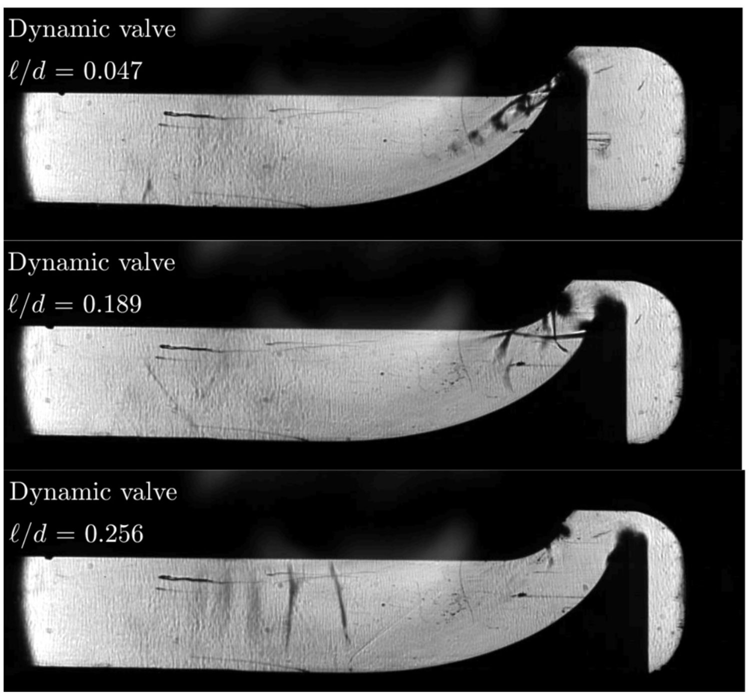
Final Report
CCGEx 2018-2022

Competence Center for Gas Exchange at KTH Royal Institute of Technology



Gas dynamics in the exhaust port: Schlieren imaging data presented for different valve lifts. Winroth, P.W. and Alfredsson, P.H. (2019), "On shock structures in dynamic exhaust valve flows." Physics of Fluids 31 (2): 026107. KTH, Department of Engineering Mechanics, Competence Center for Gas Exchange - CCGEx, https://doi.org/10.1063/1.5084174

CCGEx at KTH Royal Institute of Technology

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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 Engineering Mechanics (School of Engineering Sciences - SCI School) and Machine Design (Industrial Engineering and Management - ITM School) at KTH, the Swedish Energy Agency (STEM) and industrial partners from Sweden, Finland, Germany, and from USA. Initiated as CICERO center in 2006, CCGEx officially started on the 1st of January 2011. It entered during 2018 in its third financing phase (2018-2021). Due to delays linked to Covid-19 pandemic, the Swedish Energy Agency (STEM) concluded that the current competence centra can be extended by 6 months. A formal decision letter with *extension of CCGEx until June 30, 2022,* has been received and approved by KTH.

The research within CCGEx is organized 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 and the industrial partners. The industrial partners for CCGEx (2018-2022) are: Scania, Volvo Cars, Aurobay, Volvo Technology, BorgWarner Turbo Systems, Wärtsilä, and Convergent Science (since January 2021). 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 focus on three research areas has facilitated for the industry and academy to jointly identify the challenges to tackle and formulate research questions. The "in-kind" contributions from industry enabled advancing the projects and provided possibilities that go far beyond those that the academy itself possesses.

Concerning the academic results obtained during 2018-2022 within CCGEx, one can mention that 8 (eight) PhD students graduated with a PhD degree. 5 (five) other CCGEx PhD students, including here one Industry PhD student with Volvo Cars, are planned to defend their PhD theses within VT2023. 6 MSc theses (x-jobb) were related to CCGEx activities during this time.

CCGEx published 72 peer-reviewed contributions between 01/2018 to 09/2022, among which 25 journal articles. Throughout this time, CCGEx has been an important presence at international and national conferences, meetings, and symposia of relevance to automotive industry and related research. One shall mention that during 2020 and 2021 many conferences were canceled, postponed, or took place as virtual on-line events due to the Covid-19 pandemic.

CCGEx had a key role in Sweden for educating expert engineers and scientists who are currently creating future technologies to enable sustainable transports. Remarkably, since its initiation, ***30 PhD students involved in the Competence Center for Gas Exchange graduated with Doctoral Degree****. Based on the statistics, approximately 80% of the educated researchers within the CCGEx are remaining in Sweden, with more than 70% of them continuing their careers in the Swedish Industry (including consulting business).*

Background and Introduction

The Competence Center for Gas Exchange (CCGEx[1]) followed to the reorganization of the CICERO center, founded in 2006, as the third competence center in the field of Internal Combustion Engine technology in Sweden with focus on gas exchange and turbocharging. In 2017, the Swedish Energy Agency decided on a new financing phase 2018–2021 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 & 2014-2017), the 2018-2021 phase (*prolonged by the Swedish Energy Agency due to Covid-19 pandemic until 2022.06.30*) meant that the Center entered its third financing round. The purpose of this document is to present the final report on the research activities within CCGEx for its third financing round 2018-2022.

Sweden has a strong and dynamic automotive industry, which continuously advances and develops its products so that it 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 *carbon neutral and carbon-free fuels*, 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 increased as efficient ICE systems require high EGR-percentages and boost pressures. *Turbocharging is a key technology* in powertrain systems with variable valves' opening and closing times as well as cylinder deactivation/activation. Moreover, the requirements of air-charging systems with carbon-free (e.g., H2) are higher than for conventional ICEs. One must note also that technologies like 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

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

within SICEC (CERC at Chalmers and KCFP at Lund University, LTH). Notably, in 2018 after about 3 years of collaboration, BorgWarner Turbo Systems (BWTS) became partner for CCGEx.

