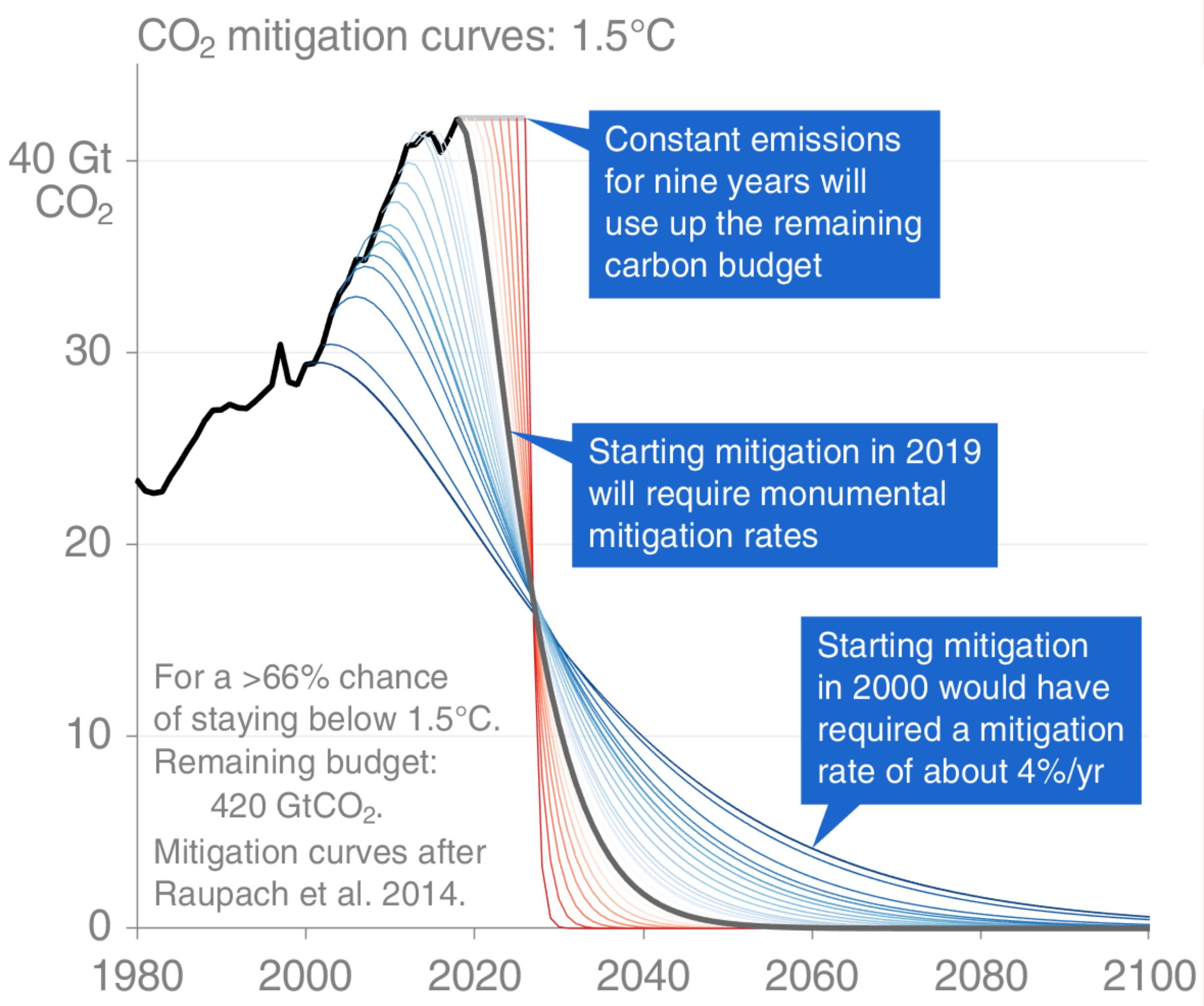
# Are Combustion Engines Entirely Bad?

- Electric
- Battery
- Renewable
- Carbon Free
- Zero-emission

- Combustion
- Diesel
- Conventional
- Engine
- Fuel

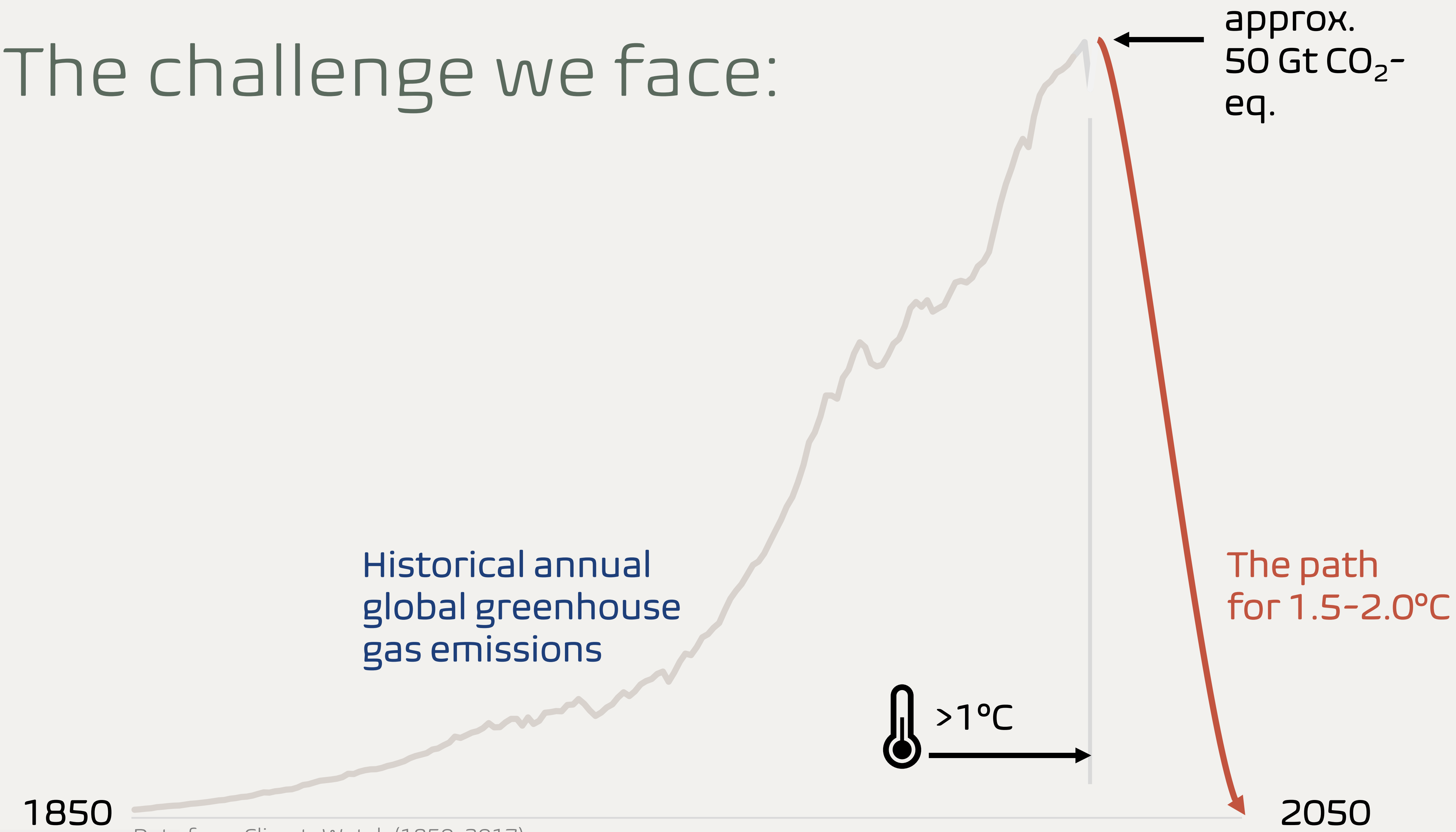
# CO2 Budget

- After a certain amount of emitted CO2, we cannot reverse the average temperature increase.
- Time is running out!



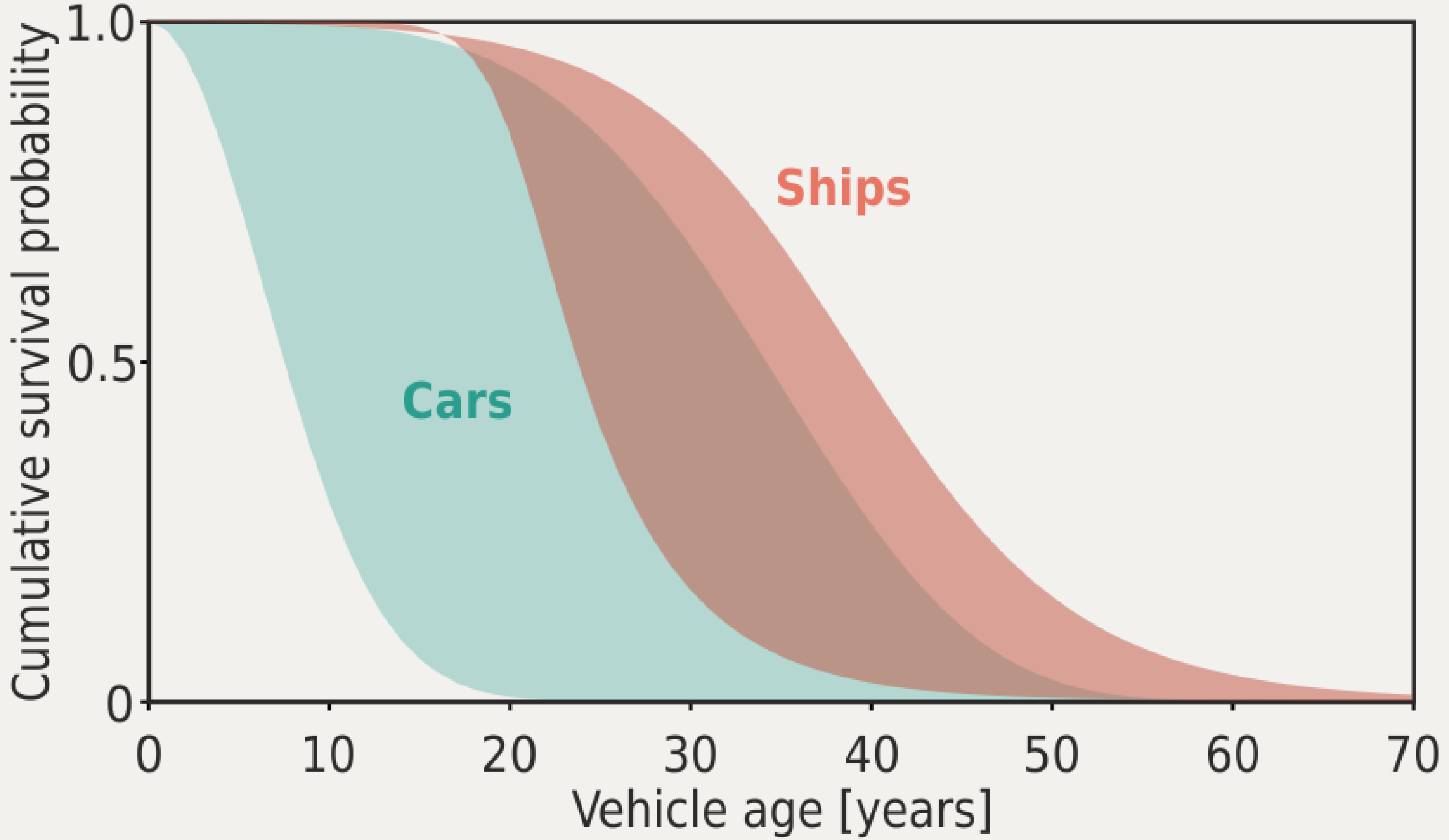

Sources: Robbie Andrew, GCP, IPCC SR1.5

# The challenge we face:




Data from ClimateWatch (1850-2017)

# If we have 30 years, why is immediate action imperative?



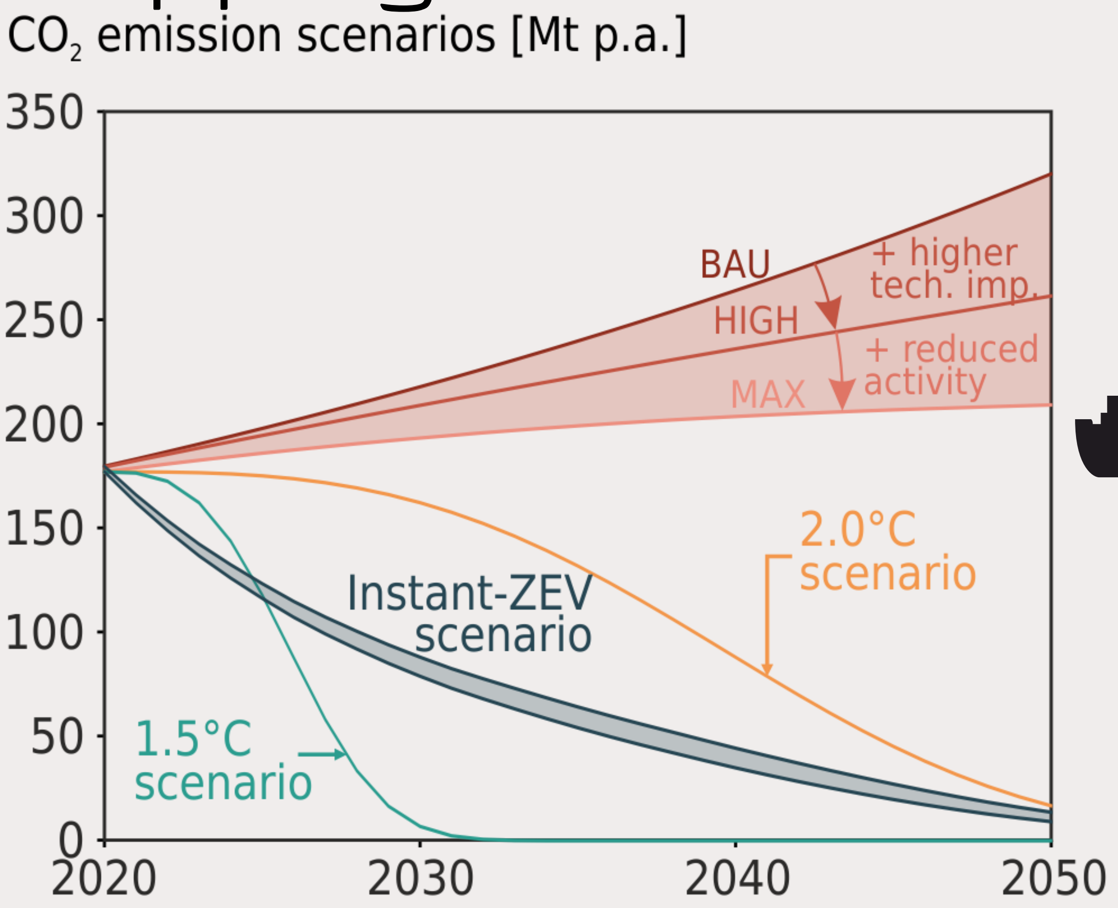

Data for cars from Held et al. (2021): *European Transport Research Review*, vol. 13, art. 9
Data for ships from Held et al. (2021): *7th Internat. Symposium on Ship Operations, Management, & Economics*
Data for aircraft from Dray (2013): *Journal of Air Transport Management,* vol. 28, pp. 62-69

