6th Two-Day Meeting on Propulsion Simulations Using OpenFOAM Technology

Modelling of hydrogen-fueled spark-ignition engines for light-duty applications

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ENGINE COMBUSTION NETWORK

- ECN
- Valencia
- Dumarey

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

DUMAREY

Outline

1) **Background and motivation**

2) **Direct injection configuration**: *Sandia's optical H2 engine* (**SOpHy**)
   - Experimental setup
   - Numerical models
   - Results

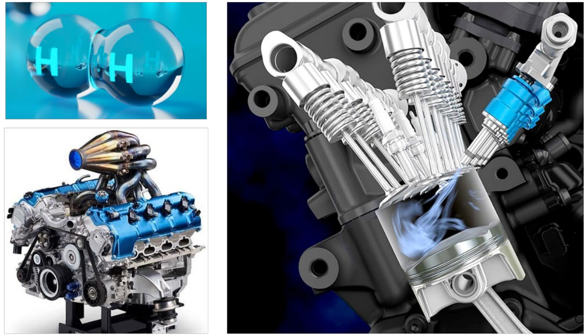
3) **Port-fuel injection configurations**:
   Valencia's pent-roof (**PenHy**) *and Dumarey's flat-head* (**FLHy**) H2 engines
   - Experimental setup
   - Numerical models
   - Results

