Internal Combustion Engines research in the TU/e Zero Emission Laboratory

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Mechanical Engineering, Power & Flow

ZERO EMISSION lab

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

Content

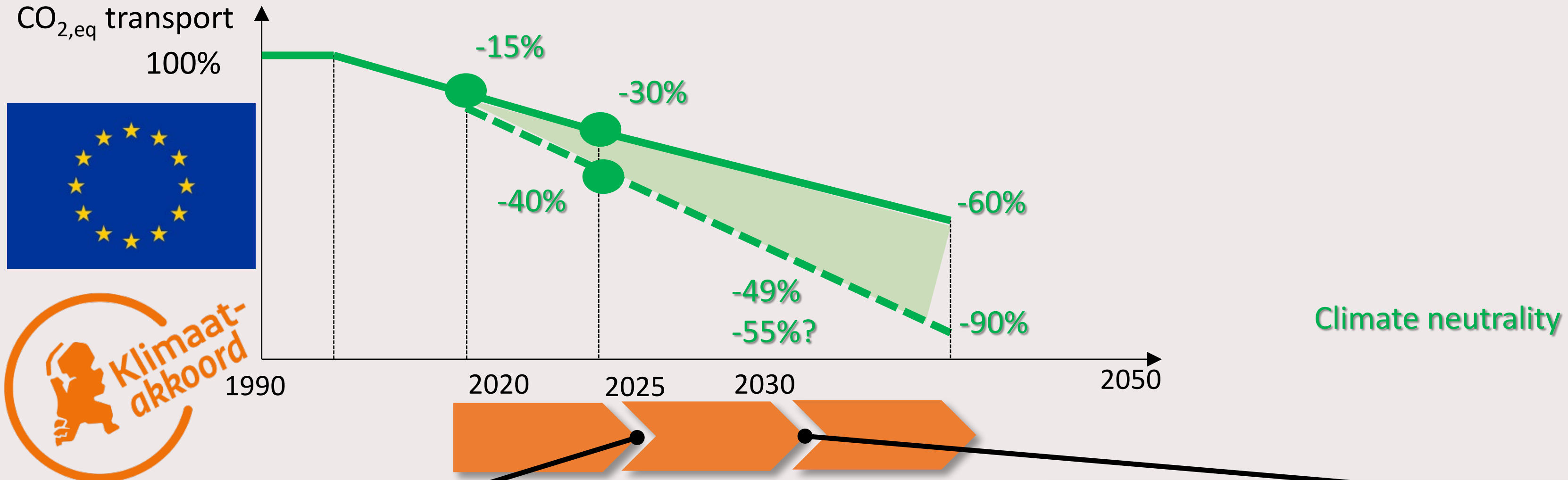
Zero Emission Laboratory
- Vision & organization
- Setups

Recent & current work

Quick reference to CFD

Zero Emission Lab vision

- EU-funded Mission D+: emission-free, future-proof mobility for people & goods by 2050



- **Zero emission public transport**
- **Zero-emission zones in 30-40 larger cities for city logistics**

- **1.9M electric vehicles**
- **33% renewable energy in mobility**

Zero Emission Lab vision

- **ICE0.0**

0-impact GHG emissions

- H_2/NH_3
- E- and advanced bio-fuels

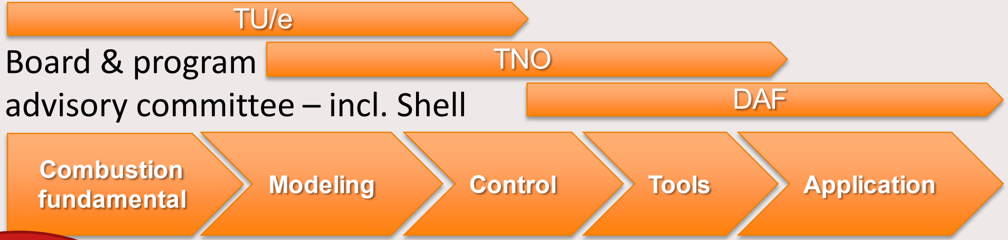
0-impact pollutant emissions

- NO_x & Soot
- UHC & CO

- **Combination of ultra-efficient internal combustion engines and sustainable fuels is key to accelerate GHG emission reduction in heavy-duty transport**

- Key scientific challenges:
  - In-cylinder mixture formation
  - Heat release shaping & control
  - Fuel flexibility

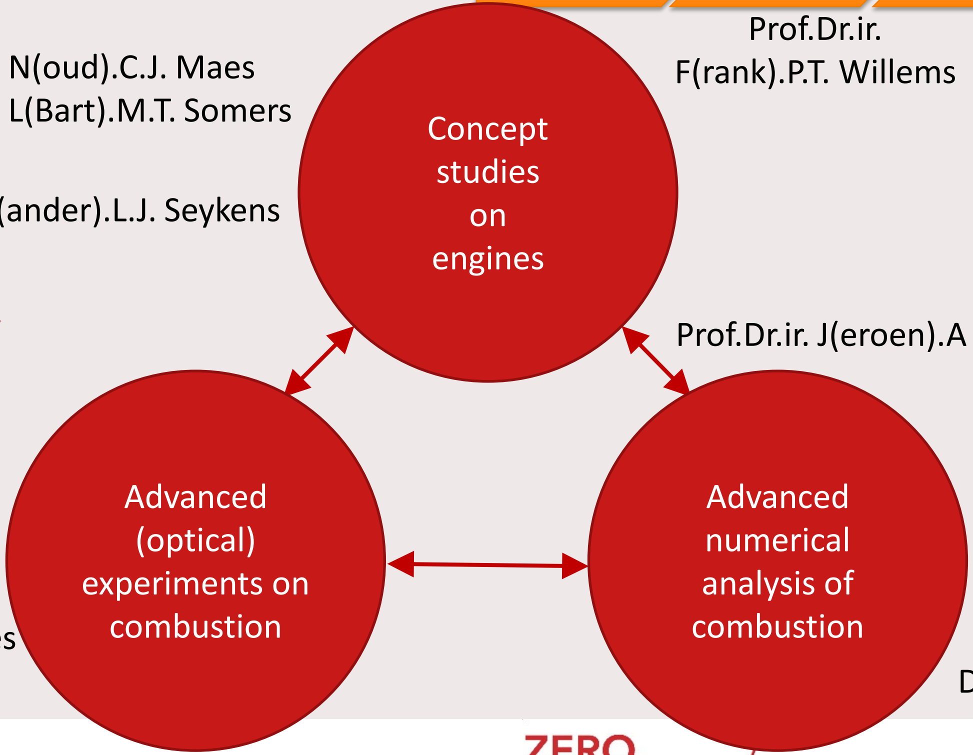
Zero Emission Lab vision



Prof.Dr.ir.
F(rank).P.T. Willems

Dr.ir. N(oud).C.J. Maes
Dr.ir. L(Bart).M.T. Somers

Dr.ir. X(ander).L.J. Seykens



... and indispensable help by many other (support) staff members & (PhD) students!

Prof.Dr.ir. J(eroen).A van Oijen

Dr.ir. N(oud).C.J. Maes
Dr. N(ico).J. Dam

Dr.ir. L(Bart).M.T. Somers

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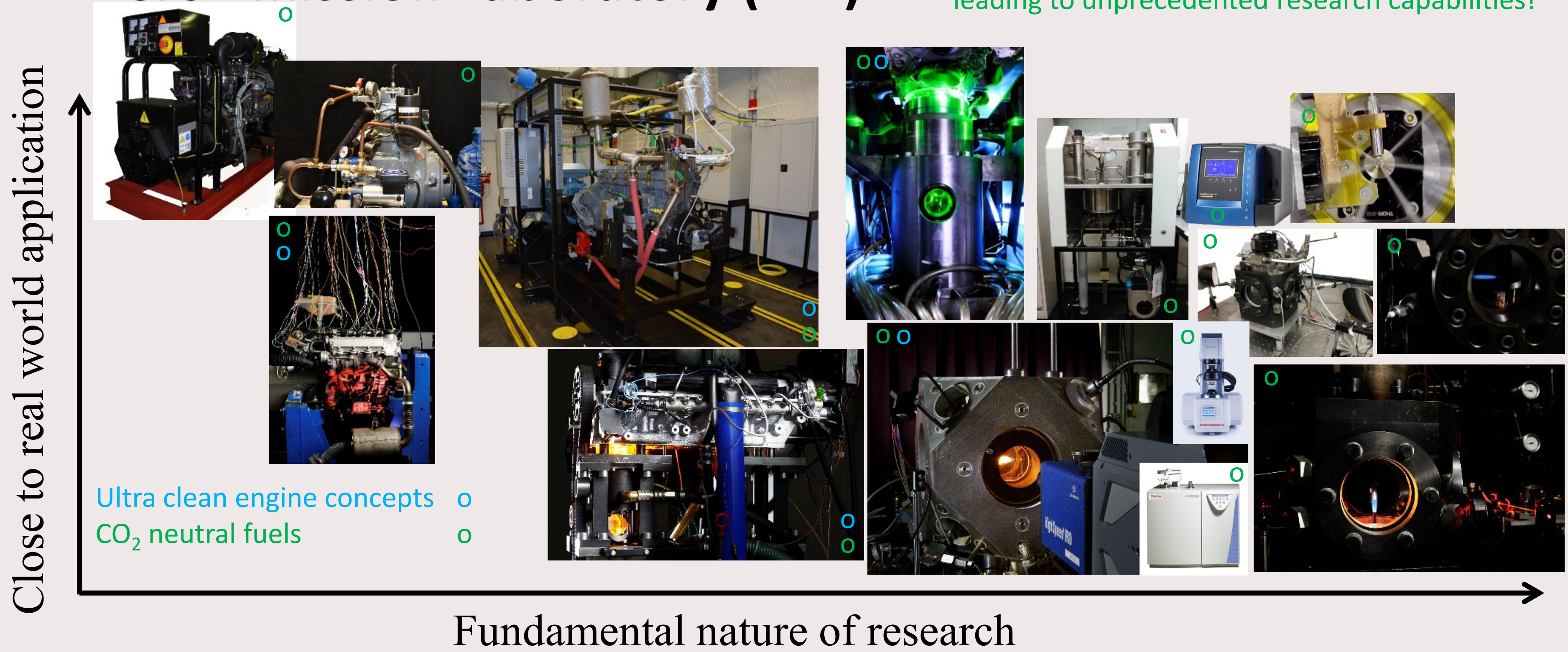
Zero Emission Laboratory (ZEL)

Unique setups (even on a global scale) leading to unprecedented research capabilities!



Zero Emission Laboratory (ZEL)

Lubricity, stability, & elemental composition testing

- Prior to engine tests
  - Limited batch sizes & preventing damage
  - Insight in applicability/usability

CO_2 neutral fuels o

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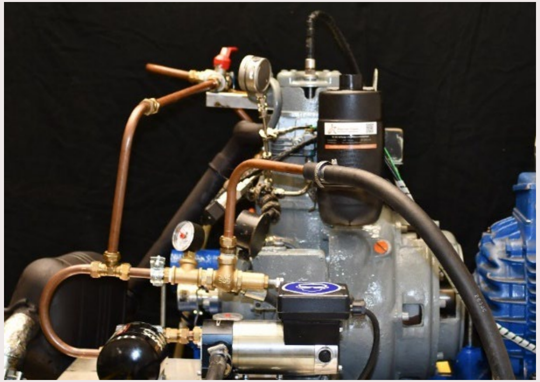
Zero Emission Laboratory (ZEL)

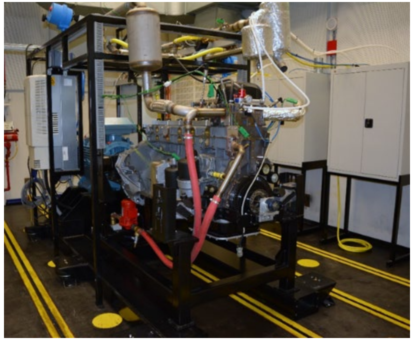
Hatz engine
Generator engine with emission and in-cylinder pressure analysis
Robust, cheap, fuel-flexible DI CI commercial setup

New: 3 Hatz engines on moving frames for BSc students



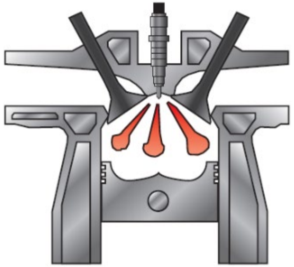
CO_2 neutral fuels o

Zero Emission Laboratory (ZEL)



Paccar MX13 single-cylinder (RCCI capable) engine
Reactivity Controlled Compression Ignition
Ultra clean & fuel flexible with fuels that inherently prevent soot formation!

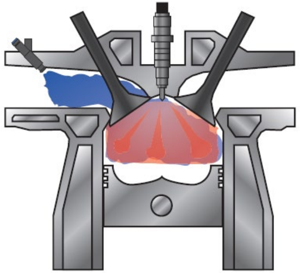
Classical Concept



Hot burning soot

Chemiluminescence

New Concept



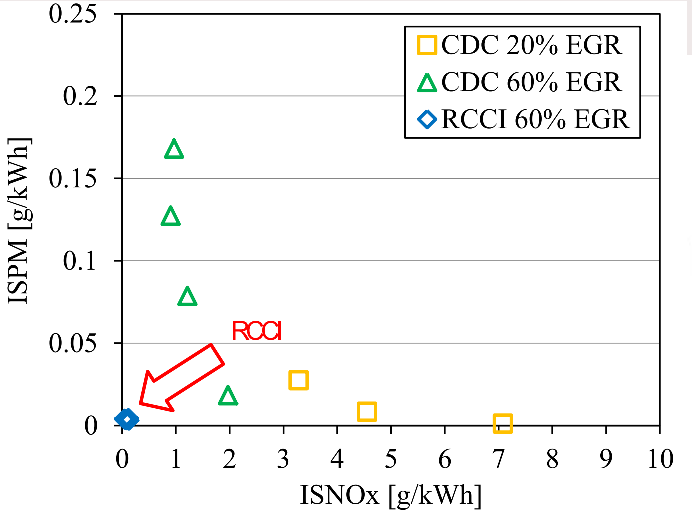
Ultra clean engine concepts o
CO_2 neutral fuels o

Zero Emission Laboratory (ZEL)

Paccar MX13 single-cylinder (RCCI capable) engine
Reactivity Controlled Compression Ignition

Low emissions with combustion phasing control!

- Change high/low octane fuel ratio
- Timing of the DI low octane fuel



Ultra clean engine concepts o
CO_2 neutral fuels o

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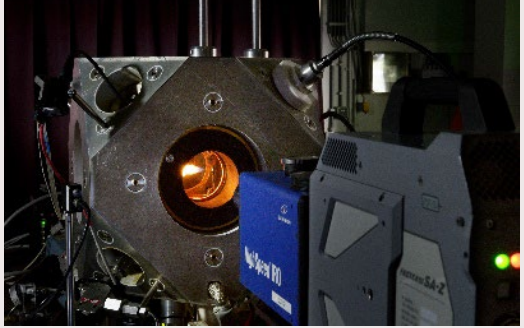
Zero Emission Laboratory (ZEL)



Eindhoven High-Pressure Cell (EHPC)

Pre-burn of lean charge of C_2H_2, Ar, N_2, and O_2 – sequential fill!

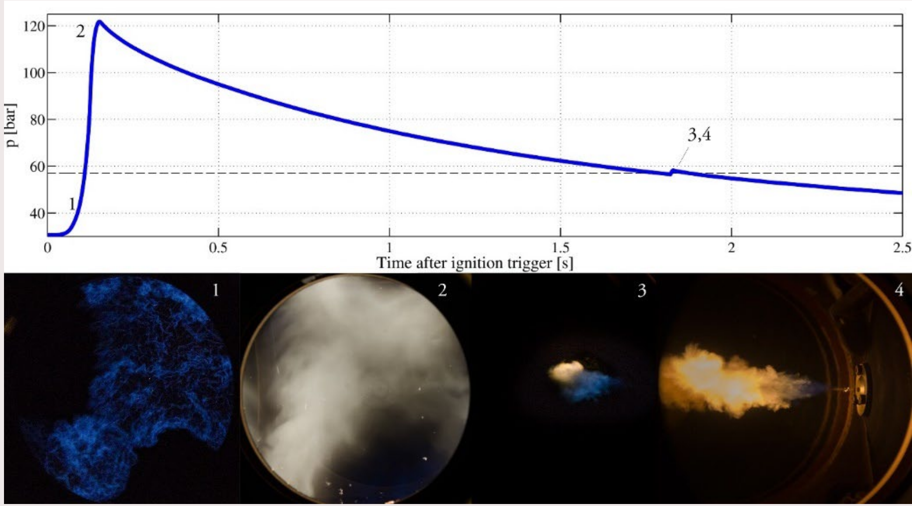
Relatively long cool down

Diesel surrogate fuel injection

Engine-like conditions:

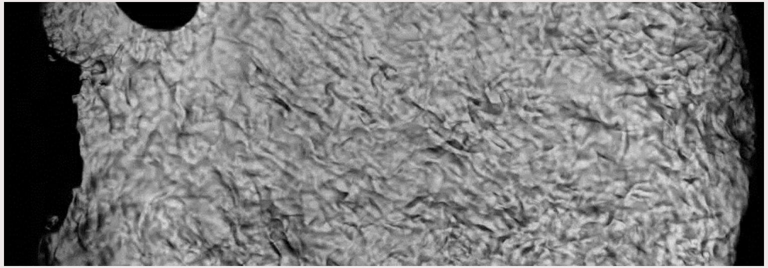
- Densities up to 40 kg/m^3 (350 bar)
- Peak temperatures up to 2000 K
- O_2 from 0 to 35 vol-%