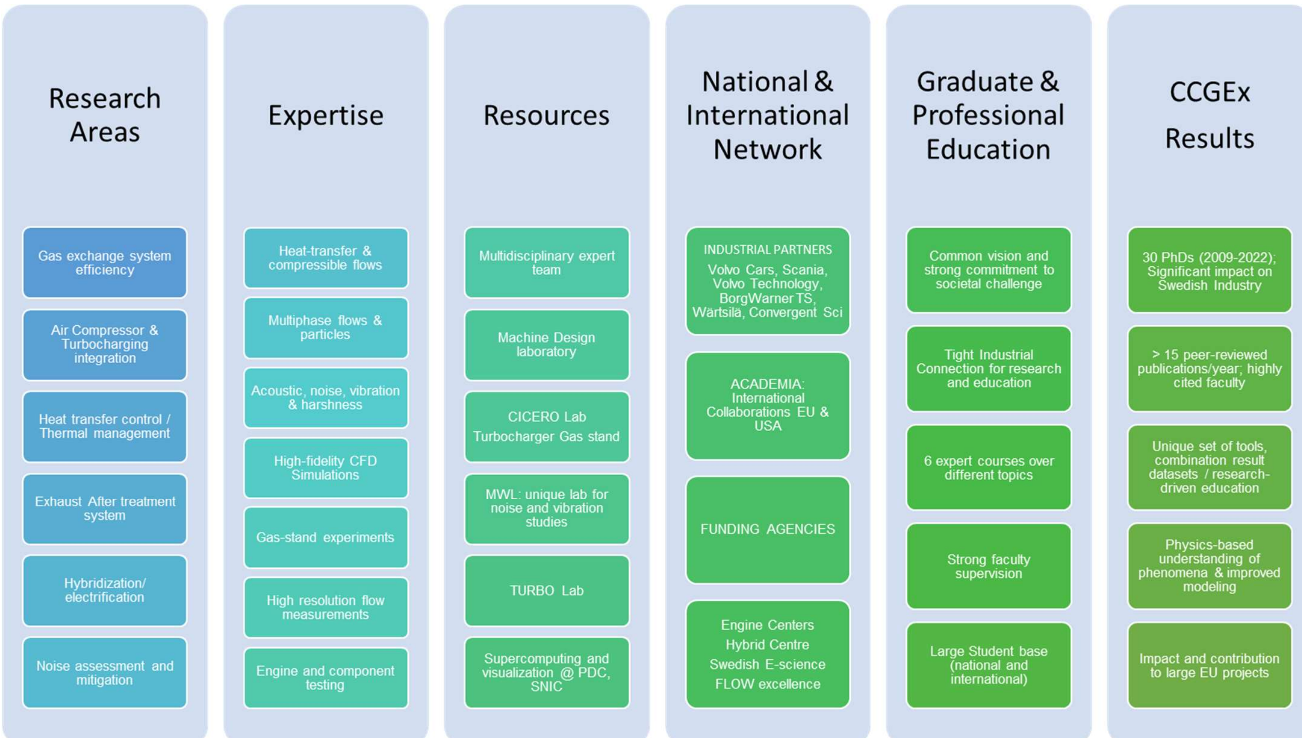

Figure 1: CCGEx ramifications of research, expertise, and areas of impact, https://www.ccgex.kth.se/

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 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, models, and approaches for this purpose (high-fidelity simulations including Large Eddy Simulation-LES calculations and advanced data post-processing techniques; dynamic system simulations; gas-dynamics & gas-stand experiments; flow measurements & optical laser diagnostics; reduced order modeling & optimization for virtual design; gas-stand testing & instrumentation).

The research is/has been carried out in close collaboration with the Swedish Automotive Industry (Volvo Cars/Aurobay, Volvo GTT/Technology, 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. In 2021, the CFD software company Convergent Science joined CCGEx as partner.

By making use of advanced methods for post-processing, analyses, measurements and synthesis, the understanding of basic fluid flow, heat-transfer, and acoustics phenomena of relevance to gas exchange processes and turbocharging is set to increase. With physics-based built knowledge, CCGEx researchers can identify new technical possibilities and solutions in gas exchange, EGR, turbocharging, and after-treatment systems associated with the ICEs using Carbon-neutral or Carbon-free fuels.

Mission, and strategy

The vision with CCGEx has been to make possible the change from extensive physical testing to innovative virtual development using predictive simulation tools developed on physics-based understanding of phenomena. The overall goal was to enable knowledge based and efficient design of next generation clean propulsion systems with focus on advanced gas exchange and turbocharging technologies. Within CCGEx, *cross-disciplinary and integrated research has been promoted*, which combines dedicated competences, expertise, and facilities in *gas dynamics*, *acoustics*, and *engine technology*. The research within the Center is based on extensive knowledge of fluid mechanics and transport phenomena, turbocharging, and combustion engine technology and includes both fundamental and applied experiments and simulations. The starting point for the formulation of research projects was represented by the challenges with the current propulsion systems for automotive applications.

