KTH ROYAL INSTITUTE
OF TECHNOLOGY

Exergy Evaluation of Engine Operations: Combustion Process to Exhaust Flow

Beichuan Hong

Competence Center for Gas Exchange (CCGEx) & Department of Engineering Design

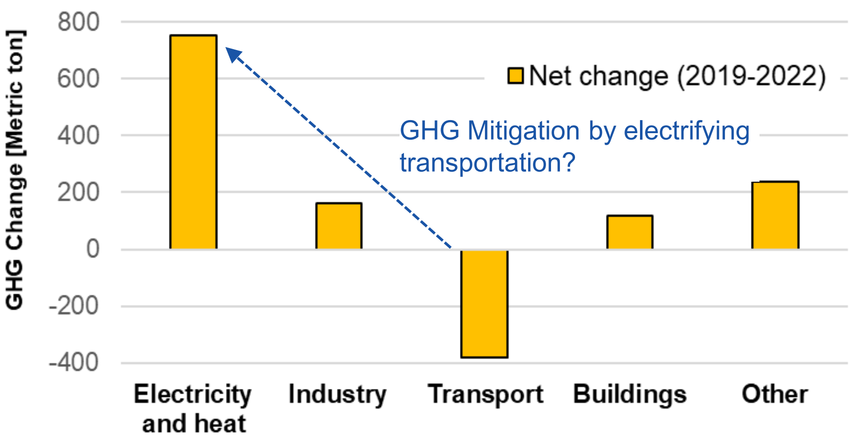
KTH Royal Institute of Technology

Outline

1. Introduction
   - Background & Motivation
   - Exergy Concept
2. Research Questions (RQs)
3. Methodology
   - Engine Setup and Test Matrix
   - Research Approach
4. Answers to RQs
5. Conclusions
6. Outlook

Introduction: Background & Motivation

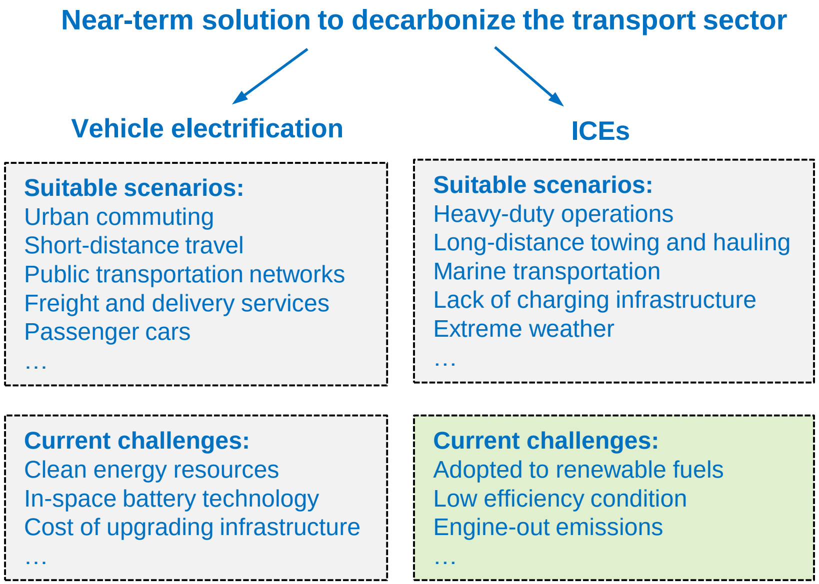
Global Greenhouse Gas Emissions Change By Sector:



- ☐ Transportation GHG emissions are associated with the use of fossil fuels (e.g., coal, gasoline, diesel), instead of internal combustion engines (ICEs).
- ☐ Both vehicle electrification and ICEs need to transition towards increased use of renewable energy sources.

Source: IEA (2023), Global CO2 emissions by sector https://www.iea.org/reports/co2-emissions-in-2022 Accessed on 2023-07-24

Introduction: Background & Motivation



Near-term solution to decarbonize the transport sector

Vehicle electrification

Suitable scenarios:
Urban commuting
Short-distance travel
Public transportation networks
Freight and delivery services
Passenger cars
…

Current challenges:
Clean energy resources
In-space battery technology
Cost of upgrading infrastructure
…

ICEs

Suitable scenarios:
Heavy-duty operations
Long-distance towing and hauling
Marine transportation
Lack of charging infrastructure
Extreme weather
…

Current challenges:
Adopted to renewable fuels
Low efficiency condition
Engine-out emissions
…

☐ Combining these two technical approaches, rather than competing, is a practical near-term solution to decarbonize the transport sector.

☐ Reducing the efficiency losses and emissions from ICEs with renewable fuels remains a valuable goal.

Introduction: Exergy Concept

Can heat and work be equalized?

Energy Balance (1st law):

$$U_2 - U_1 = Q_{12} - W_{12}$$

Exergy = Available Energy

$$E = U_{useful} = U_{total} - U_{inavaliable}$$

Exergy refers to the maximum amount of work obtainable from a given resource of energy.

$$E = (U - U_0) + p_0(V - V_0) \underline{- T_0(S - S_0)}$$

Subscript 0: Dead state (i.e., the state of surroundings)

- The system’s ability to do work depends upon both the state of the resource and the state of surroundings.
- Energy quality can be different, e.g., heat is low quality energy.

Using entropy to re-evaluate heat: $\underline{X_Q = Q - T_0 S}$

Research Questions (RQs)

The aim of this thesis is to evaluate engine efficiency, losses, and irreversibilities, as well as the power of exhaust flows from an exergy perspective, with a particular concern on combustion processes and exhaust pulsations.

Research Objective 1: Combustion and its exhaust exergy assessment

RQ. 1: Where and to what extent do engine exergy losses occur, associated with combustion, heat dissipation, and flow viscosity?

RQ. 2: How does lean-burn combustion impact energy and exergy in an HD SI engine with regard to:

i. Combustion timing advancement due to knock mitigation;

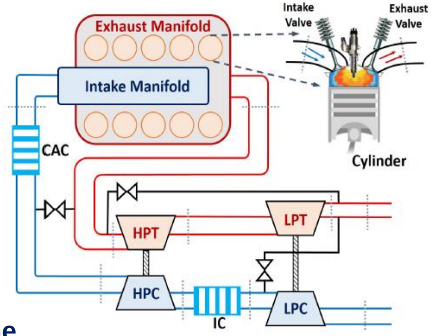
ii. Relevant turbocharging requirement?

Methodology

RQ. 1: Where and to what extent do the engine exergy losses occur, associated with combustion, heat dissipation, and flow viscosity?

