“HOT SIDE” project

HOlistic approach **T**argeting to reduce/recover exhaust losses and increase **S**park **I**gnited & **D**iesel **E**ngines performance

Summary: Integrated use of 1D and 3D flow modelling together with measurements for assessing exhaust flow, maximize exhaust energy extraction and increase ICE efficiency

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Framework: HOTSIDE

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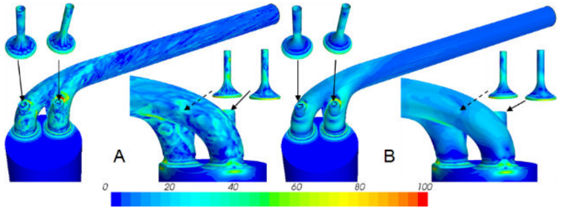
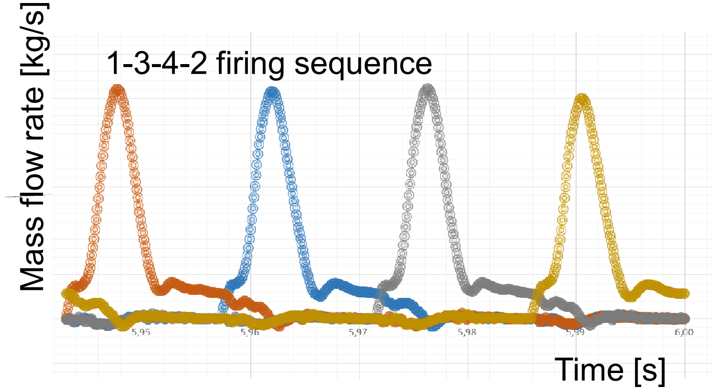
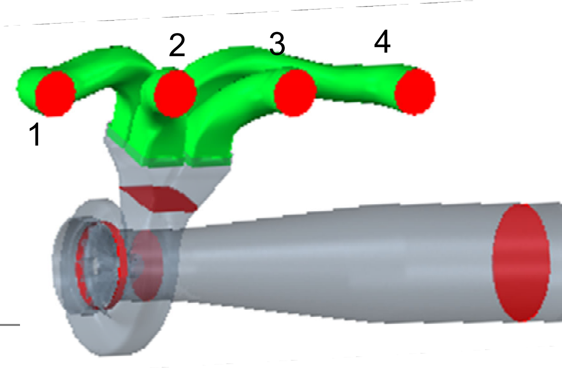
STEM / Swedish automotive industry supported project

- VT 2014 - HT 2017: *“**HOTSIDE**” project.* **HO**listic approach **T**argeting to reduce/recover exhaust losses and increase **S**park **I**gnited & **D**iesel **E**ngines performance
- *KTH-MWL, KTH-ICE, KTH-CICERO, KTH-Mek (applied CFD)*
- Partners/Collaborators: *SCANIA, Volvo Cars/GTT, BorgWarner*



Pulse information data by Volvo Cars Corp





Swedish Energy Agency

Overview: HOTSIDE

WHY

Maximize open cycle efficiency

Enhance understanding of the pulsatile exhaust flow and of its interaction with the turbine for a better usage of exhaust flow's energy available to be used

HOW

- Integrated high-fidelity simulations / detailed experiments / gas stand experiments / 1D simulations
- Accurate predictive models

- Flow characterization & heat transfer effects
- System overview & optimization (ICE+Turbo)

Activities

Industry Input
Volvo Cars (geometry, 1D)
Borg Warner (geometry, maps)

Exhaust valve strategies (ICE)
Ted Holmberg, PhD stud
1D Gas Dynamics / On engine Exp

CFD, manifold & turbine (Mek)
Shyang Maw Lim, PhD stud
High-fidelity LES, models

System Integration
NN, Ind PhD stud (Volvo GTT)
1D simulations/integration

Internal
Combustion
gine

n Effective
e (PMEP)

exhaust valve strategy

pulsed flow characteristics

Turbine response
- upstream flow instabilities
- exhaust valve strategy used
- heat transfer effects
- turbine maps / torque / efficiency

Exhaust engine manifold

back pressure

Industry Input
SCANIA (geometry, 1D)
Volvo GTT (1D)

Exhaust port & valve (CICERO)
Marcus Winroth, PhD stud
Exp. Fluid Mechanics

Exhaust pulsating flow
Chris Ford, Postdoc, CICERO
Exp. Fluid Mechanics

Turbomachinery design, 2D (ICE)
Nicholas Anton, Ind PhD stud (SCANIA)
2D simulations & turbo aero-design

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Project Aims

- Improve understanding of the pulsating flows in complex manifolds
  - high-fidelity simulations / experiments
  - intermittent flows effects on heat transfer
- Quantify the characteristics of the pulsating flow and effect on turbocharger’s efficiency
  - different exhaust valve strategies
- Improve understanding of heat transfer and heat transfer related losses for unsteady, pulsating, hot flows in complex manifolds
- Develop better calibrated 1D models and reduced order models

Post doctoral student:
Chris Ford, (Exp), Mek-CICERO

Doctoral students:
Marcus Winroth, (Exp), Mek-CICERO
Ted Holmberg (GT-Power, Exp), ICE
Shyang Maw Lim, (CFD), Mek
Nicholas Anton (2D Aerodesign), Scania

