Interim research report CCGEX

November 4

2016

For the International Advisory Board

CCGEx at the Royal Institute of Technology (KTH) • www.ccgex.kth.se

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Summary

The Competence Center for Gas Exchange (CCGEx) at the end of 2016 will enter in the last quarter of its third period (2014-2017). Funding from the Swedish Energy Agency, KTH, Scania, Volvo Cars and Volvo GTT is agreed for the 2014-2017 period. The Center's third period of activity involves a continuation of the operations in the three established research areas: ”Cold Side: Compressor off Design - CoD”, ”HOTSIDE”, and ”Engine After Treatment - EAT”. Moreover, a new area ”Power Train System Integration - SYSINT” has been introduced during 2016 and will be developed further in 2017.

All projects, PhD Students and research activities are organized within the four mentioned research areas. The purpose with the Center’s activities is to build a deeper knowledge of the gas exchange processes, 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 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.

When it comes to academic results, during 2016 the CCGEx published 18 peer-reviewed publications, among which 13 journal publications. Most of the CCGEx Doctoral students are now in their third year, three of them being in position to defend their Doctoral thesis during the 2017. One Licentiate thesis was defended during 2016 and three Licentiate thesis seminars are scheduled for 2017. CCGEx has been/will be represented at eight international conferences in 2016 (e.g. ASME-TurboExpo meeting, Seoul; THIESEL meeting, Valencia; 11th International ERCOFTAC Symposium on Engineering Turbulence Modelling and Measurements, Palermo; IMechE Turbochargers and Turbocharging meeting, London; Baltic-Nordic Acoustic meeting, Stockholm; Noise, Vibration and Harshness Congress, Graz; American Physical Society-Division of Fluid Dynamics meeting, Portland; 21st Supercharging Conference, Dresden). Four MSc projects were carried out into connection with the Center during 2016.

During the course of the year, industry contributions have been added via e.g. Volvo GTT, BorgWarner in addition to the in-kind contributions from Scania and Volvo Cars. Two new PhD students joined CCGEx during 2016, one as part of the EAT research area and the second as part of the SYSINT research area. An Industry PhD student (Volvo Cars) and a Postdoctoral student (Borg Warner) will join CCGEx before the end of the year. The research activities for these two projects are firmly established with the industry partners. By the end of 2016, the program is essentially fully funded, with a positive outlook regarding future in-kind contributions from the industry.

Introduction

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 internal combustion engine center of KTH (CICERO 2006-2009, CCGEx 2010-2013), this period means that the center will enter its third financing round. The purpose of the annual report of 2016 is to present the current situation and a layout plan for 2017.

Background

The Competence Center for Gas Exchange (CCGEx) (previously CICERO), was initiated in 2006 as a third competence center in the field of internal combustion engine technology.

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 number of 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 makes 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 internal combustion engine concepts.

Players in the Swedish engine industry have been early adopters of supercharging, 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. 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 strong competence in the field. This includes expert knowledge as well as researchers with relevant skills. The field Gas Exchange and Supercharging is specific to Competence Center Gas Exchange (CCGEx) and exclusive for KTH – it is not covered by any of the other competence centers.

The purpose of CCGEx is to carry out academic research with the highest quality in the field Gas Exchange in the Internal Combustion Engine, in close collaboration with the Engine Industry, and 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. Through this increased understanding, researchers in CCGEx will be able to identify new technical possibilities and solutions in gas exchange, EGR systems, supercharging 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), and the turbocharging manufacturer BorgWarner Turbo Systems Engineering GmbH in Germany.

The involved departments at KTH are the Department of Machine Design (Internal Combustion Engines), Department of Mechanics (Computational and experimental fluid mechanics), and Department of Aeronautical and Vehicle Engineering (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.

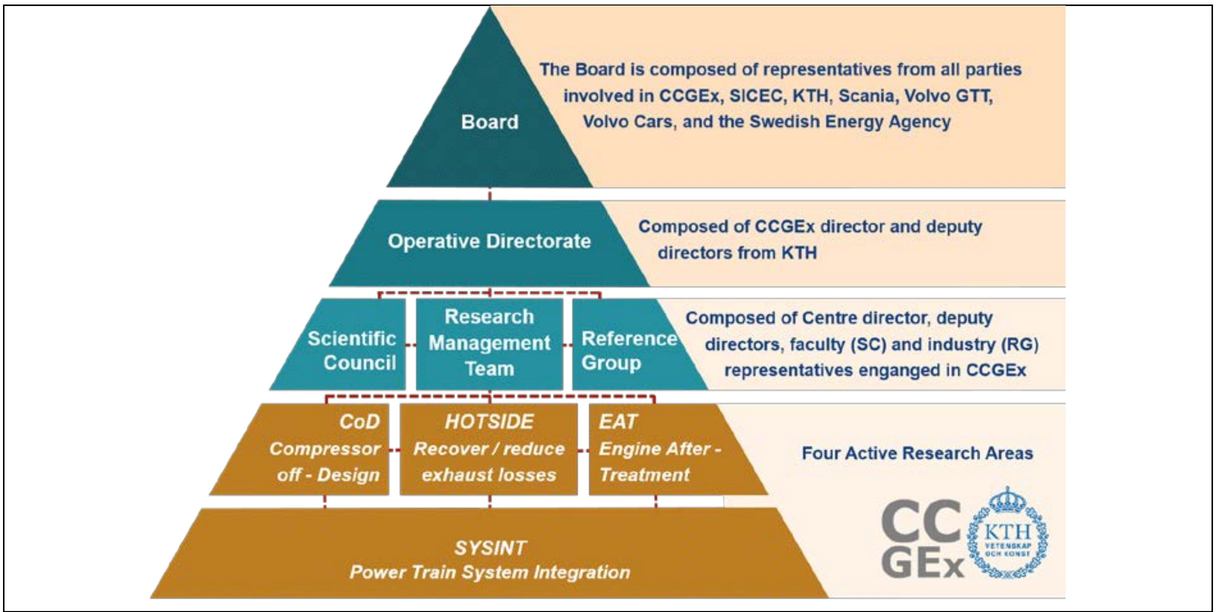


Figure 1: CCGEx Organization.

As shown in the diagram above (Fig. 1), there are four research areas active in the Center, namely: ”Cold Side: Compressor off Design - CoD”, ”HOTSIDE”, ”Engine After Treatment - EAT”, and ”Power Train System Integration - SYSINT”.

The majority of research within CCGEx is conducted by Doctoral students (including Industry PhD students) under faculty guidance and supervision. 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. Thus, there is a strong collaboration with the identified industry working groups, which are linked to the four CCGEx active research areas and individual projects. These working groups meet regularly 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, the following persons were engaged during 2016:

Board

Sören Udd	SICEC Ordförande
Jan Wikander	KTH
Daniel Söderberg	KTH since 09/2016

Mikael Lindström	KTH untill 09/2016
Jonas Holmborn	SCANIA since 09/2016
Per Lange	SCANIA untill 09/2016
Lucien Koopmans	VCC
Johan Wallesten	Volvo GTT
Anders Johansson	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	Fl Mech
Mats Åbom	MWL
Susann Boij	MWL until 01/2016
Andreas Cronhjort	MFM
Christophe Duwig	Mek
Bengt Fallenius	Fl Mech & CICERO Lab
Mikael Karlsson	MWL
Bertrand Kerres	MFM (PhD Stud. representative) since 09/2016
Christer Spiegelberg	MFM
Ramis Örlü	Fl Mech until 09/2016

Scientific Council

Anders Christiansen Erlandsson	MFM
Mihai Mihaescu	Fl Mech
Mats Åbom	MWL
Henrik Alfredsson	Fl Mech
Hans Boden	MWL
Andreas Cronhjort	MFM
Christophe Duwig	Fl Mech
Jens Fransson	Fl Mech
Laszlo Fuchs	Fl Mech

The Research Team

Research Area ”Compressor off Design - CoD”	
Mihai Mihaescu	Project Leader
Raimo Kabral	PhD Student, MWL
Bertrand Kerres	PhD Student, MFM/Mechanics
Elias Sundström	PhD Student, Fl Mech
Athanasia Kalpakli Vester	Post-doc, Assoc. project, Fl Mech
Research Area “HOTSIDE”	
Mihai Mihaescu	Project Leader
Chris Ford	Researcher, Assoc. project, Fl Mech, until 01/10
Shyang Maw Lim	PhD Student, Fl Mech
Marcus Winroth	PhD Student, Fl Mech

Ted Holmberg	PhD Student, MFM
Nicholas Anton	Industrial PhD Student (Scania), MFM
Research Area "EAT"	
Mikael Karlsson	Project Leader
Ghulam Mustafa Majal	PhD Student, MWL/Mechanics
Zhe Zhang	PhD Student, Associated project, MWL
Arun Prasath	PhD Student, MFM
Mireia Altimira	Researcher, Fl Mech
Research Area "SYSINT"	
Anders Christiansen Erlandsson	Project Leader
Senthil Mahendar	PhD Student, MFM (Volvo GTT)
Sandhya Thantla	PhD Student, MFM WHR associated project

Measurable Outcomes

CCGEx deliveries 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 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 table represents a summary of the main measurable outcomes delivered by CCGEx in 2016.

Doctoral theses (HT2015-HT2016)	1
Hynninen, A. (HT2015)	*Acoustic In-duct Characterization of Fluid Machines with Applications to Medium Speed IC-engines.* PhD thesis, KTH The Marcus Wallenberg Laboratory for Sound and Vibration Research, ISBN: 978-91-7595-765-4, Stockholm, Sweden
Licentiate theses	1
Sundström, E. (2016)	*Centrifugal compressor flow instabilities at low mass flow rate.* Licentiate thesis, KTH Mechanics, ISBN: 978-91-7595-931-3, Stockholm, Sweden.
MSc theses	5
Heide, J. (2016)	Numerical analysis of evaporating sprays in a cross flow environment. KTH Mechanics, Stockholm, Sweden.
Sanz, S. (2016)	Analytical prediction of turbocharger compressor performance: A comparison of loss models with numerical data. KTH Machine Design, Stockholm, Sweden.
Persson, T. (2016)	*Wind tunnel effects on truck aerodynamics and soiling*. Scania AB, Södertälje and KTH Mechanics, Stockholm, Sweden.
de Laval, J. (2016)	Simulation of thermal tests in the climatic wind

	tunnel CD7 at Scania. Scania AB, Södertälje and KTH Mechanics, Stockholm, Sweden.
Chiara Olivieri (2016)	Characterization of flow structures during continuous valve opening testing for swirl number evaluation in diesel engine cylinder.), Scania AB Södertälje and University of Bologna.
Journal Publications	13 - J. of Visualization - J. Sound Vibration - Springer Proceedings in Physics - J. of Energy - Int. J. Heat Fluid Flows - Sensors - SAE Int. J. Engines - SAE Int. J. Mater. Manuf. - Appl. Mech. Rev. - Meas. Sci. Tech.
Conference Contributions	- ASME-TurboExpo meeting, Seoul - THIESEL meeting, Valencia - 11th International ERCOFTAC Symposium on Engineering Turbulence Modelling and Measurements, Palermo - IMechE Turbochargers and Turbocharging meeting, London - Baltic-Nordic Acoustic meeting, Stockholm - Noise, Vibration and Harshness Congress, Graz - American Physical Society –Division of Fluid Dynamics meeting, Portland - 21st Supercharging Conference, Dresden
New Industrial Partners/Collaborations	- BorgWarner Turbo Systems Engineering GmbH, Kirchheimbolanden, German as partner in the Center - GE Oil & Gas, Italy as collaborator
Invited Seminars	- RWTH Aachen University - KAIST Dept of Mechanics, KOREA - European Research Community on Flow, Turbulence and Combustion (ERCOFTAC) workshop by PC Nordic, Stockholm

Overview on Research Activities 2016

Over the year of 2016, CCGEx research efforts continued to be focused on the well-defined now research areas “Compressor off-design operation - CoD”, “HOTSIDE”, and “Engine After Treatment - EAT”. Moreover, a new research area “Power train System Integration - SYSINT” was introduced.

