Yearly Report CCGEx

2018

Competence Center for Gas Exchange
Charging for the Future!

CCGEx at the Royal Institute of Technology (KTH)

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Director: Anders Christiansen Erlandsson
Vice Director: Mihai Mihaescu
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Summary

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

As a difference from the previous period (2014-2017), the research within CCGEx is organized for the 2018-2021 period, under three research areas: the integrated COLD side (i-COLD), integrated HOTside (i-HOT), and integrated SYstem Studies (i-SYS). The i-SYS research area includes also active research with respect to engine aftertreatment. All CCGEx projects, PhD Students and research activities are organized within these research areas. These are financed by the Swedish Energy Agency, KTH, Scania, Volvo Cars, Volvo GTT, and BorgWarner Turbo Systems. Noteworthy, during 2018 BorgWarner Turbo Systems (BWTS) Engineering GmbH, Kirchheimbolanden, Germany became a full partner for CCGEx. One must note that BWTS has been a collaborator of CCGEx since 2015. During 2018, Wärtsilä joined also as collaborating partner committed to support and invest in the future research within CCGEx.

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

The area focus has increased the possibility for a joint academy and industry view regarding which issues are dealt with, and what the respective projects aim to answer and provide. 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 2018 within CCGEx, one can mention that 1 PhD student graduated with a PhD degree, while another obtained his Lic. degree. CCGEx published 14 peer-reviewed publications, among which 5 journal articles. CCGEx students and faculty have been an important presence to international and national conferences, meetings, and symposia of relevance to automotive industry and related research.

During the year, industry contributions have been added via e.g. Scania, BorgWarner Turbo Systems in addition to the in-kind contributions. Five new PhD students and one post-doc were recruited during 2018 and were able to join CCGEx the Center during 2018. By the end of 2018, the program essentially was fully funded, with a positive outlook regarding its future.

Background and Introduction

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

Sweden has a strong engine industry, which, to survive, is dependent on being able to renew its products so that the industry is at the forefront among international competitors when it comes to environmental and energy related requirements. The current trend, with ever stricter emission requirements – which are more and more focused on CO_2 emissions, minimizing the use of energy, increasing the proportion of biofuels and hybrid engines – means that the margins for the components of the engine, system and processes are decreasing.

This means that the Swedish engine industry is facing a few big challenges, in the form of requirements for higher efficiency in engines, tighter optimizations, the reducing of emissions and strong international competition.

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

Companies in the Swedish engine industry have been early adopters of turbocharging technology and are strong in this field from an international perspective. The significance of this field is increasing as new internal combustion systems require high EGR-percentages and boost pressures. 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. The field Gas Exchange and Turbocharging is specific to Competence Center for Gas Exchange (CCGEx) and exclusive for KTH – it is not covered by any of the other competence centers within SICEC. Moreover, in 2018 after about 3 years of collaboration, BorgWarner Turbo Systems (BWTS) became a full partner for CCGEx, joining Scania, Volvo Cars, and Volvo GTT.

The purpose of CCGEx is to carry out academic research with the highest quality in the field of Gas Exchange processes and Turbocharging with relevance to the modern power train systems used in the automotive industry. This is carried out in close collaboration with the Swedish Automotive Industry (Volvo Cars, Volvo GTT, Scania), BorgWarner Turbo Systems (BWTS), and Wärtsilä; thereby effectively contributing to an efficient, sustainable and competitive transport system based on efficient alternative fuels adapted to engine systems combined with electrification.

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

Long-term vision, mission and strategy

The vision 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 technologies.

Organization

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

The involved departments at KTH are the Department of Machine Design (MFM, Internal Combustion Engines), Department of Mechanics (Mek, Computational and experimental fluid mechanics), and Department of Aeronautical and Vehicle Engineering (MWL, The Marcus Wallenberg Laboratory for Sound and Vibration Research). The complementary and consistent views within the organization as well as the set-up of the working environment promote cooperation across group boundaries and with industry.

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

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

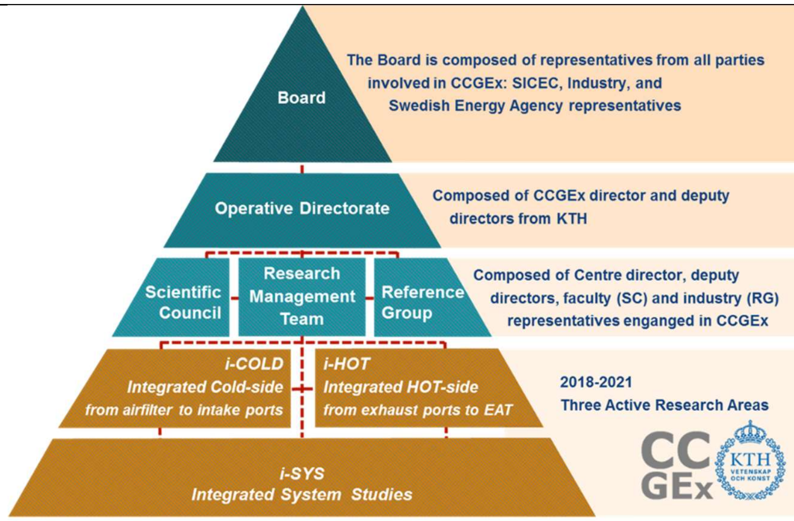

Figure 1: CCGEx Organization 2018-2021.

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

Most of the research within CCGEx is conducted by Doctoral students (including Industry PhD students) under faculty guidance and supervision and with guidance from the industrial partners. At the end of their studies these will earn a Licentiate and / or a Doctoral Degree. Post-doctoral students or Researchers were/are also involved in Center’s research activities but in a smaller number.

The main advisors/supervisors for the conducted projects are Associate Professors and Professors part of LG and/or VR. The pursued projects within CCGEx are using the broad expertise available within the Center and therefore it is aimed that as many projects as possible will involve an assistant supervisor with a complementary profile other than that of the main supervisor.

At the same time, it is important that within each research area, one can early and continuously seek the possibility of working together and involve industry partners, thus being able to utilize the expertise and resources of all the participants within the Center. There is a strong collaboration with the identified industry working groups (reference groups), which are linked to the three CCGEx active research areas and individual projects. These working groups have regular meetings (usually on-line meetings, 4 to 6 weeks apart) to discuss the division of labor and project results, as well as new research and project ideas.

In addition to the research activities funded through CCGEx, there are also a few associated projects and complementary activities, funded from extramural funding (e.g. FFI, CSC).

Within Center's activities and functions during 2018, the following persons were engaged:

Board

Sören Udd	SICEC Ordförande
Sofia Ritzén	KTH
Daniel Söderberg	KTH
Jonas Holmborn	SCANIA CV
Eva Iverfeldt	SCANIA CV
Carolin Wang - Hansen	Volvo Car Corporation
Håkan Persson	Volvo Car Corporation
Johan Wallesten	Volvo GTT
Angela Johnsson	Volvo GTT
Anders Johansson	Swedish Energy Agency
Sofia Andersson	Swedish Energy Agency

CCGEx Directorate

Director	Anders Christiansen Erlandsson / MFM
Deputy director	Mihai Mihaescu / Mekanik
Deputy director	Mats Åbom / MWL

Management Group

Anders Christiansen Erlandsson	MFM
Mihai Mihaescu	Mek
Mats Åbom	MWL
Christophe Duwig	Mek
Bengt Fallenius	Mek/CICERO Lab (until Sept. 2018)
Mikael Karlsson	MWL
Shyang Maw Lim	Mek (PhD Stud. representative)
Christer Spiegelberg	MFM

Scientific Council

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

The Research Team

Research Area "i-COLD"	
Mihai Mihaescu	Research Area PI
Mats Åbom	Co-investigator
Elias Sundström	Research Engineer, until 06/2018
Asuka Gabriele Pietroniro	Ind. PhD Student, Volvo Cars, Mek/MWL

Emelie Trigell	PhD Student, Mek, from 09/2018
Stefan Sack	Post-doc, MWL, from 12/2018
Research Area "i-HOT"	
Mihai Mihaescu	Research Area PI
Henrik Alfredsson	Co-investigator
Jens Fransson	Co-investigator
Andreas Cronhjort	Co-investigator
Anders Christiansen Erlandsson	Co-investigator
Anders Dahlkild	Faculty involved
Shyang Maw Lim	PhD Student, Mek
Marcus Winroth	PhD Student, Mek/CICERO Lab
Ted Holmberg	PhD Student, MFM
Nicholas Anton	Ind. PhD Student (Scania), MFM
Roberto Mosca	PhD Student, Mek, since 06/2018
Yushi Murai	PhD Student, Mek/CICERO Lab, since 11/2018
Research Area "i-SYS"	
Anders Christiansen Erlandsson	Research Area PI
Mikael Karlsson	Co-Investigator
Hans Boden	Co-investigator
Mats Åbom	Co-investigator
Mihai Mihaescu	Co-investigator
Ghulam Mustafa Majal	PhD Student, MWL/Mek
Zhe Zhang	PhD Student, Associated project, MWL
Arun Prasath	PhD Student, MFM
Senthil Mahendar	PhD Student, MFM
Sandhya Thantla	PhD Student, MFM WHR associated project
Beichuan Hong	PhD Student, MFM, since 09/2018
Varun Venkataraman	PhD Student, MFM, since 09/2018
Jianhua Zhou	Post-doc, MWL, since 09/2018

Five new PhD students and two post-doctoral students joined CCGEx during the last six months of 2018. These added to the existent eleven PhD students within the Center (number that includes associated projects and Industrial PhD students). Two Industry PhD students are active within CCGEx, i.e. Asuka Gabriele Pietroniro with Volvo Cars and respectively Nicholas Anton with SCANIA.