Reference group:
Lucien Koopmans, Volvo Cars
Habib Aghaali, Volvo Cars
Mattias Ljungqvist, Volvo Cars
Sofia Wagnborg, Volvo Cars
Johan Wallesten, Volvo GTT
Martin Bauer, Volvo GTT
Jonas Holmborn, Scania
Björn Lindgren, Scania
Magnus Genrup, LTH
Thomas Lischer, Borg Warner
Tom Heuer, Borg Warner
Marc Gugau, Borg Warner

Highlights & Plans: HOTSIDE

PROJECT HIGHLIGHTS (start HT2014):

- Verification phase for the CFD solver was completed
- Numerical & experimental studies indicate that the quasi-steady assumption used for modeling exhaust flow in the port is incorrect
- Demonstrated the capability to measure time-dependent mass flow in variable density flows both in pulsatile and steady cases

SHORT & LONG TERM PLANS:

- Perform dynamic valve experiments
- Unsteady mass flow measurements under on-engine realistic condition
- 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)
- Industrial PhD students integration (Scania, Volvo GTT)
- Identify and apply for EU project calls (Ho2020) and other funding opportunities

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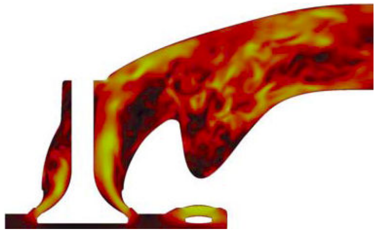
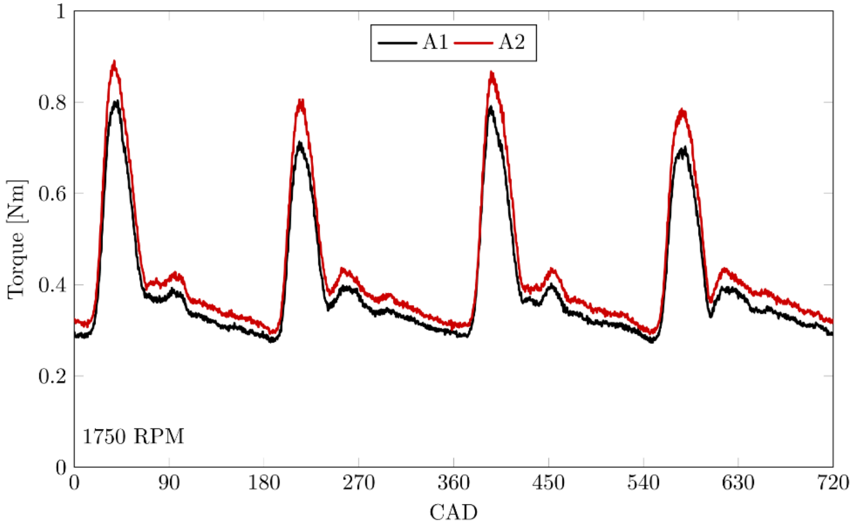
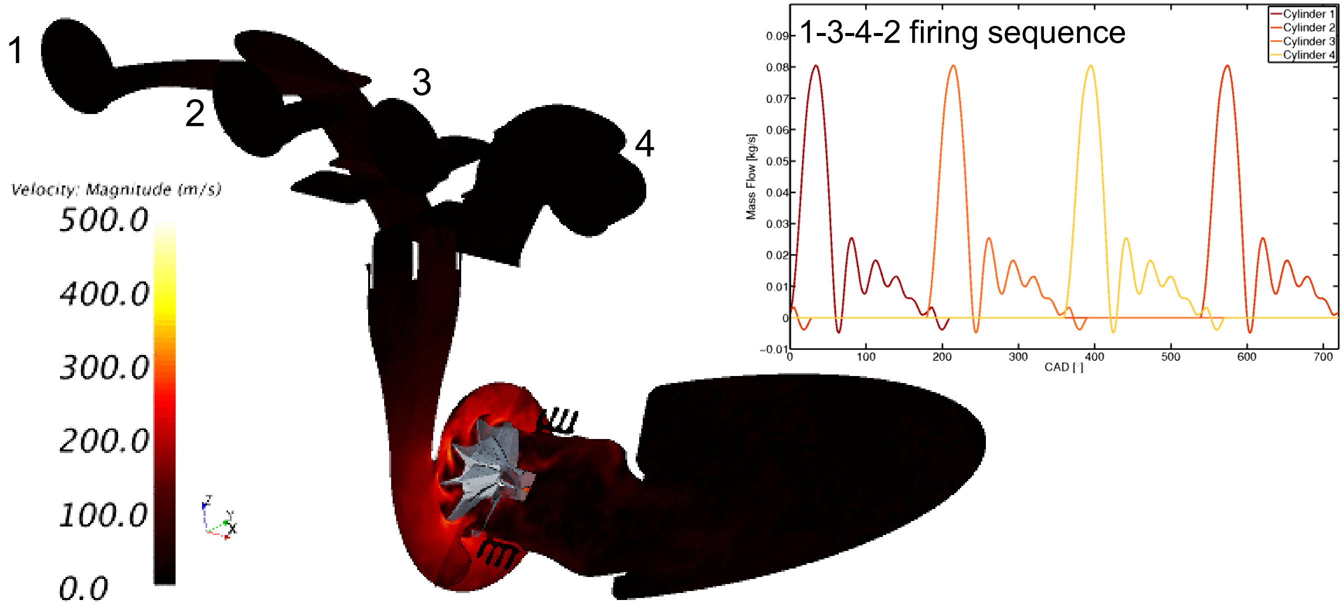
Integrated use of 1D & 3D flow modelling together with measurements for assessing exhaust flow, maximize exhaust energy extraction and increase ICE efficiency