4) **Conclusions**

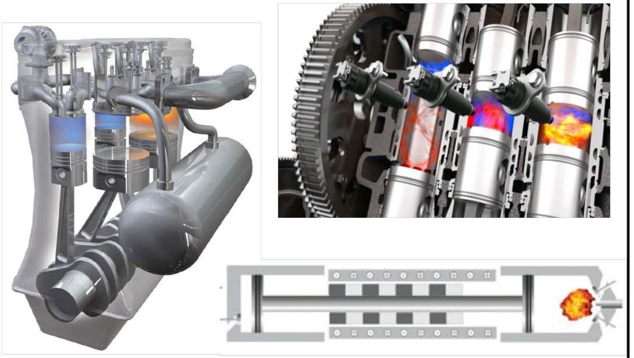
Future of IC engines

- Efficiency increase
- Reduction of emissions
- New applications

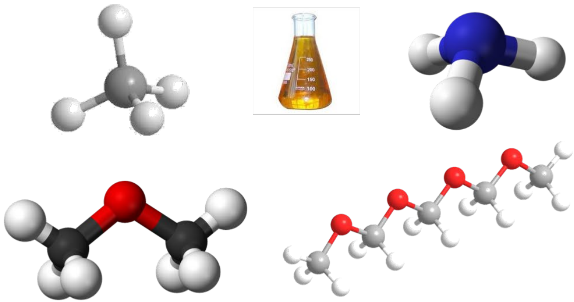
Hydrogen engines



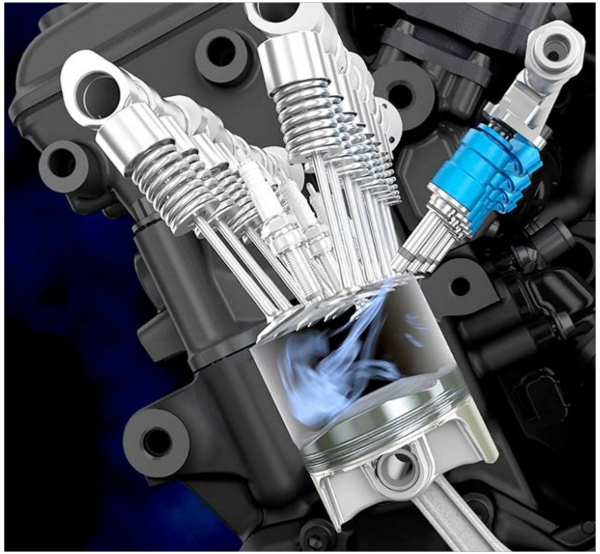
New engine concepts



Alternative fuels



Hydrogen engines



A solution to decarbonize powertrain technology

Non-conventional fuel

⇩

Need to assess consolidated CFD models

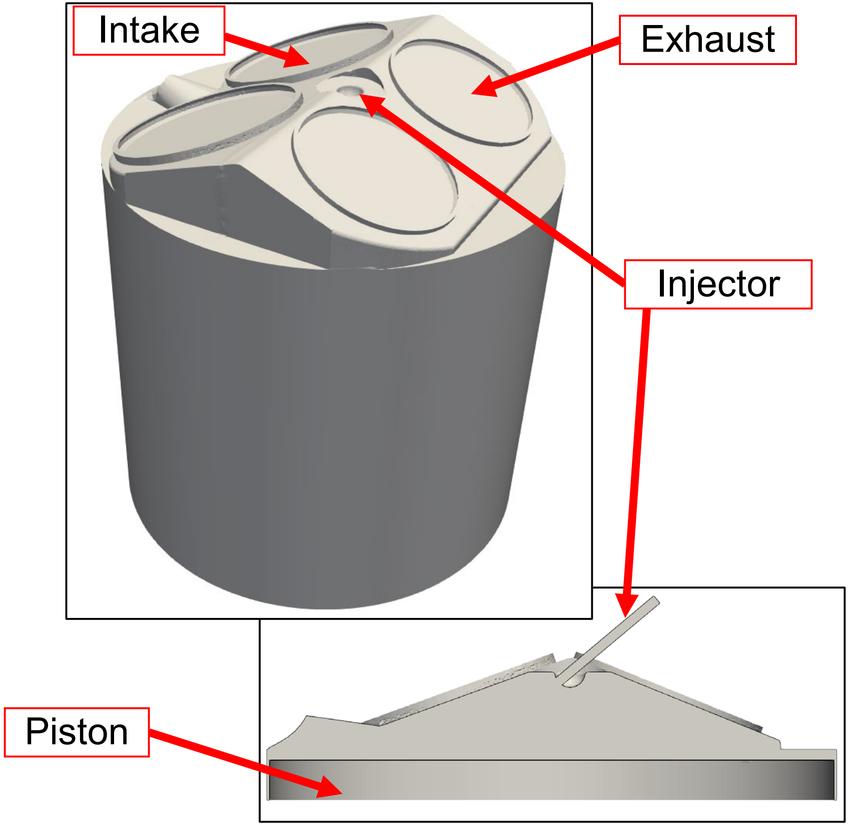
Direct injection H_2 engine

SOpHy

Experimental setup – *DI – SOpHy*

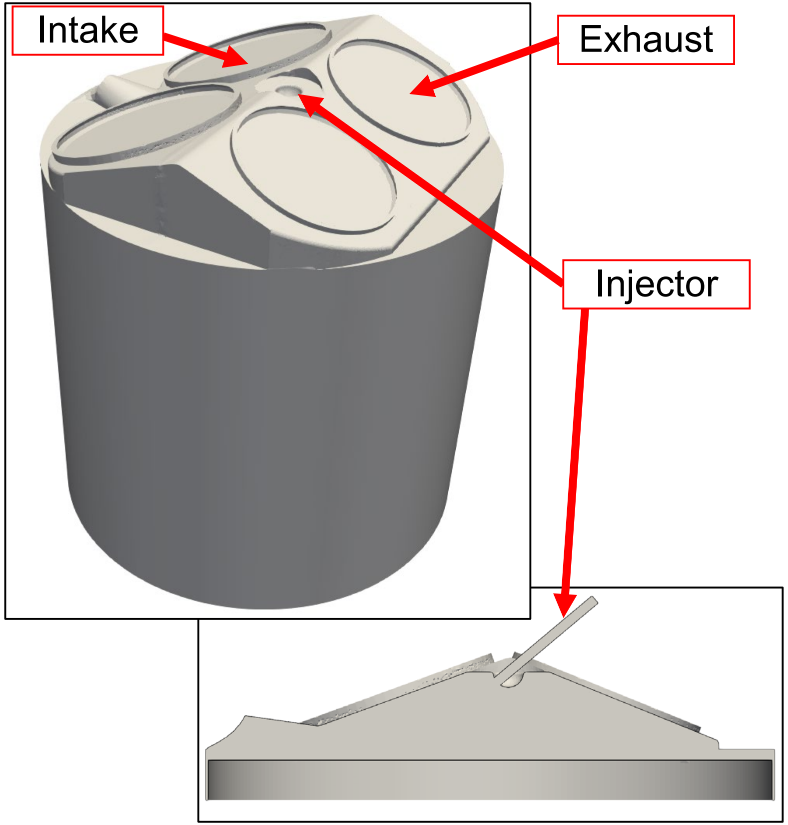
- **1-hole injector**
- **Flat piston**

Feature	Value	U.o.M.
Bore	92	[mm]
Stroke	85	[mm]
Conn. rod length	166.6	[mm]
Compression ratio	11	[-]
IVC	-140	[CAD aTDC]
EVO	130	[CAD aTDC]



Experimental setup – *DI – SOpHy*

- 1-hole injector
- Flat piston
- **Non-reacting condition** → DI of H_2 into pure N_2

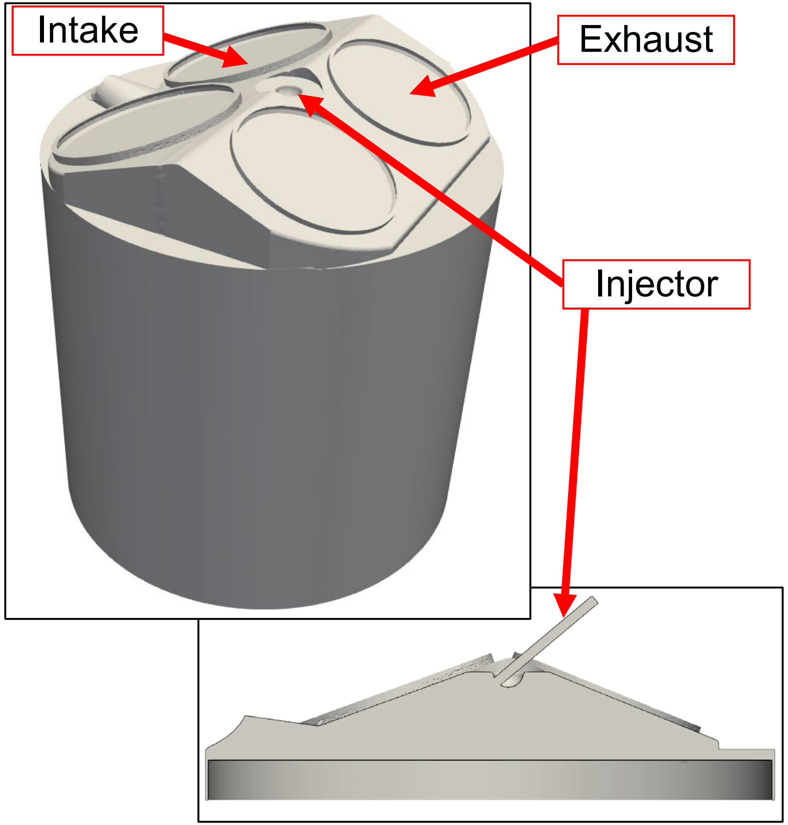


Operating condition	λ [-]	Speed [rpm]	TR [-]	IVC	SOI	DOI
				[CAD aTDC]		
DI	4.0	1500	≈ 0	-140	-137	17.5

Experimental setup – *DI – SOpHy*

- 1-hole injector
- Flat piston
- Non-reacting condition → DI of H_2 into pure N_2
- **Negligible tumble**
- **H2 injection during compression**

Operating condition	λ [-]	Speed [rpm]	TR [-]	IVC	SOI	DOI
				[CAD aTDC]		
DI	4.0	1500	≈ 0	-140	-137	17.5

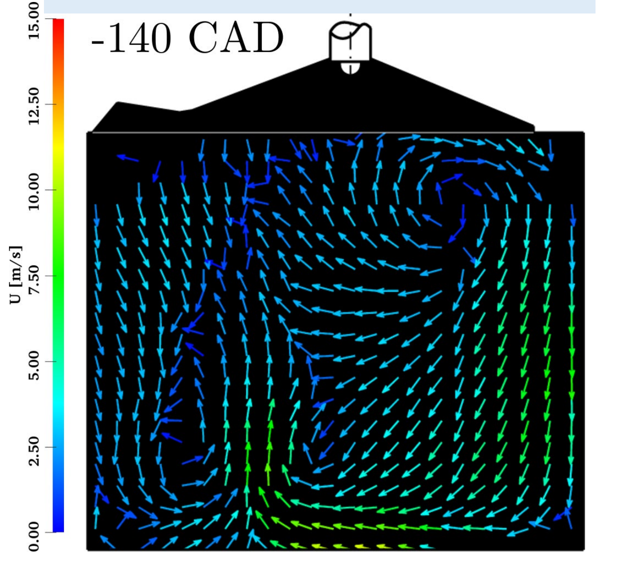


Numerical models – *DI – SOpHy*

- Only power-cycle simulation → SOI > IVC
- RANS approach
- Turbulence models → $k - \varepsilon$
- IVC flow at rest →
- IVC conditions according to measurements

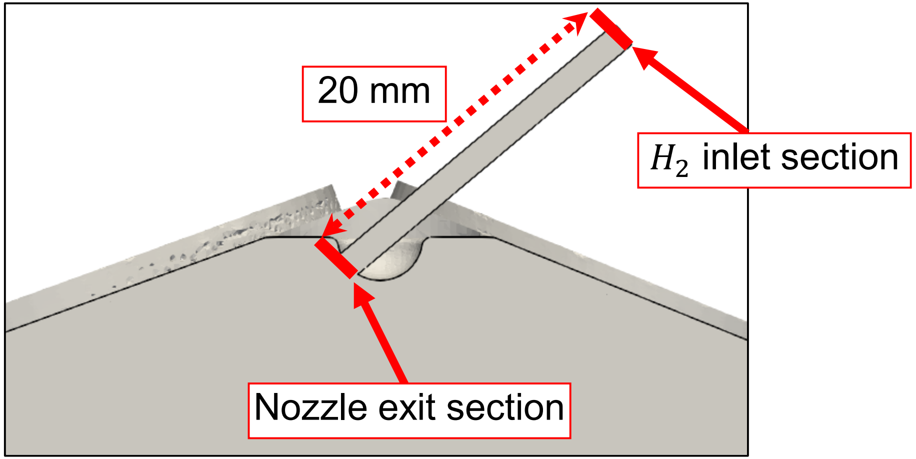
Operating condition	P_{IVC} [bar]	T_{IVC} [K]	$m_{H_2,inj}$ [mg/cycle]	H_2 inlet section	
				$\dot{m}_{H_2}$ [g/s]	T^0 [K]
DI	1.08	309.15	4.36	2.38	310