Ø100 mm optical access – ~1.3 L

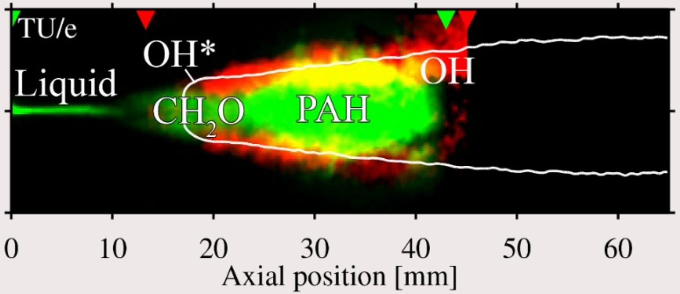


Zero Emission Laboratory (ZEL)

Eindhoven High-Pressure Cell



Visualization of
- Liquid/vapor-phase fuel
- Species distributions
- Soot (precursors)



Zero Emission Laboratory (ZEL)

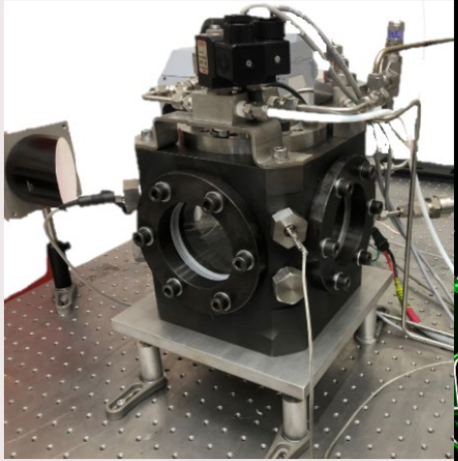
Combustion Research Unit (CRU):
Commercial ignition quality tester
Constant volume chamber ~0.4 L, pre-heating and compressed gases
Engine-like conditions:

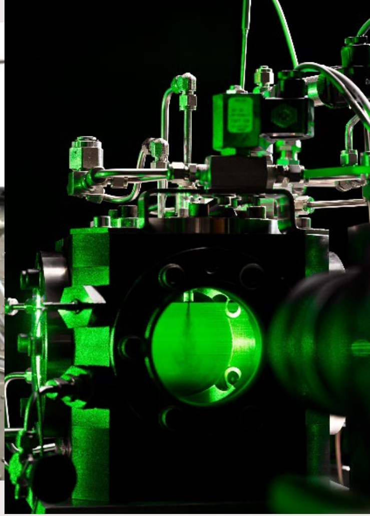
- Pressures up to 60 bar
- Peak temperatures up to 1050 K
- O_2 from 0 to 21 vol-%

Robust, fuel-flexible commercial setup for analyzing heat-release
Optional optical access through borescope
Equipped with dual-circuit heavy-fuel oil injector

CO_2 neutral fuels o

Zero Emission Laboratory (ZEL)

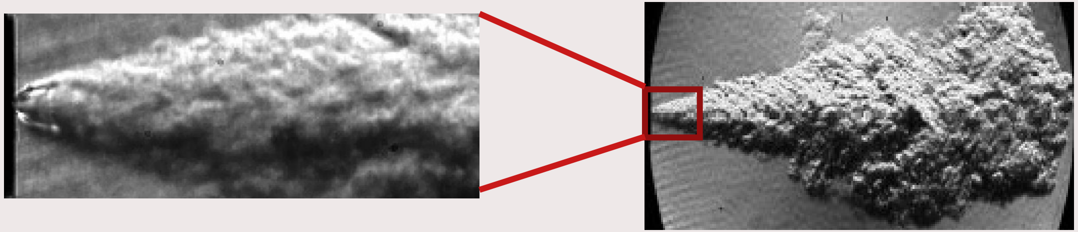


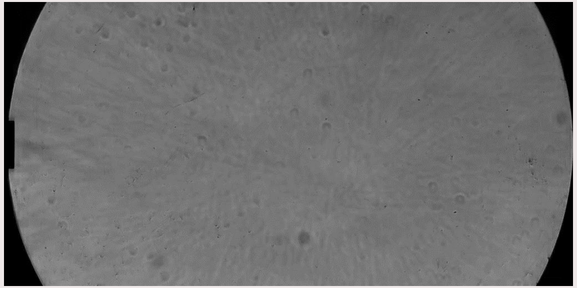


Eindhoven Low-Pressure Cell (ELPC)

Constant volume chamber ~1 L

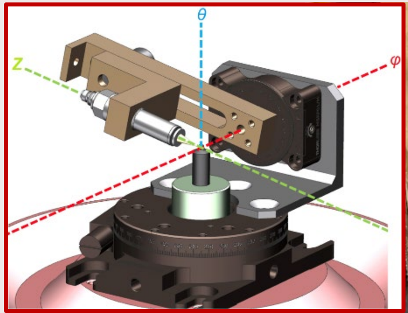
- Filled with compressed gases (N_2, He, Ar)
- Pressures up to 50 bar
- Mostly used for hydrogen research – fuel pressure up to 100 bar
- Full optical access
- Mach-disk formation, mixing, & penetration studies

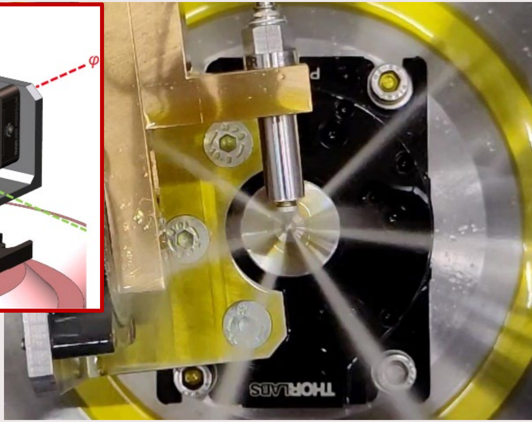




CO_2 neutral fuels o

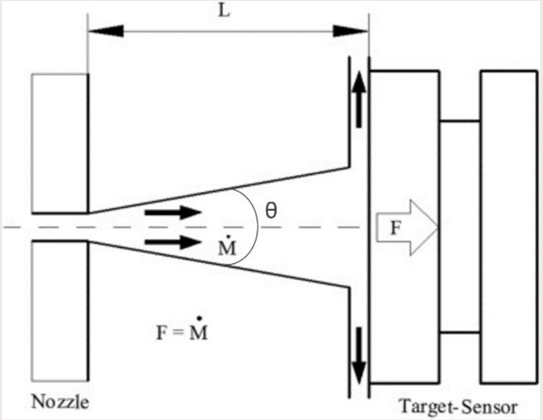
Zero Emission Laboratory (ZEL)

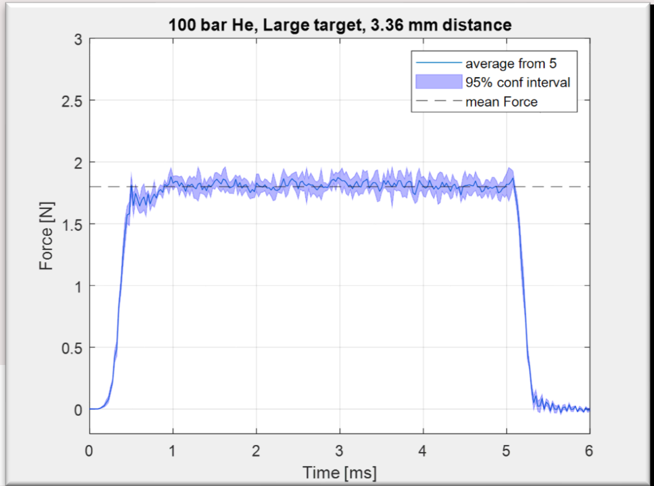


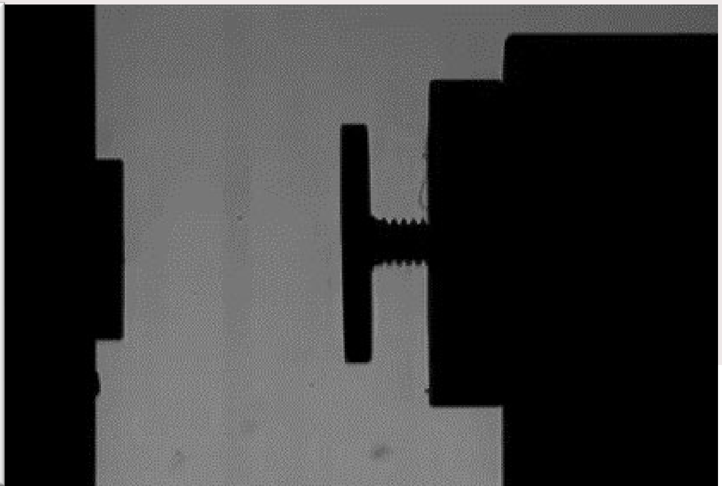


Atmospheric momentum exchange setup

- Essential parameters for modeling fuel injections!
- Syringe pump: momentum & mass flow up to 200 MPa
- Currently in use for H_2 injections (starting with He)
    - Up to 200 bar gas bottle pressure



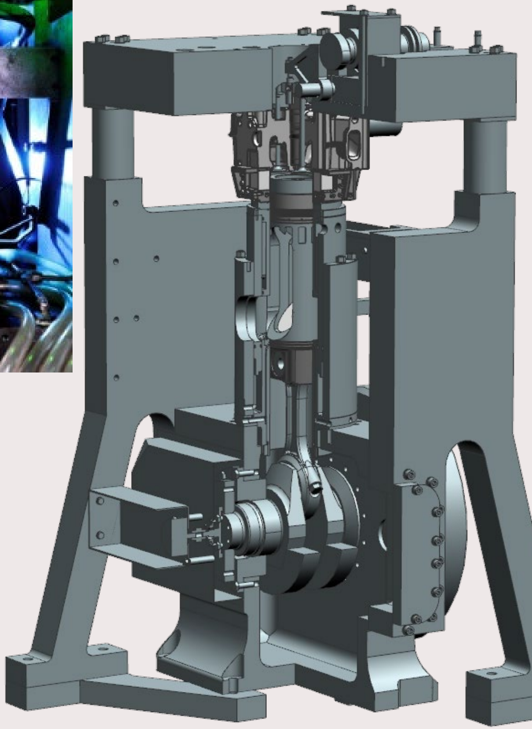




CO_2 neutral fuels o

Proteus “ICE H2.0”

- Base engine: 1-cylinder, 2L CI
  - Proteus Ricardo base
  - DAF MX13 liner, piston, & head
  - Extended piston “Bowditch” → Optical access
  - Quartz/sapphire piston
  - Adjustable CR
  - Flexible skip-firing



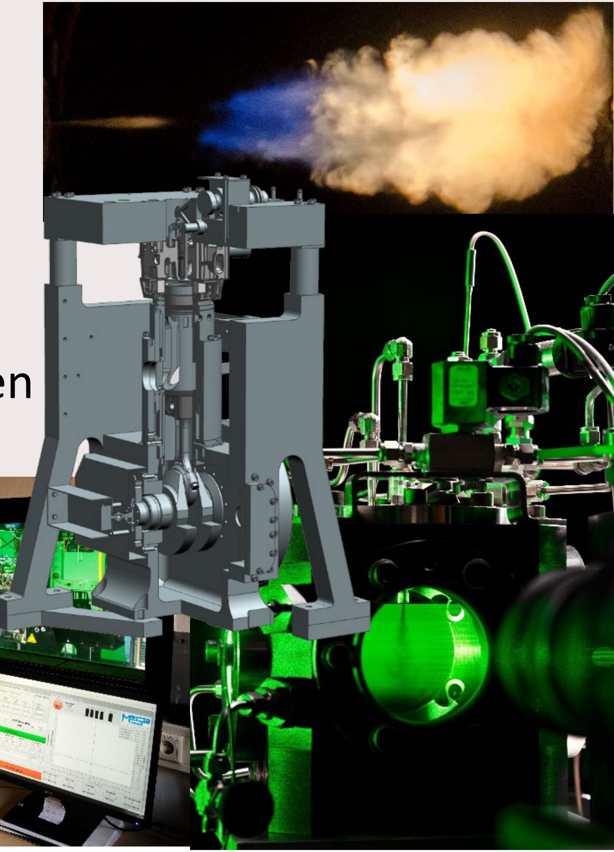
Recent & current work

SmartCHP: Yu Wang → PhD defended 28th of May!
Using Fast-Pyrolysis Bio-oils in engines

ZEL project/ACD-call (DAF, Shell, TNO, PNB): Stan Latten
(Re)building an optical H2-ICE

APC (vici prof. v. Oijen): Max Peters
Hydrogen jets

CSC (future fuels): Zhoncheng Sun
Biofuels & oxymethylene ethers



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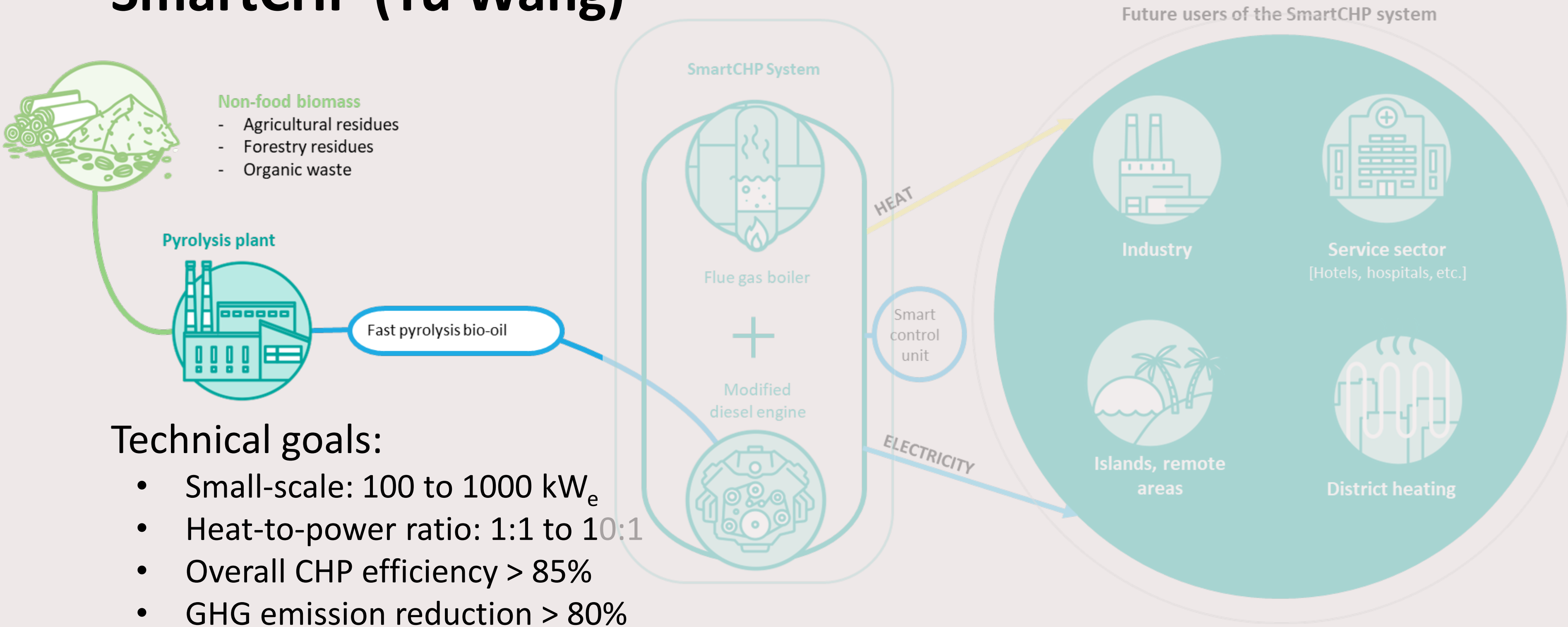
Yu Wang, “Direct application of fast pyrolysis bio-oil in combined heat and power”, PhD thesis, TU/e, 2024.

SmartCHP (Yu Wang)



Technical goals:

- Small-scale: 100 to 1000 kW_e
- Heat-to-power ratio: 1:1 to 10:1
- Overall CHP efficiency > 85%
- GHG emission reduction > 80%

SmartCHP (Yu Wang)

FPBO properties (compared to diesel)

- High viscosity (×15)
- Low energy density (~37%)
- High oxygen and water content
- Impurity particles
- Strong acidity

Challenges in engine application:

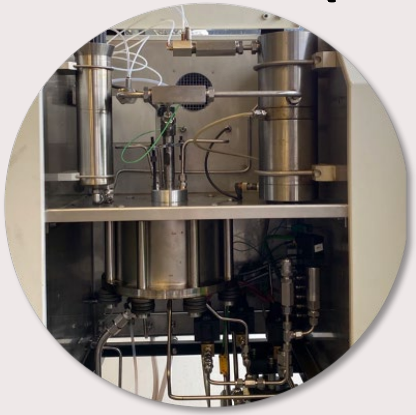
- Unknown ignition & combustion characteristics
- Corrosivity, nozzle clogging, poor ignitability

FPBO

Diesel

SmartCHP (Yu Wang)

Fundamental research → Engineering practice



- Ignition
- Combustion
- Fuel recipe

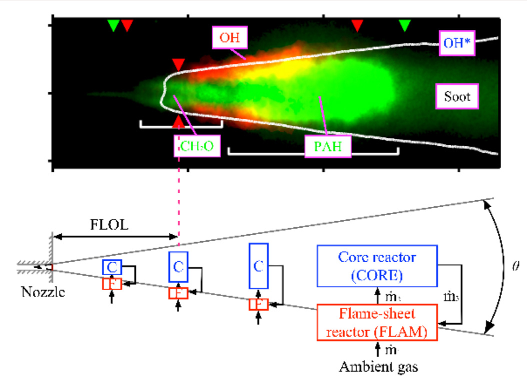
CVCC

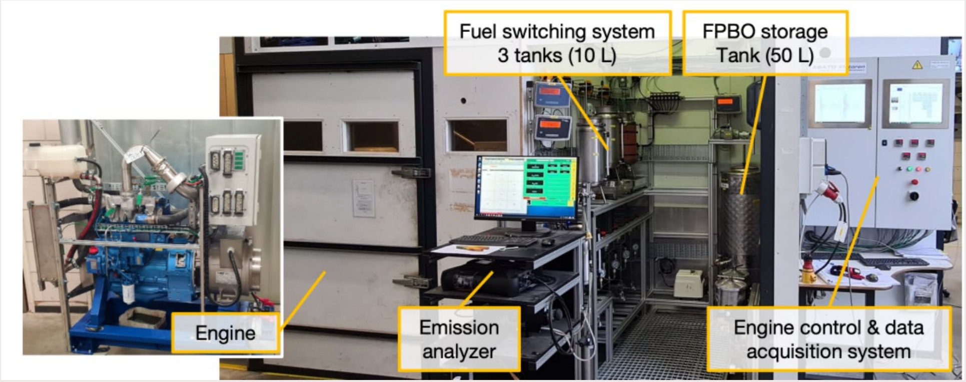
Engine

- Durability
- Emission
- Efficiency

Modeling

- Ignition
- Fuel composition





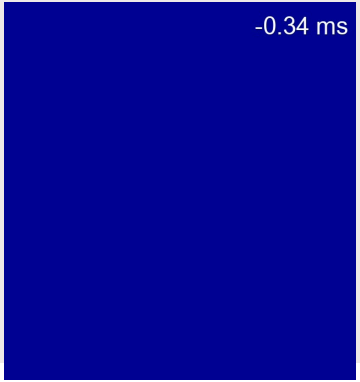
Wang, et al. "Spray combustion of fast-pyrolysis bio-oils under engine-like conditions." *Energy Conv. Management: X 20* (2023): 100433.