Johan Fjällman, *thesis title: "Large Eddy Simulations of Complex Flows in IC-Engine's Exhaust Manifold and Turbine", Doctoral thesis, ISBN 978-91-7595-270-3, 2014.*

- At the exhaust valve & port, quasi-steady approximation is not valid and large dynamic effects are anticipated (e.g. on discharge coefficient)
- Non-uniformities leading to an uneven load of the turbine were exposed when pulsating conditions are considered
- Demonstrated the capability to measure time-dependent mass flow in variable density flows

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Gas dynamics of exhaust valves

Doctoral student:
Marcus Winroth (Exp), Mek-CICERO

Supervisors:
Henrik Alfredsson
Ramis Örlü

DOCTORAL PROJECT CONTENT/SCOPE:

1. Develop an experimental set-up for flow through a moving exhaust valve
2. Develop measurement techniques to determine the dynamic mass flow rate
3. Investigate the effect of valve position relative to e.g. cylinder wall, pressure ratio, opening speed
4. Compare static and dynamic results of exhaust valve flows

PROJECT RESULTS (since start 2014-09-15):

- Experimental set-up developed and taken into operation
- Measurement method promoted based on pressure data and isentropic relation
- First results on dynamic flow measurements obtained

FUTURE PLAN, SHORT & LONG TERM:

- Perform dynamic valve experiments at different; pressure ratios, valve opening speeds, valve lift profiles and radial position of the valve with one and two valves.
- Perform static valve experiments.

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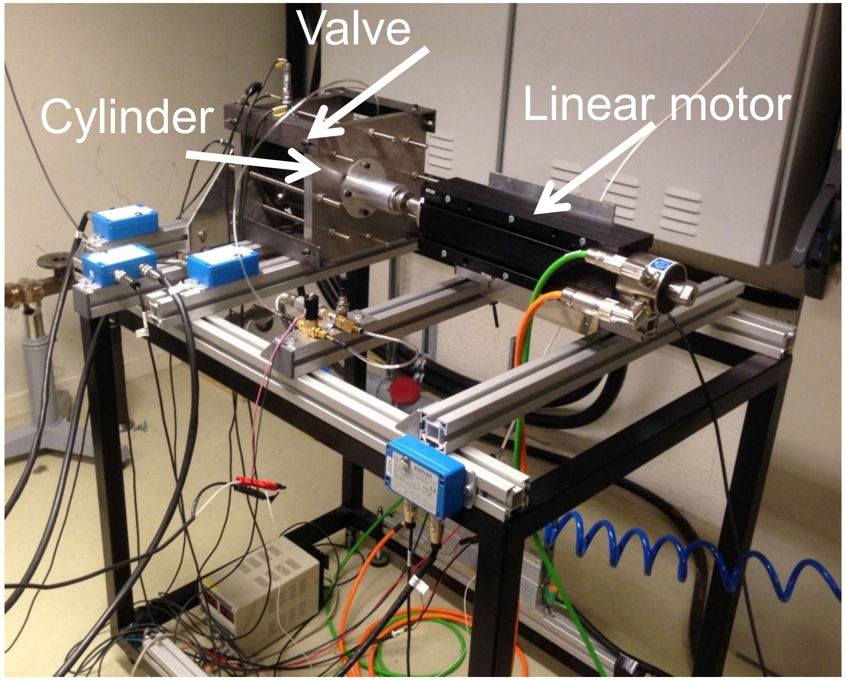
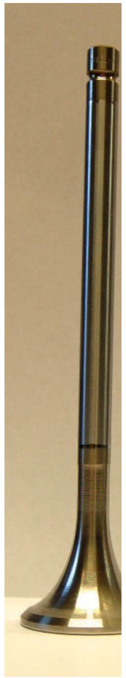
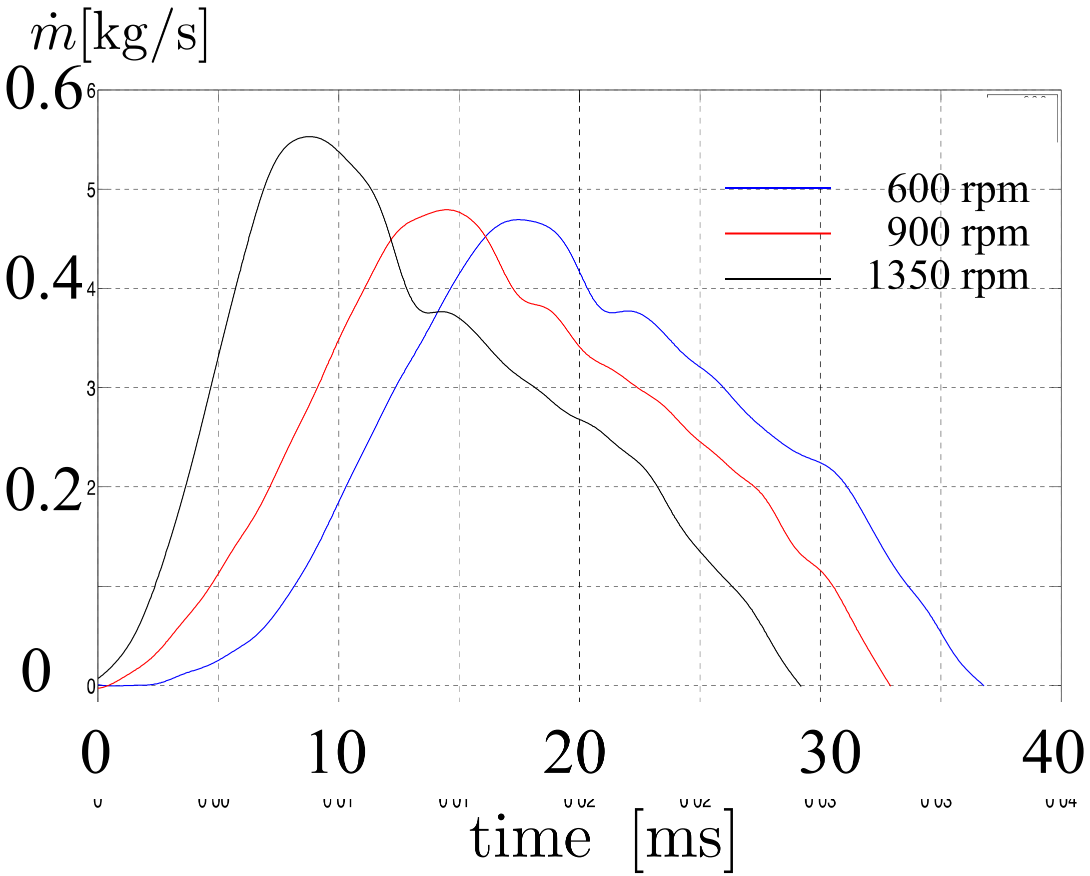
Gas dynamics of exhaust valves