PIV measurement at IVC



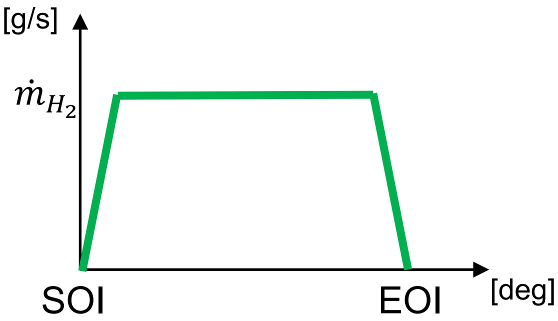
Numerical models – *DI – SOpHy*

- H_2 inlet 20 mm before nozzle exit

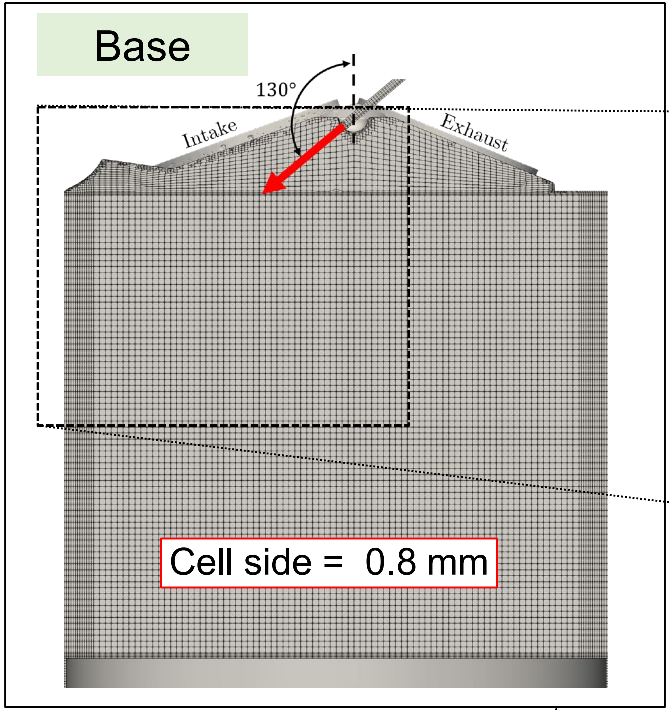


- Imposed conditions at H_2 inlet

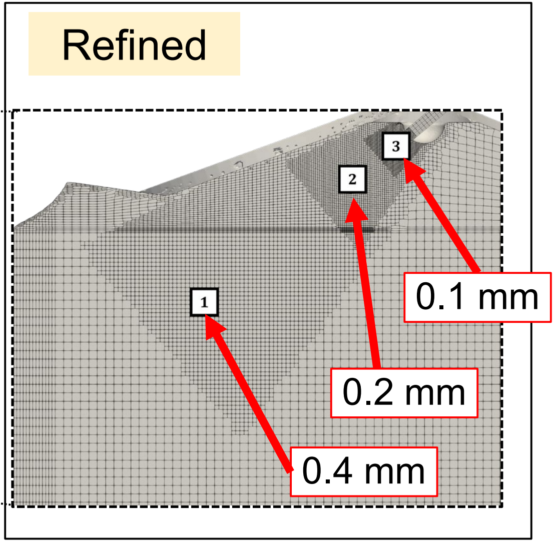
Operating condition	P_{IVC} [bar]	T_{IVC} [K]	$m_{H_2,inj}$ [mg/cycle]	H_2 inlet section	
				$\dot{m}_{H_2}$ [g/s]	T^0 [K]
DI	1.08	309.15	4.36	2.38	310



Mesh features – *DI – SOpHy*



Symmetry plane



Mesh	Max cell n. (@ IVC)
Base	600k
Refined	740k

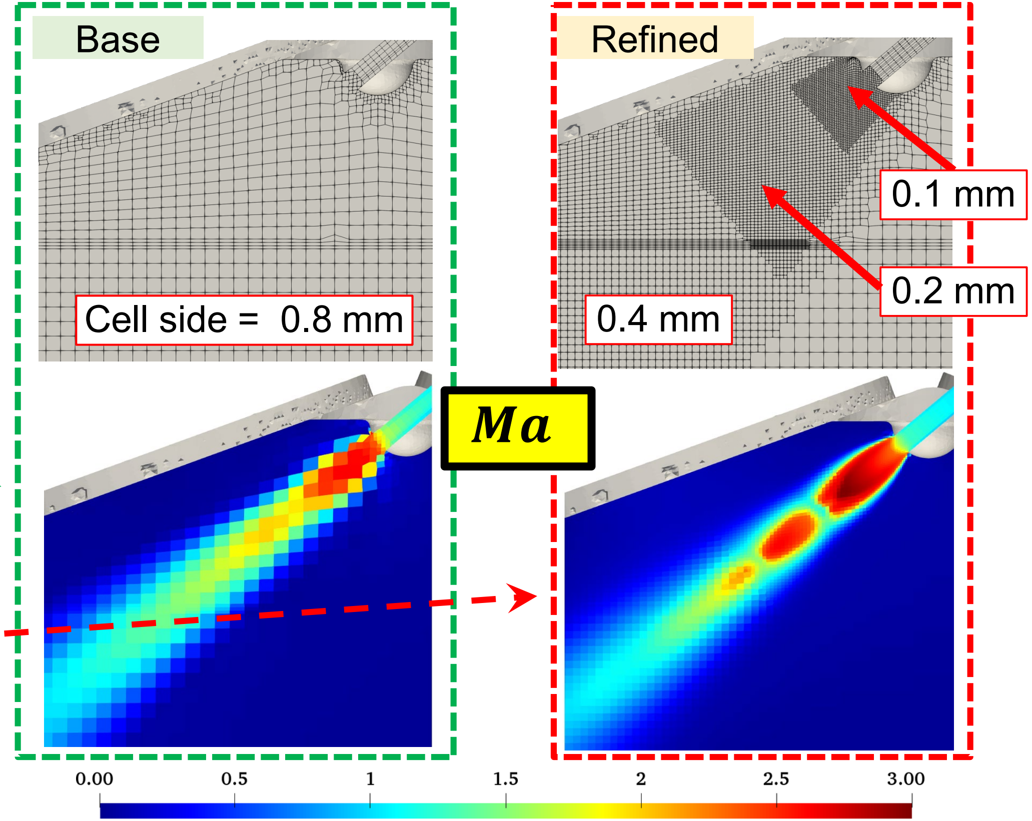
- **1/2** engine **domain**
- Non-oriented
- Hexahedral-dominant topology
- **Piston motion** with dynamic <u>addition/removal of layers</u>