Methodology | RQ.1: Engine Setup & Test Matrix

Wärtsilä 31V10DF marine engine



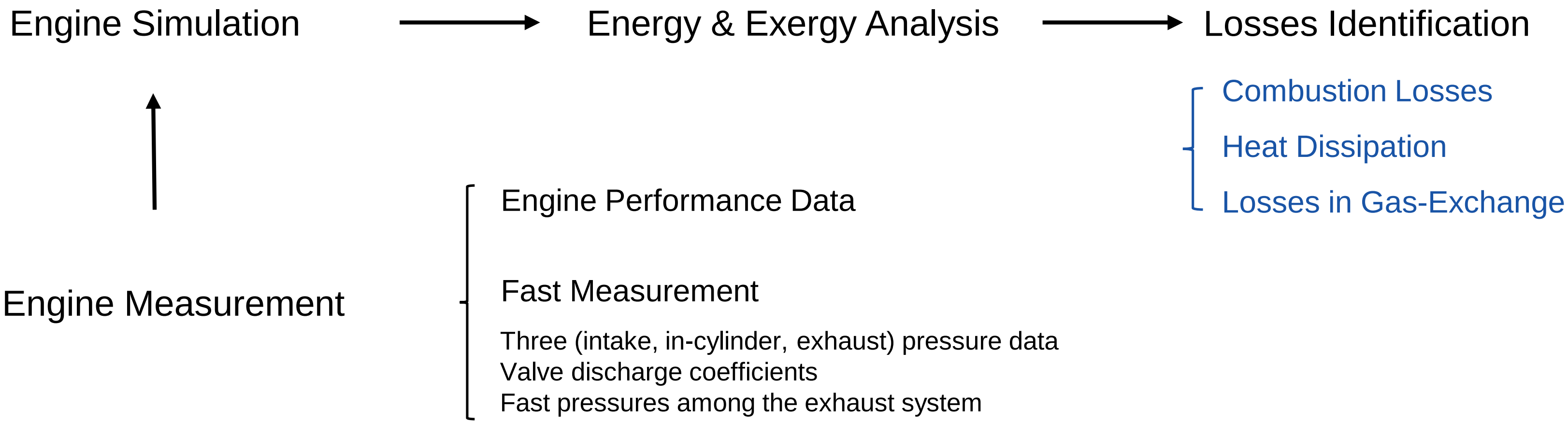
Cylinder layout	10-cylinder, V-bank engine
Bore × Stroke	310 mm × 430 mm
Displacement	2152 litre
Max Brake Power	5500 kW at 750 rpm
Gas exchange	Two-stage serial turbocharging Hydraulic valve actuation
Fuel system	Gas mode: CNG premixed charge, pilot diesel ignition DI mode: Diesel direct injection

Tested engine specifications

Test Matrix

Operating Load	25%, 50%, 75%, 100%
Engine Speed	750 rpm
Combustion Mode	Gas and DI modes

Methodology | RQ.1: Research Approach



Engine Simulation → Energy & Exergy Analysis → Losses Identification

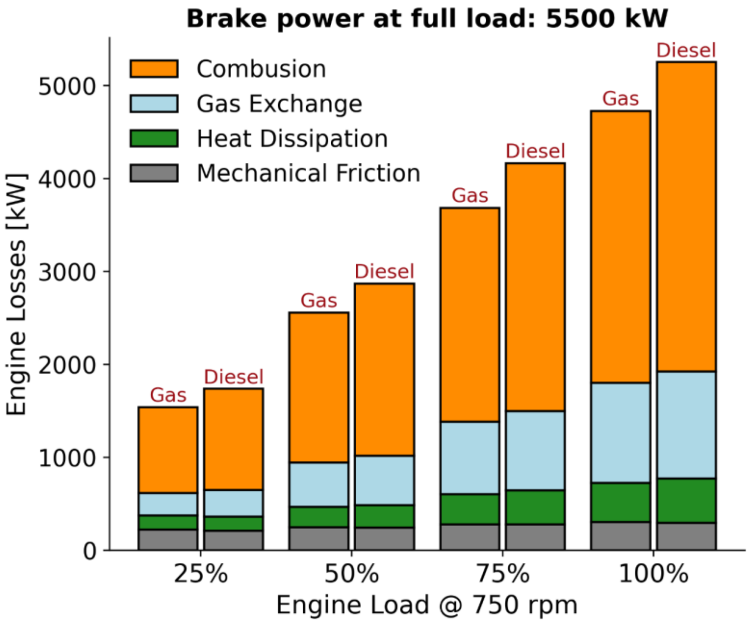
- Combustion Losses
- Heat Dissipation
- Losses in Gas-Exchange

Engine Measurement ↑

- Engine Performance Data
- Fast Measurement

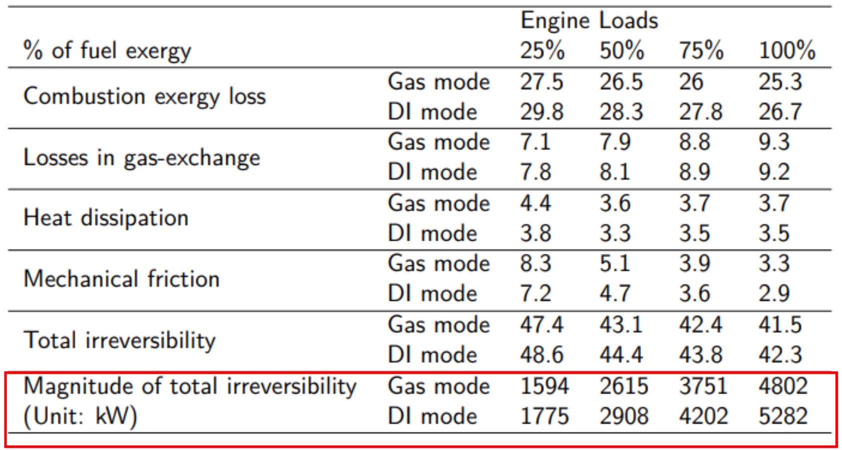
Three (intake, in-cylinder, exhaust) pressure data
Valve discharge coefficients
Fast pressures among the exhaust system

Answer to RQ.1: Losses Identification



Magnitude of engine exergy losses:
Gas Mode (left), Diesel Mode (right)

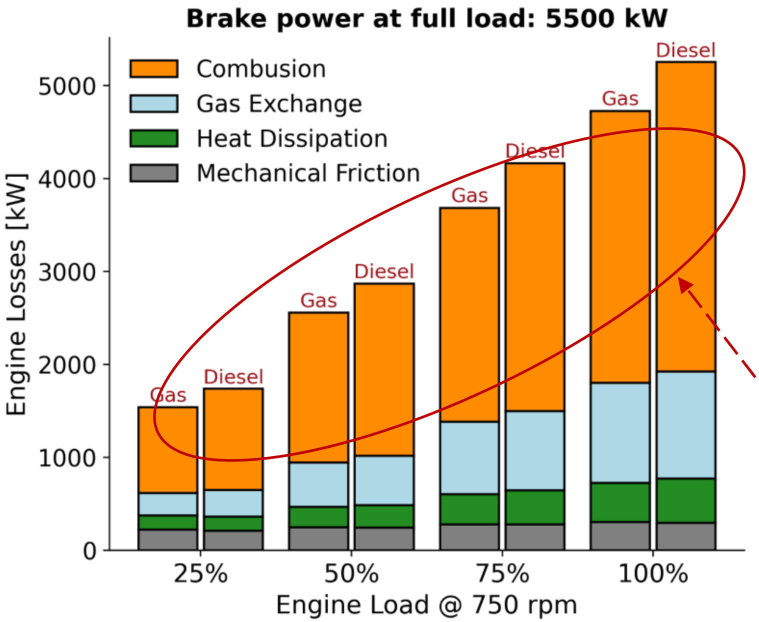
Fraction of different types of loss to fuel exergy