Measurable Outcomes

CCGEx deliverables and results are measurable through publications, participation in conferences, education and examinations of MSc and PhD students, as well as through the involvement of CCGEx faculty within the undergraduate education program. To this should be added the knowledge built within the Center, the exchange of information, experience and resources, respectively among all partners involved in the Center's activities on both experimental and simulation campaigns. This includes as well transfer of information, data, and resources from the industry partners in form of in-kind contributions to CCGEx. The following tables (Tables 1-5) represent a summary of the most important measurable outcomes delivered by CCGEx during 2018. A total of 14 peer-reviewed articles had been published in 2018 by CCGEx.

Table 1: Doctoral theses (2018)	**1**
Maw S.M. (Mek, 2018)	*Aerothermodynamics and exergy analysis in turbocharger radial turbine*. PhD thesis, KTH Mechanics, *ISBN 978-91-7729-956-1,* Stockholm, Sweden. http://kth.diva-portal.org/smash/get/diva2:1262773/FULLTEXT01.pdf

Table 2: Lic. theses (2018)	**1**
Majal, G.M. (Mek/MWL, 2018)	*On the agglomeration of particles in exhaust gas.* Licentiate thesis, KTH Mechanics, Stockholm, Sweden. http://kth.diva-portal.org/smash/get/diva2:1254089/FULLTEXT01.pdf

Table 3: Summary on peer-review publications and conference attendance (2018)
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	9	1	5	3	(2)	(3)
Int. Journal publications	5	0	1	4	(0)	(0)
Total	14	1	6	7	(2) out of 14	(3) out of 14

Table 4: Attended conferences and presentations (2018)
- Energimyndighetens stora fordonskonferens, Energirelaterad fordonsforskning, Göteborg, April, 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 - THIESEL conference, Valencia, Spain - SAE 10th Int. Styrian Noise, Vibration & Harshness Congress, Graz, Austria - SAE WCX World Congress, Detroit, USA - SAE F & L, Heidelberg, Germany - ICSV 25, Hiroshima, Japan - The 15th Int. Symposium on Unsteady Aerodynamics, Aeroacoustics & Aeroelasticity of Turbomachines ISUAAAT15, Oxford, UK - Thermoacoustic Hub, Le Mans, France

Table 5: Other important Highlights (2018)
- 5 new PhD students and two post-docs joined CCGEx during 2018. - BorgWarner Turbo Systems Engineering GmbH, Kirchheimbolanden, Germany is full partner in the Center. - Wärtsilä is partner in the Center. - *54 external visitors during CCGEx Research Days 11-12 October, 2018, Stockholm.* - Shyang Maw Lim CCGEx PhD student, received the 2018 ASME Young Engineer Turbo Expo Award (YETEP)!

CCGEx has been positively evaluated during the CCGEx Research Days (11-12 October 2018) by the Internationally Advisory Board (IAB). The IAB considered the research effort done in the Center of “high scientific quality” with a “good balance between computational and experimental work”.

“A special mention of excellent work to the project “Compressor flow instabilities at low mass flow rates: an LES approach” and to the remarkable Schlieren visualizations of the project "Gas dynamics of Exhaust valves”

Prof. Isabelle Trebinjac, Ecole Centrale de Lyon, France
Prof. Martti Larmi, Aalto University, Finland
Internationally Advisory Board (IAB) Report, December 19th 2018

Overview on Research Activities

During the 2018, CCGEx research efforts were focused on the three research areas “i-COLD”, “i-HOT”, and “i-SYS”. Substantial efforts from both KTH and industry partners have been dedicated to defining and establish the details of the new research projects. The interactive process between academia and industry with respect to the new projects has been concluded in the second half of 2018. At the end of this process 5 new PhD students and 2 post-docs were recruited by the Center.

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

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

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

i-COLD research highlights:

The high-fidelity Large Eddy Simulation (LES) calculations and the usage of adequate mode decomposition techniques allowed detailed assessment of the compressor flow and developed instabilities at off-design operating conditions. It was also demonstrated the capability of extracting acoustic information from the LES data. Very good agreement with gas -stand experimental data in terms of compressor performance parameters has been found out. For a ported-shroud compressor configuration, excellent agreement has been found between experimental data and LES data in terms of time-averaged pressure data and frequency spectra based on pressure signals at both design and off-design operating conditions.

Steady-state fluid flow calculations were used to cover 78 operating points for a smaller, BorgWarner centrifugal compressor of interest to our industrial partners. Very good agreement has been found out between the steady-state simulation data and the gas-stand experimental data provided by our industrial partner. Acoustic data were generated using the available acoustic models (Curle and Proudman, respectively) in Star CCM+ commercial solver. The purpose has been to localize areas of noise generation in the compressor and estimate acoustic power levels. An acoustic power map corresponding to the 78 operating points for the compressor has been generated. In the second step, unsteady computational aeroacoustic calculations and experimental measurements will be used for verifying and validating the findings with the steady-state computational models.

One new PhD student (Emelie Trigell) and one post-doc (Stefan Sack) were recruited during HT2018 to continue, respectively to complement the current work. Thus, for 2019 it is expected that high-fidelity simulations at off-design compressor operating conditions and experiments in the CICERO Lab will complement the current computational aeroacoustics calculations. Moreover, the experimental efforts in the CIERO Lab will be complemented when possible with experimental measurements on the hot gas-stands at Volvo Cars and SCANIA.

Research Area: Integrated HOT-side

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

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

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

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

i-HOT research highlights:

Among the research highlights one can mention the evaluation of the adiabatic & diabatic turbine performance under different flow scenarios (continuous and pulsating) using Detached Eddy Simulations-DES. The boundary conditions and temperature data are provided by industry parteners for engine operating points of interest. An exergy-based model was developed and applied on the DES data. The exergy method allowed quantifying the heat loss, the extracted power by the turbine, and the internal irreversibilities (viscous and thermal) in the entire exhaust system, or at sub-component level (e.g. exhaust manifold, scroll, turbine rotor, outlet pipe). This enabled studying the effectiveness of the available energy usage in the exhaust system. The findings were summarised in Shyang Maw Lim's doctoral dissertation (2018.12.07).

Experimental efforts within CICERO Lab were focused on assessing the exhaust port flow characteristics and the impact of the exhaust valve opening profile as well as other variables (e.g. engine speed, pressure ratio, radial valve position) on the discharge coefficient. The discharge coefficient has been shown to have a strong dependency on both valve opening speed and pressure ratio. The static measurements overestimate the value of the discharge coefficient, thus indicating that neither the quasi-steady nor the pressure-ratio insensitivity assumption holds. It has been shown that the radial position of the valve does not have a significant impact on the discharge coefficient. Performed shock-visualization experiments on the flow past the exhaust valve were carried out in the CICERO Lab, using Schlieren photography for different conditions and valve lifts. The flow visualizations indicate shock patterns are present in the exhaust port during the blowdown pulse and that the shock pattern is altered when using a static geometry (typically used during the gas-stand measurements). These experiments ended the experimental campaign planned for this project. Marcus Winroth will present the findings in his PhD dissertation planned for 24th of May, 2019.

The experimental efforts were complemented by the development of 1D computational models within GT-Power frame of work, where pressure dependent flow coefficients were implemented.

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

Two new doctoral students joined this research area during 2018. Yushi Murai (started 11/2018) is studying experimentally in the CICERO Lab (using LDV) the pulsed flow generated by the current pulse generator. Roberto Mosca (started 06/2018) is analyzing using unsteady simulations (DES) the impact of different exhaust valve strategy on a radial turbine performance.

Research Area: Integrated System Studies (i-SYS)

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

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

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

i-SYS research highlights:

The project **"Heavy Duty DISI Gas Exchange Requirements with Renewable Fuels"** – Senthil Mahendar (Started August 2016)

Spark Ignition (SI) finds limited application in Heavy Duty (HD) engines since these engines have lower power density and efficiency. Still, SI engines remain an attractive option for HD engines because they provide an inexpensive, low noise, and low emission solution in applications such as city buses and delivery trucks. The objective of this study is to increase the knowledge and establish the limits of utilizing alcohols in HD SI engines.

In 2018, a literature review [SAE 2018-01-0907] was compiled identifying methods of mitigating knock in HD SI engines and highlighting gaps and research questions. In addition, the SI predictive combustion model in GT Power was evaluated and requirements for improved accuracy were discussed in an internal report. Volvo Penta (Q2 2017) had provided the model and experimental data for this evaluation. Based on the observations from the model evaluation, a method was developed where motoring CFD was used to resolve turbulence and improve combustion speed calculation in 1D simulation. The effect of increased turbulence on knock and efficiency was derived from this method and the results would be published in August 2019.

An experimental campaign is planned (Q2 2019) to investigate the research questions highlighted in the literature study. The experiments would capture the effect of dilution in alcohol fuel combustion at both full load and part load. Scania had provided a prototype 13CR piston in 2018 for this study. These experiments would give the required dataset for combustion and knock modelling at diesel-like operating conditions (Q4 2019). Using the models developed and the experimental combustion limits, gas exchange architecture requirements for high efficiency HD SI engines could be derived (Q2 2020).