- Mass flow through exhaust valve is determined from pressure variation in cylinder using isentropic relationship to determine density variation
- Experimental results show that quasi-steady approximation is not valid, and large dynamic effects are at hand

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Dynamic mass flow measurements in compressible flows

Post-doc:
Chris Ford (Exp), Mek-CICERO

Supervisors:
Henrik Alfredsson
Ramis Örlü

POST DOCTORAL PROJECT CONTENT/SCOPE:

1. Develop a method measurement of time-dependent mass flow in compressible flows
2. Use the method to determine the mass flow in the gas exchange system on engines

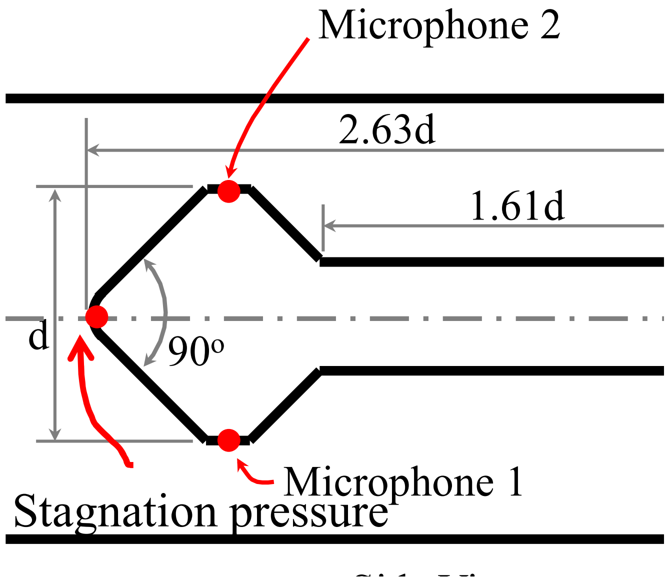
PROJECT RESULTS (since start 2014-09-15):

