Yearly Report CCGEx

2020

Competence Center for Gas Exchange
Charging for the Future!

CCGEx at KTH Royal Institute of Technology

Report prepared by Mihai Mihaescu with inputs from the Management Group

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Summary

The Competence Center for Gas Exchange (CCGEx) at KTH Royal Institute of Technology is a joint effort of the Departments of Machine Design (ITM School) and Engineering Mechanics (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 2020 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). All CCGEx projects and research activities are organized within these three research areas and are financed and supported by the Swedish Energy Agency, KTH, Scania, Volvo Car, Volvo GTT, BorgWarner Turbo Systems, and Wärtsilä. 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 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 2020 within CCGEx, one can mention that one PhD student graduated with a PhD degree. Three other CCGEx PhD students are planned to defend their PhD theses within 2021. During 2020 many conferences were canceled, postponed, or took place as virtual on-line events due to the Covid-19 pandemic. However, CCGEx published 14 peer-reviewed publications in 2020 (among which *4 journal articles*) with relevance to automotive industry and related research.

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 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 (ICE) technology. For CCGEx (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 2020.

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

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 powertrain 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 energy efficient powertrain 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 derived from 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 the components required by future highly efficient powertrain concepts involving ICE 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 ICE systems require high EGR-percentages and boost pressures. Turbocharging is a mature and key technology in the hybrid powertrain systems with variable valves' opening and closing times as well as cylinder deactivation/activation. Moreover, the requirements of air-charging systems with carbon neutral fuels (e.g., H2) are higher than for conventional ICEs. 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 partner for CCGEx.

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 powertrain 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, more sustainable, competitive and energy efficient transport system based on carbon-neutral 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 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 2020 are the Department of Machine Design (MFM, Internal Combustion Engines, ITM School) and the Department of Engineering Mechanics (Fluid Mechanics and Engineering Acoustics, incl. Marcus Wallenberg Laboratory for Sound and Vibration and the CICERO Lab, SCI School). Since January 2020, the Department of Mechanics, the Department of Aeronautical and Vehicle Engineering, and the Solid Mechanics Department at the School of Engineering Sciences (SCI), joined in one larger department called Engineering Mechanics (Teknisk Mekanik). The complementary and consistent views within the 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 of CCGEx is composed of representatives of all research groups involved in the Center (*Table 1*). CCGEx is headed by a director and two deputy directors with the help of the Research Management group. As shown in *Tables 2* and *3*, the Research Management group (LG) consists of director, deputy-directors, representatives of the CICERO and ICE Labs, one student representative, faculty and researchers actively involved in Center's activities. The Research Management Team is advised by the Scientific Council (see *Table 4*), formed of faculty at KTH (professors from the involved departments), and by the Industry Reference Group (specialized personnel from CCGEx's industry partners[3]). Both the Scientific Council and the Industry Reference Group are acting as consultative

[3] https://www.ccgex.kth.se/aboutccgex/organisation/reference-group-1.374281

bodies for the management team and ensure the scientific level and relevance of the Centre's research areas and projects.

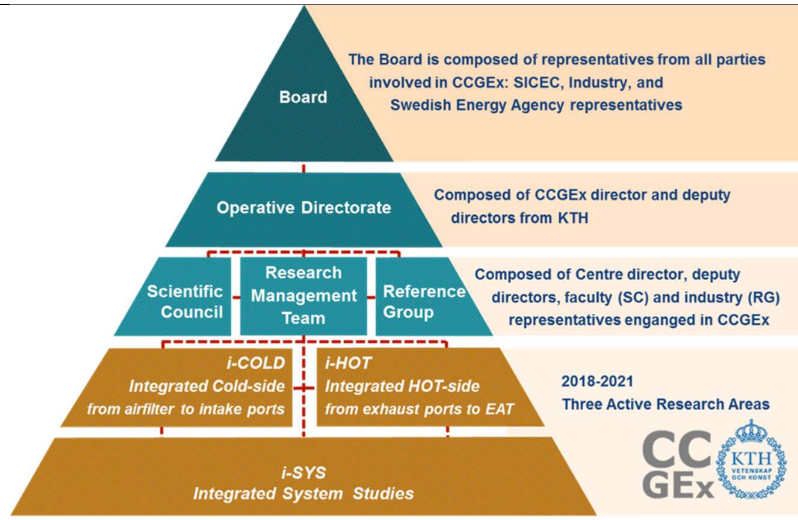

Figure 1: CCGEx Organization 2018-2021.

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[4] within CCGEx is conducted by Doctoral students[5] (including one Industry PhD student with Volvo Cars) 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*). The main advisors/supervisors for the conducted projects are faculty at KTH. 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[3]), 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 the Centre, the CCGEx researchers and faculty were able to attract additional extramural funding and foster several associated projects financed by Swedish Energy Agency FFI programme, EU Ho2020 Green Vehicle initiative, or EU H2020 Marie Skłodowska-Curie ITN programme.

