SAE 2018-01-0907). Further a method was developed to improve turbulence resolution in 1D model and improve combustion speed calculation: its effect on knock and efficiency (SAE 2019-01-2302)

HD SI experiments with dilution and alcohol fuels (ethanol and methanol) is ongoing Q1 2020. Modelling combustion and knock in diluted conditions with alcohol fuels are planned for Q3 2020. Using these knock models and experimental limits, the objective is to derive gas exchange requirements for high efficiency HD SI engines – Q1 2021.

The project **''Low Temperature Waste Heat Recovery (WHR)''** Sanhya Tahntla started August 2016, investigates the suitability of volumetric expanders in the Organic Rankine Cycle WHR system of heavy-duty engines. Actual performance maps of volumetric expanders are obtained through semi-empirical models. System model (1D) simulated with real-time road data and the expander maps are used to evaluate the efficiency of the engine and WHR system. Scroll-type expanders have shown a promising potential in a study performed recently. Further investigation is to be carried out on a reciprocating piston expander using experimental data, followed by an analysis using a vane-type expander. It is planned to assess the impact of expander's design on the overall performance of the vehicle by investigating different system design approaches for WHR in HD Trucks with an ORC system

The **Exergy analysis for high efficiency ICE gases exchange system** – Ph.D. student Beichuan Hong (started in November 2018). The target for the project, cooperated between CCGEx and its industrial partners, is to enhance understanding of the ICEs exergetic flow and its impact on overall engine performances. Based on the exergy analyses, methodologies are developed for ICEs gas exchange system optimization with relevance to both marine and vehicle applications. Exergy refers to the maximum amount of work obtainable from a given resource of energy, which can be destroyed by the irreversible processes according to the second law of thermodynamics. The exergy-based methodology focuses on energetic quality in addition to quantity, while the irreversibilities inside system can be identified as the source of energy deficiency. Therefore, exergy analyses applied on Internal Combustion Engines (ICEs) provide an insight on the engine energy flow, and thus it can help us reduce irreversibilities and maximize the usage of exergy flow in ICEs system.

The study targets to characterize engine energy losses, model and optimize the utilization of energy flow, especially in relation to gas exchange system. The research questions to be answered: Q1: How to evaluate and quantify the irreversible processes among the ICE system? Q2: What is the mechanism behind energy losses, and how reduce the level of engine irreversibility. Q3: How to maximize the utilization of engine inner energy flow based on the answers of previous questions?

The strategy/methods are to apply: Thermal analysis on engine sub-system based on measurement or simulation data; 0D/1D model-based optimization to reduce engine irreversibilities by improving engine configurations or its operation strategies.

The goals: Understanding the mechanism behind engine power losses; Providing novel exergy-based methods to improve the engine energy utilization.

Exergy analysis were on two engine systems for quantifying the irreversibilities (i.e. useful energy losses) at each component. It was found that gas-exchange process produces around 14.6% loss of fuel energy in marine engine, and 5.3% loss in heavy-duty truck engine. Also, most of such loss is caused by turbochargers.

The project **Time Resolved Fast Measurements for Enthalpy, Exergy and Efficiency Calculations of the Air Handling System**- Ph.D. student Varun Venkataraman (started November 2018). The study focuses on understanding the on-engine instantaneous exhaust gas flow parameters (Temperature, T and mass flow, $\dot{m}$) using direct and indirect measurements (estimation)

The motivation is to bridge the gap in the lack of time-resolved flow measurements on-engine.

The methodology involves a combination of custom fabrication of sensors (resistance thermometers and thermocouples), 0D/1D simulations at the sensor and engine level along with experiments in a shock tube, high pressure flow rig and on-engine

The goal is to understand sensor requirements for on-engine measurements and highlight their applicability potential through experiments. Applications could include exhaust pulse (T/$\dot{m}$) characterization, analyzing the valve discharge process onengineand measurements on the turbocharger.

Preliminary on-engine tests (low-loads) were performed on custom fabricated resistance wire thermometers (RWTs) with 5, 10 and 25 µm wires as sensing elements. The survival of RWTs on-engine appear to increase with the application of a protective ceramic adhesive coating over the welded joints.