% of fuel exergy		Engine Loads 25%	50%	75%	100%
Combustion exergy loss	Gas mode	27.5	26.5	26	25.3
	DI mode	29.8	28.3	27.8	26.7
Losses in gas-exchange	Gas mode	7.1	7.9	8.8	9.3
	DI mode	7.8	8.1	8.9	9.2
Heat dissipation	Gas mode	4.4	3.6	3.7	3.7
	DI mode	3.8	3.3	3.5	3.5
Mechanical friction	Gas mode	8.3	5.1	3.9	3.3
	DI mode	7.2	4.7	3.6	2.9
Total irreversibility	Gas mode	47.4	43.1	42.4	41.5
	DI mode	48.6	44.4	43.8	42.3
Magnitude of total irreversibility (Unit: kW)	Gas mode	1594	2615	3751	4802
	DI mode	1775	2908	4202	5282

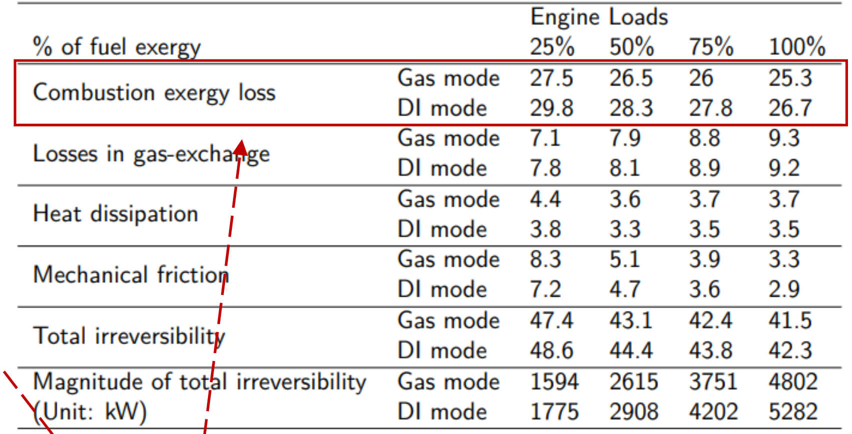
Compared to Gas mode, Diesel mode shows greater magnitudes of engine losses.

Answer to RQ.1: Combustion Exergy Loss



Magnitude of engine exergy losses:
Gas Mode (left), Diesel Mode (right)

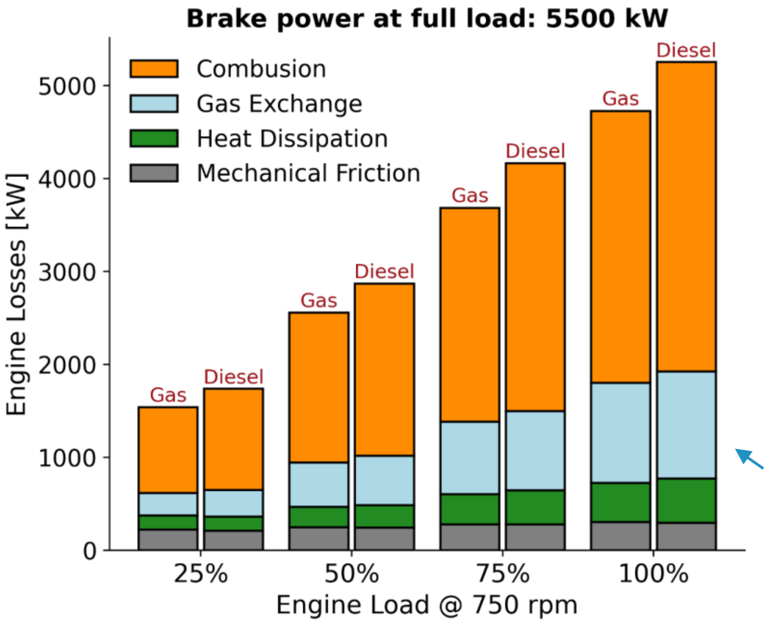
Fraction of different types of loss to fuel exergy



		Engine Loads			
% of fuel exergy		25%	50%	75%	100%
Combustion exergy loss	Gas mode	27.5	26.5	26	25.3
	DI mode	29.8	28.3	27.8	26.7
Losses in gas-exchange	Gas mode	7.1	7.9	8.8	9.3
	DI mode	7.8	8.1	8.9	9.2
Heat dissipation	Gas mode	4.4	3.6	3.7	3.7
	DI mode	3.8	3.3	3.5	3.5
Mechanical friction	Gas mode	8.3	5.1	3.9	3.3
	DI mode	7.2	4.7	3.6	2.9
Total irreversibility	Gas mode	47.4	43.1	42.4	41.5
	DI mode	48.6	44.4	43.8	42.3
Magnitude of total irreversibility (Unit: kW)	Gas mode	1594	2615	3751	4802
	DI mode	1775	2908	4202	5282

Combustion exergy loss dominates, as it accounts for more than half of the total engine losses.

Answer to RQ.1: Losses in Gas-Exchange



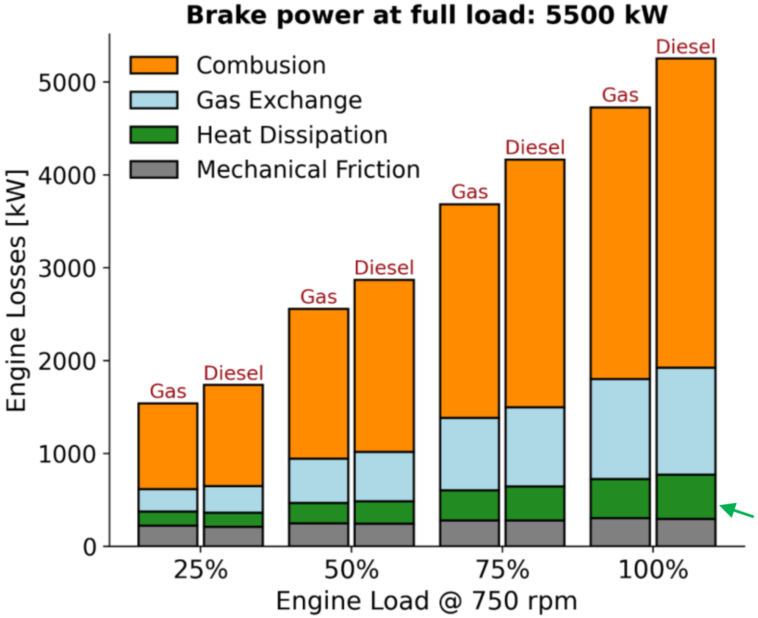
Magnitude of engine exergy losses:
Gas Mode (left), Diesel Mode (right)

Fraction of different types of loss to fuel exergy

% of fuel exergy		Engine Loads 25%	50%	75%	100%
Combustion exergy loss	Gas mode	27.5	26.5	26	25.3
	DI mode	29.8	28.3	27.8	26.7
Losses in gas-exchange	Gas mode	7.1	7.9	8.8	9.3
	DI mode	7.8	8.1	8.9	9.2
Heat dissipation	Gas mode	4.4	3.6	3.7	3.7
	DI mode	3.8	3.3	3.5	3.5
Mechanical friction	Gas mode	8.3	5.1	3.9	3.3
	DI mode	7.2	4.7	3.6	2.9
Total irreversibility	Gas mode	47.4	43.1	42.4	41.5
	DI mode	48.6	44.4	43.8	42.3
Magnitude of total irreversibility (Unit: kW)	Gas mode	1594	2615	3751	4802
	DI mode	1775	2908	4202	5282