Organization

CCGEx emerged as a combined effort between KTH, the Swedish Energy Agency, the Swedish automotive companies (i.e., Scania CV, Volvo Car/Aurobay, and Volvo GTT/Technology), the turbocharging manufacturer BorgWarner Turbo Systems Engineering GmbH (Germany), Wärtsilä (Finland), and Convergent Science (USA). Notably, Convergent Science joined CCGEx in January 2021.

The involved Departments at KTH Royal Institute of Technology 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 at 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, 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 located at the Industrial Engineering and Management (ITM) School; however, it has been directed since 2019 by Prof. Mihai Mihaescu at the Department of Engineering Mechanics (SCI School). The Board of CCGEx is composed of representatives of all research groups involved in the Center (*Table 1*). Since 2019, CCGEx is led by a director and one deputy director with the help of the Research Management group. As shown in *Tables 2* and *3*, the Research Management group (LG) consists of director, deputy-director(s), representatives of the CICERO and ICE Labs, one student representative, faculty and researchers actively involved in the 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 act as consultative bodies for the management team and ensure the scientific level and relevance of the Centre's research areas and projects.

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

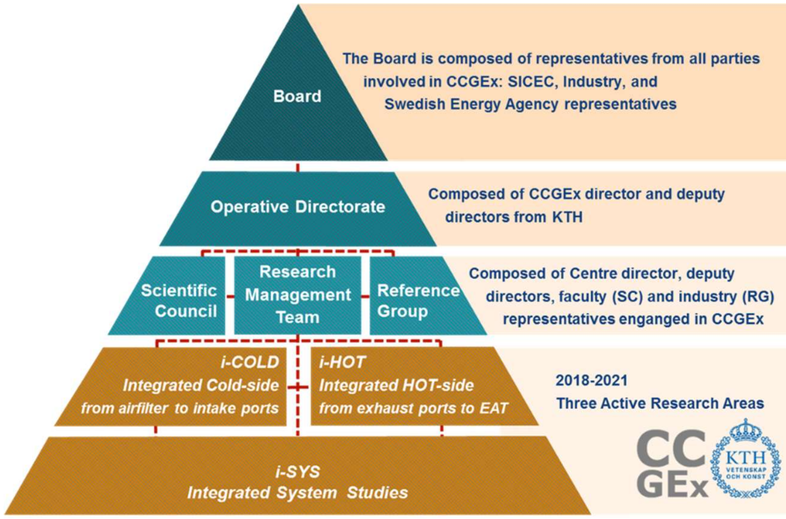

Figure 2: Organization of the Competence Center for Gas Exchange, CCGEx (01/2018-06/2022).

As shown in the diagram above (Fig. 2), 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 (on-line meetings using Skype/Zoom/Teams, approximately 6 to 8 weeks apart) to discuss the division of labor and project results, as well as new research and project ideas.

During 01/2018-06/2022 financing period, within CCGEx's activities and functions the following persons were engaged:

Table 1: CCGEx Board (01/2018-06/2022)

Johan Engström	SICEC Ordförande/Chair person (since 01/2022)
Sören Udd	SICEC Ordförande/Chair person (until 12/2021)
Sofia Ritzén	KTH (until 12/2019)

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

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)
Catharina Tillmark	SCANIA CV (since 11/2020 until 06/2021)
Jenny Kron Kylefors	SCANIA CV (since 01/2022)
Simon Reifarth	SCANIA CV (since 06/2021)
Carolin Wang - Hansen	Volvo Car Corporation
Håkan Persson	Volvo Car Corporation (until 12/2020)
Angela Johnsson	VOLVO GTT
Johan Wallesten	VOLVO GTT (until 03/2019)
Johan Engström	VOLVO GTT
Erik Svahn	Swedish Energy Agency (since 03/2022)
Anders Johansson	Swedish Energy Agency (until 02/2022)
Sofia Andersson	Swedish Energy Agency
Tom Heuer	BorgWarner Turbo Systems (until 02/2021)
Ewa Goch	BorgWarner Turbo Systems (until 02/2021)

Table 2: CCGEx Directorate (01/2018-06/2022)

Director	Mihai Mihaescu / Mekanik (since 07/2019)
Director	Anders C. Erlandsson /MFM (until 01/2019)
Deputy Director	Mats Åbom / Engineering Mechanics MWL

Table 3: Management Group (01/2018-06/2022)

Mihai Mihaescu	Mek, CCGEx Director
Anders Christiansen Erlandsson	MFM, CCGEx Deputy Director (until 06/2019)
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)
Andreas Cronhjort	MFM (since 07/2019)
Hanna Bernemyr	MFM (since 09/2019)

Table 4: CCGEx Scientific Council

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

Table 5: CCGEx Research Team (01/2018-06/2022)