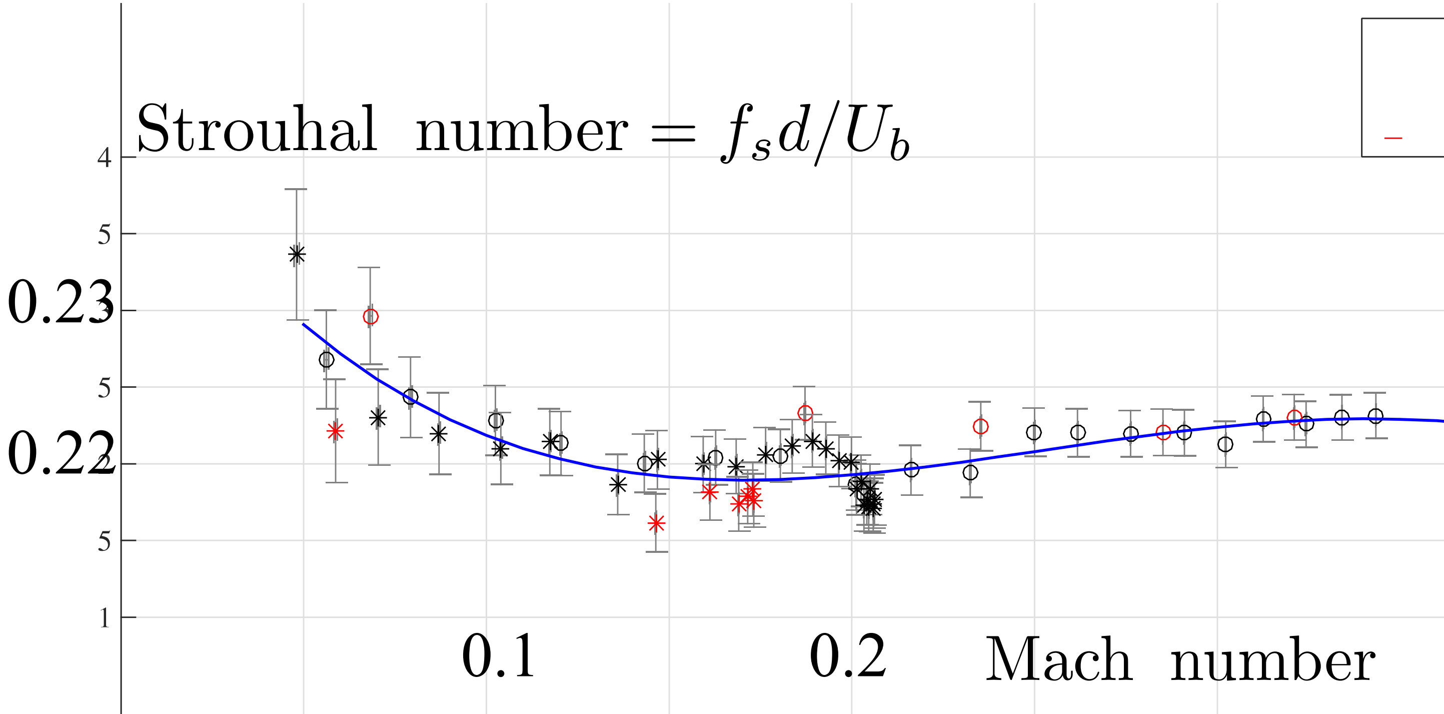
- Designed a vortex shedding device capable of determining mass flow rates typical in the gas exchange system of engines through pressure measurements
- Developed a time-signal analysis method to determine the frequency through short time FFT
- Demonstrated the capability to measure mass flow in variable density flows both in pulsatile and steady cases.

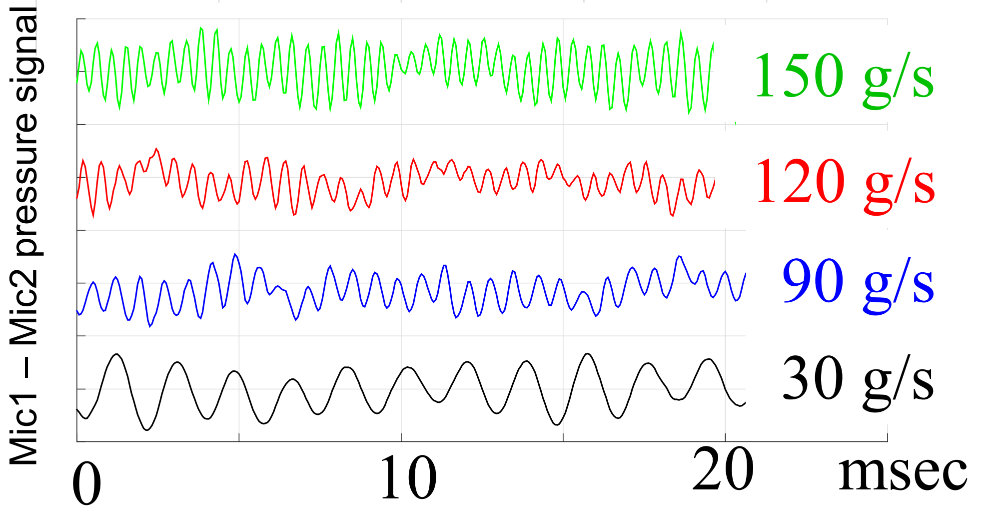
FUTURE PLAN SHORT & LONG TERM:

- Test various shapes in order to improve the signal-to-noise ratio
- See if modified shapes can improve linear range of meter calibration
- With the final design implement it in the engine environment

Dynamic mass flow measurements







- Design of probe body for vortex shedding
- Established Strouhal-Mach number relationship
- Used the setup to determine time dependent mass flow in compressible flows

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Flow & Heat Transfer Effects on Radial Turbine Efficiency

Doctoral student:
Shyang Maw Lim (CFD), Mek

Supervisors:
Mihai Mihaescu
Anders Dahlkild
Laszlo Fuchs

DOCTORAL PROJECT CONTENT/SCOPE:

1. 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)
2. Assessment of the exhaust system in an integrated manner (different levels of integration and complexity) for a realistic quantification of turbine’s performance
3. Advance fundamental knowledge regarding the exhaust flow and its interaction with turbine’s components to provide guidance for developing more efficient turbocharging

PROJECT RESULTS (since start 2014-08-11):

- Verification and Validation studies carried out; heat transfer effects on turbine performance were quantified under continuous flow conditions (conference publication ICJWSF15)
- The preliminary pulse profile sensitivity studies on Borg Warner turbine performance completed

FUTURE PLAN, SHORT & LONG TERM:

- Quantify the exhaust pulsating flow and charactersitic flow structures under specific engine like conditions, with and without heat transfer.
- Provide complementary maps based on RANS data for BorgWaner turbine (VEP-HP engine)
- Assess turbine flow and performance under stable and unstable conditions when integrated with the exhaust manifold; LES and mode decomposition techniques (selective points on the map).
- Assess heat transfer effects on turbine flow characteristics and performance, when integrated with the exhaust manifold.