The project "**Particulate Characterization in the gas exchange system of DI/SI engines"** started in 2016 and PhD student is Arun Prasath. The study targets at understanding the evolution of particles in the exhaust system of a DI/SI engine by investigating the influence of the various devices. The project benefits from the experimental work carried out in the Internal Combustion Engine Laboratory and an experimental campaign on to evaluate the effect of individual after-treatment components on particle emissions is ongoing from Jan-March 2020.

A grouping pipe was designed fabricated and tested with thermal insulation to evaluate the grouping phenomenon with particles in the exhaust. A positioning system was designed and programmed for the movement of the particle sampling probe to sample along length in the centre line. Experiments on HD Scania diesel engine has been completed (Support of instruments from Scania from Jan-May 2018; March-April 2019; Jan-March 2020). The hydrodynamic grouping of particles was not observed in the grouping pipe was evaluated for non-volatile particles was not observed. The previous literature has reported grouping with volatile particles. The work has been published in SAE, Fuels and Lubricants Meeting 2019, San Antonio, Texas.

An experimental campaign to evaluate the effect of Turbocharger on particle emissions was completed in April 2019. Fragmentation of particles of non-volatile particles were observed at low temperatures. While oxidation of particles was noticed observed at high temperatures.

A collaborative paper on simulation of particle grouping is in progress with Ghulam and a paper on the effect of Turbocharger is in progress. An experimental campaign to evaluate the effect of (DOC+DPF+SCR) with different particle dilution systems is ongoing Jan-March 2020.

The project "**Waste Heat Recovery in Pulsating Flows - ThermoAcoustic Engine**" was initiated 2018 and ran until October 2019 with a post-doctoral student (Jianhua Zhou).. The projects investigate the applicability of thermoacoustic engines for automotive waste heat recovery. The system is modeled as low order acoustic network including non-linear losses. The network model facilitates system studies to evaluate the thermal efficiency over for example legislative driving cycles. But can also be rearranged to allow for more fundamental studies of the working principles. A comprehensive similarity study has been performed. Another area of interest is to quantify the non-linearities of the system. For this, experimental techniques are developed (e.g. experimental measurements for nonlinear effects in different acoustic components). Parts of the results were presented during the SAE world congress 2019 and two more publications are under review.

The Particle characterization and agglomeration project was part of the Exhaust AfterTreatment (EAT) research area that is now integrated in the I-Sys portfolio. Hence it has been running for a few years and has student that are near the end of their individual projects. The scope of the project is to further the understanding of transport of particles in the exhaust line and possible ways of manipulating them. The approach is both numerical and experimental and an integral part is to find the appropriate tools for studying the problem. Both the numerical and experimental work so far has been applied on a specific agglomeration concept. The concept has also been extended to include agglomeration stimulated by acoustics. There are three students involved: Ghulam Majal, Arun Prasath Karuppasamy, and Zhe Zhang (CSC - Associated project). Their individual project updates for 2019 are summarized below.

Ghulam Majal develops numerical techniques from 1D to high fidelity 3D to study the particle agglomeration. 2019 was initially spent on investigating and setting up the numerical framework. Once established a number of validation cases have been setup. First a benchmark case, then the prototype geometry for which experimental data are available.

The framework for using acoustic forcing to stimulate particle agglomeration has been put forward. It has been shown that the use of acoustic metamaterials (where one in this application change the speed of sound in the media) greatly improves the applicability of the technique. (see further description below in the associated project section.

On the experimental side, a particle agglomeration pipe was designed fabricated and tested to evaluate the particle grouping phenomenon in the exhaust. A positioning system was designed and programmed for the movement of the particle sampling probe. Sampling along the length in the centre line of the agglomeration pipe and an equivalent length straight pipe has been completed. Experiments were conducted on HD Scania diesel engine using a fixed geometry turbine. The hydrodynamic grouping of particles was not observed in the grouping pipe evaluated for non-volatile particles. The previous literature has reported grouping with volatile particles.

Associated projects with CCGEx

Project Title: Virtual Component and System Integration for Efficient Electrified Vehicle Development (VISION-xEV, 2018-2021)[10]

Project type: CCGEx Associated project (Horizon 2020-LC-GV-2018), PI: Mihai Mihaescu

Post-doctoral student: Shyang Maw Lim

"The project targets development and demonstration of a scalable modeling and simulation framework for seamless virtual component and system integration to support the efficient development of all kinds of future electrified/hybrid vehicle powertrain systems."