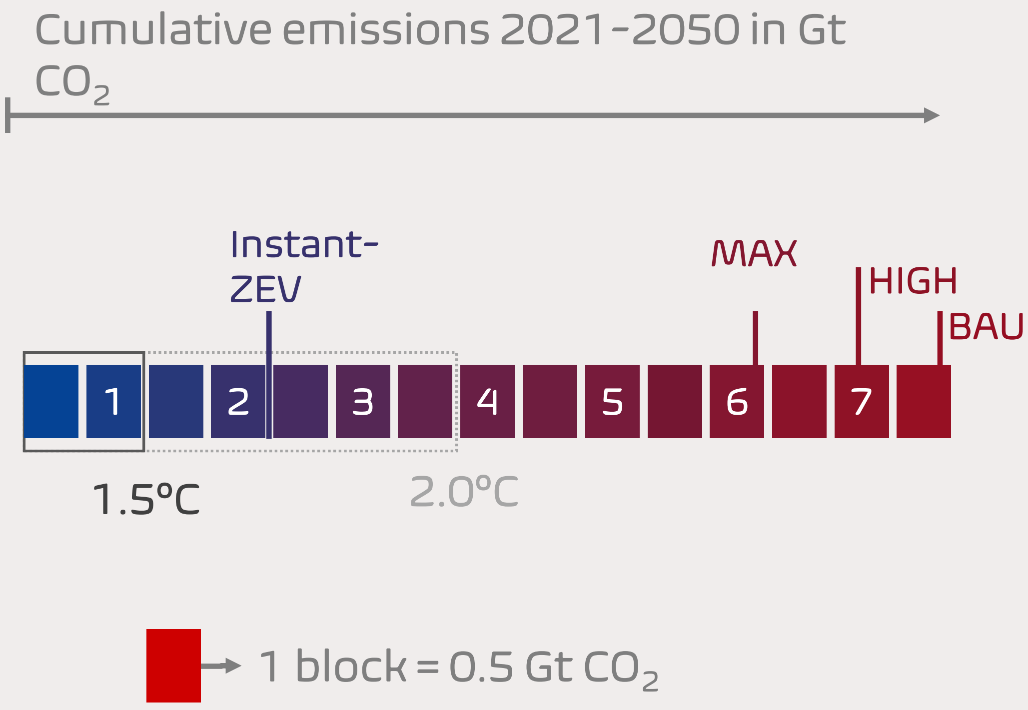
# One Fast Solution

# Global Lockdown

# Parallel Parking Skills Level EVERGREEN

# Emission trajectories for the European shipping sector…



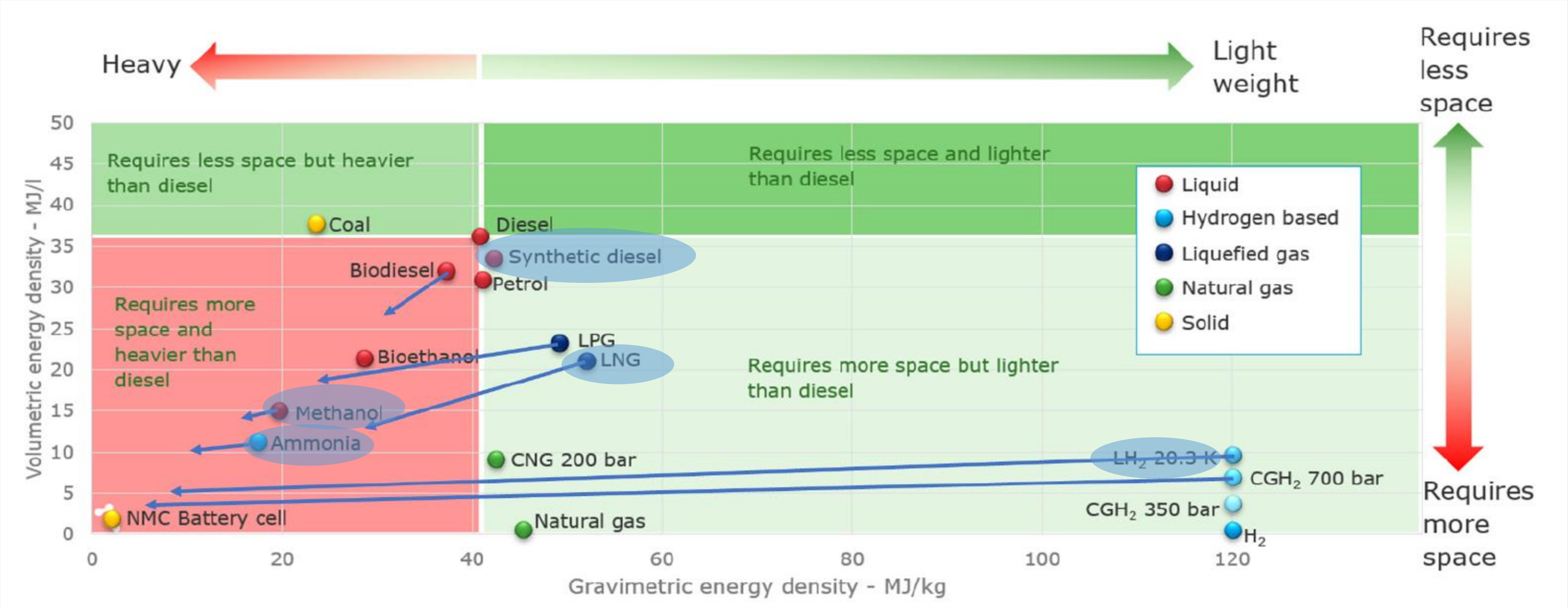

But immediate action could dramatically turn things around!

Maximillian Held!

Used methodology for emission scenarios: Stolz & Held et al. (2021): *Applied Energy*, vol. 285: 116425

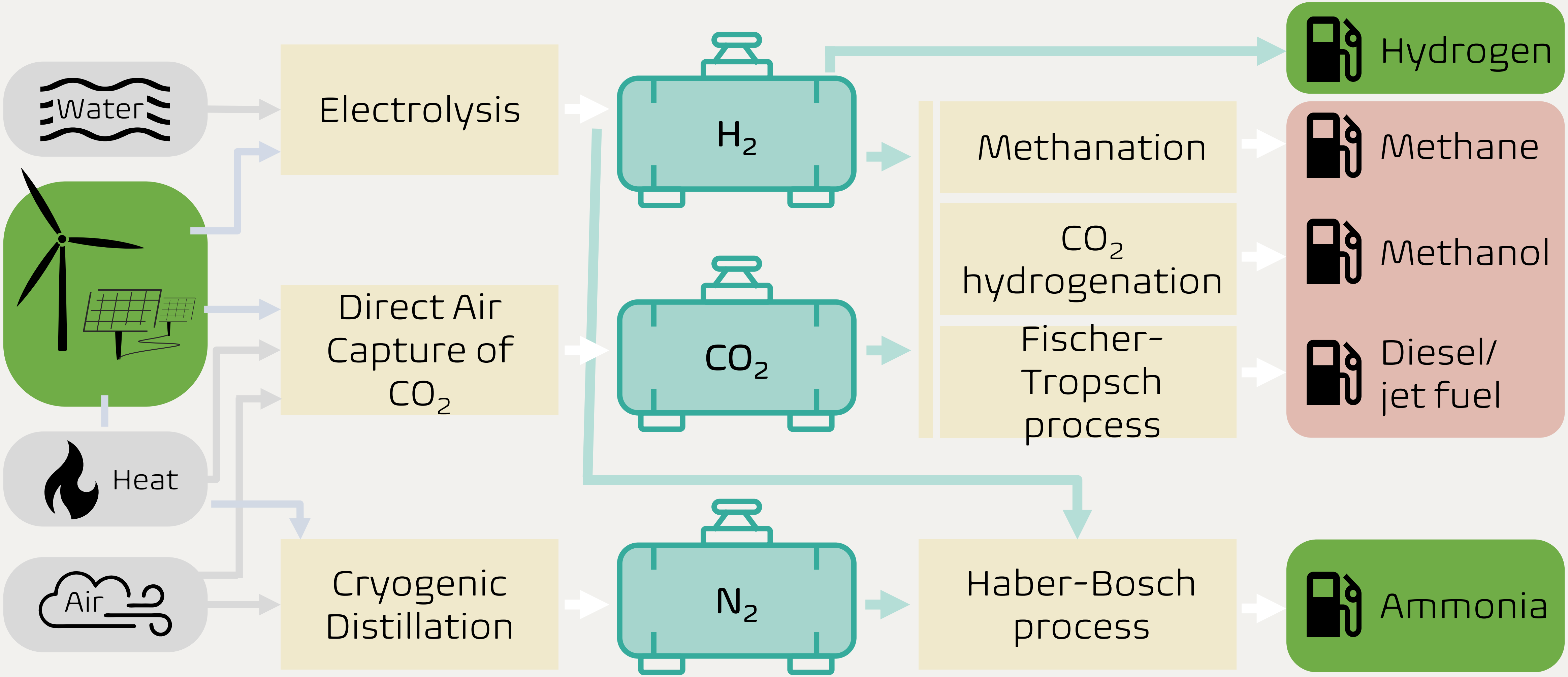
# Carbon Free or Carbon Neutral Fuels

## Batteries are not feasible!




GL DNV - For SEALNG, DNV GL rep, 2019

# Production pathways for renewable fuels




Used methodology for emission scenarios: Stolz & Held et al. (2021): *Applied Energy*, vol. 285: 116425

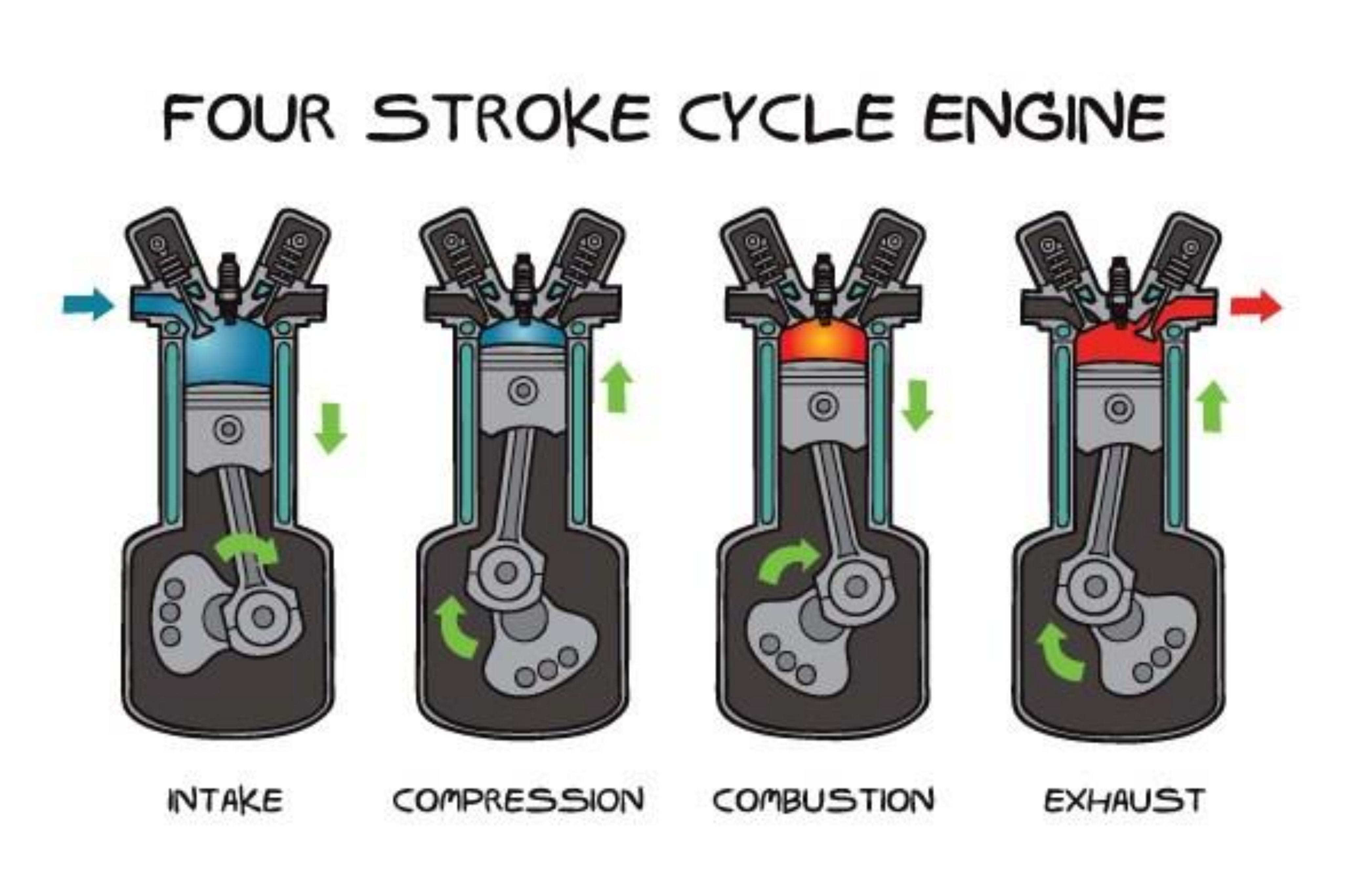
# The Challenge For the Shipping Industry Engine Manufacturers ?

Not Enough Scientific Studies to Incite Change!

# Here is my proposed solution:
# A Dual Fuel Engine!

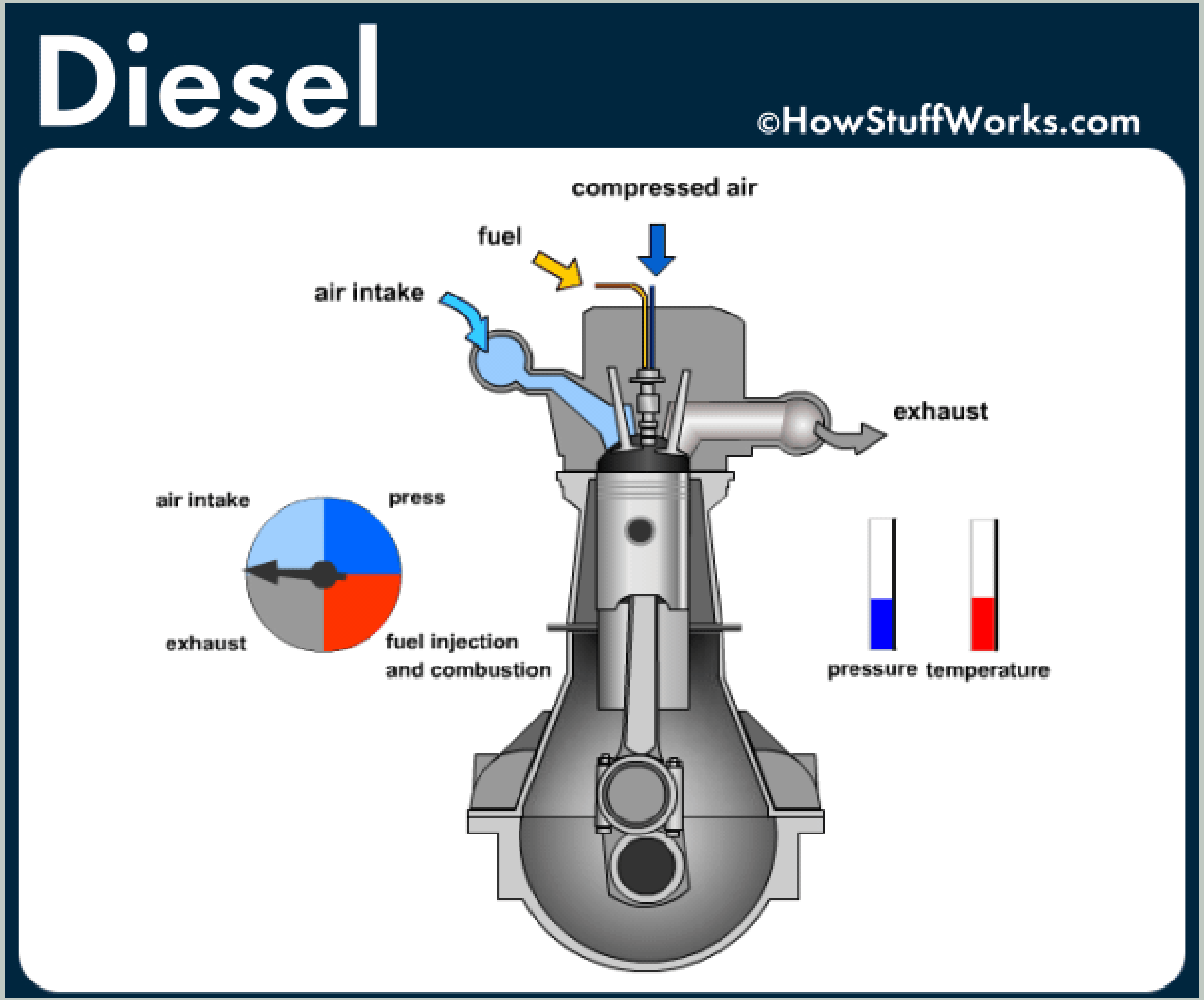
Fuel Flexible – Efficient – Low Capital Cost