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

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

New project started: **Time Resolved Fast Measurements for Enthalpy, Exergy and Efficiency Calculations of the Air Handling System**- Ph.D. student Varun Venkataraman (November 2018)

This project aims to investigate the validity of common practice measurement and modelling approaches concerning pulsatile exhaust gas flow with the use of state-of-the-art time resolved measurement/estimation of pressure, temperature and velocity (mass flow) in on-engine operating conditions and arrive at a better understanding of our current ability to describe the instantaneous flow parameters in the engine exhaust. A better understanding of these parameters could provide insight 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 aftertreatment system. The project plan in 2019 includes foundational coursework, literature review and possible joint studies with established and new projects. The planned collaboration is with the established project on gas dynamics of exhaust valves at ICE and with instrumentation and experiments in the CICERO lab at Mechanics.

A new project "**Waste Heat Recovery in Pulsating Flows - ThermoAcoustic Engine**" has been initiated during 2018. A post-doctoral student (Jianhua Zhou) has been recruited (HT2018). The projects investigate the applicability of thermoacoustic engines for automotive waste heat recovery. The system is modeled as low order acoustic network including non-linear losses. The network model facilitates system studies to evaluate the thermal efficiency over for example legislative driving cycles. Nevertheless, the model also allows detailed studies of components. For this, experimental techniques are developed (e.g. experimental measurements for nonlinear effects in different acoustic components).

The Particle characterization and agglomeration project was part of the Exhaust AfterTreatment (EAT) research area that is now integrated in the I-Sys portfolio. Hence it has been running for a few years and has student that are halfway or further in their individual projects. The scope of the project is to further the understanding of transport of particles in the exhaust line and possible ways of manipulating them. The approach is both numerical and experimental and an integral part is to find the appropriate tools for studying the problem. Both the numerical and experimental work so far has been applied on a specific agglomeration concept. The concept has also been extended to include agglomeration stimulated by acoustics. There are three students involved: Ghulam Majal, Arun Prasath Karuppasamy, and Zhe Zhang (CSC - Associated project). Their individual project updates for 2018 are summarized below.

The 1D agglomeration modeling was finalized and published (SAE World Congress, Lic. Ghulam Majal). The original model has been developed and improved to include the influence of different engine pulses, varying agglomeration geometries as well as acoustic forcing. The first 3D steady-state simulations were initiated based on the findings with 1D calculations.

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.

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

Associated projects with CCGEx

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

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

PhD student: Zhe Zhang

Meta-materials are engineered materials with properties not found in nature. Typically, such materials are realized in the long wave length limit of a periodic system with local resonances. Such devices can be designed to create new types of efficient and compact silencers e.g. by reducing the sound speed. Such slow sound devices could perhaps also be applied in connection with acoustic agglomeration. An experimental analysis of the heavy-duty size agglomeration pipe investigated in a parallel project by Arun Prasath Karuppasamy has been carried out. Further development of the concept 'Cremer impedance' will be performed.

Improvements during 2018

During 2018, CCGEx Leading Group meetings were regularly hold (every 2-4 weeks). The minutes can be accessed using the CCGEx website.

The Industry Reference Groups were redefined in 2018 based on Industry Inputs. Their members are playing a major role in providing feedback on the individual projects. During 2018, regular meetings organized by the academic PI's responsible for the individual Research Areas were carried out with the reference groups every 4-6 weeks.

The collaboration between the doctoral students and faculty from the different departments (i.e. KTH-MWL, KTH-Machine Design, and KTH-Mechanics) involved within CCGEx research areas resulted in 2 joint peer-reviewed publications as shown earlier in the text (see Table 3). Moreover, the collaboration with our industrial partners led to 3 publications reported for 2018 period. For a complete list of publications the reader is directed towards CCGEx website: https://www.ccgex.kth.se/publications/journal-conference-papers-1.368301 .

The CCGEx PhD students and postdocs are holding regular meetings with a frequency of cca. 4 every year. There is agreement among the participants that four seminars per year is a good frequency. Each meeting is concluded with a dinner. During these student meetings several topics of interest to the CCGEx students were tackled (e.g. LabVIEW and NI CompactRIO real-time programming, CFD using StarCCM+ +, from mesh generation to solving the equations to post-processing, practice session on good coding practice in MATLAB SWOT-like analysis of CCGEx from the PhD students' perspective, and brainstorming ideas for improvement).

CCGEx seminars were regularly hosted by KTH-Mechanics and KTH-MFM where students are presenting their research and have a possibility to receive feed-back from their peers. The aims are to increase the interaction among the CCGEx students and improve knowledge transfer within the group.

Partners development

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

The CCGEx research areas benefits from a strong interaction with the industrial partners and collaborators. Reference groups from the industry partners are associated with each of the CCGEx research area. Thus, researchers, doctoral students, industry representatives (part of the reference groups) are interacting every 4 to 6 weeks with the purpose of presenting and discussing the latest updates on each of the specific research areas and to clarify the near- and far-future planned research activities.

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

BorgWarner Turbo Systems Engineering GmbH, Kirchheimbolanden, Germany has been a collaborator of CCGEx since 2015. During 2018, BorgWarner Turbo Systems became a full partner in the Center and will have representation in the Board. One has to mention as well that Wärtsilä became partner of CCGEx in 2018.

Important contributions from our industrial partners (e.g. BorgWarner, Volvo, Volvo Cars, Scania) during 2018 consisted in hardware, CAD data, and performance maps measured on industry gas-stands. Such experimental data were used for verification and validation purposes as well as for imposing boundary conditions. Another important industry input (from e.g. Volvo Cars and Scania) has been to provide calibrated 0D/1D data with respect to various exhaust valve strategies of relevance to realistic operating conditions, data used for boundary conditions or verification purposes by the CCGEx projects.

Extensive high-fidelity calculations of several compressor and turbine geometries under various operating conditions from peak efficiency to near surge conditions have been carried out using the computing facilities at the KTH-Mechanics, the Swedish National Infrastructure for Computing (SNIC) and PDC at KTH. KTH has the capabilities to operate on several high-performance clusters for single and parallel computations KTH[1]. A variety of commercial solvers as well as developmental research ("in-house") Large Eddy Simulation (LES) based codes can be used, which incorporate among other features, e.g. sliding mesh capabilities and aeroacoustics prediction capabilities. The available commercial software programs include among other Star-CCM+ by CD-Adapco™, ANSYS ICEMCFD®, ANSYS CFX, Fluent®. Additionally, advanced post-processing methods developed "in-house" are in use at KTH-Mechanics, e.g. Proper Orthogonal Decomposition (POD) and Dynamic Mode Decomposition (DMD) techniques. The data processing and visualization is accomplished using e.g. ParaView, Tecplot®, Matlab, OpenDX and "in-house" developed software.

Finances 2018

During 2018, financing consisted in 10 MSEK/year in cash contributions from the Swedish Energy Agency. The same contribution, in the form of one cash part and a larger part in kind, was secured from KTH.

The main industrial partners increased their commitment to a total of 7,8 MSEK/year (as cash and in kind contributions). During the year of 2018 Borg Warner has joined the center as full member of the center, in addition Wärtsilä Oy has joined as a member ramping up under 2018.

The center embarked on a new 4-year period in 2018 and 5 new PhD students along with 2 Post Docs. were hired. The recruitment process was concluded and the new students arrived from mid year til November. Since there was a delay in recruitment, also the budget for spending under 2018 was not met. Unspent funds will be carried over to 2019.

[1] http://www.pdc.kth.se/, http://www.nsc.liu.se/, http://www.lunarc.lu.se/

Actuals vs. Budget 2018

		Budget	Actuals
		B 2018	A 2018
Ingående balans		0	0
INTÄKTER			
KTH medfinansiering		1 000 000	1 000 000
Energimyndigheten		10 000 000	10 000 000
Scania		800 000	800 000
Volvo Car		500 000	0
Volvo GTT		800 000	800 000
Borg Warner		800 000	800 000
Wärtsilä		100 000	0
SUMMA INTÄKTER		**14 000 000**	**13 400 000**
KOSTNADER			
Director	ACE 40%, MMK	800 000	720 000
Vice Director 10%	Mats MWL	180 000	180 000
Vice Director 10%	Mihai, Mekanik	180 000	180 000
Admin assistent 25%		200 000	84 666
LG members		360 000	360 000
IAB + CCGEx day		100 000	100 000
Board chairman		300 000	300 000
Travel		50 000	54 915
Meetings		50 000	55 000
Verksamhetsutveckling, internat		45 000	44 137
Konferens		50 000	35 000
Delsumma ledning		**2 315 000**	**2 113 718**
CICERO Lab			
Labchef , 20%		250 000	0
Lokalhyra lab	CICERO	120 000	108 738
Driftkostnader lab	CICERO	15 000	25 112
Delsumma CICEROlab		**385 000**	**133 850**
ITM MMK			
System Studies	ACE	450 000	450 000
Gas exchange for DISI HD	Senthil Mahendar	950 000	950 000
iSYS: ENCHEAT	Varun Venkataraman	950 000	158 333
iSYS: EXERGY LOSSES in efficient charging	Beichuan Hong	950 000	158 333
iHOT : "Interaction between ICE exhaust pulses and Turbin	Ted Holmberg	950 000	950 000
iSYS: Particulate characterization ov exhaust system	Arun Prakatsh	950 000	950 000
iHOT : "TurboMachinery interaction with exhaust pulses"	Nicholas Anton	150 000	0
iHOT: Range extender manifold and turbine	NN Post Doc	0	0
Tekniker 50%		350 000	225 000
Material		250 000	75 000
Delsumma MMK		**5 950 000**	**3 916 667**