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 (**PhD defense: VT2023**)
Emelie Trigell	PhD Student, Mek (**PhD defense: VT2023**)
Stefan Jacob (born Stefan Sack)	Post-doc, MWL (until 06/2021)
Research Area “i-HOT”	
Mihai Mihaescu	Research Area PI (until 12/2019)
Michael Liverts	Research Area PI (since 01/2020)
Henrik Alfredsson	Co-investigator (until 08/2019)
Jens Fransson	Co-investigator (since 09/2019)
Andreas Cronhjort	Co-investigator
Anders Dahlkild	Co-investigator
Shyang Maw Lim	PhD Student, (until 12/2018), **PhD**
Marcus Winroth	PhD Student, Mek/CICERO Lab (until 08/2019), **PhD**
Ted Holmberg	PhD Student, MFM (until 01/2020) (**PhD defense: TBD**)
Roberto Mosca	PhD Student, Mek (10/2022), **PhD**
Nicholas Anton	Ind. PhD Student (Scania) MFM (until 07/2019), **PhD**
Yushi Murai	PhD Student, Mek/CICERO Lab (**PhD defense: VT2023**)
Varun Venkataraman	PhD Stud., MFM (**PhD defense: VT2023**)
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
Jens Fridh	Co-investigator
Ghulam Mustafa Majal	PhD Stud., MWL/Mek (until 10/2020), **PhD**
Arun Prasath	PhD Stud., MFM (until 06/2021), **PhD**
Senthil Mahendar	PhD Stud., MFM (until 06/2021), **PhD**
Sandhya Thantla	PhD Stud., *Assoc. project*. MFM (**PhD defense: VT2023**)
Beichuan Hong	PhD Stud., MFM (**PhD defense: VT2023**)
Zhe Zhang	PhD Stud., *Assoc. project*, MWL (until 07/2019), **PhD**
Jianhua Zhou	Post-doc, MWL, (until 09/2019)

Table 6: Grants granted to CCGEx faculty & Researchers (activities associated with CCGEx)

- 2019-2021 H2020-LC-GV-2018; EU Proposal: 824314 - VISION-xEV; Virtual Component and System Integration for Efficient Electrified Vehicle Development; Coordinator: AVL, Austria. PI-KTH: Mihai Mihaescu, Role: Co-investigator, Team Leader. https://vision-xev.eu/
- 2021-2022, High Performance Computing (HPC) grant: PRACE DECI, 2.8 mil CPU hours. 2.8M CPU hours, HPC Mahti-Finland (PI: Mihaescu)
- 2021-2024: Swedish Energy Agency FFI programme: two PhD projects at Machine Design: "ASKA2 Framtidens partikelfilter för nästa generations biobränslen" and "DIB 3 Injektorbeläggningar av biobränslen" (PI: Hanna Bernemyr, leading KTH research activities)
- 2021-2024: Swedish Energy Agency FFI programme: "eFan Noise” PhD project with Chalmers, KTH-MWL and Volvo GTT+Cars, (co-PIs: Mikael Karlsson & Mats Åbom)
- 2021-2024: *EU H2020 Marie Skłodowska-Curie ITN Grant*. No. 956803. *INSPIRE* project: Pressure Gain Combustion solutions for the efficient use of carbon neutral fuels such as Hydrogen.

Coordinator: Univ. Firenze. (PI-KTH: Mihai Mihaescu, Role: Co-investigator, Team Leader). https://inspire.cerfacs.fr/en/

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 (see Table 6).

Results and 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 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 7 to 11 represent a summary of the most important measurable outcomes delivered by CCGEx between 01/2018 to 06/2022. During these four years and a half, *eight (8) CCGEx doctoral students graduated with a PhD degree*. Four other CCGEx PhD students that started their PhD studies during 2018 (HT2018) and one Industry PhD student are planned to defend their doctoral theses during Spring 2023 (VT2023). All doctoral students involved in CCGEx projects carried out administrative or teaching duties of up to 20%. Six Master of Science projects were associated with CCGEx.

Table 7: Doctoral theses (2018-2022)	8 PhDs
Mosca, Roberto **(2022)**	*Numerical Investigation of Radial Turbines Subject to Pulsating Flow*, KTH, TRITA-SCI-FOU; 2022:48, ISBN: 978-91-8040-362-7. https://www.diva-portal.org/smash/get/diva2:1696901/FULLTEXT01.pdf
Mahendar, Senthil Krishnan **(2021)**	*Mitigating Knock in Heavy Duty Spark Ignition Engines*, PhD thesis, KTH, TRITA-ITM-AVL ; 2021:17, ISBN: 978-91-7873-850-2. http://www.diva-portal.org/smash/get/diva2:1546956/FULLTEXT01.pdf
Karuppasamy, Arun Prasath K. **(2021)**	*Particle Characterization in the Exhaust Devices of Direct Injection Engines*, PhD thesis, KTH, TRITA-ITM-AVL ; 2021:18, ISBN: 978-91-7873-858-8. https://www.diva-portal.org/smash/get/diva2:1548566/FULLTEXT01.pdf
Majal, Ghulam M. **(2020)**	*Flow dynamics in corrugated pipes: Effect on particle agglomeration.* PhD thesis, KTH Engineering Mechanics, TRITA-SCI-FOU, ISBN: 978-91-7873-646-1. http://kth.diva-portal.org/smash/get/diva2:1473573/FULLTEXT01.pdf
Zhang, Zhe **(2019)**	*Optimal damping and slow sound in ducts*. PhD thesis, KTH Aeronautical and Vehicle Engineering, Stockholm, Sweden. http://www.diva-portal.org/smash/get/diva2:1315635/FULLTEXT01.pdf

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

Winroth, Marcus **(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
Anton, Nicholas (**2019**)	*Engine Optimized Turbine Design*. PhD thesis, KTH Internal Combustion Engines, Stockholm, Sweden. http://www.diva-portal.org/smash/get/diva2:1302822/FULLTEXT01.pdf
Lim, Shyang Maw **(2018)**	*Aerothermodynamics and exergy analysis in turbocharger radial turbine.* PhD thesis, KTH Mechanics, Stockholm, Sweden. http://kth.diva-portal.org/smash/get/diva2:1262773/FULLTEXT01.pdf