Disclaimer: I did not invent it

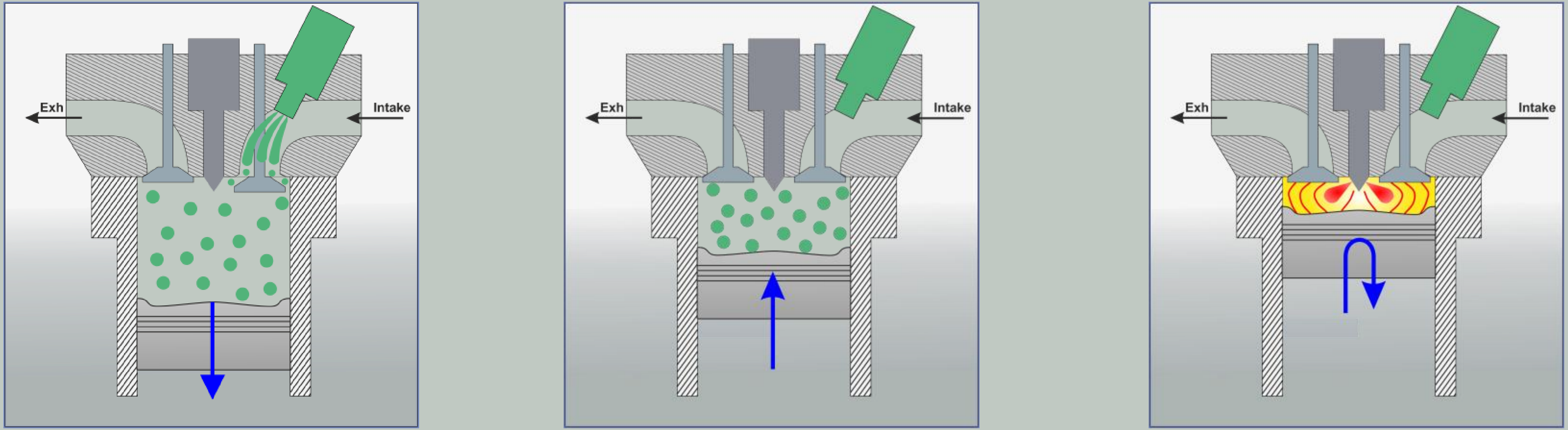



4-stroke-engine.jpg (600×400) (wp.com)

# Compression Ignited (CI) Engines

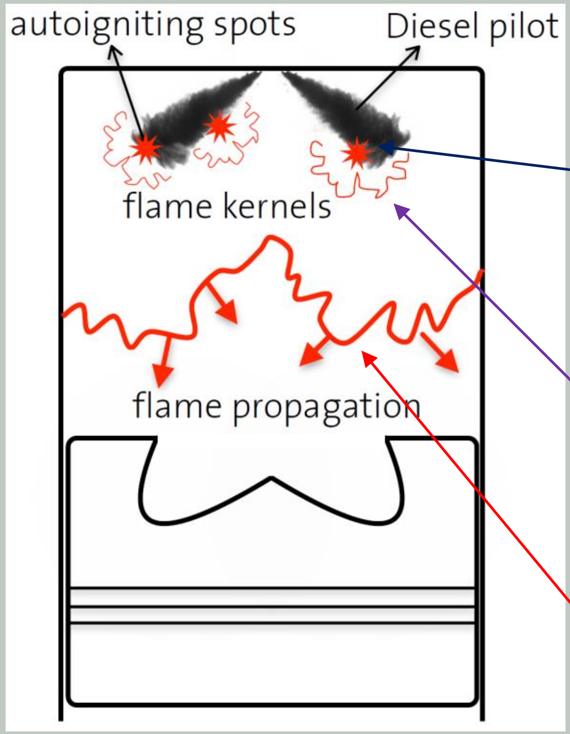


# Dual Fuel Engine




Fuel Flexible – Efficient – Low Capital Cost

# Dual Fuel Engine




Auto-igniting Diesel/fuel spray
- Atomization and secondary break-up
- Evaporation and fuel-air mixing
- Auto-ignition
- Non-premixed flame

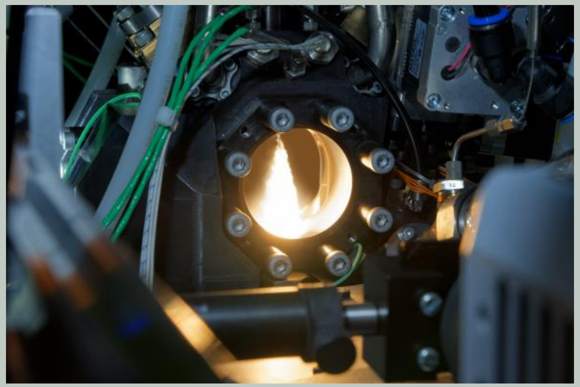
Regime transition
- Premixed charge forced ignition
- Flame kernel(s) growth

Turbulent premixed flame
- Turbulent flame propagation
- Extinction?
- Flame-wall interaction!

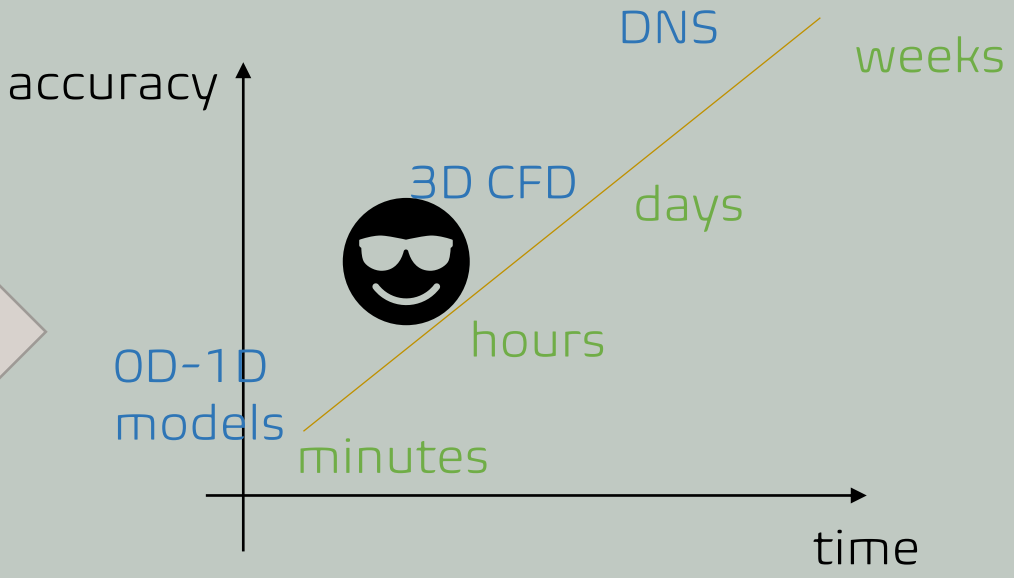
Dual Fuel engines are gaining market share but not well understood!

# We need to provide tools to help manufacturers design better engines

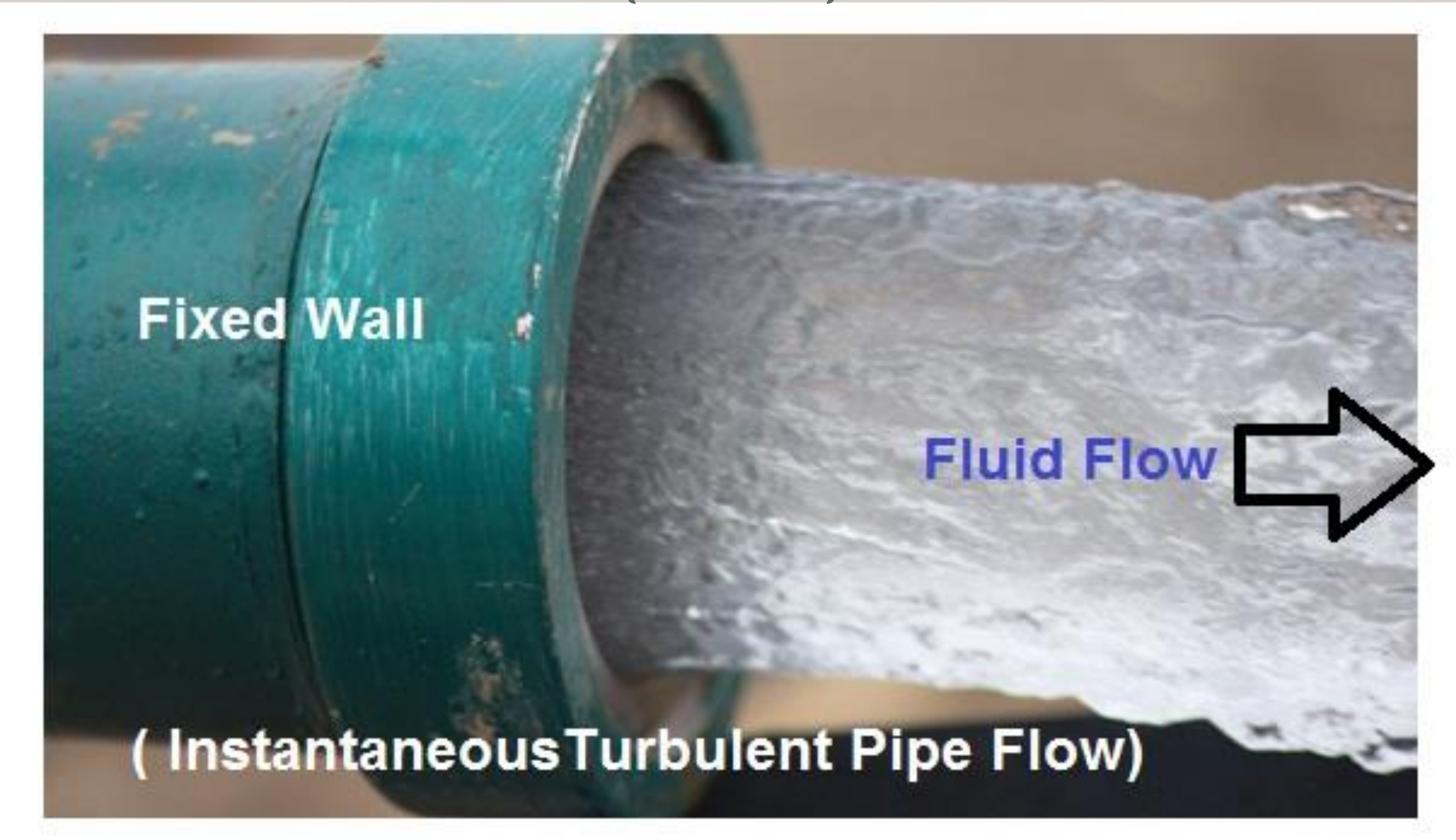
- Experiments
  - Expensive
  - Burns fuel (>10,000tons/year!!)→ emissions!
  - time consuming
  - Cannot "see" everything



- Simulation
  - Accuracy vs. speed

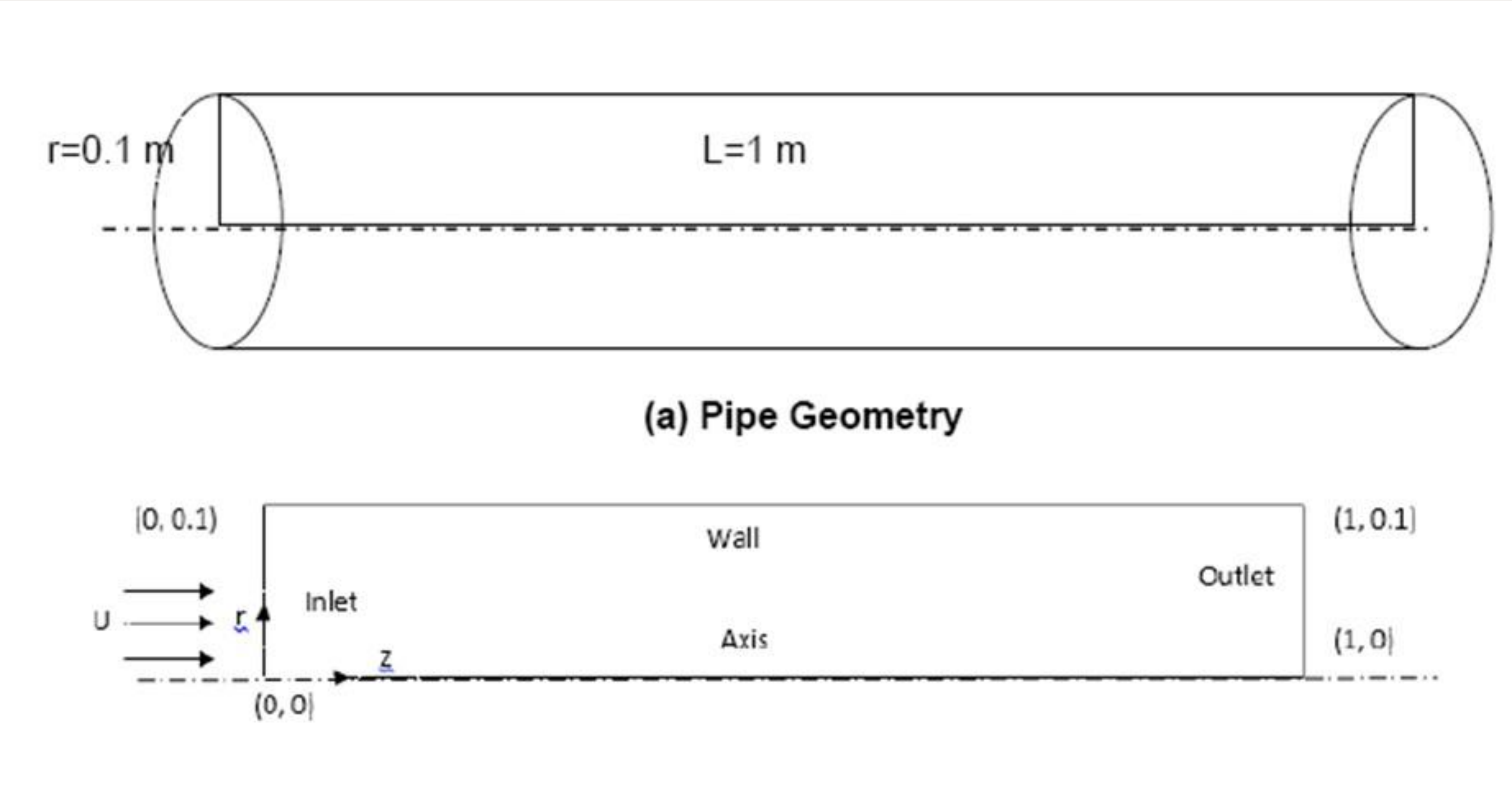


# Computational Fluid Dynamics (CFD)




Basics of CFD Modeling for Beginners - CFD Flow Engineering
*Jiyuan Tu Guan Heng Yeoh Chaoqun Liu, Computational Fluid Dynamics: A Practical Approach,Butterworth-Heinemann, Elsevier Publication,. 2018*
*Henk Kaarle Versteeg, WeeratungeMalalasekera,An Introduction to Computational Fluid Dynamics: The Finite Volume Method,Pearson Education Limited, 2007*

# Problem Geometry

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# Grid Generation



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# Governing equations

Mass

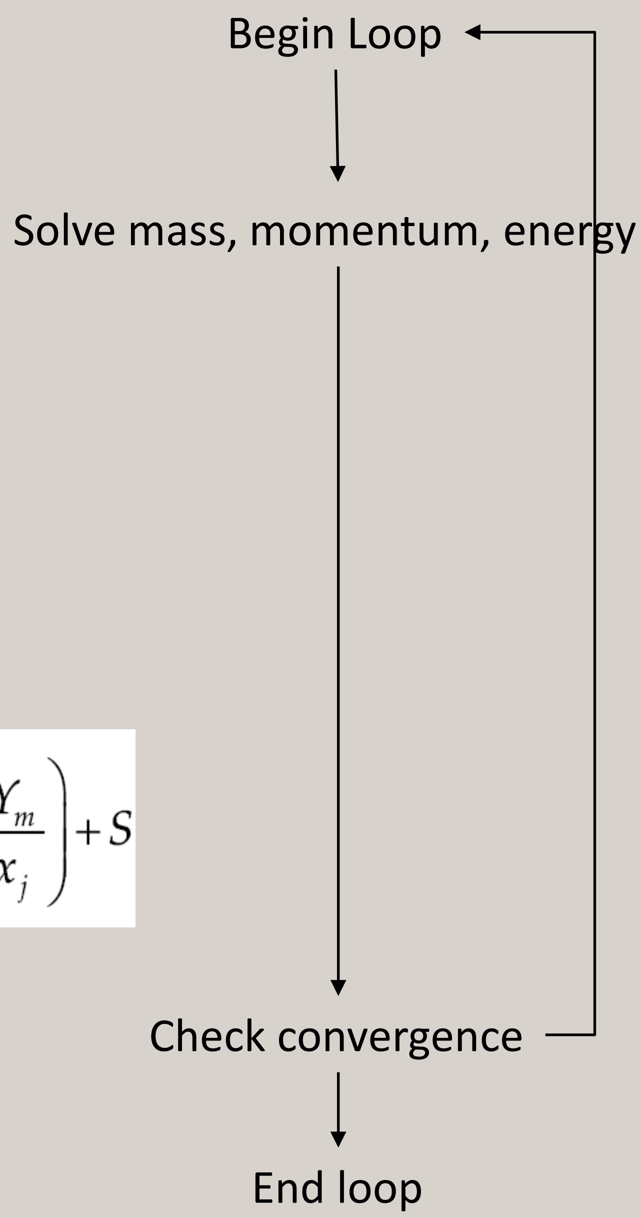
$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = S$$