SCI, MWL			
Non-linear system identification for Turbo chargers	NN PhD	0	0
Thermoaccoustic WHR	NN Post Doc	545 000	205 000
iCOLD: AeroGen Noise in Centrifulgal Comp	NN Post Doc	0	105 000
"TurboMachinery Acoustic Fl.Sim"	PhD Asouka Pietronemo	50 000	50 000
EAT Particulate grouping	Ghulam Majal	950 000	950 000
EAT: coordinator / researcher	Mikael Karlsson	360 000	360 000
Material		175 000	175 000
Delsumma MWL		**2 080 000**	**1 845 000**
SCI, MEKANIK			
iHOT : "Exhaust Valve Flow"	Marcus Winroth	950 000	791 667
Cold Side: coordinator / researcher	Mihai Mihaescu	450 000	450 000
iHOT: coordinator / researcher	Mihai Mihaescu	450 000	450 000
iHOT: Turbo max efficiency with pertubations	Roberto Mosca	950 000	475 000
iHOT: "Flow and Heat Transfer Effects on the Efficiency of	Shyang Maw Lim	950 000	950 000
iCOLD variable boosting system respons topertubations	Emelie Trigell	950 000	395 833
"TurboMachinery Acoustic Fl.Sim"	PhD Asouka Pietronemo	100 000	100 000
iHOT : Turbine characterization in pulsating flow	Yushi Murai	950 000	237 500
Delsumma Mekanik		**5 750 000**	**3 850 000**
SUMMA KOSTNADER		**16 480 000**	**11 859 236**
PREL RESULTAT 2018		**-2 480 000**	**1 540 764**

Appendix - Project descriptions/posters

On the Aerodynamically Generated Sound in Centrifugal Compressors

KTH CCGEX

Asuka Gabriele Pietroniro
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The present project aims at a physics-based understanding of the aerodynamically generated noise in centrifugal compressors and its propagation in turbocharging systems such as those employed by Volvo Cars.

An initial stage of the project focuses on using Reynolds-averaged Navier-Stokes (RANS) based formulations and available acoustic models implemented in commercial solvers. Given the unsteady nature of acoustics, the project will develop towards correlation of acoustic sources and far-field noise by means of compressible flow simulations using the detached/large eddy simulation (DES/LES) approach. Enhanced understanding of the aerodynamic noise generation process in centrifugal compressors will open new avenues towards developing noise suppression technologies.

Introduction and Motivation:

Increasing environmental concerns, along with demand for passenger safety and comfort, pressure the automotive industry to achieve competitive edges by pursuing, among others, lower noise levels for the power train system. 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.

The current research targets a quantification of the sound generating acoustic sources in centrifugal compressors for operating conditions of interest. The problem of noise propagation in the intake system will be assessed by considering the coupling between the compressor and the upstream/downstream installation elements (e.g. intercooler, ducts, resonators, bypass pressure valves). Noise suppression technologies at source will be proposed and analysed.

Setup:

BorgWarner Turbo Systems (BWTS) - MP compressor, on Siemens PLM Software STAR-CCM+, Reynolds-averaged Navier-Stokes (RANS) simulations:

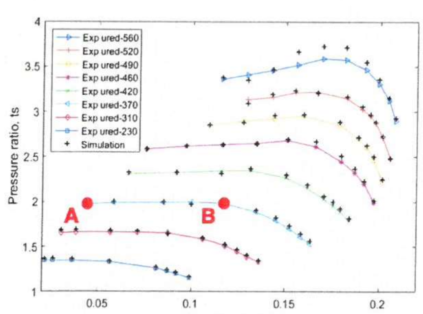
- Equations solved: Continuity, Momentum, Energy, Equation of State
- Turbulence modelling: SST k-ω
- Solver: Coupled flow (density based)
- Discretisation: 2nd order upwind
- Mesh: polyhedral, ~4.5 M cells, circumferential time averaged interface, moving reference frame

Boundary Conditions: Mass Flow Inlet, Pressure Outlet

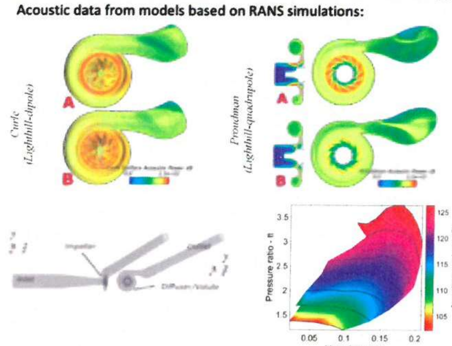
Initial conditions: velocity (depending on operating point)

Convergence was assessed monitoring residuals, pressure ratio, and mass flow rate.

Results:



Acoustic data from models based on RANS simulations:



Summary and Conclusion:

A full compressor map was simulated. The extracted RANS results showed good match with the experimental data from BWTS. Acoustic models (Proudman, Curle) were implemented on RANS data, in order to find trends in the acoustic behaviour of the specific compressor and to compute a noise map. Unsteady simulations, such as unsteady RANS (URANS) and DES/LES will be carried out in the future, to verify the initial RANS findings and to extend the analysis to direct noise calculation and correlation of acoustic sources with far field noise.

Acknowledgement:

The simulations performed in the project are carried out on the computational resources provided by the Swedish National Infrastructure for Computing (SNIC) at PDC Centre for High Performance Computing (PDC-HPC). The project is funded by Volvo Car Group.

Academic supervisors: Assoc. Prof. Mihai Mihaescu (*mihai@mech.kth.se*), Prof. Mats Åbom (*matsabom@kth.se*)

Industrial supervisors: Dr. Magnus Knutsson (*Volvo Car Group, magnus.knutsson@volvocars.com*), Dr. Chenyang Weng (*Volvo Car Group, chenyang.weng@volvocars.com*)

KTH CCGEx

Gas Dynamics of Exhaust Valves

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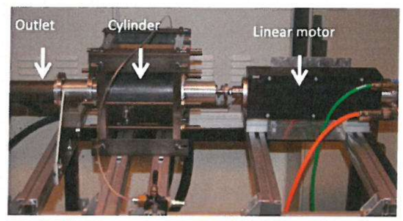
Due to tougher legislations on exhaust emissions from combustion-engine vehicles, the development of more efficient engines with lower emissions is necessary. Exhaust gases are hot and at high pressure and are thus rich in energy and to maximize the energy recovery, the engine system needs optimisation. In current one-dimensional engine simulations complex flows (such as the flow past the exhaust valves) are represented by a straight pipe-flow with a corresponding discharge coefficient, usually obtained experimentally under assumption of quasi-steadiness and independence of pressure ratio. Here these assumptions are investigated in a dynamic flow setup at different pressure ratios, with both static and dynamic valves (corresponding to engine speeds in the range 800-1350 rpm). Furthermore, experiments investigating the shock system in the exhaust port have been performed.

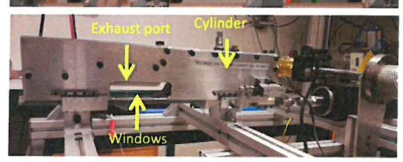
Experimental setups:

The upper photo shows the setup for the dynamic valve experiments designed for evaluation of the discharge coefficient (C_D). The valve is operated using a linear motor, which allows for a controllable valve lift profile. The exhaust port is connected to a straight outlet pipe exhausting to atmosphere. By measuring the initial temperature and the pressure in the cylinder as function of time, the dynamic mass flow can be obtained using the isentropic relationship and the gas law, giving C_D as function of time, i.e. as a function of valve lift.

$$C_D = \frac{\dot{m}_{actual}}{\dot{m}_{ideal}}$$

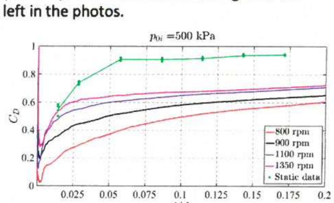
The lower photo shows the setup used for visualising shock waves in the exhaust port. It is a 30 degree slice of the above described geometry. It has two windows which allow for optical access to the valve seat region as well as the exhaust port. The gas dynamics in the port have been captured using high speed Schlieren imaging (6000 fps), under both steady and dynamic conditions.

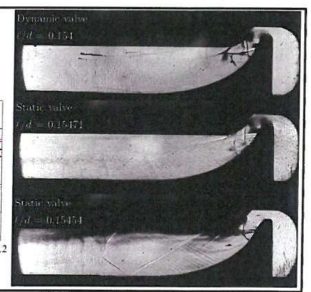




Results:

In the left figure C_D for different equivalent engine speeds is plotted as a function of valve lift over port diameter (l/d). The value of C_D shows a large dependency on engine speed, where a faster opening speed leads to a higher value of C_D. Note that C_D obtained with a static valve can be seen to generally overestimate the value of C_D. The right figure shows Schlieren images of the exhaust port with a dynamic valve (top), static valve at a "low" pressure ratio (middle) and static valve at a similar pressure ratio as in the dynamic valve case (bottom). The flow is from the right to the left in the photos.