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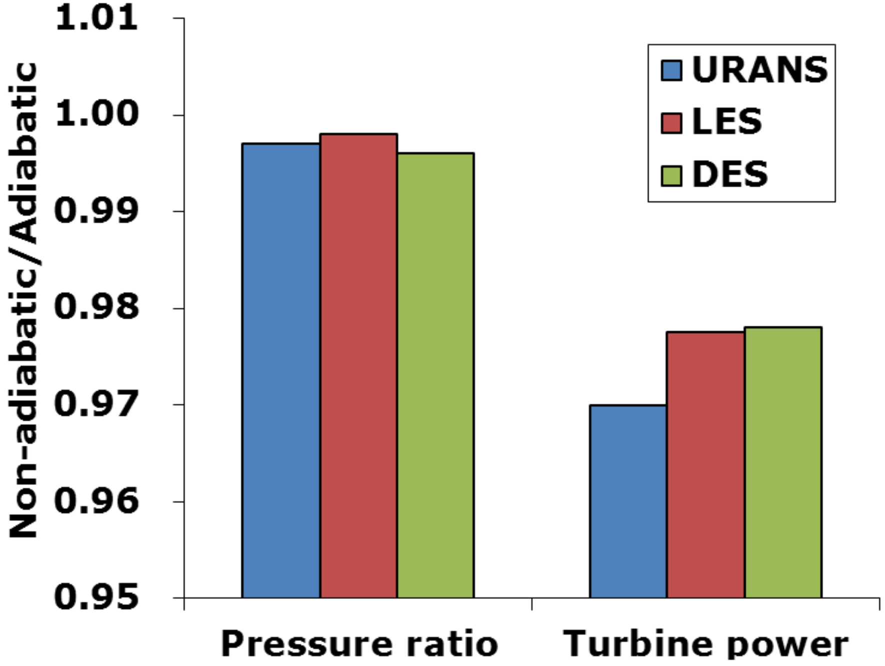
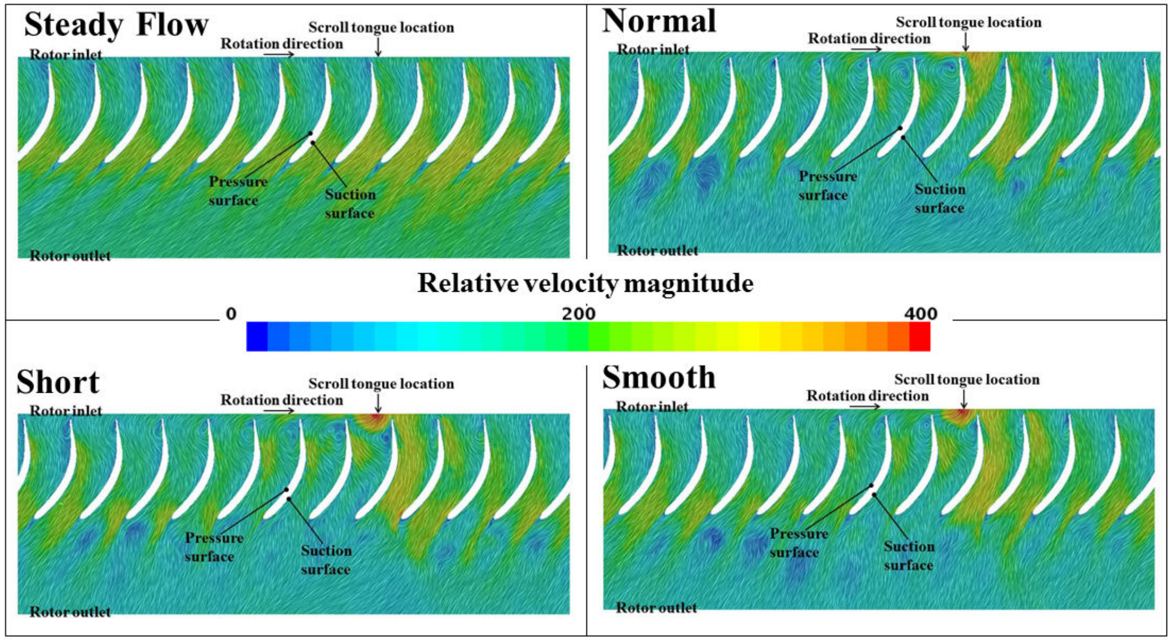
Turbine’s performance under continuous flow and heat transfer conditions (Left) and Flow field evaluations of turbine under pulsating flow conditions (Right)





- The effects of heat transfer on pressure ratio is insignificant (<1%) but significant on turbine power.
- Under pulsating flow conditions the flow field in the turbine exhibits large non-uniformities, unlike the case when the continuous flow conditions are imposed (same mass flow).