[4] https://www.ccgex.kth.se/aboutccgex/research-ccgex
[5] https://www.ccgex.kth.se/aboutccgex/current-phd-students-and-postdocs-1.267893

Within CCGEx's activities and functions during 2020, the following persons were engaged:

Table 1: CCGEx Board (2020)

Sören Udd	SICEC Ordförande
Sofia Ritzén	KTH (until 12/2019)
Annika Borgenstam	KTH (since 01/2020)
Daniel Söderberg	KTH (until 10/2020)
Fredrik Lundell	KTH (since 10/2020)
Jonas Holmborn	SCANIA CV
Hua Lu Karlsson	SCANIA CV (since 01/2020)
Eva Iverfeldt	SCANIA CV (until 12/2019)
Catharina Tillmark	SCANIA CV (since 11/2020)
Carolin Wang - Hansen	Volvo Car Corporation
Håkan Persson	Volvo Car Corporation
Angela Johnsson	VOLVO GTT
Johan Engström	VOLVO GTT
Anders Johansson	Swedish Energy Agency
Sofia Andersson	Swedish Energy Agency
Tom Heuer	BorgWarner Turbo Systems (2019-2020)
Ewa Goch	BorgWarner Turbo Systems (2019-2020)

Table 2: CCGEx Directorate (2020)

Director	Mihai Mihaescu / Engineering Mechanics Mek
Deputy Director	Anders C. Erlandsson / MFM
Deputy Director	Mats Åbom / Engineering Mechanics MWL

Table 3: Management Group (2020)

Mihai Mihaescu	Mek, CCGEx Director
Anders Christiansen Erlandsson	MFM, CCGEx Deputy Director
Mats Åbom	MWL, CCGEx Deputy Director
Lisa Prahl Wittberg	Mek
Mikael Karlsson	MWL
Emelie Trigell	Mek (PhD Stud. Representative)
Michael Liverts	Mek /CICERO Lab
Hanna Bernemyr	MFM

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 (2020)

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 Jacob (b. Sack)	Post-doc, MWL
Research Area "i-HOT"	
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)
Ted Holmberg	PhD Student, MFM (until 01/2020)
Roberto Mosca	PhD Student, Mek
Yushi Murai	PhD Student, Mek/CICERO Lab
Varun Venkataraman	PhD Stud., MFM
Research Area "i-SYS"	
Hanna Bernemyr	Research Area PI
Mikael Karlsson	Co-Investigator
Mats Åbom	Co-investigator
Lisa Prahl Wittberg	Co-investigator
Ghulam Mustafa Majal	PhD Stud., MWL/Mek (until 10/2020)
Arun Prasath	PhD Stud., MFM
Senthil Mahendar	PhD Stud., MFM
Sandhya Thantla	PhD Stud., *Assoc. project*. WHR, MFM
Beichuan Hong	PhD Stud., MFM

During 2020, ten PhD students (including one Industry PhD student with Volvo Cars and one associated PhD project) as well as two postdoctoral students (including one associated project) were active within CCGEx. Based on a collaboration between CCGEx and CMT-Motores Térmicos at Universidad Politécnica of Valencia (UPV), Ferran Roig Villanueva carried out a three-months virtual internship with CCGEx between October-December 2020. Research topic: Advanced post-processing for Computational Fluid Dynamics and Computational Aeroacoustics; host at KTH: Mihai Mihaescu. Ferran Roig Villanueva is currently a PhD student affiliated with UPV (adviser: Prof. Alberto Broatch).

Measurable Outcomes

CCGEx deliverables and results are measurable through publications, participation in conferences, education and examinations of MSc and PhD students[6], as well as through the involvement of CCGEx faculty within educational programs (undergraduate and 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

[6] https://www.ccgex.kth.se/publications/phd-1.265928

campaigns. This includes transfer of information, knowledge, data, and resources towards industry partners and from CCGEx's industry partners (e.g., in form of in-kind contributions to CCGEx).

Tables 6 to 10 represent a summary of the most important measurable outcomes delivered by CCGEx during 2020. One CCGEx doctoral student graduated with a PhD degree during 2020 and two MSc theses were also generated. Three other CCGEx PhD students are planned to defend their doctoral theses within the first part of 2021. A total of 14 peer-reviewed articles were published in 2020, among which 4 journal articles[7].

Table 6: Doctoral theses (2020)	**1**
Ghulam Majal (Mek&MWL, 2020)	Flow dynamics in corrugated pipes: Effect on particle agglomeration. Doctoral Thesis, KTH, Engineering Mechanics, Stockholm, Sweden. http://kth.diva-portal.org/smash/get/diva2:1473573/FULLTEXT01.pdf

Table 7: MSc theses (2020)	**2**
Da Cao (MWL, 2020)	Modelling of the vibrational behavior of housing plates filled with fibrous material. KTH, School of Engineering Sciences (SCI), Engineering Mechanics, Marcus Wallenberg Laboratory MWL. http://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A1465506&dswid=-9699
Adam Sandström (Mek, 2020)	Simulating flow-noise for after-treatment systems. KTH, School of Engineering Sciences (SCI), Engineering Mechanics. http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1505481&dswid=-9699