Results – *DI – SOpHy*

Flow structures of
under-expanded supersonic jets

➢ <u>Base mesh</u> **fails**

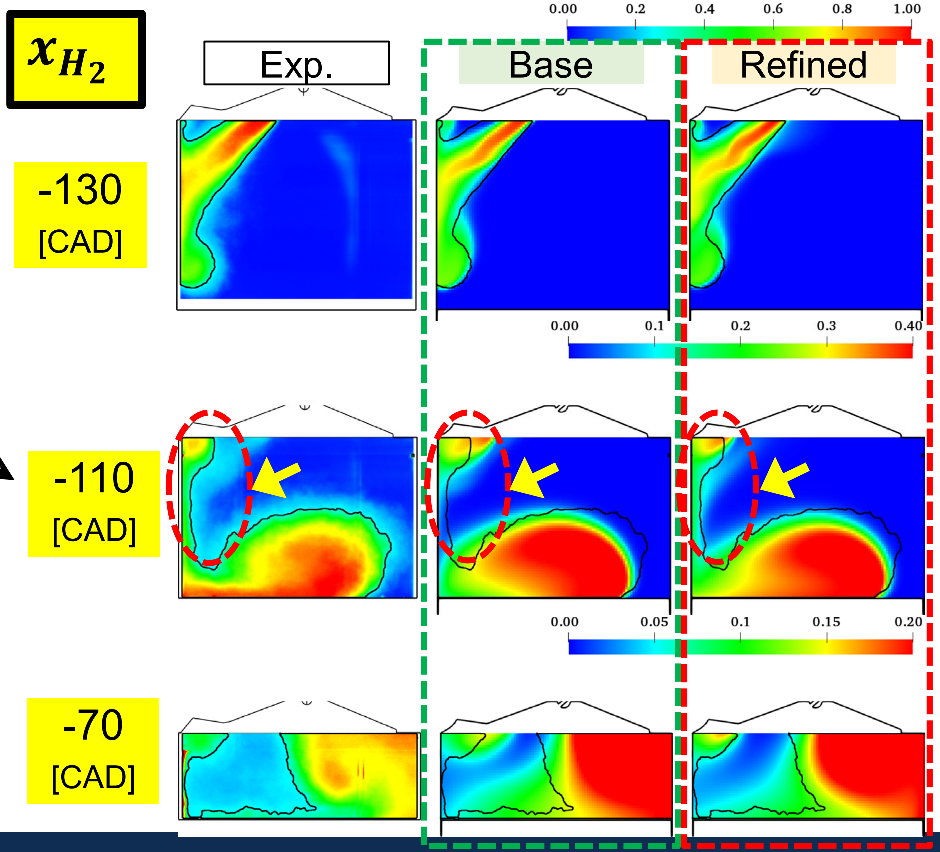
➢ <u>Refined mesh</u> seems **successful**



Results – *DI – SOpHy*

- Satisfactory (with "refined" mesh):
  - Improved results near liner
  - ↑ H_2 diffusion into N_2 after EOI

↓ jet momentum
due to resolved normal shocks

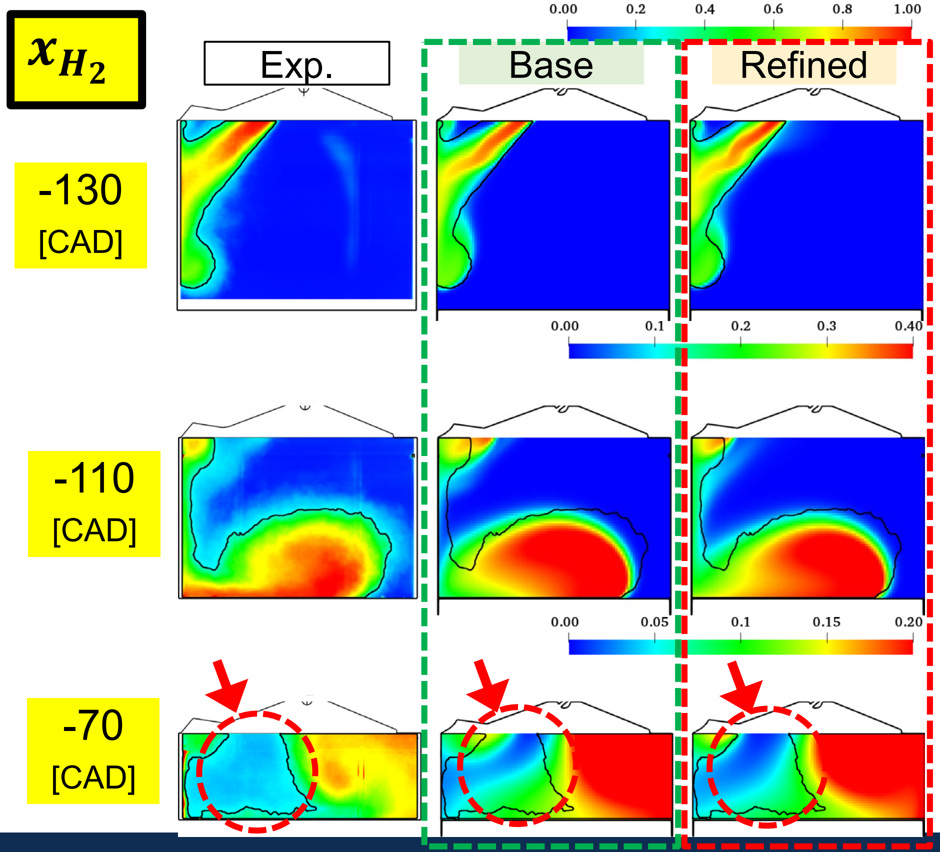


Results – *DI – SOpHy*

- Satisfactory (with "refined" mesh):
  - Improved results near liner
  - ↑ H_2 diffusion into N_2 after EOI

↓ jet momentum
due to resolved normal shocks

- Lacks (with "refined" mesh):
  - ↓ H_2 diffusion into N_2 during compression →

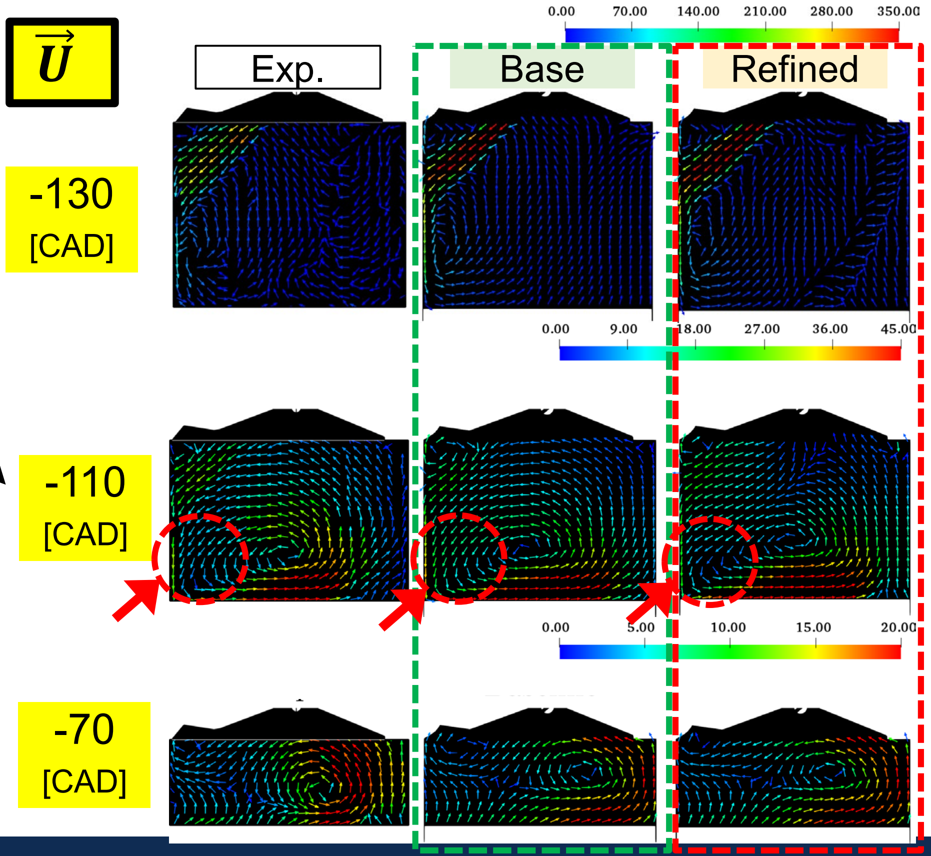


Results – *DI – SOpHy*

- Satisfactory (with "refined" mesh):
  - Improved results near liner
  - ↑ H_2 diffusion into N_2 after EOI

↓ jet momentum

↑ agreement with exp.