Research Area: Compressor off-Design (CoD)

Summary: Use advanced experimental and computational techniques with the purpose of predicting and understanding compressor surge.

A general flow chart depicting the research activities within the CoD research area is presented in Fig. 2. Over the last year, within this framework, the experimental efforts at CICERO & MWL Labs continued for the evaluation of compressor flow and aeroacoustics at design and off-design conditions. Moreover, 0D/1D modeling and 3D CFD predictions (steady-state and high-fidelity CFD) are complementing the experimental efforts. The

Among the targeted aims with the individual projects are: characterize and understand compressor behaviour at low mass flow rates and high pressure ratios by assessing the flow structures and the developed flow instabilities; assessment of compressor installation effects on compressor performance; identify surge precursors and develop more sensitive methods for surge prediction; assess the validity range of 0D/1D models for compressor performance under different operating regimes; develop improved techniques for studying scattering and generation of sound in centrifugal compressors.

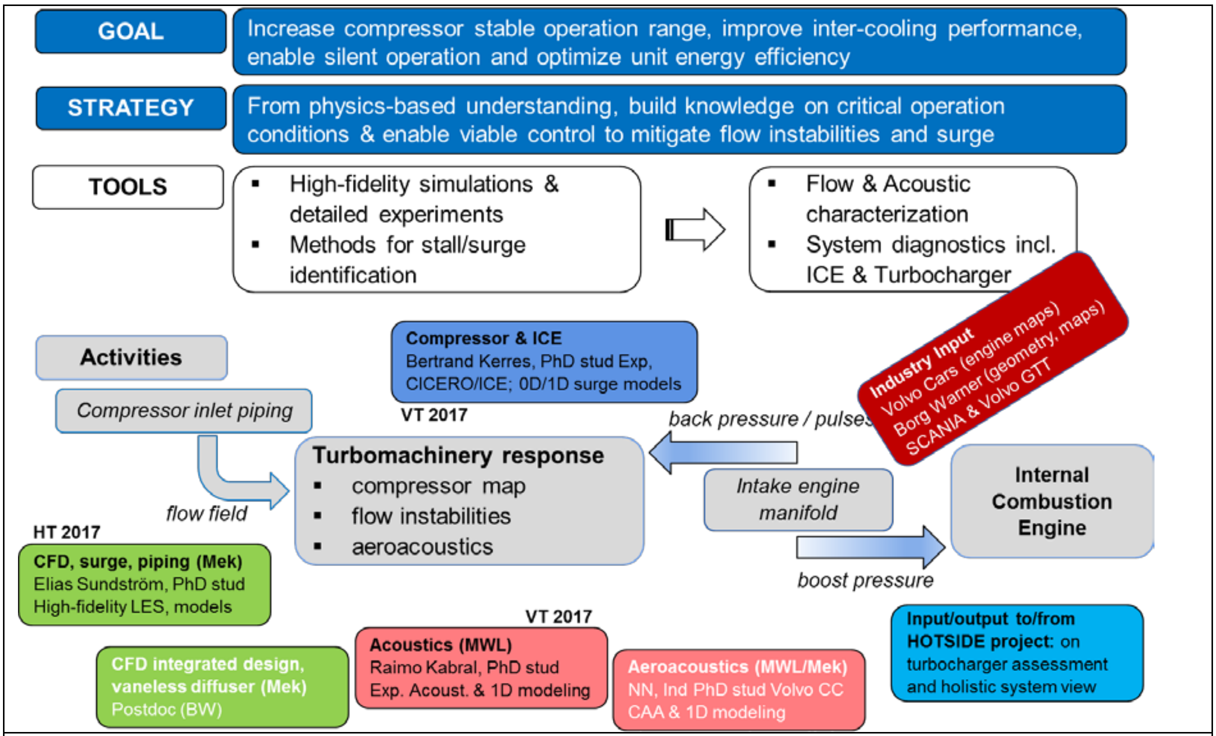


Figure 2: Overview of the current and foreseen activities within the "Compressor off-Design" research area.

As depicted in Fig. 2, three PhD students are presently involved in the CoD research activities. Two more persons will join the group once the recruitment processes for an Industrial PhD student (Volvo Cars) and a Postdoctoral student (BorgWarner) are finalized (HT2016).

CoD - research highlights (2016):

The high-fidelity Large Eddy Simulation 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. Upstream installation effects (i.e. bended pipe geometries) on surge line were quantified experimentally. An assessment of the validity range for steady-state RANS & theoretical models for predicting compressor performance maps associated with particular compressors provided by BorgWarner was carried out.

The combined experimental and simulation efforts allowed establishing synergies between the different individual projects within the CoD research area. The experimental data obtained at the University of Cincinnati, USA (by Dr. Gutmark and his team) were extensively used not only for verifying and validating the CFD solver but also for assessing a new proposed surge criterion, which is based on monofractal/multifractal distinction of the pressure signal. The results are summarized in four joint publications (published or submitted for publication) between the three departments (MWL-MFM-Fl. Mech) involved in CCGEx.

The aeroacoustics measurements carried out in CICERO-Lab led to a successful determination of aero-acoustic coupling and characteristics in the system (centrifugal compressor and piping arrangement) at both design and off-design conditions. For such an arrangement, an efficient and compact noise control solution, based on the optimal flow channel wall impedance (Cremer impedance) was developed and proposed.

Short & medium-term plans with CoD:

- Detailed experimental & computational efforts focused on the BorgWarner geometries (flow & acoustics)
- Evaluation / calibration /development of improved compressor surge models & assess the mechanisms for losses in centrifugal compressors
- Noise generation mechanisms; quantification of the acoustic noise sources at off-design; noise supression
- New Ind. PhD stud: Compressor Aeroacoustics (VCC) & Postdoc: CFD integrated design (BW); by HT2016
- PhD defenses: Raimo Kabral (Mar 2017); Bertrand Kerres (Jun 2017)

Research Area: HOTSIDE

Summary: **HO**listic approach **T**argeting to reduce/recover exhaust losses and increase **S**park **I**gnited & **D**iesel **E**ngines performance (HOTSIDE). Integrated use of 1D and 3D flow modelling together with measurements for assessing exhaust flow, maximize exhaust energy extraction and increase ICE efficiency.

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 characterising the pulsatile behaviour 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. An overview of the project and of the research activities is presented in Fig. 3.

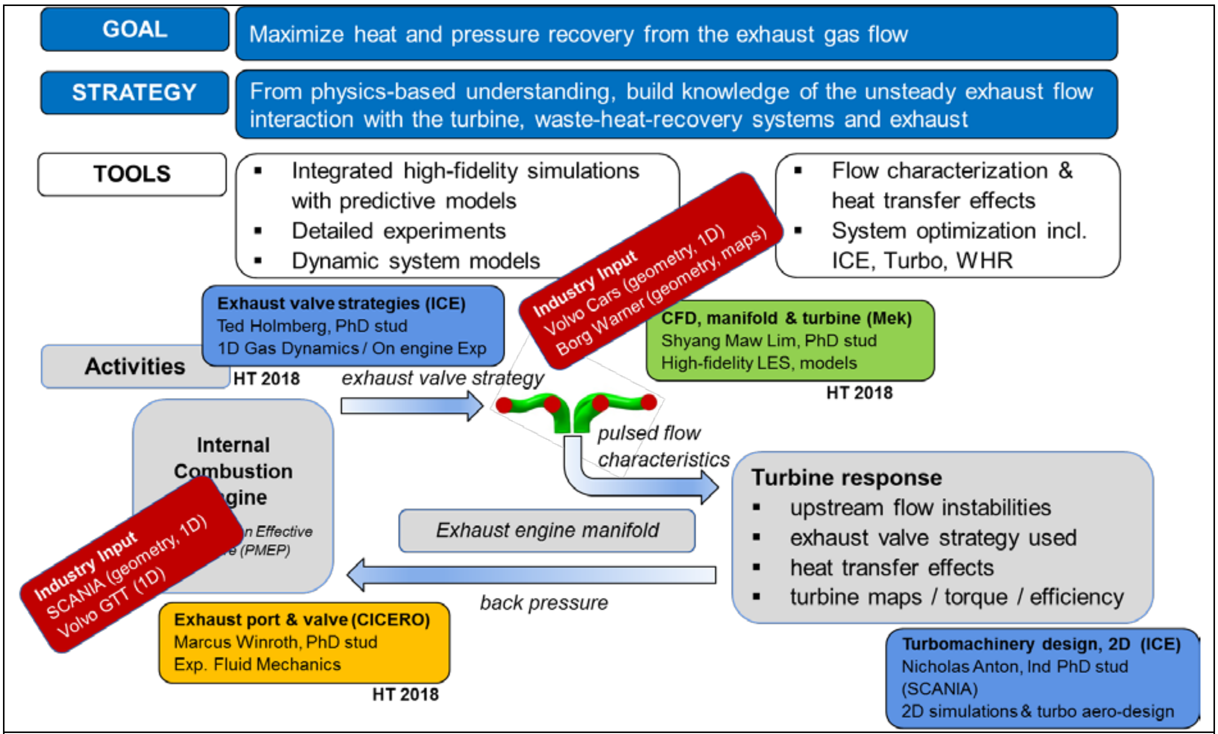


Figure 3: Overview of the current and foreseen activities within the "HOTSIDE" research area.

HOTSIDE - research highlights (2016):

Among the research highlights one can mention quantifying the exergy destroyed for different heat transfer levels and the impact on the turbine performance under hot continuous flow conditions (simulating the gas stand experiments). The simulations under engine-like pulsating conditions considering the integration of the turbine with the exhaust manifold were initiated. In this case the pulsating boundary conditions and temperature data were provided by industry for engine operating points of interest. The evaluation of the adiabatic and diabatic turbine performance under such conditions is currently an on-going investigation.