Momentum

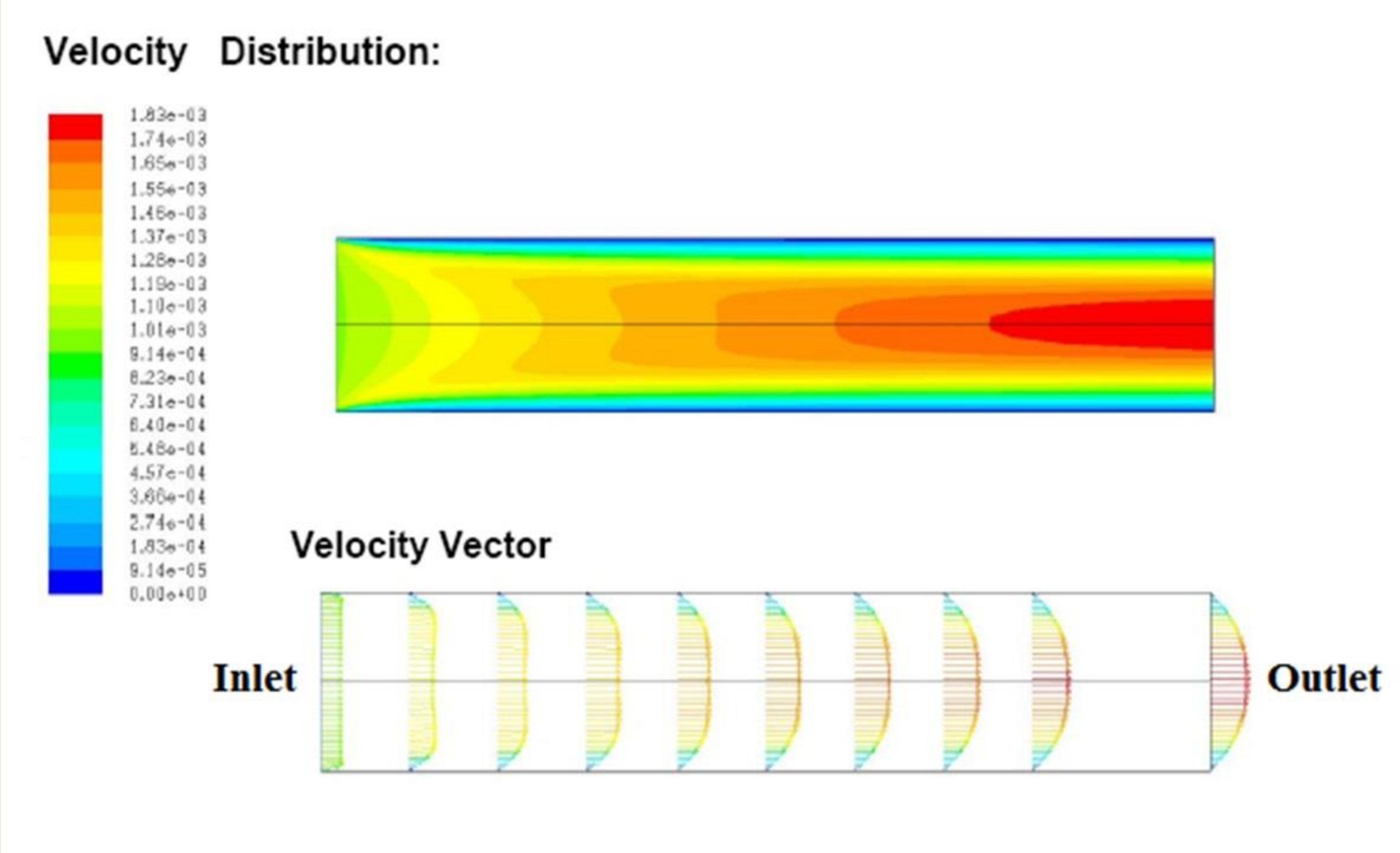
$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial \sigma_{ij}}{\partial x_j} + S_i$$

Energy

$$\frac{\partial \rho e}{\partial t} + \frac{\partial u_j \rho e}{\partial x_j} = -P\frac{\partial u_j}{\partial x_j} + \sigma_{ij}\frac{\partial u_i}{\partial x_j} + \frac{\partial}{\partial x_j}\left(K\frac{\partial T}{\partial x_j}\right) + \frac{\partial}{\partial x_j}\left(\rho D \sum_m h_m \frac{\partial Y_m}{\partial x_j}\right) + S$$



# Results and Analysis

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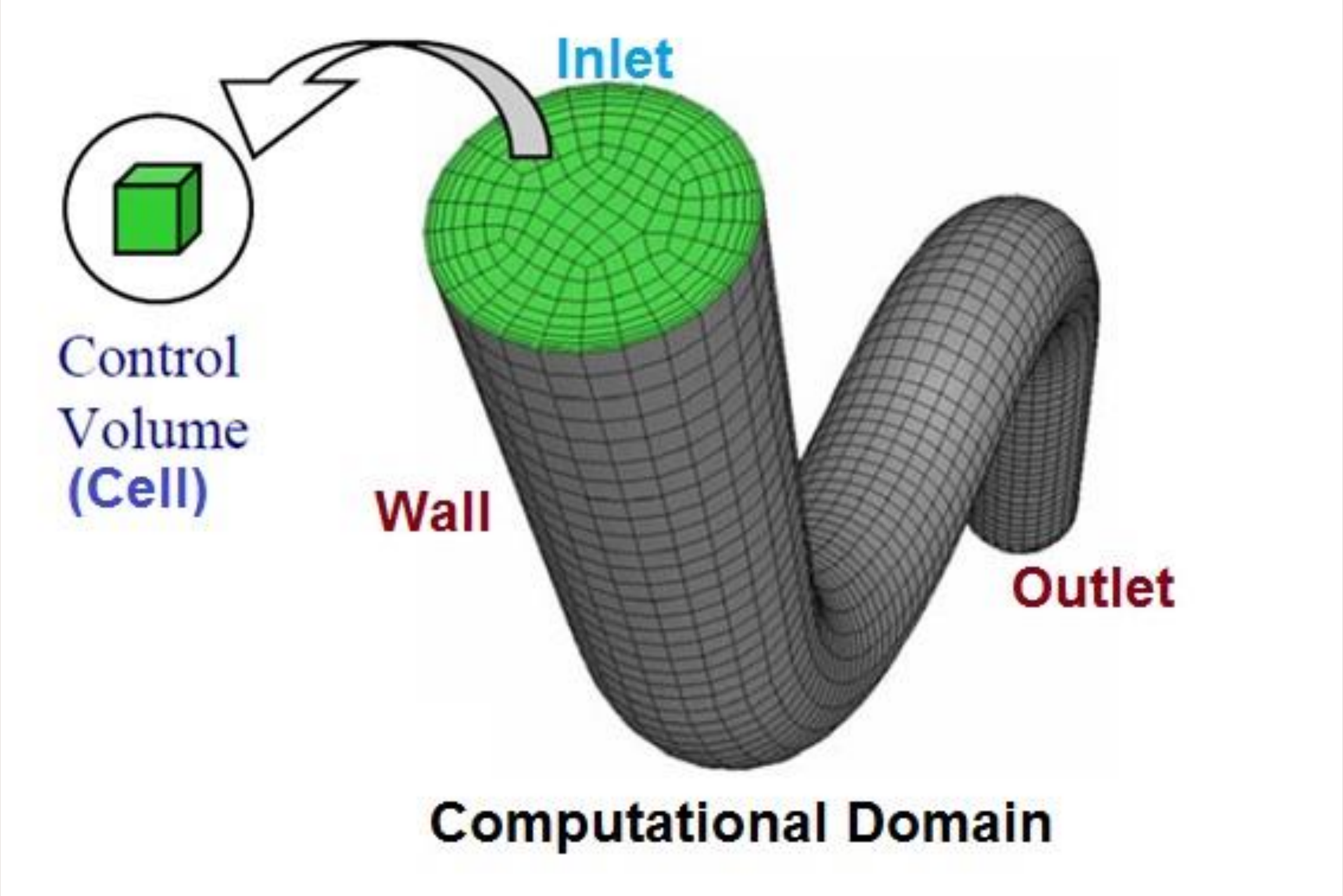
# 3-D Grid

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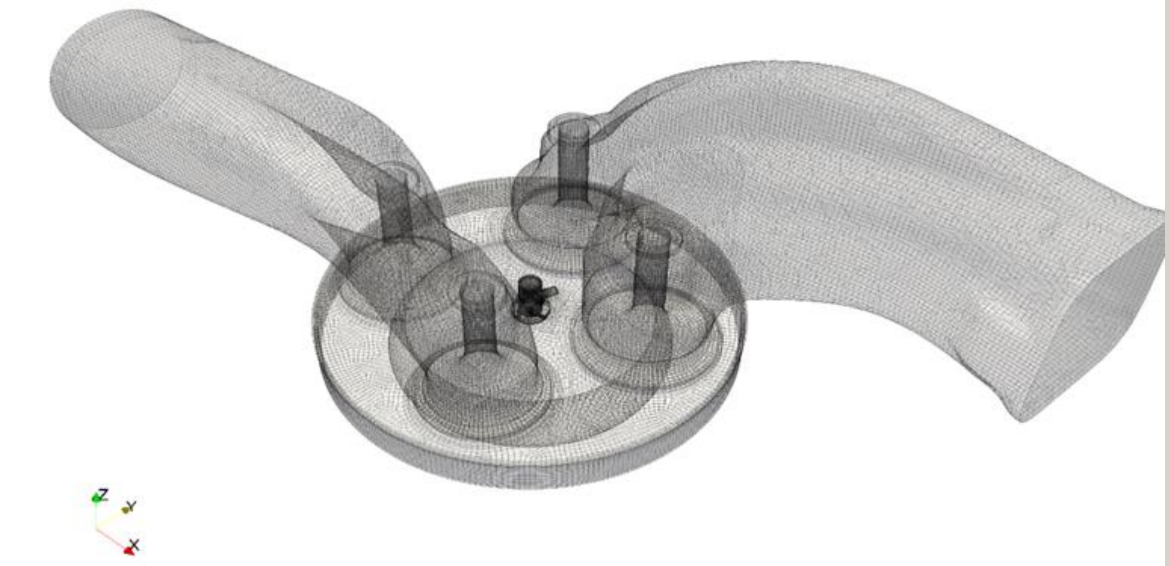
*Henk Kaarle Versteeg, WeeratungeMalalasekera,An Introduction to Computational Fluid Dynamics: The Finite Volume Method,Pearson Education Limited, 2007*

# CFD Solver Flow




Begin Loop

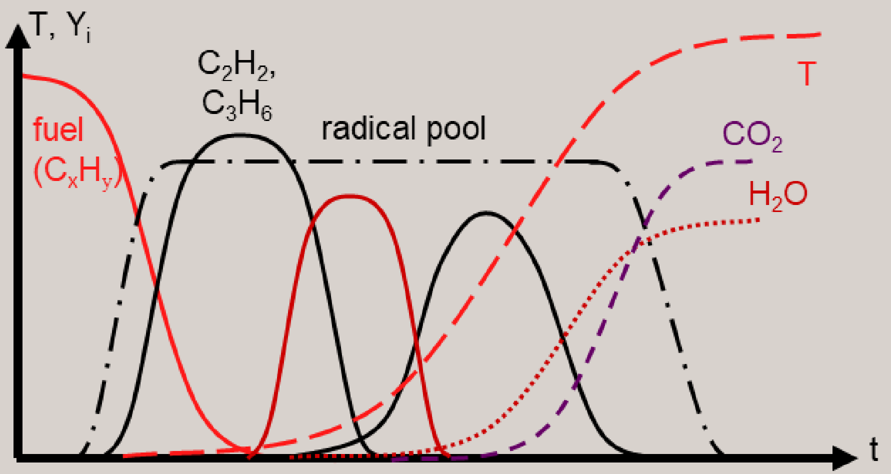
Solve mass, momentum, energy

Check convergence

End loop

# And with Combustion…

Fuel + O2 → CO2 + H2O




Mass

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u_i}{\partial x_i}=S$$

Momentum

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial \rho u_i u_j}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial \sigma_{ij}}{\partial x_j}+S_i$$

Energy

$$\frac{\partial \rho e}{\partial t}+\frac{\partial u_j \rho e}{\partial x_j}=-P\frac{\partial u_j}{\partial x_j}+\sigma_{ij}\frac{\partial u_i}{\partial x_j}+\frac{\partial}{\partial x_j}\left(K\frac{\partial T}{\partial x_j}\right)+\frac{\partial}{\partial x_j}\left(\rho D\sum_m h_m\frac{\partial Y_m}{\partial x_j}\right)+S$$

Species

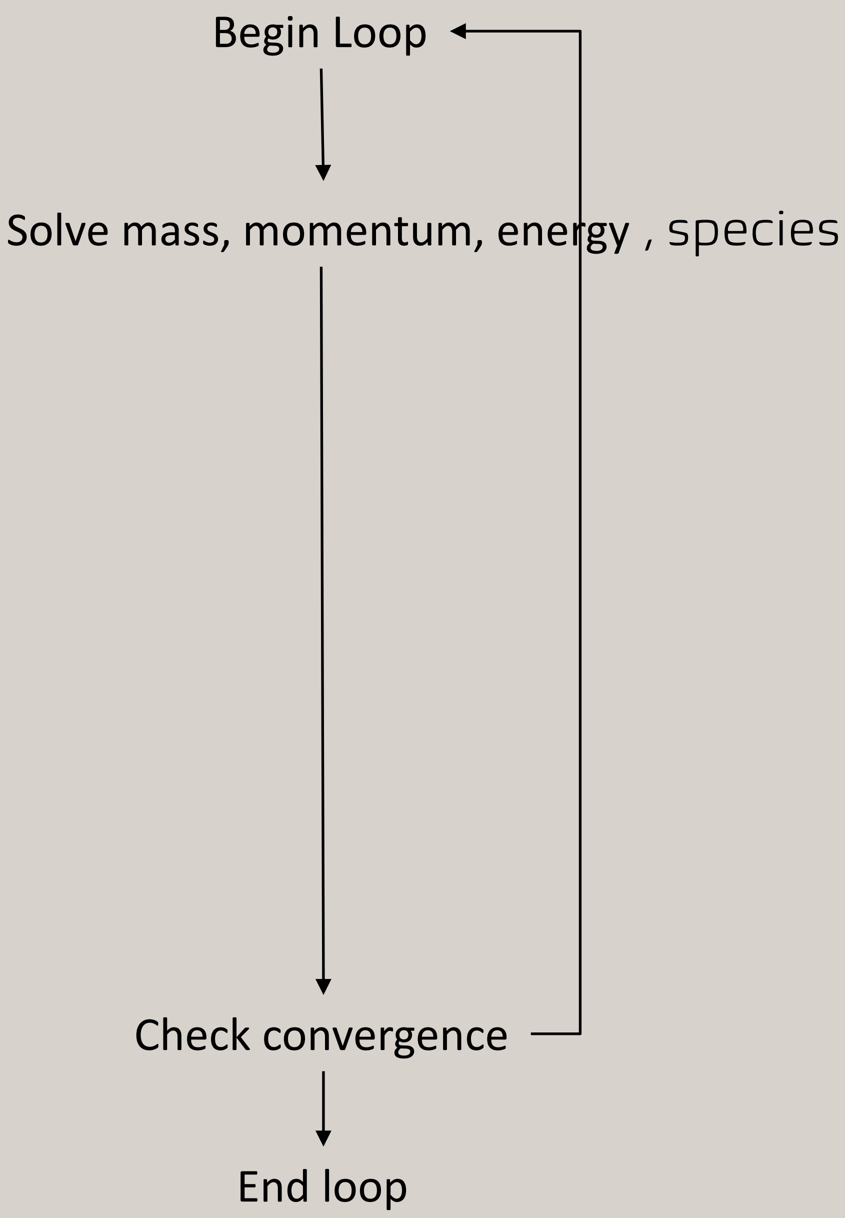
$$\frac{\partial \rho_m}{\partial t}+\frac{\partial \rho_m u_j}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\rho D\frac{\partial Y_m}{\partial x_j}\right)+S_m$$

Species: chemical molecules (e.g. O2, CO2)