Table 8: MSc theses (2018-2022)	**7 MSc Degrees**
Massiquet, R.C.P. **(2022)**	*Compressor Surge: Simulation, Modeling and Analysis.,* KTH School of Engineering Sciences (SCI), Engineering Mechanics. (External cooperation: Scania CV AB), TRITA-SCI-GRU; 2022:168.
Achary, N. L. *and* Dasgupta, S. **(2021)**	*Performance Investigation & Gas Exchange Assessment of Exhaust Piston–assisted Turbocharged Engine (EPTE) Concept: A simulation-based assessment.,* KTH Industrial Engineering and Management Machine Design, Division of Internal Combustion Engines, TRITA-ITM-EX 2021:546. https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1596260&dswid=-6380
Granlöf, M. **(2021)**	*Shape optimization of axial cooling fan via 3D CFD simulation and surrogate modeling.,* KTH, School of Engineering Sciences (SCI), Engineering Mechanics. (External cooperation: Volvo Cars Co), TRITA-SCI-GRU ; 2021:354. http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1614088&dswid=-8413
Sandström, A. **(2020)**	*Simulating flow-noise for after-treatment systems.* KTH Royal Institute of Technology, Department of Engineering Mechanics. (External cooperation: Scania CV AB), TRITA-SCI-GRU ; 2020:367. http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1505481&dswid=6699
Cao, D. **(2020)**	*Modelling of the vibrational behavior of housing plates filled with fibrous material.* (External cooperation: Scania CV AB), TRITA-SCI-GRU 2020:007. http://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A1465506&dswid=4587
Vejendla, B. **(2019)**	*Acoustic source strength determination of turbocharger in an unfavourable acoustic environment.* (External cooperation: Scania CV AB), TRITA- SCI-GRU ; 2019:400. http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1380341&dswid=7795

The results associated with the research activities within CCGEx (between 2018 to 2022) were disseminated as part of *72 peer-reviewed contributions* (i.e., conference papers and journal publications), among which *25 journal publications in well-known international journals e.g., Energy Conversion and Management, Energies, Journal of Sound and Vibration, Journal of Engineering for Gas Turbines and Power, SAE International Journal of Advances and Current Practices in Mobility, applied Thermal Engineering, Journal of Fluid Mechanics, International Journal of Heat and Fluid Flow, Physics of Fluids, ASME J. Energy Resour. Technol., Journal of Turbomachinery)*[7]. Table 9 gives a summary of these paper contributions, while Table 10 highlights the events where research presentations were given by CCGEx PhD students and researchers.

Table 9: Summary on peer-review publications and conference attendance (2018-2022)
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	47	23	13	11	(6)	(16)
Int. Journal publications	25	5	5	15	(2)	(2)
Total	72	28	18	26	(8) out of 72	(18) out of 72

Table 10: Attended conferences by CCGEx researchers (2018-2022)

- ASME Turbo Expo 2022, Rotterdam, NL, June 13-17, 2022.
- SAE WCX World Congress 2021, Virtual event, April 13-15, 2021.
- SAE Powertrains, Fuels and Lubricants 2021 Online, Sept 28-30, 2021.
- ASME IGTI Turbo Expo Congress 2021, Virtual event, June 7-11, 2021.
- ASME Fluids Engineering Summer Meeting FEDSM, Virtual event, August 10-12, 2021.
- SAE Naples 2021; 15th International Conference on Engines & Vehicles, 09/12-16, 2021.
- 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, Fall 2020 (on-line)
- Energimyndighetens stora fordonskonferens, Energirelaterad fordonsforskning, Göteborg, 04/2019.
- WCX SAE World Congress, Apr. 21-23, Detroit, 2019.
- 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.
- Energimyndighetens stora fordonskonferens, Energirelaterad fordonsforskning, Göteborg, 04/2018
- VIPP Annual Conference, Volvo Cars, Göteborg, Sept 2018
- The IMECHE 13th International Conference on Turbochargers and Turbocharging, London, UK
- ASME IGTI 2018, Oslo, Norway
- SAE 10th Int. Styrian Noise, Vibration & Harshness Congress, Graz, Austria
- SAE WCX World Congress, Detroit, USA, 2018
- SAE F & L, Heidelberg, Germany, 2018

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

- ICSV 25, Hiroshima, Japan, 2018
- The 15th Int. Symposium on Unsteady Aerodynamics, Aeroacoustics & Aeroelasticity of Turbomachines ISUAAAT15, Oxford, UK, 2018

**) Most of the conferences planned for 2020-2021 were canceled, postponed or transformed as virtual events due to the Covid-19 pandemic.*

Table 11: Other important Highlights (2018-2022)
○ Internship by Dr. Roberto Navarro (Assoc. Professor at UP Valencia, Topic: CFD turbocharging). Host @ KTH: Mihaescu The internship was planned initially for June-August 2021 but has been postponed to June-August 2022 due to Covid-19 pandemic.
○ CCGEx Research Days 2021: November 8th- November 9th, 2021, On-line Zoom, between 47 to 88 participants; two key-note speakers.
○ Application for a National Competence *Center for Sustainable ICE related research (SICEC)* has been submitted jointly by Chalmers, KTH, and LTH to the Swedish Energy Agency on 31/05/2021.
○ 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. 7-8 & Nov. 28-29, 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".
○ CCGEx Research Days 2019: October 10-11, 2019, KTH Openlab, Stockholm, 50+ registered participants.
○ BorgWarner Turbo Systems Engineering GmbH, Kirchheimbolanden, Germany joined CCGEx as full partner in the Center (2018).
○ Wärtsilä is partner in the Center (2018).
○ CCGEx Research Days 2018: *11-12 October 2018,* KTH Openlab, *54 external visitors, Stockholm.*
○ Shyang Maw Lim CCGEx PhD student, received the 2018 ASME Young Engineer Turbo Expo Award!