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Interaction between ICE Exhaust Pulses and Turbine

Doctoral student:
Ted Holmberg (GT-Power, Exp), ICE

Supervisors:
Andreas Cronhjort
Henrik Alfredsson

DOCTORAL PROJECT CONTENT/SCOPE:

1. Increase understanding of the trade-off between pumping losses and potential turbine work
2. Investigate how different exhaust valve strategies influence the potential turbine work
3. Motivate exhaust valve strategies for different operating conditions and turbine concepts

PROJECT RESULTS:

- Current investigation of potential and limitations of 1D simulation tools to predict the losses from the cylinder to the turbine inlet

FUTURE PLAN, SHORT & LONG TERM:

- Planning tests in a steady state air flow bench to quantify losses over the valve and port
- Integrate the new knowledge in a 1D simulation model and perform a study of different valve strategies

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Students; timeline (est): HOTSIDE

Turbocharging Research Area	**2015**				**2016**				**2017**				**2018**			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
HOTSIDE Project																
Ted Holmberg, PhD student, ICE, 1D/Exp	🟦	🟦	🟦	🟦	🟦	🟦	🟦 Lic	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦 PhD	
Marcus Winroth, PhD student, Mek, Exp	🟨	🟨	🟨	🟨	🟨	🟨	🟨 Lic	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨 PhD	
Shyang Maw Lim, PhD student, Mek, CFD	🟩	🟩	🟩	🟩	🟩	🟩	🟩 Lic	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 PhD	
Chris Ford, Postdoc, Mek, Exp	🟧	🟧	🟨	🟨	🟧	🟧										
Nicholas Anton, Ind. PhD stud Scania, ICE, 2D AeroDesign				🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦 Lic	🟦	🟦	🟦
NN, Ind. PhD stud Volvo GTT, 1D Intgr Turbo						🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

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Publications: HOTSIDE project

2014 – 2015 (selective)

Aghaali, H. (2014) *Exhaust Heat Utilisation and Losses in Internal Combustion Engines with Focus on the Gas Exchange System*, **PhD thesis**, KTH Machine Design, Stockholm, Sweden.

Fjällman, J. (2014) *Large Eddy Simulations of Complex Flows in IC-Engine's Exhaust Manifold and Turbine*. **PhD thesis**, KTH Mechanics, Stockholm, Sweden.

Aghaali H. and **Ångström H.E.** (2015) *A review of turbocompounding as a waste heat recovery system for internal combustion engine*s, Renew. Sust. Energ. Rev., **49**:813-824, dx.doi.org/10.1016/j.rser.2015.04.144

Lim, S. M., **Dahlkild, A.** and **Mihaescu, M.** (2015) *Wall Treatment Effects on the Heat Transfer in a Radial Turbine Turbocharger*. International Conference on Jets, Wakes and Separated Flows (ICJWSF15), Stockholm, June 2015.

Semlitsch B., **Wang Y.**, and **Mihaescu M.** (2015) *Flow effects due to valve and piston motion in an internal combustion engine exhaust port.* Energy Convers. Manage., **96**, 18–30. http://dx.doi.org/10.1016/j.enconman.2015.02.058

Fjällman J., **Mihaescu M.**, and **Fuchs L.** (2015) *Exhaust Flow Pulsation Effect on Radial Turbine Performance.* The Proceedings of The 11th European Turbomachinery Conference (ETC11), Madrid, March 2015.

Aghaali, H. and **Ångström, H.E.**(2014) *Performance Sensitivity to Exhaust Valves and Turbine Parameters on a Turbocompound Engine with Divided Exhaust Period*, SAE Int. J. Engines **7**:1722-1733, 2014. dx.doi.org/10.4271/2014-01-2597

Aghaali, H., **Ångström, H.E.**, and **Serrano, J.R.** (2014) Evaluation of Different Heat Transfer Conditions on an Automotive Turbocharger, I. J. Engine Res. dx.doi.org/10.1177/1468087414524755

Semlitsch B., **Wang Y.**, and **Mihaescu M.** (2014) *Flow Effects due to Pulsation in an Internal Combustion Engine Exhaust Port.* Energy Convers. Manage., 86, 520-536. dx.doi.org/10.1016/j.enconman.2014.06.034

Wang, Y., **Semlitsch, B.**, **Mihaescu, M.**, and **Fuchs, L.** (2014) Flow induced Energy Losses in the Exhaust Port of an Internal Combustion Engine. J. Fluids Eng. dx.doi.org/10.1115/1.4027952

Fjällman J., **Mihaescu M.**, and **Fuchs L.** (2014) *Analysis of 3-Dimensional Turbine flow by Using Mode Decomposition Techniques.* ASME Paper, GT2014-26963. dx.doi.org/10.4271/2014-01-0006

Directions with HOTSIDE

- Engine sub-systems of importance treated individually
  - Detailed experiments and CFD simulations: the intake and exhaust ports & turbo (turbine + compressor)
  - Use of experimental, and GT power data at the boundaries of the computational domains
  - Use measurements for validation purposes (various engine sub-systems & operating conditions
- Integrated approach: assessment of the engine system
  - Integrate reduced order models (steady-state flow & GT-Power simulations) & Complex LES; exchange of information at the interfaces between domains
  - ICE Test Cell measurements (pressure, temperature, engine performance)