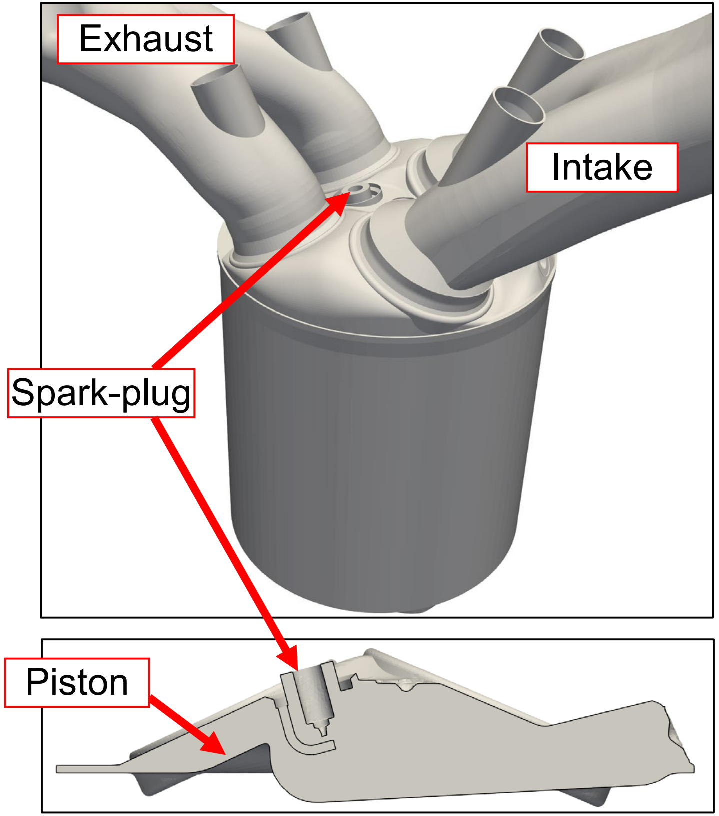
Port-fuel injection H_2 engine

PenHy

Experimental setup – *PFI – PenHy*

- **Central spark-plug**
- **Shaped piston**

Feature	Value	U.o.M.
Bore	84	[mm]
Stroke	86	[mm]
Conn. rod length	144	[mm]
Compression ratio	11	[-]
IVC	-134.8	[CAD aTDC]
EVO	119.5	[CAD aTDC]



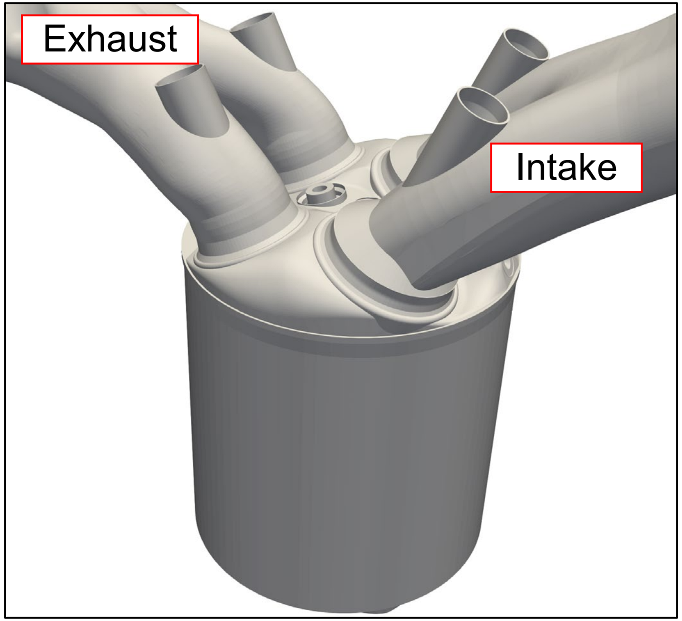
Experimental setup – *PFI – PenHy*

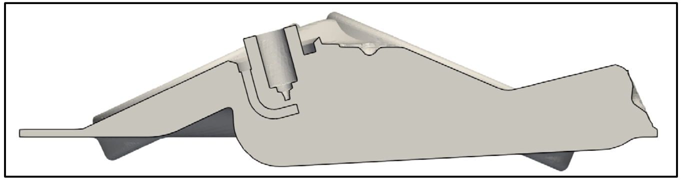
- Central spark-plug
- Shaped piston
- **High tumble**
- **Ultra-lean combustion**

Load ↑

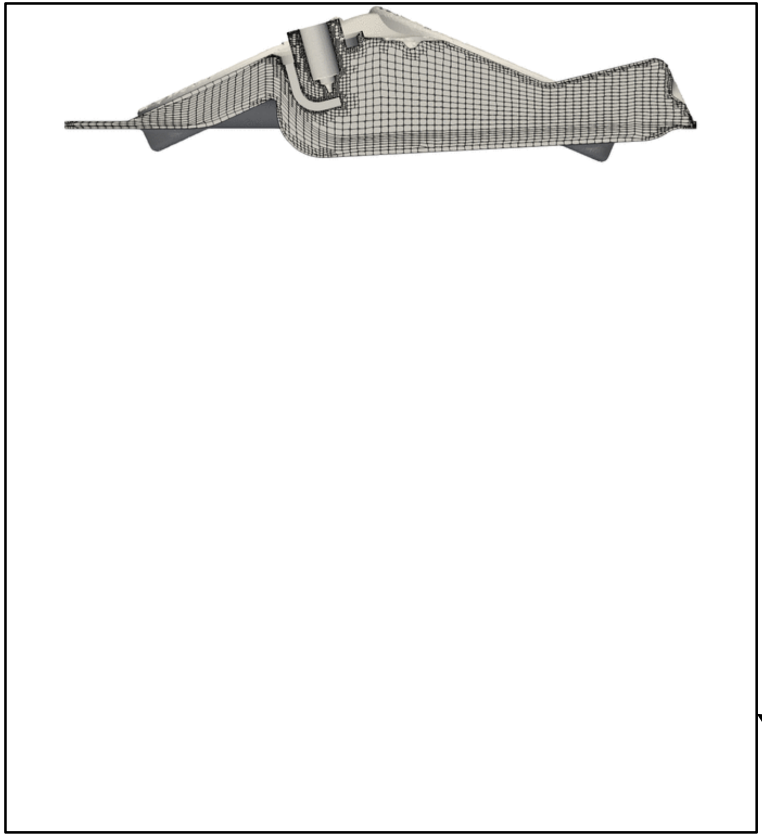
λ ↑

Operating conditions	**Speed** [rpm]	**TR** [-]	**IMEP** [bar]	λ [-]	SA [CAD aTDC]
L2.4 ML	1500	≈0.9	8.5	2.4	-24
L2.6 ML			8.5	2.6	-26
L3.0 ML			8.7	3.0	-32
L2.6 HL			11.2	2.6	-30