SmartCHP (Yu Wang)

Natural luminosity (soot) of diesel & neat FPBO at 300 bar P_{inj}

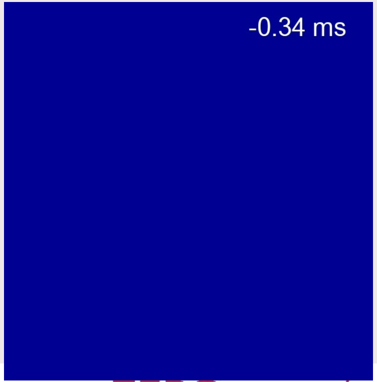
- Nozzle clogging
- Poor atomization
- Shorter burn duration

Diesel

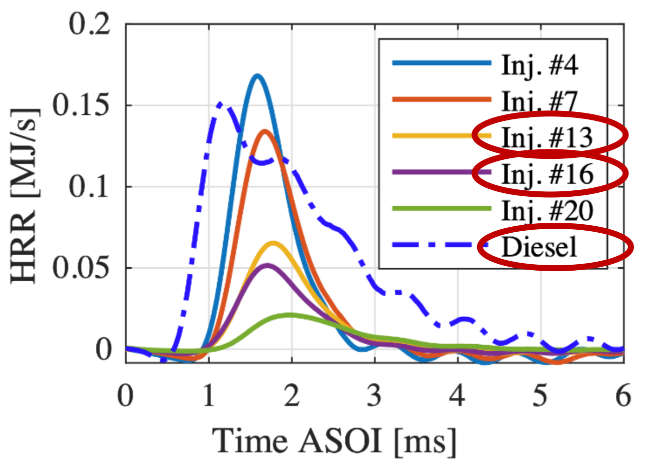


FPBO Inj. #13

FPBO Inj. #16



Heat release rate



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Wang, et al. "Spray combustion of fast-pyrolysis bio-oils under engine-like conditions." *Energy Conv. Management: X 20* (2023): 100433.

SmartCHP (Yu Wang)

Neat FPBO at 300-bar P_{inj}

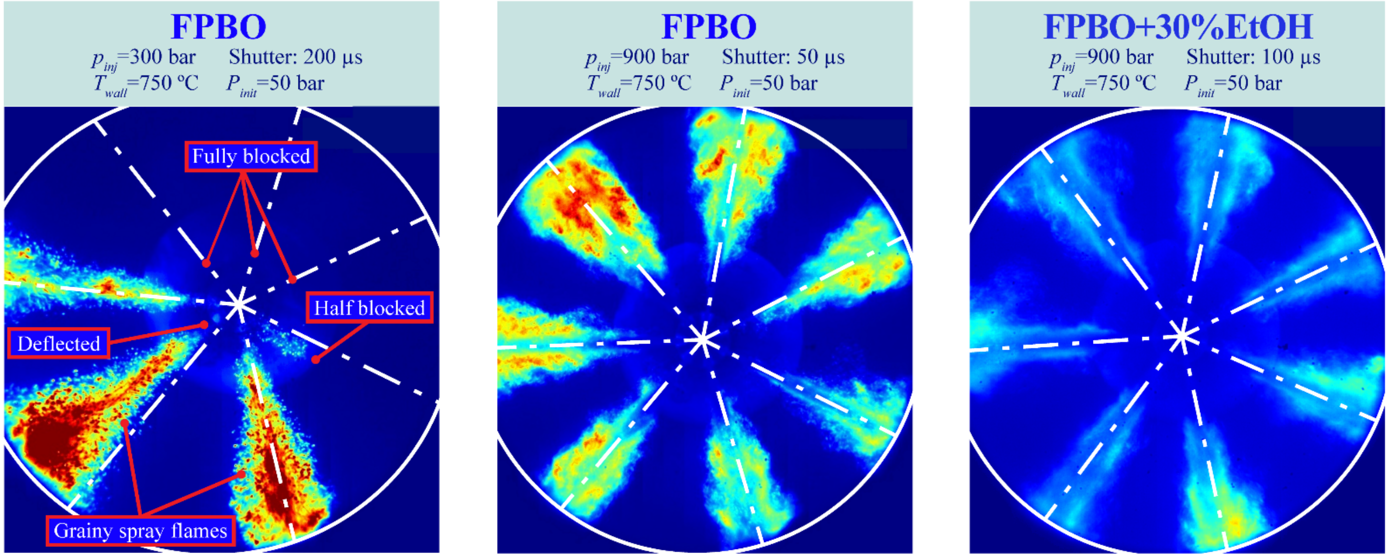
- Nozzle clogging
- Poor atomization
- Shorter burn duration

Neat FPBO at 900-bar P_{inj}

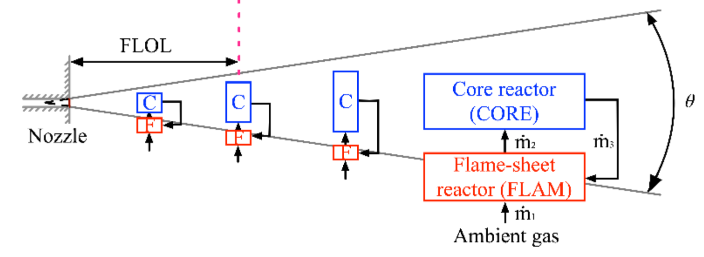
- Improved nozzle durability
- Improved atomization

FPBO with addition of 30% EOH

- Further improved atomization
- Reduced sooting tendency
- Slightly shortened ignition delay



SmartCHP (Yu Wang)



Two-stage Lagrangian model

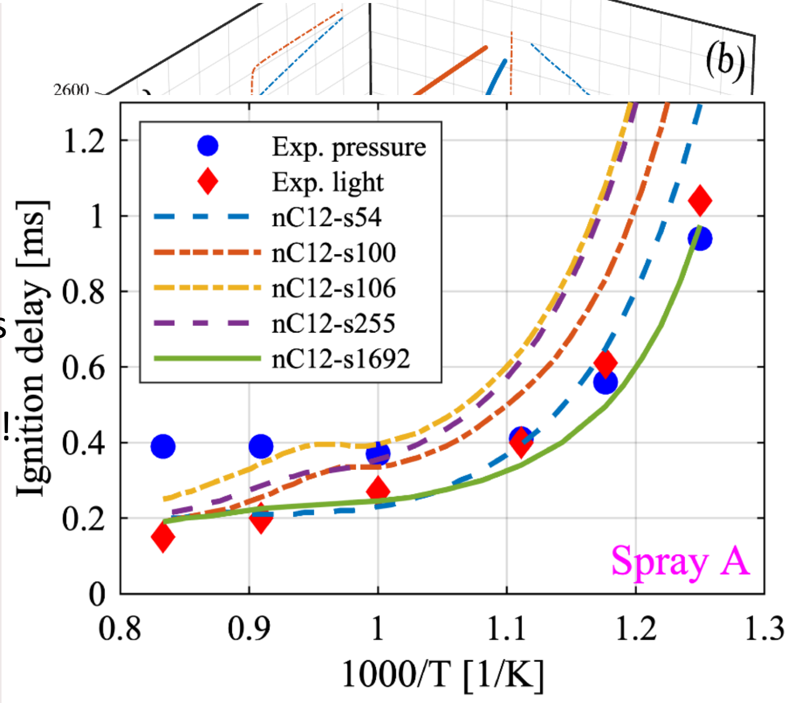
- Simulates mixing-limited spray combustion
  - Minimalistic flow model (1D entrainment model)
  - 2 perfectly stirred reactors with transport
  - Detailed chemistry

Multiple-step ignition process

- Transport between spray core and periphery regions
- Validated at Spray A conditions
- Powerful tool to investigate spray ignition processes!

Application to FPBO and blends

- High T_{amb} is required (>1000 K)
- Ethanol addition promotes the 2nd-stage ignition



Wang, et al. "Evaluation of fuel spray ignition delay behavior using a two-stage Lagrangian model." *Combustion and Flame* 265 (2024): 113449.

SmartCHP (Yu Wang)

Dedicated engine modifications

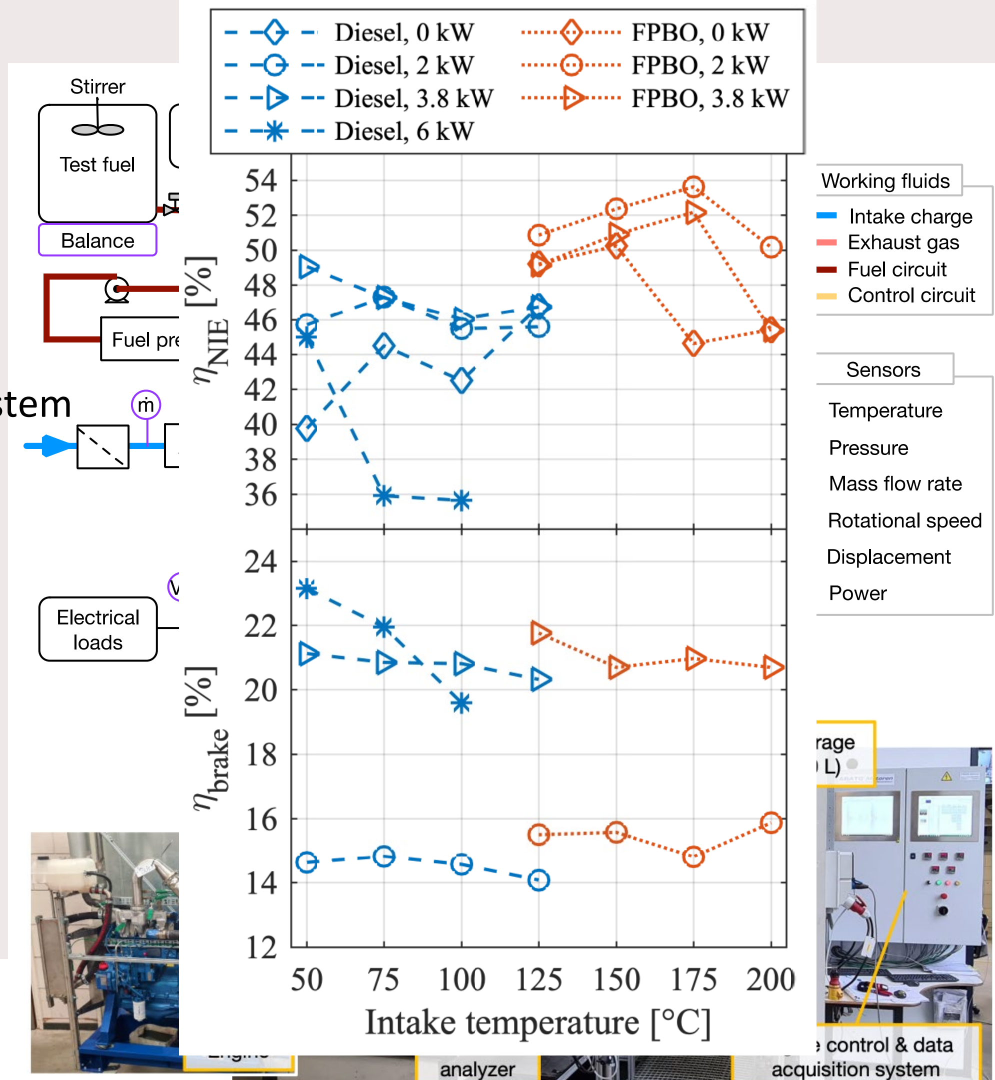
- Intake preheating & elevated CR
- Fuel switching & dual-circuit injection system
- Unattended engine operation system

500-hour durability test

- For the first time ever in the world

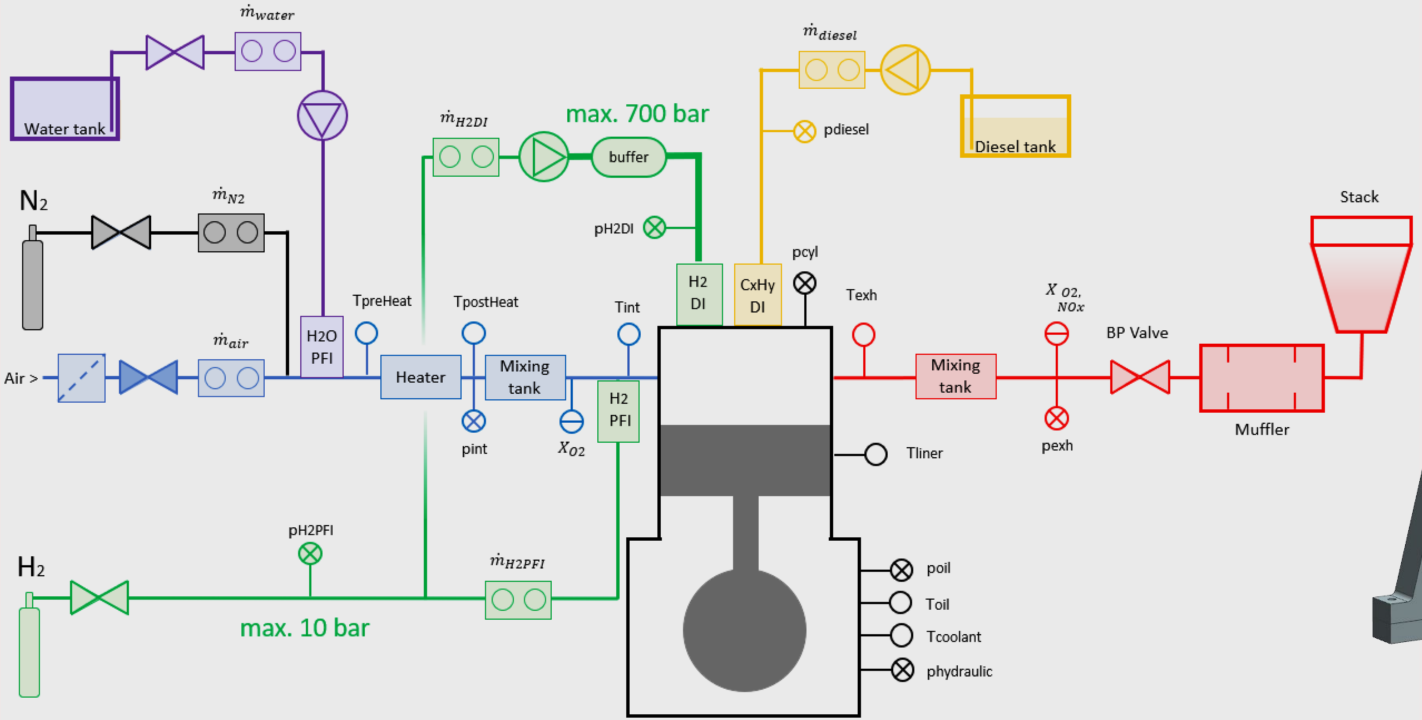
Efficiencies & emissions

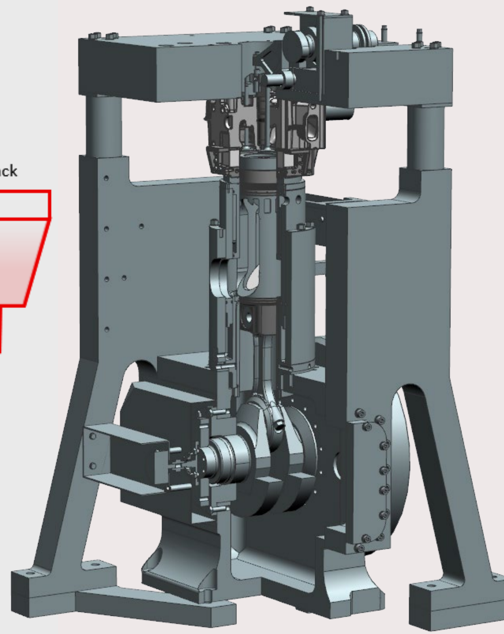
- Improved η_{NIE} due to faster burning rate
- Lower NO_x but higher CO than diesel



Wang, et al. "Application of fast pyrolysis bio-oil in a genset engine for combined heat and power generation.", *under review*.