	Pulse Generation Flow Convection & Pulse Propagation Characterization	Turbocharger Assessment	Integrated Exhaust System		Heat Transfer
GENERAL GOALS	Improve understanding of the pulsating exhaust flow in complex manifolds	Characterization of the pulsating flow and asses the effect of the exhaust flow on turbocharger's efficiency		Understanding the reason for failure of 1D and steady-state based tools for certain operating conditions	Improve understanding of heat transfer and heat transfer related losses for unsteady, pulsating, non-isothermal flows in complex manifolds
RESEARCH QUESTIONS	How the Combustion concept influences the pulse shape? How the various valve strategies (lift speed, lift height, phasing) are influencing pulses (press., temp., mass flow as function of time)?	Why/How does the pressure-mass flow phase shift affects turbocharger's performance?	Why/How does manifold's geometry (curvature, diameter, length) affects turbocharger's performance?	Which is the operability range for 1D and steady-state modeling tools? What is the best threshold quantity to be used for identifying operability ranges?	How to measure properly heat transfer with and without effect of unsteadiness?
	How is the Pressure-Mass Flow phase shift influenced by: Valve strategy (lift height, lift speed, phasing); Exhaust manifold shape; Number of cylinders	Which is the cause (rotor inertia/flow dynamics) for triggering a hysteresis loop or unstable operating conditions at the margins of the turbine map?	Why/How do pulsations in the exhaust flow (frequency, amplitude, pulse shape) affect turbine and turbocharger's performance?	How does the non-linear interaction between engine components (through flow and pressure) affects the system? What is the receptivity of the flow to acoustic perturbations?	Why/How do manifold's curvature, swriling flow, and pulsations affect heat transfer within the exhaust manifold?
	How are the flow structures in the exhaust manifold (their shape, energy content) affected by flow's curvature, flow's swirl, or pulses (different frequency, amplitude and shape)?	What is the effect of the swirling flow on turbocharger's performance?	How the overall problem scales from one turbo to the other?		How the heat transfer alters the discharge coefficient in the exhaust port?
HYPOTHESES	Energy of the pulse is enclosed within the large coherent structures	Pulsations and exhaust flow characteristics have important effects on turbine performance	The non-linear interaction (by means of flow & pressure) between system's components (e.g. Manifold-turbo-manifold, turbo-turbo, exhaust port-manifold-turbo-exhaust pipe) is important		Heat transfer is important to be considered and is affected by the exhaust flow unsteadiness, geometrical complexity, and surface quality

	Pulse Generation Flow Convection & Pulse Propagation Characterization	Turbocharger assessment	Integrated Exhaust System		Heat Transfer
GENERAL GOALS	Improve understanding of the pulsating exhaust flow in complex manifolds	Characterization of the pulsating flow and asses the effect of the exhaust flow on turbocharger's efficiency		Understanding the reason for failure of 1D and steady-state based tools for certain operating conditions	Improve understanding of heat transfer and heat transfer related losses for unsteady, pulsating, non-isothermal flows in complex manifolds
RESEARCH ACTIVITIES	Quantify the exhaust flow, its characteristics in the exhaust port and manifold under steady and pulsating (amplitudes, frequencies and pulse shapes) conditions. Run engine specific conditions (CICERO, CFD)	Assess turbocharcher's flow characteristics and performance under stable and unstable conditions; complementary maps, hot vs. cold simulations vs. experiments (CFD, CICERO)	Numerical and experimental assessment of turbocharger' flow and performance for different upstream and downstream geometrical configurations and operating conditions (CFD, CICERO)	1D discretization of turbocharger; Characterize the system (different levels of integration) using 1D modeling and steady-state flow solvers (CFD, ICE Lab)	Development of method for time-resolved temperature measurements and for heat transfer measurements (CICERO)
	Characterize the coherent structures in the exhaust flow field using mode decomposition techniques (CICERO, CFD)	Characterize the turbocharger flow using LES and experiments (selective points on the map) (CFD, CICERO)	Assess exhaust and turbocharger flow for different set-ups (pulse shape, pulse frequency, pulse amplitude) to maximize exhaust exergy utilization; characterise the flow, pressure and turbochrg.'s performance (ALL)	Based on LES data provide models for flow losses in turbine / compressor rotor & volute (CFD)	Development of turbocharger test loop for high temperature flow experiments (CICERO)
	Numerical and experimental characterization of exhaust valve effective area and discharge coeff. for various specific conditions (ALL)	Acoustic characterization of turbocharger's system under stable and unstable conditions (MWL / CICERO, CFD)	Turbine design suggestions for specific valve strategies / selection for best turbine based on efficiency in relation to valve strategies (ALL)	Assess turbocharger's performance on engine (ICE Lab)	Assessment of heat transfer effects computationally and experimentally (ALL)
DELIVERABLES	Guidelines for design of exhaust port and exhaust manifold and exhaust valve strategy to maximize exhaust flow's exergy.	Guidelines for exhaust valve strategies to maximize exhaust flow's exergy.	Guidelines for broadening the operation map of the turbocharger	Parameters that can be integrated in the process of engine system assessment and optimization; Better calibrated models / data to be used for developing reduced models	Guidelines for a better integration of turbine for maximum energy extraction; Guidelines for a better turbine design

Summary: deliverables

1. Guidelines for design of exhaust port and exhaust manifold
2. Guidelines for exhaust valve strategies to maximize exhaust flow’s exergy.
3. Improved measurement techniques for heat transfer measurement under unsteady flow conditions
4. Complementary turbine and compressor maps for different upstream/downstream flow and geometrical settings
5. Guidelines for broadening the operation map of the turbocharger
6. Operating ranges (turbo) suitable for investigation using simple and inexpensive tools
7. Operating ranges (pressure ratios & mass flows) suitable to complex & expensive tools (e.g. LES)
8. Data to be use for improving the reduce models
9. Parameters to be measured/calculated so that can be integrated in the process of engine system assessment and optimization
10. Guidelines for a better integration of turbine for maximum energy extraction
11. Guidelines for a better turbine design