NTNU – Trondheim
Norwegian University of Science and Technology

Experimental investigation of injection and combustion processes in marine gas engines using constant volume rig

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SMART MARITIME

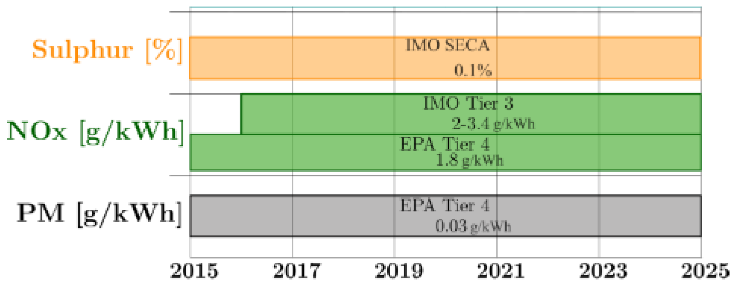
Trondheim – Gjøvik – Ålesund

Agenda

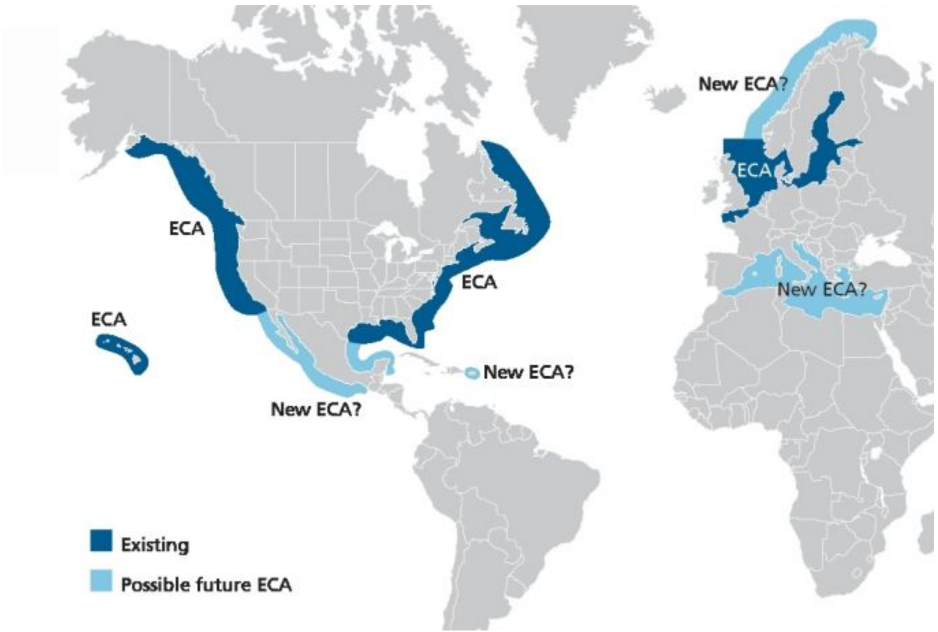
- Motivation
- Development of an experimental combustion facility
- Study of diesel injection
- Study of alternative fuel for pilot diesel injection
- Study of high-pressure gas injection
- Conclusion
- Further work

Motivation

Emission regulation in existing Emission Control Areas[1]



Location of Emission Control Areas



DNV recommendations to comply with NOx[2]:

1. Diesel + Selective catalytic reduction (SCR)
2. Diesel + Exhaust gas recirculation (EGR)
3. Batteries/ Hybrid system
4. Fuel cells/ Hybrid system
5. Dual Fuel engines/ pure gas engines

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[1] – International Maritime Organization

[2] – DNV GL, IMO NOx Tier III requirements to take effect on January 1st 2016, 2015

Motivation

Emissions from gas engine vs emissions from diesel engines[1]

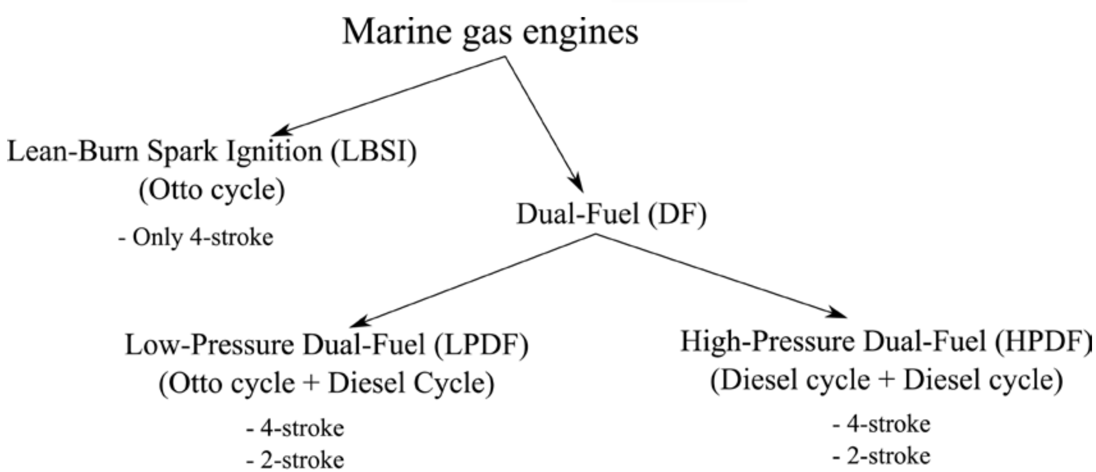
Emission	Reduction w.r.t. diesel fuel
CO_2	20-28%
NOx	25-90%
PM	30-99%
SOx	95-99%

Higher specific energy [MJ/kg]

Lower combustion temperature

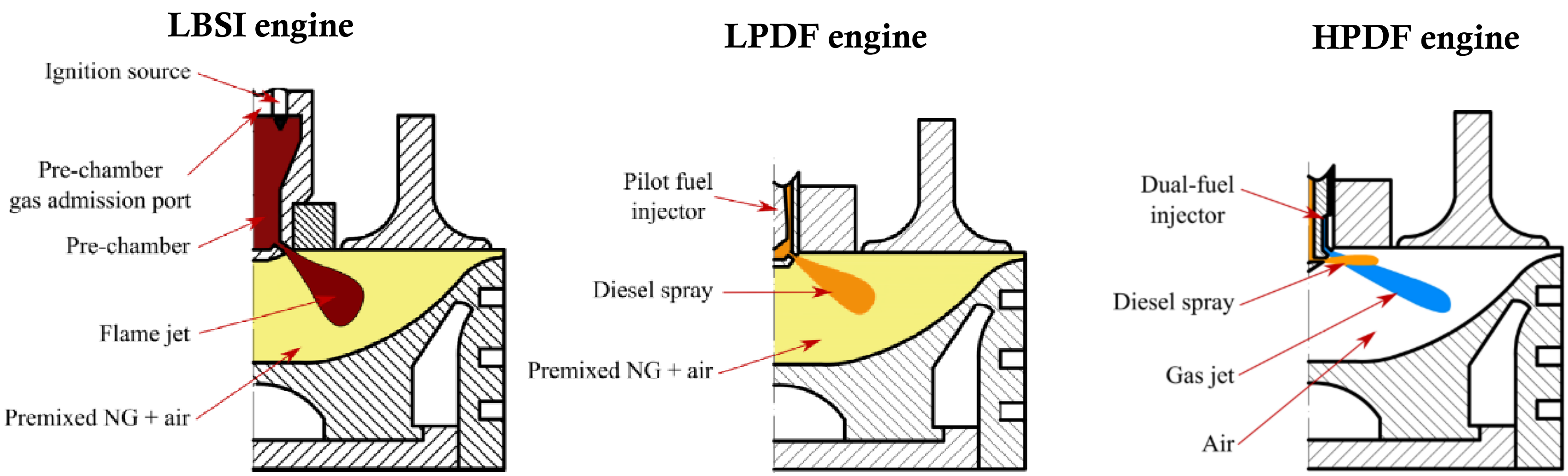
Simple molecules

No sulphur



[1] – D. Stenersen and O. Tonstad, GHG and NOx emissions from gas fueled engines, 2015

Motivation



Identified research gaps and technological challenges[1]:

1. Unburned hydrocarbons (UHC) from lean-burn gas engines - methane slip
2. Operational instability for LBSI and gas mode LPDF engines.
4. Lack of optimization of HPDF concept

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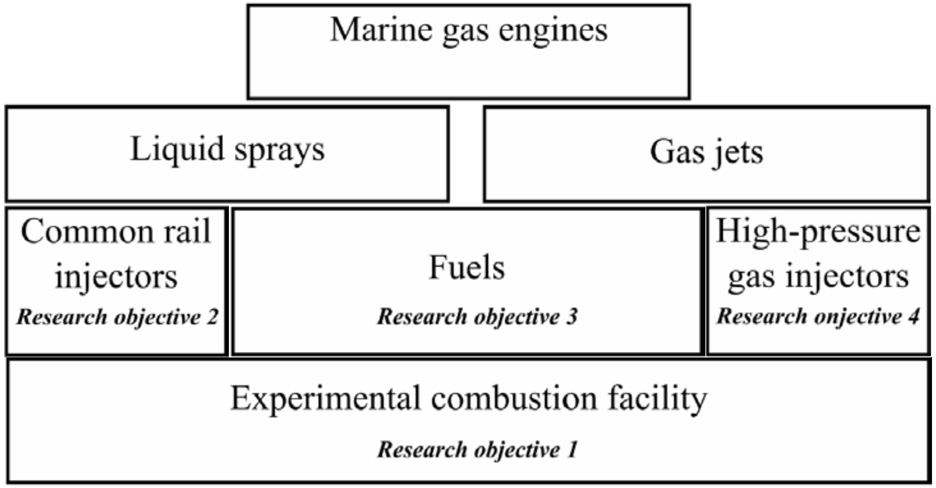
[1] – V. Krivopolianskii.et.al, Control of the combustion process and emission formation in marine gas engines, 2018

Research objectives:

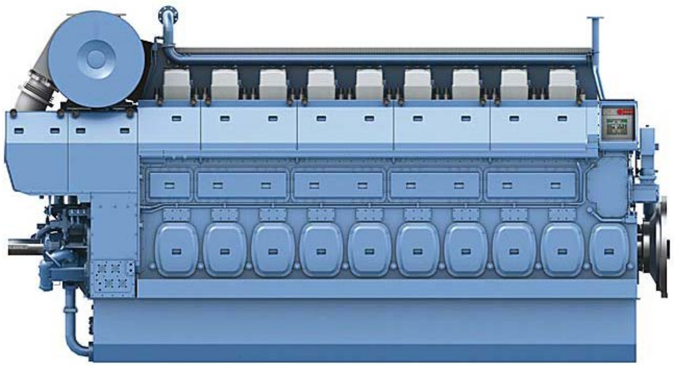
1. Develop an experimental testbed that insures fundamental investigation of combustion-related processes in marine gas engines
2. Develop a theoretical model, capable to simulate performance of diesel injector over its whole operational range
3. Experimentally investigate combustion and emission performance of biodiesel, as an alternative fuel for pilot injection
4. Experimentally study the effect of nozzle hole geometry on high pressure gas jet formation in combustion chamber



Research objective 1:

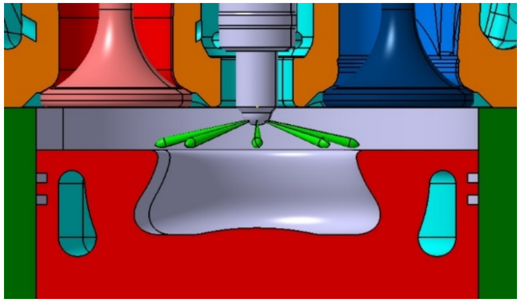
Experimental research facility

Motivation



https://www.rolls-royce.com

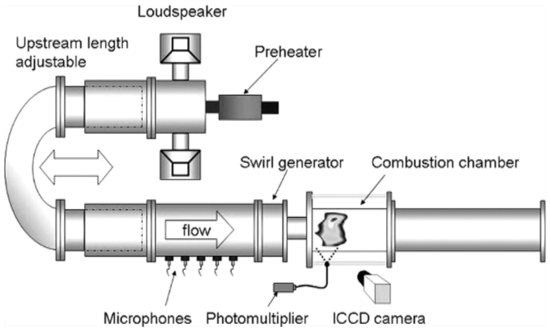
Combustion chamber



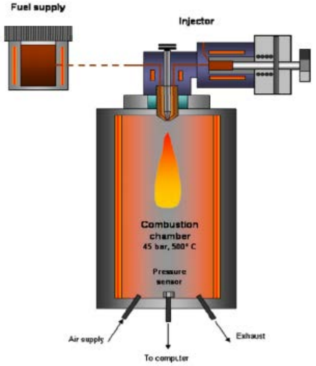
1. Complex ambient air flow pattern (moving parts)
2. Complicated heat transfer (wall wetting)
3. Obstructed for optical access

Isolation of injection and combustion processes

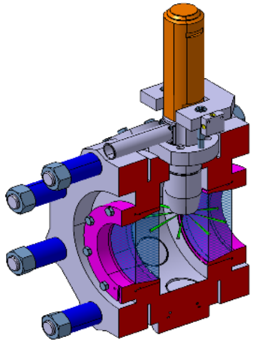
Constant Pressure Flow Rig (CPFR)[1]



Constant Volume Hot Cell (CVHC) [2]



Constant Volume Combustion Rig (CVCR)



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[1] – Krebs, W et al. Comparison of Nonlinear to Linear Thermoacoustic Stability Analysis of a Gas Turbine Combustion System

[2] – CIMAC, Fuel quality guide – Ignition and Combustion, 2011

Constant volume chambers

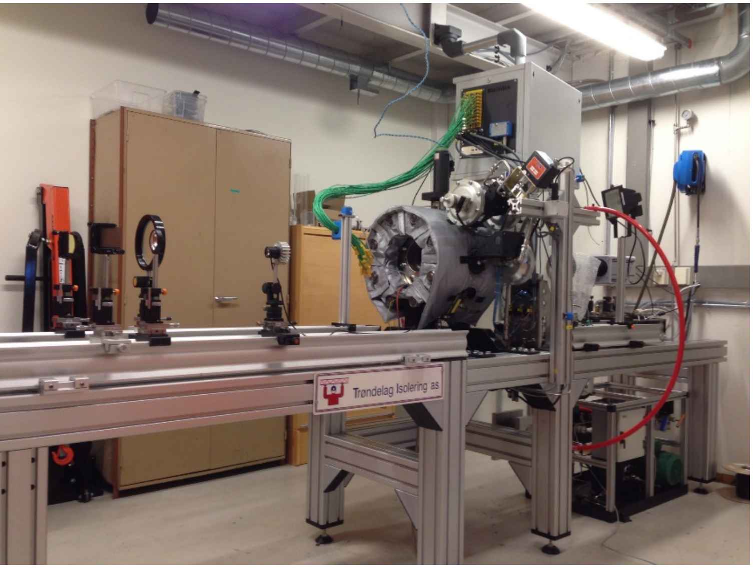
Comparison of constant volume rigs

Type of optical rig	Constant volume chambers		
	CPFR	CVHC	CVCR
Optical accessibility	++	-	+
Similarity to the real engine situation	--	--	--
Free spray penetration distance	+++	++	++
Control on trapped gas p/T	++	++	++
Control of gas composition	+	++	+++
Flow field impact on combustion	0	-	-
Test facility volume	0	++	++
Time to switch b/w oper. conditions	--	--	++
Time between tests [s]	1-3	60	600

CVCR was chosen due to:

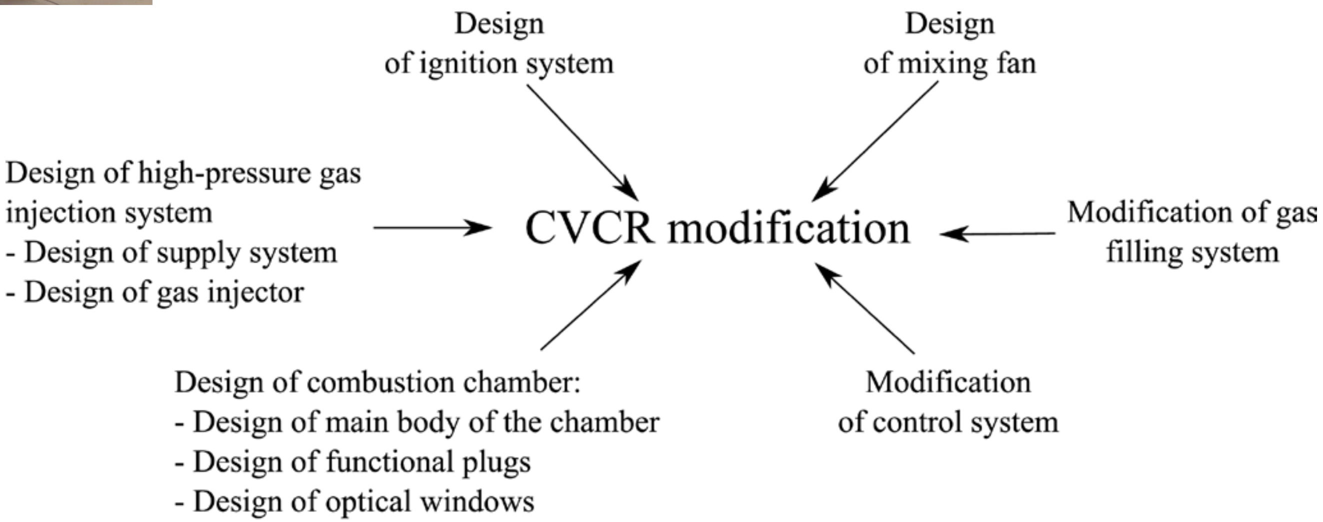
1. High range of in-chamber operational conditions
2. Closed system
3. Control of gas composition

CVCR. Development



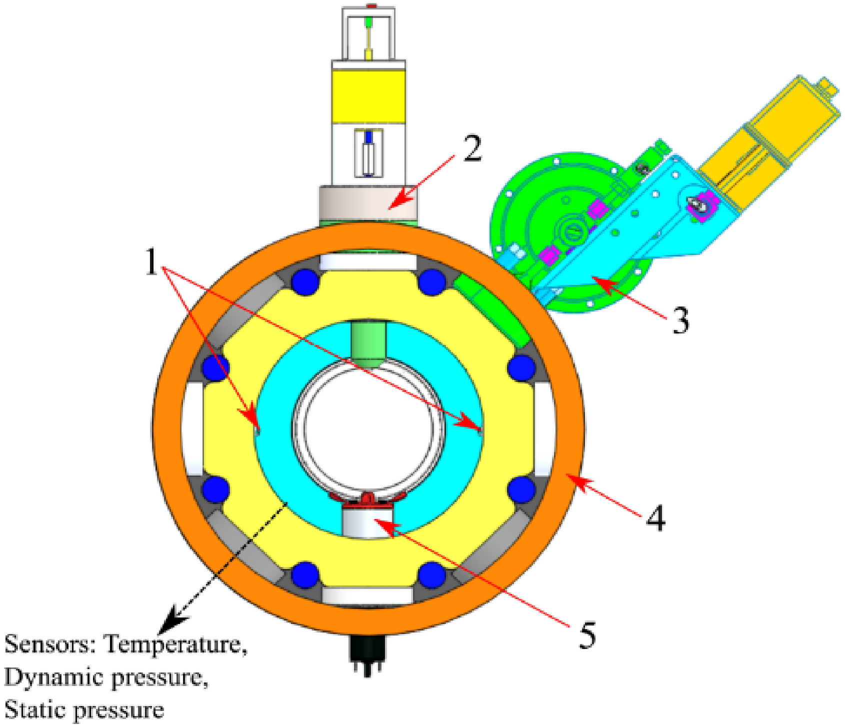
2015 version of the CVCR:

1. Low maximum ambient density
2. Lack of experimental controls
3. Absence of equipment for experimental research on gas jets



CVCR

Chamber arrangement



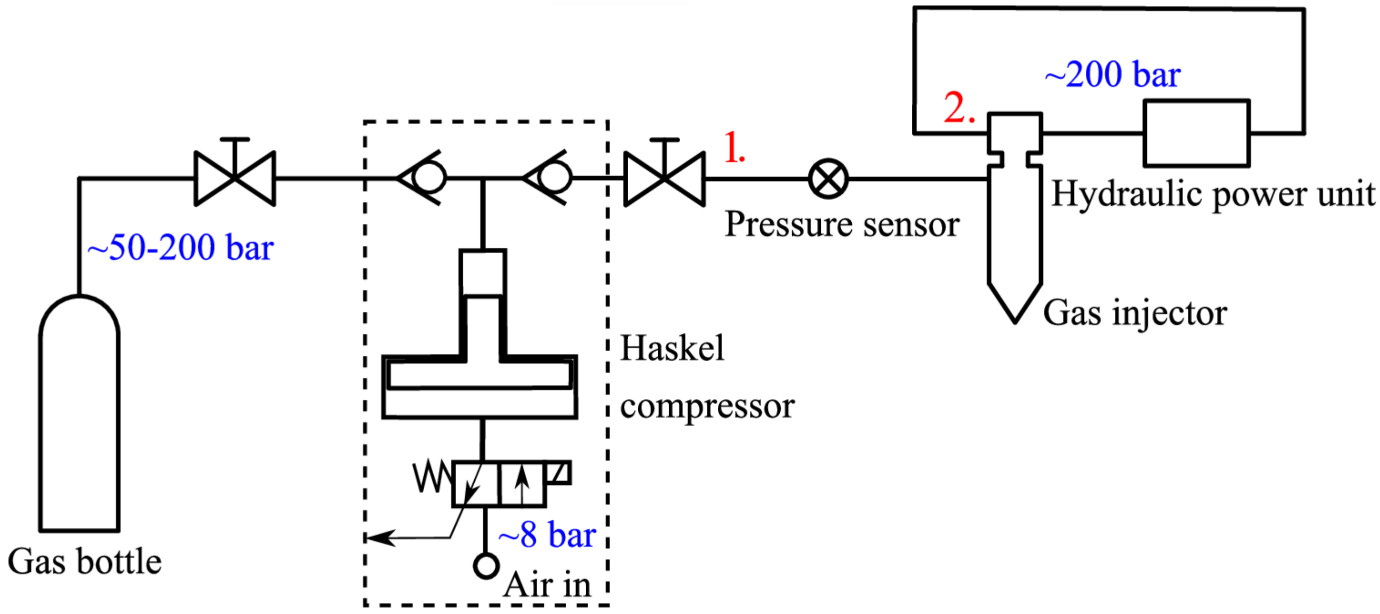
Appearance of the CVCR

1. Ignition sources
2. Gas injector
3. Pre-combustion gas exchange systems
4. Insulation
5. Mixing fan

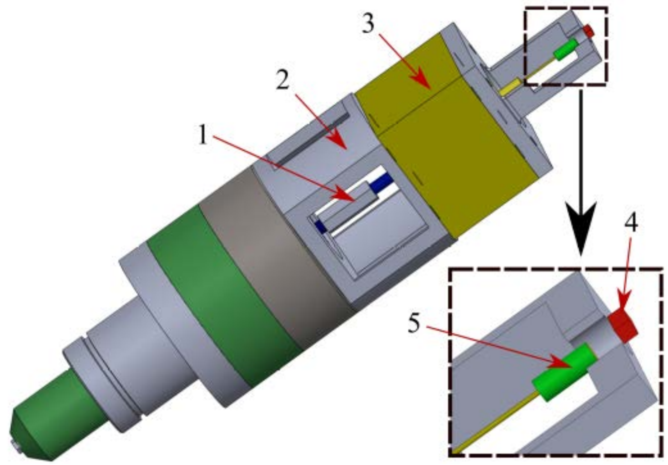
High-pressure gas injection system

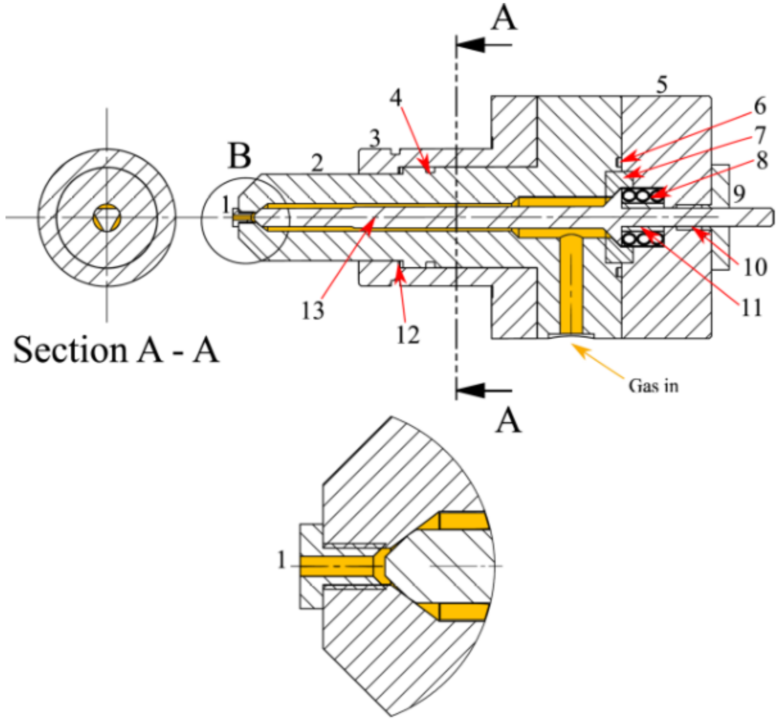
Specification:

- Haskel compressor
- Leak free proven (with He)
- Operation pressure up to 400 bar



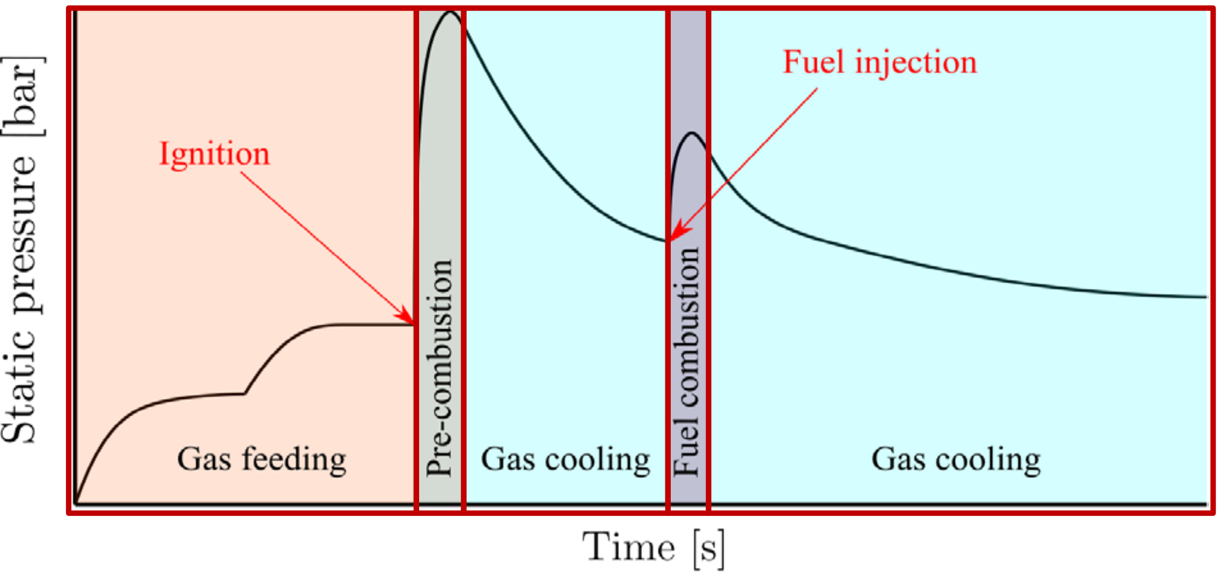
High-pressure gas injector





- Hydraulic driven valve (analog to MAN injectors)
- Needle lift sensor (hall effect sensor)
- Replaceable nozzle
- Maximum operational pressure 400 bar

CVCR. Operation principle



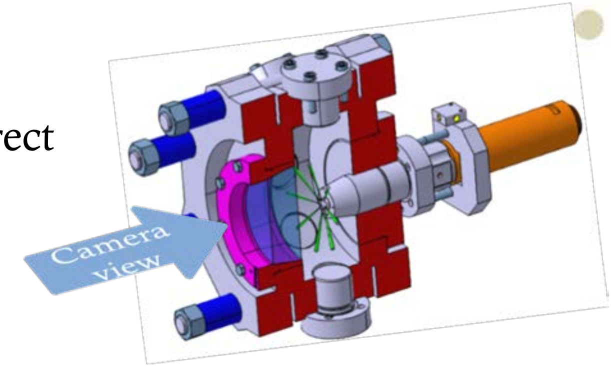
Phases:

1. Gas feeding (for pre-combustion)
2. Pre-combustion
3. Gas cooling
4. Fuel combustion
5. Gas cooling

Pre-combustion. Temperature field

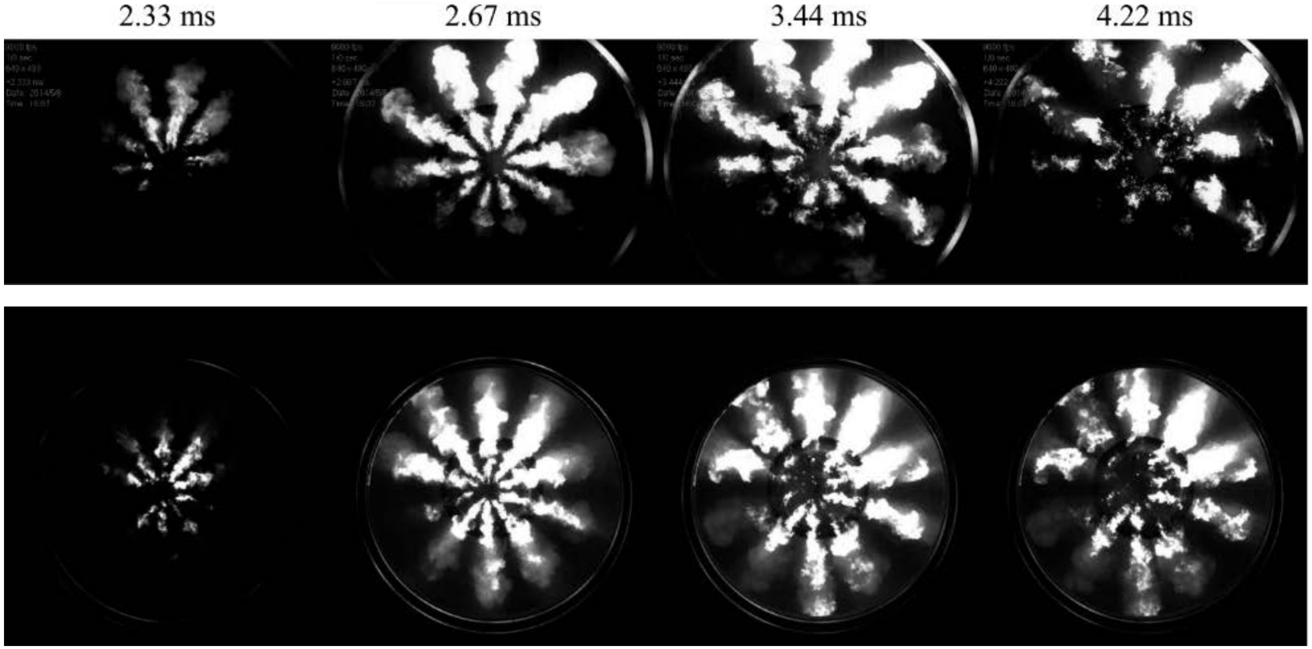
“Indirect” analysis of temperature field inside the CVCR:

- Temperature is approx. 3000 K (challenging to apply direct measurements)
- Combustion symmetry as an indicator of temperature homogeneity
- Fuel was injected in 600 K (bulk temperature)



Before modification of CVCR

After modification of CVCR



Control system

Requirements:

- High experiment repeatability
- Operational safety
- Simple in operation

Predefined procedures

CVCR main sequences:

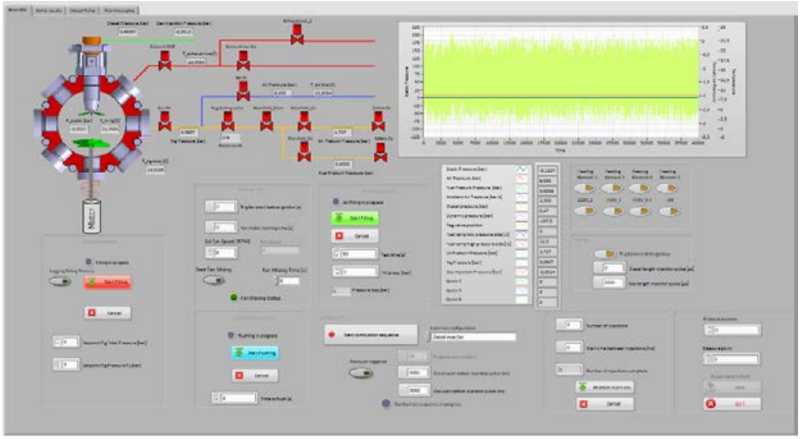
1. Filling sequence
2. Pre - combustion sequence
3. Combustion sequence (time or pressure tracing)
   - 3.1 Diesel fuel injection
   - 3.2 Gas injection
   - 3.3 Duplet mode (both injectors in service)
4. Flushing sequence
5. Leakage test sequence
6. Data acquisition

GUI

Real time

FPGA

Intuitive user interface

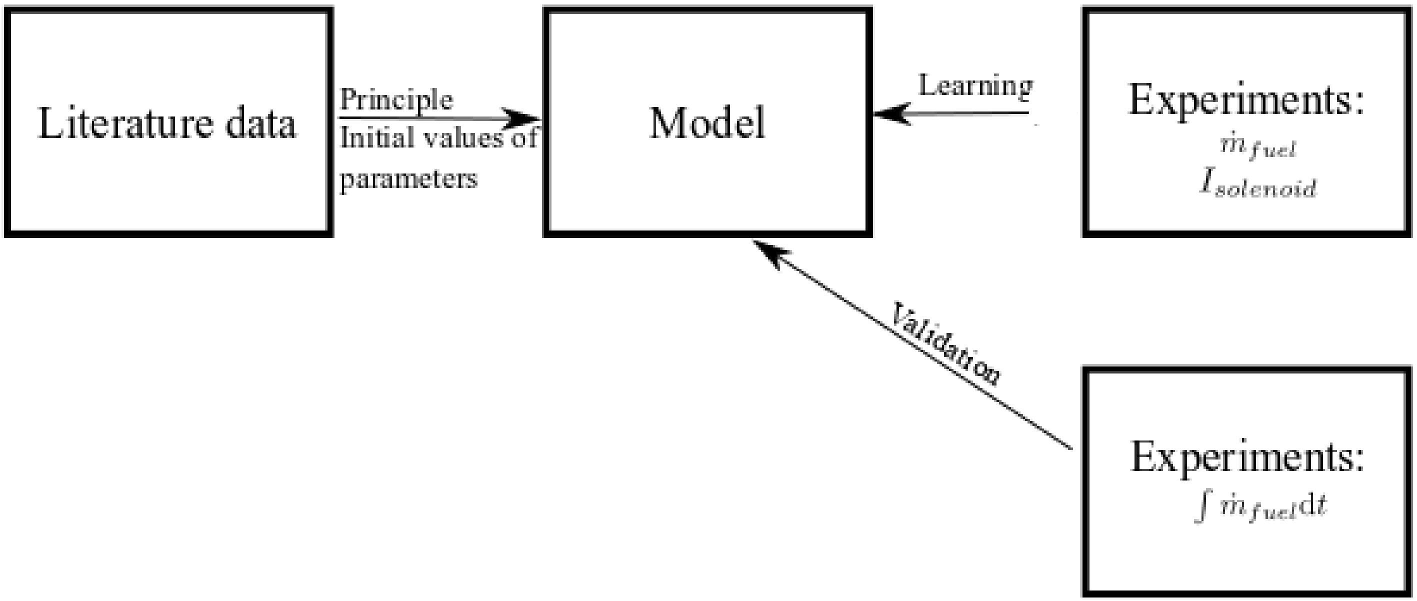


Research objective 2:

Common rail injectors

Overview

1. Experimental investigation of diesel injection
2. Development of an accurate model of diesel without knowing its internal arrangement

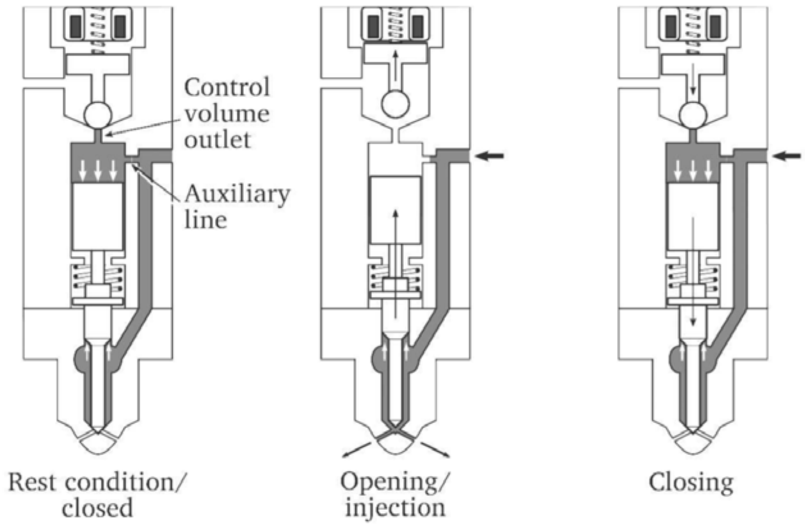


Diesel injector

Experiments:

1. Solenoid current (input)
2. Rate of injections (ROI) measured using momentum flux method (output).
3. Total injected mass measured by weighting injected fuel (output)

Hypothesis: Injection characteristics under near-ballistic (transient) needle position are sufficient for complete understanding of injector dynamics.



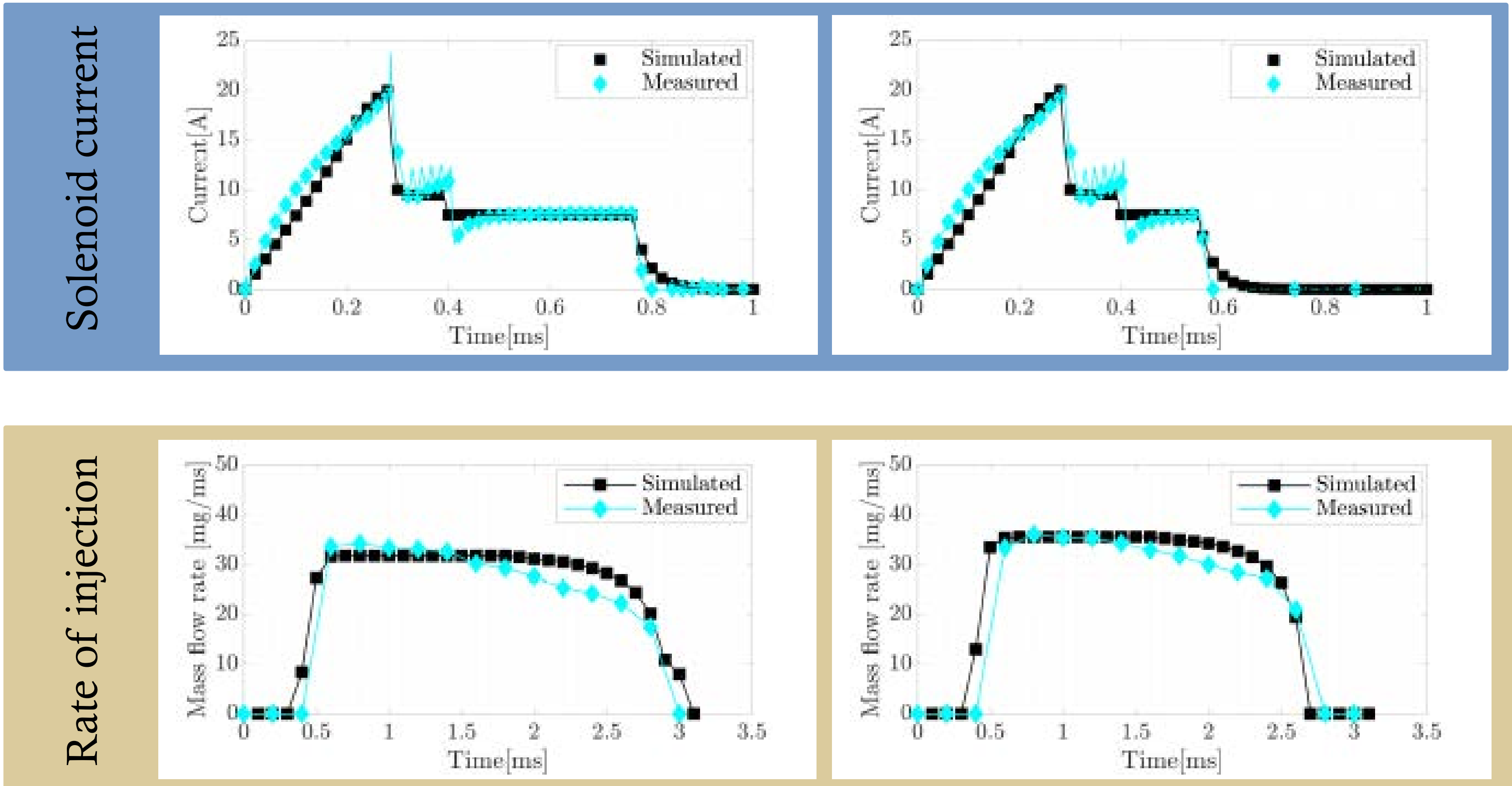
J. Gimeno Garcıa., 2010

Diesel injector. Model learning

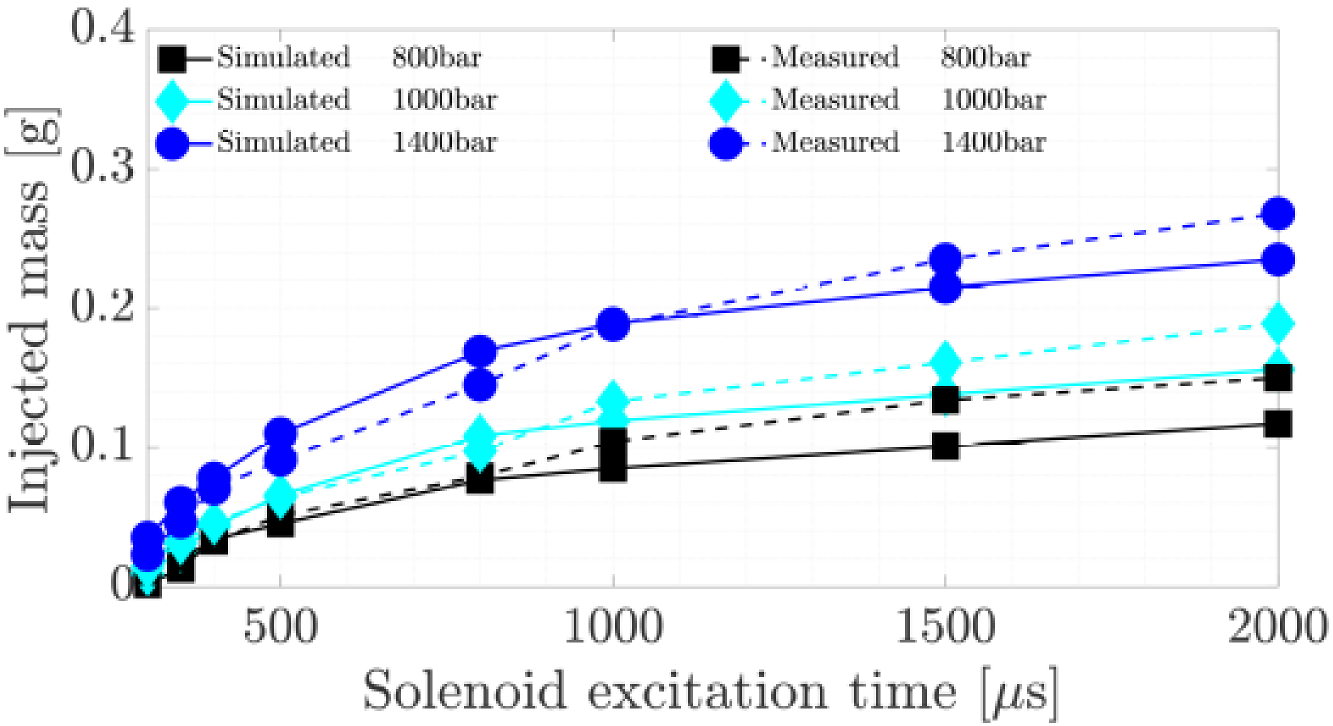
Main settings:

1. 800, 1000, 1400 bar injection pressure
2. 42, 69 mg injected diesel fuel
3. Parameter sweep and gradient descent as model parametrization tool

800 bar , 69 mg | 1000, 69 mg



Diesel injector. Model validation



Summary:

1. Model is valid at injection settings near to learning conditions
2. Maximum deviation between measured and simulated results reached 28%
3. The hypothesis was not correct
4. Set of experiments for model learning should be reconsidered

Research objective 3:

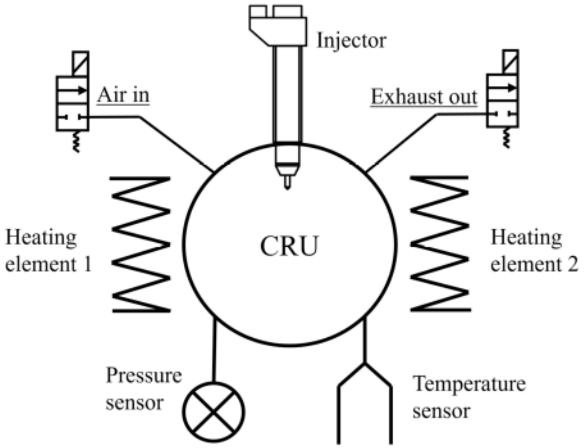
Fuels

Alternative fuels. Overview

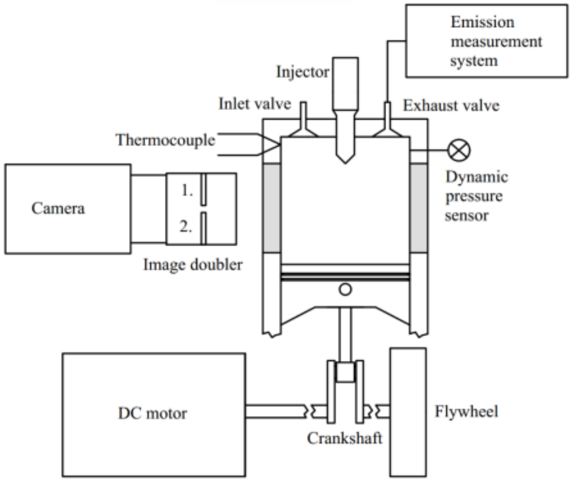
Objectives:

1. To experimentally study the combustion process of hydrogenated vegetable oil as an alternative for conventional diesel
2. To study limitations of CVCR by comparing results with those obtained on other experimental setups:

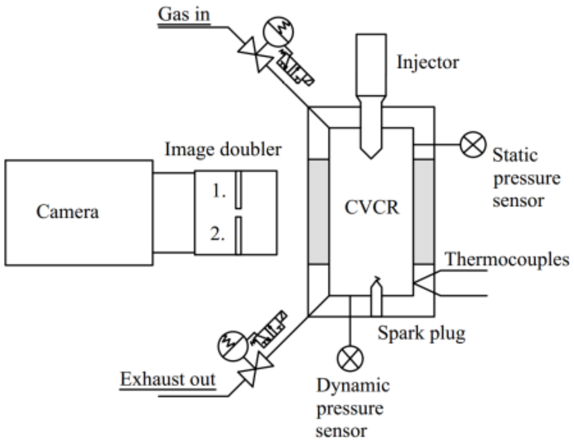
Combustion Research Unit «FuelTech Solutions AS»



Optically Accessible Compression Ignited Chamber (OACIC)



CVCR



Alternative fuels. Overview

Hydrogenated vegetable oil: Saturated long-chain hydrocarbon ($C_{15}H_{32}$ – $C_{18}H_{38}$) processed from unsaturated oils by adding H_2 using catalysts (Ni, at 60^{o}C)

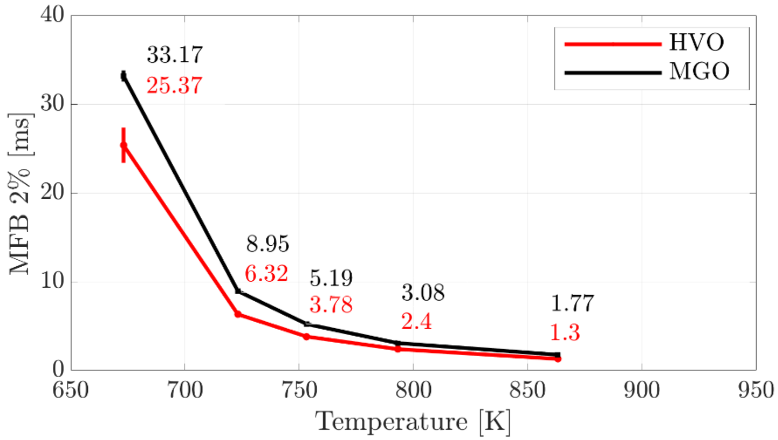
Studied parameters:

	NO(Horiba PG250)	ID(MFB 2%)	FT(Two-color)
CRU		X	
OACIC	X		X
CVCR		X	X

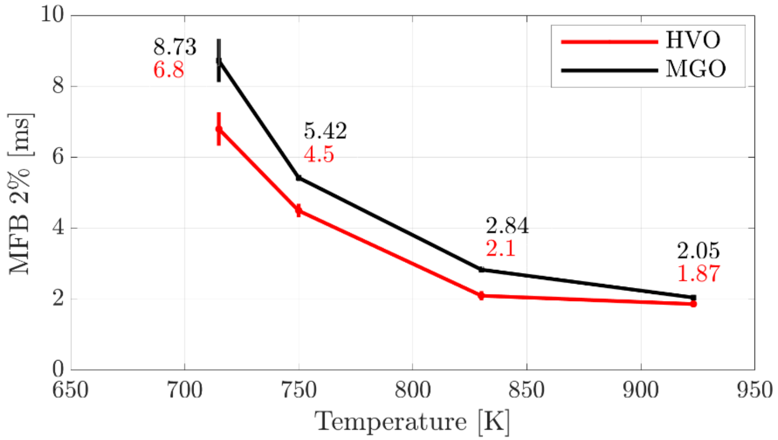
ID – Ignition delay
FT – Flame temperature

Alternative fuels. Ignition delay vs temperature

CRU



CVCR

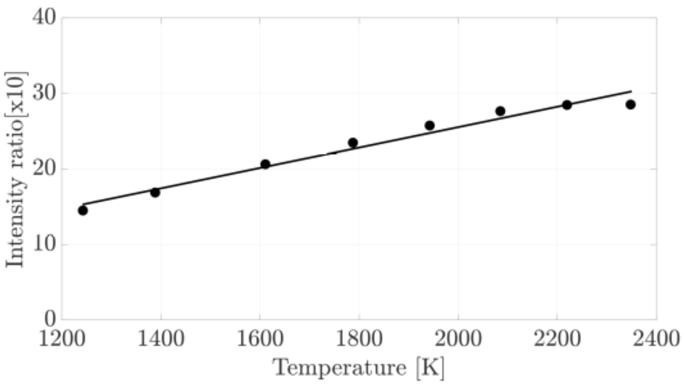


- Results of ID appeared similar in both testbeds in range 720 – 870 K
- Higher cetane number of HVO led to lower ignition delays
- Slight difference could be attributed to difference in injection systems and oxidizers
- It was challenging to measure ID in CVCR at temperatures < 700K

Alternative fuels. Flame temperature

<u>Two-color pyrometry requires calibration of camera:</u>

Intensity = f(Temperature)



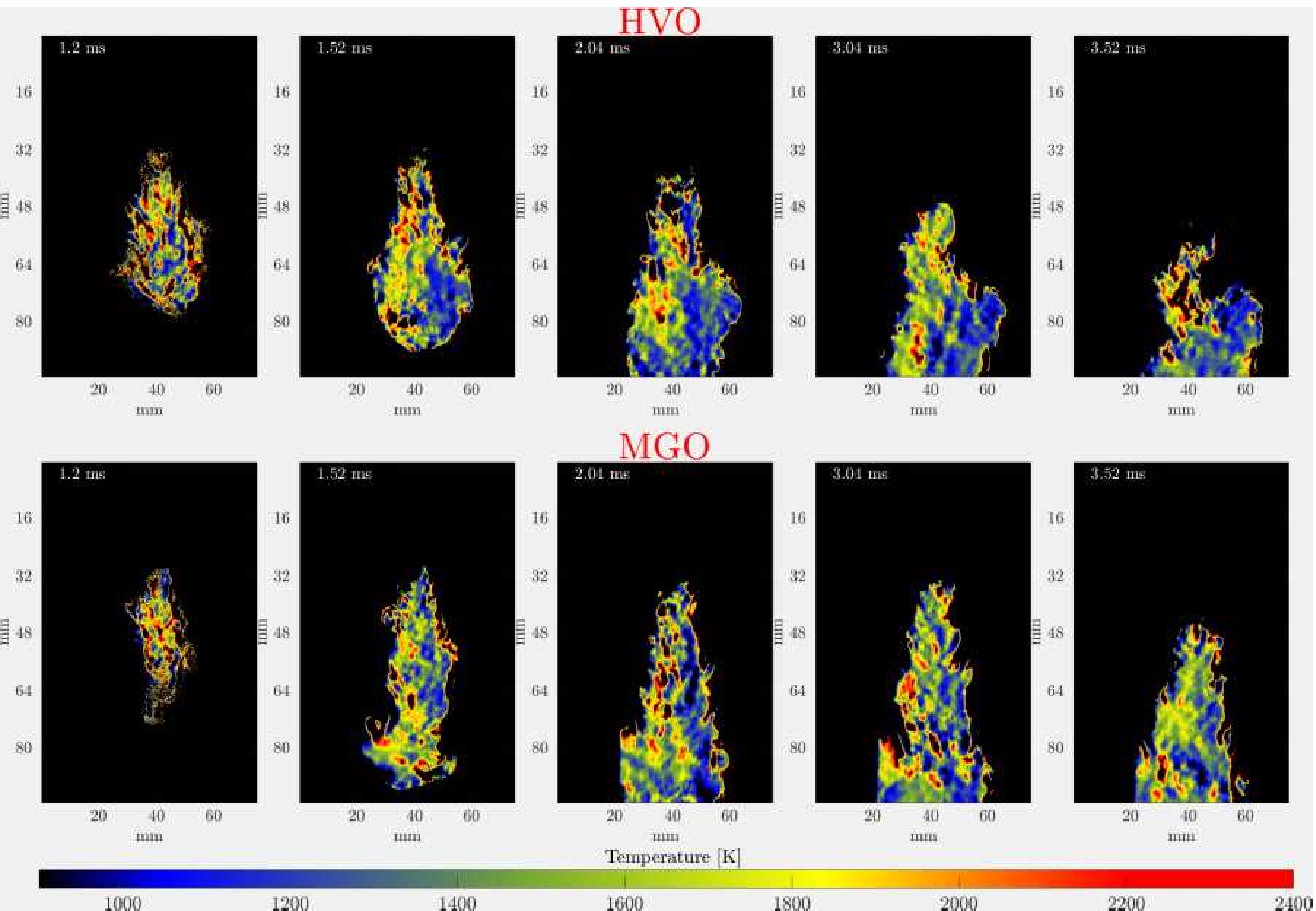
- At temperatures > 2350 the intensity appears ambiguous

<u>Reference for calibrations:</u>

- Benson groups as method to estimate enthalpy of formation
- No fuel composition data was available
- Adiabatic flame temperatures at 300K, 1 bar

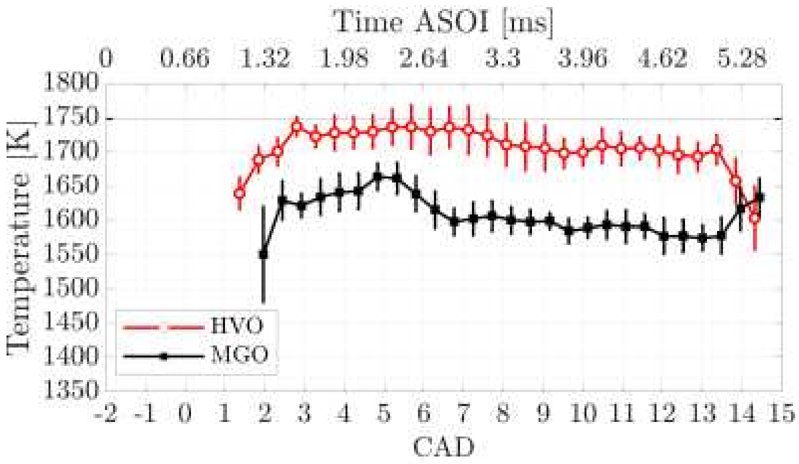
Fuel	Adiabatic flame temperature [K]	
	Air	Synthetic air
$C_{15}H_{32}$	2413	2189
$C_{16}H_{34}$		
$C_{17}H_{36}$		
$C_{18}H_{38}$		
MGO	2487	2253

Alternative fuels. Flame temperature. CVCR

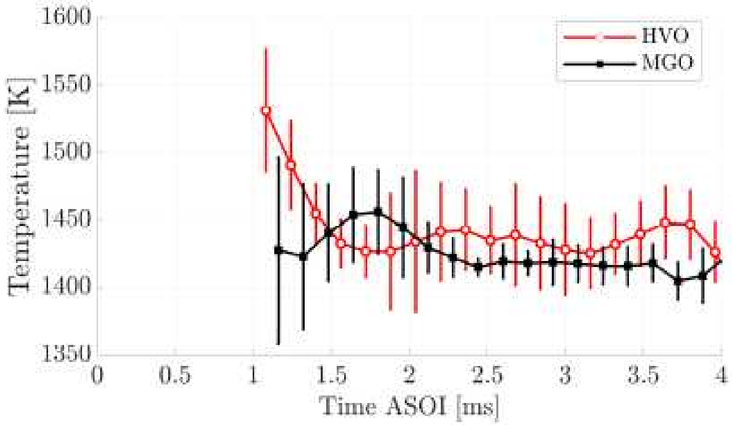


Alternative fuels. Spatial averaged FT

OACIC



CVCR

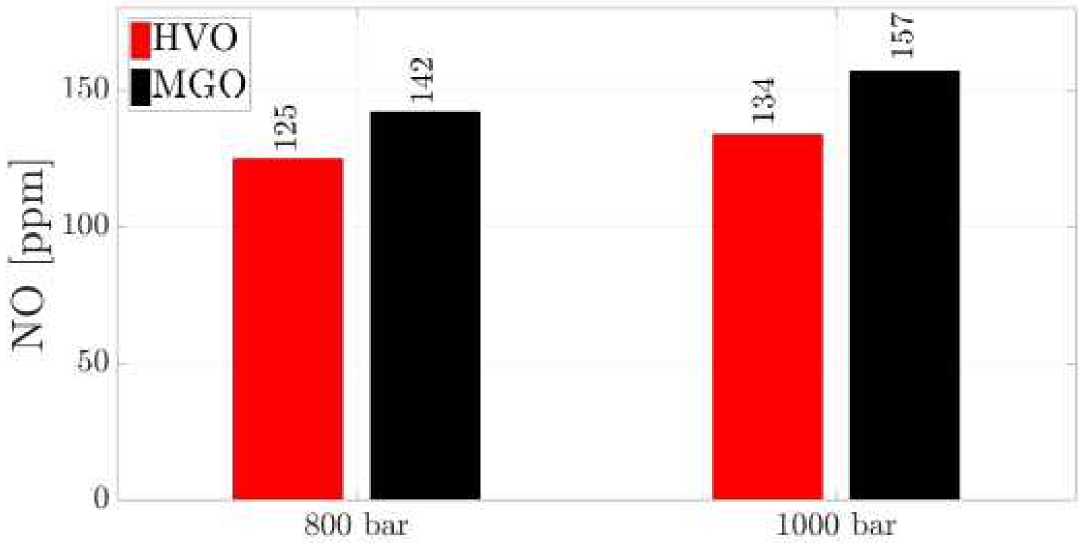


- Limitations of the method influenced the maximum temperature values
- Experiments in CVCR did not reveal difference between fuels

Alternative fuels. NO results

Settings:

- Same amount of energy was injected
- Two injection pressures 800, 1000 bar



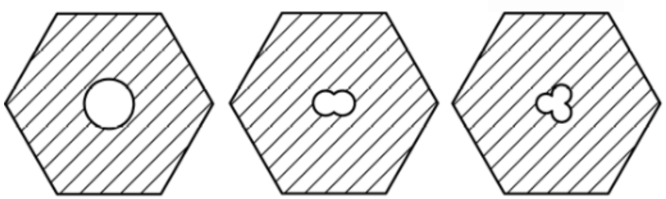
- 12-15% NO reduction when using alternative fuel compared to diesel
- Increase of injection pressure contributed to increase of NO (both fuels)

Research objective 3:

High pressure gas injectors

High pressure gas injection

1. Optical investigation of high pressure gas jets
2. Development of a theoretical model (1D) of the gas injector

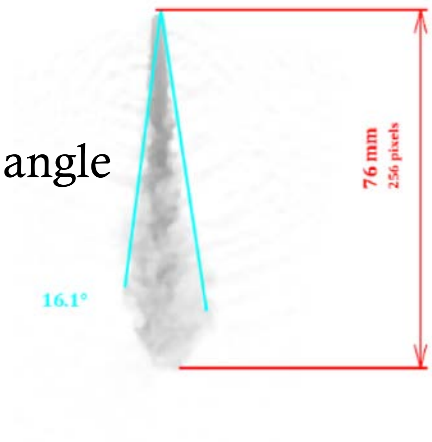
	Orifice geometries	Orifice CS area	P injection
Variables:	 a b c	1.72 mm^2 3.27 mm^2 6.51 mm^2	≈220 bar ≈380 bar

Hypothesis: Complex geometry with sharp longitudinal edges will improve gas fuel – air mixing

High pressure gas injection. Optical studies

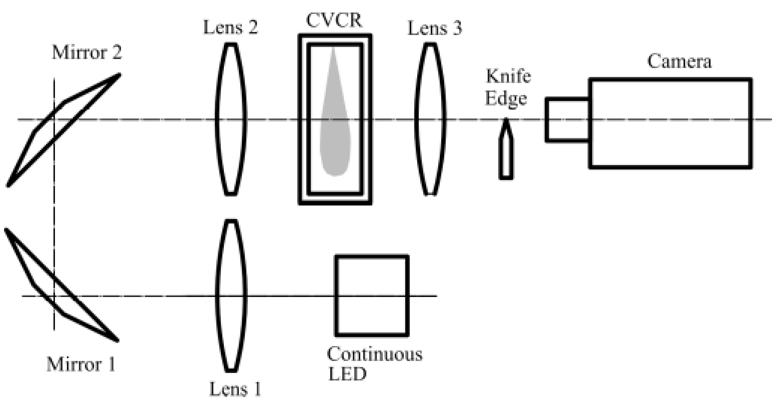
Schlieren: to measure macroscopic properties of gas jets

Cone angle

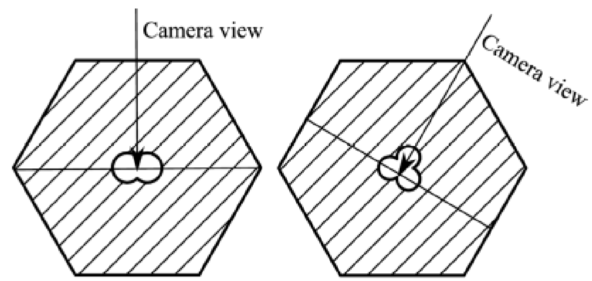


Penetration length

Setup

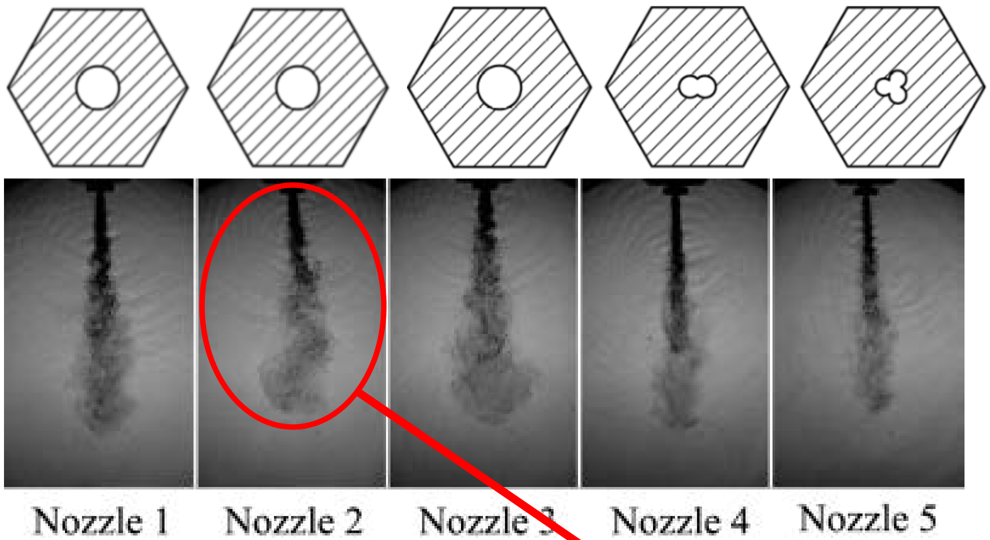


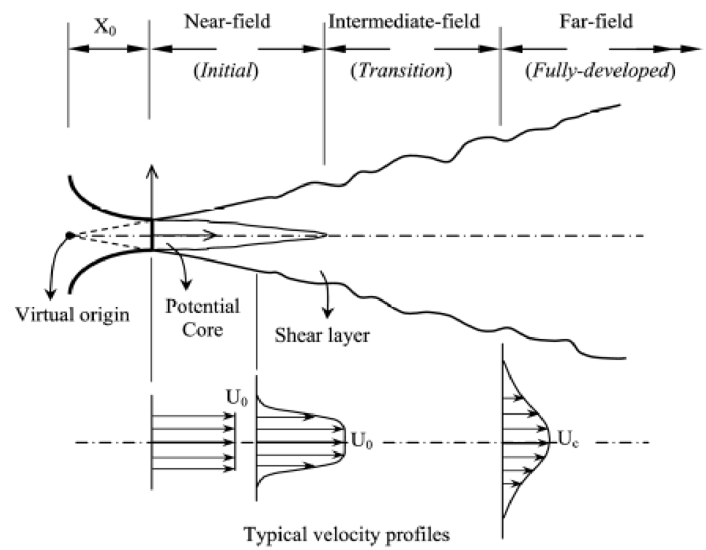
Camera – orifice orientation



High pressure gas injection. Optical studies

D (mm) = 1.48 2.04 2.88





Gas jets in “oscillation mode”. According to D.M.Kyle (1993) it depends on:

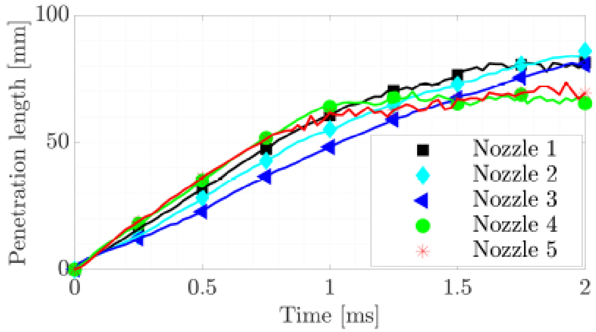
- Density ratio
- Nozzle diameter
- Momentum thickness of the boundary layer at the nozzle exit.

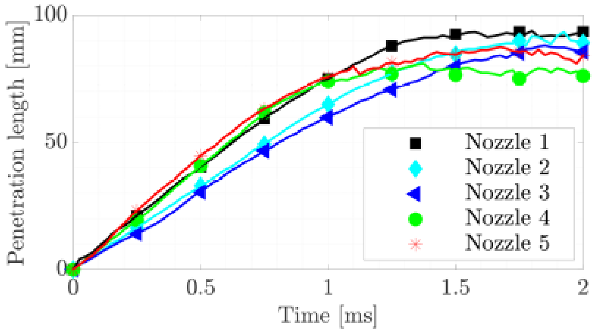
High pressure gas injection. Optical studies

P_o/P_a = 19 (220/20)

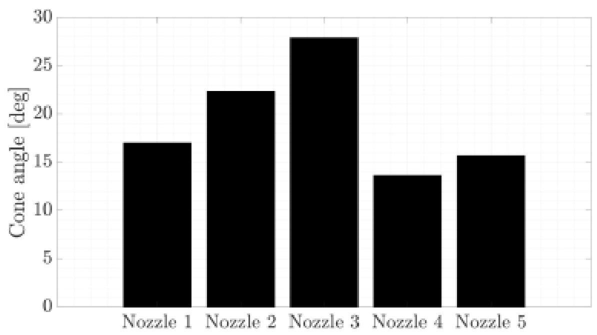
P_o/P_a = 19 (380/20)

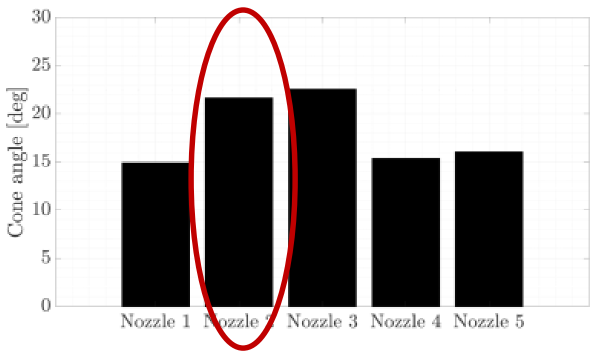
Penetration length





Cone angle

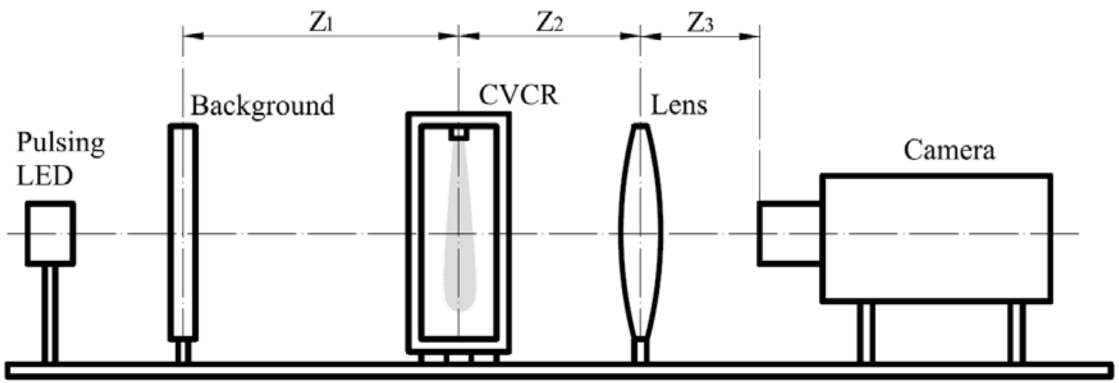


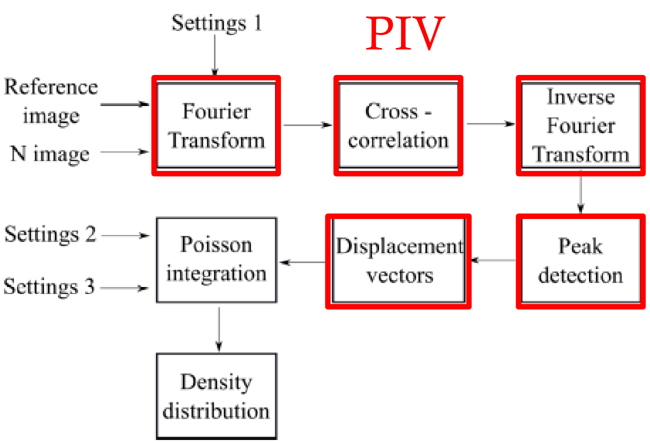


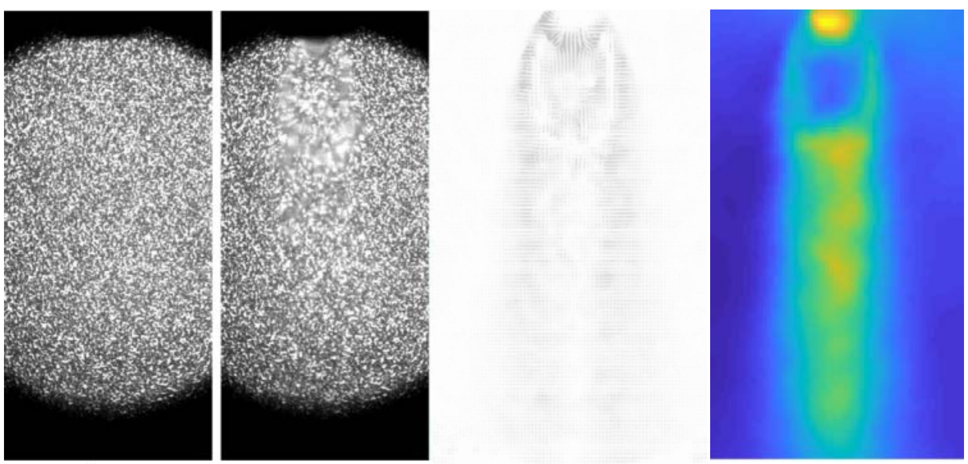
Due to "oscillation mode"