Summary and Conclusion:

A large dependence on both valve opening speed and pressure ratio is found. Measurements using a static valve overestimates the value of C_D and shows a different shock pattern in the exhaust port, compared to a dynamic valve. This indicates that any study of the exhaust valve flow (quantitative or qualitative) should be performed under dynamic conditions at relevant pressure ratios.

Reference

Winroth, P.M., Ford, C.L. & Alfredsson, P.H. (2018), On discharge from poppet valves: effects of pressure and system dynamics. *Experiments in Fluids*, **59**(2), 24.

Supervisors: Prof. Henrik Alfredsson, Dr. Ramis Örlü

SCANIA Energimyndigheten VOLVO BorgWarner VOLVO

Valve Strategies and Exhaust Pulse Utilization

KTH CCGEX

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This project aims to improve the understanding of how pulsating exhaust flow from the internal combustion engine interacts with the exhaust turbine of the turbocharger. Variable valve actuation is used to influence the exhaust pulse properties to increase turbine efficiency and thereby improve fuel efficiency. The interaction will be primarily studied with 1-D simulation software supported by experiments on a single-cylinder Diesel engine equipped with a hydraulic variable valve actuation system and a six-cylinder Diesel engine equipped with a fixed geometry turbocharger.

Motivation

Turbocharged internal combustion engines used for road vehicles utilize pulse turbocharging, where a small exhaust manifold volume preserves the pulses generated by the operating cycle of the piston engine. The initial phase of the exhaust pulse, known as the blowdown, occurs at high flow rates due to the large pressure difference between the cylinder and exhaust manifold. The blowdown contains a large share of the energy remaining in the cylinder after the expansion stroke. It is therefore of interest to model this process as accurately as possible in 1-D simulation software.

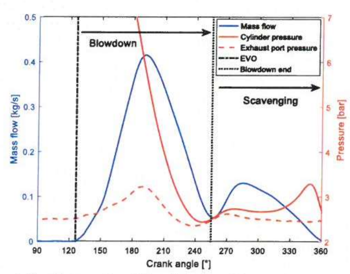

Figure 1. Blowdown portion of the exhaust emptying process.

Simulation setup

In 1-D simulation software the flow through the exhaust valve is described by a flow coefficient. This coefficient contains all the flow losses through the valve and port. It is generally assumed to be a function of only valve lift. Experiments at the fluid mechanics department at KTH indicate that this assumption does not hold true. By comparing experiments and simulations a flow multiplier model was developed to account for this deviation. The influence of the model varies with engine speed and the pressure ratio across the valve, suggesting that the impact of the modelling error varies over the operating range of a engine. This was investigated by implementing the flow multiplier model in a single-cylinder engine GT-Power model and the results compared with the default model.

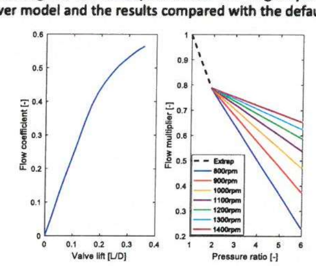

Figure 2. Default flow coefficient to the left and flow multiplier to the right

Results

On global parameters such as pumping work, the influence of the flow multiplier varies across the operating range of the engine. The largest increase in pumping work occurs at high engine speeds , see Figure 3, despite the largest reduction of flow capacity occurring at low speeds. This is due to the shorter time available to empty the cylinder at high engine speeds as not induce a large pumping penalty when the piston changes direction at the bottom of the stroke. For time resolved parameters such as the exhaust pulse, the amplitude is affected primarily by the pressure ratio over the valve and as such the influence scales primarily with load even if the effect is larger at higher engine speeds.

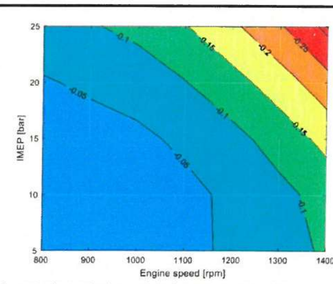

Figure 3. Flow multiplier model effect on pumping work

Conclusion

It was shown that a valve flow compensation model described in earlier publications has an impact on global and time-resolved engine parameters. This is assuming that the trends are general and applicable across engine types. Engine experiments are under way to investigate further.

Acknowledgement:

Dr. Andreas Cronhjort

Dr. Ola Stenlåås

Prof. Anders Christiansen Erlandsson

VOLVO Swedish Energy Agency SCANIA BorgWarner

On the impact of non-isothermal and pulsating flow on turbocharger turbine performance

KTH CCGEX

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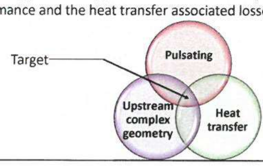
The aim of this study is to investigate the impact of upstream exhaust manifold on the performance, heat transfer and the associated flow physics of a turbocharger radial turbine operating under engine-like flow conditions. We integrate the exhaust manifold to the turbine, and compare its results to the commonly employed model without the exhaust manifold. Based on the three-dimensional (3D) and unsteady flow field predicted by using Detached Eddy Simulation (DES), the exergy budget for each turbine component is computed to quantify the aerothermodynamic losses, heat loss and turbine power. Furthermore, the impact of secondary flow due to the presence of upstream exhaust manifold is assessed. The incident angle of the flow at the rotor inlet is quantified to understand the effect of flow non-uniformities in the rotor on the turbine performance.

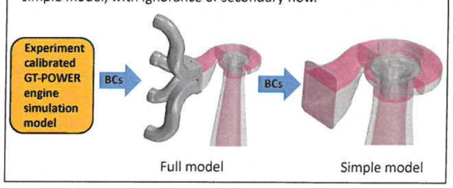
Introduction and Motivation:

A turbocharger turbine for automotive engine application is subjected to unsteady hot and pulsatile flow, with significant heat loss. The upstream exhaust complex manifold further disturbs the flow into the turbine. Despite the aforementioned operational characteristics, most of the experiments and numerical studies ignore the presence of the exhaust manifold and assume adiabatic conditions. The impact of the secondary flow and flow non-uniformities on turbine performance and heat transfer is unknown. The exergy-based approach is used to quantify turbine's performance and the heat transfer associated losses.



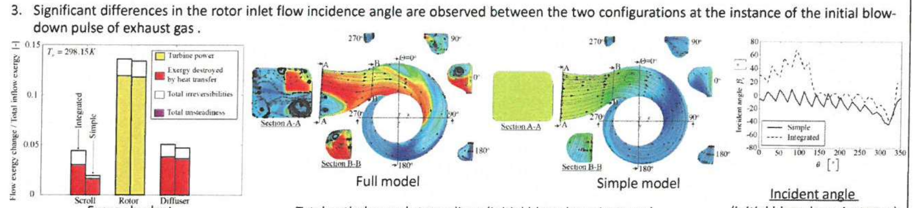
Setup:

A turbocharger turbine operating at low engine speed of 1500 rpm is considered. Time-varying boundary conditions (e.g. inlet mass flow rate, total temperature, outlet pressure) and wall temperatures predicted by an experimentally calibrated GT-POWER engine simulation model are imposed on the integrated model. Then, the time-varying flow variables at the exhaust manifold-scroll interface predicted by the integrated model is imposed on the simple model, with ignorance of secondary flow.



Results:

1. Exergy budget shows that upstream exhaust manifold enhances the heat loss and total irreversibilities in the scroll. Nevertheless, the impacts of exhaust manifold on the exergy budget of the downstream component (i.e. rotor, diffuser) are insignificant.
2. Total enthalpy distribution superimposed on flow streamlines shows that while the flow for the simple model is generally undisturbed, strong secondary flow exists in the scroll due to the presence of exhaust manifold. The flow physics between the integrated and simple models are different.
3. Significant differences in the rotor inlet flow incidence angle are observed between the two configurations at the instance of the initial blow-down pulse of exhaust gas .



Exergy budget — Total enthalpy and streamlines (initial blow down instance) — Incident angle (initial blow down instance)

Summary and Conclusion:

Results show that upstream exhaust geometry can generate secondary flow and circumferential non-uniformities, with significant impact on heat transfer and total irreversibilities. Although there is significant difference in the rotor inlet flow incidence angle circumferentially, as comparing between the two geometrical models, this does not affect the average turbine power significantly. The outcomes of this study show that integration of the exhaust manifold to the turbine is necessary to understand both the flow physics and the associated global performance correctly.

Acknowledgements:

Advisors: Mihai Mihaescu, Anders Dahlkild

VOLVO
BorgWarner
Energimyndigheten
SCANIA

Turbocharger turbine efficiency in steady and pulsating inlet flow

KTH CCGEX

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Turbocharger turbines are widely modeled under quasi-steady flow assumption when their performance are considered in integration with internal combustion engines. However, the engine exhaust gas has highly complex flow and thermal characteristics in reality. Therefore, there is a great interest in understanding its interaction with the power unit components, as well as a way to take advantage of the rich energy in hot pulsatile turbulent flow. This project mainly focuses on studying the flow field upstream and downstream of the turbine using laser diagnostics under controlled environment in CICERO laboratory, to provide time and spatially resolved data for better modelling of turbocharger turbines, for a rational integration with an engine.