Table 8: Summary on peer-review publications and conference attendance (2020) **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	10	7	1	2	(2)	(4)
Int. Journal publications	4	1	2	1	(0)	(0)
Total	14	8	3	3	(2) out of 14	(4) out of 14

Table 9: Attended conferences and presentations (2020)
Most of the conferences planned for 2020 were postponed or transformed as virtual events due to the Covid-19 pandemic. - AIAA SciTech meeting Orlando, FL, Jan 2020 - SAE WCX World Congress 2020 Online, April 2020 - SAE Powertrains, Fuels and Lubricants Digital Summit 2020 - CSM 2nd Conference on Sustainable Mobility - ASME 2020 Internal Combustion Engine Division Fall Technical Conference November 4–6, 2020 - Forum Acusticum, December 2020 Lyon, France (on-line) - Energimyndighetens konferens Energirelaterad transportforskning 2020 HT2020 (on-line)

[7] https://www.ccgex.kth.se/publications/journal-conference-papers-1.368301

Table 10: Other important Highlights (2020)
- CCGEx Research Days 2020: September 30th - October 1st, 2020, On-line Zoom & KTH Openlab, Stockholm, cca. 60 registered participants (most of them online: 2/3). - FSG3132 course "Gas Dynamics for ICE" (Nov. 2019 – Feb. 2020, KTH); Level: *doctoral level*, *third cycle course* (16 participants), Course Leader: Mihai Mihaescu. - Workshop on "Turbomachinery and supercritical CO2 cycles; theory and applications"

The 2020 research activities and achievements of CCGEx have been presented during the CCGEx Research Days 2020, event organized as a two-days symposium between September 30th to October 1st, 2020. With this occasion, the Internationally Advisory Board (IAB) of CCGEx (i.e., Professors Silvia Marelli and Martti Larmi) evaluated the Center's research and activities. Due to the Covid-19 pandemic the event has been arranged as a hybrid symposium (face-to-face and virtual meeting). In addition to the presentations given by the CCGEx doctoral students and postdocs, key-note lectures were given by Prof. Ricardo Martinez-Botas (Imperial College, London) and Dr. Peter Kelly Senecal (Convergent Science, USA). CCGEx has been positively evaluated by the Internationally Advisory Board. Below are a couple of paragraphs extracted from the IAB report 2020 dated Nov. 5th, 2020:

" The overall evaluation is **excellent** as demonstrated by the quality of the research presented in high number of scientific papers and also in conjunction with Industrial partners. The research activity developed is well aligned with the actual necessity to achieve targets of interest for Industry."

" IAB can conclude that the CCGEx works in an excellent manner. It would be most desirable that the competence center could keep the high momentum of academic and industrial contribution."

Prof. Silvia Marelli, University of Genova, Italy
Prof. Martti Larmi, Aalto University, Finland
Internationally Advisory Board - IAB - Report, November 5th, 2020

Overview on Research Activities

During 2020, CCGEx research efforts were focused on the three research areas "i-COLD", "i-HOT", and "i-SYS". The CCGEx personnel and projects employ the experimental gas-stand in the CICERO Laboratory at KTH-Engineering Mechanics, have access to the state-of-the-art measurement techniques available in Odqvist Laboratory at KTH (SCI School), and to the Engine Laboratory at Machine Design (ITM School). Moreover, 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.

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: to characterize and understand compressor behavior at low mass flow rates and high pressure ratios by assessing the flow structures and the developed flow instabilities; to characterize and understand the aerodynamically generated sound in centrifugal compressors; to assess the aerodynamically generated acoustic sources and propose methods for noise mitigation; to evaluate the impact of upstream and downstream perturbations on compressor performance; to identify surge precursors and develop more sensitive methods for surge prediction; to develop improved techniques for studying scattering and generation of sound in centrifugal compressors.

i-COLD research highlights:

The project ***On the Aerodynamically generated Sound in Compressors*** with Industrial PhD student Asuka Gabriele Pietroniro (Volvo Cars) started March 2017. On downsized engines equipped with turbochargers, the enhanced efficiency comes with an increase in noise production from the inlet side. As compared to the exhaust side, where the acoustic damping is an established practice and large volumes are available, the inlet side is confined under a car's bonnet; here, the limited volumes available for noise damping makes it crucial to tackle the issue of noise at its roots: generation and propagation. The industrial need linked with the project is to reduce the acoustic impact of Volvo cars on the environment and increase the comfort of both driver and passengers. Thus far, only relatively few Computational Fluid Dynamics / Computational Aeroacoustics (CFD/CAA) studies have been reported in the literature, most of them without quantifying the aeroacoustic sources of interest or quantifying the acoustic properties of the computational domain and solution's sensitivity to the boundary conditions. The current research targets a quantification of the aerodynamically generated sound and acoustic sources in centrifugal compressors for operating conditions of interest and correlating this information with the far-field noise. Noise suppression technologies at the source will be proposed and analyzed. The project has developed by starting with steady-state flow simulations, in which computationally inexpensive Reynolds averaged Navier—Stokes (RANS) analyses were used to localize the main acoustic sources and to estimate their contribution to the total acoustic power, and continuing with unsteady fluid flow simulations by Detached Eddy Simulations (DES), in which the acoustic capabilities of the computational setup were investigated and quantified and the meshes were optimized for the specific purpose of capturing the acoustic sources. Specifically, the computational setup was developed to yield reflection coefficients smaller than 1%, and low damping in space (characterized by values of the imaginary part of the propagating wave's wave number be low unity). This was tested for several combinations of computational parameters, e.g. including mesh type, cell size, cell size transition, cell stretch factor, time-step size. Also, the computational grids in the noise source regions were generated so that they would match the Large Eddy Simulation (LES) requirements. This was achieved scaling the mesh size to the estimated local Taylor microscale size. The results associated with this project were published in the proceedings of two conferences (SAE – ISNVH 2019, Forum Acusticum 2020). Two other publications are in the process of being completed, one targeting the SAE Noise and Vibration Conference 2021, and the second targeting the Computers and Fluids Journal.