ZEL project (Stan latten): rebuilding optical ICE H2.0





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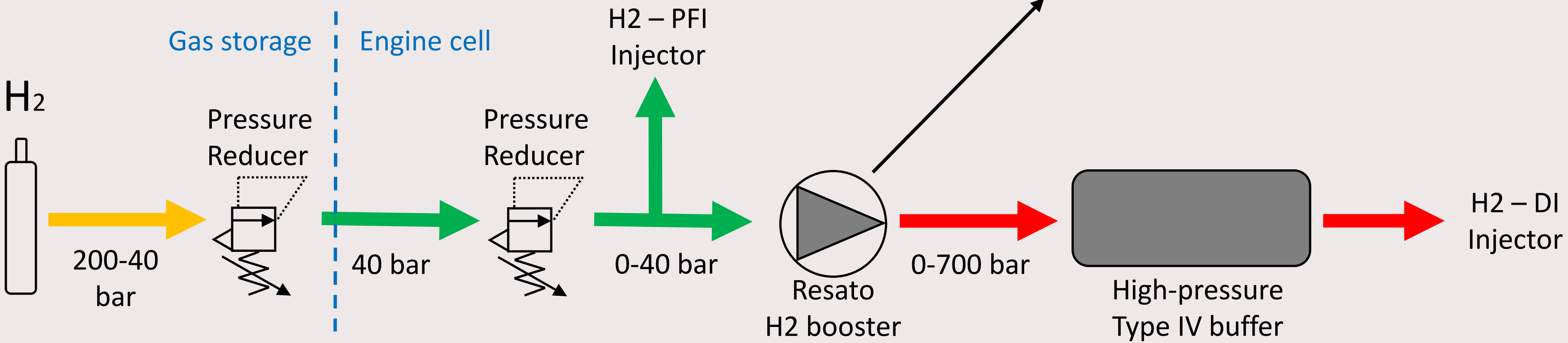
ZEL project (Stan latten): rebuilding optical ICE H2.0

- 200 bar H_2 pack, reduced to 40 bar before entering lab
- In engine cell further reduced to ~7 bar for PFI operation
- For DI: reducer set to 40 bar to feed H_2 booster
- Up to 700 bar achievable for H_2-DI applications
- **Just 3 bar H_2 inlet pressure required for booster → allows for emptying H_2 pack!**

Resato B-series booster datasheet



ZEL project (Stan latten): rebuilding optical ICE H2.0

Stepwise approach ↓

Input parameters:

- Injection mode (PFI/DI)
- Ignition mode (CI, SI, TJI)
- Boost pressure / temperature
- Load point (IMEP/RPM)
- Diesel/H_2 ratio
- EGR rate
- Etc.

Output parameters:

- Efficiency
- NO_x (and CO, CO_2, HC, PM) emissions
- Mixing / flame evolution

Phase	Strategy	Diesel fuel	H_2 fuel	Ignition method	Compression ratio
1	Diesel	Yes	No	Compression Ignition	High
2	Diesel-H2 DF	Yes	Yes, various quantities PFI	Compression Ignition	Low/High
3	H2 PFI SI	No	Yes, through PFI	Spark Ignition	Low
4	H2 LPDI SI	No	Yes, through early DI (partially premixed)	Spark Ignition	Medium
5	H2 HPDI SI	No	Yes, through late DI (diffusion flame)	Turbulent Jet / prechamber assisted spark-ignition	High

ZEL project (Stan latten): rebuilding optical ICE H2.0

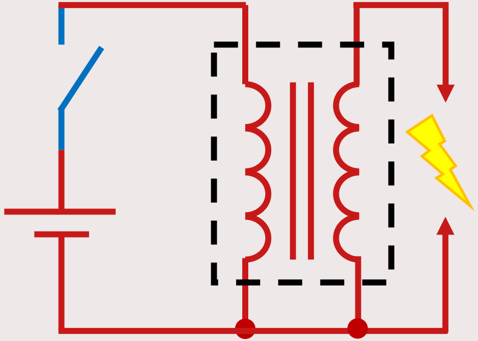
- H_2: lower minimum spark energy than gasoline
- In some ignition systems, residual energy may remain after spark
- Additional, low-energy spark during exhaust / intake stroke
- Spark breakdown voltage scales with pressure

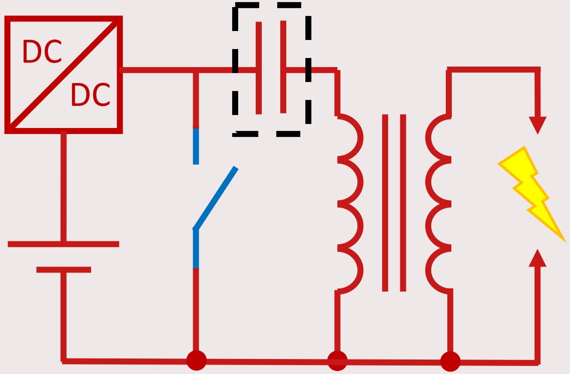
- Spark energy too low to ignite gasoline, but will ignite H_2!
- Ignition system without residual energy required!

ZEL project (Stan latten): rebuilding optical ICE H2.0

- Transistor Controlled Ignition (TCI)
  - Conventional method (contact-breakers)
  - Energy stored in coil (as magnetic field)
  - Charges while switch is closed, discharges upon opening
  - **Residual energy may remain after spark extinguishes!**

- Capacitor Discharge Ignition (CDI)
  - Supply voltage boosted to 400V
  - Energy stored in capacitor (as electric field)
  - Charges continuously, discharges upon closing switch
  - **No residual energy after switch opening!**





Both schematics are highly simplified!

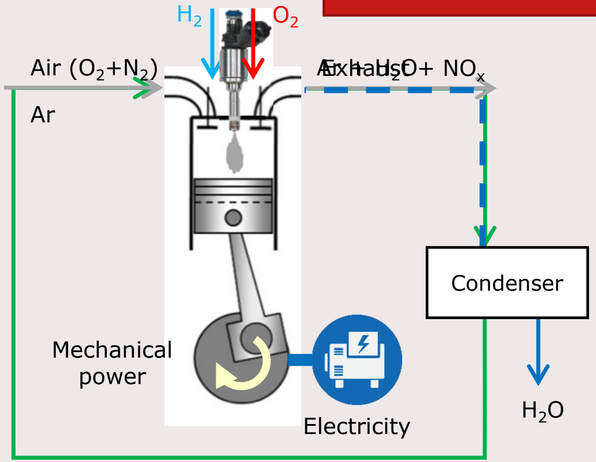
ZEL project (Stan latten): rebuilding optical ICE H2.0

- EGR control
  - Skip-firing makes conventional EGR impossible
  - Exhaust gases are diluted by intake air
  - Solution: simulated EGR by pre-mixing air, N_2, and H_2O using mass flow controllers

- EGR measurements
  - H_2 combustion → No CO_2 formation
  - Using O_2 concentration instead
  - Wideband O_2 sensors in intake + exhaust (verified by IAG/Horiba emission analyzer)

Argon Power Cycle (Max Peters)

“traditional situation”

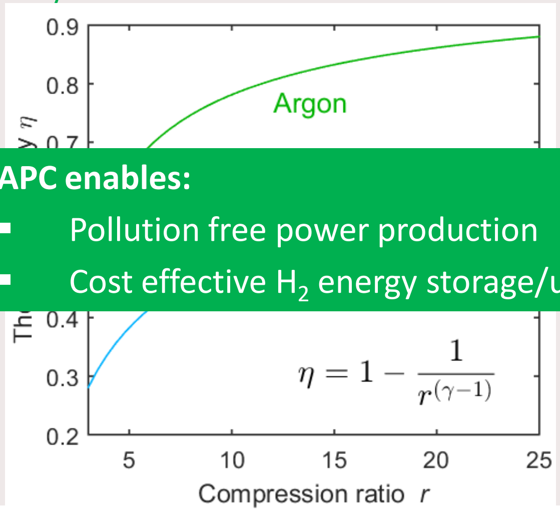


compression ignition (CI)

Fuel directly injected into pressurized chamber (DI)

Revolutionary power cycle

Use argon (Ar) instead of air (N_2)
Affordable, non-toxic gas
Recirculate in closed loop
Monoatomic: Theor. Efficiency 55% → 80%
Only water formed



APC enables:

- Pollution free power production
- Cost effective H_2 energy storage/utilization

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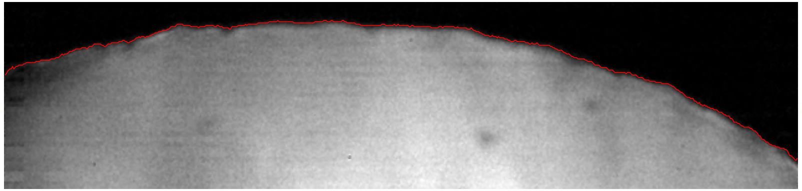
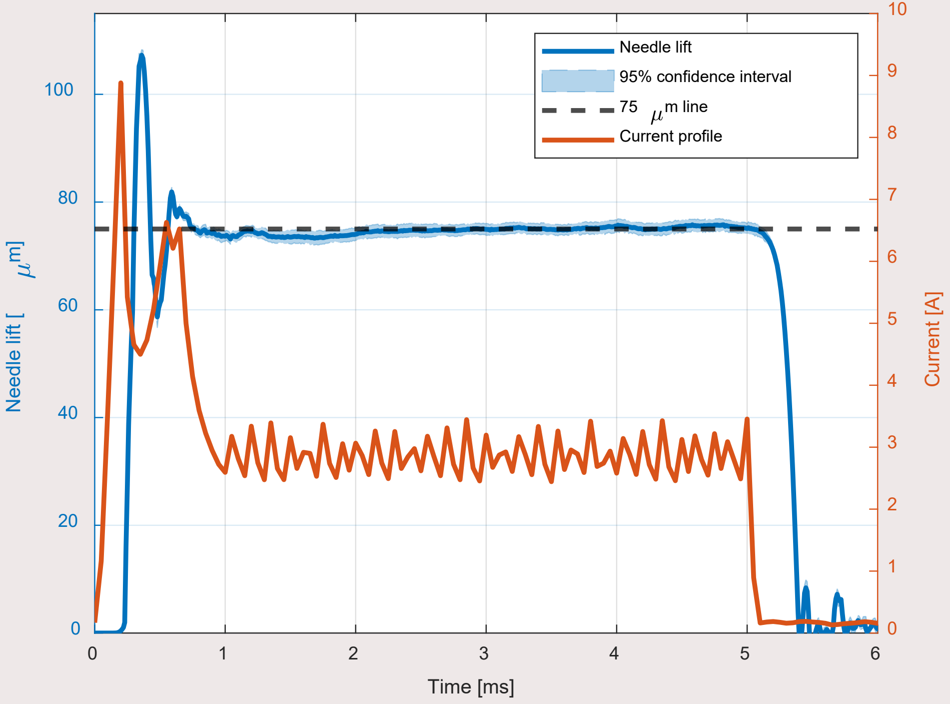
Needle lift measurement

Resolution: 0.87 µm/pixel
Frame rate: 100 kHz



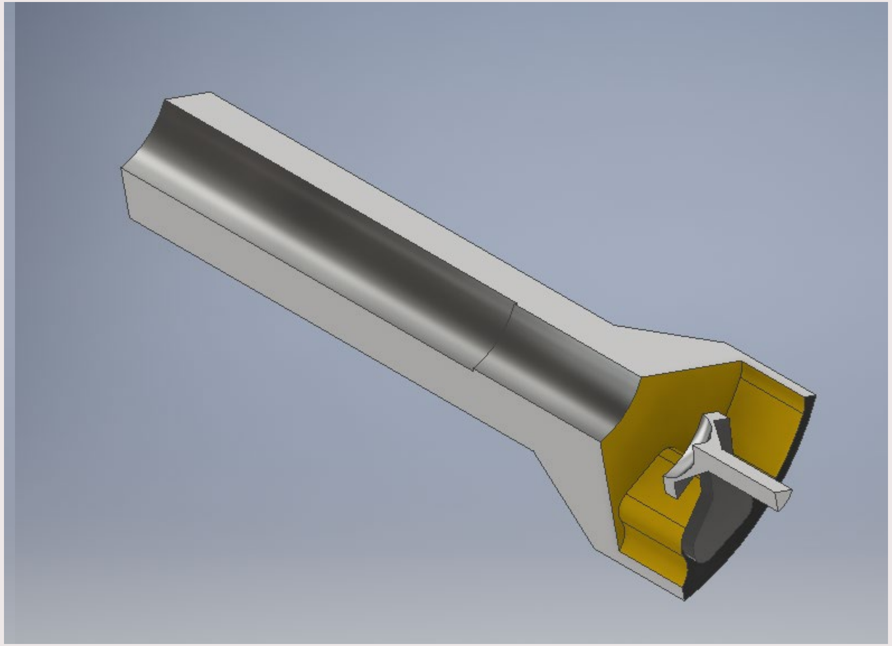
Additional measurement credits Vincent Fontijn

Final geometry



Conclusion:
Smallest flow area around needle due to small lift!

+ Experiments validated with Laser Doppler Vibrometer!



Additional measurement credits Vincent Fontijn

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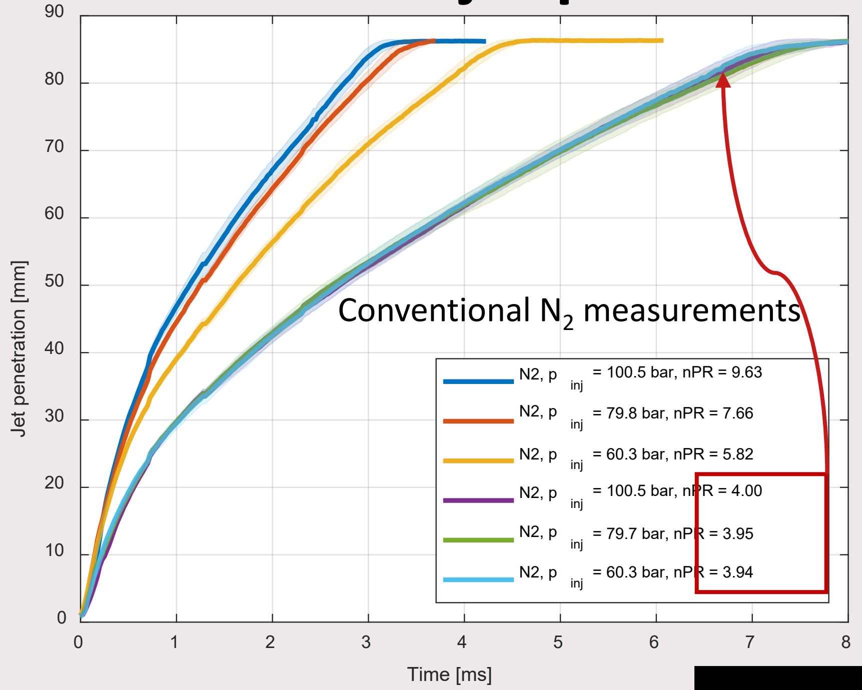
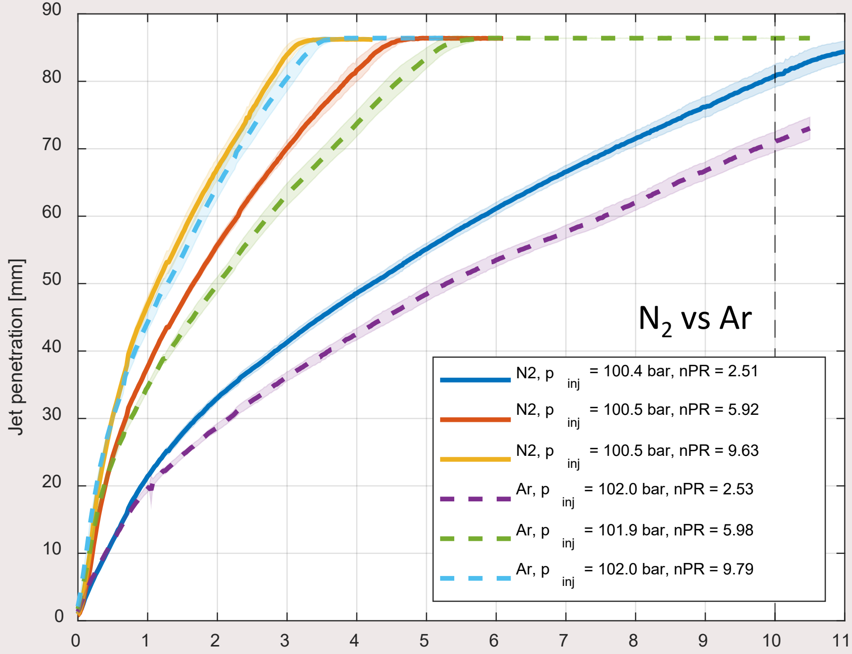
Schlieren: jet penetration

Line 'shadow': 95% confidence interval





Empirical jet penetration:

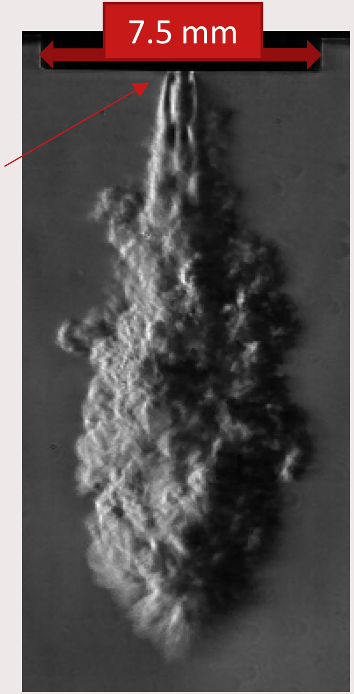
N_2: $x(t) = [16{,}37 \cdot nPR^{0{,}52}] \cdot t^{0{,}5} - 3{,}65$

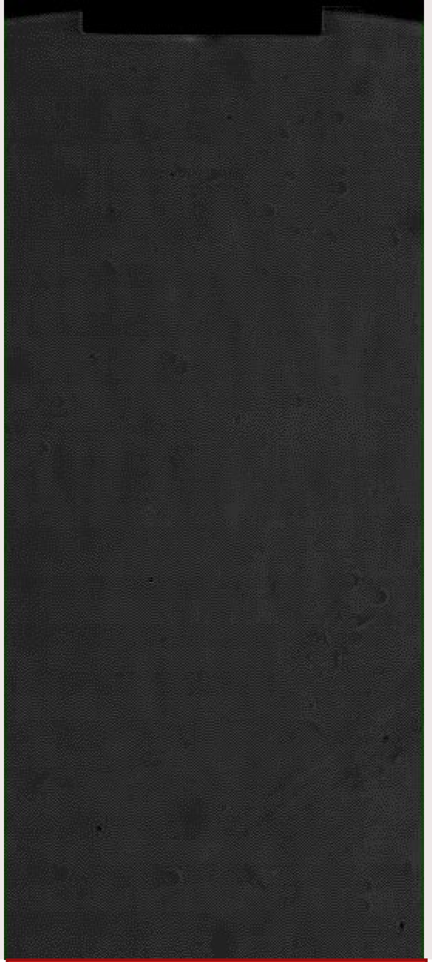
Argon: $x(t) = [13{,}31 \cdot nPR^{0{,}58}] \cdot t^{0{,}5} - 4{,}38$

Barrel shock & Mach disk

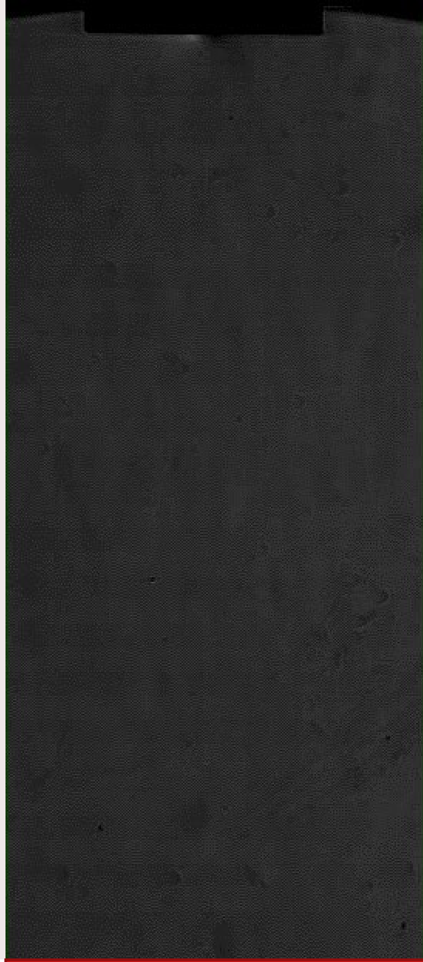
$d_e = 0.65\ mm$

Barrel shock are small!
(max. $\sim 5 \cdot d_e$)
At very high nPR





nPR = 50



nPR = 20

Rayleigh scattering

What do we need?