High pressure gas injection. Optical studies

Background Oriented Schlieren



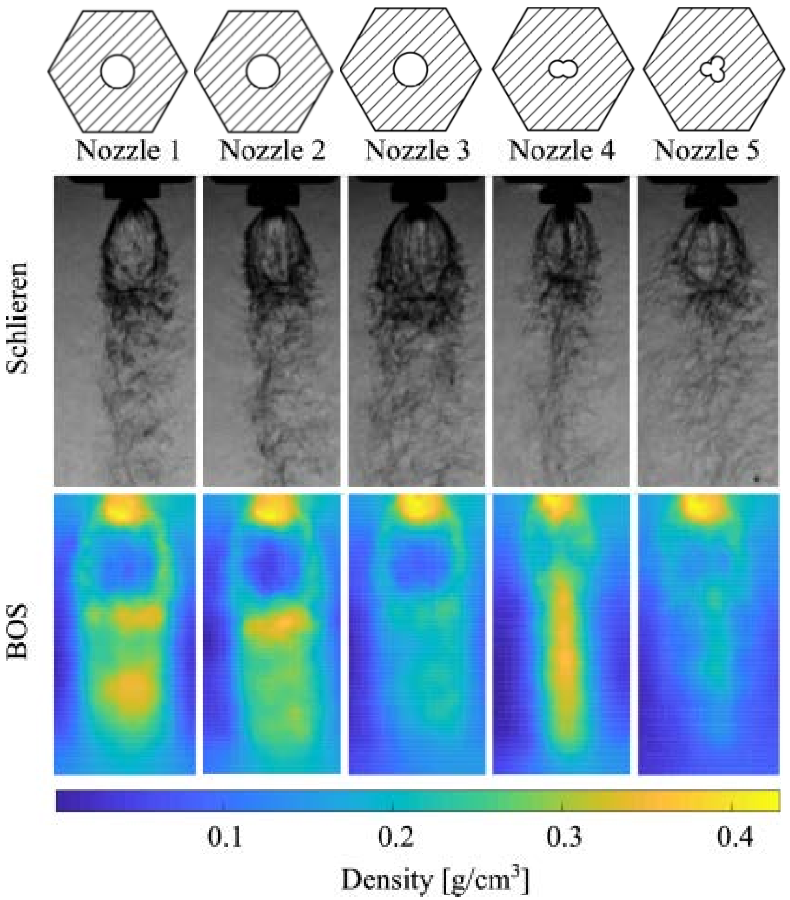


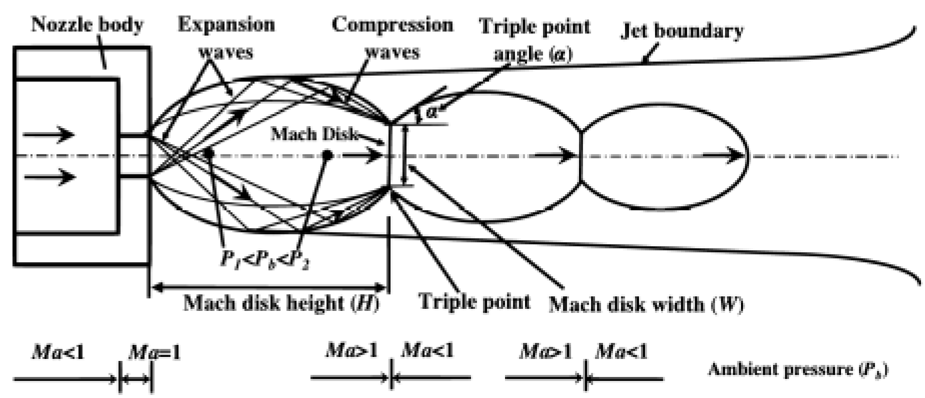


Reference image | N image | Displacement vectors | Density distribution

High pressure gas injection. Optical studies

D (mm) =
1.48 2.04 2.88



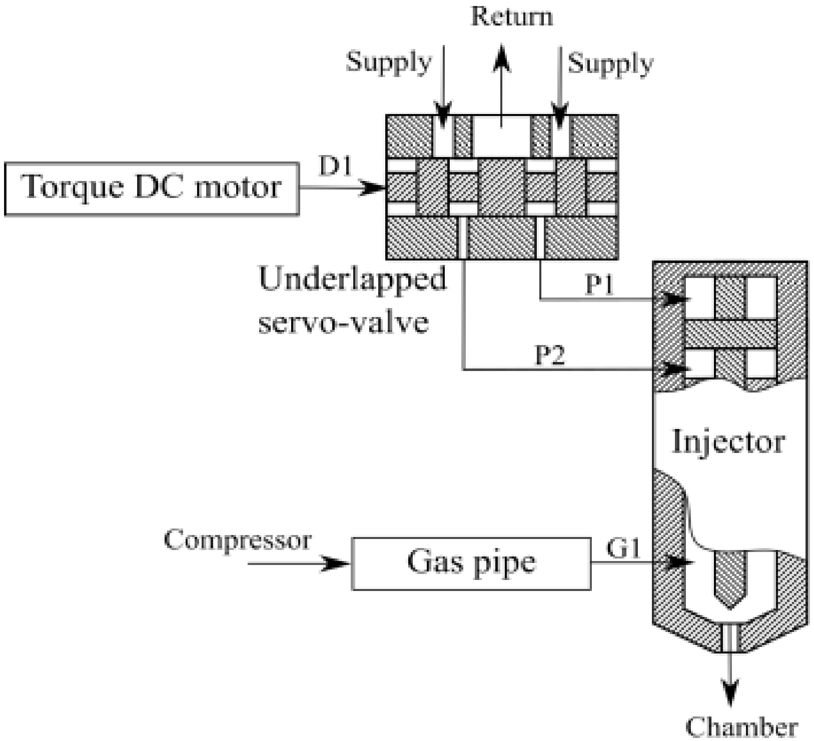


Non-circular orifices did not improve gas injection due to significant deformation of waves near nozzle exit!

High pressure gas injection. Theoretical model

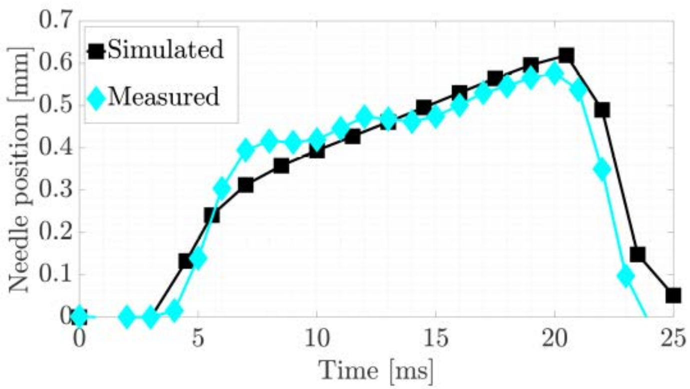
Theoretical model is need for:

- Estimation of injected energy (without preliminary experiments)
- 1D model as a part of 1D-3D CFD model scheme
- Improvement of Background Oriented Schlieren post-processing algorithm

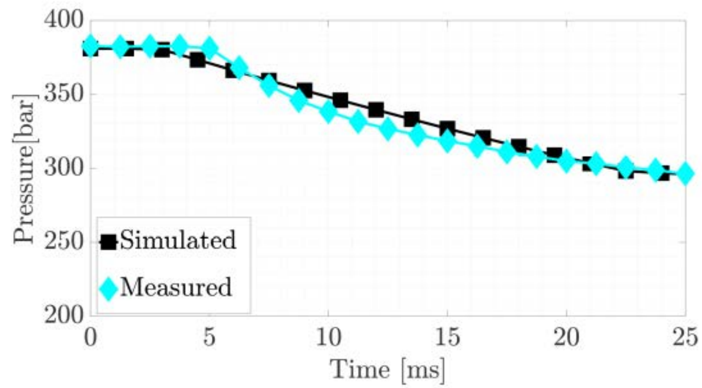


High pressure gas injection. Model

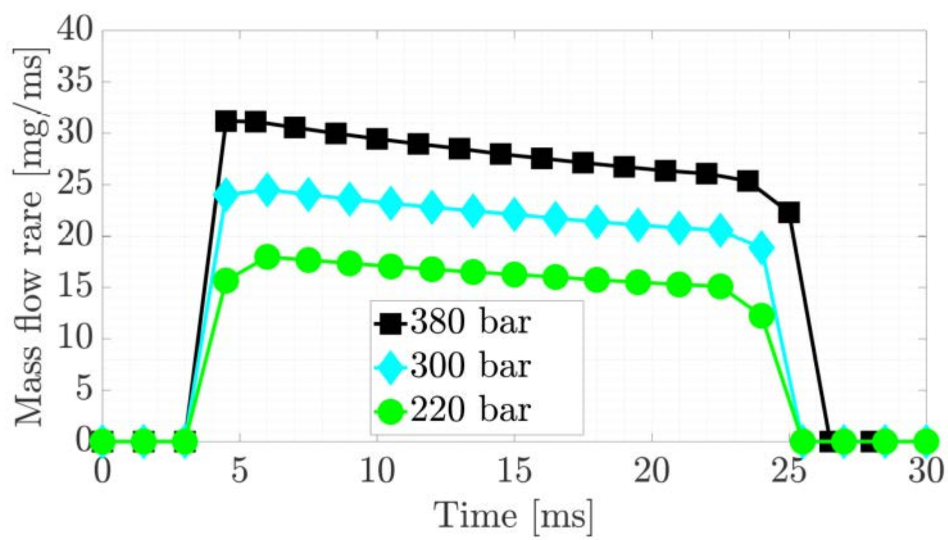
Needle position



Pressure drop before injector



Mass flow rate



Conclusion

1. CVCR was developed to experimental investigation on combustion process in marine gas engines (mainly HPDF concept)
2. Theoretical model of diesel injector was developed. Method to study diesel injector with unknown architecture was suggested.
3. Hydrogenated vegetable oil as was studied as alternative fuel for pilot injection and proved to be a good candidate for replacement of conventions diesel fuels.
4. Effect of non-circular orifice on gas jet formation was optically studied in CVCR.

Further work

- Suggest a model/scheme "to connect" the CVCR with an internal combustion engine
- Further develop the two-color pyrometry method
- Develop a 3D model of the gas injector to study different nozzle geometries/ gas types
- Study dual-fuel injection/combustion (diesel – gas injections)

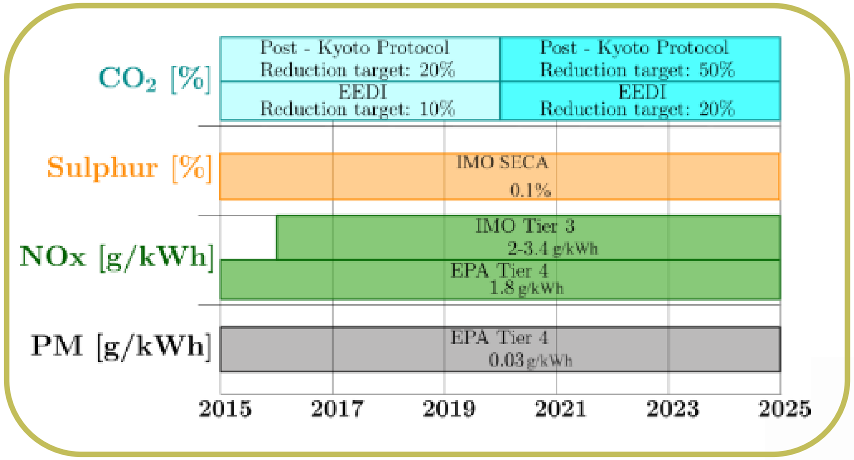
Q/A

Thank you for your attention!

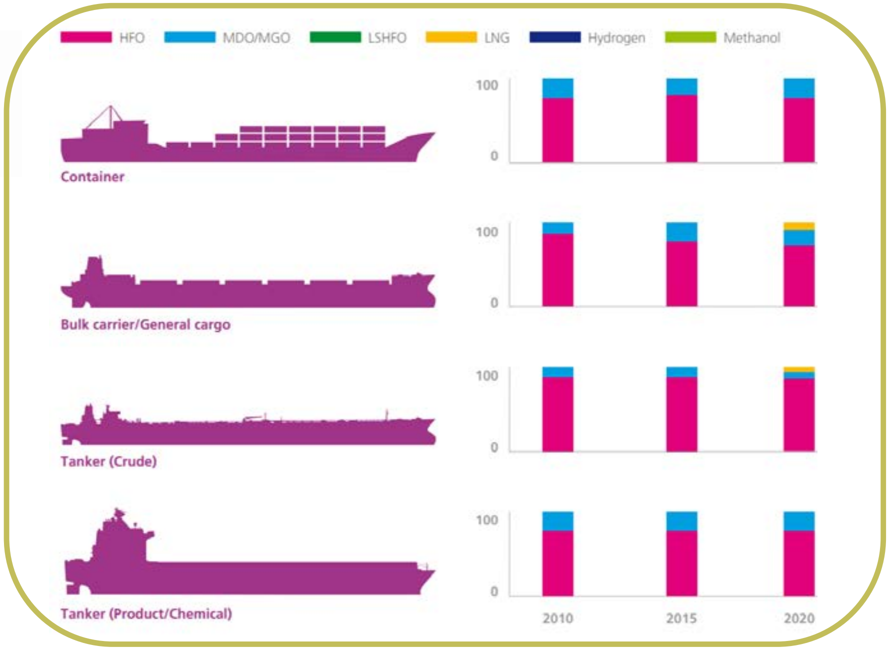
Questions?

Motivation

Emission regulation in existing ECAs[1]



Fuels for 4 types of vessels[2]



HFO[3]:

1. NOx > 10 g/kWh
2. PM > 0.6 g/kWh
3. Sulphur = 1.6 %

MGO[3]:

1. NOx > 9 g/kWh
2. PM > 0.38 g/kWh
3. Sulphur = 0.03 %

---

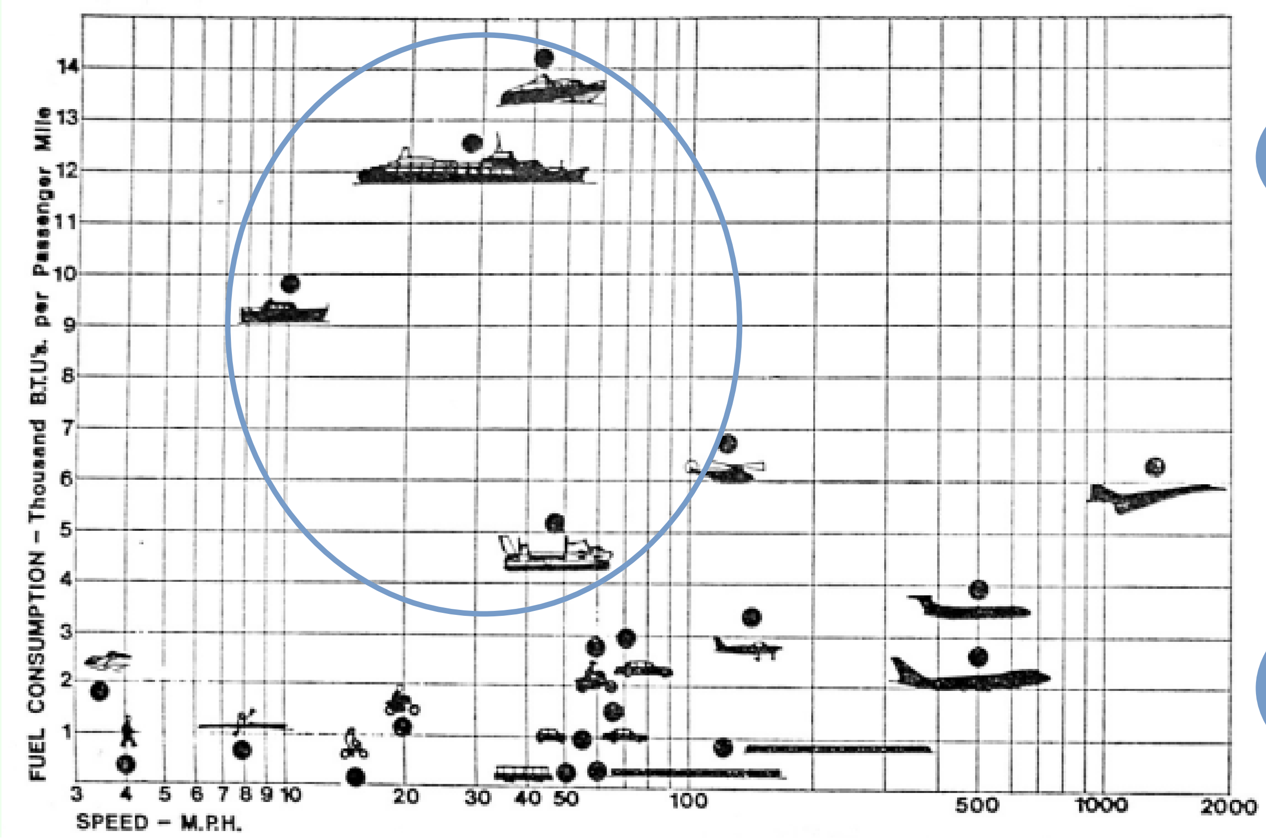
[1] – V. Krivopolianskii.et.al, Control of the combustion process and emission formation in marine gas engines, 2018

[2] – Lloyds Register Marine, Global marine fuel trends 2030, 2015

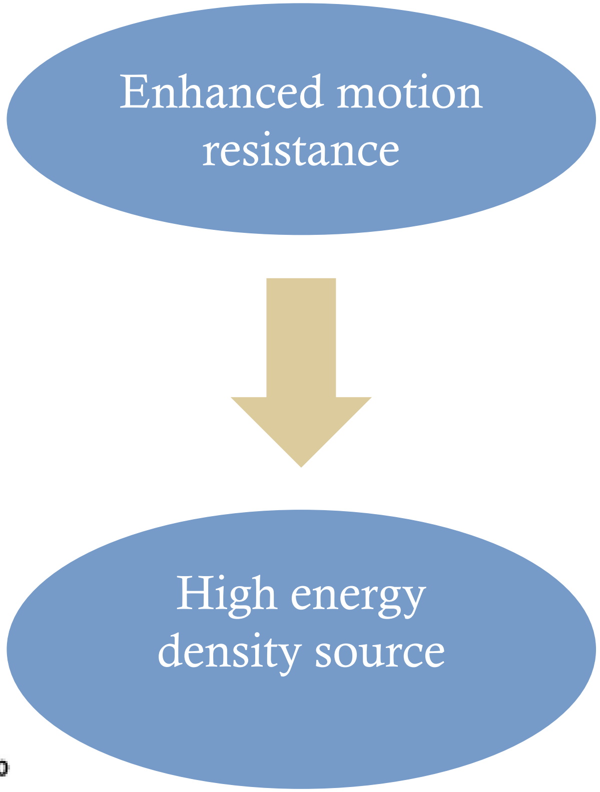
[3] – H. Winnes, E. Fridell, Particle emissions from ships: dependence on fuel type 2012