A second computational research effort part of i-COLD research area is the project ***Turbocharger compressor response to installation effects and perturbations***, with Emelie Trigell as doctoral student. The project started August 2018. In the field of turbocharging, there is an increasing demand to understand the interaction between the gas exchange processes and the compressor system. Designing of an efficient centrifugal compressor with a broad operating range and improved noise signature implies also considering the challenges associated with the realistic boundary conditions, e.g., considering the pressure pulses associated with the motion of the valves. The objective of this project is to study the impact of inlet/outlet perturbations on the onset of compressor flow instabilities, noise, and system behavior at off-design operating conditions. A Direct Noise Computation method was developed, resolving the unsteady compressible fluid flow and acoustic wave propagation in the compressor system. This is done in collaboration with Ind. doctoral student Asuka Pietroniro (Volvo Cars). Turbulence is handled by using the Large Eddy Simulation (LES) approach. Reduced order modelling is used to understand the developed coherent flow structures and to correlate them to the acoustic waves in the ducts. Validation and verification studies have been performed to assess the uncertainty associated with the numerical simulations. Comparisons between LES, DES, and RANS approaches were carried out at design and off-design operating conditions. Measurements have been performed in the CICERO Lab at KTH by Dr. Stefan Jacob (b. Sack) where internal unsteady pressure data was collected at different positions around the compressor volute. Future development of the project will involve installation effects targeting their impact on inflow distortion and compressor stability.

The two computational projects exposed have an experimental counterpart, i.e., ***Advanced methods for the characterization of compressor noise from turbochargers***, involving the postdoctoral researcher Stefan Jacob (b. Sack). Turbocharger compressors are a key component for efficient combustion and fuel-cell technologies. Their noise signature, however, comprises strong broadband characteristics with distinct tones of high annoyance within the human audible range. This research aimed to examine and improve today's predictive models, by extracting the compressor's noise signatures from measurements or direct computational fluid-dynamic calculations. Quantifying the noise is a requirement when identifying noise mechanisms and developing quieter air-compressors. As key results one can summarize: i) we improved the existing turbocharger test bench in CCGEx's CICERO Lab installing new loudspeaker sources and adding probes to acquire internal, unsteady pressure along the compressor volute; ii) used the improved CICERO rig to generate a comprehensive acoustic database with acoustic data of three compressors at 35 operation conditions that can be used for validation purposes; ii) designed and built a new test rig to conduct basic research on non-linear effects; iii) tested a numerical method to capture non-linear acoustics in aeroacoustic simulations; iv) developed a novel aero-acoustic wave decomposition method that allows a more accurate extraction of acoustic signals from non-uniform, turbulent flows using machine learning[8]; v) disseminated a documented version of the developed codes free to use for other researchers and engineers[9]; vi) Presented the outcome of this work and findings at numerous conferences and workshops.

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

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[8] Sack, S., & Åbom, M. (2020). Acoustic plane-wave decomposition by means of multilayer perceptron neural networks. Journal of Sound and Vibration.

[9] Sack, S. (2020). acdecom—A Python module for acoustic wave decomposition in flow ducts, Software Impacts. (https://acdecom.readthedocs.io).

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 i-HOT 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 project ***Numerical Investigation of a Turbocharger Radial Turbine*** - PhD student Roberto Mosca - started July 2018. This work is a continuation - at a higher level of complexity - of Shyang Maw Lim's work (PhD defended 12/2018). With the increasingly more stringent emission regulations, the need for energy efficient powertrain systems is as high as ever in the automotive field. The new regulations aim to inspire the automotive companies in researching and developing new and more efficient technologies to fulfill the required standards. Among the possible solutions, air turbocharging has been demonstrated an effective and mature technology in reducing fuel consumption of powertrain systems using internal combustion engines. The research project targets the 3D numerical investigation of turbocharger turbines under engine-like conditions, both in terms of system performance and flow physics characterization. At first, a parametric study on the effects of the pulse characteristics on the hot-side system performance has been carried out. The study identified the pulse amplitude as the primary parameter driving the unsteady behavior of the turbine compared to the pulse frequency and temporal gradient. As conditions of low and high mass flow rate periodically alternate during the pulse cycle, the relative inflow angle spans a wide range of values and determines whether the separation occurs on the suction or pressure side. The outcome of this research has been published in Journal of Engineering for Gas Turbines and Power and accepted for publication at the ASME TURBO EXPO 2021. Moreover, a high-resolved LES approach has been used to investigate the characteristic flow structures developed inside the rotor under pulsating flow conditions (work accepted for publication and presentation at the ASME Fluids Engineering Division Summer Meeting, FEDSM 2021).