$\frac{\sigma_f}{\sigma_a}$ **(Rayleigh cross section for H_2 and ambient)**

$\frac{N_{a,0}}{N_{mix}}$ **(density field inside the jet)**

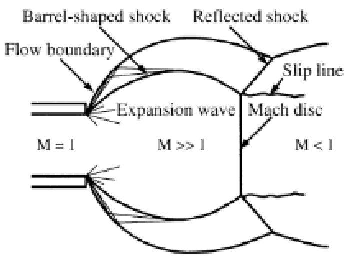
Tsujimura [2003] & Ewan and Moody [1986] for number density

$p_{MD} = p_a$

$T_{MD} = \sim T_0 = T_a$

Assumed: $\frac{N_{a,0}}{N_{mix}} = 1$

Outside of shock barrel (small)



	Nozzle exit	Barrel-shaped shock	Mach disc
Pressure	p^*	$p^* < p < p_a$	$p_{MD} = p_a$
Density	ρ^*	$<< \rho^*$	$\rho_{MD} = p_a/R_0T_{MD}$
Temperature	T^*	-	$T_{MD} = T_0$
Velocity	u^*	$>> u^*$	$u_{MD} = \sqrt{\kappa R_0 T_{MD}}$
Mach number	1	>> 1	1

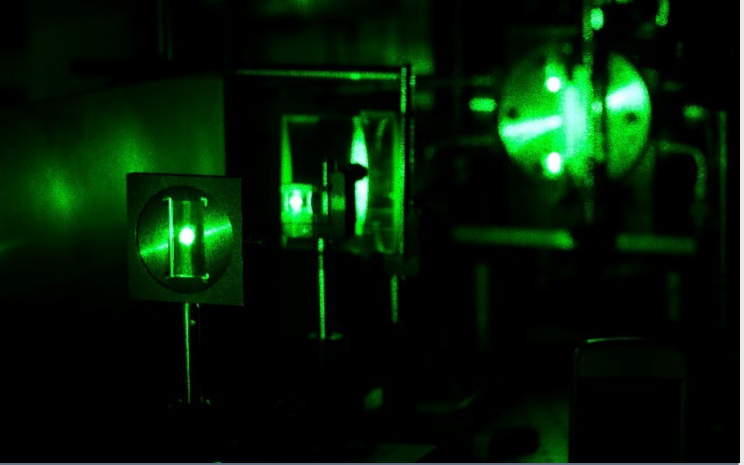
Figure 6. Schematic diagram of underexpanded jet behavior just downstream of nozzle exit [17].

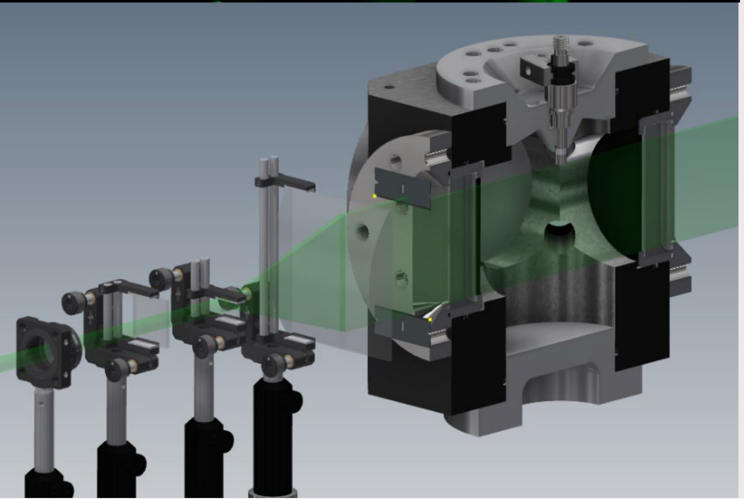
After MD purely dependent on Rayleigh cross sections:

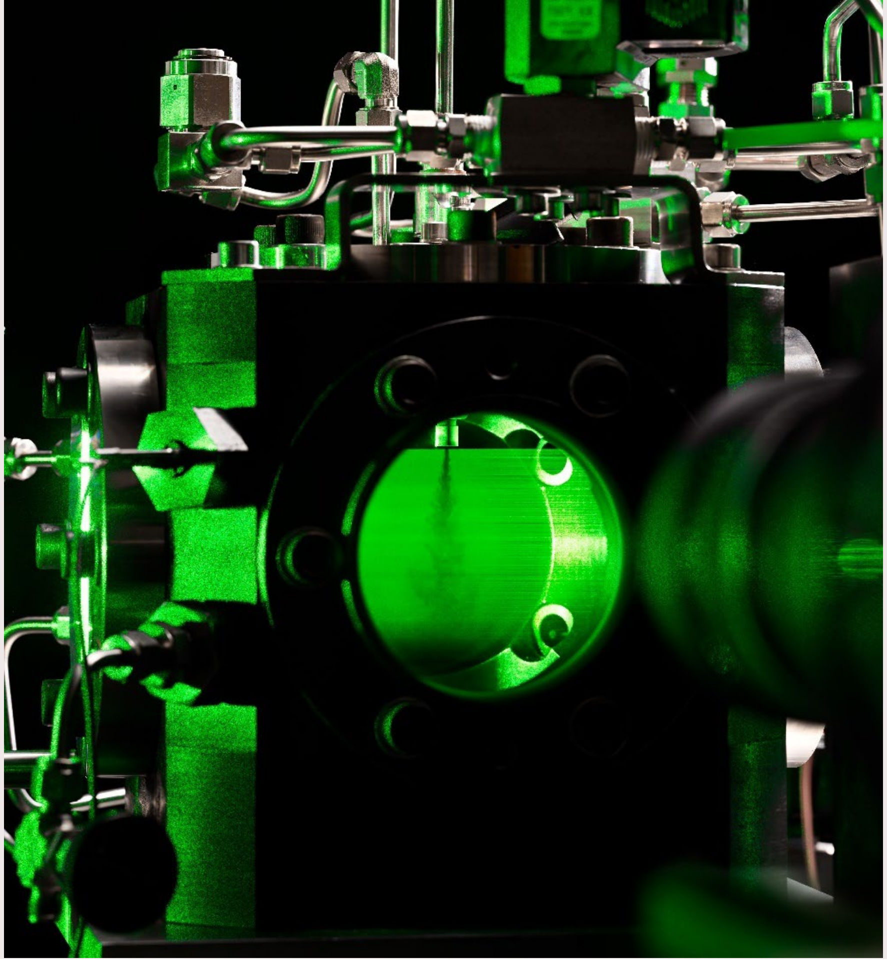
$$X_f = \frac{\left(\frac{I_{R,j}}{I_{R,a}} - 1\right)}{\left(\frac{\sigma_f}{\sigma_a} - 1\right)}$$

Rayleigh cross section σ_i $[10^{-27} cm^2]$ at 532 nm.			
N_2	Ar	H_2	$n - heptane$
5.23	4.56	1.13	309.8

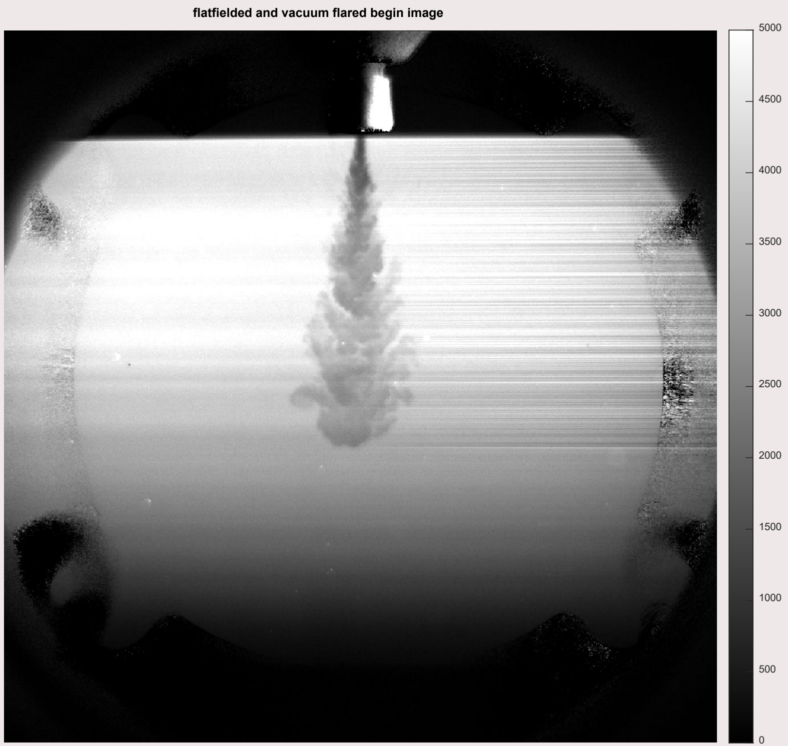
Reduced signal in the H_2 jet vs. ambient!

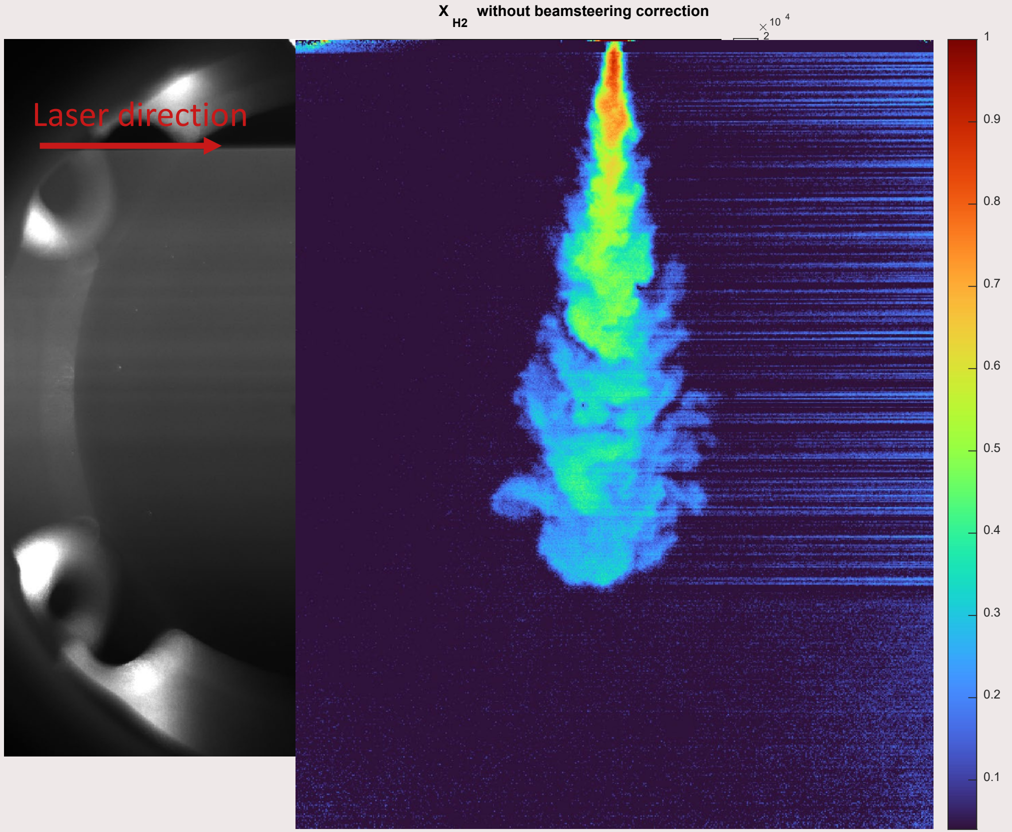






Pixis, 50-mm f/1.2, 3-nm filter @532, & 0.5-μm particle filters



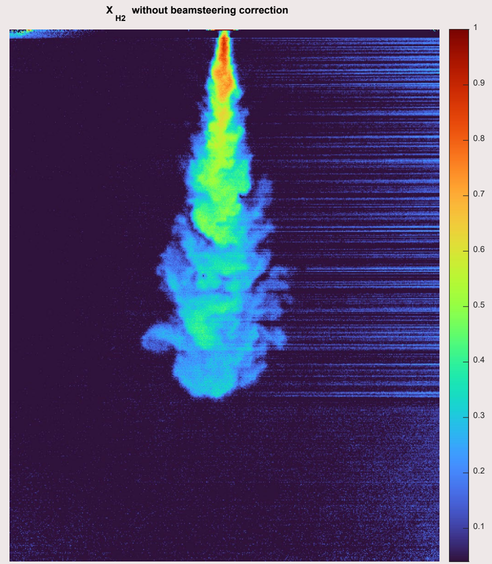


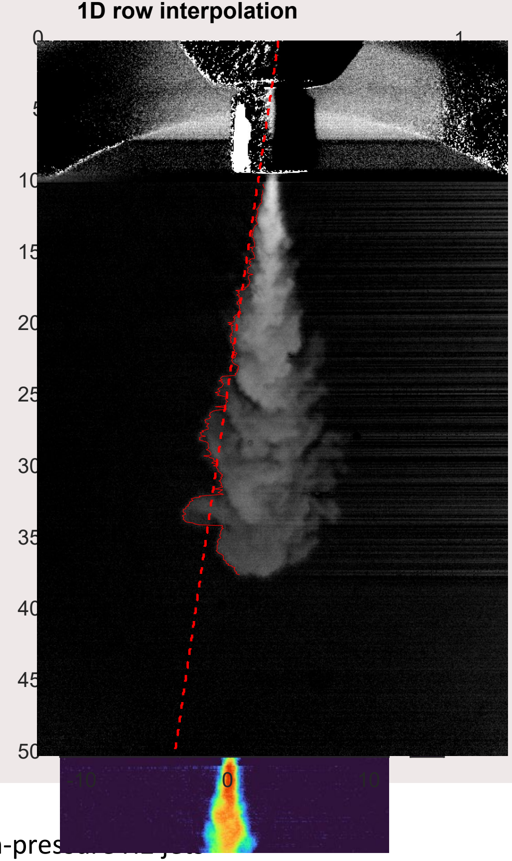
Result: Image - ‘Vacuum’ image @ 0,03 bar (for flare correction)