Introduction and Motivation:

By virtue of advancement in computational methods, many authors have come up with various ways of modelling turbocharger turbines in unsteady condition. However, especially for small turbocharger used for automotive application, there have been lack of data to corroborate the proposed modelling because of the difficulty and limitation in experiments due to its size and harsh environment.

Nevertheless, the previous research conducted in CICERO flow facility made important input to the field: in the engine-exhaust-flow-like simulated environment, Laurantzon (2012) provided one of the first simultaneous time resolved measurements of mass flux and temperature using hot-wire anemometry. Kalpakli (2014) provided both time and spatially resolved data on the effect of bend in pipe flow using Particle Image Velocimetry, showing combined effects of secondary flow and flow pulsation on turbine performance.

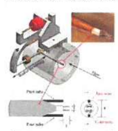
Building on these results, further campaign to obtain both time and spatially resolved data in more sophisticated setup is motivated for better physical understanding and modelling of turbine behaviour in highly turbulent pulsatile flow.

Setup:

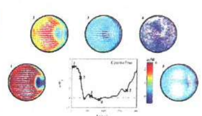
Following are considered for the experimental campaign.

1. **Improved design of pulse generator**
   - Previous design had a simple rotating ball with symmetrically-cut segments
   - Implement more controllable valve to replicate more engine-like pulsation
2. **Simultaneous time resolved laser diagnostic upstream and downstream of turbocharger, steady and pulsating flow**
   - Laser Doppler Velocimetry and Particle Image Velocimetry
   - No obstacles in the flow unlike hot-wire with traverse
   - Potential use of temperature sensitive phosphors to measure temperature field simultaneously is reviewed
   - Comparison with simpler vortex shedding flow meter
3. **Secondary flow effect due to various upstream geometry**
   - Various bending angle
   - Flow downstream of two converging pipes, partial admission

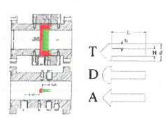
Research Activities:



Laurantzon conducted simultaneous time resolved measurements of mass flux and temperature



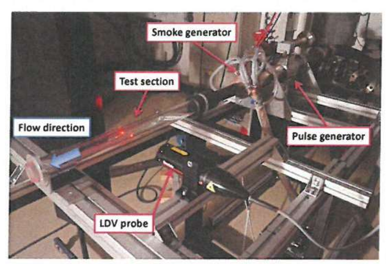
Kalpakli conducted intensive PIV measurements on bent pipe flow



Vortex shedding flow meter has been investigated by several authors

Steady and pulsating turbine performance map evaluation with:
- time and spatially resolved
- simultaneous mass flow and temperature measurement
- under various inlet flow conditions

+ Compare against simple vortex shedding flow meter measurement



First attempt on Laser Doppler Velocimetry measurement downstream of current pulse generator (February 2019)

Summary and Conclusion:

It is expected that the project will propel the knowledge on interaction of turbocharger turbine with pulsatile flow, which will be beneficial for modelling the turbine for the whole system design, based on experiments with:

1. more engine-like pulse shape
2. laser diagnostics with detailed set of time and spatially resolved flow field data, potentially with simultaneous temperature field
3. various inlet flow condition to the turbine

Acknowledgement:

Supervisors: Professor Jens Fransson, Dr Ramis Örlü

SCANIA WÄRTSILÄ VOLVO BorgWarner Swedish Energy Agency

Experimental analysis of whistle noise in a particle agglomeration pipe

KTH CCGEX

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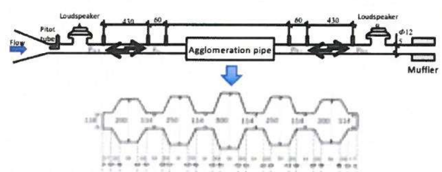
A self-sustained sound, more usually known as a whistle, refers to a distinct tonal noise created due to the interaction between the sound and flow field which is, in engineering practice, destructive as it can produce high sound and vibration levels and may result in risk for mechanical failures. In this work, a flow-related high level tonal noise was found during a measurement on a particle agglomeration pipe designed for the exhaust system of heavy-duty trucks. To investigate the origin of the detected tonal noise additional measurements were carried out. Based on the measurement result, the aero-acoustic coupling in the agglomeration pipe was analyzed, revealing that the pipe has a large potentiality to amplify the incident sound power in the presence of a mean flow. Furthermore, the Nyquist stability criterion was applied to confirm the existence of exponentially growing modes in the system at certain conditions.

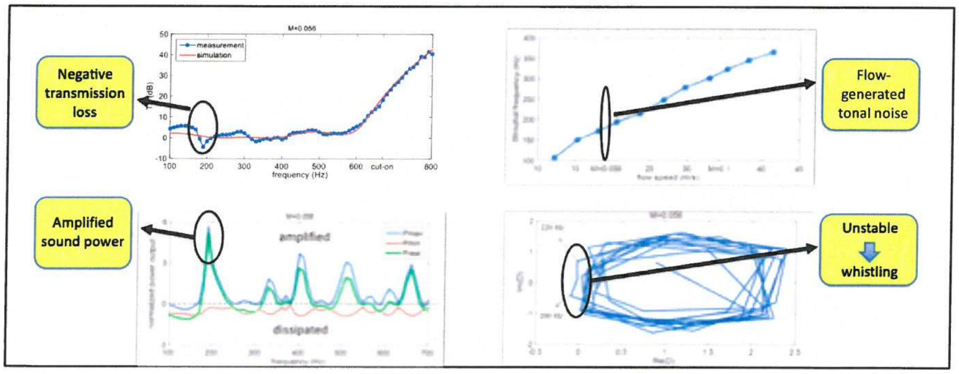
Introduction and Motivation:

To investigate the acoustic properties of the agglomeration pipe, which may have some sound attenuation ability due to its corrugated structure, a measurement campaign was carried out in the Marcus Wallenberg Laboratory (MWL). During the measurement, a clear tonal noise could be heard in the presence of a moderate mean flow in the test rig, and the spectral property of the tone is related to the flow speed. Given the sharp edges in the pipe where flow separation is prone to happen, the tonal noise might well be flow-induced noise associated with periodic vortex shedding around the edges. Furthermore, if the hydrodynamic mode (regular shedding of vortices) coincides with an available structural/acoustic mode of the pipe, and a positive (unstable) feedback loop is formulated between the two kinds of modes, the flow-induced noise will evolve into a whistle noise, which can lead to unwanted high noise levels.

Setup:

As illustrated below, the agglomeration pipe was connected to the test rig, whose upstream end was connected to an anechoic chamber where a stable and silent air flow came in, and the downstream end was connected to a muffler to reduce reflections and block external noise. Microphone arrays and loudspeakers were available on both sides of the test section for the determination of the passive property. A pitot tube was mounted on the upstream rig to measure the incident flow profile.





Summary and Conclusion:

The flow-induced noise in a quasi-periodic corrugated pipe was experimentally analyzed, with the vortex-sound interaction quantified by the measured two-port data. Two formulations to describe the net power output were provided, both of which showed that the pipe had a large potentiality to amplify the incident sound power. The stability of the system was checked via the Nyquist stability criterion, confirming the noise as a whistle.

Acknowledgement:

The authors would like to express their sincere gratitude to Dr. Mikael Karlsson for his kind support and valuable suggestions during the work. The financial support from all the sponsors of CCGEx is gratefully acknowledged. H.Tiikoja gratefully acknowledges the financial support from the Estonian Research Council grant PUTJD681. Also, support from the Chinese Science Council (CSC) is acknowledged.

KTH VETENSKAP OCH KONST

KTH CCGEX

Particulate characterization in the gas exchange system of DI/SI engines

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The work is aimed at reducing the particles emitted from a DI/SI engine. Understanding the evolution of particles in the exhaust system of a DI/SI engine is a step towards it. The influence of the various geometries in the exhaust line will be studied. For this purpose, particulate size distributions will be measured along the exhaust system of an engine. A 1-D model of the evolution of particle size distribution will be subsequently developed. Based on the gained knowledge, a hydrodynamic agglomeration device will be tested for particle grouping and the devices shall be fine-tuned for best agglomeration of particles.

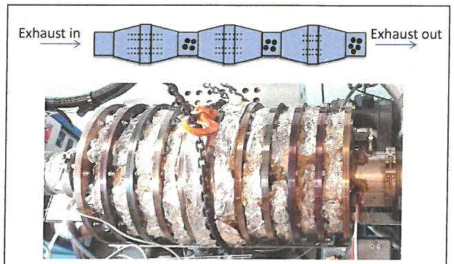
Objectives:

The study examines the evolution of non-volatile particles with respect to total Particle Number and particle size distribution in an agglomeration pipe (AP) and straight pipe (SP) owing to:

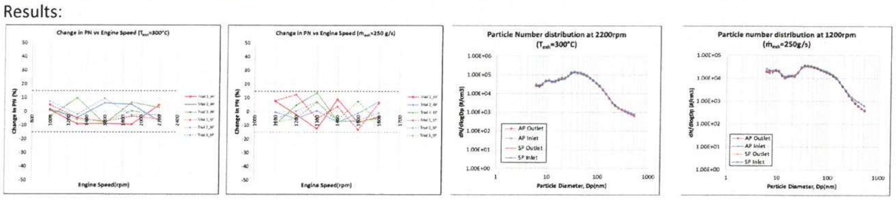
(i) the effect of exhaust mass flow rates

(ii) the effect of exhaust temperatures

(iii) the effect of engine speed



Results:



Research questions (2018-19)

- How does particle size distribution change along various exhaust systems?
- How does sampling line influence the measurement of particles?