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 experiments were carried out by the doctoral students Yushi Murai and Varun Venkataraman. This is another example of cooperation between the different research groups active within CCGEx.

The experimental project ***Turbocharger turbine efficiency in steady and pulsating flow*** involves Yushi Murai as doctoral student and started in November 2018. Turbocharger's turbine harvests the energy from otherwise-wasted engine exhaust gas flow. Turbocharger's performance and efficiency are directly impacting the energy efficiency of the powertrain system. However, turbines (designed under steady-state conditions) are driven by highly pulsating flows; thus, maintaining a high performance across a wide operating range remains a challenge. In this project, the aim is to understand by means of experimental measurements how the turbine performance is altered by the pulsating flow conditions as compared to the steady, continuous flow conditions. Turbochargers impose challenging conditions for the flow sensors and expanding the measurement capability is an important element of the research. The main achievements to the date are: 1) Cold-wires have been chosen and shown to have the potential to perform time-resolved temperature measurements in the hot engine exhaust flow. 2) The Shock tube facility at KTH-Engineering Mechanics has been modified to assess and optimize the cold-wire sensor design for its dynamic response. The on-going efforts are directed towards: 3) Assessing LDV (Laser Doppler Velocimetry) to obtain improved time-resolved velocity measurements in turbine performance testing. 4) Improving the pulse generator for simulating engine-like pulse shapes in a controllable manner. 5) Completing the cold-wire study by presenting the results at SMSI 2021 and ETMM 13.

The project ***Time resolved flow measurement for engine applications*** - PhD student Varun Venkataraman - started November 2018. It combines experimental measurements with modeling capabilities. Initially considered under i-SYS research area, the project has been revised and became an i-HOT project since 06/2020. This is justified by the close collaboration and complementing research effort to the Turbocharger turbine efficiency in steady and pulsating inlet flow project (PhD student Yushi Murai). The study focuses on understanding the on-engine instantaneous exhaust gas flow parameters (temperature and mass flow) using direct and indirect (estimations) measurements. The motivation is to bridge the gap in the lack of time-resolved flow measurements on-engine beyond fast pressure measurements. The methodology involves a combination of custom fabrication of sensors (i.e., resistance wire thermometers and thermocouples), 0D/1D simulations at the sensor and engine level along with experiments in Shock Tube facility, the 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 but are not limited to exhaust pulse characterization on-engine, analyzing the valve discharge process on-engine and measurements on the turbocharger. A better understanding of these parameters could provide insights into the real flow condition in the exhaust along with flow and heat losses through the exhaust flow path that influence the performance of the turbocharger turbine and the aftertreatment system. The main achievements to date are: 1) Prototype cold-wires (i.e., resistance wire thermometers) with the application of a protective ceramic coating were shown to survive engine exhaust conditions at conservative loads up to 4 bar BMEP on a single pipe exhaust of a heavy duty Diesel engine (SMSI 2020 conference paper); 2) A heat transfer based sensor model has been developed in GT-Power (SMSI 2021 conference paper) for assessing sensor design sensitivities and flow sensitivities based on sensor location and engine type (LD/HD/marine). Ongoing activities to mention are: 3) testing static and dynamically calibrated cold-wires in a shock tube (ETMM 13 conference) on-engine at higher loads to establish application guidelines; 4) validate the sensor heat transfer model with shock tube/high pressure flow rig experiments to continue with model-based assessments; 5) test pitot tubes on-engine to establish its application potential for velocity/mass flow measurements.

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 knowledge.

As such the area is relying on a 1-D capable framework 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
- 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*** - PhD student 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 the research gaps and the research questions with respect to utilizing alcohol fuels in HD SI engines (SAE 2018-01-0907). Further, a method was developed to improve turbulence models thereby improving the combustion speed estimation and its impact on knock and efficiency (SAE 2019-01-2302). HD SI experiments with dilution and alcohol fuels (ethanol and methanol) was completed in Q2 2020. A gross IMEP of 25 bar was attained for both ethanol and methanol. A peak indicated efficiency above 48% was recorded for ethanol and methanol at λ=1.6 and gross IMEP of approximately 21 bar. The findings were published in the Journal of Engine Research. Modelling combustion and knock in diluted conditions with alcohol fuels was completed in Q3 2020. The modifications needed to utilize a semi-predictive combustion model in diluted operation were presented in SAE 2021-01-0386. Using the validated combustion and knock models, the gas exchange requirements for high efficiency HD SI engines was derived. The impact of turbulence reduction when using E-IVC Miller timing was investigated, with results to be published in the SAE Journal of Engines.