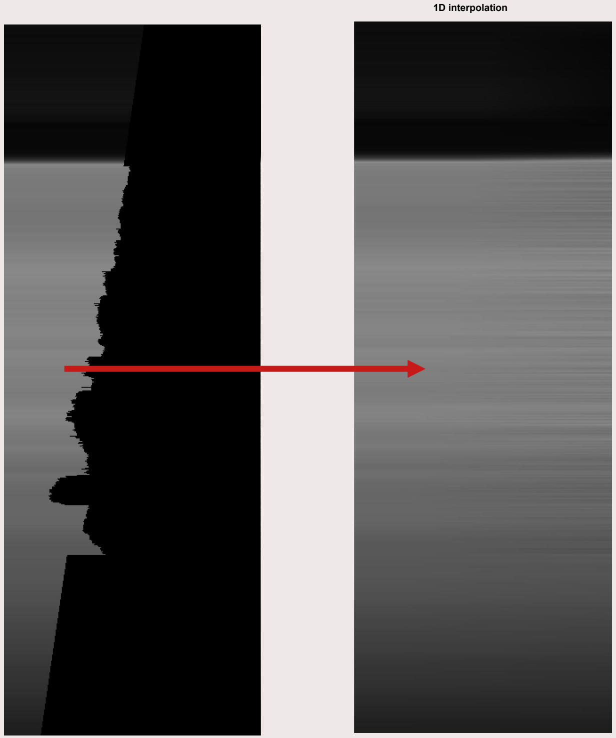
100 bar H_2 in 10 bar N_2

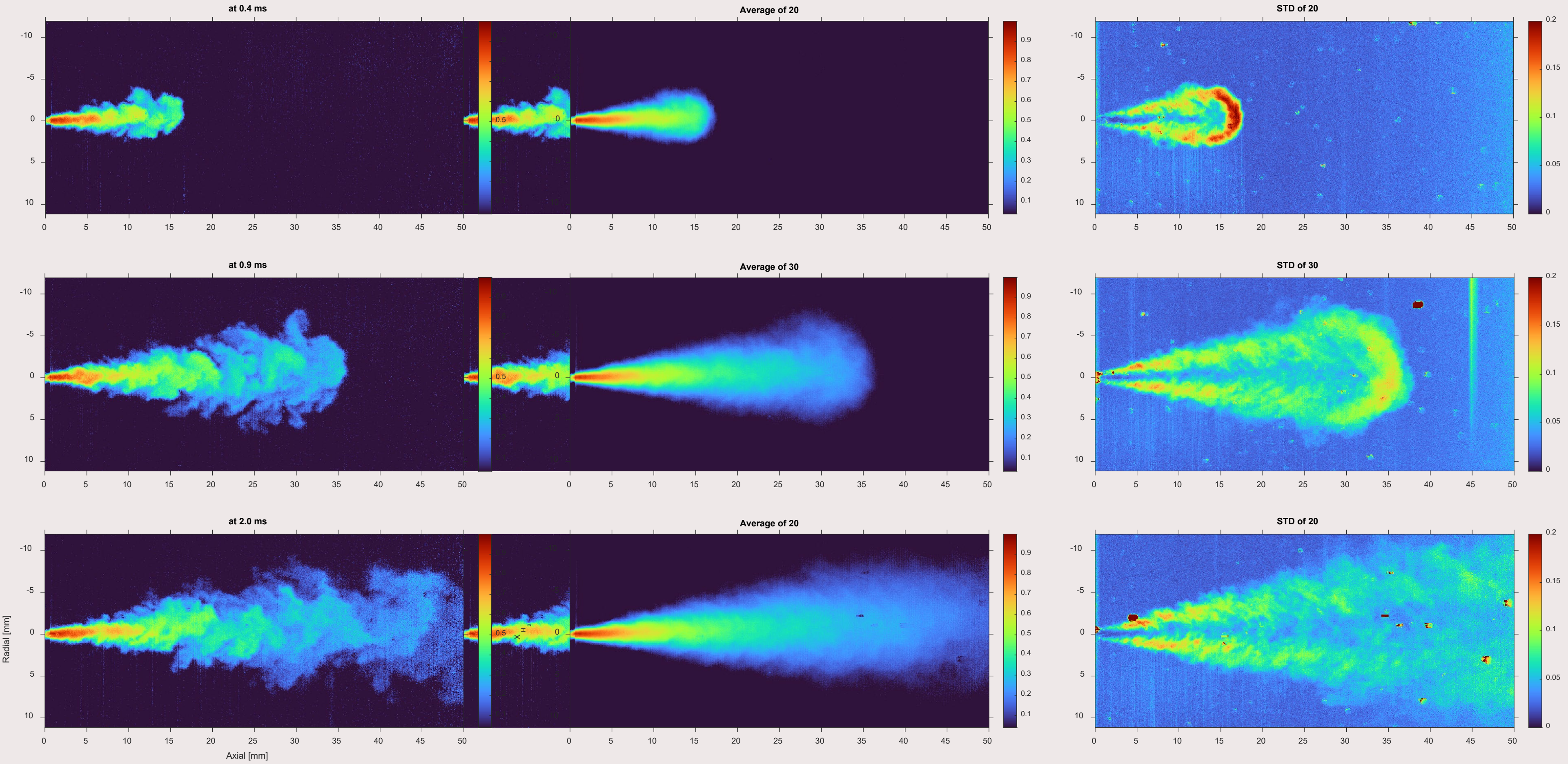
TU/e

Beam steering improvements








at 0.4 ms
Average of 20
STD of 20
at 0.9 ms
Average of 30
STD of 30
at 2.0 ms
Average of 20
STD of 20
Radial [mm]
Axial [mm]

Argon Power Cycle

Schlieren OH* Chemiluminescence

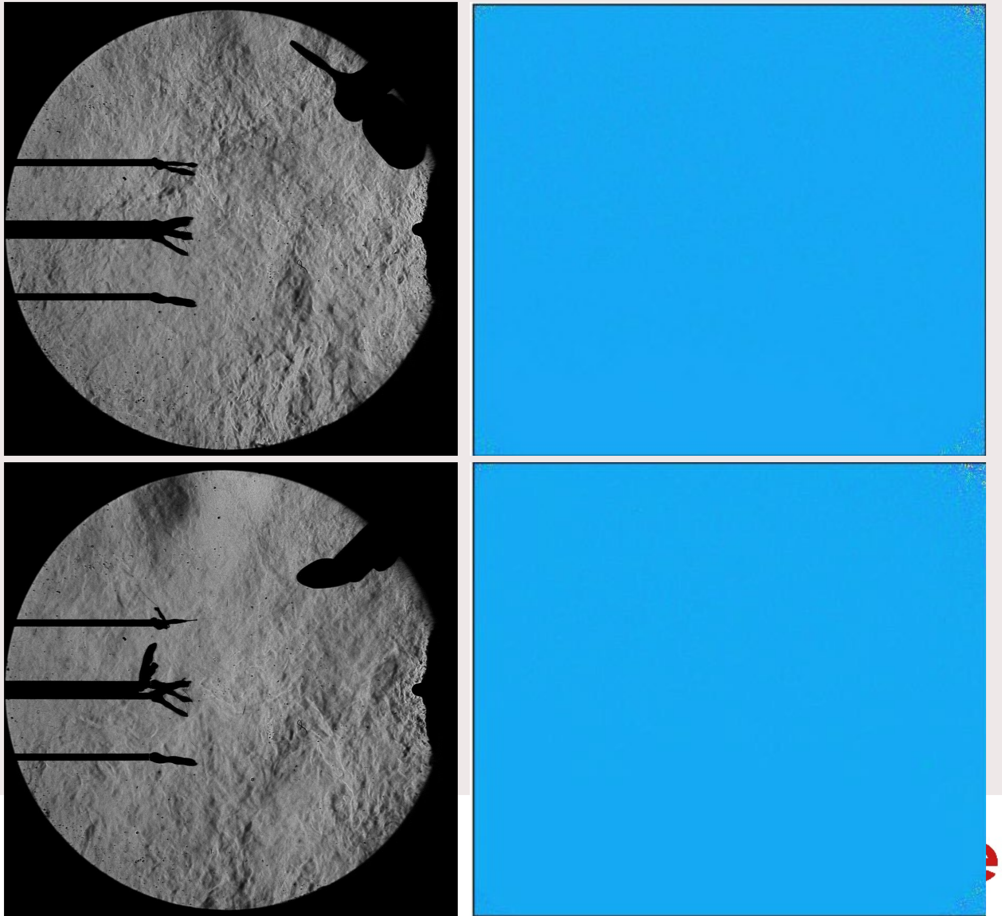
Next: combustion!

Tcore ≠ Tbulk

High-speed 50-µm bare-wire TC measurements for core T

N_2

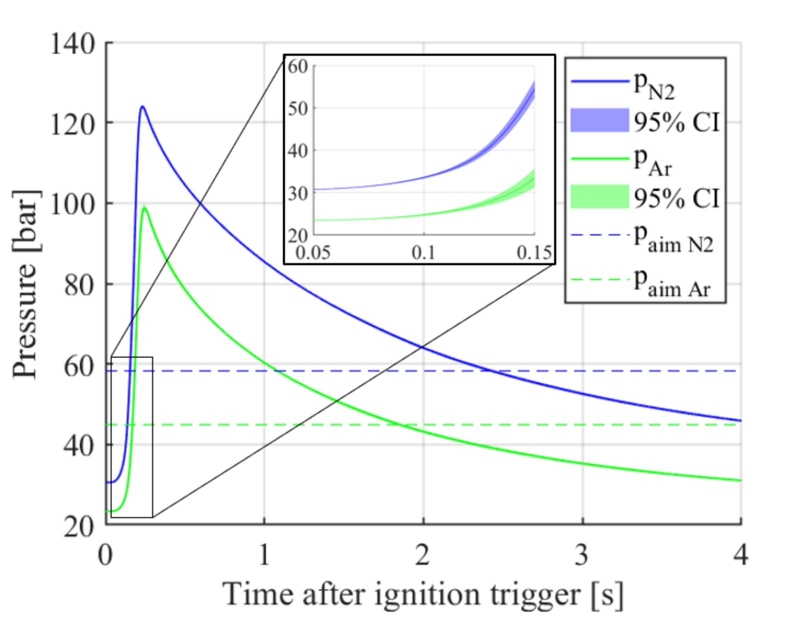
Ar

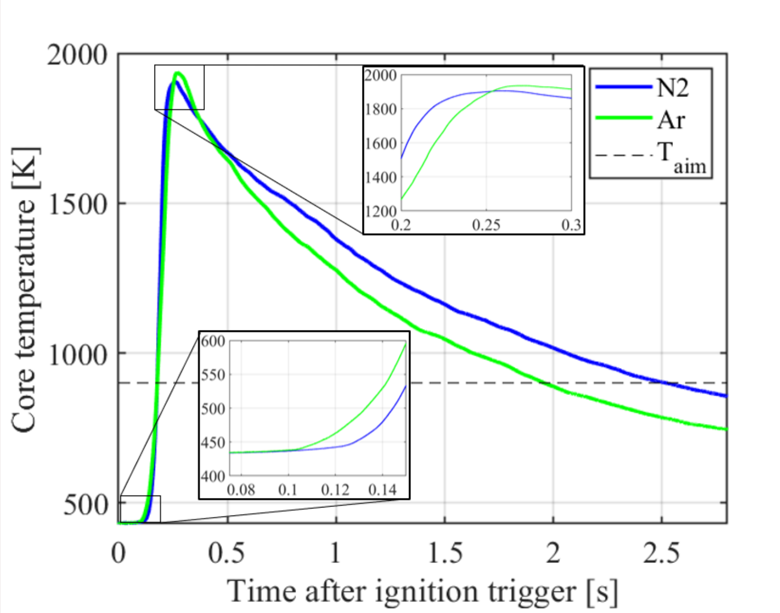


Additional measurement credits Steef Licher

Argon Power Cycle

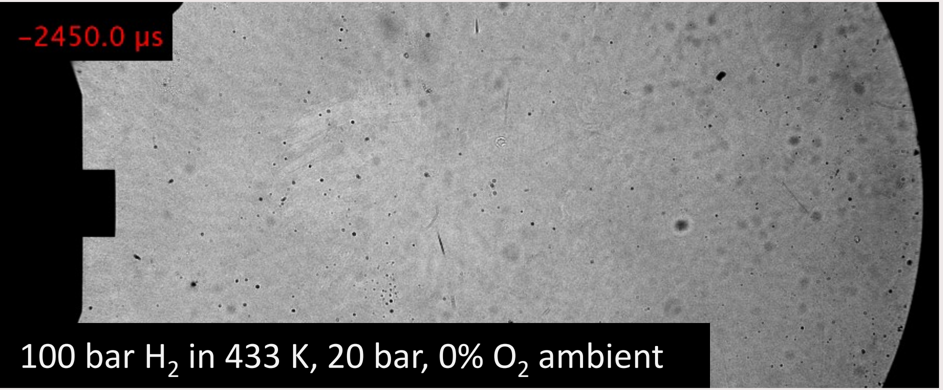
Target: 22.8 kg/m^3 & 900 K @ inj., peak 2000 K → 50% of the C_2H_2 in Ar!

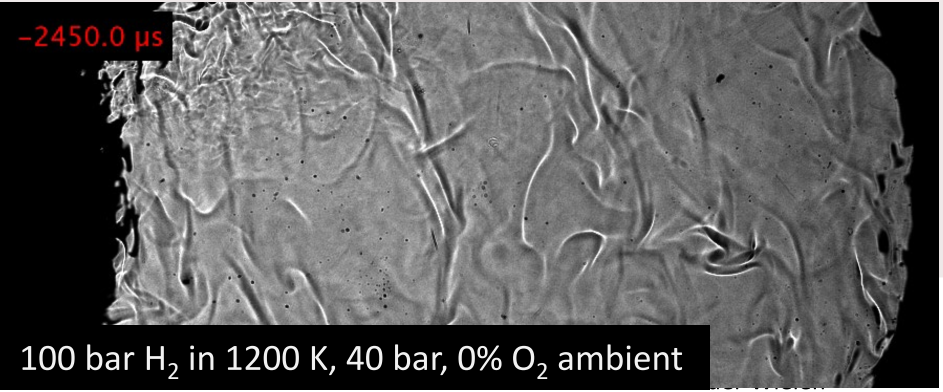


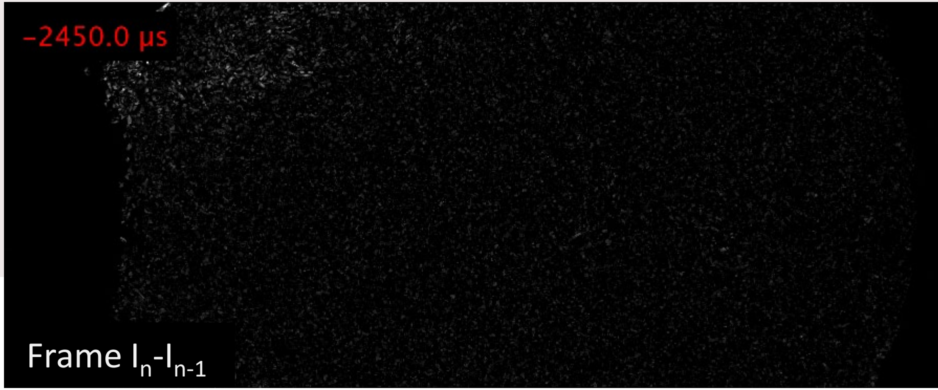


Additional measurement credits Steef Licher

Argon Power Cycle – non-reacting, high temperature

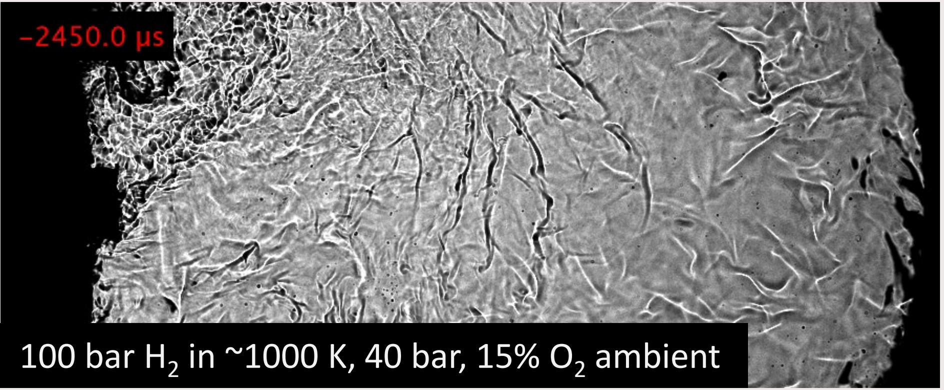


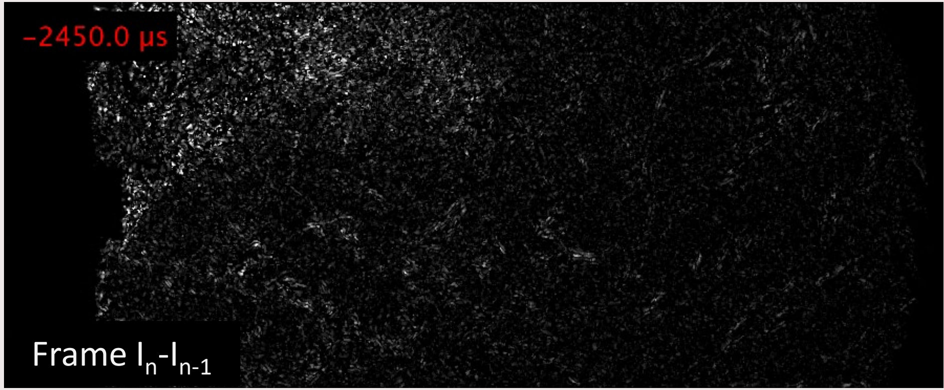


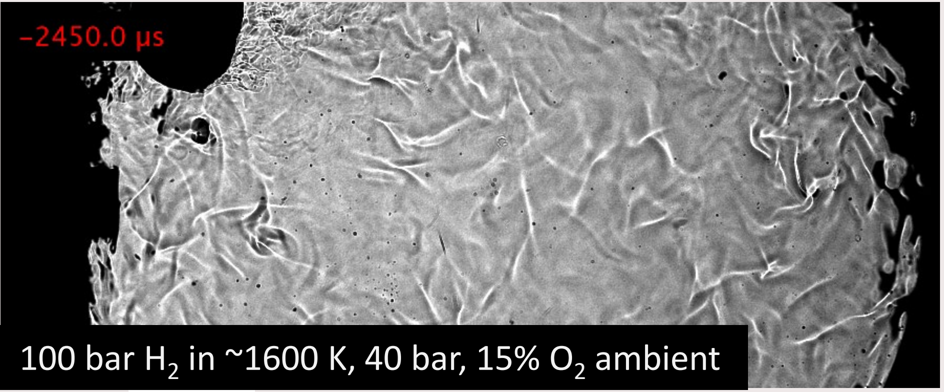


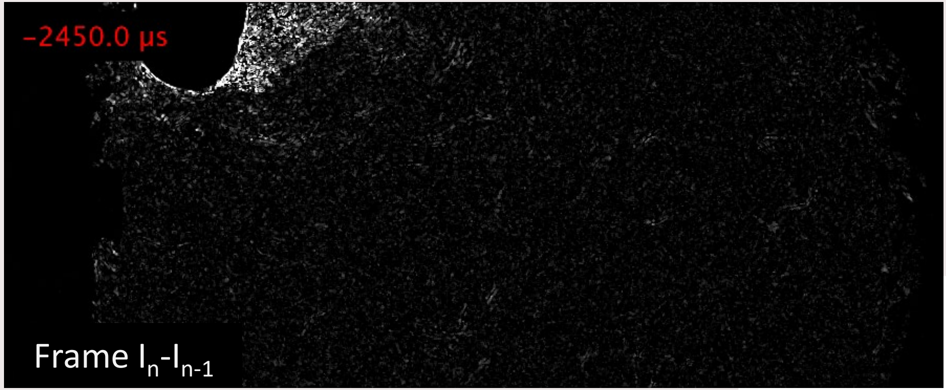
Additional measurement credits Giliam van der Wielen