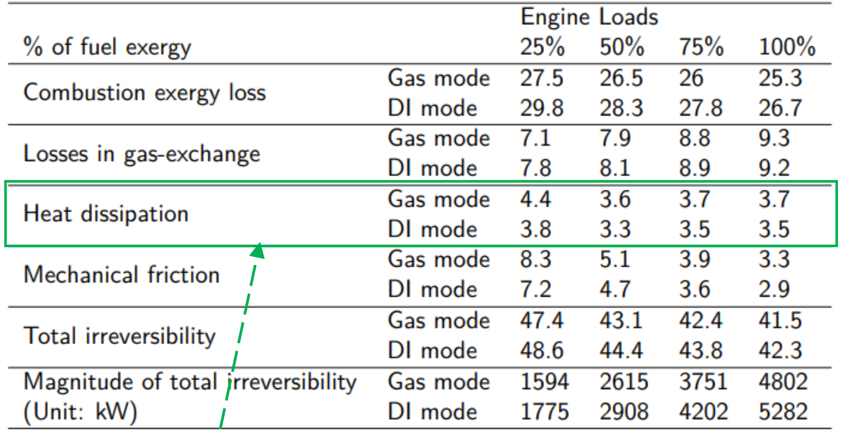
Losses in gas-exchange increases more significantly with load. Flow losses in the gas-exchange constitute the second major contributor to engine exergy destruction, primarily attributable to the turbocharging process.

Answer to RQ.1: Heat Dissipation



Magnitude of engine exergy losses:
Gas Mode (left), Diesel Mode (right)

Fraction of different types of loss to fuel exergy



% of fuel exergy		Engine Loads 25%	 50%	 75%	 100%
Combustion exergy loss	Gas mode	27.5	26.5	26	25.3
	DI mode	29.8	28.3	27.8	26.7
Losses in gas-exchange	Gas mode	7.1	7.9	8.8	9.3
	DI mode	7.8	8.1	8.9	9.2
Heat dissipation	Gas mode	4.4	3.6	3.7	3.7
	DI mode	3.8	3.3	3.5	3.5
Mechanical friction	Gas mode	8.3	5.1	3.9	3.3
	DI mode	7.2	4.7	3.6	2.9
Total irreversibility	Gas mode	47.4	43.1	42.4	41.5
	DI mode	48.6	44.4	43.8	42.3
Magnitude of total irreversibility (Unit: kW)	Gas mode	1594	2615	3751	4802
	DI mode	1775	2908	4202	5282

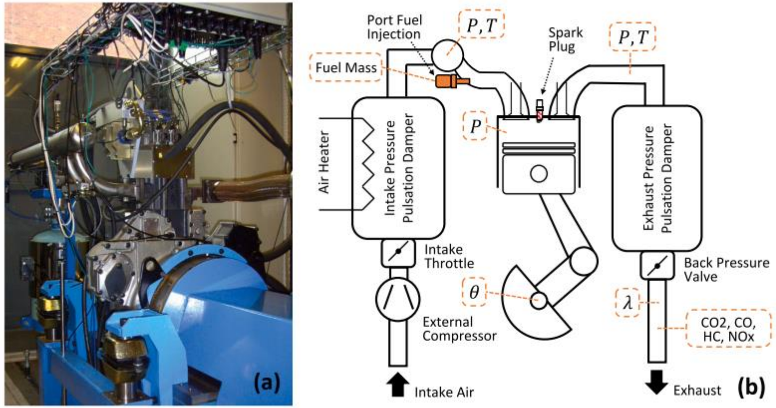
Heat dissipation accounts for the smallest fraction at low load and exceeds mechanical friction loss as the load increases.

Methodology

RQ. 2: How does lean-burn combustion impact energy and exergy in an HD SI engine with regard to:

1. **Combustion timing advancement due to knock mitigation;**
2. **Relevant turbocharging requirement?**

Methodology | RQ.2: Engine Setup & Test Matrix



Bore × Stroke	127 mm × 154 mm
Compression ratio	12.7:1
IVO/IVC	346 °CA aTDC/-154 °CA aTDC
EVO/EVC	145 °CA aTDC/355 °CA aTDC
Mixture formation	Port fuel injection
Ignition	Central-mounted spark plug
Fuel	Ethanol
Combustion chamber	Bowl-in piston

***Tested engine specifications**

Test Matrix

KLSA operating points

gIMEP	[bar]	20	20	20	20	20
Engine speed	[rpm]	1200	1200	1200	1200	1200
Excess air ratio	[-]	1.0	1.2	1.4	1.6	1.8
Boost pressure	[bar abs.]	1.76	2.03	2.23	2.46	2.74
Air mass rate	[g/s]	190	214	237	273	306
Exhaust temperature	[K]	1170	1033	943	879	820
Back pressure	[bar abs.]	1.22	1.33	1.48	1.69	1.94

KLSA: knock-limited spark advance

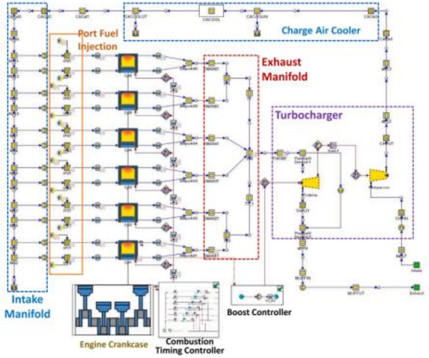
*Mahendar S.K., Larsson T., Erlandsson A.C. Alcohol lean burn in heavy duty engines: Achieving 25 bar IMEP with high efficiency in spark ignited operation. International Journal of Engine Research. 2021.

Methodology | RQ.2: Research Approach

Single-Cylinder Engine

Lean-Burn Measurement Data

Predictive Combustion Model
(SITurb Model)

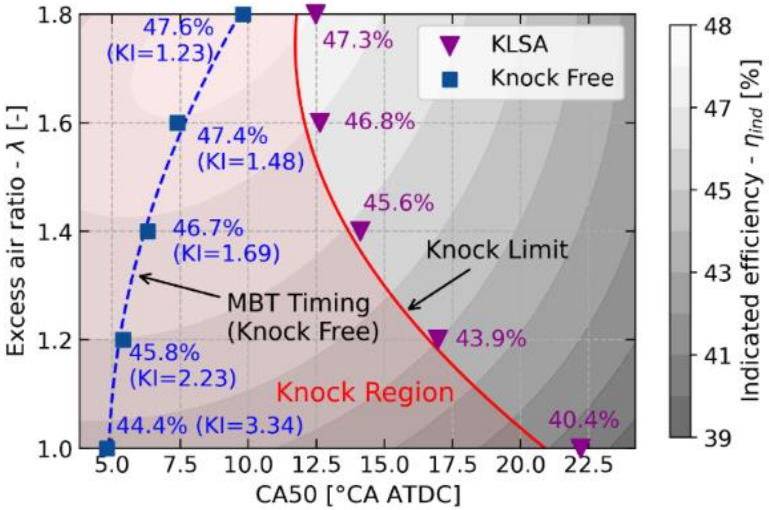


6-Cylinder Engine Model

Energy & Exergy Analysis

- Knock Mitigation
- Combustion Losses at KLSA
- Entropy Generation through Lean Burn
- Exhaust Exergy Recovery

Answer to RQ.2: Efficiency Improvement due to Knock Mitigation



Efficiency comparison of KLSA and knock-free MBT across excess air ratios up to λ = 1.8