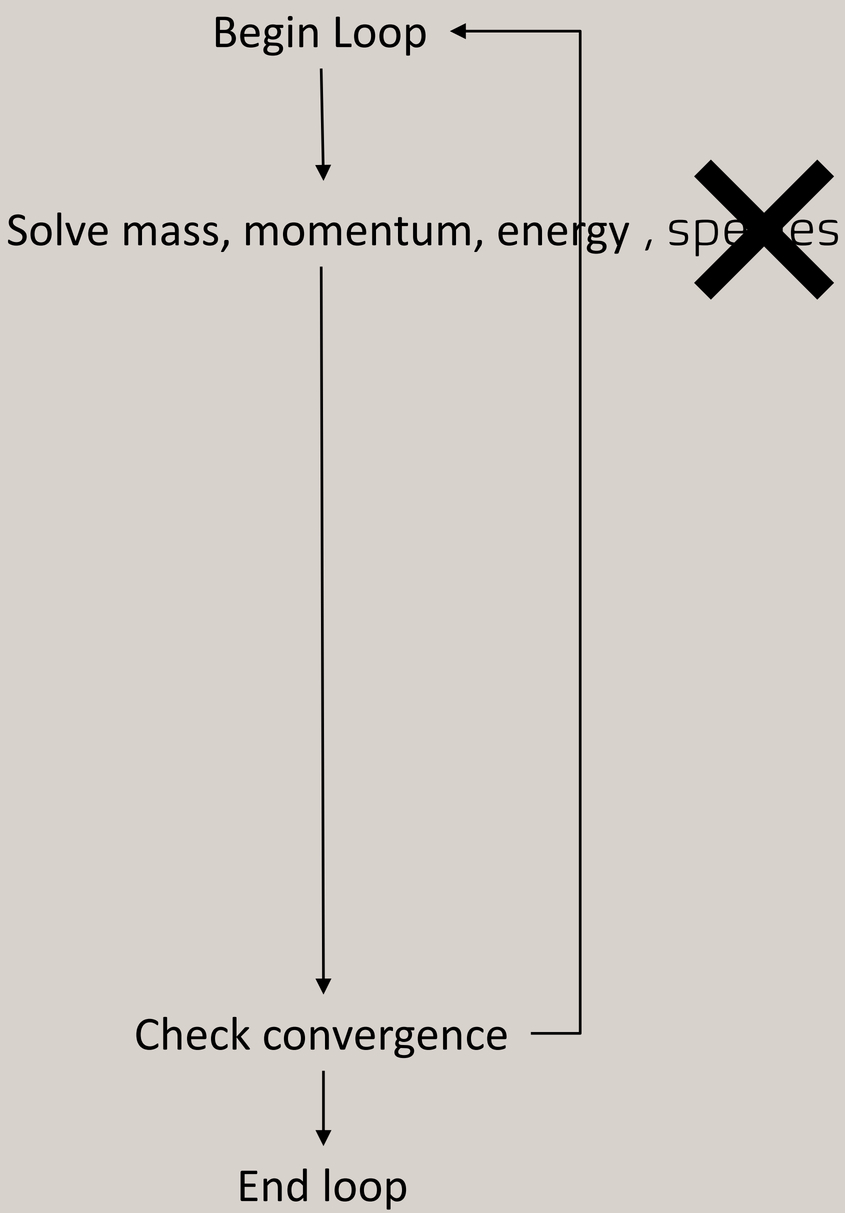
# Dual Fuel Model

- Reduces computation time by not solving the chemical species equations
- Still chemically accurate
- Accounts for both non-premixed and premixed combustion modes

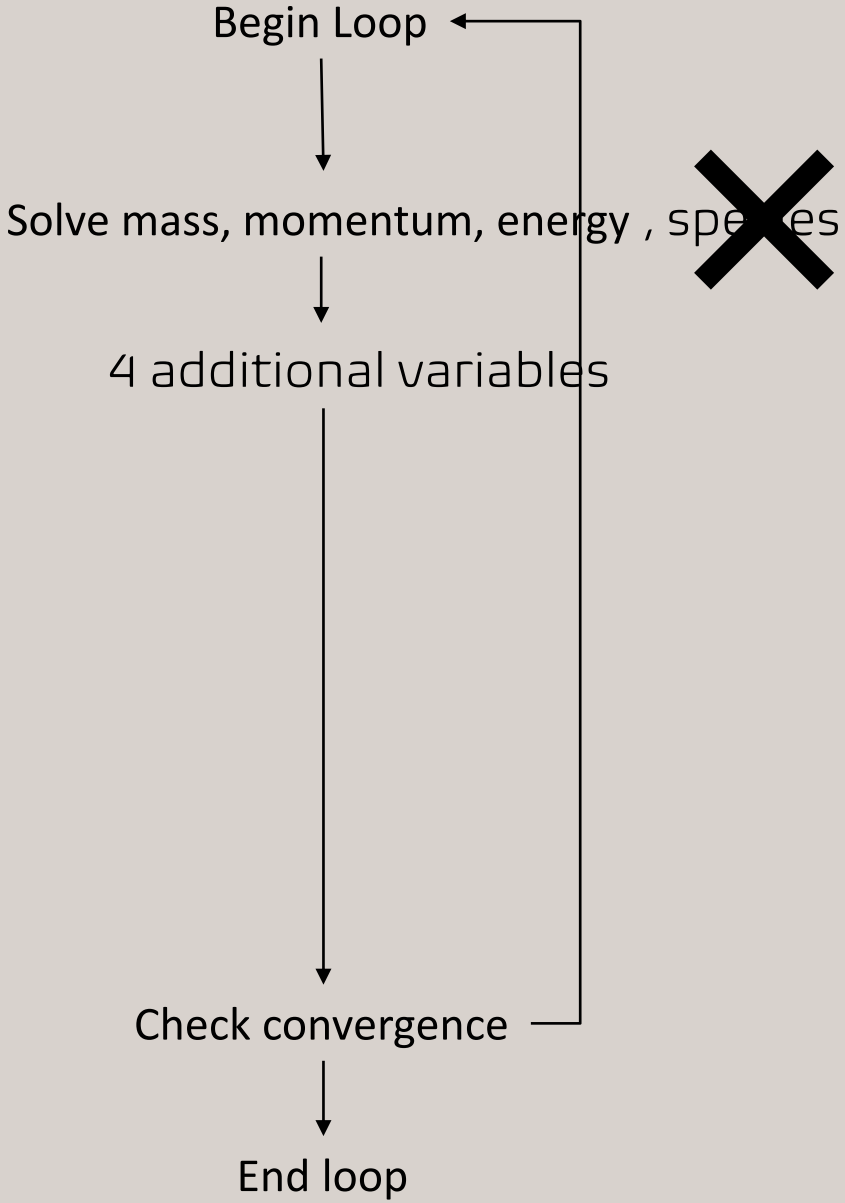
# Dual Fuel Model



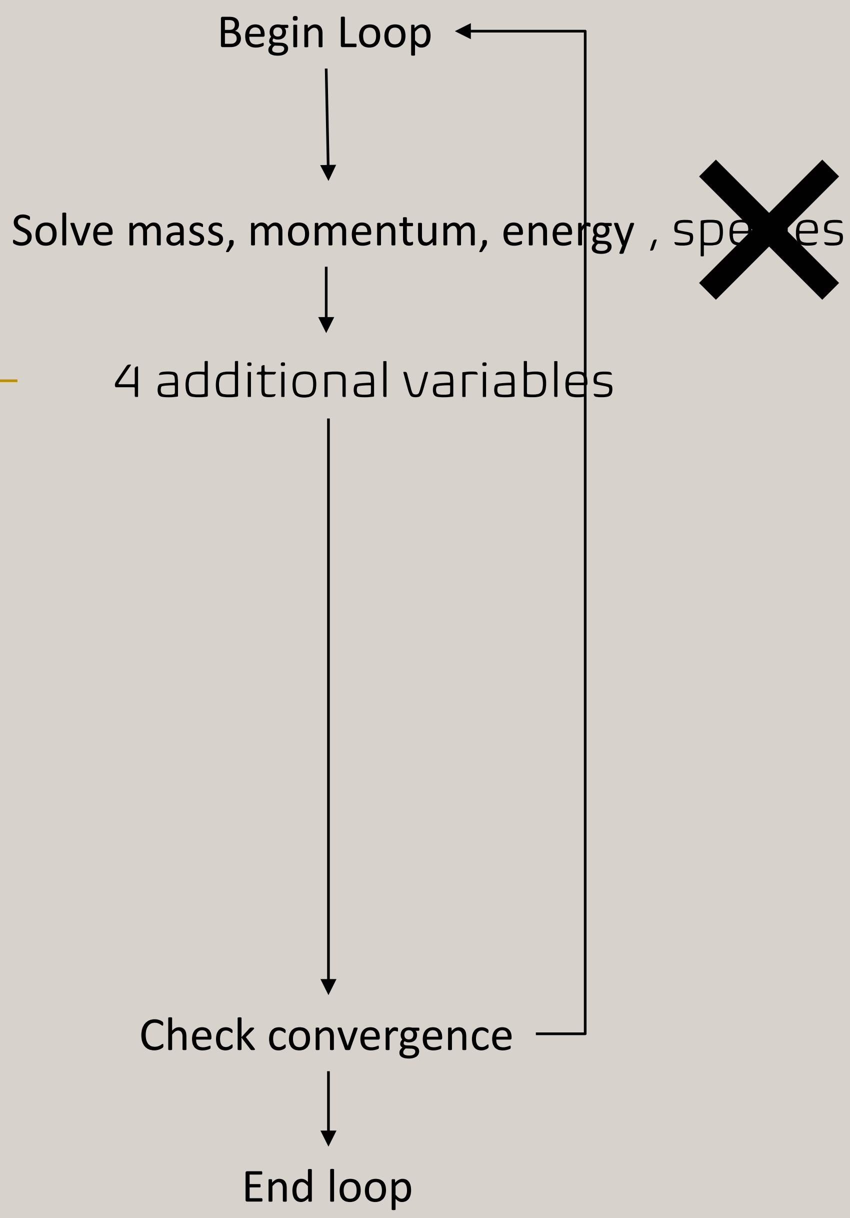
# Dual Fuel Model



# Dual Fuel Model



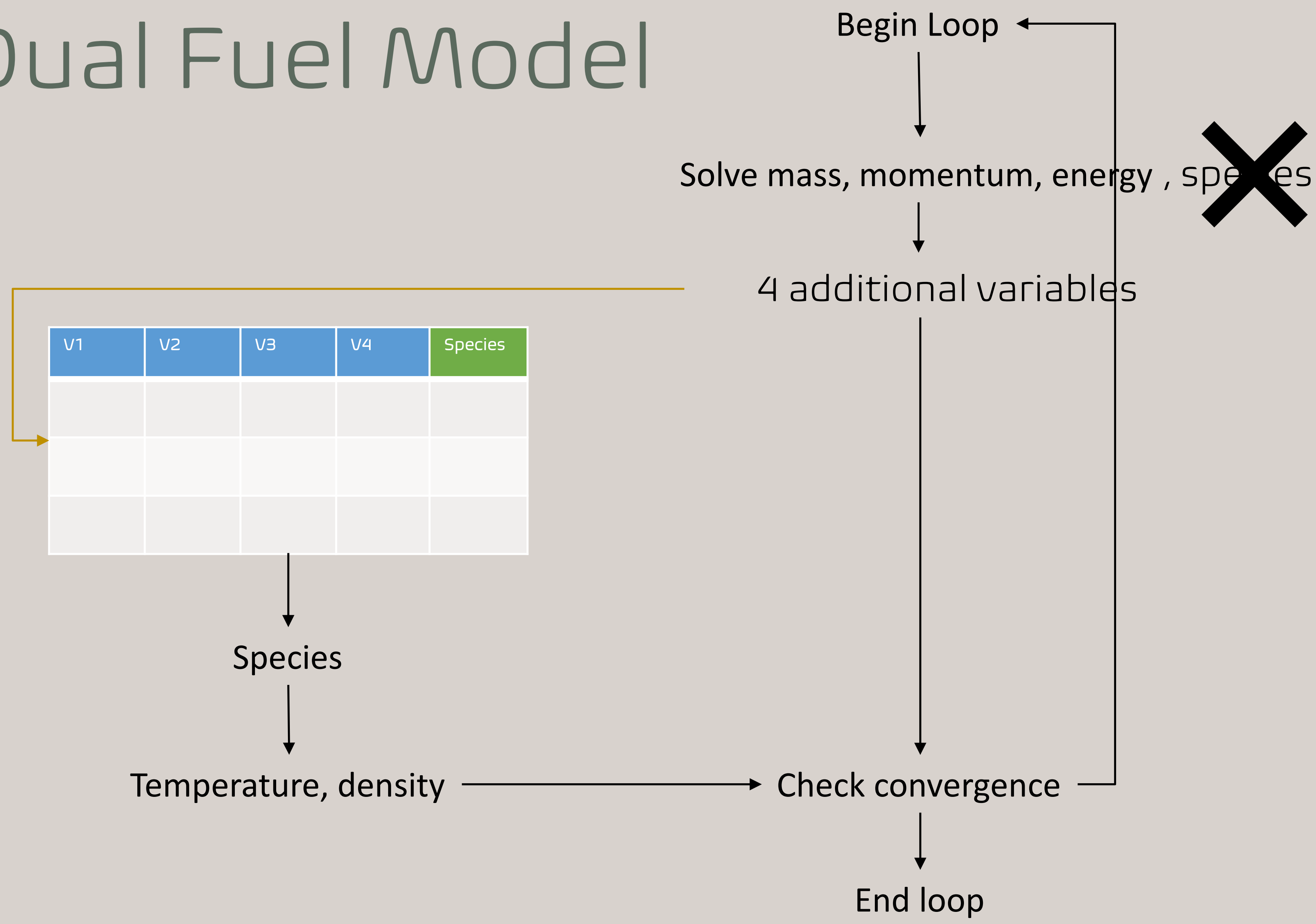
# Dual Fuel Model




| V1 | V2 | V3 | V4 | Species |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |

# Dual Fuel Model

2 Tables:
Premixed and
Non-Premixed



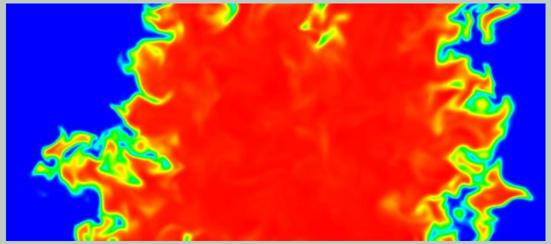
# Dual Fuel Model

- Reduces computation time by not solving the chemical species equations
  - Only 4 additional equations
- Still chemically accurate as complex chemical mechanisms could be used in the tabulation step
- Accounts for both non-premixed and premixed combustion modes
  - 1 table for each combustion mode