This project aims to enhance the understanding of heat transfer and thermal effects impact on the performance of the turbocharger under engine-like conditions. Detached Eddy Simulations (DES) of a turbocharger turbine under realistic pulsating conditions are complemented by detailed experiments at TU Berlin, providing data for verification and validation purposes. Together with PoliMi and TU Berlin, an improved more efficient and accurate reduced order predictive performance model of the turbine-engine system will be developed by KTH, which takes into account thermal and unsteadiness effects.

Project Title: Particle agglomeration with acoustic metamaterials and optimal sound damping in duct

Project type: CCGEx Associated PhD project (CSC=Chinese Science Council), PI: M. Åbom

PhD student: Zhe Zhang

Meta-materials are engineered materials with properties not found in nature. Typically, such materials are realized in the long wave length limit of a periodic system with local resonances. Such devices can be designed to create new types of efficient and compact silencers e.g. by reducing the sound speed. It has been shown that such slow sound devices could also be applied in connection with acoustic agglomeration.

The work of slow sound was finished and summarized by two papers included in the PhD thesis of Zhe Zhang. The main part of the thesis focused on optimal damping of sound in ducts, created by so called exceptional points which implies a merging of two modes. It can be shown that under such conditions the merged modes will be optimally damped. The merging of modes is controlled by the duct wall boundary condition or impedance. In the PhD thesis the values of this impedance also referred to as the Cremer impedance is investigated in detail and the validity of the resulting damped wave solution is examined. It is found that the optimum damping always can be created in the downstream direction, but in the upstream there is a low frequency limit beyond which the solution or mode merging fails. The practical importance of the results is that it allows for the design of very efficient dissipative types of silencers which can have a damping of hundreds of dB/m. The work on the optimal damping resulted in 4 papers that were included in the PhD thesis. The thesis was defended in June 2019.

[10] https://vision-xev.eu/

Further, an experimental analysis of the heavy-duty size agglomeration pipe investigated in a parallel project by Arun Prasath Karuppasamy has been carried out. Finally, development of the concept 'Cremer impedance' (a way of finding the optimum damping for a silencer) was achieved. Zhe Zhang successfully defended his Ph.D. thesis during June 2019.

Improvements during 2019

A *Gender Equality Plan* has been formulated in 2018 by the members in the *Management Group within CCGEx* with the purpose to promote gender equality and diversity within the Centre. The implementation of the Gender Equality Plan has been carried out during the year 2019. Female scientists with competences needed within CCGEx (e.g. after-treatment and particle measurements, multi-phase flows, rotating machinery, system studies) were identified, promoted, and recruited (Assoc. Prof. Lisa Prahl Wittberg and Dr. Hanna Bernemyr). After the implementation of the Gender Equality Plan the Gender balance within the CCGEx Management Group is 38% - 62%.

A *CCGEx Inspirational meeting* (May 15th, 2019), has been organized by CCGEx with the purpose *to promote gender equality and diversity* and to facilitate contact between our students and successful professionals from Industry. CCGEx students and MSc students at KTH were exposed to successful career stories presented by two female scientists (Dr. Olga Roditcheva and Dr. Mireia Altimira) working in the Swedish Industry (Volvo Car Co. and Ericsson AB, respectively).

The collaboration with our industrial partners led to seven (7) publications reported for 2019 period. For a complete list of publications the reader is directed towards CCGEx website: https://www.ccgex.kth.se/publications/journal-conference-papers-1.368301 .

A graduate course on *Gas Dynamics for Internal Combustion Engines (ICE): FSG3132 (5 ECTS, course leader: Mihai Mihaescu)* has been designed and hosted by KTH-Mechanics in November 2019 (16 participants). It emerged from the need to have within CCGEx a more comprehensive course in gas dynamics within the field of Internal Combustion Engines. The course has been developed using a previous VINNPRO course on "Compressor Flows", organized in 2013 (course leader: Mihai Mihaescu), also within the framework of CCGEx.