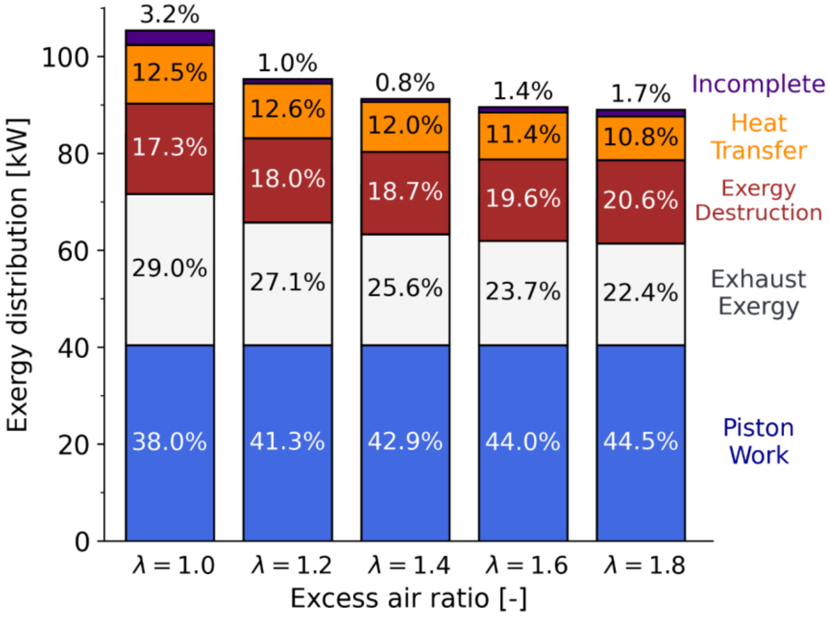
- Knock mitigation by increased dilution (λ=1 → λ=1.8) advances combustion phasing. Advanced KLSA CA50 (22.3 CAD ATDC → 12.4 CAD ATDC) leads to an increase in indicated efficiency from 40.4% to 47.3%.

- KLSA combustion with dilution approaches the knock-free highest efficiency (Convergence of KLSA CA50s and knock-free MBT CA50s).

MBT: maximum brake torque which referrers to the optimal combustion timing to engine's maximum power and efficiency.

KI: knock integral which is calculated by Livengood–Wu knock integral, and KI ≥ 1 indicates knock onset.

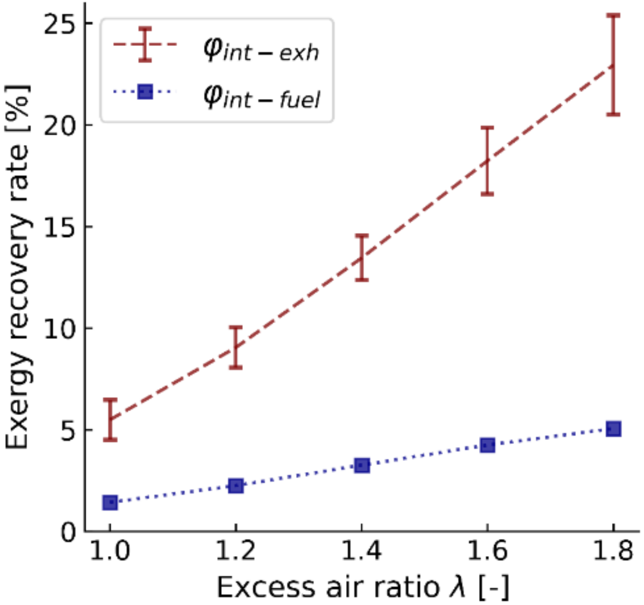
Answer to RQ.2: Exergy Distribution



Exergy distribution per cylinder at KLSA timing across the dilution range

- ❑ Significant reduction in heat transfer loss and exhaust gas segments with dilution.
- ❑ Diluted combustion causes more exergy destruction.
- ❑ Challenging requirements for lean-burn combustion due to lower exhaust gas exergy and higher boost pressures.

Answer to RQ.2: Turbocharging Requirement



Exergy recovery rate across the dilution range.

Error bar of $\varphi_{\text{int−exh}}$ is caused by η_{tc} from 0.5 to 0.7.

- ☐ Exergy recovery rate: intake to exhaust

  5.4% (λ = 1.0) ➔ 22.6% (λ = 1.8)

$$\varphi_{\text{int−exh}} = \frac{Intake}{Exhaust}$$

- ☐ Exergy recovery rate: intake to fuel

  1.1% (λ = 1.0) ➔ 4.8% (λ = 1.8)

$$\varphi_{\text{int−fuel}} = \frac{Intake}{Fuel}$$

Research Questions (RQs)

The aim of this thesis is to evaluate engine efficiency, losses, and irreversibilities, as well as the power of exhaust flows from an exergy perspective, with a particular concern on combustion processes and exhaust pulsations.

Research Objective 2: Characterization of exhaust pulsating flow

RQ. 3: How do variations in flow parameters such as pressure, temperature, and velocity affect the energy and exergy quantification of exhaust pulsating flows?

RQ. 4: How to characterize exhaust pulsating mass flows by using a Pitot tube-based approach considering the effect of attenuated temperature pulsations?

RQ. 5: Based on fast measurement using a Pitot tube-based approach, what is the characterization of exhaust mass flow pulses with regard to blow-down and scavenge phases?

Methodology

RQ. 3 How do variations in flow parameters such as pressure, temperature, and velocity affect the energy and exergy quantification of exhaust pulsating flows?

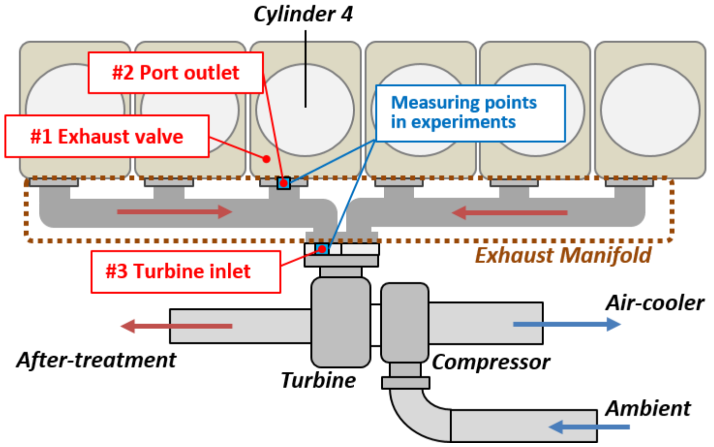
Methodology | RQ.3: Tested Engine & Matrix