The project ***Low Temperature Waste Heat Recovery (WHR)*** with the doctoral student Sandhya Thantla started August 2016 (March to October, 2020: Maternity leave 100% & February to July, 2021: Maternity leave 50%). This is an Associated project with CCGEx, which investigates the suitability of volumetric expanders in the Organic Rankine Cycle WHR system of heavy-duty engines. Organic Rankine cycle (ORC) is one of the most effective systems for waste heat recovery (WHR) from heavy-duty (HD) long-haul truck engines due to its reliability and efficiency. This research work focuses on developing and assessing different ORC WHR system architectures and selection of expansion machines. The study began with the assessment of the suitability of volumetric expanders in a HD ORC WHR system. The analysis was performed as a simulation study using the 1D model (GT-SUITE) of Scania's 450 hp HD truck engine; the engine operating conditions were derived from a road-data. The truck was integrated with the ORC WHR system and the same was included in the 1D model. Engine exhaust gas was used as the heat source for WHR. Performance of three-types of volumetric expanders viz. open-drive scroll, hermetic scroll and axial piston were compared based on the efficiency of the complete (engine + WHR) system. Actual performance maps (including losses) of the two types of scroll expanders were integrated with the 1D model. It was observed that higher system efficiency (6.3%) was achieved with the open-drive scroll expander (size: 36.54 cm3; built-in volume ratio - bvr: 4.05), with R123 as the working fluid; corresponding fuel-saving predicted was 3.6% at 3400 rpm (expander speed). Overall performance of the system improved with modified and improved sizing of expander(s). The axial piston expander exhibited a consistent performance over a wide range of expander speeds and displayed a capability of reaching higher pressure ratios, with ethanol as the working fluid. The results were published in the SAE conference proceedings in 2019 (https://doi.org/10.4271/2019-01-2266). Further, the engine coolant, a low temperature (LT) heat source, was included in the ORC circuit besides the engine exhaust. Effect of elevated engine coolant temperature(s) on the WHR system was investigated using a dual-loop ORC circuit model. Performance of the system was assessed based on the expander used in the corresponding system architecture(s); R1233zDE was used as the ORC working fluid. When the two heat sources were used for WHR simultaneously, around 5.7% and 5.5% fuel-savings were predicted with the open-drive scroll and the hermetic scroll expander, respectively. Optimum engine coolant temperatures for higher fuel-savings were predicted to be 150°C (open-drive scroll) and 130°C (hermetic scroll). Results were presented/published in orc2019.com. The investigation was continued with the dual-loop ORC WHR circuit using suitably-sized scroll expanders. The characteristics of the chosen system architecture and expanders were analyzed at different steady-state engine operating points and at an elevated engine coolant temperature; benefits of varying the expander speeds while the vehicle is in operation, were also assessed. At higher engine loads, the overall net power output from the system increased; However, the overall system efficiency decreased due to significant increase in cooling demand from the engine part. Increase in engine coolant temperature from 120°C to 140°C, considerably improved the net power output at all the engine operating points but at the lowest point, as a result of significant heat losses from the engine block to its surroundings. Varying the expander speeds showed an improvement of only 0.04 kW in the net power output, against having fixed expander speeds. Results are yet to be published. As an upcoming activity, semi-empirical model of a vane expander is to be developed and utilized for further simulation studies on the system. PhD will be finished by summer 2022.

The project ***Thermal analysis for high efficiency ICE gases exchange system*** - Ph.D. student Beichuan Hong - started in November 2018. The target for the project is to enhance understanding of the ICE's exergetic flow and its impact on overall engine performances. Exergy analyses, based on Second Law of Thermodynamics, can provide an insight on how to reduce irreversibilities and maximize the usage of available flow energy in ICEs gas-exchange systems. Exergy analyses were separately conducted on two engine systems (a Scania truck engine and a Wärtsilä marine engine) to quantify the available energy losses of different components associated with the gas-exchange process. The results of the truck engine were reported as an inner report at Q3 2019, and the analysis of marine engine was published at Q3 2020 (ICEF 2020-2956). Further, a sensitivity-analysis-based method was applied to identify the significance of different flow parameters on the assessment of exhaust pulsation energy (Q2 2020). This study shows that the effects of instantaneous flow velocity are not negligible. Therefore, a Pitot-tube-based technique (Q3 2020) was employed to measure the velocity of exhaust pulsating flow. The design and manufacture steps were finished at Q4 2020, while the calibration of Pitot tube response is still ongoing for Q1 2021. On-engine tests for measuring flow energy and exergy of exhaust pulsation are planned for 2021/2022.