Motivation

Transport fuel consumption vs speed[1]



Energy demand



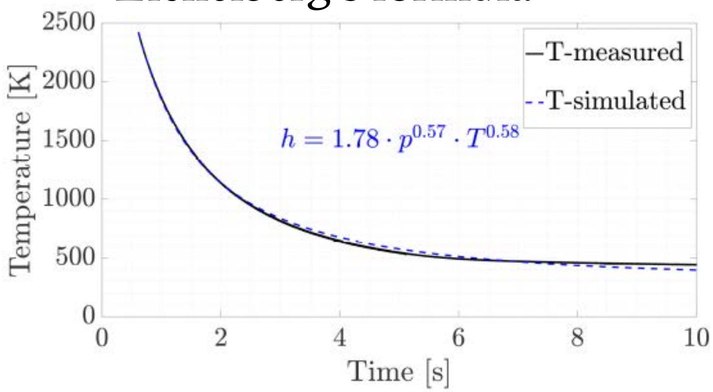
[1] – T. Brendixson, Instead of cars, 1977

Gas cooling

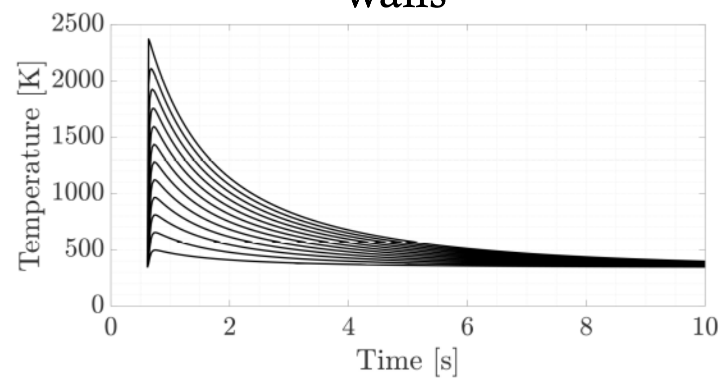
$$\dot{q}_{cv} = hA_t(T_g - T_{w,g})$$

Bulk temperature
(calculated using IGL)

Convection: using modified Eichelberg's formula

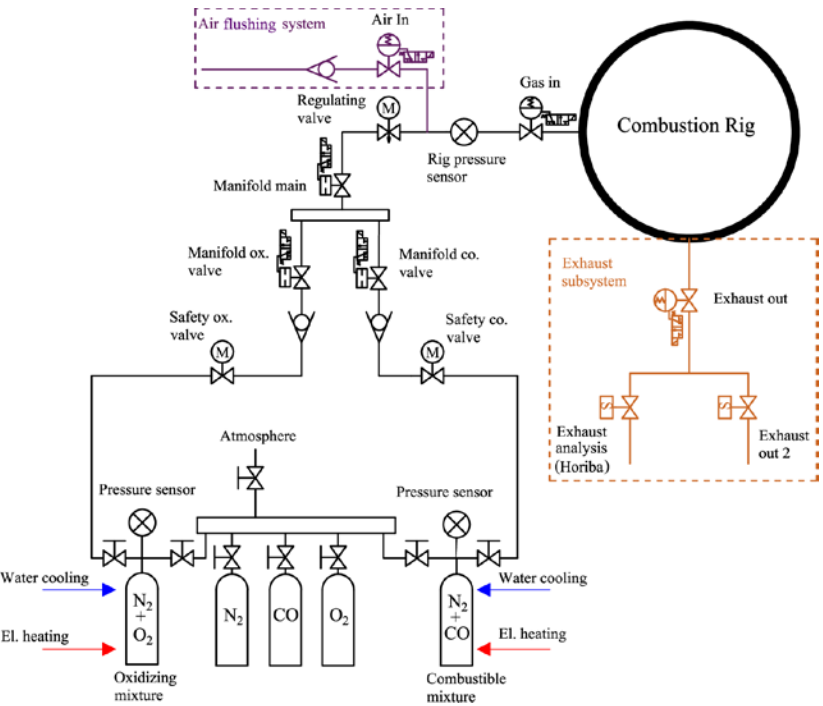


Modelled conduction in rig walls



Developed heat loss model is mainly applicable for pre-combustion
The model could used in fuel combustion analysis with skepticism

Gas feeding

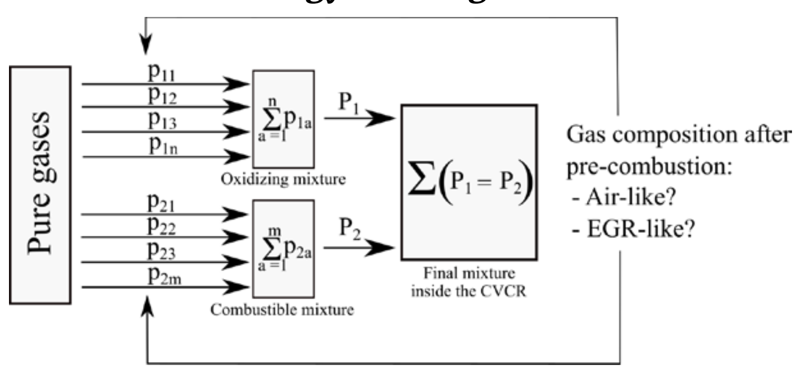


Gas feeding procedure:

1. Gas composition is controlled by partial pressure (pressure sensor)
2. CVCR is electrically heated
3. Heating leads to increase in-chamber pressure

Solution: To develop a procedure that ensures control over gas composition and takes into account pressure rise due to heating

Strategy to mix gas:

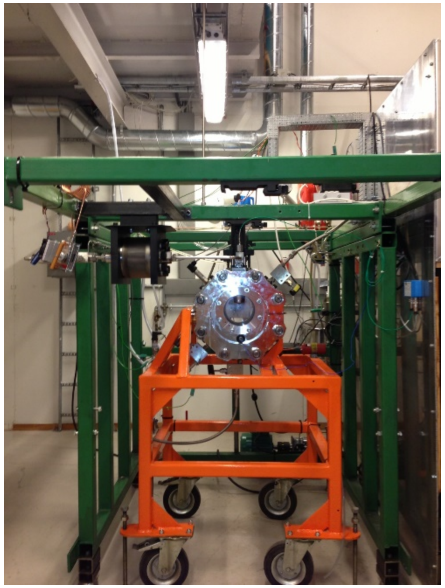


History of the CVCR

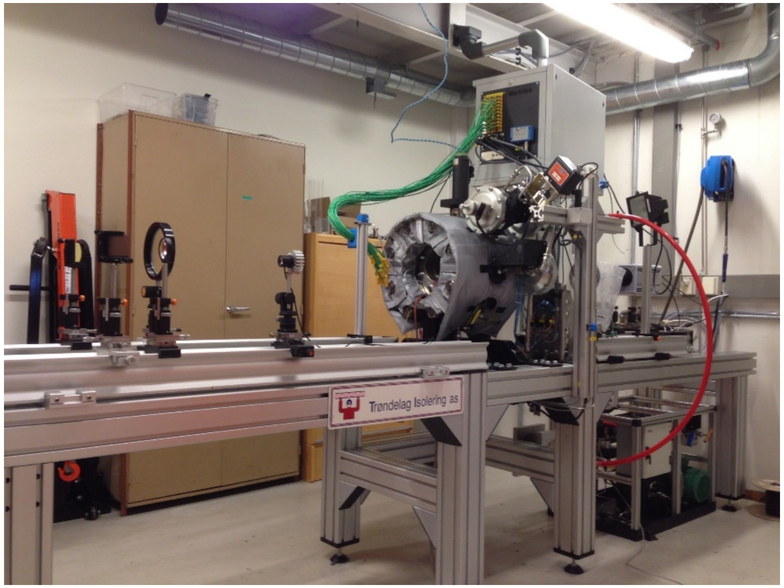
2013

Start of development of the CVCR for diesel combustion studies

2014



2015



Case Studies

Research objectives:

- Study limitations of the CVCR
- Develop methods for investigation of injection and combustion processes in marine gas engines

Case studies:

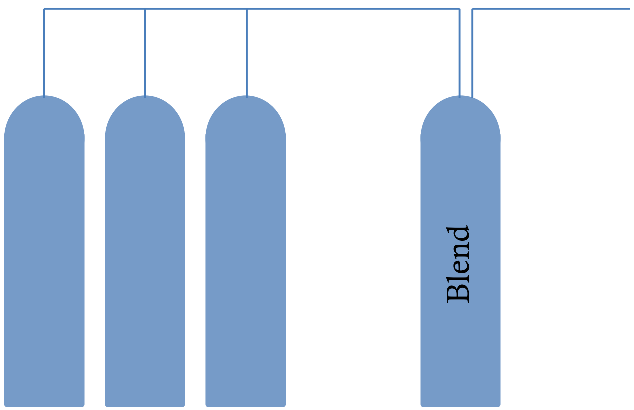
Case 1. Pilot diesel injection. Reverse engineering of unknown diesel injector

Case 2. Alternative pilot fuel. Study of combustion of hydrogenated vegetable oil

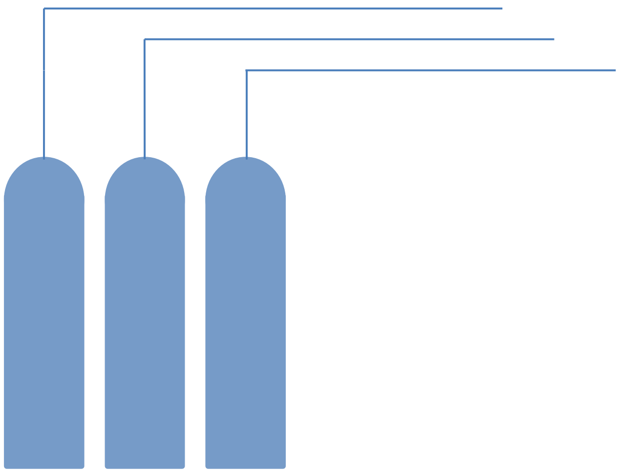
Case 3. Study of high pressure gas injection

Pre-combustion gas feeding system

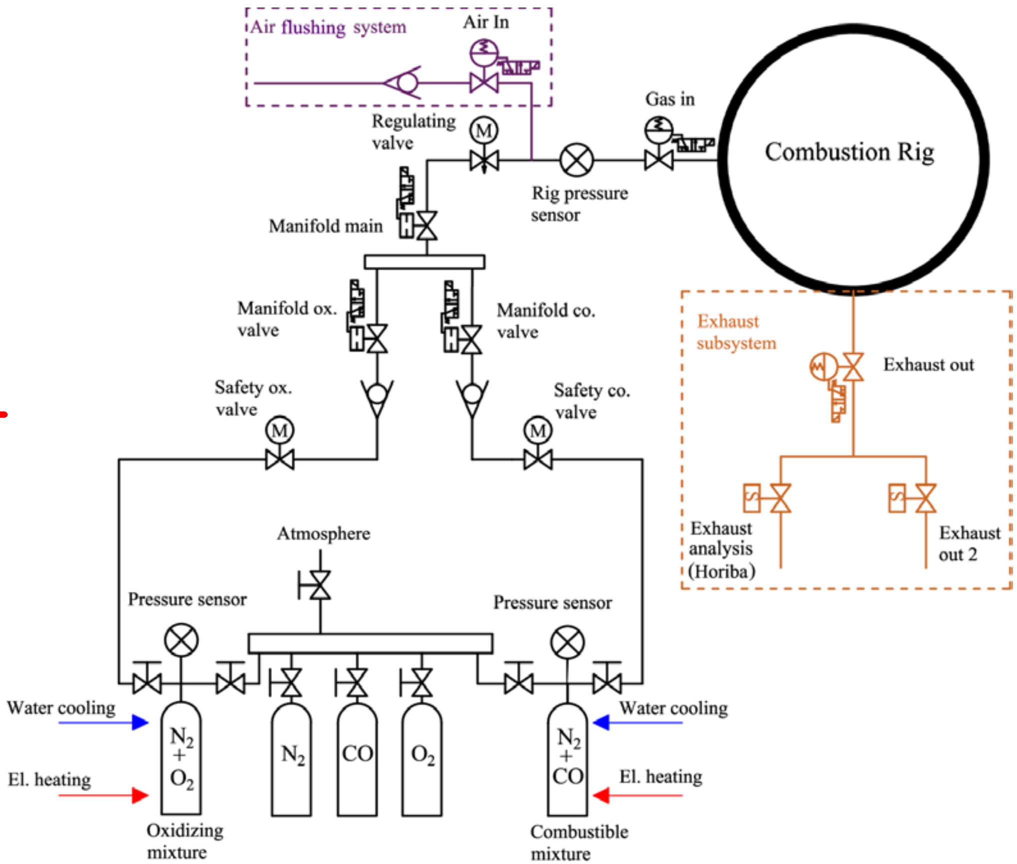
Fully premixed method



Sequential gas feeding



Hybrid feeding system



Pre-combustion. Gas blends

Two gas mixtures:

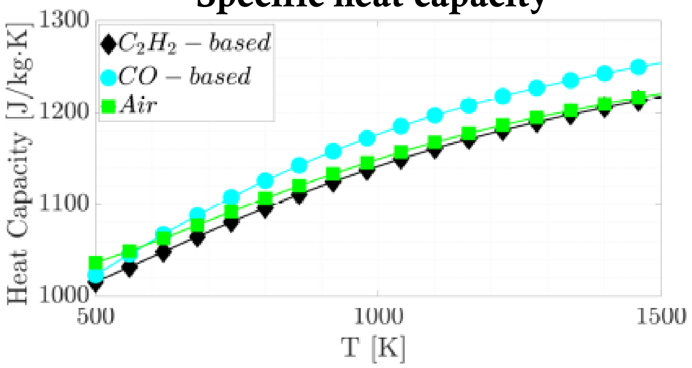
1. TU/e – blend of C_2H_2, Ar, O_2, N_2 **(C_2H_2-based)**
2. NTNU – blend of CO, O_2, N_2 **(CO-based)**

Statistical analysis of pre-combustion

Parameters	C_2H_2-based Mean ± 95% confidence interval	CO-based Mean ± 95% confidence interval
Charge density [kg/m^3]	16.1 ± 0.07	15.9 ± 0.04
Bulk T_1 [K]	1190 ± 7	1410 ± 6.8
Bulk T_2 [K]	798 ± 5.5	932 ± 4.3
Bulk T_3 [K]	609 ± 4.3	696 ± 3
Bulk T_4 [K]	505 ± 3.4	565 ± 2
Oxygen content [% vol]	21 ± 0.2	21 ± 0.2

High heat capacity is a cost paid for using hydrogen- free gas blend (CO-based)

Specific heat capacity

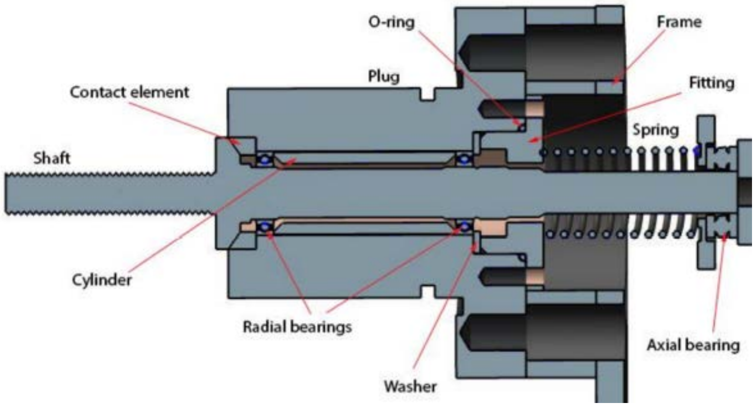


Mixing fan

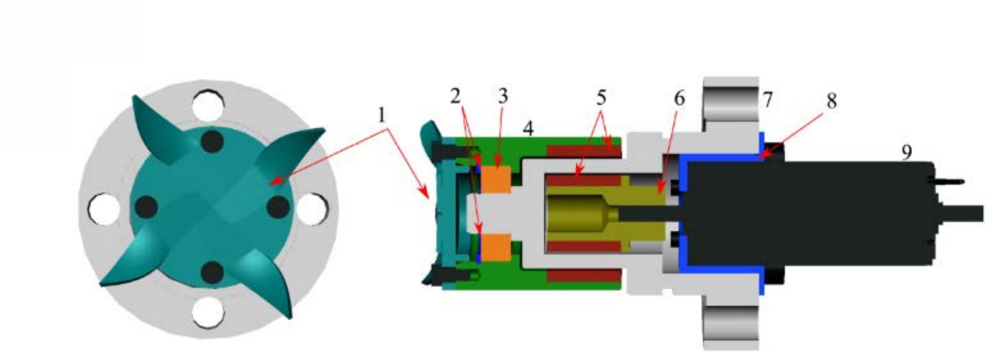
Why?