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

1D engine simulations are performed also for evaluating engine performance for different turbine designs. Turbomachinery design software on a 1D and 3D basis are the main tools for the design process. Prototype hardware manufacturing and engine/gas stand testing are carried out at SCANIA. An initial campaign concerning a twin-scroll turbine performance evaluation was carried out. It involved steady flow gas stand measurements as well as a model-based study.

Short & medium-term plans with HOTSIDE:

- Dynamic measurements of the discharge coefficient: dynamic valve experiments with a double valve set-up; assess the influence of different valve lift profiles
- Detailed unsteady computational efforts on the BorgWarner turbine integrated with the manifold with Boundary Conditions provided by Volvo Cars (VEP-HP engine; different exhaust valve strategies)
- Quantify the associated losses and impact on turbine performance
- Lic. seminars: Shyang Maw Lim (Jan 2017); Marcus Winroth (Jan 2017)

Research Area: Exhaust After Treatment (EAT)

Summary: Study of fluid mechanics, multi-phase flow, heat transfer, and acoustics along the exhaust line of the engine with relevance to engine after treatment, without considering the catalysis.

The EAT research area is vast even though we do not enter the catalysis part. We have activities within two areas that fit well with the competences of the center:

1. Atomization and mixing of urea water solution (SCR)
2. Particle characterization and agglomeration (PCA)

The SCR project has been a shorter prestudy that was finalized during 2016. Even though SCR is a well established technology—at least for heavy duty—and is in commercial use there are fundamental issues to address. One is the proper understanding of the introduction and mixing of the urea water solution into the exhaust stream. The approach of CCGEx has been to take a step back from applications and instead evaluate numerical schemes on very basic setups. One problem however, is the lack of good experimental reference data sets. A part of the project has therefore been to produce these.

The major project in EAT is the particle characterization and agglomeration project. It is topic that has become increasingly important the last few years with engines producing more and more health critical sub micron particles. This is also reflected in the legislation that now introduce limits on particle numbers. The project focus on understanding the evolution of particles along the exhaust line and the possible manipulation of the particles to make them agglomerate. A schematic overview of the PCA research area and is presented in Fig. 4.

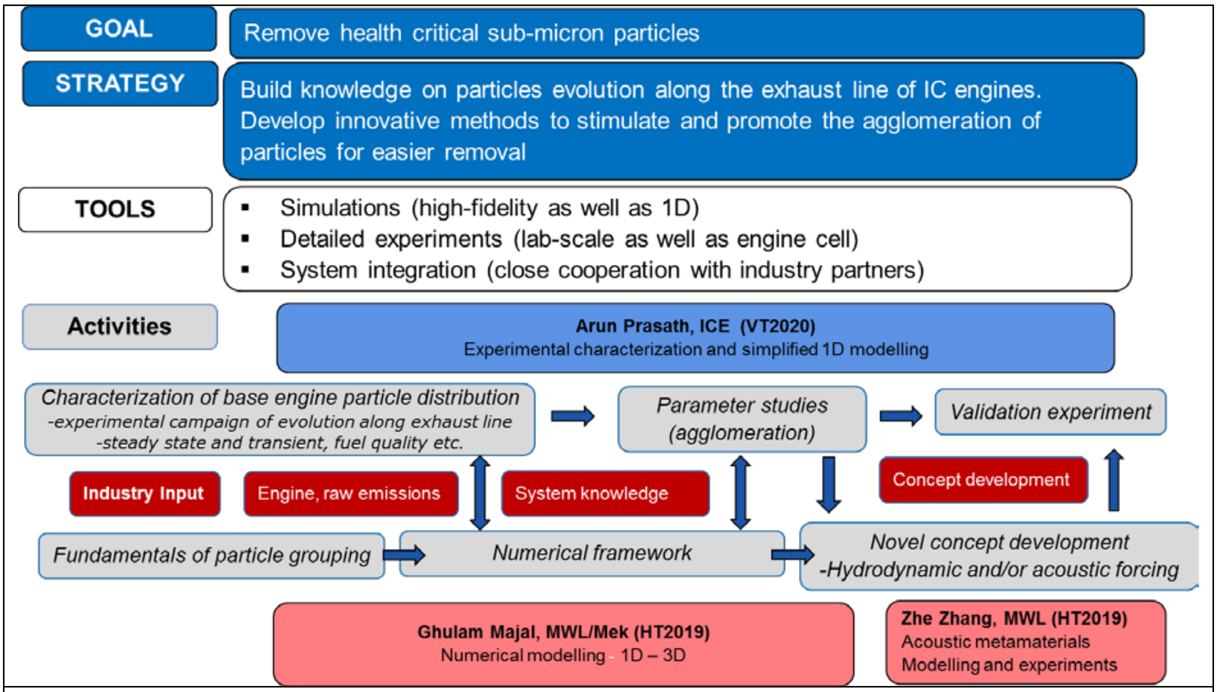


Figure 4: Overview of the current and foreseen activities within the "EAT-PCA" research area.

EAT - research highlights (2016):

Within the SCR project the experimental data set determined is a good contribution to the research community as a reference case. A known injector has been used to spray into a generic spray chamber with and without crossflow under a number of operating condition. This is the foundation we will use for further studies in the area.

The experimental characterization of particles has not started yet, we are in a preparatory phase where the engine and exhaust line is started up and instrumented. More work has been done on the numerical side. The 1D agglomeration modeling is finalized and has been improved to include influence of different engine pulses, varying agglomeration geometries as well as acoustic forcing.

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.

Short & medium-term plans with EAT:

- Start up of engine and first characterization of particle evolution in the exhaust line (steady state operating point)
- First hydrodynamic agglomeration prototypes to be tested
    - Designed for validation of 1D modeling.
- Experimental validation of "slow sound" concept derived.
  Experimental validation of particle agglomeration in flow ducts using acoustic forcing.

High fidelity modeling of particle agglomeration

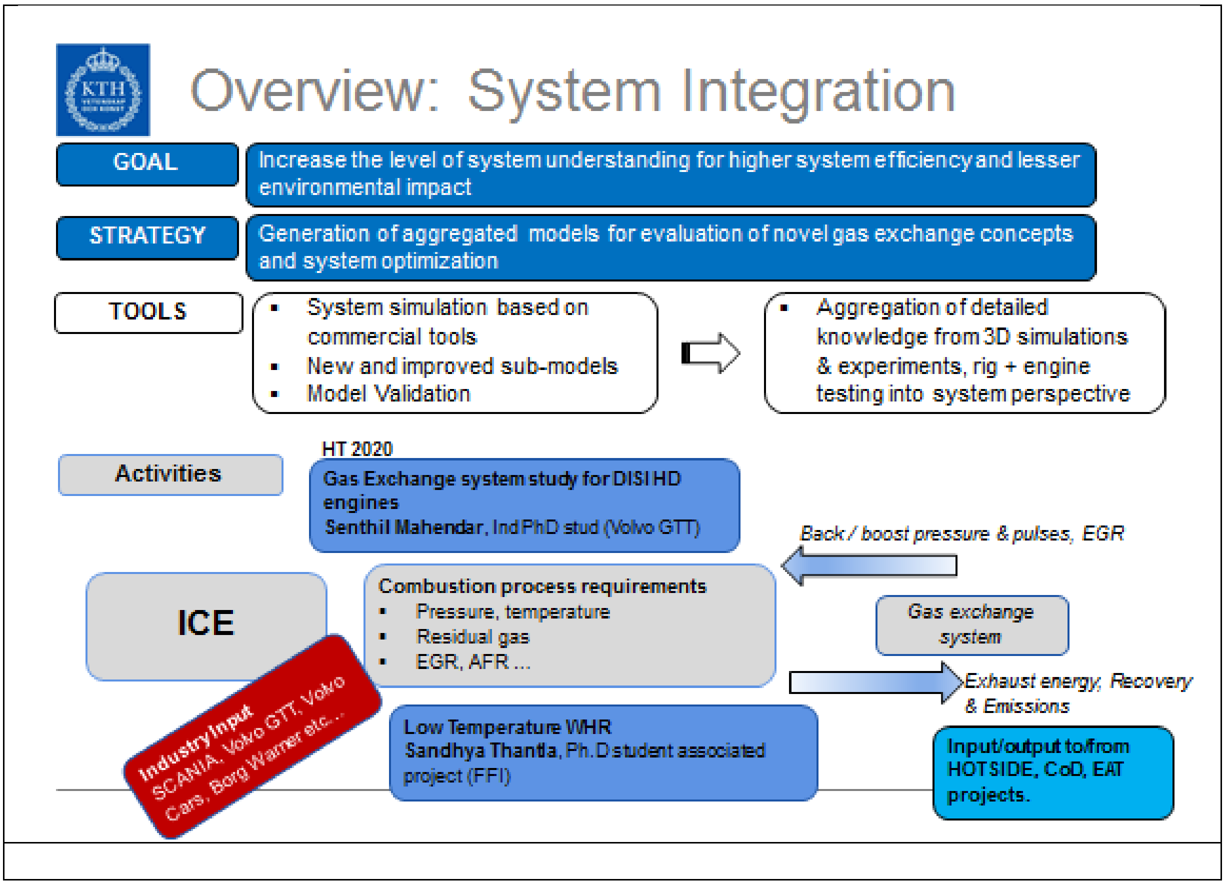
Research Area: Power Train System Integration (SYSINT)

Summary: The system integration area (SYSINT) 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 will be 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

An overview of the SYSINT research area and of the associated research activities is presented in Fig. 5.



SYSINT - research highlights (2016):

Since the reaserch area is newly started the main focus under 2016 has been on project definition, recruitment and manning

- New project started: Gas Exchange system for DISI HD engines – Ph.D. student Senthil Mahendar(August 2016)
  New project started: Low Temperature Waste Heat Recovery LT-WHR – Ph.D. student Sandhya Thantla (Associated, August 2016))

Short & medium-term plans with SYSINT:

- Detail planning of projects ongoing
- Establishing the baseline ”state-of-art” for vehicular WHR systems
- Selection of working fluids, thermodynamic WHR processes to investigate for integration with gas exchange system.
- Defining testing needs for understanding alcohols in HD DISI processes.
- Development of modeling approach for WHR and HD DISI combustion.

Associated projects with CCGEx

During 2016, there were a few associated projects developed around CCGEx. These are summarized below.

Project Title: “In-cylinder flow of a Diesel water-analogue engine”

Project type: CCGEx Associated Project, PI: P.H. Alfredsson

The project aims to assess how swirl and tumble depend on the dynamics of the valves/piston as well as how they vary between cycles. Particle Image Velocimetry (PIV) measurements as well as numerical simulations are performed at KTH Mechanics in collaboration with the leading car industry in Sweden in order to tackle some of these questions. Experiments (planar PIV) were performed at one tumble plane examining the effect of piston presence, Reynolds number as well as the dynamic motion of the inlet valves. The results will be presented at the American Physical Society Division of Fluid Dynamics meeting in Portland, OR, USA in November 2016.