Tested Scania D13 engine specifications

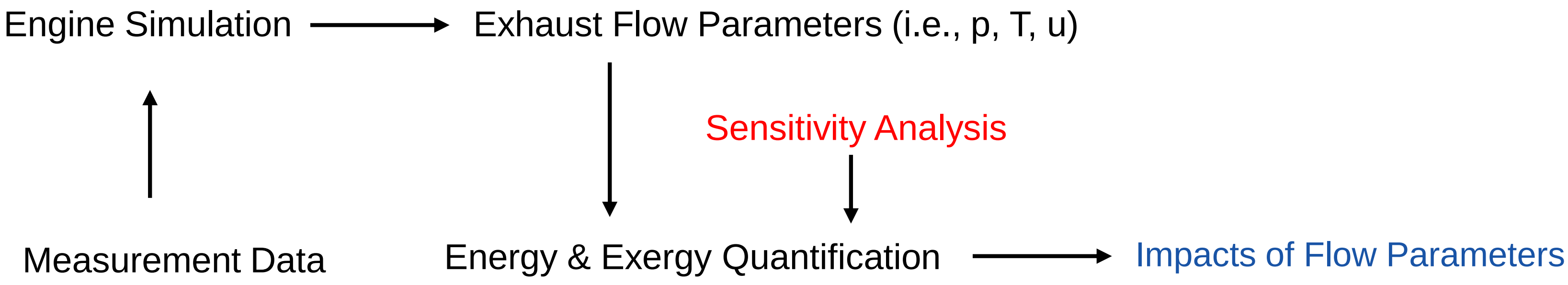
Cylinder layout	6 inline
Bore×Stroke	130 mm × 160 mm
Compression ratio	18 : 1
Displacement	12.7 liter
IVO/IVC	346 °CA ATDC/-154 °CA ATDC
EVO/EVC	125 °CA ATDC/ 373 °CA ATDC
Fuel system	Common rail
Turbocharger	Honeywell GT-4594
Emission standard	Euro VI

Test Matrix

	Point (a)	Point (b)
Speed [rpm]	1300	900
nIMEP [bar]	17.8	11.5
Load [kW]	245	110
Fuel mass injected [mg/cylinder]	202	136
Intake air flow [kg/s]	0.22	0.10



Methodology | RQ.3: Research Approach



Engine Simulation

Exhaust Flow Parameters (i.e., p, T, u)

Sensitivity Analysis

Measurement Data

Energy & Exergy Quantification

Impacts of Flow Parameters

Specific Enthalpy & Exergy [kJ/kg]

$$h(T,u) = \int_{T_0}^{T} c_p(T)\,dT + \frac{1}{2}u^2$$

$$e(p,T,u) = \int_{T_0}^{T} c_p(T)\,dT - T_0 \int_{T_0}^{T} c_p(T)\frac{dT}{T} + \mathrm{T_0 R_g} \ln\left(\frac{p}{p_0}\right) + \frac{1}{2}u^2$$

Enthalpy & Exergy Rate [kW]

$$H = h \cdot \dot{m}$$

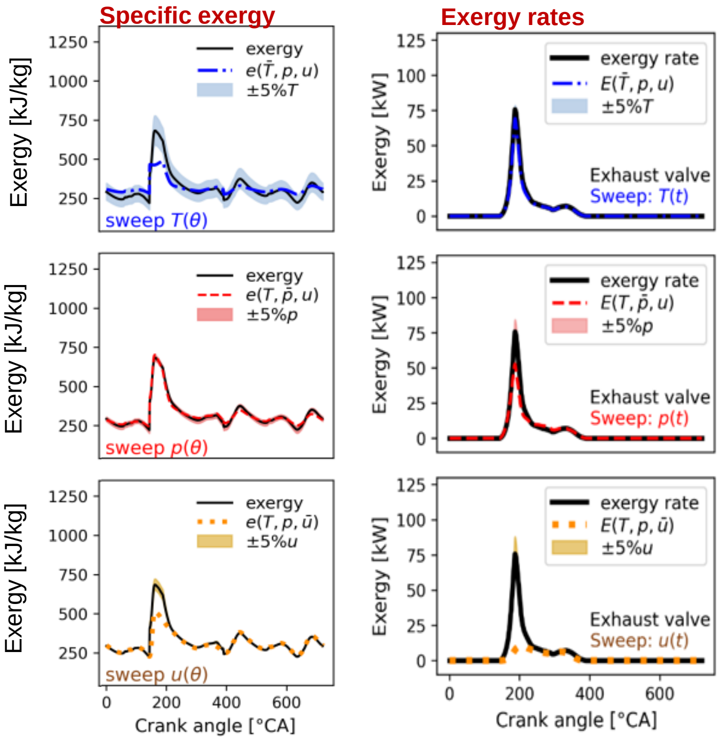
$$E = e \cdot \dot{m}$$

&

$$\dot{m}(p,T,u) = u\,A\,\frac{P}{R_g T}$$

Answer to RQ.3: Impacts of Flow Parameters

$$\boxed{\begin{matrix}H\\E\end{matrix}} \begin{matrix}=\\=\end{matrix} \boxed{\begin{matrix}h\\e\end{matrix}} \begin{matrix}\cdot \dot{m}(p,T,u)\\\cdot \dot{m}(p,T,u)\end{matrix}$$

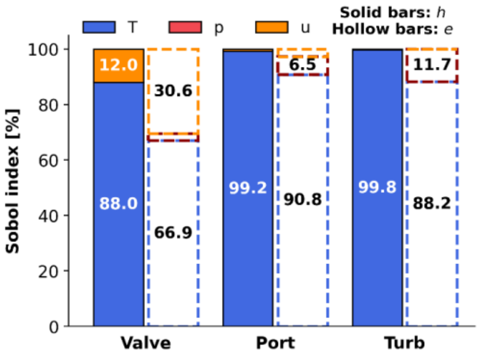


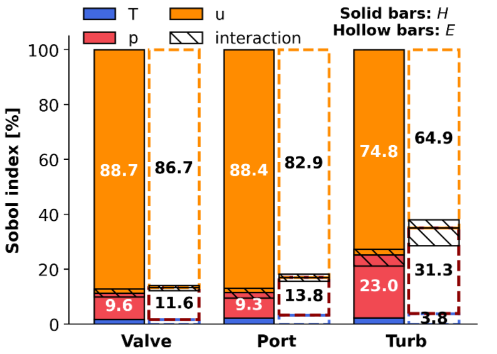
Exergy at Exhaust Valve

Flow enthalpy and exergy have a similar trend:

For specific exergy or enthalpy:
Temperature >> Velocity > Pressure

For exergy and energy rate:
Velocity > Pressure > Temperature





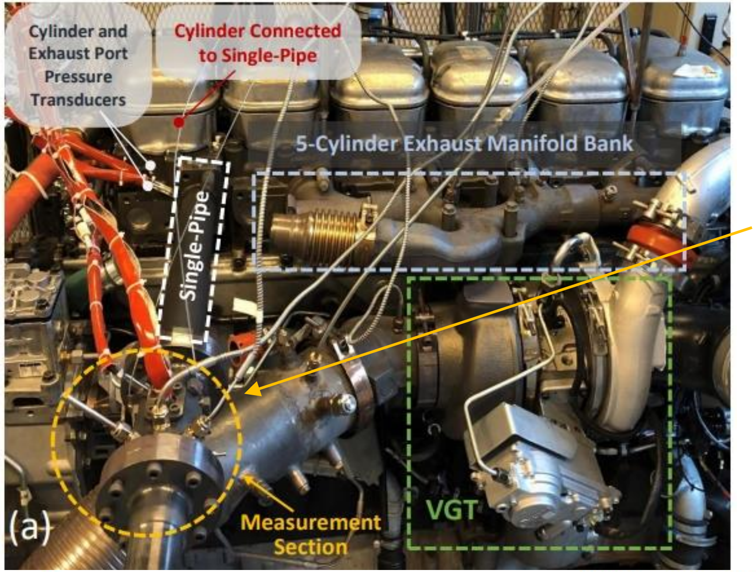
Sobol index: In global sensitivity analysis, Sobol index can quantify the relative significance of all variables regarding the variances of system attributed by inputs.