Every year between 2018 to 2021, the research activities and achievements of CCGEx doctoral students and postdocs have been presented during the *CCGEx Research Days (2018, 2019, 2020, 2021 editions),* see also Table 11. The event has been organized yearly as a two-days symposium hosted by KTH in the Fall semester. In addition to the presentations given by the CCGEx doctoral students, postdocs and faculty, key-note lectures were given among other by: *Dr. John Zagone* (Director of Engineering, Commercial Vehicles at BorgWarner Turbo Systems, USA); *Prof. Federico Millo* (Politecnico di Torino, Italy); *Prof. Ricardo Martinez-Botas* (Imperial College London, UK); *Dr. Peter Kelly Senecal* (Convergent Science, USA); *Dr. Johan Engström* (VOLVO GTT); *Prof. Clemens Biet* (TU Berlin, Germany); *Dr. Jari Hyvönen* (Wärtsila).

Overview of Research Activities

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).

CCGEx faculty and students have access, between 2018 to 2022, 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). In addition, starting with 2021, CCGEx PhD students have access to HPC Mahti in Finland as part of the European Tier-1 supercomputing infrastructure PRACE DECI (Distributed European

Computing Initiative). A variety of commercial solvers as well as developmental research “in-house” and advanced post-processing codes are available to CCGEx students, researchers, and faculty.

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 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. Asuka has been also on parental leave for about 6 months during 2022. 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 acoustic reflection coefficients smaller than 1%, and low acoustic damping in space. 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. The computational grids in the noise source regions were generated so that they would match the Large Eddy Simulation (LES) requirements. This was achieved by scaling the mesh size to the estimated local Taylor microscale size. The results associated with this project were published in the proceedings of three conferences (SAE – ISNVH 2019, Forum Acusticum 2020, and SAE-12th International Styrian Congress: the European Automotive Noise conference). One journal publication in *SAE International Journal of Advances and Current Practices in Mobility has been published and* two other publications are in the process of being completed. Volvo Cars prolonged the project; the PhD defense being planned for VT2023.

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 in 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 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. The current developments of the project involve installation effects targeting their impact on inflow distortion and compressor stability. Emelie presented her work at one ASME conference (peer-reviewed conference paper as first author). She has also three other contributions as second author. Her PhD defense is planned for VT2023.

The two computational projects exposed had 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

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

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. The project has been completed on 2021.05.31.

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 losses 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 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 to develop new and more efficient technologies to fulfill the required standards. Among the possible solutions, air turbocharging has been demonstrated as 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. By treating the hot-side system as a stand-alone device, parametrization of the pulse shape imposed as inlet boundary conditions has led to highlight specific trends of the system response to pulse amplitude and frequency variations. Reduced-order models to predict the deviations of the turbine performance from quasi-steady to pulsating f low conditions are developed. A neural network

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

model is demonstrated to accurately predict the unsteady turbine performance given a limited number of training data. A gradient-based optimization method is developed to identify the optimum working conditions, in terms of pulse shape, to maximize the power output of the turbine. Moreover, a high-resolved LES approach has been used to investigate the characteristic flow structures developed inside the rotor under pulsating flow conditions. The outcome of this research has been published in three peer-reviewed journal contributions and presented at two conferences. Roberto Mosca defended his PhD thesis on 2022.10.07.

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. Turbine harvests the energy from otherwise-wasted engine exhaust gas flow. The 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) The use of cold-wire sensors have been demonstrated both in lab and industrial facilities for exhaust-gas temperature pulsation measurements. 2) A thorough study to quantify the influence of the cold-wire design to the sensor sensitivity and performance are being finalized. The on-going efforts are directed towards: Characterizing the new pulse generator system for an improved controllability of pulse shapes; Setting up a time-resolved measurement system of static & total pressure, temperature (developed cold-wire sensors) and velocity (3D LDV) to quantify the mass flow pulses; Turbocharger turbine performance tests at selected operating points to investigate the influence of pulse shapes. Yushi Murai's PhD defense is planned for June 2023.

The project ***Time resolved flow measurement for engine applications*** - PhD student Varun Venkataraman - started November 2018. It combines experimental measurements with modeling capabilities of thin wire based thermal sensors. 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/temperature measurements on-engine beyond fast pressure measurements. The methodology involves a combination of custom fabrication of thin wire thermal sensors (i.e., resistance wire thermometers and thermocouples), 0D/1D simulations at the sensor and engine level along with experiments on-engine complemented by measurements in the Shock Tube facility and the high-pressure flow rig. The goal is to understand sensor requirements for on-engine time resolved temperature 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) On-engine experiments with pitot-tubes, multiwire thermocouples and resistance wire thermometers (cold-wires) completed at KTH engine lab; 2) The listed measurement techniques were showcased on Wärtsilä's single cylinder research engine looking into sensitivities related to EVO and exhaust valve profiles along with added spatial resolution with multiple simultaneous measurements (main contribution: multiwire thermocouples); 3) 2x conference short papers (main author, SMSI 2020/2021) and 1x journal (co-author, Energies 2021). Ongoing activities to mention are: 4) 1x journal paper in progress targeting SAE. J. Engines on multiwire thermocouple design and operational limits on-engine 5) Continue data analysis and write subsequent papers relating to fast temperature measurement applications, thermal sensor modelling and challenges with reconstruction techniques. His PhD defense is planned for HT2023.