The ***Particle characterization and agglomeration*** program was part of the Exhaust After Treatment (EAT) research area that is now integrated in the i-SYS portfolio. Three doctoral students were involved: Ghulam Majal, Arun Prasath Karuppasamy, and Zhe Zhang (CSC - Associated project). The scope is to enhance understanding with the transport of particles in the exhaust line and identify methods to agglomerate 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. Numerical methods e.g., 0D/1D modeling as well as 3D CFD simulations were developed and applied by Ghulam Majal to study particle agglomeration under simulated continuous and pulsating flow conditions. Ghulam Majal successfully defended his PhD thesis with ten title “Flow dynamics in corrugated pipes: Effect on particle agglomeration” on 23/10/2020. The concept has also been extended to include agglomeration stimulated by acoustics. Thus, 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. Zhe Zhang successfully defended his Ph.D. thesis during June 2019.

The project ***Particulate Characterization in the gas exchange system of DI/SI engines*** started in 2016 and PhD student is Arun Prasath Karuppasamy. The study targets at understanding the evolution of particles in the exhaust system of a DI/SI engine by experimentally investigating the influence of the various exhaust devices. The project benefits from the experimental work carried out in the Internal Combustion Engine Laboratory at KTH. Three experimental campaigns on the HD Scania diesel engine have been completed (from Jan-May 2018; March-April 2019; Jan-March 2020), with support from Scania in terms of instruments and sensors. First, an experimental campaign to evaluate the grouping phenomenon was performed. A grouping pipe was designed, fabricated, and tested 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 the length of the pipe. In the experimental grouping pipe, periodic grouping of particles (non-volatile) was NOT observed, while the previous literature has reported grouping. The work has been published in SAE International Powertrains, Fuels and Lubricants Meeting 2019, San Antonio, Texas (2019-01-0044). Next, an experimental campaign to evaluate the effect of Turbocharger on particle emissions was completed. Particle number (PN) and size distribution measurements were performed across the turbocharger. In the turbocharger, a fragmentation of larger particles was observed at low temperatures (300°C) and oxidation of particles was noticed at higher temperatures (400°C). The work has been presented to the SAE Conference on Sustainable Mobility 2020, Catania, Italy (2020-24-0007). The paper is accepted for publication in the SAE International Journal of Advances and Current Practices in Mobility. Further, an experimental campaign to evaluate the effect of selective catalytic reduction unit (SCR) with different particle dilution systems was performed. PN and size distribution measurements were performed across the SCR. Across the SCR, an increase in particle number at high NOx operating points was observed and the increase was higher with higher urea injection. The work has been accepted for publication in the Proceedings of SAE International Powertrains, Fuels and Lubricants Meeting 2020, Krakow, Poland (2020-01-2196). Another experimental campaign has been considered to compare two dilution systems and measure non-volatile and volatile particles along the exhaust after-treatment (DOC+DPF+SCR). PN and size distribution measurements were performed across the individual exhaust devices. By measurements, a comparison between a 2-stage ejector diluter system with hot air dilution and a Particle Measurement Program (PMP) compliant rotating disk diluter system with evaporation tube was made. It was found out that evaporation of particles happens with the rotating disk diluter system as the system has an externally powered evaporation tube to remove volatiles, whereas the ejector diluter system with hot dilution relies on the heat capacity of the dilution air. The work has been accepted for publication in the proceedings of SAE World Congress WCX 21, Detroit, USA (2021-01-0619). A collaborative paper on the experiments with Tara Larsson on the "Undiluted Measurement of sub 10 nm Non-volatile and Volatile Particle Emissions from a DISI Engine fuelled with Gasoline and Ethanol" has been completed. The work has been accepted for publication (SAE World Congress WCX 21, Detroit, USA, 2021-01-0629). Arun Prasath is planning to defend his PhD thesis on 28/05/2021.

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 has been developed, which considers thermal and unsteadiness effects. The half-term report and the research associated with the VISION-xEV project has been positively evaluated by the European Commission (July 2020).

Improvements during 2020

The CCGEx seminar series continue during 2020 and all the CCGEx doctoral students have the possibility to present their work and report on research progress a couple of times per semester.

In addition to the research activities funded through CCGEx, the researchers and faculty active in the Center were able during 2020 to attract funding and foster several associated projects:

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

- Swedish Energy Agency FFI programme: two started PhD projects at Machine Design running 2021-2024 (Hanna Bernemyr leading KTH research activities).): "ASKA2 Framtidens partikelfilter för nästa generations biobränslen" and "DIB 3 Injektorbeläggningar av biobränslen"
- Swedish Energy Agency FFI programme, 2021-2024: "eFan Noise" PhD project with Chalmers, KTH-MWL and Volvo GTT+Cars, (co-PIs: Mikael Karlsson & Mats Åbom)
- *INSPIRE* project: aimed at studying Pressure Gain Combustion solutions for the efficient use of carbon neutral fuels such as Hydrogen. https://inspire.cerfacs.fr/en/ 2021-2024: *EU H2020 Marie Skłodowska-Curie ITN Grant*. Mihai Mihaescu (leading KTH research activities) Partners: ENSMA, CERFACS, SAFRAN, UNI Firenze, UNI Genova, Poli Torino, TU Berlin, and KTH. Coordinator: Univ. Firenze (Coordinator).
- *VISION-xEV:* Virtual Component and System Integration for Efficient Electrified Vehicle Development, https://vision-xev.eu/ 2019-2022: EU Grant, Coordinator: AVL, (Mihai Mihaescu leading KTH research activities). 14 partners from 9 EU countries. Scope: Largely improve overall energy efficiency of future powertrain systems & emission legislation compliance with respect to EU CO_2 fleet emission target for 2025.