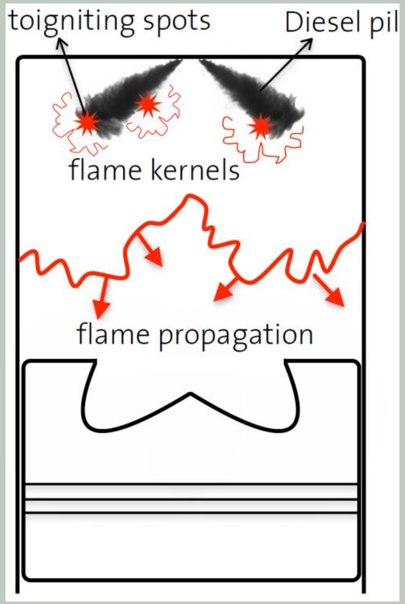
# Model Validation

Non Premixed

Premixed

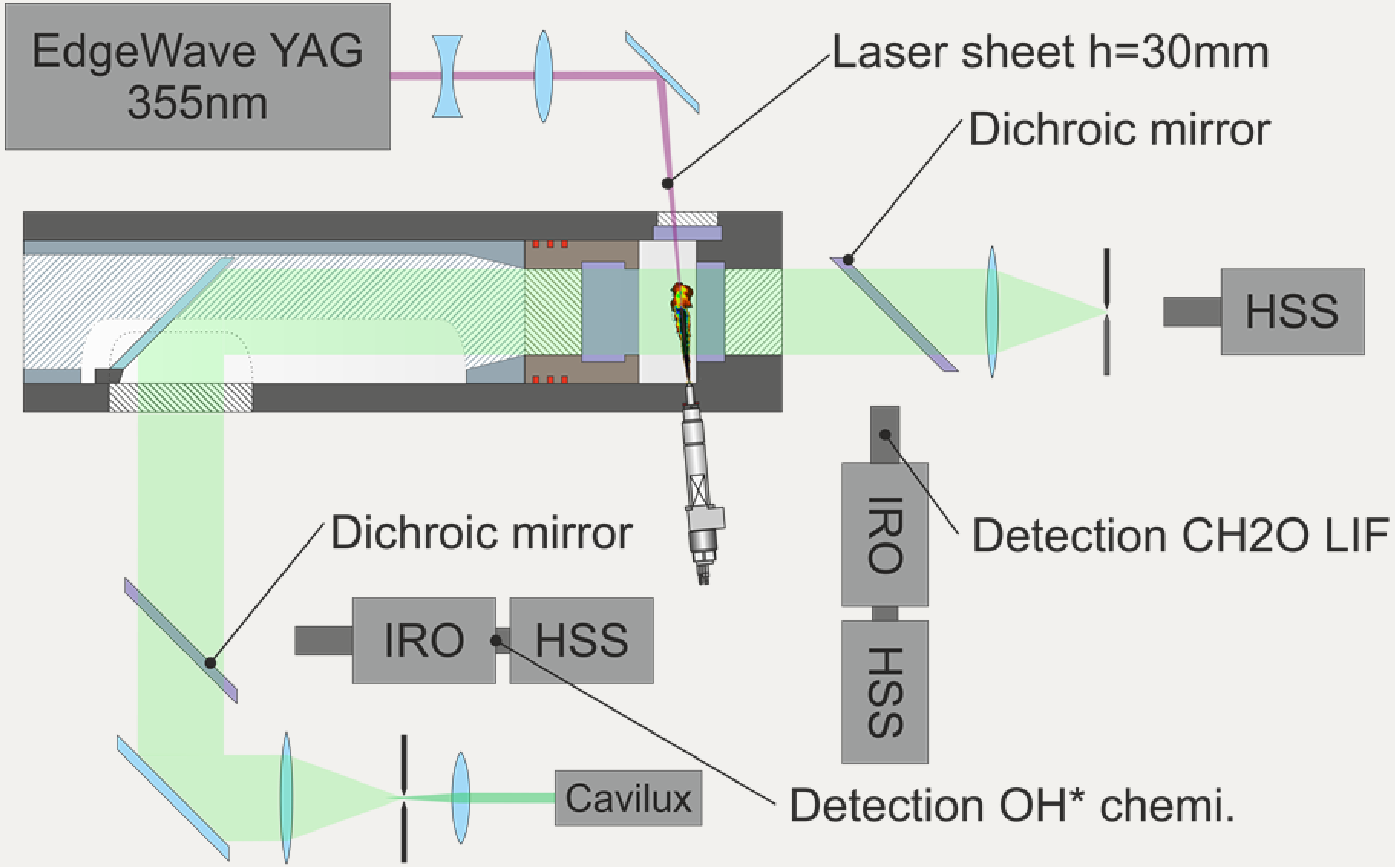


Dual Fuel



# Ignition Validation

## Rapid compression-expansion machine (RCEM)



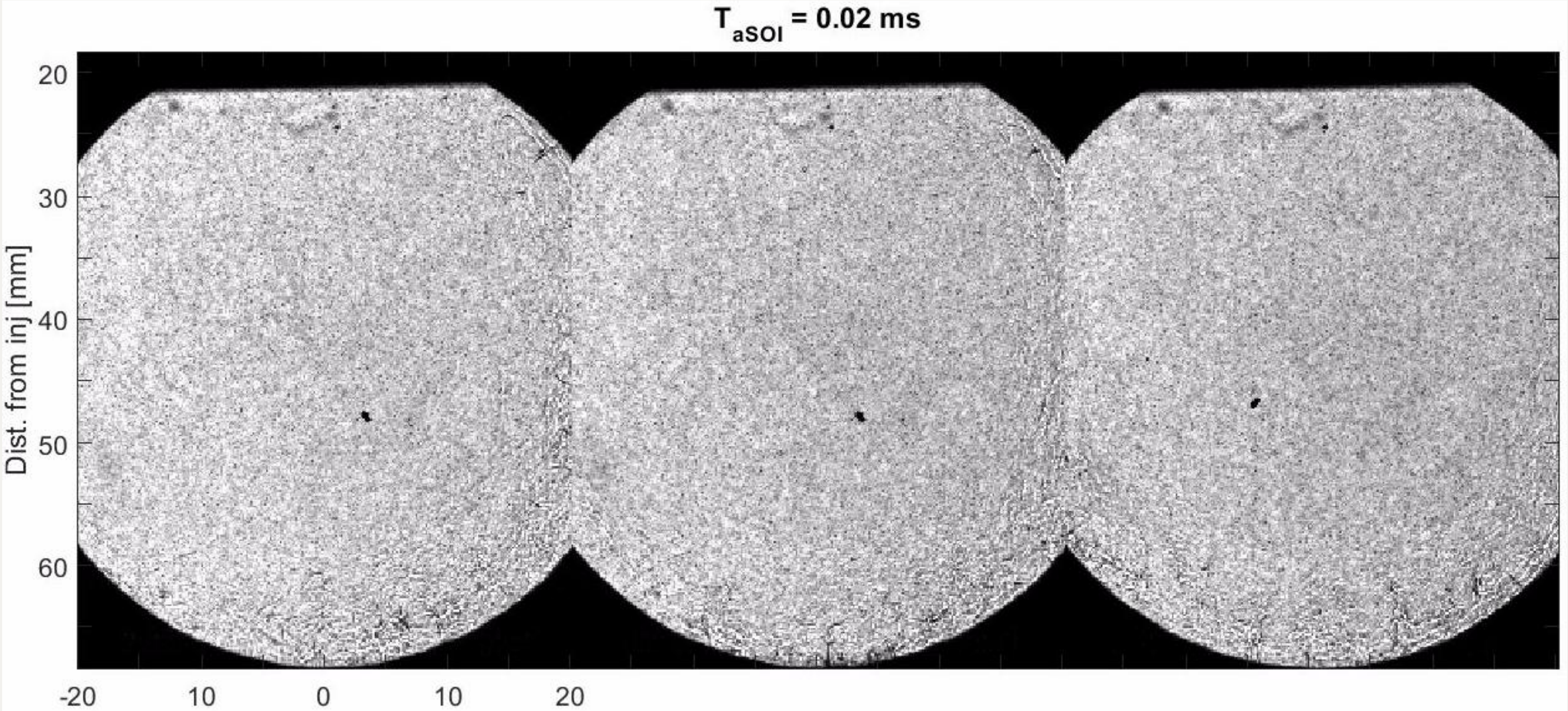


Srna, Aleš, et al. "Effect of methane on pilot-fuel auto-ignition in dual-fuel engines." *Proceedings of the Combustion Institute* 37.4 (2019): 4741-4749.
Srna, Aleš, et al. "Experimental investigation of pilot-fuel combustion in dual-fuel engines, Part 2: Understanding the underlying mechanisms by means of optical diagnostics." *Fuel* 255 (2019): 115766.

# Dual-fuel combustion: optical diagnostics

Conditions: $T_{SOI}$ = 810K, pilot: 600bar ET = 400µs

Only Diesel ($\lambda_{CH4} = \infty$) | $\lambda_{CH4}$ = 3.0 | $\lambda_{CH4}$ = 1.5

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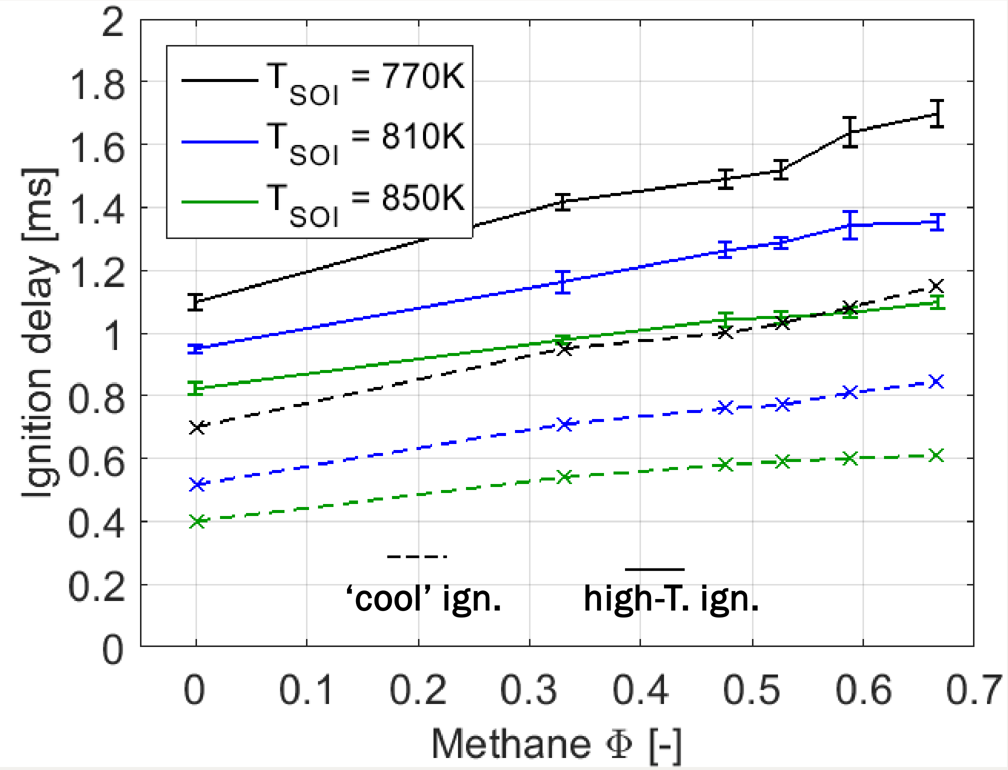
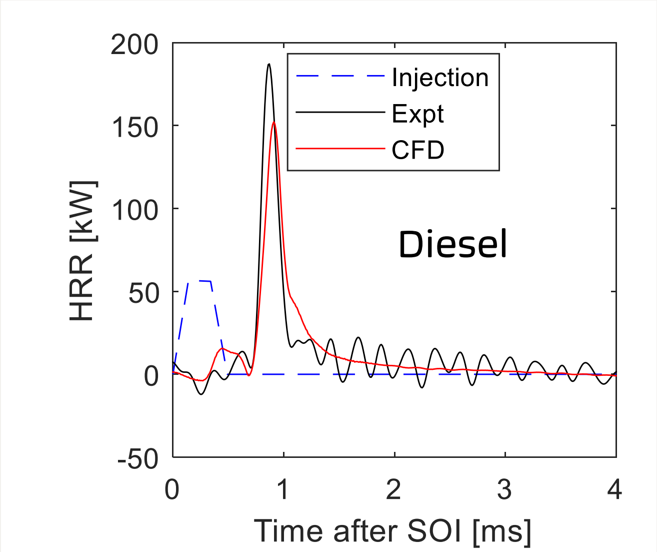
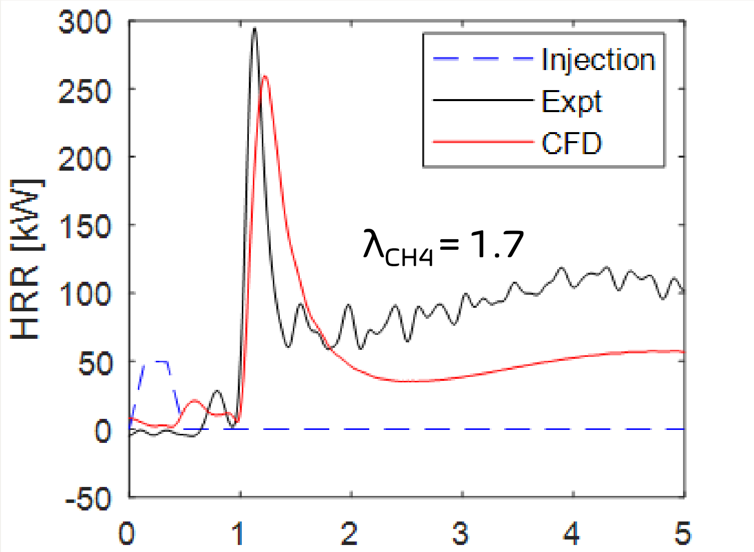
# $CH_4$ influence on the ignition delay

- $CH_4$ chemically influences ignition
- Ignition modelling has to capture this behavior

Ignition delay




Seddik, Omar, et al. *Flamelet generated manifolds applied to Dual-Fuel combustion of lean methane/air mixtures at engine relevant conditions ignited by n dodecane micro pilot sprays*. No. 2019-01-1163. SAE Technical Paper, 2019.

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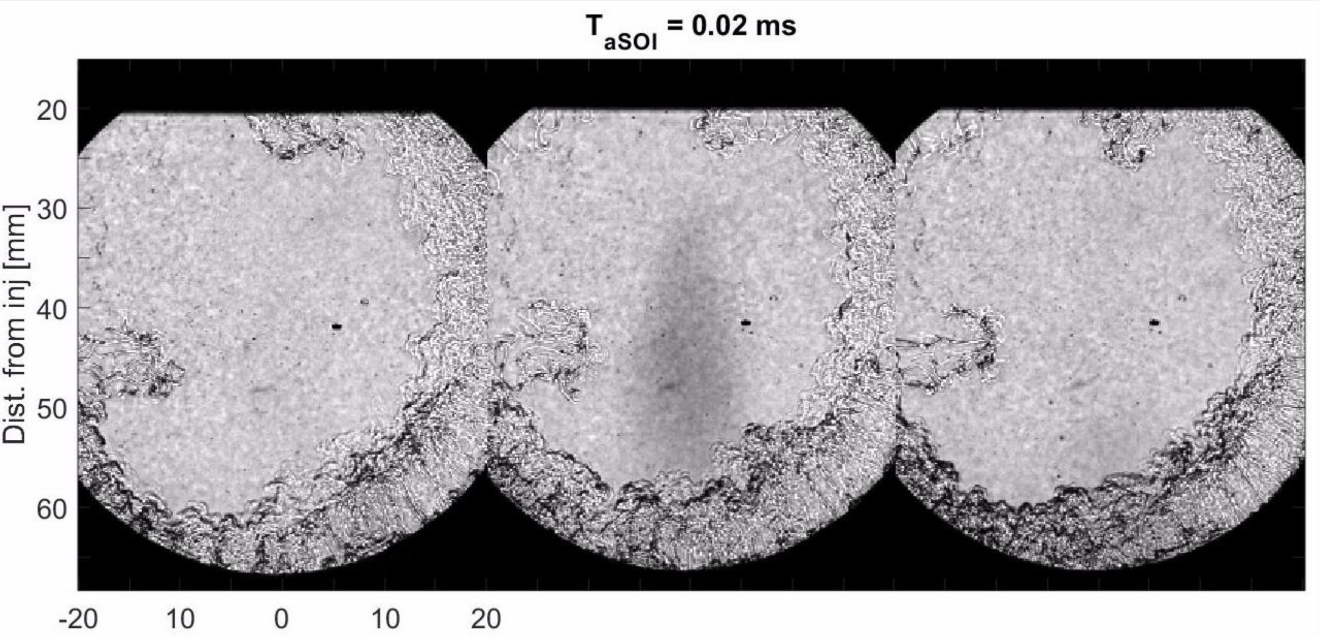
Srna, Aleš, et al. "Experimental investigation of pilot-fuel combustion in dual-fuel engines, Part 2: Understanding the underlying mechanisms by means of optical diagnostics." *Fuel* 255 (2019): 115766.

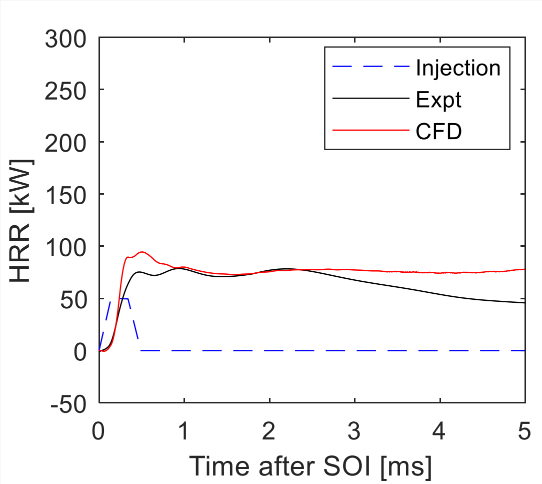
# Higher-T Diesel Combustion

$\lambda_{CH4}$ = Inf $\lambda_{CH4}$ = 3.0 $\lambda_{CH4}$ = 2.1

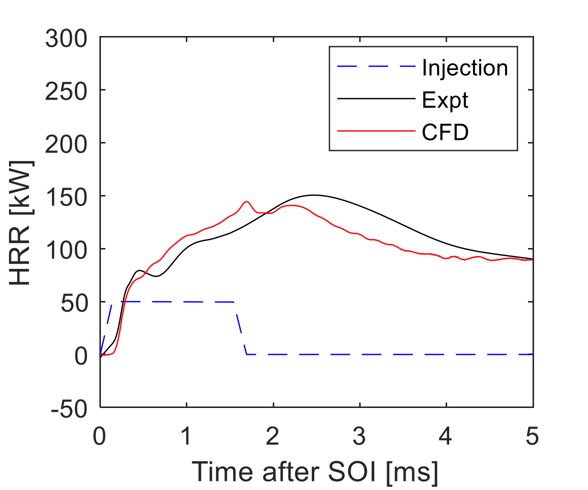



## Characteristic difference from gas-engine condition cases:

- Very short (negligible) ignition delay
- Methane has no influence on ignition delay




Short injection ( 0.7 ms )




Long injection ( 1.7 ms )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Srna, Aleš, et al. "Experimental investigation of pilot-fuel combustion in dual-fuel engines, Part 2: Understanding the underlying mechanisms by means of optical diagnostics." *Fuel* 255 (2019): 115766.