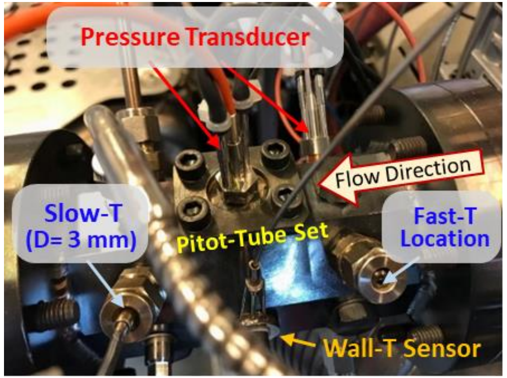
Methodology

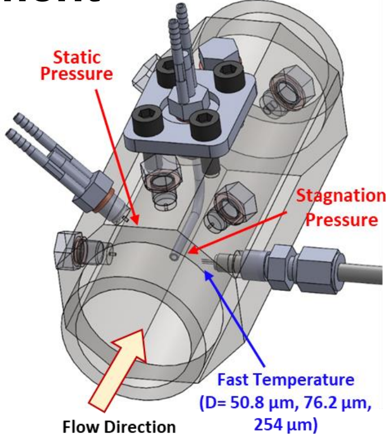
RQ. 4: How to characterize exhaust pulsating mass flows by using a Pitot tube-based approach considering the effect of attenuated temperature pulsations?

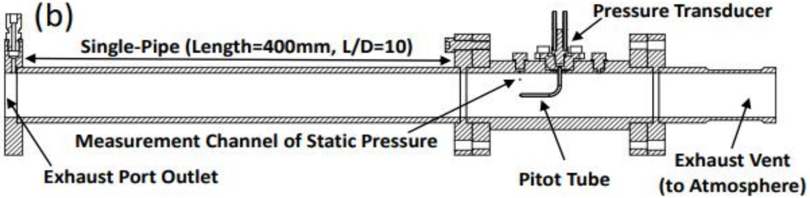
RQ. 5: Based on fast measurement using a Pitot tube-based approach, what is the characterization of exhaust mass flow pulses with regard to blow-down and scavenge phases?

Methodology | RQs. 4&5: Exhaust Pulse Measurement









Schematic of experimental setup and the single-pipe measurement system

Single-Pipe Measurement Section

Flow Measurement Techniques

- Pitot tube & Piezo-resistive sensor for total pressure
- Piezo-resistive sensor for static pressure
- Thin-wire thermocouples for static gas temperature

Methodology | RQs. 4&5: Research Approach

On-Engine Experiments
(Load & Speed Sweep)

Exhaust Flow Parameters

Sensitivity Analysis on
Temperature Variations

Mass Flow Rate Pulsations

Exhaust Pulse
Measurement System

Single-Pipe Measurement Section

Flow Measurement Techniques

- Pitot tube & Piezo-resistive sensor for total pressure
- Piezo-resistive sensor for static pressure
- Thin-wire thermocouples for static gas temperature

T_{f1}	50.8 µm
T_{f2}	76.2 µm
T_{f3}	254 µm
T_m	3 mm

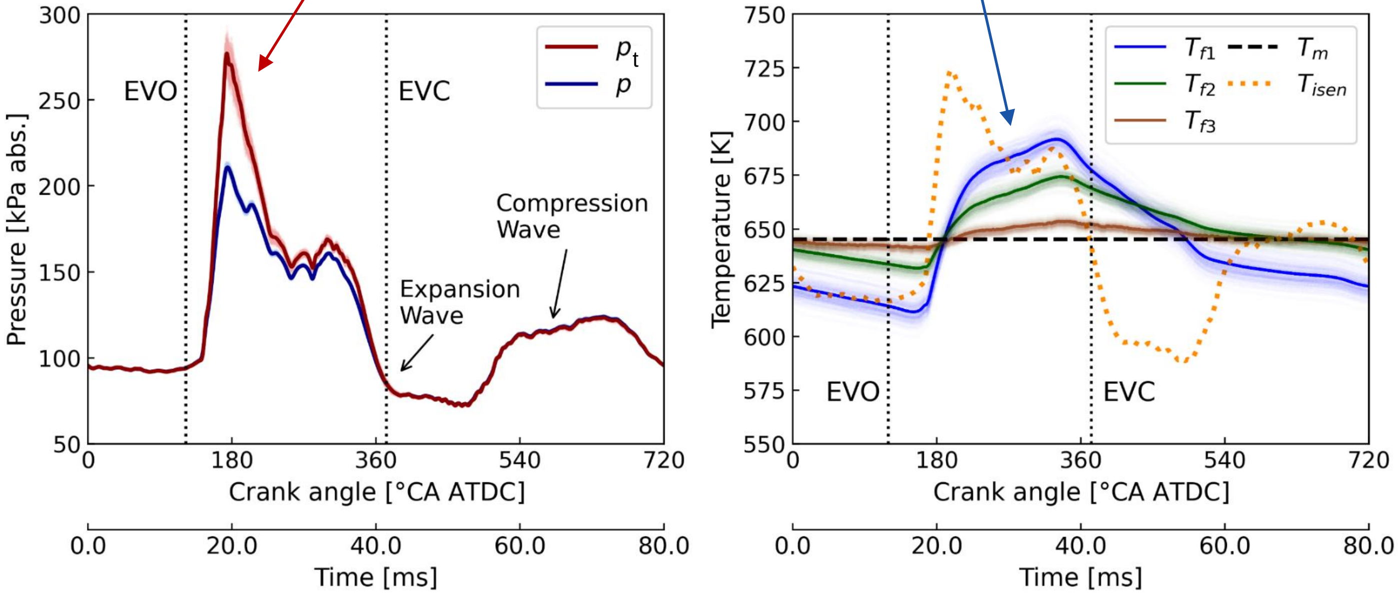
*Thin-Wire Thermocouples

*Venkataraman, V., Stenlåås, O., and Cronhjort, A., Thin-Wire Thermocouple Design for Exhaust Gas Temperature Pulse Measurements in Internal Combustion Engines, SAE Int. J. Engines 16(7):987-1005, 2023

Answer to RQ.4: Flow Measurement & Temperature Attenuations

The dynamic pressure between stagnation and static pressures indicates the exhaust flow.

Due to increased thermal inertia, the attenuation of the thermocouple's response became more obvious as the wire diameters increased.



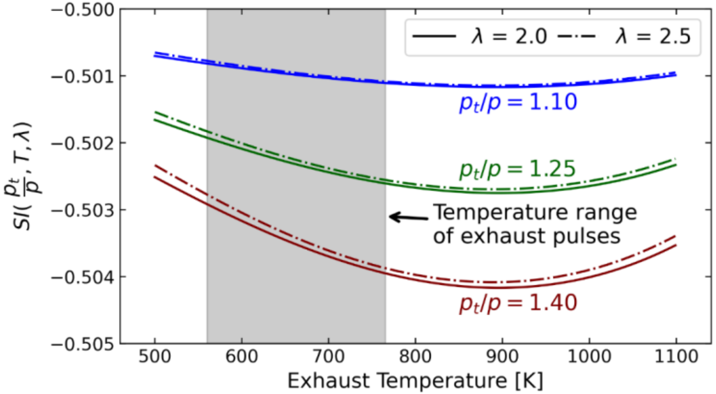
Thermocouples with different wire diameters