Numerical models – *PFI – PenHy*



Mesh features

- **1/2** engine **domain**
- Non-oriented
- Hexahedral-dominant topology
- **Piston motion** with dynamic <u>addition/removal of layers</u>

Cell side = 0.8 mm

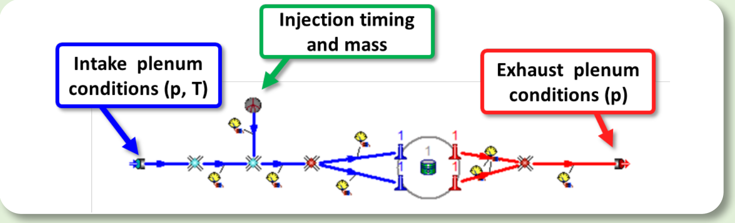
Symmetry plane

Numerical models – *PFI – PenHy*

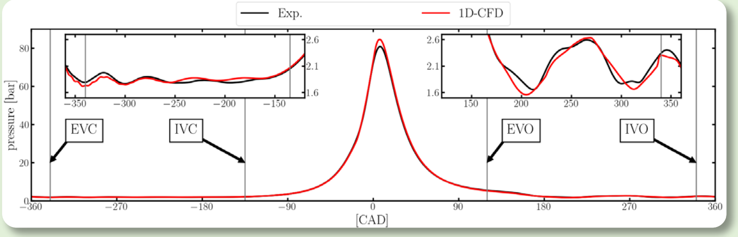
"Fast" 1D-3D approach

1D: multi-cycle

- Full engine schematic



- Multi-cycle simulation

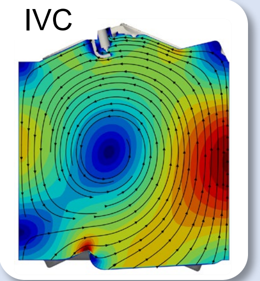


3D: power-stroke

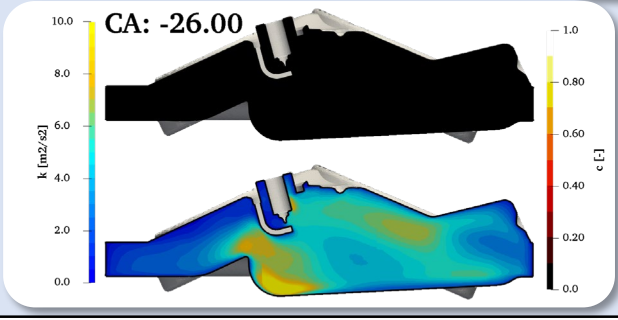
- IVC initialization

In cylinder P_{IVC} and T_{IVC}

Tumble initialization



- Power-stroke simulation



Numerical models – *PFI – PenHy*

IVC tumble initialization

Initialization

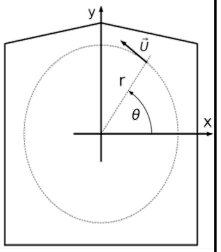
Turbulence

$$u' = C_t U_{mean}$$
$$k = \frac{3}{2}(u')^2$$
$$\varepsilon = C_\mu^{3/4} \frac{k^{3/2}}{C_l D}$$

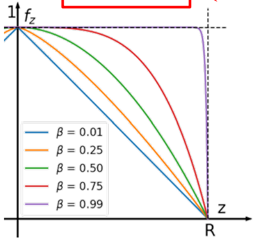
Velocity

$$TR = \frac{\iiint_{vol} (-U_x y + U_y x)\, dV}{\omega \iiint_{vol} (x^2 + y^2)\, dV}$$

$$\begin{cases} U_x = \hat{U}\, f_z(z)\, f_r(x,y) \left(\vec{\tau} \cdot \hat{i}_x\right) \\ U_y = \hat{U}\, f_z(z)\, f_r(x,y) \left(\vec{\tau} \cdot \hat{i}_y\right) \\ U_z = 0 \end{cases}$$

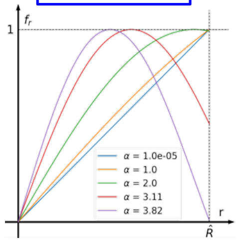


Axis



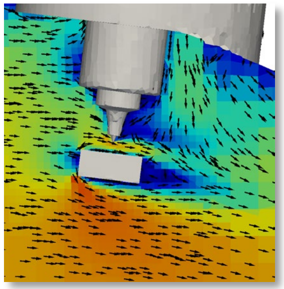
Tumble shape functions

Radius



Adaptation

Fixed piston position

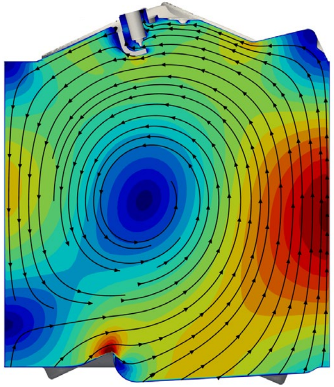


Adaptation time

$$\Delta t = C_\tau \frac{C_l D}{U_{mean}} \propto \tau_{turb}$$

Correction

Rescaled $\vec{U}$ field for energy losses



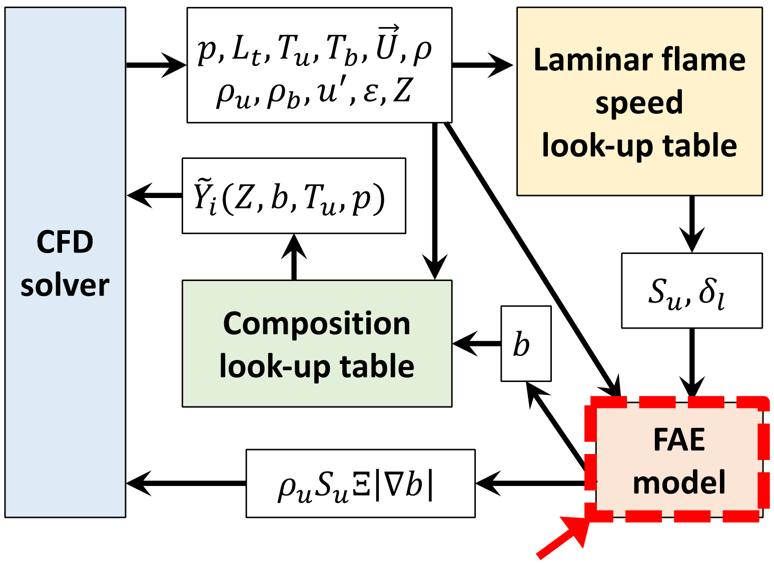
Initialized 1-eddy structure ⟺ **Actual multi-eddy structure**

Premixed combustion models – *PFI – PenHy*

Ignition deposition model

LibICE OpenFOAM

$$\frac{\partial \rho \tilde{b}}{\partial t} + \nabla \cdot \left(\rho \tilde{\boldsymbol{U}} \tilde{b}\right) + \nabla \cdot \left(\mu_t \nabla \tilde{b}\right) = \rho_u \tilde{S}_u \tilde{\Xi} \left|\nabla \tilde{b}\right| + \dot{\omega}_{ign}$$