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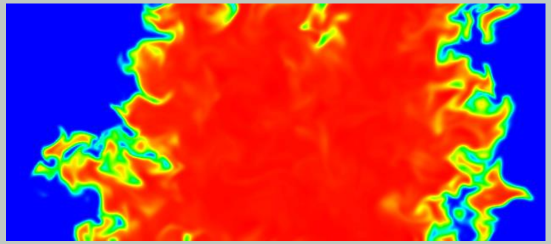
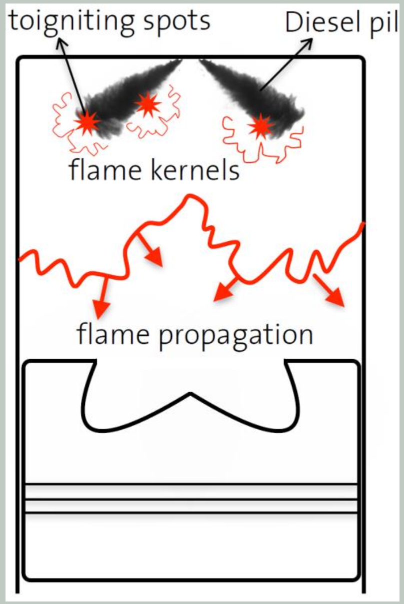
# Model Validation

Non Premixed

Premixed

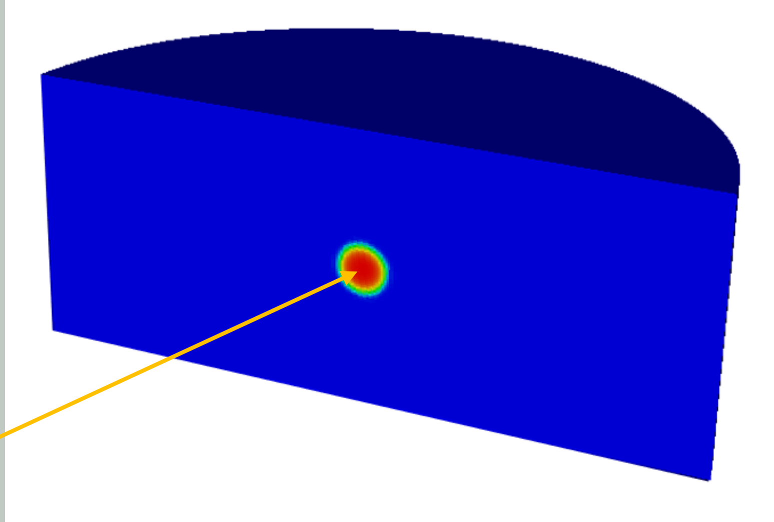


Dual Fuel



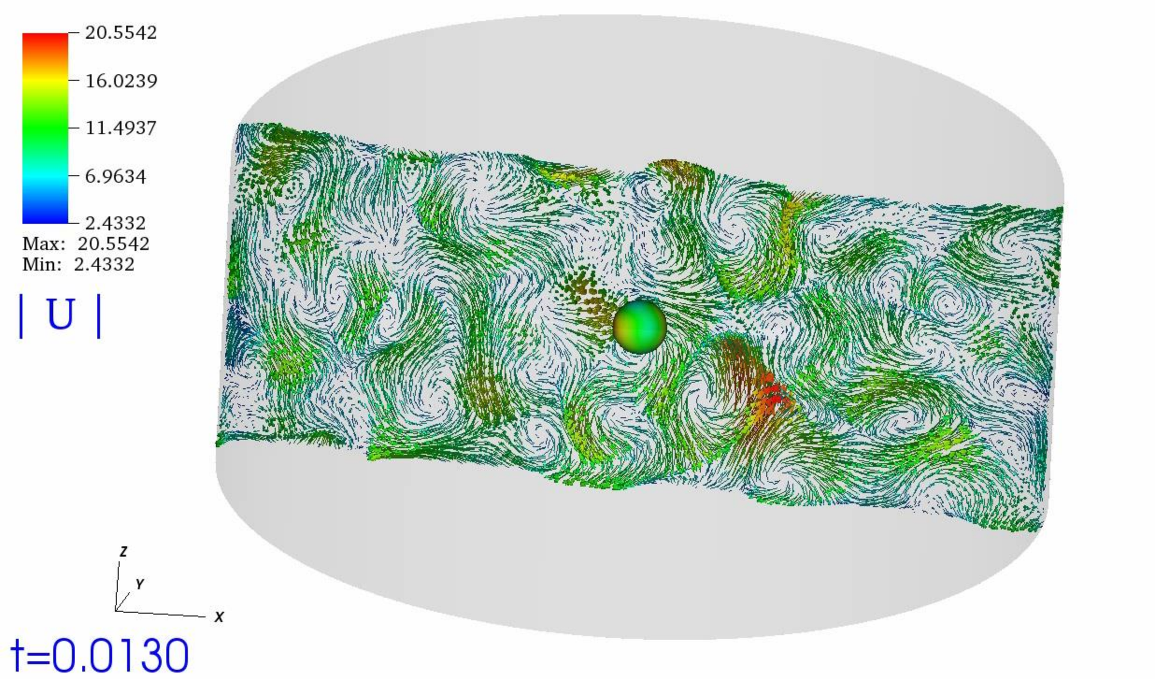
# Flame Propagation Validation

## Direct Numerical Simulation of Syngas Premixed Flame



Ignition spot

| | |
|---|---|
| $S_L^0$ | 1.38m/s |
| $d_L^0$ | 1.14mm |
| $p^0$ | 1bar |
| $T_{wall}$ | 550K |
| $T_u$ | 822K |
| Fuel | Syngas (H2 & CO) |




Jafargholi, Frouzakis et al., LAV/ETHZ

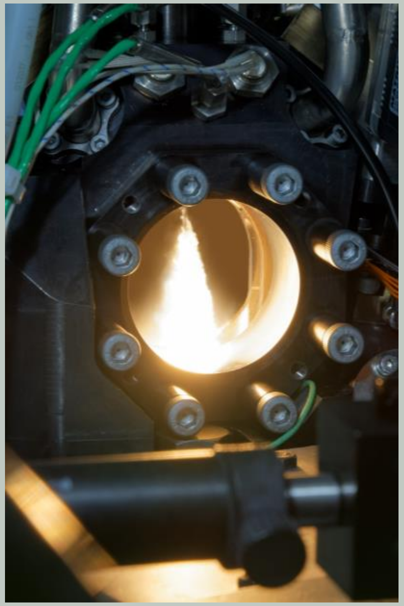
Millions of CPU hours!!