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 has been completed 2021.05.31.*

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 performance. Exergy analyses, based on the Second Law of Thermodynamics, can provide 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 in Q3 2019, and the analysis of the marine engine was published in Q3 2020. Further, a sensitivity-analysis-based method was applied to identify the significance of different flow parameters in the assessment of exhaust pulsation energy (Q2 2020). This study showed that the effects of instantaneous flow velocity are not negligible. Therefore, a Pitot-tube-based technique was employed to measure the velocity of exhaust pulsating flow. Combined with the fast temperature measurement of other CCGEx projects, the Pitot-tube experiments were finished in the Scania truck engine (Q2-Q3 2021) and the Wärtsilä single-cylinder engine (Q4 2021 - Q2 2022). Data analysis for measuring flow energy and exergy of exhaust pulsation is planned for 2022/2023. The planned defence time for Beichuan's PhD is June 2023.

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 was 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 the 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 changes 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). *The project has been completed 2021.05.31.*

Associated projects with CCGEx

The Associated Project ***Low Temperature Waste Heat Recovery (WHR)*** with Sandhya Thantla as doctoral student started August 2016. (Interruptions: March to October, 2020: Maternity leave 100% & February to July, 2021: Maternity leave 50%). This is an Associated project with CCGEx. This project investigates the scope of improvement in overall system efficiency of a heavy-duty (HD) truck engine integrated with an organic Rankine cycle (ORC) waste heat recovery system (WHRS). This work is carried out at two levels viz. component level and system level. At the component level, volumetric expanders are incorporated to assess their adaptability and contribution towards improving the system efficiency. At the system level, studies are conducted to evaluate the performance difference between single-loop (SL) and dual-loop (DL) architectures. The SL system is designed for recovering heat only from the exhaust gas, whereas, DL system is designed for recovering heat from both the engine coolant and the exhaust gas, simultaneously. The impact of increasing the engine coolant temperature up until 160 ^{o}C has also been evaluated to determine its impact on the system. The analyses are carried out in the 1D simulation tool GT-SUITE, for which the input data is extracted from the road data of Scania's HD truck installed with a SL exhaust heat recovery system. The 1D model, validated against the road data, has further been modified to carry out analyses using desired system architectures, expanders and working fluids. The results, for the analyses performed at an average steady-state (SS) engine operating point (EOP), convey that for the chosen HD truck engine system, scroll expander has proven to be an appropriate expansion machine due to its efficiency, simplicity and lower rotational speed when compared with the piston-type expansion machine. R1233zd(E) suits quite well as the working fluid. The results also show that increased engine coolant temperatures have a positive impact on the overall system efficiency. Furthermore, on evaluating the performance at multiple SS EOPs (part-load to maximum engine load) using the DL architecture, overall system efficiency significantly decreased with increased engine loads due to the limited heat rejection capacity the radiator installed for the indirect condensation of the ORC working fluid. Besides, on elevating the engine coolant temperature from 120 ˚C to 140 ˚C, net power output improved at higher EOPs; however, at the lowest part load condition, the net power dropped due to significant heat loss from the engine coolant to the surrounding air. A perfectly insulated engine could result in better performance. Another interesting conclusion is that for the chosen system configuration and control strategies, varying the speed of expanders (in the DL system) during operation yields only 0.12 kW (1.6% points) more power than having the expander speeds fixed throughout the entire engine operation. Comparing the DL and SL ORC systems, the former improved the fuel-saving between 0.4% points and 0.8% points compared to the latter, at the conventional engine coolant temperature.

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, No. 824314; Coordinator: AVL), PI: Mihai Mihaescu, Post-doctoral student: Shyang Maw Lim (until 03/2021) "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." The following partners were involved in the VISION-xEV project: AVL List GmbH project coordinator (Austria), Aristotle University of Thessaloniki (Greece), AVL QPUNKT Deutschland GmbH (Germany), Consiglio Nazionale delle Ricerche (Italy), CRF – Centro Ricerche Fiat (Italy), FPT Motorenforschung AG (Switzerland), Kungliga Tekniska Hoegskolan (Sweden), Politecnico die Milano (Italy), Renault SAS (France), Technische Universität Berlin (Germany), Universidad Politecnica de Valencia (Spain), Univerza v Ljubljani (Slovenia), Vrije Universiteit Brussel (Belgium), ZF Friedrichshafen (Germany). KTH part of the project aimed 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

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

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. Among the achievements with the work carried out by KTH team one shall mention: development of a validated, time-accurate method for high-fidelity performance prediction; analysis and quantification of the complex flow field in the turbocharger turbine under realistic engine-like hot pulsatile flow via high-fidelity simulations; further development of the exergy-based method to identify & to quantify thermo-fluid physics of turbocharger turbine under different engine-like conditions for light-duty and heavy-duty applications. The research associated with the VISION-xEV project has been positively evaluated by the European Commission. *VISION-xEV* officially ended March 2022. KTH team delivered two *deliverables that were accepted by the European Commission (EC).*

CCGEx Projects, beyond 2022

Important to mention is that 4 (four) CCGEx Projects listed below started later than January 1st, 2018 (6 to 10 months later). The reason has been that the contract was signed by all partners later than anticipated, which delayed the recruitment process.