Project Title: “Confined Bluff-body Flows and Unsteady Mass-flow Metering”

Project type: CCGEx Associated project (FFI), PI: P.H. Alfredsson

An experimental program was launched to determine the influence of geometry on the shedding characteristics of a confined bluff-body, with a view to informing the design of a vortex mass-flow meter. Experiments have been conducted on two rigs: a 40mm diameter pipe-flow rig in the CICERO lab, and a Reynolds matched 194mm diameter pipe-flow rig in the NT windtunnel. These rigs allowed frequency data to be collected for various geometries and an associated flow visualization study to be performed. Reynolds numbers in the range $10^4 – 10^5$ were considered, and Mach numbers from 0.04 to 0.4. Some of the highlight of the project are:

- Developed vortex-shedding meter and validated use in steady flows.

- Extended vortex-shedding meter to be used in pulsating (time dependent) flows.
- Found evidence of a topological change between long and short-tailed bluff bodies.
- Established that the shedding phenomena generally scale, but depend on pressure gradient. Implying that one must match Mach number, Reynolds number and physical scale to correctly replicate behavior.

Project Title: Meta-materials for sound in ducts

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

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. In the present PhD project the student has started to work on this last possibility.

Finances

In the current period 2014-2017, financing – and as a result available means within CCGEx – increased to 8 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. In the new period, the three main industrial partners increased their commitment to a total of 1.7 MSEK/year and partner (as cash and in kind contributions). During the year Borg Warner has joined the center through an accession agreement and will sponsor two post-docs under 2016/2017.

A lot of work has also been put into the preparation and carrying out of the research projects, to come to an agreement on, and to plan for, the in kind contribution from partners (KTH and industry) that are under these commitments.

In the table below, the interim (year-to-date 2016-08-31) financial report can be found. The major deviations estimated to year-end close will be due to late recruitments for some positions. The funds will however be spent the following year. Thus it is expected that the full year of 2016 will close better than budget.

Budget 2016

		B 2016	ACTUALS 2016-08-31
IB2015		431 317	431 317
INCOME			
KTH medfinansiering		1 000 000	666 667
Energimyndigheten		8 000 000	8 000 000
Scania		800 000	400 000
Volvo Car, saknas inköpsorder för 2016		600 000	0
Volvo GTT, bet för år 2015		1 600 000	800 000
Borg Warner	1) Tbc	950 000	0
Annan finansiering	utgår 450 000	0	
TOTAL		12 950 000	9 866 667
EXPENSES			
Föreståndare	Hultqvist 40%, MMK	800 000	677 153
Vice Director 10%	Susann B, MWL	180 000	0
Vice Director 10%	Mihai, Mekanik	180 000	120 000
Support hemsida	Ramis, Mekanik	90 000	60 000
Centre Admin 20%	Nora E, MMK, t o m 160630	200 000	92 046
IAB + CCGEx day		100 000	103 945
Styrelseordförande		200 000	150 000
Resekostnader	var 70 000	50 000	7 233
Driftkostnader (repr m m)		50 000	43 697
Verksamhetsutveckling, internat		45 000	
Konferens		50 000	90 000
Delsumma ledning		1 945 000	1 344 074
CICERO Lab			
Labchef , 20%	Bengt Fallenius	300 000	200 000
Lokalhyra lab		120 000	92 960
Driftkostnader lab		30 000	32 459
Utrustning / infrastruktur/avskrivning		20 000	17 234
Air heater installation	utgår 200 000	0	0
Delsumma CICEROlab		470 000	342 653
ITM INTERNAL COMBUSTION ENGINES			
System intergration	Area senior researcher	450 000	300 000
Gas exchange for DISI HD	In-kind PhD. Volvo GTT	100 000	66 667
Cold Side: compressor off design	Bertrand Kerres	950 000	633 333
"ICE exhaust pulses and Turbine"	Ted Holmberg	950 000	633 333

EAT (Exhaust After Treatment)	Arun Prakatsh	700 000	466 667
"T/C interaction with exhaust pulses"	Nicholas Anton	150 000	64 588
Labdrift		200 000	133 333
Utrustning / infrastruktur motorlabb		50 000	33 333
TOTAL ICE		3 550 000	2 331 255
SCI, MARCUS WALLENBERG LABS (MWL)			
Cold Side: "Acoustics & Liners"	Raimo Kabral	950 000	633 333
Accoustic damping in Exhaust systems			
"TurboMachinery Acoustic Fl.Sim"	PhD NN - VCC	100 000	0
EAT Particulate grouping	Ghulam Majal	950 000	633 333
EAT: coordinator / researcher	Mikael Karlsson	360 000	240 000
TOTAL MWL		2 360 000	1 506 667
SCI, MECHANICS			
Borg Warner Project X	2x Post Doc.	950 000	0
iHOT : "Exhaust Valve Flow"	Marcus Winroth	950 000	633 333
Cold Side: coordinator / researcher	Mihai Mihaescu	450 000	300 000
iHOT: coordinator / researcher	Mihai Mihaescu	450 000	300 000
" 3D Flow in a Centrifugal compressor"	Elias Sundström	950 000	633 333
"Heat Transfer Effects on the Efficiency"	Shyang Maw Lim	950 000	633 333
EAT : Ureaspray simulation	Researcher Mireja	400 000	266 667
TOTAL MECHANICS		5 100 000	2 766 667
TOTAL EXPENSES		13 425 000	8 291 315
PREL RESULT 2016		-475 000	1 575 352

Improvements during the year

The collaboration between the doctoral students from the different departments involved in the CoD research area (i.e. KTH-MWL, KTH-Machine Design, and KTH-Mechanics) was significantly strengthen during 2016. This lead to several joint publications (published or accepted for publication).

Moreover, the CCGEx PhD students and postdocs are holding regular meetings and seminars with a frequency of cca. 4 every year. There is agreement among the participants that four seminars per year is a good frequency. The aims are team building and improving knowledge transfer within the group. Each seminar is concluded with a dinner.

During 2016, three seminars have been held, and a fourth one is scheduled. The first seminar was held on 19/02. Topic was a LabVIEW programming course. The participants were asked to develop a simple pressure transducer calibrator in LabVIEW, under supervision from the PhD students more experienced in LabVIEW. Short presentations were given on the concept of a state machine and NI CompactRIO real-time programming. The second seminar was held on 22/06. Topic was a course in the CFD environment StarCCM+, from mesh generation to solving the equations to post-processing. After a short presentation by the teacher, the participants were asked to simulate a simple case under supervision. The third seminar was held on 24/08. Topic was the SWOT-like analysis of the competence centre from the PhD students' perspective, and brainstorming ideas for improvement. The fourth seminar is scheduled for 04/11. Since the sharing of programme code was found to be lacking in the SWOT analysis, the topic will be an introduction to bitbucket, a code sharing platform and version control system. A practice session on good coding practice in MATLAB is also planned.

Partners development

Interaction with Industry (Scania, Volvo Cars, Volvo GTT, BorgWarner)

Each of the research areas benefits from a strong interaction with the industrial partners and collaborators. Researchers, doctoral students, industry representatives 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 which cannot travel to KTH have the possibility of joining these technical meetings on-line via telephone and web based programs.

BorgWarner (BW) Turbo systems Engineering GmbH, Kirchheimbolanden, Germany became a new collaborator for CCGEx during 2015. During the month of October 2016, BW and all involved parties within CCGEx signed the Accession Agreement. As a result BW will finance the research activities of one Postdoctoral student within the CoD research area, which will join CCGEx before the end of the year. Moreover, an Industrial PhD Student from Volvo Car Corporation AB will join CCGEx research activities within CoD Research area at the beginning of December, 2017. These adds to the in-kind contributions (e.g. hardware, geometries, and hot-gas stand experimental data) from the industry partners.

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.

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

Presently, the computational efforts within the framework of CoD & HOTSIDE research areas are doubled by the experimental activities within the CICERO Lab and MWL Lab on assessing compressor flow and aeroacoustics, as well as on measuring in-cylinder and exhaust port flows. Moreover, extensive experimental data sets obtained at the University of Cincinnati, USA on an academic compressor rig were used for verifying and validating the computational tools used.

During 2016 interest was shown by several companies (e.g. Wärtsilä, GE Oil & Gas, Converge CFD, AVL) into CCGEx research activities. A NDA was signed with GE Oil & Gas, which opened the possibility of starting associated projects within the CoD research area. Moreover, there are advanced discussions with Converge CFD for providing free academic licenses to be used by CCGEx students. The solver will be evaluated in the near-future for predicting rotational flows relevant to turbomachinery.

List of Publications (2016)

(For a complete list of publications please check https://www.ccgex.kth.se/publications)

Du, L., **Holmberg, A.**, **Karlsson, M.** and **Åbom, M.** (2016) *Sound amplification at a rectangular T-junction with merging mean flows.* Journal of Sound and Vibration, **367**:69-83. dx.doi.org/10.1121/1.4933594

Du, L., **Åbom, M.**, **Karlsson, M.** and **Knutsson, M.** (2016) *Modelling of Acoustic Resonators Using the Linearized Navier Stokes Equations.* SAE Technical Paper. dx.doi.org/10.4271/2016-01-1821

Du, L., **Holmberg, A.**, **Karlsson, M.** and **Åbom, M.** (2016) *Numerical Study on the Sound Amplification of a T-Junction with Bias Flow.* Proceedings of the 5th International Conference on Jets, Wakes and Separated Flows (ICJWSF2015), Springer Proceedings in Physics 185, p.373-381. dx.doi.org/10.1007/978-3-319-30602-5_47

Ford, C., **Winroth, M.** and **Alfredsson, P.H.** (2016) *Development of a pressure based vortex-shedding meter - Measuring unsteady mass-flow in variable density gases.* Meas. Sci. Tech. 27 085901.

Kabral, R., **Du, L.**, **Åbom, M.** and **Knutsson, M.** (2016) *Optimization of Compact Non-Fibrous Silencer for the Control of Compressor Noise.* SAE Technical Paper 2016-01-1818. dx.doi.org/10.4271/2016-01-1818

Kabral, R., Du, L. and Åbom, M. (2016) *Optimum sound attenuation in flow ducts based on the "exact" Cremer impedance.* Acta Acustica united with Acustica 102:851. dx.doi.org/10.3813/AAA.918999

Kalpakli Vester, A., **Örlü, R.** and **Alfredsson, P. H.** (2016) *Turbulent flows in curved pipes: recent advances in experiments and simulations*. Appl. Mech. Rev. 68 050802.