Argon Power Cycle – reacting conditions



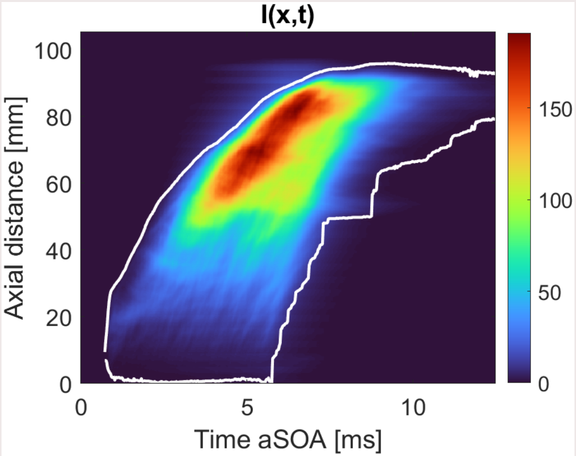


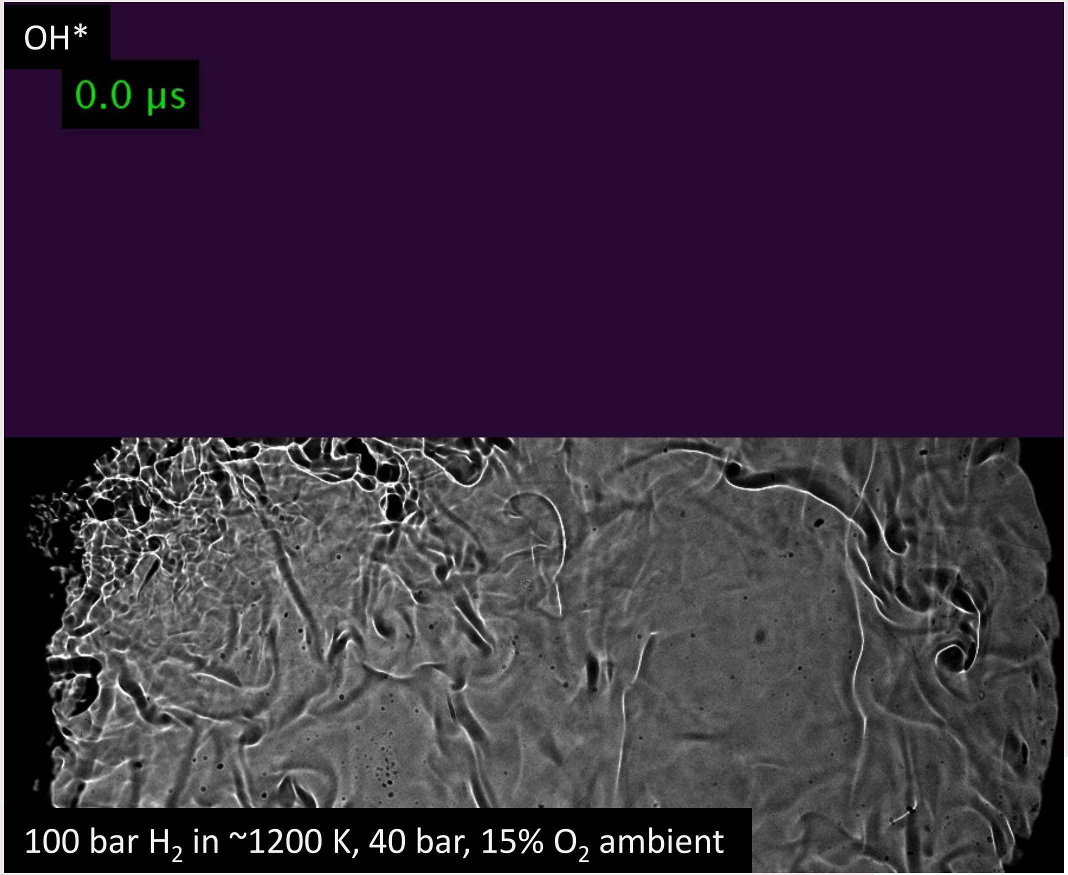




Argon Power Cycle – reacting conditions

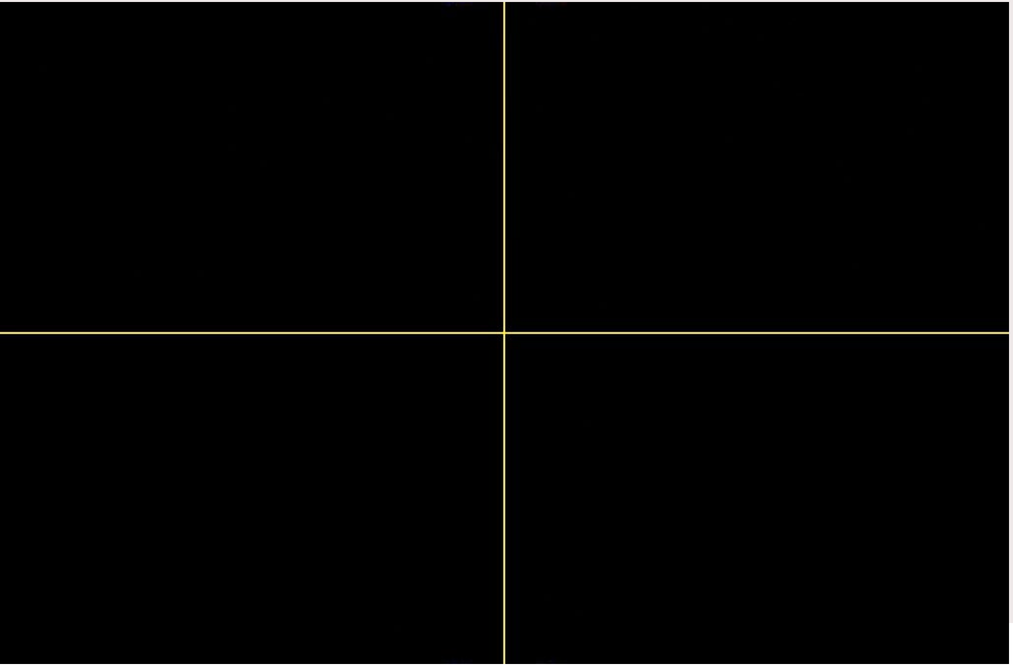
OH* top view
Schlieren side view

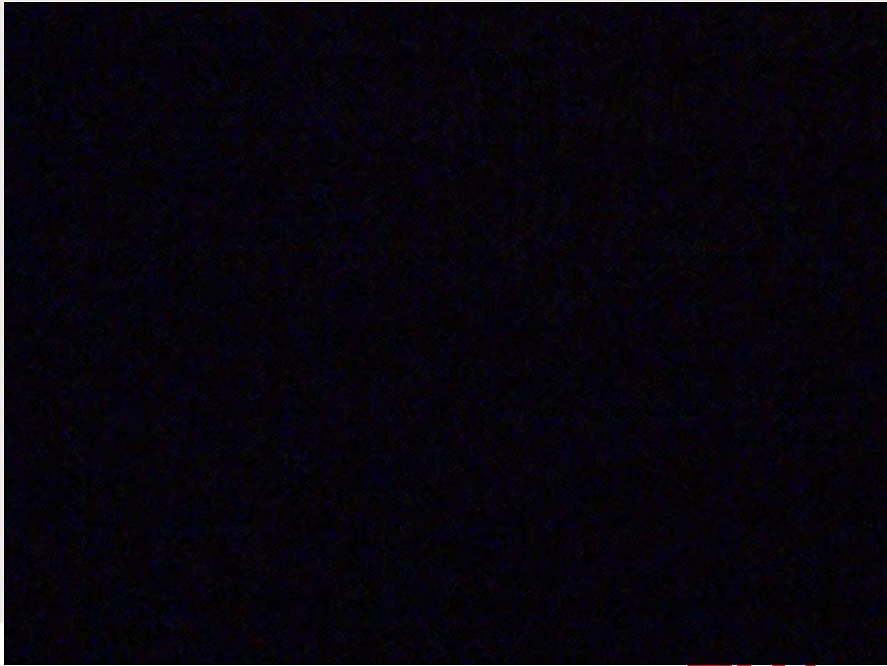




Argon Power Cycle

Some true-color recordings

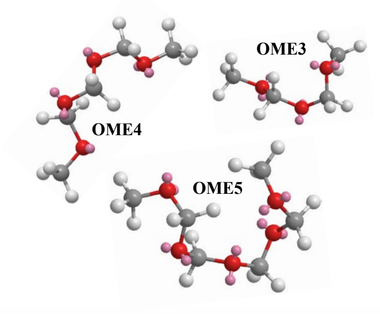




Additional measurement credits Giliam van der Wielen

Renewable "drop-in" fuel research by Zhongcheng Sun (GTL → GTLB30 → OME_n)

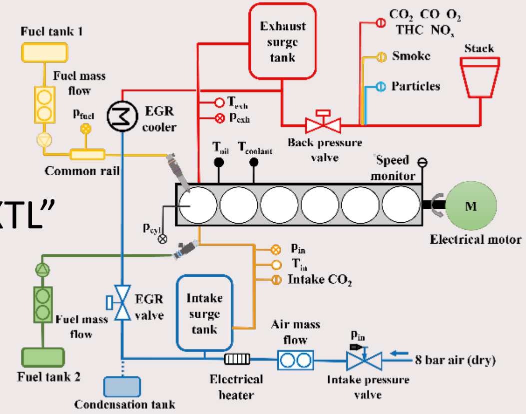
- From short- to long-term solutions
- Gas to liquid (GTL)
- GTL blends with 30 vol% FAME (GTLB30)
- Oxymethylene dimethyl ether (OME_n)



Zhongcheng Sun

Background

- GTL: EN 15940 compliant, higher CN, negligible sulfur & aromatics
  - Note: similar properties as HVO/HEFA → can be regarded as "XTL"
- OME_n: no C-C bonds, high oxygen content, & high CN



	Density [kg/m³]	CN [-]	LHV [MJ/kg]	Viscosity [mm²/s]	Flash Point [°C]	Freezing point [°C]	Oxygen mass% [-]	$(A/F)_{st}$ ratio [-]
OME_x*	1067.1	82.2	19.4	1.18	64.5	-20.5	48.01	5.84
GTL	777.1	74	44	2.58	72	-19	0	14.98
GTLB30	808.3	65.8	42	2.97	66	-23	3.2	14.24
Diesel	836.1	52.2	43	2.76	66	-24	0.60	14.46

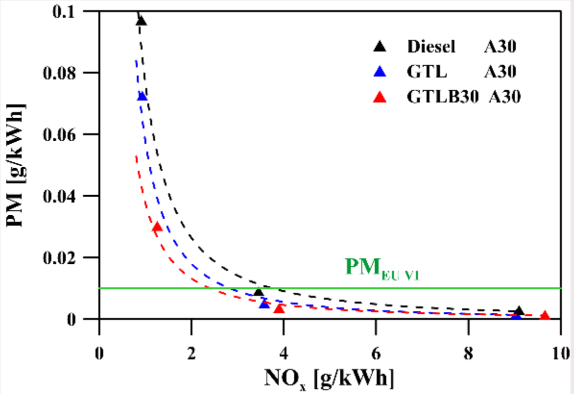
* OME_x (47.65% OME_3, 29.7% OME_4, 16.98% OME_5, 5.67% OME_6)

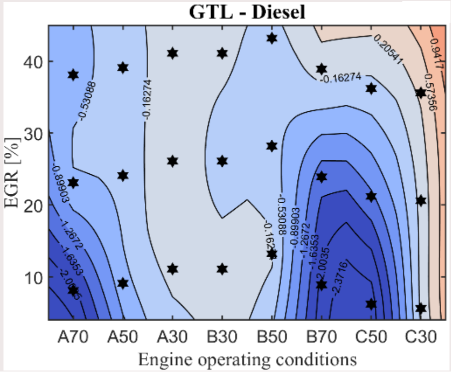
MX13 specification

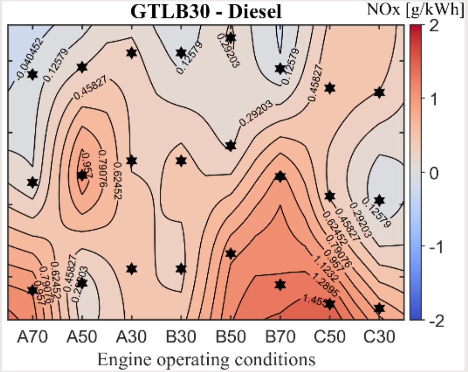
MX 13	Parameter
Number of cylinder	1
Displaced volume	2.15 L (single)
Bore	130 mm
Stroke	162 mm
Compression ratio	17.2
Piston bowl shape	Double step
Cylinder head	Low swirl

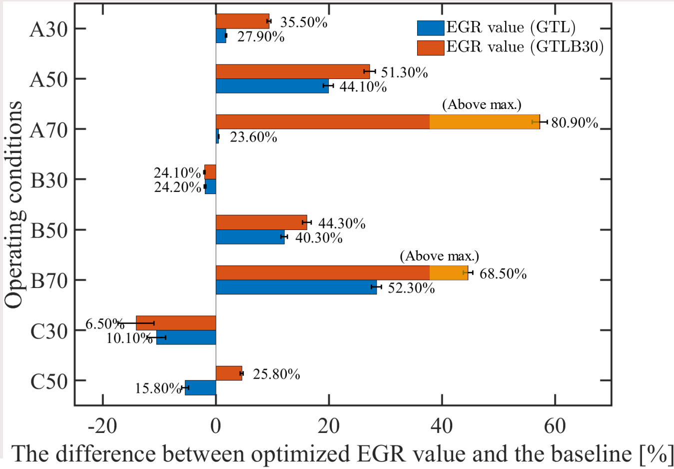
GTL & GTLB30 engine research

- Both GTL & GTLB30 illustrate potential in improving the PM-NO_x trade-off
- NO_x emissions impact on weighted average across the engine map:
  - GTL ↓ 16.1% & GTLB30 ↑8.3%
- Potential EGR optimization strategy for minimizing NO_x while adhering to Euro VI PM limits for both GTL & GTLB30
- Drop-in optimization means different EGR calibration!





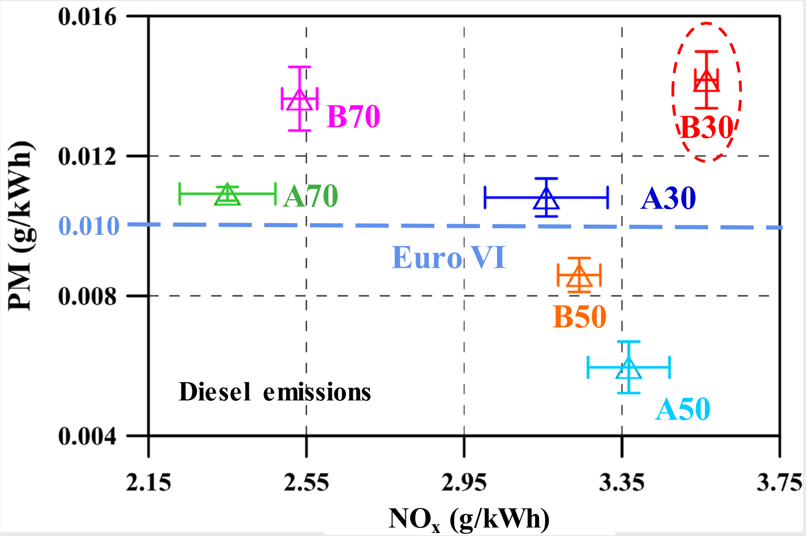


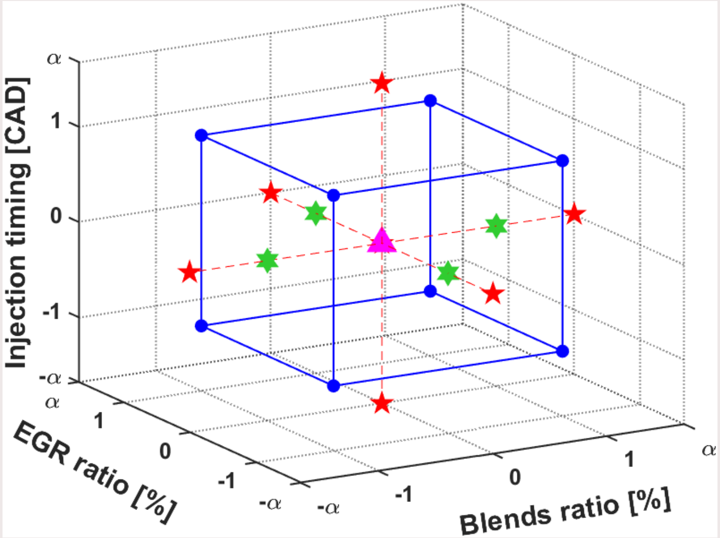


Additional measurement credits Shriram Jagannathan

OME_x optimized research on heavy-duty engine

- OME = expensive, how much do you need? If you have *x* amount, fuel one or fuel many?
- Case selection: commercial B7 diesel worst emissions @ B30 (1425 RPM, 30% load)
- Design of Experiments (DOE) approach to provide a comprehensive global emissions map [1]





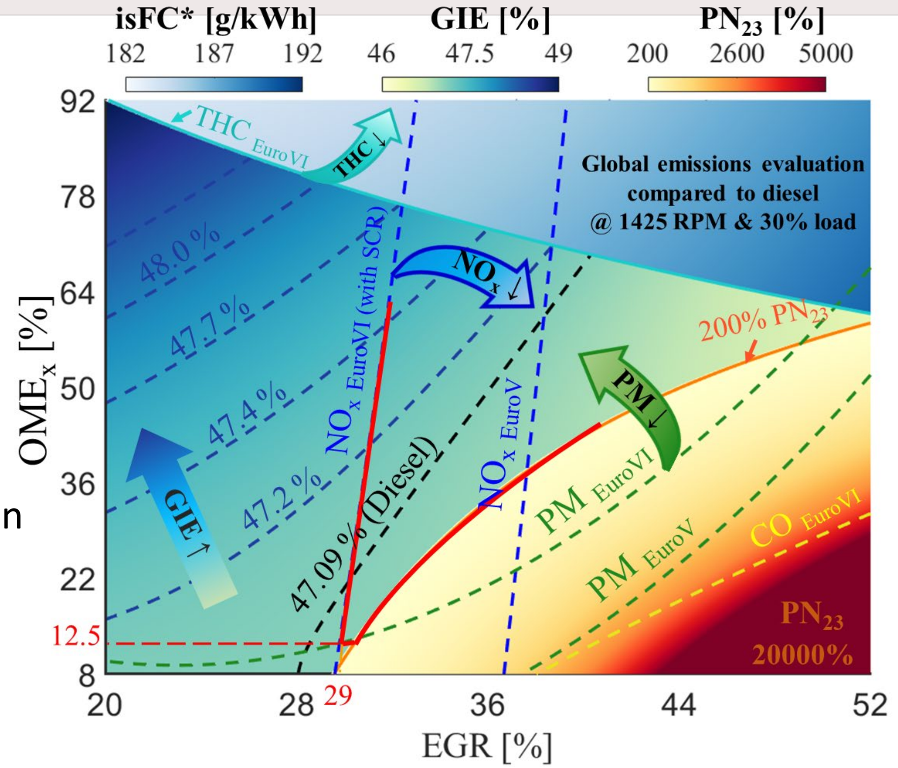
[1] Andersson Oivind. John Wiley & Sons, 2012.