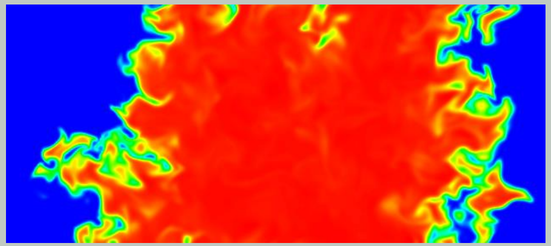
# Model Validation

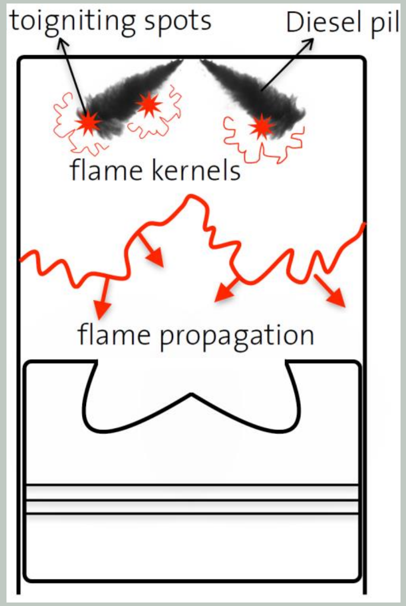
Non Premixed

Premixed

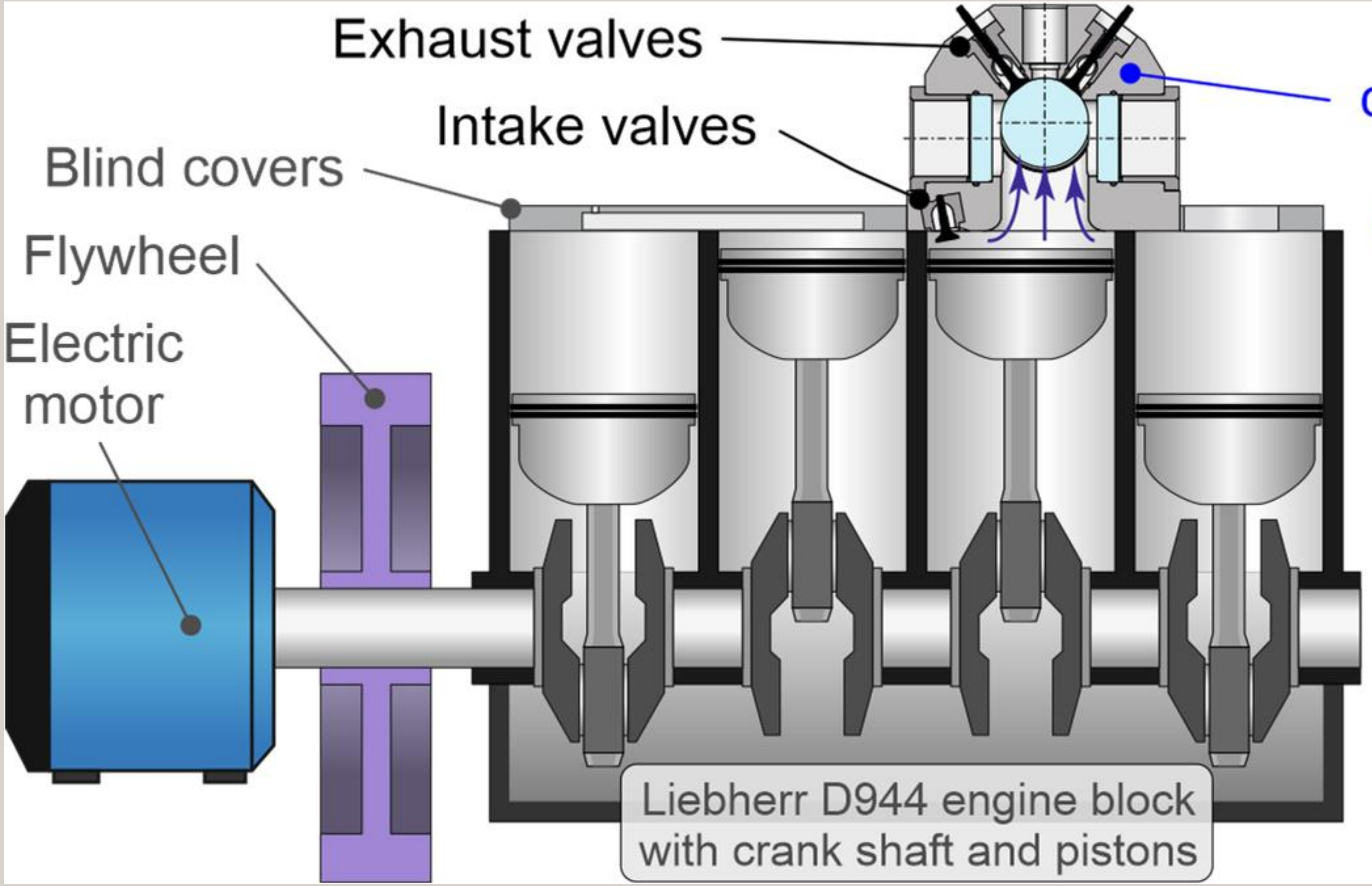
Dual Fuel

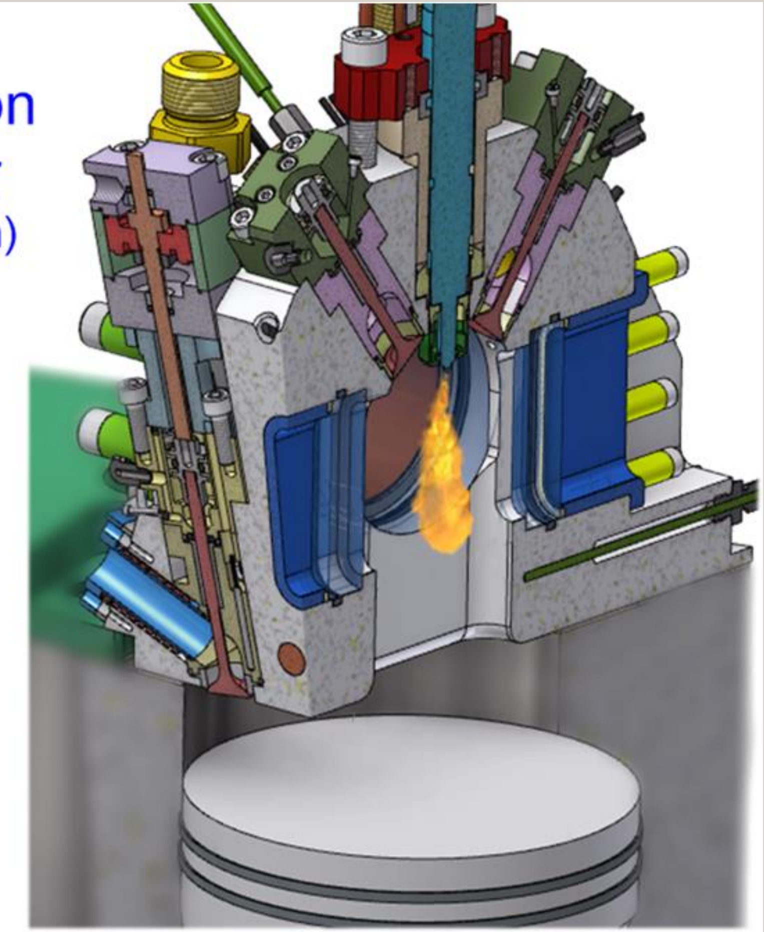






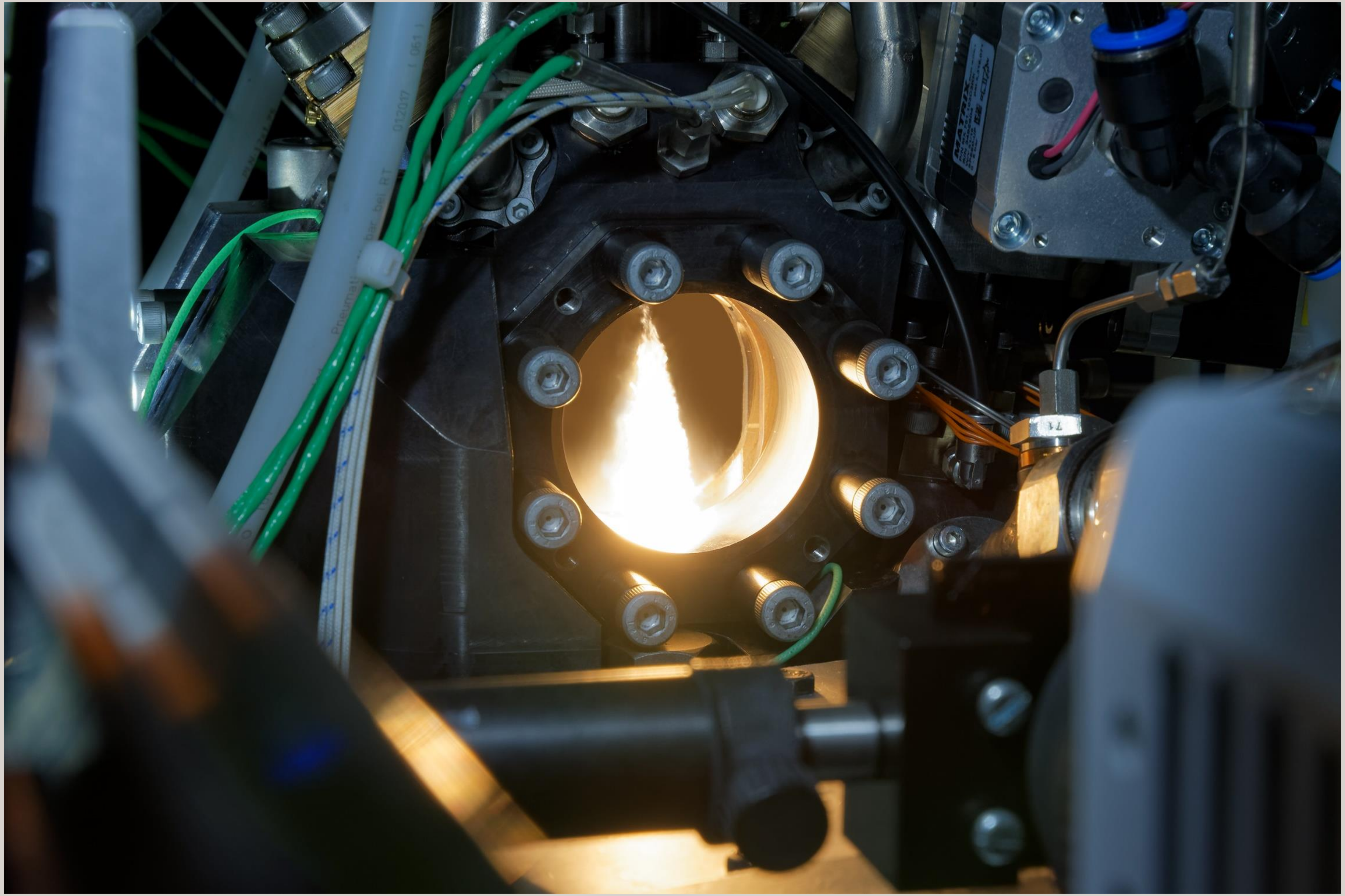
# The Test Rig – an Overview



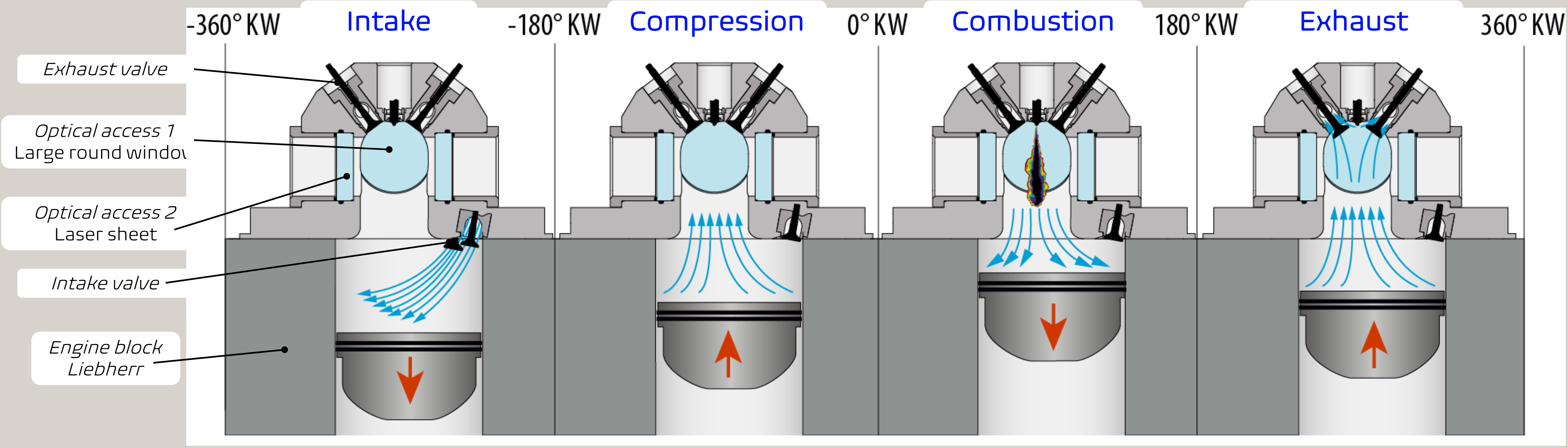
Characterization of dual-fuel combustion processes
D. Humair, P. Cartier, P. Süess, S. Wüthrich, K. Herrmann, C. Barro, B. Schneider, C. Schürch, K. Boulouchos

# Optical Access?



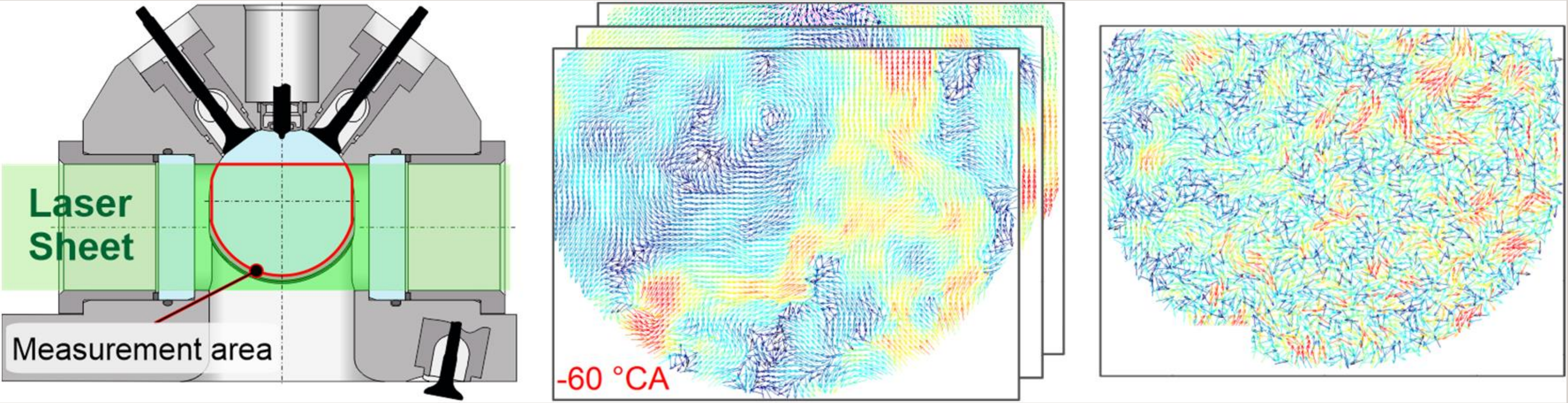
# Test Rig Working Principle

ETH zürich LAV
n|w University of Applied Sciences and Arts Northwestern Switzerland




Schneider, B.; Schürch, C.; Boulouchos, K.; Herzig, S.; Hangartner, M.; Humair, D.; Wüthrich, S.; Gossweiler, C.; Herrmann, K. The Flex-OeCoS—a Novel Optically Accessible Test Rig for the Investigation of Advanced Combustion Processes under Engine-Like Conditions. *Energies* **2020**, *13*, 1794. https://doi.org/10.3390/en13071794

# PIV – Results I

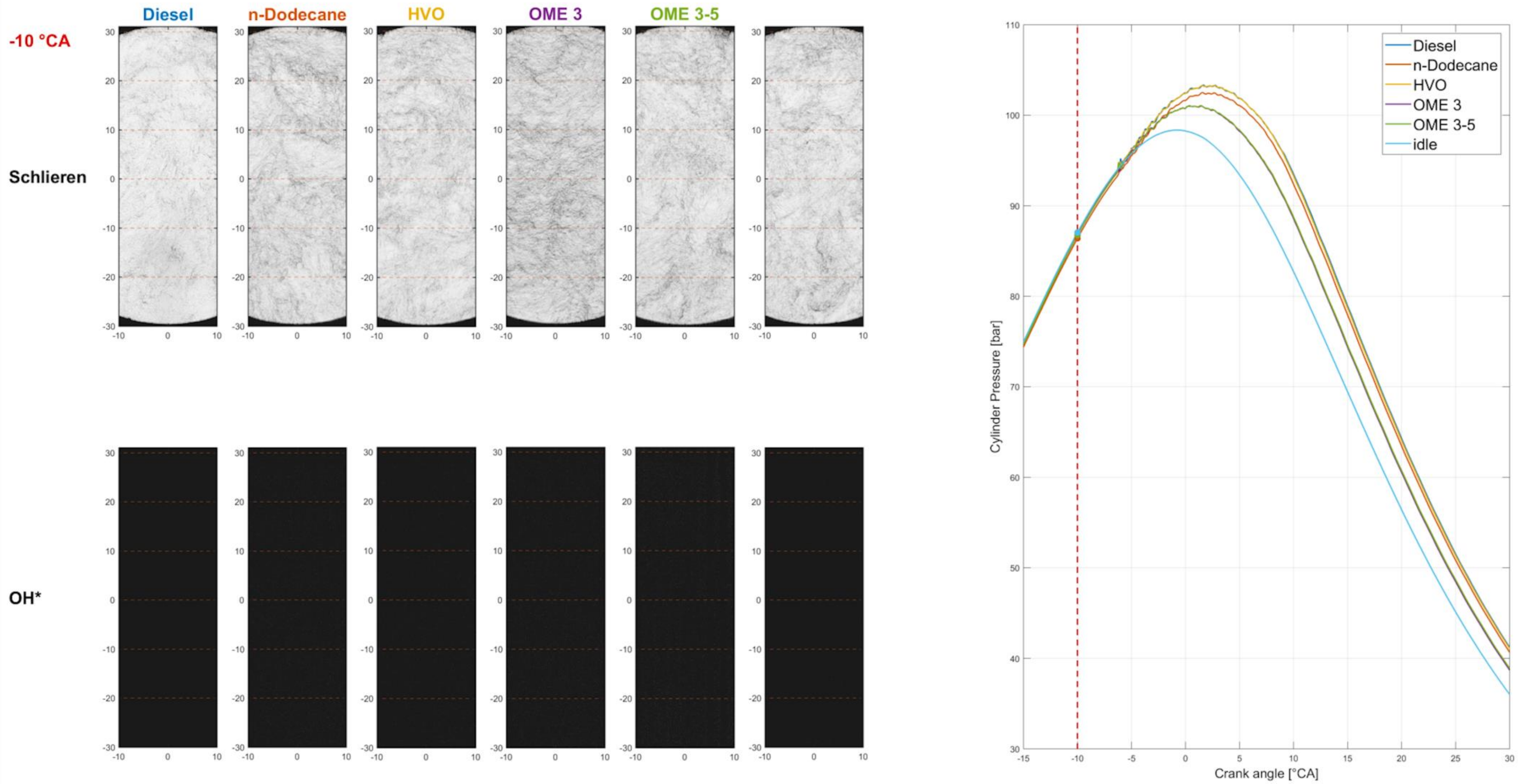



**Characterization of dual-fuel combustion processes**
D. Humair, P. Cartier, P. Süess, S. Wüthrich, K. Herrmann, C. Barro, B. Schneider, C. Schürch, K. Boulouchos

Schneider, B.; Schürch, C.; Boulouchos, K.; Herzig, S.; Hangartner, M.; Humair, D.; Wüthrich, S.; Gossweiler, C.; Herrmann, K. The Flex-OeCoS—a Novel Optically Accessible Test Rig for the Investigation of Advanced Combustion Processes under Engine-Like Conditions. *Energies* **2020**, *13*, 1794. https://doi.org/10.3390/en13071794

# Optical Diagnostics for Diesel Operation

## Fuel Variation



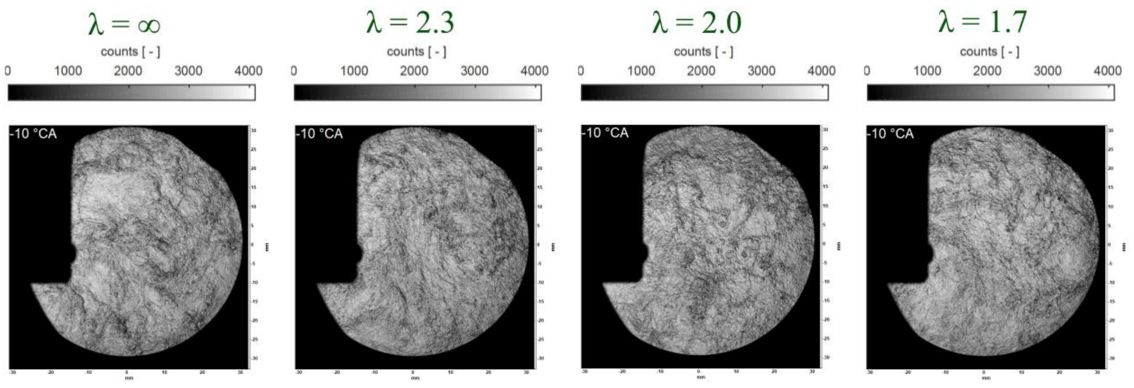

Schneider, B.; Schürch, C.; Boulouchos, K.; Herzig, S.; Hangartner, M.; Humair, D.; Wüthrich, S.; Gossweiler, C.; Herrmann, K. The Flex-OeCoS—a Novel Optically Accessible Test Rig for the Investigation of Advanced Combustion Processes under Engine-Like Conditions. *Energies* **2020**, *13*, 1794. https://doi.org/10.3390/en13071794

# Schlieren Imaging for Dual Fuel Operation

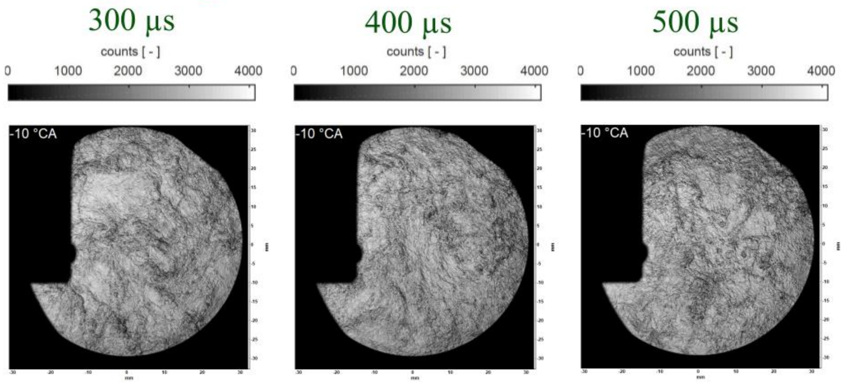
ETH zürich LAV

n|w University of Applied Sciences and Arts Northwestern Switzerland

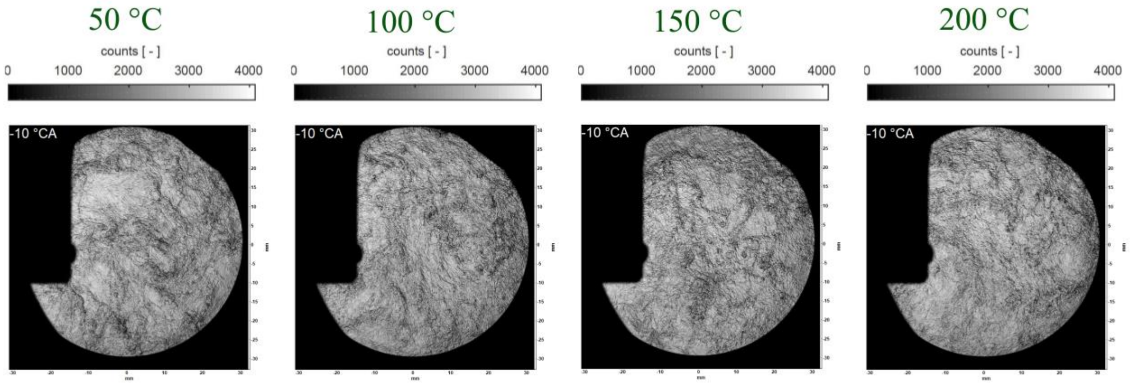
## Lambda Variation




## Energizing Time Variation




## Temperature Variation

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# Stay Tuned For More CFD Results!

# Summary

## We must act NOW

~50 Gtons $CO_2$ in 30 years

## Combustion Engines are not that bad

Fossil fuel is

## The shipping industry's future is still unclear

Communication between academia and industry is crucial

## Dual Fuel engines could be the solution

They are already gaining popularity

## A good dual fuel CFD model will already mitigate thousands of tons of $CO_2$

Industry still relies heavily on experimental R&D testing

## We as academic researchers must play our role in the energy challenge

Develop fast and reliable tools to help engine manufacturers

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