Kalpakli Vester, A., Sattarzadeh, S. S. and **Örlü, R.** (2016) *Combined hot-wire and PIV measurements of a swirling turbulent flow at the exit of a 90° pipe bend*. J. Vis. dx.doi.org/10.1007/s12650-015-0310-1

Karlsson, M., **Åbom, M.**, **Lalit, M.** and **Glav, R.** (2016) *A note on the applicability of thermo-acoustic engines for automotive waste heat recovery*. SAE Int. J. Mater. Manuf. 9:286-293. dx.doi.org/10.4271/2016-01-0223

Karlsson, M., **Knutsson, M.** and **Åbom, M.** (2016) *Predicting Fluid Driven Whistles in Automotive Intake and Exhaust Systems.* SAE Technical Paper. dx.doi.org/10.4271/2016-01-1820

Kerres B., **Cronhjort A.** and **Mihaescu M.**, (2016) *Experimental investigation of upstream installation effects on the turbocharger compressor map*, In the Proceedings of The ImechE 12th International Conference on Turbochargers and Turbocharging, London, ImechE, May 2016.

Kerres, B., **Nair, V.**, **Cronhjort, A.**, and **Mihaescu, M.**, (2016) *Analysis of the turbocharger compressor surge margin using a Hurst-exponent-based criterion*. SAE Int. J. Engines 9:2016. dx.doi.org/10.4271/2016-01-1027

Lim, S.M., **Dahlkild, A.** and **Mihaescu, M.** (2016) *Wall treatment effects on the heat transfer in a radial turbine turbocharger*. A. Segalini (ed.), Proceedings of the 5th International Conference on Jets, Wakes and Separated Flows (ICJWSF2015), Springer Proceedings in Physics 185, pp. 439-447, dx.doi.org/10.1007/978-3-319-30602-5_55.

Pastuhoff, M., **Tillmark, N.** and **Alfredsson, P.H.** (2016) *Measuring surface pressure on rotating compressor blades using pressure sensitive paint*. Sensors, *16*:344. dx.doi.org/10.3390/s16030344

Rabault, J., **Vernet, J.A.**, **Lindgren, B.** and **Alfredsson P.H.** (2016) *A study using PIV of the intake flow in a diesel engine cylinder.* Int. J. Heat Fluid Flows (accepted)

Semlitsch, B. and **Mihaescu, M.** (2016) *Flow phenomena leading to surge in a centrifugal compressor.* Energy, 103:572-587. dx.doi.org/10.1016/j.energy.2016.03.032

Sundström E., **Kerres B.** and **Mihaescu M.**, (2016) *Evaluation of centrifugal compressor performance models using Large Eddy Simulation data*, ASME Paper, GT2016-57169

Sundström E., **Semlitsch B.** and **Mihaescu M.**, (2016) *Similarities and differences concerning flow characteristics in centrifugal compressors of different size*, A. Segalini (ed.), Proceedings of the 5th International Conference on Jets, Wakes and Separated Flows (ICJWSF2015), Springer Proceedings in Physics 185, pp. 457-464, dx.doi.org/10.1007/978-3-319-30602-5_57

Örlü, R. and **Kalpakli Vester, A.** (2016) *Flow visualization of an oblique impinging jet: vortices like it downhill, not uphill.* J. Vis. **19**:7–9, dx.doi.org/10.1007/s12650-015-0295-9

Note: The Doctoral students involved in the Center are caring out the educational and research activities as established in the Individual Study Plans

Plans for action (2017)

The BorgWarner compressor will be installed on the CICERO Lab. Experiments on BW compressor with full intake geometry corresponding to the Volvo VEP MP engine will be carried out. The Hurst exponent methodology for surge detection will be applied to the acquired data. The acquired data will be used not only to verify/validate or to provide boundary conditions for CFD calculations, but also to calibrate and improve a 0D/1D compressor model that was recently implemented.

It is intended that on-engine experiments will be carried out in the future for assessing turbocharger efficiency under realistic operating conditions. This tests will be performed at ICE Lab. *However, we shall look together with our industrial partners into the possibility to run such tests at Volvo Cars or at BorgWarner facilities*.

The high-fidelity LES simulations will target the BorgWarner compressors under stable and off-design conditions. The flow losses and corresponding mechanisms will be quantified. Based on the LES data, evaluations of the simplistic performance models will be carried out.

During 2016, two projects were suggested by BorgWarner to accommodate simulations on both Cold Side (CoD research area) and HOTSIDE, respectively. BW will finance one post-doctoral student on CoD that will join CCGEx by the end of 2016. However, during 2017 discussions should be initiated for financing a second post-doc on the HOTSIDE (possible together with BorgWarner Heavy-Duty division), action supported also by Scania. Such a project targeting maximising energy transfer from hot-side to cold-side can complement the project on turbine design optimization (Ind. PhD. Student Nicholas Anton).

On the HOTSIDE, the efforts on quantification of the exhaust pulsating flow and of its interaction with the turbine will be performed under specific engine like conditions, with and without heat transfer.

The vortex-shedding meter device developed within the center will be used for measuring the time dependent gas velocity on the cold side (Scania engine).

Experiments in the CICERO Lab will be conducted for finalizing the measuring campaign for characterizing the flow in the exhaust port(s) using a double valve setup. It is also planned to verify the findings with 1D simulations using experimental data acquired in the CICERO Lab. It is possible to calibrate the 1D models using both experimental data as well as high-fidelity LES calculations. The experimental campaign investigating the influence of different valve lift profiles will start in 2017 and the influence of different valve geometries will be assessed.

Concerning the EAT research area, an important step forward during 2017 will be the experimental characterization of particles in the exhaust line. We will start with an engine from Volvo Cars that should be installed and instrumented by January 2017. First, base maps of particle size distributions at different steady state operating conditions will be determined. Next step is to measure the evolution along a reference agglomeration device. Both of these data sets will serve as validation cases for the 1D modeling cases already finalized as well as the high fidelity simulations to be started during the year. Another milestone will be the experimental validation of the "slow sound" agglomeration concept. Well established in duct measurement techniques developed at KTH will be used and furthered to validate the numerical work done during 2016.

Shyang Maw Lim (KTH-Mechanics), expected date for Licentiate thesis Jan. 2017.

Marcus Winroth (KTH-Mechanics), expected date for Licentiate thesis Feb. 2017.

Bertrand Kerres (KTH-MFM/ICE), expected date for PhD thesis Jun. 2017.

Raimo Kabral (KTH-MWL), expected date for PhD thesis Jun. 2017.

List of papers under review (2017)

- El Nemr, Y., Veloso, R., Girstmair, J., Kabral, R., Åbom, M., Schutting, E., Dumböck, O., Ludwig, C., Mirlach, R., Panagiotis, K., & Masrane, A., Experimental Investigation of Transmission Loss in an Automotive Turbocharger Compressor under Ideal and Real Engine operating Conditions, submitted to *12th European Conference on*

Turbomachinery Fluid dynamics & Thermodynamics ETC12, April 3-7, 2017; Stockholm, Sweden

- Sundström, E., Mihaescu, M., Giachi, M., Belardini, E. & Michelassi V., Analysis of Vaneless Diffuser Stall Instability in a Centrifugal Compressor, submitted to *12th European Conference on Turbomachinery Fluid dynamics & Thermodynamics ETC12, April 3-7, 2017; Stockholm, Sweden*
- Kerres, B., Sanz, S., Sundström, E. & Mihaescu, M., A Comparison of Losses in a 0D/1D Radial Compressor Performance Model with Numerical Data, submitted to *12th European Conference on Turbomachinery Fluid dynamics & Thermodynamics ETC12, April 3-7, 2017; Stockholm, Sweden*
- Kerres, B., Mihaescu, M. & Gutmark, E., On the Pressure Sensor Position Role for Best Assessing Compressor Instabilities: An Analysis Using the Hurst Exponent Criterion, submitted to *SAE World Congress Experience 2017, April 4-6, 2017, Detroit, MI, USA*

Several other manuscripts are in preparation and expected to be submitted before Dec. 2016.

New funding opportunities (2017)

Several faculty part of CCGEx will be involved in generating the application for answering to the European Training Network (ETN) in Innovative Gas Management. (ITN/ETN) call (call identifier: H2020-MSCA-INT-2016). The project will be coordinated by KTH. The Consortium is formed by Academia and Industry from Sweden, Italy, Germany, Spain, and Hungary.

Outlook - CCGEx program period (2018-2022)

In the period from June 2016 to March 2017 intense work has and will be done to form a program for the next period. Strategic discussions have been held with all stakeholders and viewpoints have been collected. During the winter months, a draft proposal on the new program period will be synthesized. In this program the strategic targets are to support knowledge development to:

1) Increase engine efficiency
2) Introduce renewable fuels
3) Explore potentials of Electrification
4) Meet the future emission challenge

Agreed with the Swedish Energy Agency the next period will include significant degrees of innovation, novel concepts and technology.

Posters

The Hurst Exponent as a Compressor Surge Criterion

KTH CCGEx

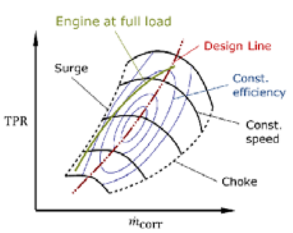
Bertrand Kerres

kerres@kth.se

The aim of this project is to investigate the Hurst exponent as a new criterion for compressor surge. It is based on the fractal properties of an underlying time series, e.g. a compressor pressure measurement signal. Investigations show that the Hurst exponent has potential as a surge indicator. The advantages compared to other signal characteristics like the standard deviation are that it decreases from 0.5 for pure white noise to 0 for noise-free oscillations, and that the method can easily be generalized.

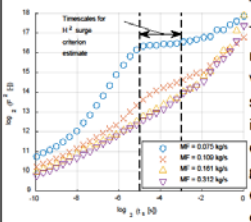
Compressor Surge

Compressor surge narrows the operational range of turbo-compressors at low mass flows. In surge, the compressor can no longer supply a steady outlet pressure to overcome downstream flow resistances, and pressure and mass flow start oscillating.



On turbocharged internal combustion engines, turbocharger compressor operation needs to incorporate a safety margin towards its surge line. This limits the engine low-end torque.

The Hurst Exponent



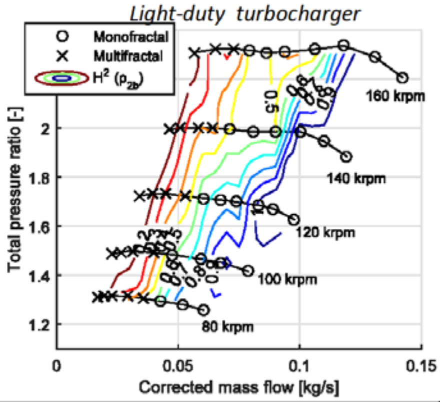
The Hurst exponent is estimated by plotting the average window variance over window length in a log-log diagram. It corresponds to the slope of the resulting lines. Here shown for several mass flows at one impeller speed.