- Blends "Fuel gas" and "Oxidizer" before pre-combustion
- Required for homogeneous temperature field inside the chamber

Alternative 1



Alternative 2



Mechanical sealing in analogy to engine valves:

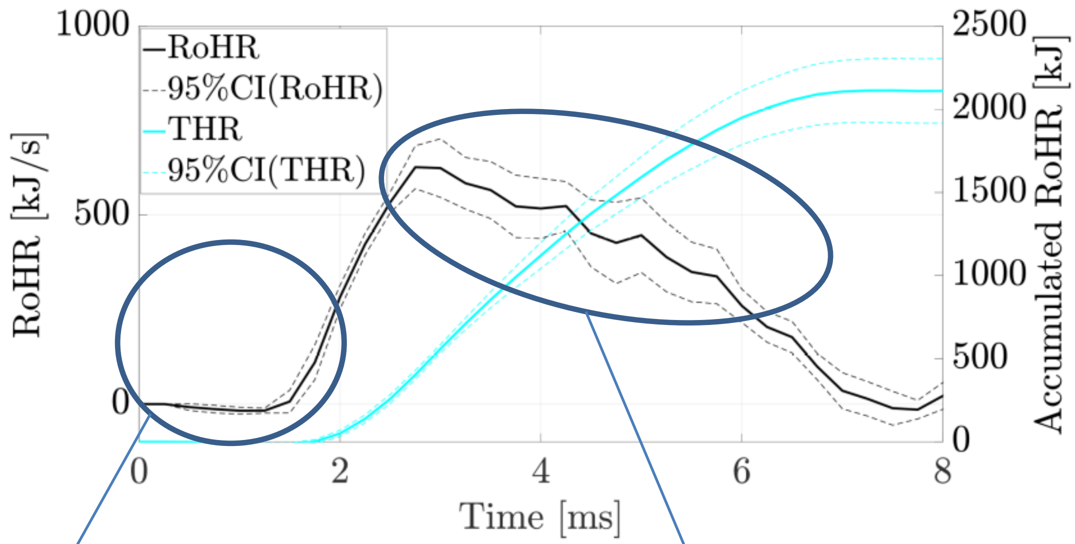
- Contamination of surface led to shaft jamming
- Requires high torques

Magnet clutch (similar to Sandia, Tue..)

- Low toques (DC motor is sufficient)
- Leak free

Fuel combustion. Stability test

<u>Statistical analysis of diesel-fuel combustion using rate of heat release (RoHR):</u>
850 K of bulk temperature, 1000 bar of inj. pressure

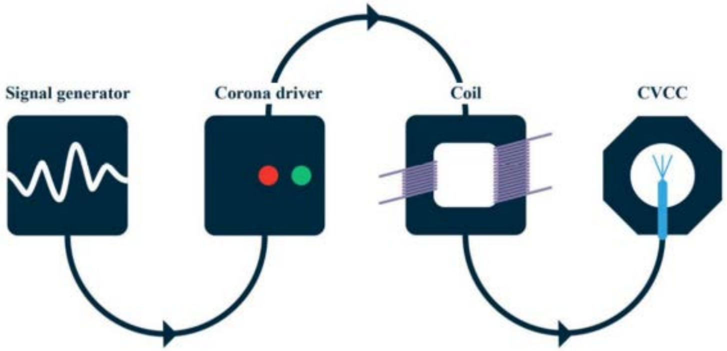


Reproducible ignition delay

Fuel burns in relatively cold zones

Ignition systems

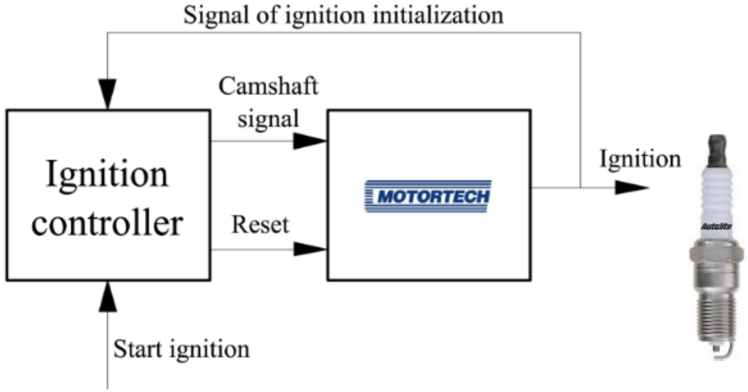
Corona discharge



High voltage: 50 kV

P.S.Jaer, 2016

Conventional spark plugs



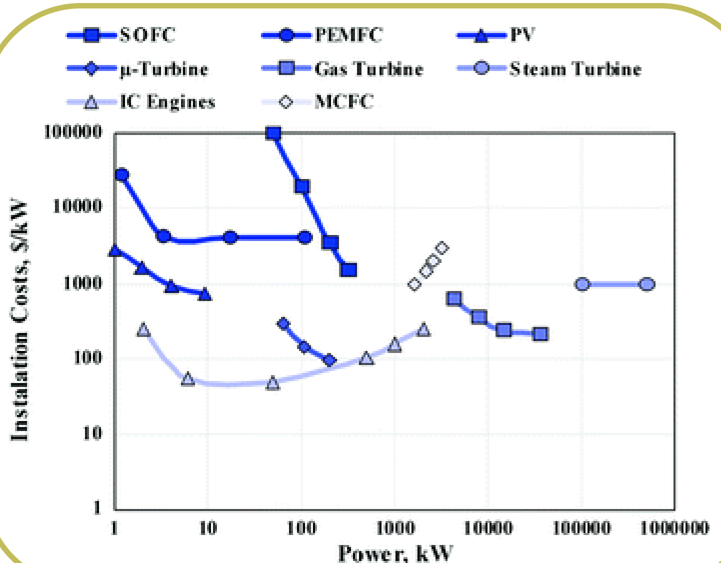
- Stable ignition is achieved.
- Energy content in pre-combustion
- Mixture is 12% less than in previously used gas blends.

Motivation

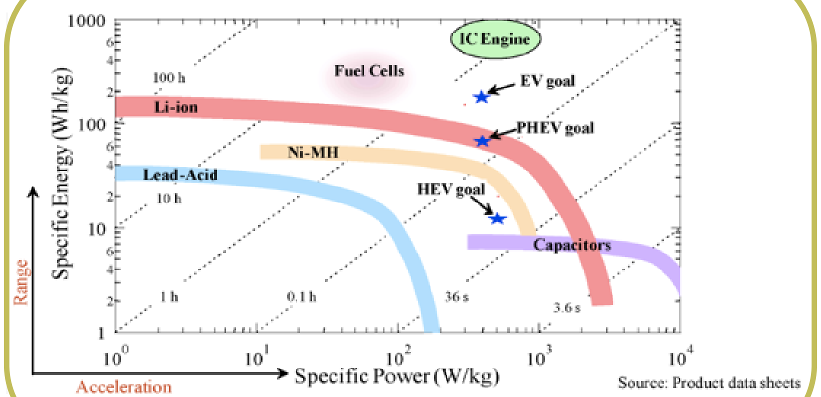
DNV recommendations to comply with NOx[1]:

1. Diesel + Selective catalytic reduction (SCR)
2. Diesel + Exhaust gas recirculation (EGR)
3. Batteries/ Hybrid system
4. Fuel cells/ Hybrid system
5. **<u>Dual Fuel engines/ pure gas engines</u>**

Installation costs for some energy converters[2]



Specific power of some energy converters[3]



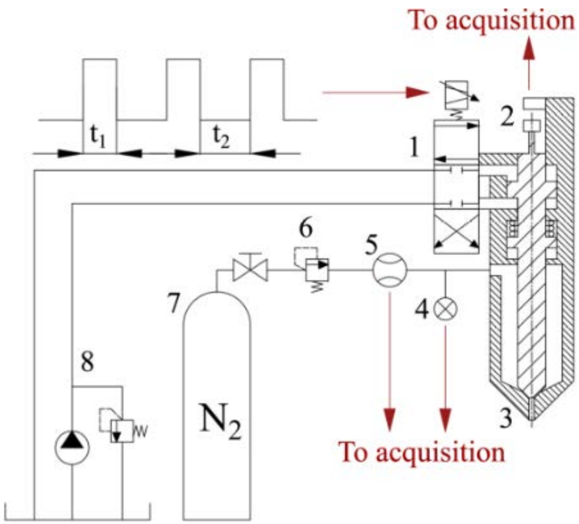
[1] – DNV GL, IMO NOx Tier III requirements to take effect on January 1st 2016, 2015

[2] – J. Milewski, Advanced methods of solid oxide fuel cell modeling, 2011

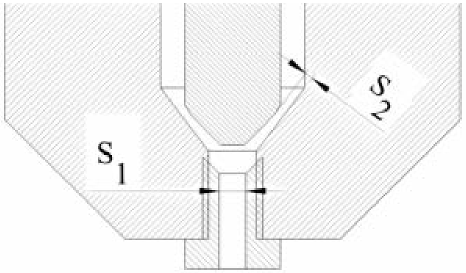
[3] – T. Murphy, The battery performance deficit disorder, 2012

High pressure gas injection. Flow Coefficients

Experimental setup and settings:



$$\dot{m} = \frac{C_d \cdot P_u \cdot Area \cdot \Psi(\kappa, x)}{\sqrt{RT}}$$

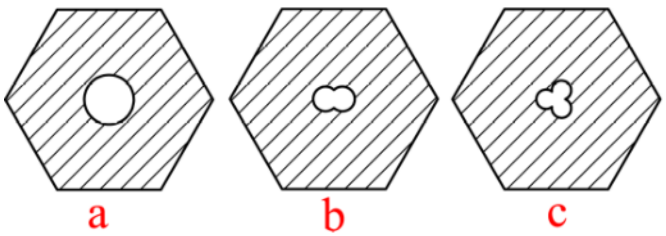


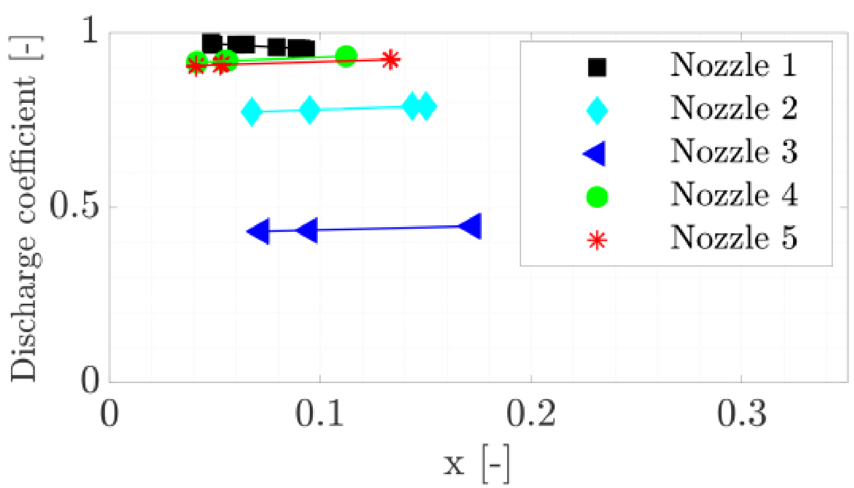
Discharge coefficient	Conditions	Signal In
Cd_1	$Area(S_1) < Area(S_2)$	A long signal pulse (≈ 2 sec)
Cd_2	$Area(S_1) > Area(S_2)$	High frequency 50% duty TTL signal

High pressure gas injection. Flow Coefficients

Long injection pulses – discharge coefficient at complete needle lift

Label	Orifice shape	Diameter [mm]	Cross-sectional area [mm^2]
Nozzle 1	a	1.48	1.72
Nozzle 2	a	2.04	3.27
Nozzle 3	a	2.88	6.51
Nozzle 4	b	-	1.72
Nozzle 5	c	-	1.72



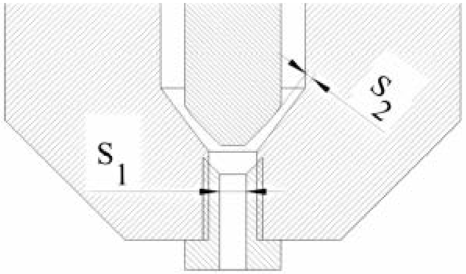


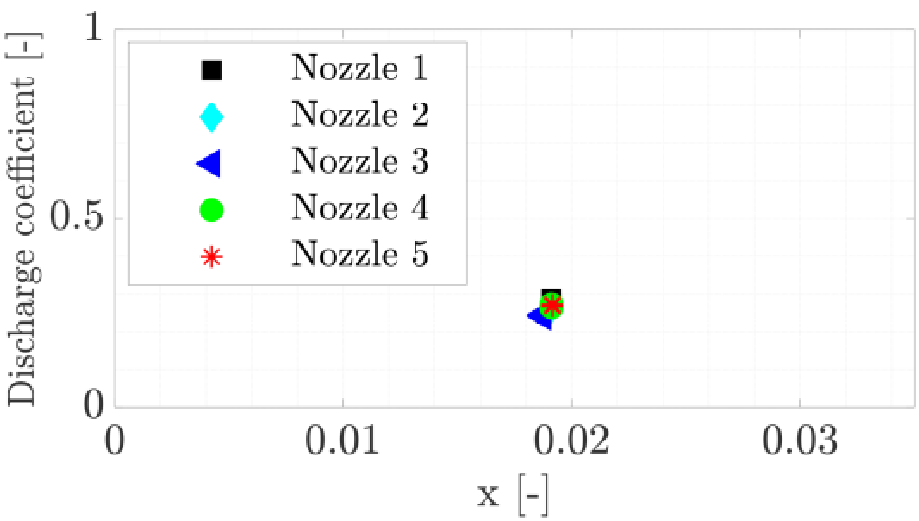
$$x = {}^{P_d}/{}_{P_u}$$

High pressure gas injection. Flow Coefficients

<u>Short injection pulses – discharge coefficient at transient needle position</u>

Label	Orifice shape	Diameter [mm]	Cross-sectional area [mm^2]
Nozzle 1	a	1.48	1.72
Nozzle 2	a	2.04	3.27
Nozzle 3	a	2.88	6.51
Nozzle 4	b	-	1.72
Nozzle 5	c	-	1.72





$$x = {}^{P_d}/_{P_u}$$

Results are converged!

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