Research activities (2017-18)

- Design and fabrication of the agglomeration pipe and moving measuring probe system – completed!
- Experimental Campaign on the Measurement of particle number and the size distribution under various steady state engine operating points with the standard agglomeration device – completed!
- The Results are published in SAE 2019-01-0044 in International Powertrains, Fuels and Lubricants Meeting, San Antonio, TX, USA

Acknowledgements:

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Supervisor: Ola Stenlåås

Energimyndigheten SCANIA VOLVO VOLVO BorgWarner

Volumetric Expanders for Waste Heat Recovery in Heavy-Duty Trucks

KTH CCGEX

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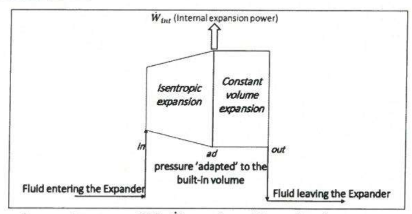
Recovering waste heat from Heavy Duty (HD) truck engines is beneficial in improving fuel economy and reducing emissions. Waste Heat Recovery (WHR) is being implemented in HD truck engines using the Organic Rankine cycle (ORC) system that comprises of Heat exchangers, Pump and an Expansion machine/Expander. WHR from these type of engines is challenging due to their transient behaviour including changes in vehicle speed and load, road profile, ambient conditions, etc. To handle this behaviour and to achieve effective heat recovery, it is necessary to study the adaptability of the components of the ORC system, in particular, of the Expanders. The aim of this work is to analyze the performance of a Volumetric Expander at different boundary conditions, with respect to its built-in volume ratio.

Introduction and Motivation:

The transient behaviour of a HD truck engine lays constraints on the evaporating and condensing boundary conditions which in turn affect the performance of the Expander used. Based on the geometry, every volumetric Expander has a built-in volume ratio ($r_{v,in}$), that is, the ratio of volume of the fluid before discharge (V_{ad}) to the volume of the fluid before expansion (V_{in}). The built-in volume ratio has a corresponding Design Pressure Ratio (DPR) defined by the formula, $\frac{P_{in}}{P_{ad}} = (r_{v,in})^{\kappa}$, where κ is the specific heat ratio of the fluid. In transient conditions of a typical HD truck engine, it is not always possible to maintain an operating pressure ratio (OPR) that matches the DPR. Therefore, it is necessary to analyse the performance of a volumetric Expander having a fixed volume ratio, at different boundary conditions, to identify the zones of efficient operation. In this work, a semi-empirical model representing a Scroll Expander using R123 as the working fluid is implemented to analyse the Expander's performance characteristics at various built-in volume ratios with different boundary conditions imposed to the Expander.

Schematic depiction of the model representing the expansion process inside the Scroll Expander

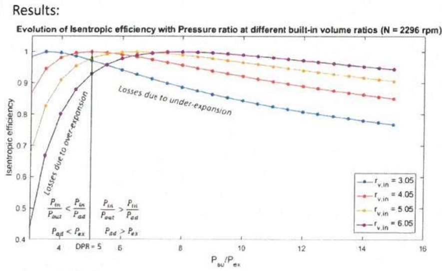


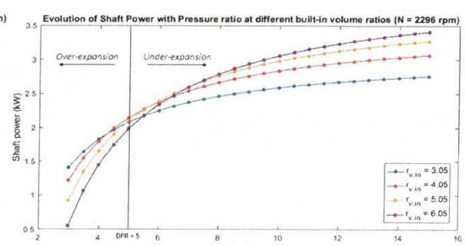
Internal expansion power (W), $\dot{W}_{int} = \dot{m}_{fluid}(h_{in} - h_{out})$;

Isentropic efficiency, $\eta_{is} = \frac{\dot{m}_{fluid}(h_{in} - h_{out})}{\dot{m}_{fluid}(h_{in} - h_{out,s})}$

where, h – enthalpy, s – isentropic, $\dot{m}_{fluid}$ - mass flow rate of the working fluid, W - watt

Results:





- When the OPR deviates from the DPR,
  - Expander's Isentropic efficiency decreases gradually due to under-expansion losses, but, decreases abruptly due to over-expansion losses.
  - Shaft power decreases during the over-expanded operation, but increases during the under-expanded operation.
- With the increase in built-in volume ratio, the peak efficiency of the Expander shifts to higher Design Pressure Ratios.

Summary and Conclusion:

- Choosing a Scroll Expander with a built-in volume ratio whose Design pressure ratio falls in the under-expanded region, leads to wider operating ranges with less loss in efficiency compared to the losses in the over-expanded region.
- Increasing the built-in volume ratio aids in increasing the Expander's Shaft power and Isentropic efficiency with a compromise on Expander's volume and weight.
- Applying the concept of variable built-in volume ratio in volumetric Expanders would help achieve peak efficiencies with increased Shaft power.

Acknowledgement:

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2. Dr. Jens Fridh, Energy technology, KTH
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Energimyndigheten SCANIA VOLVO VOLVO

Exergy analysis for high efficiency ICE gases exchange system

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This study aims to provide insight on the energy availability (exergy) of ICE gas exchange system architecture with respect to design parameters and engine performances. Efficiency improvement and exergy optimization of ICE gases exchange system are studied utilizing 1D engine modelling with experimental validation. This study focuses on applied exergy observation, modelling, and optimization concerning ICE systematic performance, especially for its relation with devices (e.g. valve motion, gas path geometry, turbocharger behaviors, EGR, waste heat recovery, etc.) of the overall gas exchange system.

Introduction and Motivation

Traditional approaches using the 1st-law of thermodynamics have been wildly used for describing energetic efficiency within gas exchange systems. However, relevant researches based on the 2nd-law still remain at the macroscopic analysis without exploiting the utilization of the exergy flow in term of detailed inlet and exhaust flow manners.

In this study, we investigate the thermal details of ICE gases exchange system associated with the exergy dissipation and utilization as functions of engine parameters. An novel exergy-based approach is proposed to identify irreversibility of processes detrimental to overall ICE performance, and to further optimize the systemic architecture and operating strategy by reducing the irreversibility and increasing exergy extraction.

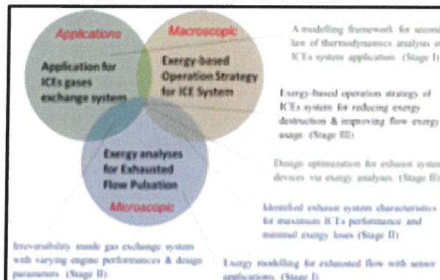
Objective

Macroscopic view: **exergy analyses of ICEs system for reducing system irreversibility and improving the exergetic utilization.**

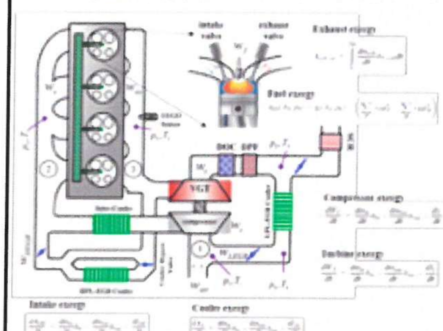
1. To establish a 1D model-based framework for modelling exergy flow in overall engine system;
2. To identify the ICEs components or processes that affect the major exergetic destruction.
3. To optimize the cooperating strategy integrating multiple gases-path devices for maximizing exergetic utilization.

Microscopic view: **understanding the ICEs exhaust pulse flow and its relations with the behavior of gases-path devices from exergetic perspective.**

1. To improve understanding of the character of the irreversibilities of gas exchange processes associated with different engine performances & design parameters.
2. To develop an applicable exergy-based methodology to optimize the design parameters & architecture of gases-path devices.



Stages of exergy project and relevant research areas



Schematic diagram of exergy analyses framework for an example diesel engine with dual-loop EGR system

Exergy destroyed can be measured using entropy generation:

- Chemical reaction, i.e. combustion process (including fuel oxidization and internal energy exchange);
- Flow restrictions occurring at the inlet and exhaust paths (e.g. throttling effects, expansion, turbulence and vorticity, friction, flow loss) ;
- Dissipative effects such as: mixing process (for example, fresh charge and burned gas), heat transfer.

Research activities (2018-19)

- Detailed 1D model describing exergy destruction in ICE exhaust system
- Exergy-based approach for improving the design parameter & architecture of the gas exchange system.

Research questions (2018-19)

- How to model and observe the exergy destruction in the gases exchange system? The weakness of 1D model?
- How to improve system exergetic efficiency based on exergy model (associated with exhaust flow manners)? [Comparison of various system architectures and operating strategies.]

Measurement of Instantaneous Exhaust Gas Flow Parameters for Gas Exchange Applications

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This project aims to investigate the validity of common practice measurement and modelling approaches concerning pulsatile exhaust gas flow with the use of state-of-the-art time resolved measurement of pressure, temperature and velocity (mass flow) in on-engine operating conditions and arrive at a better understanding of our current ability to describe the instantaneous flow parameters in the engine exhaust. A better understanding of these parameters could provide insight 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 aftertreatment system which directly impact the efficiency and emissions of the internal combustion engine.