The Hurst exponent (H^2) is a number that describes how the variance of a signal scales with the signal length. Applied to a pressure in the compression system, one can expect a scaling behaviour governed by turbulence for stable operation. For near surge operation, on the other hand, the pressure is wave-like and the signal variance becomes almost independent of the its length. One can then expect the Hurst exponent to move towards zero.

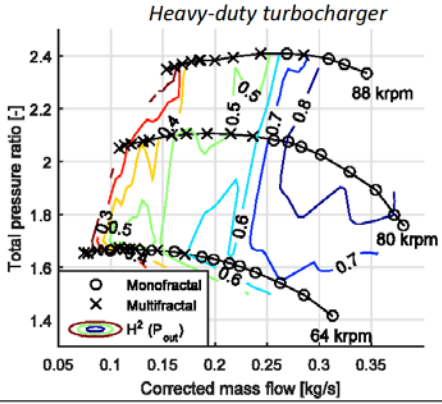
Results

Compressor maps for a passenger car sized (left) and a truck sized (right) turbocharger show a decrease of the Hurst exponent H^2 towards surge, with a limit before deep surge at around $H^2 = 0.15$. An additional criterion that distinguishes between monofractality (large and small amplitude oscillations scale equally) and multifractality (large and small amplitude oscillations scale differently) of the pressure signal at surge time scales could have some potential as an early warning indicator.

Light-duty turbocharger



Heavy-duty turbocharger



Summary and Conclusion:

Main advantages of the Hurst exponent as a surge indicator are its well-defined limit of zero for pure oscillations, and the flexibility due to the different orders and different signal detrending options. The main drawback compared to e.g. the power spectrum is the complexity of the underlying concept.

Acknowledgement:

Supervisors: Andreas Cronhjort, Mihai Mihaescu

SCANIA VOLVO Energimyndigheten BorgWarner

KTH CCGEX

Engine optimized turbine design

Nicholas Anton M.Sc

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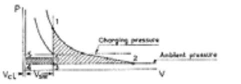
Turbocharging is a very common way of increasing both engine torque/power as well as improving engine efficiency and is found on almost every modern engine. The focus of this project is turbocharger turbine design for heavy duty internal combustion engines. The aim is to characterize the turbine operating conditions on engine and how to make best use of the remaining energy present in the exhaust gases. This is investigated by considering different design strategies for the turbine taking into account the pulsatile nature of the engine. Naturally this project is a part of the iHOT-side of CCGEX, but is also a collaboration between Scania CV AB and KTH.

Introduction and Motivation:

The turbocharger is a very common component on engines used nowadays both for Otto and Diesel cycle engines. The main drivers are improved torque/power levels, engine efficiency, possibility to downsize etc. The inherent unsteadiness of the internal combustion engine is posing a challenge for matching with steady flow turbomachinery such as a turbocharger turbine. On engine conditions is by no means the ideal for such a steady flow device. By utilizing the exhaust energy from the engine cylinders, the turbine can drive the compressor providing boost pressure as well as reduced or gain in pumping work. The result from this project can immediately become of use for achieving better engine performance, increasing power/torque while improving efficiency and emissions.

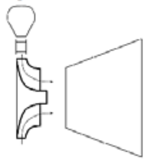


P-V diagram of a general gas exchange process,[1].

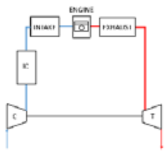
[1] Turbocharging the Internal Combustion Engine, fig. 1.6 s.5, Watson&Janota, 1982.

Setup:

The basic tools for this project is 1D engine simulation and 1D/3D turbomachinery design software. The idea is to provide a process from an initial 1D turbine design to a fully defined, manufacturable 3D prototype geometry for gas stand evaluation and/or engine testing. In the design process, the geometry specification will evolve from 1D/3D evaluation using both turbomachinery and engine simulation.



Meanline 1D turbine stage

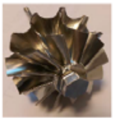


Simplified 1D engine model

Results:

Initially this project has been focusing on turbocharger turbine performance evaluation from turbocharger gas stand. A twin-scroll turbine stage, which is common for engine pulse utilization, has been modelled on a 1D level. A methodology was delevoped based on basic 1D flow and turbine theory for evaluating the main parts of the turbine stage, the volute, rotor and diffuser. This will facilitate a component analysis, characterizing the performance of the stage which is normally not deduced. An analysis on this level is very helpful as a mean of validating a design, to gain insight into aerodynamic trends and to guide the designer towards possible areas of improvement. A case study, analysing a heavy-duty twin scroll turbocharger stage was conducted using this methodology. Test data from gas stand was gathered for different flow admissions and speeds, the methodology implemented in MATLAB and subsequently an analysis of turbine stage parameters. Results show good correlation with studies in the area and comparison with a commercial meanline 1D turbomachinery software running the same conditions.

Diffuser part



Rotor part

Volute part

Admission into a twin scroll turbocharger turbine, meridional view

Further work will be focusing on the design aspect as such for a heavy duty CNG Otto-engine, designing a complete turbocharger and investigating the turbine operation at on engine conditions. The idea is to investigate turbocharger turbine design point parameters in order to gain efficiency in the very unsteady engine environment.

Summary and Conclusion:

The twin-scroll turbine stage study mentioned above show good potential of enhancing the turbocharger turbine evaluation. Providing several new dimensions of analysing compared to traditional "mapping" of the turbine stage. This can be used for improving turbocharger turbine stage efficiency and thereby engine performance.

Acknowledgement:

Main supervisor Prof. Dr. Anders Erlandsson Christiansen, Royal Institute of Technology, KTH

Co supervisor Prof. Dr. Magnus Genrup, Lund Faculty of Engineering LTH

Industrial supervisor Expert engineer Mr. Per-Inge Larsson, Scania CV AB

Rotating Machines and innovative noise control

KTH CCGEx

Raimo Kabral

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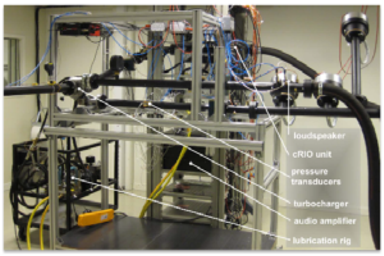
The goal of this project is to develop improved techniques for studying scattering and generation of sound in centrifugal compressors. In particular, to extend previous work to more in depth investigation in unstable flow and sound field coupling including the in-duct sound generation. The experimental work is performed in the unique turbocharger test facility at KTH CCGEx by implementing advanced experimental tools and procedures. In addition, innovative flow channel liners consisting of micro-perforated plates or metallic foams are treated in complementary noise control studies. The investigation involves experimental study of acoustic liners on dedicated high temperature test rig and numerical analyses by means of Comsol Multiphysics® FEM software. The efforts are being taken to determine high temperature acoustical properties as well as to find techniques for the optimization of such noise control solutions. The work is part of a Marie-Curie network on aero-acoustics named FlowAirS (see www.flowairs.eu).

Introduction and Motivation:

Turbochargers (TC) are essential components of modern “rightsized” internal combustion engine units. Although, the principle of TC originates from the early 20th century, two restrictive problems are still encountered today – the high level of compressor noise and compressor surge.

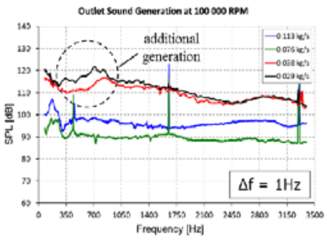
In order to achieve effective noise control, the accurate source characterization data i.e. the acoustic source data independent of the coupled flow-channel system, must be know first. Moreover, it is also assumed herein that generated sound and passive acoustic properties of the compressor contour could play significant role in the surge initiation process. Therefore, the acoustic properties of the TC, including acoustical scattering and sound generation as well as the effects of flow-acoustic coupling, are studied herein by means of detailed and accurate methods. In addition, the optimization techniques for innovative noise control materials, enabling compact jet effective noise control, are also developed.

Setup:



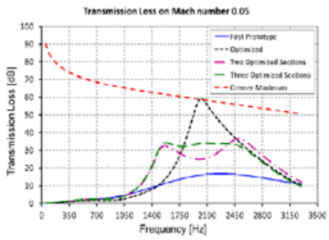
The TC acoustic characterization facility at KTH CCGEx (See the photo) have been used to determine accurate acoustical scattering and source data (full two-port data) at realistic operating conditions.

Results:



The sound pressure level (SPL) spectrum of generated sound in the outlet branch of the compressor at constant rotor frequency. The mass flow is varied from maximum to minimum i.e. near surge operation.

The prototype of compact silencer consisting of straight flow channel made of micro-perforated panel (MPP), and adjoining cavity. Such compact silencer concept can provide a very high level of sound dissipation.



Sound transmission loss spectra from the optimization of the compact silencer prototype. The optimization technique is based on so called Cremer optimal acoustic impedance concept.

Summary and Conclusion:

A high level of noise is increased further while operating the compressor near surge conditions which may require additional noise control. An effective noise control can be achieved by means of compact silencer concept when optimized according to the specific sound source. Moreover, the straight-flow compact silencer can provide a fibrous-free noise control with a negligible penalty of pressure drop.

Acknowledgement:

Prof. Mats Åbom, Marcus Wallenberg Laboratories for sound and vibration research (MWL), KTH.

Prof. Hans Bodén, MWL, KTH.

Dr. Magnus Knutsson, Volvo Car Corporation.

European Commission | Marie Curie Actions | FlowAirS | Competence Center Gas Exchange CCGEx "Charging for the future"

KTH CCGEx

Heavy Duty DISI Gas Exchange Processes with Alternative Fuels

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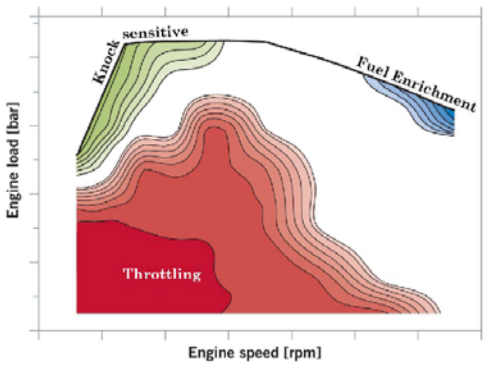
This project aims to provide insight on the requirements of the gas exchange system architecture while using renewable alcohol fuels in Direct Injection Spark Ignition (DISI) process. Efficiency improvement and emission reduction of the DISI engine will be studied using 1D engine modelling with experimental validation. This study focuses on Heavy-Duty (HD) engines constrained to run at stoichiometric conditions to reduce complexity of the after-treatment system.

Introduction and Motivation

Compression Ignition (CI) diesel engines is a preferred fuel choice for HD engines as they achieve high efficiency and returns reduced operating cost for fleet owners.