Additional measurement credits Harold van Beers

Comprehensive emissions map @B30

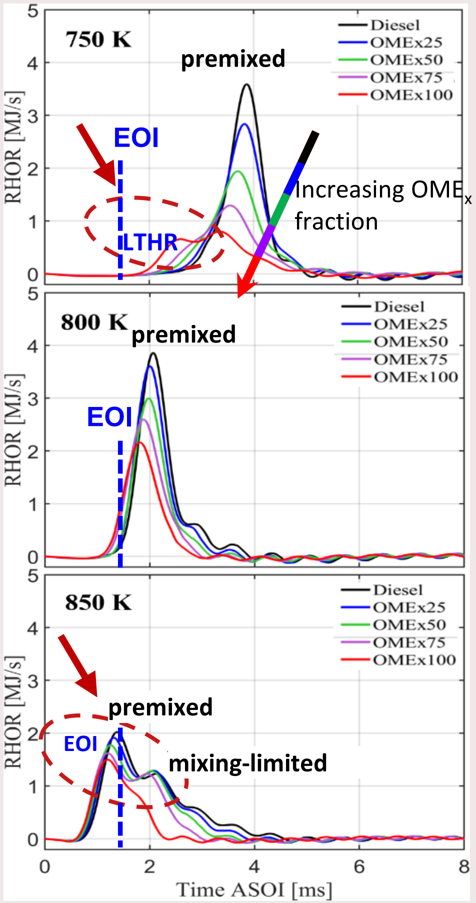
- Soot emissions ∝ to OME_x% in blends
- OME_x: slightly negative effect on NO_x emissions
  - Significantly mitigated with increasing EGR!
- CO effectively reduced with OME_x addition

- MX13 @ B30: EUV NO_x & EUVI PM compliant when
  - OME_x >40%
  - EGR >37.2%
- MX13 @ B30: EUVI with SCR & DOC compliant when
  - **<u>OME_x >12.5%</u>**
  - EGR >29%



OME_x ignition research on CRU (15 O_2%)

- @ 750 K, two noticeable ROHR peaks (LTHR & HTHR) of pure OME_x leads to a longer burn duration [2]
- 800 K as a transition point for blends (different combustion regime)
  - ROHR peak first increases with T, and then reduces (∝ BD)
- @ 850 K, now OME has the shortest burn duration



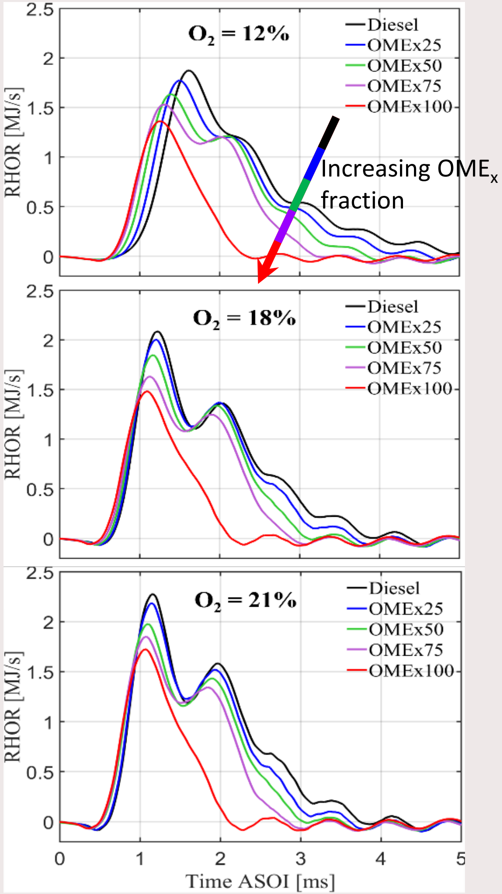
(P_{inj} = 150 MPa, O_2 =15%)

[2] Bunting, B.G., Wildman, C.B. International Journal of Engine Research, 2007.

Additional measurement credits Robert Coolen

OME_x ignition research on CRU (O_2% impact)

- At lower O_2% (high EGR to simultaneously reduce NO_x)
  - Modest impact on OME_x ID & burn duration (high fuel-oxygen content)



(P_{inj} = 150 MPa, Tc =850 K)

Additional measurement credits Robert Coolen

TU/e

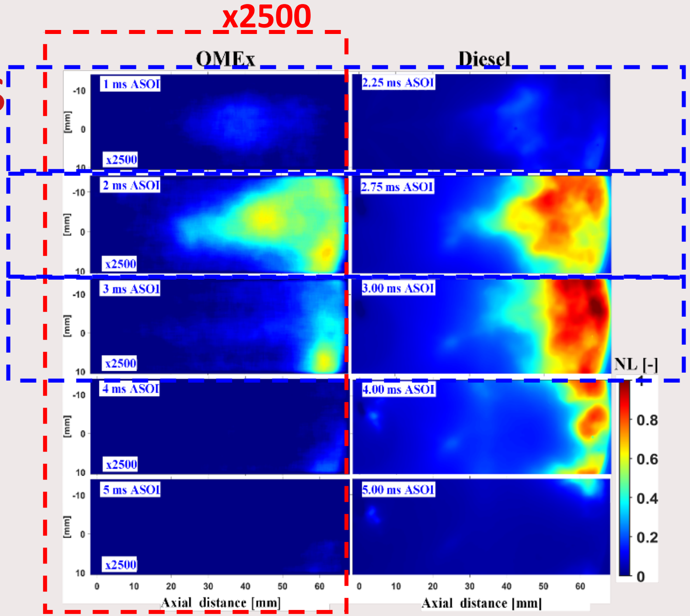
OME_x natural luminosity characteristics

Optical diagnostics: natural luminosity (NL) imaging

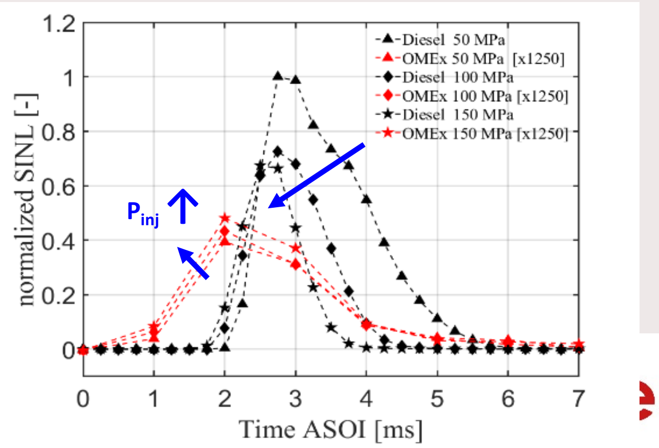
- NL signal of OME_x occurs earlier (1 ms < 2.25 ms)
- NL intensity of OME_x much lower

(chemiluminescence vs soot radiation)

- Diesel NL peak ~ combustion recession timing of OME_x



- Spatially integrated NL peak of OME_x occurs before diesel
- With increasing P_{inj}
  - OME SINL increases (more fuel)
  - Diesel SINL decreases (less soot, net)



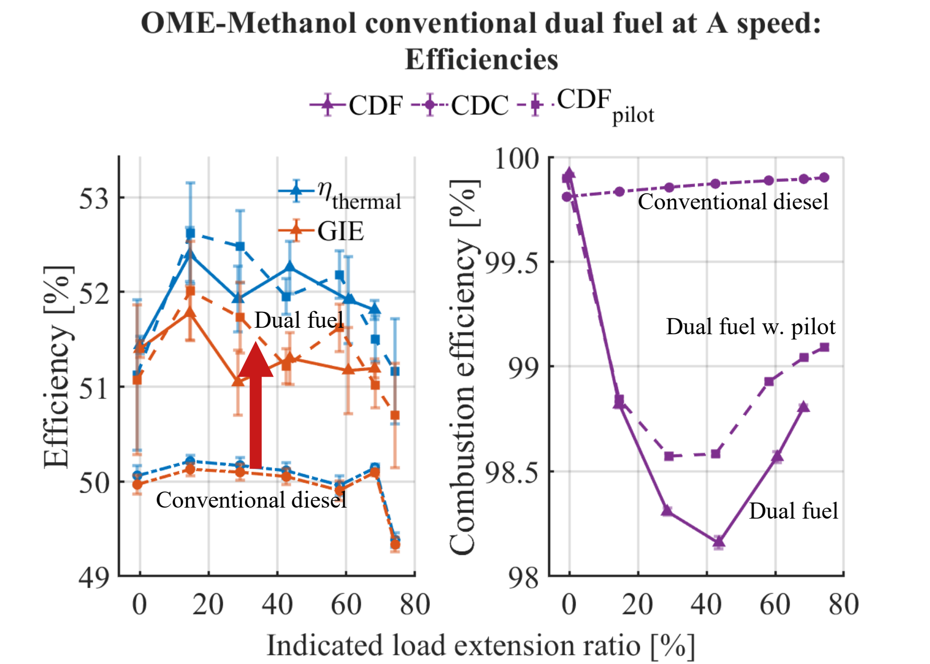
OME – Methanol dual-fuel/RCCI

Idea pitch: potential future on-board production of OME out of MeOH

Dual-fual/RCCI operation with minimal OME

OME @ 30% load, but A70 conditions

- Adding methanol in steps using PFI
- Extending load up to 59% (reaching max (PRR))
- Small additional extension to 61% with a 7% pilot injection
- 1.5% GIE improvement with dual fuel



Collaboration w. Peter de Vos (Delft), graduation project work Joel Arendsen

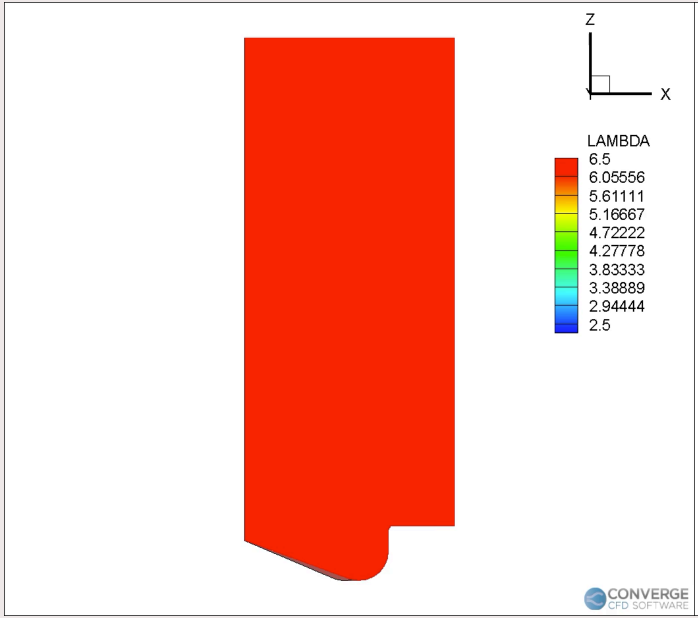
Numerical simulations

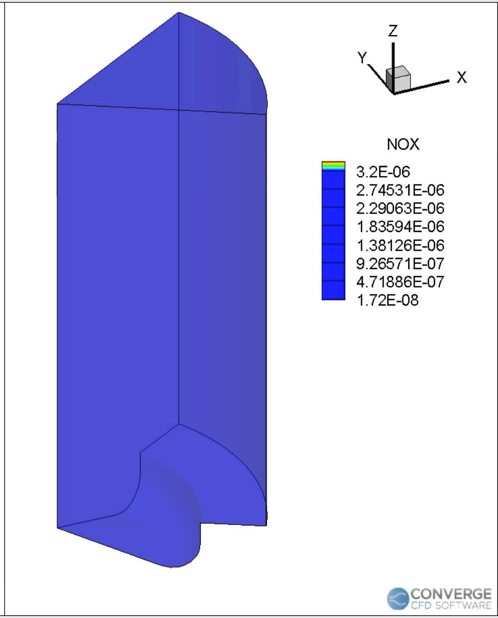
CFD
- LES
- RANS

Combustion Model
- FGM

Software
- OpenFOAM
- Converge

DME/Methanol RCCI in HD engine





Numerical simulations

CFD

- LES
- RANS

Combustion Model

- FGM

Software

- OpenFOAM
- Converge

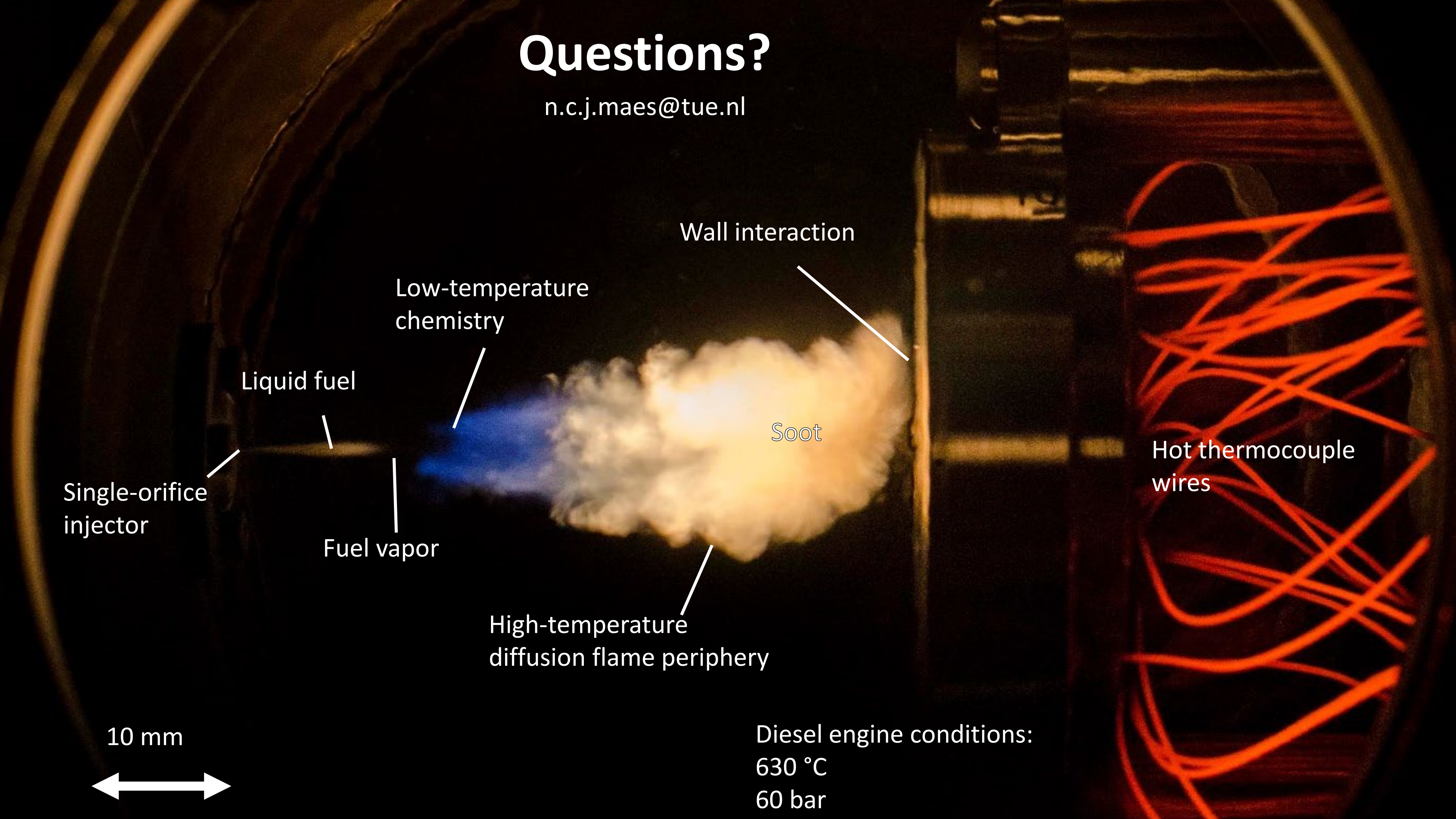
LES of spray A (combustion in the EHPC)

n-dodecane
formaldehyde
carbondioxide

time: 0.01 ms

Questions?

n.c.j.maes@tue.nl



Diesel engine conditions:
630 °C
60 bar