Turbulent flame propagation

$$\Xi = \frac{S_t}{S_u} = f\left(\Xi_{eq}^*\right)$$

Peters' correlation

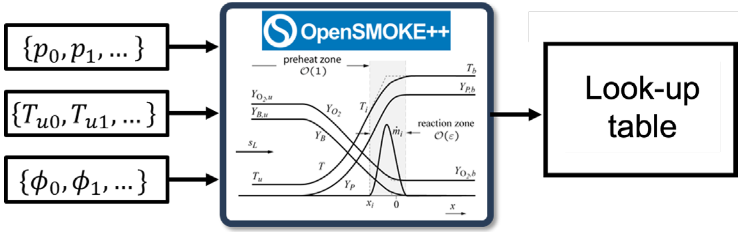
$$\Xi_{eq}^* = 1 - \frac{a_4 b_3^2}{2 b_1} \frac{L_t}{\delta_l} + \left[\left(\frac{a_4 b_3^2}{2 b_1} \frac{L_t}{\delta_l}\right)^2 + a_4 b_3^2 \frac{u'}{S_u} \frac{L_t}{\delta_l}\right]^{1/2}$$

Premixed combustion models – *PFI – PenHy*

- **Chemical composition**

$$Y_i = b\,Y_{u,i} + (1-b)\,Y_{b,i}$$

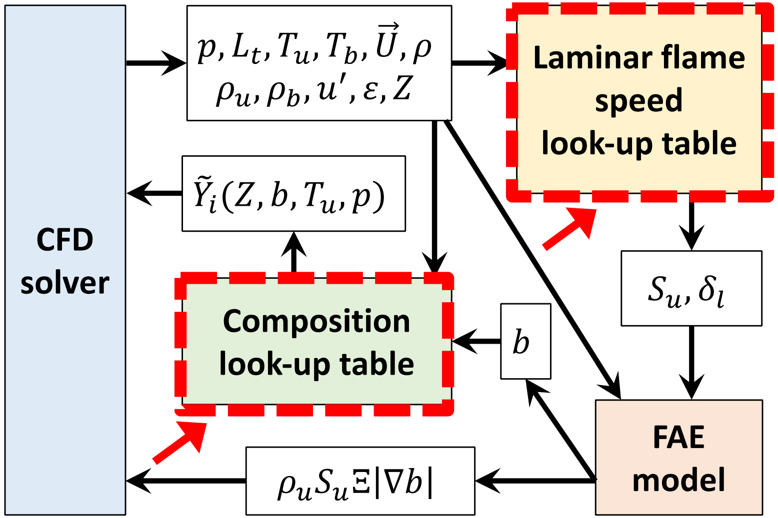
- **Tabulated kinetics**



$\boldsymbol{Y_{u,i}}$ **and** $\boldsymbol{Y_{b,i}}$

$\boldsymbol{S_{u0}}$

LibICE OpenFOAM



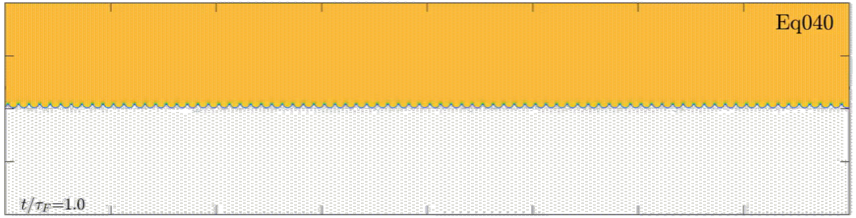
- **Laminar flame speed**

$$S_u = C_0 S_{u0}$$

S_{u0} correction for hydrodynamic instabilities [1,2]

- $\lambda \gg 1$
- $Le_{H_2} \ll 1$
- Strong H_2 preferential diffusion

$$C_0 = 1 + \left(\left. \frac{S_u}{S_{u0}} \right|_r - 1 \right) \left(\frac{\phi}{\phi_r} \right)^{\gamma_\phi} \left(\frac{T_u}{T_{u,r}} \right)^{\gamma_{T_u}} \left(\frac{p}{p_r} \right)^{\gamma_p}$$

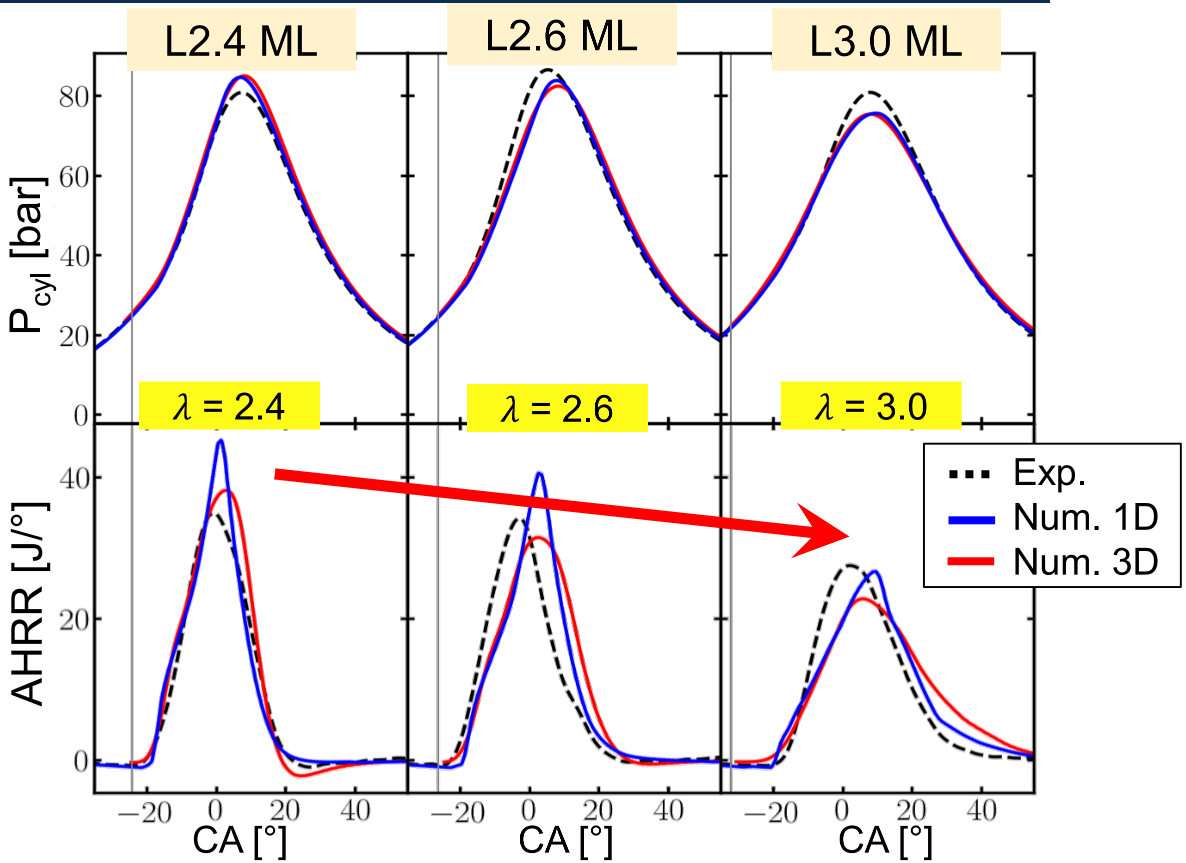


[1] L. Berger, et al., ASICI - Associazione Sezione Italiana del Combustion Institute, 2018, https://doi.org/10.18154/RWTH-2018-225009