For Euro 6, the typical Diesel after-treatment systems used are Particulate Filters (DPF) and Selective Catalytic Reduction (SCR) with aqueous urea dosing. These after-treatment systems in general constitute about 45% of the total engine cost even though they have managed to reduce emissions to about 90% of Euro 3 standards.

Alcohols when used in DISI process has the potential for high efficiency and low particulate emissions. When combined with stoichiometric operation, this could also reduce after-treatment cost of a commercial vehicle by using only a three-way catalyst.



Limits of SI engine efficiency – Gasoline

Objective

- To recommend a gas exchange system architecture based on the advantages that alcohols offer as fuel in DISI process
- To obtain the limits of operation in alcohol fuelled LD engines and to compare the scalability to HD Engines for various parameters
- Contribute to improved modelling methods based on analysing the deficits of current methods and comparing experimental results

Alcohol fuels

- High octane – less knocking tendency (+)
- High latent heat of vaporization – lower fuel enrichment (+)
- Lower stoichiometric A/F ratio – higher throttling (-)

Improvement of throttling is key for alcohol fuelled engine's efficiency

Research activities (2016-17)

- Detailed 1D engine model development
- Generation of experimental data to validate the 1D model (including trace knock, COV and particulates)

Research questions (2016-17)

- What is the attainable load and efficiency in DISI operation? What are the limits?
- How sensitive is alcohol combustion to residual gases (cooled and uncooled)?
  [Comparison of knock and misfire limits with gasoline and projection of gas exchange system architecture for alcohols.]

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 an important topic within the vehicle industry. The exhaust gases are hot and at high pressure and are thus rich in energy. Some of this energy may be recovered using a turbocharger. To maximize the energy recovery, the engine system needs optimisation. When optimizing an engine system it is common to use one-dimensional, semi-empirical models. In such models, complex flows (such as the flow past the exhaust valves) may be represented by a straight pipe-flow with a corresponding discharge coefficient (C_D).

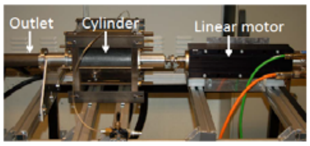
Introduction and Motivation:

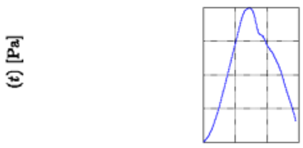
In order to decrease computational time when designing and optimizing engine systems, it is common to use 1D simulations. In these simulations complex fluid problems are simplified using mapped coefficients to describe the flow. These maps are obtained experimentally, where the experiments are typically performed with constant valve lifts at low pressure ratios. This project focuses on experimentally testing the assumptions (quasi-steadiness and independence of pressure ratio) made when determining the discharge coefficient (C_D) of the exhaust valve. This was done by performing exhaustion experiments at different pressure ratios, with both a dynamic and a static valve.

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

Setup:

The photo shows the setup for the dynamic valve experiments. The valve is operated using a linear motor, which allows for a controllable valve lift profile. The rig has a straight outlet pipe (which exhausts to atmosphere) connected to the exhaust port approximately 1 diameter downstream of the valve seat. The outlet pipe can be changed to test the effects of downstream conditions. The pressure is measured in the cylinder, in the valve seat and at two positions in the outlet pipe. The initial temperature in the cylinder is also monitored. This makes a dynamic measurement of the mass flow possible (1), by measuring the pressure in the cylinder as function of time and determining the mass that have left the cylinder using the isentropic relationship (2) and the gas law (3).





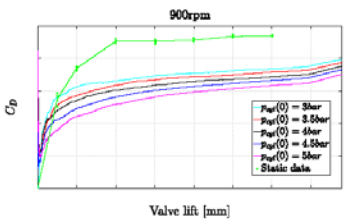
$$\frac{p}{p_0} = \left(\frac{T}{T_0}\right)^{\gamma/(\gamma-1)} \quad (2)$$

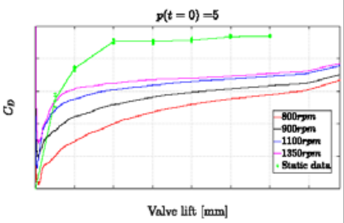
$$\frac{\mathrm{d}m}{\mathrm{d}t} = \frac{V}{\gamma R T_0}\left(\frac{p_0}{p}\right)^{(\gamma-1)/\gamma}\frac{\mathrm{d}p}{\mathrm{d}t} \quad (1)$$

$$m(t) = \frac{V}{R}\frac{p(t)}{T(t)} \quad (3)$$

Results:

The left figure shows C_D as a function of valve lift for different initial cylinder pressures, for an equivalent engine speed of 900 rpm. It can from this plot easily be seen that an increase in pressure causes a decrease in C_D. In the right figure C_D for different equivalent engine speeds is plotted. 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. In both figures C_D measured with a static valve can be seen to generally overestimate the value of C_D.





Summary and Conclusion:

In order to investigate the quasi-steady assumption, for exhaust flows, experiments have been performed using both a static and a dynamic valve.

Results show a large dependence on valve opening speed and pressure ratio. It also shows that measurements using a static valve overestimates the value of C_D, compared to the dynamic valve. Indicating that any attempt to represent the exhaust flows, from a real engine, with a steady measurement of C_D is bound to be flawed.

Supervisors: Prof. Henrik Alfredsson, Dr. Ramis Örlü

KTH CCGEX

Valve Strategies and Exhaust Pulse Utilization

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This project aims to improve the understanding of how the pulsating exhaust flow from the internal combustion engine interacts with the exhaust turbine of the turbocharger. Variable valve actuation on the exhaust side is used to influence the pulse properties to find optimum turbine power as a function of pumping losses for a given load point. The interaction will be primarily studied with 1-D simulation supported by tests on a single-cylinder diesel engine equipped with a hydraulic variable valve actuation system and a six-cylinder engine equipped with a fixed geometry turbocharger.

Introduction and Motivation:

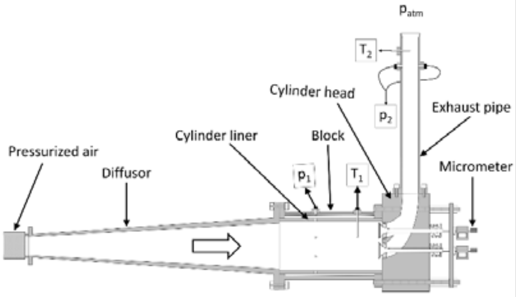
To improve fuel efficiency of turbocharged internal combustion engines it is desirable to reduce pumping losses. In the case of Heavy-Duty diesel engines this is done by carefully matching turbocharger specification to the piston engine. Generally the valve train of the Heavy-Duty engine is fixed and the turbocharger has a fixed geometry. Peak efficiency is therefore achieved in a narrow operating range and has to be weighed against other parameters such as transient response to a load step and durability.

This work will study how fully variable valve actuation (VVA) on the exhaust side can be used to create a more efficient charging system. Because of this new degree of freedom the valve strategy can be optimized for fuel efficiency in some load points and transient response in others.

Presently the only cost-effective way to simulate an entire engine is by 1D simulation tools. Flow losses over complex geometry such as valves and ports are described by flow coefficients. These are measured in steady-flow test rigs at low pressure drops. In an engine the pressure differential between cylinder and exhaust port are much larger at the time of exhaust valve opening. The influence of this has been investigated in the current study.

Air flow bench:

A steady-flow test rig designed to determine flow coefficients for a cylinder head. The flow coefficient is calculated by dividing the measured mass flow with the ideal mass flow through a reference area for a given pressure ratio (p1/p2). This is done for different valve lifts and used for input in 1D simulation tools.

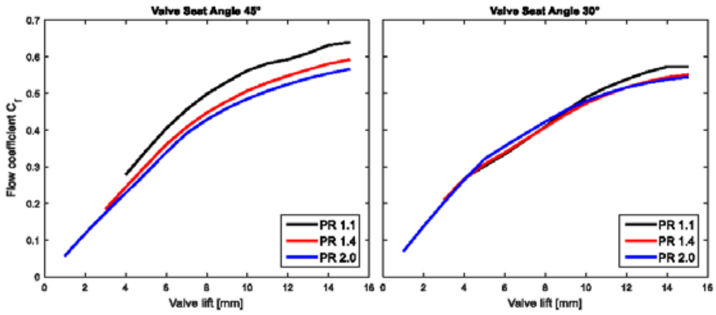


Results:

The exhaust valve flow coefficient are shown for two cases with different valve seat angles and valve shapes.

Only one of the two exhaust valves are open. The reference area is the exhaust port outlet area.

The case with the 45 degree valve seat appears to have a larger pressure dependence.



Summary and Conclusion:

The pressure ratio appears to influence the flow coefficient differently based on valve and valve seat geometry.

Acknowledgement:

Supervisor: Andreas Cronhjort

Co-Supervisor: Anders Christiansen Erlandsson

Swedish Energy Agency SCANIA VOLVO

KTH CCGEx

Control of particle agglomeration with relevance to after-treatment gas processes

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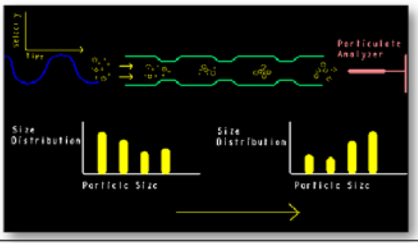
The project aims to find methods for stimulating agglomeration of particles in internal combustion engine exhaust systems by manipulation of the hydrodynamic and acoustic fields. An understanding of the evolution of particulate characteristics (e.g. particle mass, particle number, size distribution) as traveling along the exhaust system components and connections with relevance to modern engines is needed. The enhancement of the aforementioned understanding will be developed with the usage of advanced computational tools and models.

Introduction and Motivation:

Modern internal combustion engines show a tendency to form fine particles that are prone to penetrate through the human respiratory system and cause cardiovascular as well as neurological problems. This project aims at deriving predictive models for the manipulation of particles in the exhaust line through the use of forced pulsatile flow conditions and/or acoustic fields.



Setup:

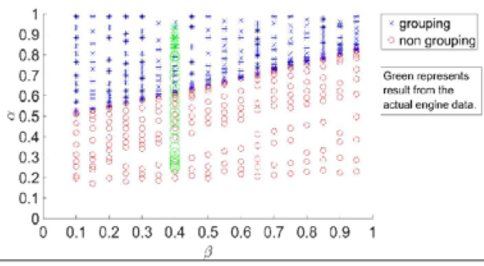
The numerical setups will initially be based on simplified **1D** models. The goal then would be to carry out sensitivity studies in order to analyze the effect of different parameters on agglomeration. Later on more complex models as well as **2D** and **3D** geometries will be considered.