Introduction and Motivation:

The pulsatile nature of exhaust gas flows in internal combustion engines is often characterised in on-engine conditions by fast sampling pressure sensors in the exhaust runners while the instantaneous mass flow and gas temperature are estimated using reduced dimension models. These models are typically calibrated to match with the steady-state cycle averaged conditions of pressure, temperature and mass flow for various engine operating conditions. The modelled pulse that originates in the exhaust is dependent on the implementation of the discharge coefficient through the exhaust valves.

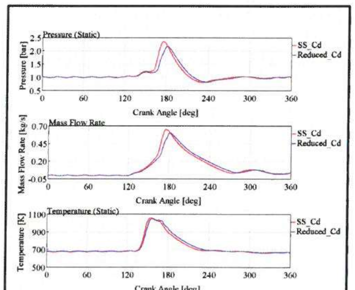
The continued increase in the application of reduced dimension modelling to develop, control and optimise new and complex engine-boosting systems demands their predictive capability and accuracy to be higher than previously required. Modelling and measurement uncertainties and errors at the reduced dimension system model level limits our understanding of the system and its interactions along with arriving at optimal solutions that are skewed by errors and uncertainty in the models and the experimental data used to calibrate them.

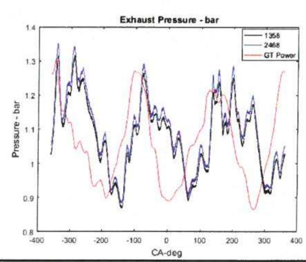
A qualitative comparison of the exhaust pulse observed at the runner simulated in GT-Power for a single-cylinder HD engine between an exhaust valve with steady state (SS_Cd) based discharge coefficient and a reduced discharge coefficient during the blowdown phase (Reduced_Cd).

Differences in amplitude and phase are clearly observable in the instantaneous pressure and mass flow while it does not appear significant for the gas temperature in this case.

A comparative example from a LD gasoline engine shows the GT-Power based pressure estimate to deviate from the experimental observations for two different cylinder banks. The valve flow model is considered to be a significant factor for these deviations.

These deviations necessitate the need to improve the valve flow model and possess a measurement reference for the temperature and mass flow traces to best represent the instantaneous exhaust flow in reduced order models





Objectives:

- Investigate and contrast methods to measure/estimate instantaneous gas temperature and mass flow in the engine exhaust stream
- Determine and assess impact of on-engine dynamic discharge coefficient of exhaust valves on instantaneous exhaust conditions through reduced order models and instantaneous pressure measurements
- Analyse instantaneous exergy of the flow and efficiency of the turbine based on measurement/estimation and reduced order models

Research Activities 2019:

•Literature review of measurement methods and techniques for time resolved pressure, temperature and velocity (mass flow)

•Fabrication and evaluation of custom thermocouple probe for instantaneous temperature measurement

•Experimental campaigns:

- Determine on-engine dynamic discharge coefficient of exhaust valves and significance on 1D flow parameter estimates

Supervisors: Prof. Anders Christiansen Erlandsson,
Dr. Andreas Cronhjort and Dr. Ola Stenlåås

SCANIA WÄRTSILÄ VOLVO VOLVO BorgWarner Energimyndigheten

KTH CCGEx

Non-linear Modeling for Thermoacoustic Engine and Its Application for Automotive WHR

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Introduction

A ThermoAcoustic Engine (TAE) can convert heat power to mechanical power (acoustic power) with high efficiency that, then, can be harvested into electricity. Theoretically, it can be driven by almost any source of heat, e.g., the hot exhaust gas from automotive engines. Compared with other External Combustion (EC) engines, the TAE has high reliability since there are no mechanical moving parts in it. This project aims at the recovery of waste heat from automotive exhaust systems by implementation of TAE to reduce the fuel consumption and environmental pollution. In the present work, models, including non-linear effects, are set up for components in the TAE and validated against the experimental data in the published literature [1]. To further our understanding of the operation of a TAE, a characteristic study of the TAE is performed. Besides, a practical application of the TAE for a light-duty vehicle is studied on system level.

Objective

Linear thermoacoustic models are insufficient to describe the propagation and dissipation of acoustic wave in a TAE operating at high-amplitude points when non-linear effects are significant. The objective of the present work is to set up robust and reliable non-linear models, and, based on these models, to establish the simulation codes which can contribute as an effective tool for design, optimization and analysis of TAE systems. Then, a detailed characteristic study of a typical traveling-wave TAE is to be performed for validation of these models and further understanding of this TAE's operation. Finally, combined with the typical operating points of light-duty vehicles, a practical implementation of this TAE is studied.

Approach

A 1-D low-order acoustic network in the frequency domain [2] is used in this work to represent the linear thermoacoustic system. Based on it, all non-linear terms are added into the network as resistances to account for non-linear effects.

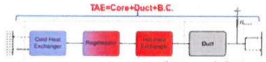

Figure 1 The model to represent the TAE setup.

The fundamental 1-D low-order linear approximation for thermoacoustic systems could be written in differential matrix form:

$$\frac{d}{dx}\begin{pmatrix} p_1 \\ U_1 \end{pmatrix} = \begin{pmatrix} 0 & -(i\omega l + r_v) \\ -\left(i\omega c + \frac{1}{r_k}\right) & \frac{f_k - f_v}{(1-f_v)(1-\sigma)T_m}\frac{dT_m}{dx} \end{pmatrix}\begin{pmatrix} p_1 \\ U_1 \end{pmatrix}$$

The source of generation/amplification of acoustic power in TAE-temperature gradient

1.Non-linear losses

In the present work, three important non-linear losses induced by different factors are considered.

a)Turbulence-induced non-linear loss

The non-linear loss caused by turbulence is introduced into each component of TAE by adding an extra resistance related to 'turbulence' or vorticity created by the oscillating gas and has the form [3]:

$$r_{v,turb} = \frac{64\rho_m|U_1|}{3\pi^3 D^5}\left[f_M - \left(1 - \frac{9\pi}{32}\right)|Re_1|\frac{df_M}{d|Re|}\right]$$

where,

$$\frac{1}{\sqrt{f_M}} = -2\log_{10}\left(\frac{\varepsilon}{3.7} + \frac{2.51}{Re\sqrt{f_M}}\right)$$

b)Porosity-induced non-linear loss

The regenerator is similar to a porous medium. An extra loss could be caused by this special structure and is related to its porosity.

$$r_{v,prop} = 150\mu\frac{(1-\phi)^2}{D_h^2\phi^3 A} + 1.75\rho_m\frac{1-\phi}{D_h A^2\phi^3}|U_1|$$

c)Non-linear loss due to system architecture

In piping systems, transitions between channels or change of direction of channels may induce additional energy loss manifested by means of pressure drop. For a bent tube with a certain bending angle and a radius of curvature, the lumped resistance is represented by:

$$R_{cur} = -\frac{8\theta}{3\pi^2}\frac{\rho_m}{A^2}\left[1.31 + 0.159\left(\frac{4D_h}{r}\right)^{3.5}\right]|U_1|$$

2.Temperature distribution along regenerator

The temperature gradient in the regenerator is the main source of generation/amplification of acoustic power in a TAE and can be estimated by the total power. Its value reflects the imperfection of the regenerator and influence the required heating and cooling power through heat exchangers of TAE directly. Based on the energy conservation, the total power flow in regenerator is a constant and can be determined by iteration until the temperatures at its two sides match specified values.

Results

1.Model validation

The experimental data for a traveling-wave TAE in the published literature is used to validate our simulation results. The simplified schematic of this TAE is shown in the Figure 2. The operating frequency of this TAE is ~84Hz with pressurized Helium (~30 bar) as working media.

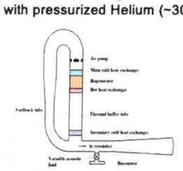

Figure 2 Simplified schematic of the traveling-wave TAE (not to scale).

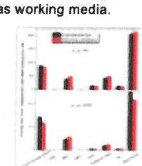

Figure 3 Comparison of exergy loss over components of this TAE for two operating points with different oscillating amplitudes.

- ***A good agreement for the exergy loss over each component of TAE indicates that the models are able to estimate the actual losses with acceptable accuracy.***

2.Characteristic study of the investigated TAE

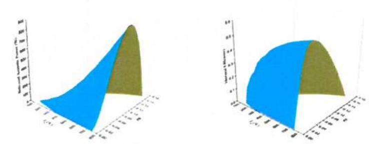

Figure 4 The characteristic surface of the investigated TAE. The left and right figures represent the delivered acoustic power and thermal efficiency, respectively. PR is the normalized pressure denoting the oscillating amplitude. The cooling temperature is kept as 30 ℃.

- ***The heating temperaure influence not only the output capability of TAE, but also the available range of oscillating amplitude.***

3.Application for automotive waste heat recovery

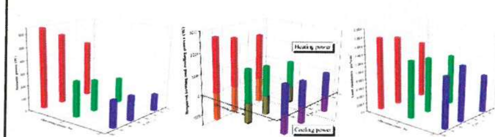

Figure 5 System performance at three operating points from a standard test cycle for a passenger car whit three cooling temperatures. The left, middle and right represent the maximum delivered acoustic power, required heating and cooling power and required load resistance at every operating point, respectively.

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Acknowledgement

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