CCGEx faculty and doctoral students met on 19/11/2019 with the purpose to discuss the outcomes and follow-up on the Internationally Advisory Board preliminary report. A SWOT analysis has been made by the CCGEx doctoral students which has been discussed and analysed with the present faculty. Constructive discussions took place with respect to the possible ways of improving the CCGEx environment and the communication within CCGEx. Most of raised points in the SWOT analysis were clarified.

There is a CCGEx seminar series operational and all the CCGEx doctoral students have the possibility to present their work and report on their research progress a couple of times per semester.

Partners development

Interaction with Industry (Scania, Volvo Cars, Volvo GTT, BorgWarner Turbo Systems, Wärtsilä)

The CCGEx research areas benefits from a strong interaction with the industrial partners and collaborators. Reference groups from the industry partners are associated with each of the CCGEx research area. Thus, researchers, doctoral students, industry representatives (part of the reference groups) are interacting every 6-8 weeks with the purpose of presenting and discussing the latest updates on each of the specific research areas and to clarify the near- and far-future planned research activities.

The industry partners and collaborators have the possibility of joining these technical meetings on-line via telephone and web-based platforms. Thus, most of the meetings are on-line meetings. Nevertheless, face-to-face meetings are taking place as well (e.g. visits to our industry partners, CCGEX research days) and it is fair to say that the CCGEx members are meeting the industry reference groups at least twice a year.

Important contributions from our industrial partners during 2019 consisted in hardware (e.g. turbochargers, exhaust manifolds, gas-stand installations), CAD data, performance maps, experimental data. Such experimental data were used for verification and validation purposes as well as for imposing boundary conditions in the computational set-ups within CCGEx. Another important industry input (from e.g. Volvo Cars and Scania) has been to provide calibrated 0D/1D data with respect to various exhaust valve strategies of relevance to realistic operating conditions.

CCGEx faculty and students have access to several high-performance clusters for parallel computations including a Cray XC40 system with a theoretical peak performance of nearly 2 petaflops (http://www.pdc.kth.se/) all part of the Swedish National Infrastructure for Computing (SNIC). A variety of commercial solvers as well as developmental research "in-house" and advanced post-processing codes can be used.

Finances 2019

Since the new projects within CCGEx started in the second half of 2018, the planned Budget for 2018 has been underspent in 2018 and carried over to 2019. The spending during 2019 has been according to the plan.

During 2019, financing consisted in 10 MSEK/year in cash contributions from the Swedish Energy Agency. The in-kind contribution from KTH during 2019 have been of approximately 10.1 MSEK. This adds to the annual KTH cash contribution to CCGEx of 1 MSEK.

The commitments from the main industrial partners (Volvo Car, VOLVO Technology, SCANIA, BorgWarner Turbo Systems, and Wärtsilä) have been of approximately 10,4 MSEK (cash+ in-kind) for 2019. The industry in-kind contribution for 2019 has been of 6,735,990 SEK.

	IN-KIND							Kontant	**Totalt upparbetade**
	KTH	VCC	SCANIA	VOLVO	B WARNER	WÄRTSILÄ	Totalt IN-KIND	Upparbetat KTH	**kostnader 2019**
Lönekostnader	4,889,157	1,489,848	839,800	-	1,028,790	271,016	8,518,610	8,797,193	**17,315,804**
Köpta tjänster	-		-	-	-	657,404	657,404	345,011	**1,002,415**
Utrustning	855,000		-	300,000	52,500	-	1,207,500	115,852	**1,323,352**
Material	1,000		1,045,645	-	-	17,621	1,064,266	98,498	**1,162,764**
Laboratoriekostnad	2,685,000		-	866,700	113,820	-	3,665,520	-	**3,665,520**
Resor	-		9,287	22,000	10,500	7,986	49,773	389,274	**439,047**
Övriga kostnader	1,654,000		-	-	-	-	1,654,000	114,827	**1,768,827**
Indirekta kostnader	105,510		-	-	-	3,085	108,595	5,673,350	**5,781,945**
Summa	**10,189,667**	**1,489,848**	**1,894,732**	**1,188,700**	**1,205,610**	**957,110**	**16,925,667**	**15,534,007**	**32,459,674**

Appendix - Project descriptions/posters