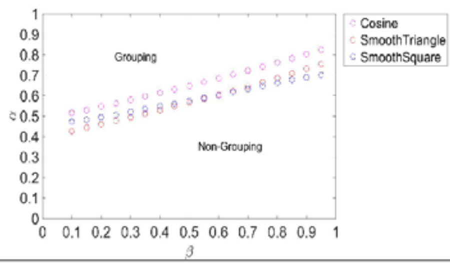
Initial numerical experiments based on the 1d model presented in Katoshevski et al. 2005 have been done. The model looks at an oscillating Stokesian flow. An additional simplification has been made by only taking into account the drag force.

In order to obtain grouping within this model two important non dimensional parameters were noted. The beta parameter which compares the mean flow field with the amplitude of the oscillations. Secondly, the alpha parameter which encapsulates the inertial effects due to the size of the particle.

Results:

Starting off from the model equation for the velocity of the host gas, the oscillations due to the engine are taken to be sinusoidal. A grouping and non grouping map using the alpha and beta parameters is made for the sinusoidal oscillations from the engine. These idealized oscillations are then compared to the actual oscillations coming from the engine. The leftmost figure below shows that a simple sinusoidal oscillation under estimates the transition from grouping to non grouping. The rightmost figure shows the result of applying different waveforms for the oscillations due to the geometry and their effect on grouping.





Summary and Conclusion:

Tests have been carried out extensively to understand the effects of the crucial non dimensional parameters and their effect on grouping. Next steps would involve moving out of the **1D** scenario and look at more realistic **2D** and **3D** modeling. This would also help in getting a more accurate feel for the effects of the oscillations due to the geometry of the pipe being utilized for particle agglomeration.

Acknowledgement:

This project is supervised by Docent Mihai Mihaescu, KTH Department of Mechanics, Prof. Mats Åbom, KTH Marcus Wallenberg Laboratory, Docent Lisa Prahl Wittberg. KTH Department of Mechanics and Dr. Mikael Karlsson, KTH Marcus Wallenberg Laboratory.

The CCGEx partners Scania AB, Volvo AB and Volvo Cars are acknowledged for their support.

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KTH CCGEX

Particle grouping in vehicle exhaust system with acoustic method

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Exhaust particulate matter (PM) from vehicular traffic is a major health and environmental issue. Increasingly strict regulations of vehicle emission have been introduced and extensive efforts have been put onto the control of PM. One potential solution is particle grouping, which can dramatically reduce particle numbers. An acoustic grouping method is proposed here, which gives the relationship between the speed of sound, the mean flow velocity and the amplitude of the acoustic particle velocity for particle grouping to be feasible. To satisfy this relationship, the so-called acoustic metamaterials, which can help control, direct and manipulate sound waves, are applied.

Introduction and Motivation:

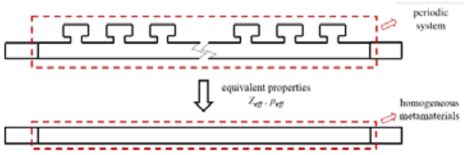
That the interaction between particles and oscillating flows may lead to the formation of particle groups yields the possibility of grouping. The oscillating flow may simply be hydrodynamic or, as assumed here, created by sound propagation. An analysis on particle motions inside a sound field leads to the conclusion that if

$$|\beta| = \left|\frac{c - V_o}{V_b}\right| < 1$$

then particle grouping is feasible. In the formula, c is the sound phase velocity, V_o is the mean flow velocity and V_b is the acoustic particle velocity. Given the practical situation inside vehicle exhaust pipes (the mean flow velocity is around 50 m/s), the speed of sound should be reduced dramatically to satisfy this grouping condition. To address such challenge, the so-called acoustic metamaterial is recommended to slow down the propagation of sound wave.

Setup:

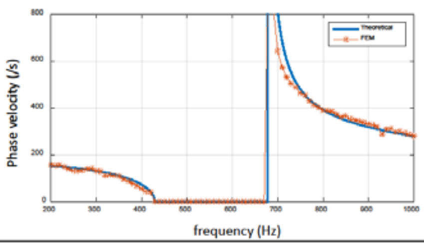
Acoustic metamaterials refer to artificially fabricated composite structures designed to control, direct and manipulate sound waves. Although normally designed as periodic structures, their properties do not just rely on periodicity but rather uniformly distributed local resonances so that in the limit of low frequencies an equivalent medium is created, which can lead to negative mass density (ρ) and bulk modulus (K). Given that $c=(K/\rho)^{1/2}$, possibly the speed of sound can be slowed down. A schematic diagram of the metamaterial prototype is illustrated below.



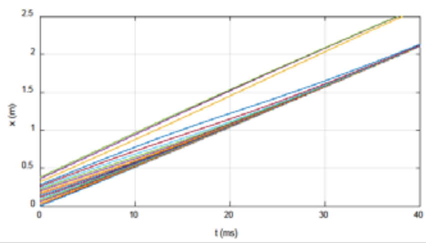
Results:

Based on two extraction methods, the effective speed of sound in the metamaterial is calculated and found to be slow in certain frequency ranges (illustrated in the figure on the left), thus providing the possibility to satisfy the grouping condition. The metamaterial model is further plugged into a vehicle exhaust system, with a running engine and a tailpipe connected to its two ends. The sound field inside the metamaterial part is decomposed and the trajectories of 20 evenly distributed particles in the exhaust pipe are calculated (illustrated in the figure on the right). Two clear particle groups can be found.

Effective Speed of Sound



Particle Trajectories



Summary and Conclusion:

A new approach to the analysis of particle grouping in a 1D acoustic field is suggested and the grouping condition is provided. In the case of grouping, the sound speed should be of the same order as the mean flow velocity. To realize such condition, locally-reacting-based acoustic metamaterials are introduced and the effective speed of sound is found to be very small in certain frequency ranges. An example of particle grouping inside a vehicle exhaust system with a plugged-in metamaterial part is shown.

Acknowledgement:

I really appreciate the supervision and instruction given by Prof. Mats Åbom, Prof. Hans Bodén and Mikael Karlsson. Also, thanks very much for the support from all the sponsors.

VOLVO BorgWarner SCANIA Swedish Energy Agency

KTH CCGEX

Flow Exergy Analysis on a Turbocharger Radial Turbine

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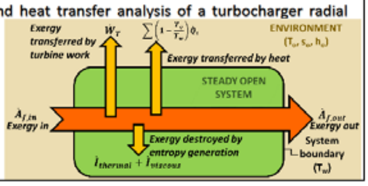
This project aims to assess the exhaust flow impact on heat transfer and performance of a turbocharger radial turbine operating under continuous and engine-like flow conditions by using Detached Eddy Simulation (DES) approach. Adiabatic and different temperatures are imposed on the wall to mimic different level of heat transfer scenarios. In addition to the commonly used energy conservation approach to relate the amount of heat loss to the turbine performance, *Exergy* (or *Availability*) concept is adopted to quantify the losses associated with heat transfers. The outcomes of exergy analysis enables us to identify the components where exergy destructions occur and rank order them according to significance. Furthermore, exergy analysis provides information about the effectiveness of exhaust gas energy utilization in the turbine system.

Introduction and Motivation:

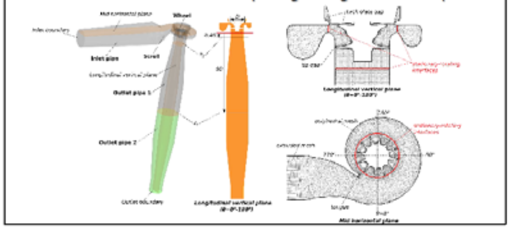
In practice, the turbocharger is not thermally insulated and the heat transfer affects its performance. Moreover, the heat transfer is affected by the flow characteristics. Within the turbocharger context, it is common to quantify the amount of heat transfer and the associated performance change by energy conservation principle. However, energy conservation idea alone is inadequate for quantifying the losses associated with heat transfer. In this study, Exergy concept derived from mass and energy conservation principles together with the Second Law of Thermodynamics are adopted to extend heat transfer analysis of a turbocharger radial turbine.

$$\dot{A}_f = \dot{m}\left[(h - h_o) - T_o(s - s_o) + \frac{U^2}{2}\right]$$



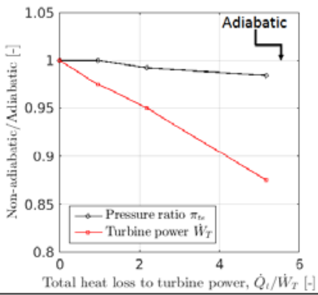
Setup:

The computational setup replicates the turbine operating at maximum efficiency point on a low speed line in hot gas stand. Nevertheless, simulations are on-going for turbine operating under pulsating engine-like conditions. Different thermal conditions (i.e. adiabatic and constant wall temperature T_w [K]= 1002, 830 and 487) are imposed on all walls to model heat transfer. The rotation of the turbine wheel is handled by using Sliding mesh technique.



Results:

1) Energy balance analysis shows that turbine power is sensitive, whereas pressure ratio is less sensitive to heat transfer.



$$\dot{Q}_t = \sum \dot{Q}_i$$

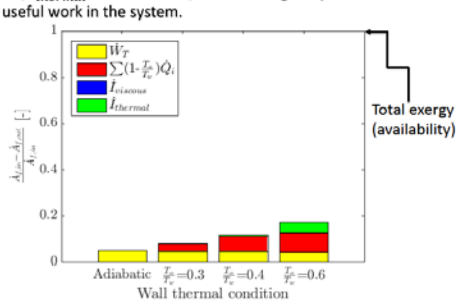
$$\dot{W}_T = \iint_{S_{wheel}} \left[(\vec{r} \times \vec{f}) \cdot \vec{\omega}\right] dS$$

$$\dot{Q}_i = \iint_{S_i} \vec{q} \cdot d\vec{S}$$

$$\dot{I}_{thermal} = T_o \iiint_{V_{cv}} \frac{k}{T^2} (\nabla T)^2 dV$$

$$\dot{I}_{viscous} = T_o \iiint_{V_{cv}} \frac{1}{T} \tau_{kj} \frac{\partial u_k}{\partial x_j} dV$$

2) Exergy analysis shows that heat transfer increases the (a) amount of exergy loss to the ambient via heat flow, $\sum\left(1 - \frac{T_o}{T_w}\right)\dot{Q}_i$ (b) exergy destroyed due to thermal entropy generation, $\dot{I}_{thermal}$. Nevertheless, there is still great potential to extract more exergy for useful work in the system.



Summary and Conclusion:

Different mechanisms of the heat transfer related losses for a turbocharger turbine can be quantified by looking at the exergy budget. Analysis based on the hot gas stand continuous flow condition shows that there exists great potential for better utilization of the hot gas energy resource. This highlights the needs for research and development in turbine design to harvest more flow exergy/availability. In near future, the exergy analysis will be extended and applied to turbine operating under engine-like conditions to assess how the upstream exhaust manifolds and flow instabilities affects the heat transfer and turbine performance.

Acknowledgement:

Supervisors: Mihai Mihaescu, Anders Dahlkild, Christophe Duwig, Laszlo Fuchs.

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