T_{f1}	50.8 µm
T_{f2}	76.2 µm
T_{f3}	254 µm
T_m	3 mm
T_{isen}	Isentropic relation

$$T_{isen} = T_m \left({}^{p}/{}_{p_m}\right)^{1-\frac{1}{\gamma_{isen}}}$$

Pressure and temperature of the engine exhaust pulsation at 1500rpm / 12 bar nIMEP

Answer to RQ.4: Effect of Temperature Attenuations

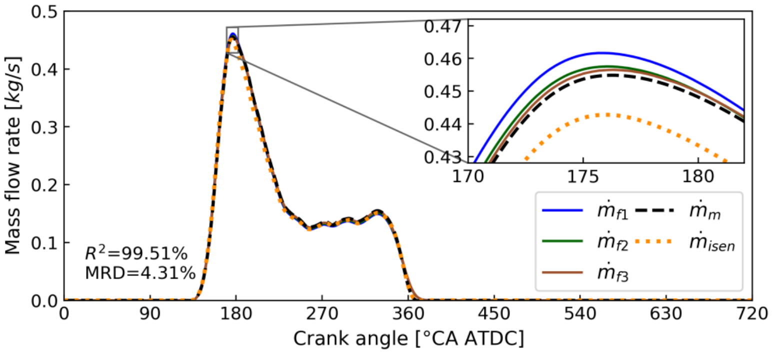


Sensitivity factor of mass flow calculation to gas temperature in Pitot tube-based approach

- ☐ Sensitivity factor indicates that mass flow change rate are half of the gas temperature change rate.

$$\frac{\Delta \dot{m}}{\dot{m}} = \mathrm{SF} \cdot \frac{\Delta T}{T}$$

- ☐ Temperature fluctuations have a noticeable impact only at the peak of mass flow pulses, while the overall difference among the pulses is not significant.

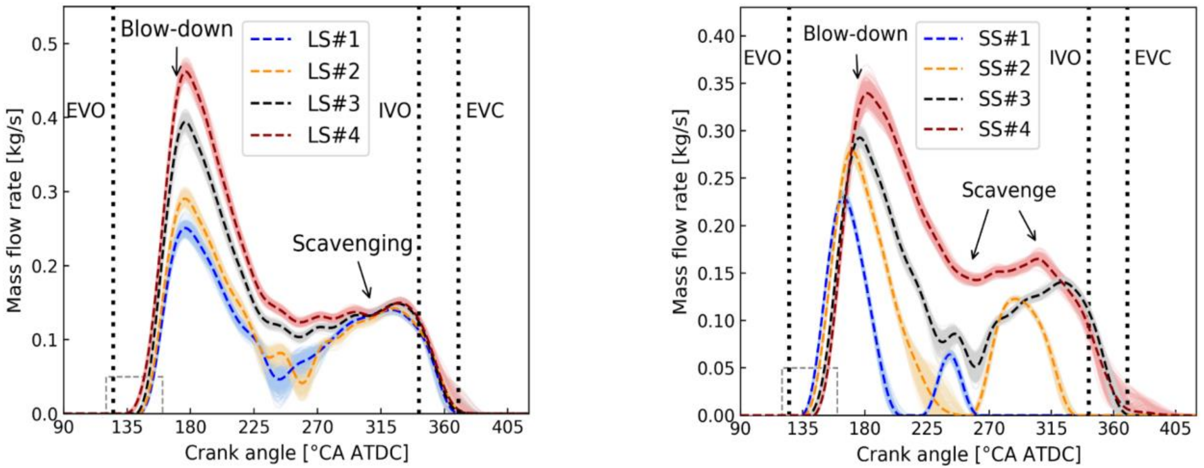


Exhaust mass pulses at 1500rpm / 12 bar nIMEP

Answer to RQ.5: Characterization of Exhaust Mass Flow Pulses

Load sweep

Speed sweep



Exhaust mass flow pulses' waveforms under the test matrix. Dashed lines refer to the cycle-averaged mass flow rates over 300 cycles.

- ❑ As engine load increases, the majority of the increased trapped mass is discharged during the blow-down phase, while the magnitudes of both the blow-down and scavenging phases rise as the engine speeds up.

- ❑ Variation in mass flow pulses over cycles is not only affected by combustion stability but also by gas-change events.

Conclusions

RQ. 1: Where and to what extent do engine exergy losses occur, associated with combustion, heat dissipation, and flow viscosity?

❑ In the tested marine engine, combustion exergy loss accounts for more than half of the total losses. Flow losses in the gas-exchange constitute the second major contributor to engine exergy destruction.

RQ. 2: How does lean burn impact energy and exergy in an HD SI engine with regards to (1) combustion timing (2) turbocharger requirement ?

❑ In the lean burn HD SI engine study, the advanced KLSA CA50 (22.3 CAD ATDC at $\lambda = 1.0$ → 12.4 CAD ATDC at $\lambda = 1.8$) leads to an increase in an indicated engine efficiency from 40.4% to 47.3%.

❑ Lower exhaust temperature and higher boost pressures make lean-burn combustion challenging. The exergy recovery rate from fuel exergy to maintain boost pressure rises from 1.1% at $\lambda = 1.0$ to 4.8% at $\lambda = 1.8$.

Conclusions

RQ. 3 How do variations in flow parameters such as pressure, temperature, and velocity affect the energy and exergy quantification of pulsating exhaust flows?

- Sensitivity analysis reveals that temperature is the dominant factor for specific enthalpy or exergy, while mass flow rate (equivalent to flow velocity) is the most crucial parameter for enthalpy or exergy rates.

RQ. 4: How to characterize exhaust pulsating mass flows by using a Pitot tube-based approach considering the effect of attenuated temperature pulsations?

- In the Pitot tube-based approach for mass flow rate measurement, the effect of temperature pulse attenuations is not significant.

RQ. 5: Based on fast measurement using a Pitot tube-based approach, what is the characterization of exhaust mass flow pulses with regard to blow-down and scavenge phases?

- The increase of engine load mainly affects the pulse waveforms during the blow-down phase, while the speed sweep changes both the blow-down and scavenging phases.

Outlook

- ❑ This study identifies the sources of irreversibility in a dual-fuel marine engine, thereby facilitating future optimization efforts aimed at minimizing energy and exergy losses. To achieve this goal, it is imperative to conduct additional research exploring potential solutions for these engine processes.

- ❑ Future research on exhaust pulse measurement can be extended to quantify crank angle-resolved enthalpy and exergy flows, employing the developed single-pipe measurement section.

Acknowledgement

Supervisors at KTH

Andreas Cronhjort

Mihai Mihaescu

Fundings

KTH VETENSKAP OCH KONST

Swedish Energy Agency

ICE & CCGEx Colleagues

- Senthil Krishnan Mahendar
- Ted Holmberg
- Varun Venkataraman
- Arun Prasath Karuppasamy
- Andreas Lius
- Sandhya Thantla
- Tara Larsson
- Botond Csontos
- Nicola Giramondi
- Nicolas Anton
- Yushi Murai
- Roberto Mosca
- Shyang Maw Lim
- Anton Boström

……

CCGEx Industrial Partners

SCANIA

VOLVO

WÄRTSILÄ

VOLVO

BorgWarner

KTH Departments and Organizations

- **Department of Engineering Design**
- **Division of Mechatronics and Embedded Control Systems**
- **Division of Internal Combustion Engines**
- **Competence Center for Gas Exchange (CCGEx)**

Comments & Questions

Welcome!

Thanks for your time!