Partners development

The CCGEx research areas benefit from a strong interaction with the industrial partners and collaborators (Scania, Volvo Cars, Volvo GTT, BorgWarner Turbo Systems, Wärtsilä). Due to the Covid-19 pandemic all the meetings with our industrial partners after March 1st, 2020 were on-line.

Reference groups from the industry partners are associated with each of the three CCGEx research areas. 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. All the "reference groups" technical meetings were hosted on-line during 2020.

As usual, important contributions from our industrial partners during 2020 consisted in hardware (e.g. turbochargers, exhaust manifolds, gas-stand installations), CAD data, performance maps, experimental data. Another important industry input has been to provide calibrated 0D/1D data with respect to various exhaust valve strategies of relevance to realistic operating conditions.

One must note that the Covid-19 situation affected our industrial partners. The pace of work for the industrial PhD project associated with VCC has been reduced from 100% to 60% during 3 months from April to June 2020 due to partial layoff throughout employing company (Covid-19 pandemic related situation). Moreover, the experimental campaigns planned during 2020 at Wärtsilä facility in Finland (with participation of CCGEx students) have been postponed to 2021.

Finances 2020

The total costs of CCGEx for 2018-2020 are cca. 86 mSEK, which is below the planed 90 mSEK for 2018-2020. 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 the next years. The spending during 2020 has been according to the plan.

During 2020, financing consisted in 10 mSEK/year in cash contributions from the Swedish Energy Agency. For 2020 the in-kind contributions from KTH have been of about 11.4 mSEK as planned. This adds to the annual KTH cash contribution to CCGEx of 1 mSEK.

The 2020 commitments from the main industrial partners (Volvo Car, VOLVO Technology, SCANIA, BorgWarner Turbo Systems, and Wärtsilä) to CCGEx have been of approximately 7,87 mSEK (cash+ in-kind). The reason is that the experimental campaigns at Wärtsilä have been postponed from 2020 to 2021. Moreover, the pace of work for the industrial PhD project associated with VCC has been reduced from 100% to 60% during 3 months from April to June 2020 due to partial layoff throughout employing company (Covid-19 pandemic related situation). The in-kind contributions are summarized in the table below.

Important to mention is that 5 (five) CCGEx Projects started later than January 1st, 2018 (6 to 10 months later). The reason has been that the contract has been signed by all partners later than anticipated, which delayed the recruiting process. These projects will continue during 2022, since the regular PhD program at KTH is for 4 years. Thus, CCGEx will ask the Swedish Energy Agency for an extension of the 5 projects below beyond 2021 (until November 2022).

- *Turbocharger compressor response to installation effects and perturbations*, PhD student: Emelie Trigell (started 20.08.2018)
- *Numerical Investigation of a Turbocharger Radial Turbine*, PhD student: Roberto Mosca (started 16.06.2018)
- *Turbocharger turbine efficiency in steady and pulsating flow*, PhD student: Yushi Murai (started 05.11.2018)
- *Time resolved flow measurement for engine applications*, PhD student: Varun Venkataraman (started 01.11.2018)
- *Thermal analysis for high efficiency ICE gases exchange system*, PhD student Beichuan Hong (started 01.11.2018)

	IN-KIND							Kontakt	Totalt upparbetade
	KTH	V Car	SCANIA	VOLVO	B WARNER	WÄRTSILÄ	Totalt IN-KIND	Upparbetat KTH	kostnader 2020
Lönekostnader	6,570,538	1,319,400	967,045	-	792,540	471,380	10,120,903	6,305,362	**16,426,265**
Köpta tjänster	-	-	-	-	-	-	-	407,297	**407,297**
Utrustning	860,000	-	4,040	247,000	-	-	1,111,040	216,866	**1,327,906**
Material	-	-	21,388	-	36,720	-	58,108	106,128	**164,236**
Laboratoriekostnad	1,960,000	-	-	450,000	-	-	2,410,000	-	**2,410,000**
Resor	-	-	-	-	-	-	-	97,192	**97,192**
Övriga kostnader	1,833,723	-	-	-	-	-	1,833,723	35,709	**1,869,432**
Indirekta kostnader	242,255	-	-	-	-	-	242,255	4,280,458	**4,522,713**
Summa	**11,466,516**	**1,319,400**	**992,473**	**697,000**	**829,260**	**471,380**	**15,776,029**	**11,449,011**	**27,225,040**
Budget 2020							**16,000,000**	**11,955,000**	**27,955,000**

Appendix – PhD Project descriptions/posters