- *Turbocharger compressor response to installation effects and perturbations*, PhD student: Emelie Trigell **(started 20.08.2018; PhD defense date: TBD, VT 2023)**
- *Turbocharger turbine efficiency in steady and pulsating flow*, PhD student: Yushi Murai (started 05.11.2018; **PhD defense date: TBD, VT 2023**)
- *Time resolved flow measurement for engine applications*, PhD student: Varun Venkataraman (started 01.11.2018; **PhD defense date: TBD, VT 2023**)
- *Thermal analysis for high efficiency ICE gases exchange system*, PhD student Beichuan Hong (started 01.11.2018; **PhD defense date: TBD, VT 2023**)

These projects are continuing beyond 30.06.2022 since the regular PhD program at KTH is for 4 years. These are also projects impacted by the Covid-19 pandemic. Moreover, all these students are/were involved in teaching and/or administrative assignments at KTH (up to 20%).

Because of these reasons CCGEx requested to the Swedish Energy Agency an extension for one more year of the center until 31st of December 2022. The Swedish Energy Agency (STEM) concluded that the current competence centra can be extended by a maximum of 6 months. This was due to delays linked to Covid-19.

Industrial partners involvement and development

The CCGEx research areas benefited from a strong interaction with the industrial partners and collaborators (Scania, Volvo Cars, Volvo GTT, BorgWarner Turbo Systems, Wärtsilä and lately Convergent Science). During 2021, Convergent Science https://convergecfd.com/ joined CCGEx after signing the Accession Agreement (28/01/2021).

During Covid-19 pandemic all the meetings involving our industrial partners (i.e., Board meetings, Reference group meetings, thematic research meetings) were hosted on-line.

Reference groups from the industry partners are associated with each of the three CCGEx research areas. Reference group meetings were hosted online (via Zoom, Teams, Skype) 6 to 8 weeks apart. The purpose is that researchers, doctoral students, industry representatives (part of the reference groups) interact, present, discuss, and analyze the latest updates on each of the specific research areas and to clarify the near- and far-future planned research activities. In addition, every two to three weeks, more individual research meetings were considered between CCGEx students and industry.

Among the important contributions from our industrial partners one can mention: Equipment and hardware for projects; performance maps & CAD & CAE data (BWTS, VCC, VOLVO, Scania); Ind PhD students and consultations (VCC, Scania); experimental campaigns involving CCGEx PhD students and researchers (VOLVO, Scania, Wärtsilä); software licenses and technical support (Convergent Sci).

It must be noted that during the month of June 2021, an experimental campaign has been carried out by Volvo Technology in Malmö, which due to Covid-19 pandemic has been redesigned as a virtual experimental campaign with CCGEx students, researchers, and faculty participated during tests and data analysis.

Moreover, due to the Covid-19 pandemic, the experimental campaigns planned initially during 2020 at Wärtsilä facilities in Vaasa, Finland (with participation of CCGEx students) have been postponed to December 2021 and to January-March 2022, respectively. They were successfully conducted with participation of CCGEx PhD students: Yushi Murai, Varun Venkataraman, and Beichuan Hong.

Discussion and Research Outlook

In 2021, Chalmers, LTH, and KTH joined efforts towards forming a national Joint *Center for Sustainable ICE (SICEC)* related research with focus on high energy efficiency powertrains with sustainable fuels. The application for SICEC national Competence Center has been submitted to the Swedish Energy Agency on 31/05/2021 (PI: Prof. Bengt Johansson, Co-PIs: Prof. Per Tunestål and Prof. Mihai Mihaescu). The proposal has been selected by the Swedish Energy Agency for the interview phase that took place on September 28th, 2021. The SICEC application has been rejected (2021.12.16), being rated #12 out of 29 applications. KTH proposed research as part of SICEC has been on advancing the *gas exchange* and *turbocharging* technologies within the context of utilizing Carbon neutral and Carbon-free fuels, *heat-transfer quantification* for smart *thermal-management* solutions; to manage sound generation and attenuation in the engine gas handling system; to enable knowledge-based and efficient design of next generation efficient and clean propulsion systems for vehicle applications.

Achieving net zero Carbon transport is possible, but the size of the challenge shall not be underestimated. Aerodynamics, fluid dynamics and heat transfer, turbomachinery & propulsion technologies, electrification, Carbon-neutral & Carbon-free fuels produced with renewable energy, alongside rapid testing, and development shall be combined to address the challenge. Within this context, the ability to measure, model and predict fluid flows is exceptionally important to the innovation of processes and products across automotive industry, road vehicles and maritime transport, energy conversion and power production systems. A greenhouse gas-neutral transportation system by 2050 can best be met by using a diverse set of propulsion technologies (e.g., Hybrids with liquid sustainable fuels, Electric, Fuell Cell vehicles, Internal Combustion Engines with renewable fuels, Hydrogen Internal Combustion Engines); technologies that are not in competition but are applied to different market segments / missions. A common basis for all these solutions is the drastic increase in the system's efficiency. As enabling disciplines, *fluid dynamics, heat transfer and mass transport* contribute substantially to more efficient technologies used to develop sustainable transport. The faculty and researchers at KTH Royal Institute of Technology involved in CCGEx activities own proved computational and experimental fluid dynamics expertise with application to sustainable transports. ***We welcome collaboration and funding support from industrial partners for continuing this research.***

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Appendix – PhD Project descriptions/posters

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