[2] L. Berger, A. Attili and H. Pitsch, Combustion and Flame, 2022, https://doi.org/10.1016/j.combustflame.2021.111936

Results – λ effect – *PFI – PenHy*

- **Dilution effect captured**



Results – λ effect – *PFI – PenHy*

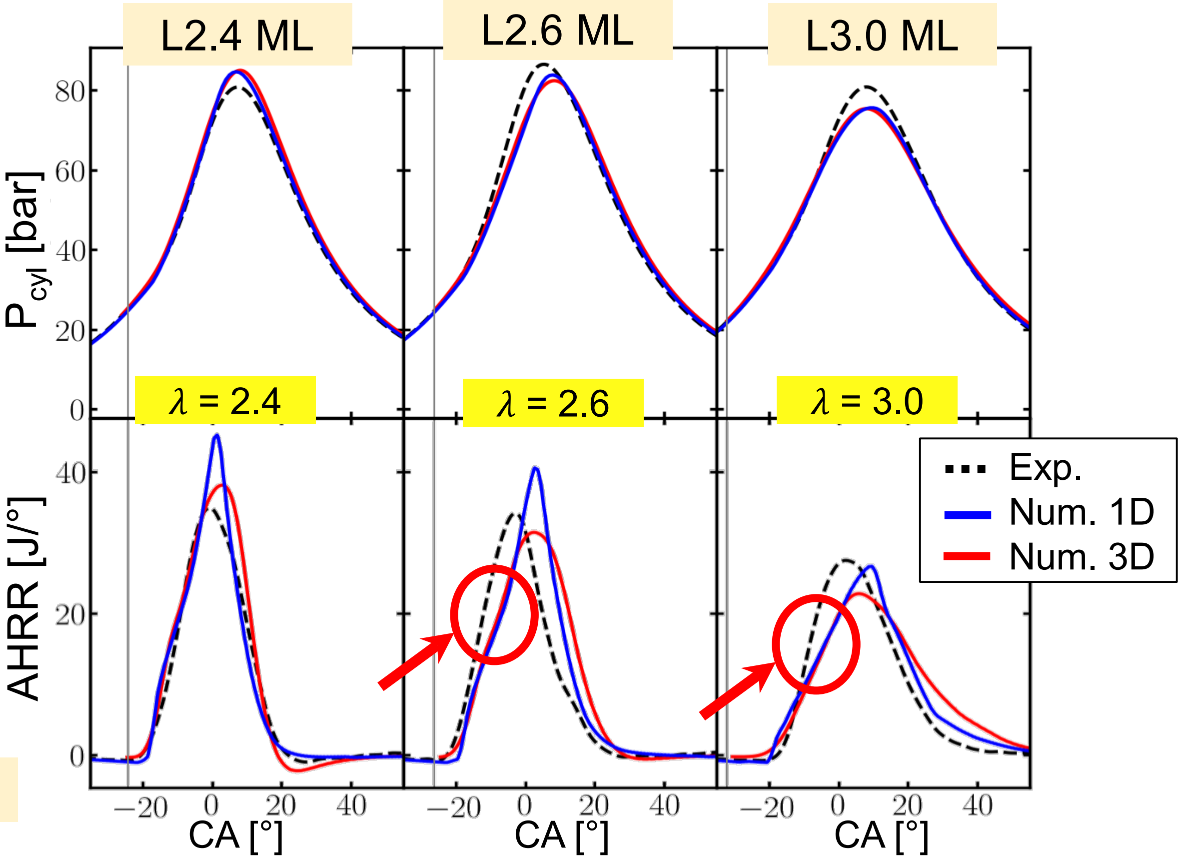
- Dilution effect captured
- **AHRR ramp underestimated at ↑ λ**

Underprediction of $\boldsymbol{S_u}$?

$$C_0 = 1 + \left(\left. \frac{S_u}{S_{u0}} \right|_r - 1 \right) \left(\frac{\phi}{\phi_r} \right)^{\gamma_\phi} \left(\frac{T_u}{T_{u,r}} \right)^{\gamma_{T_u}} \left(\frac{p}{p_r} \right)^{\gamma_p}$$

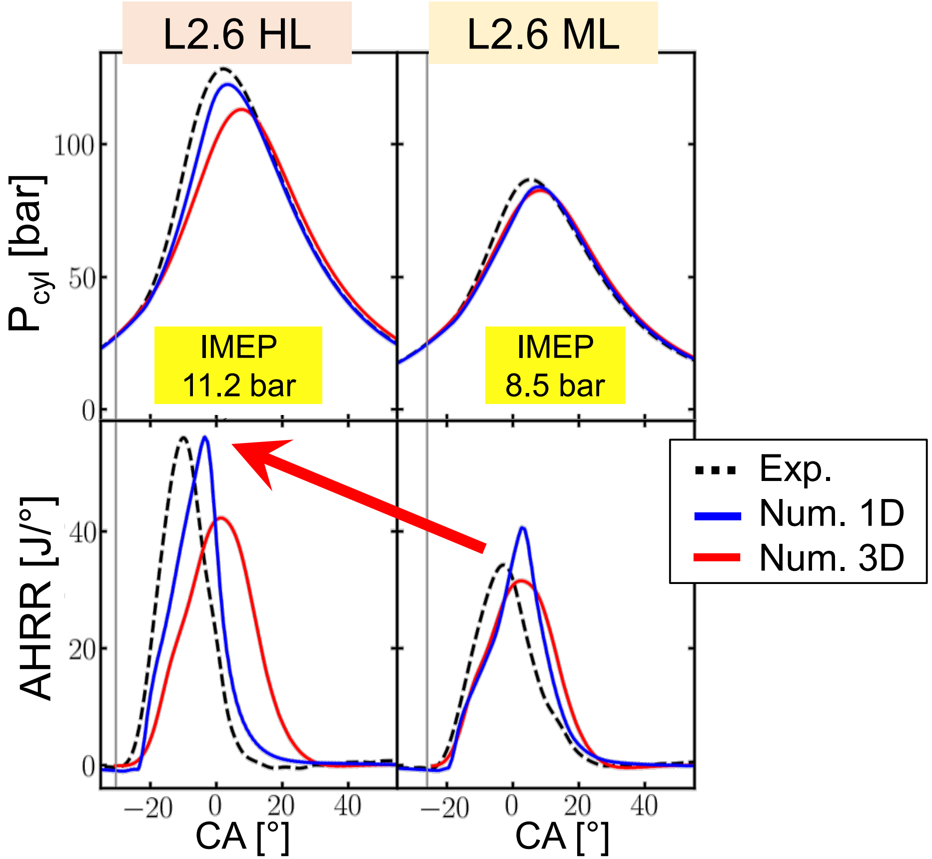
$$\boldsymbol{S_u} = C_0 \, S_{u0}$$

Validity limit: $\boldsymbol{\lambda} \leq$ **2.5**



Results – Load effect – *PFI – PenHy*

➢ **Load effect captured**



Results – Load effect – *PFI – PenHy*

- Load effect captured

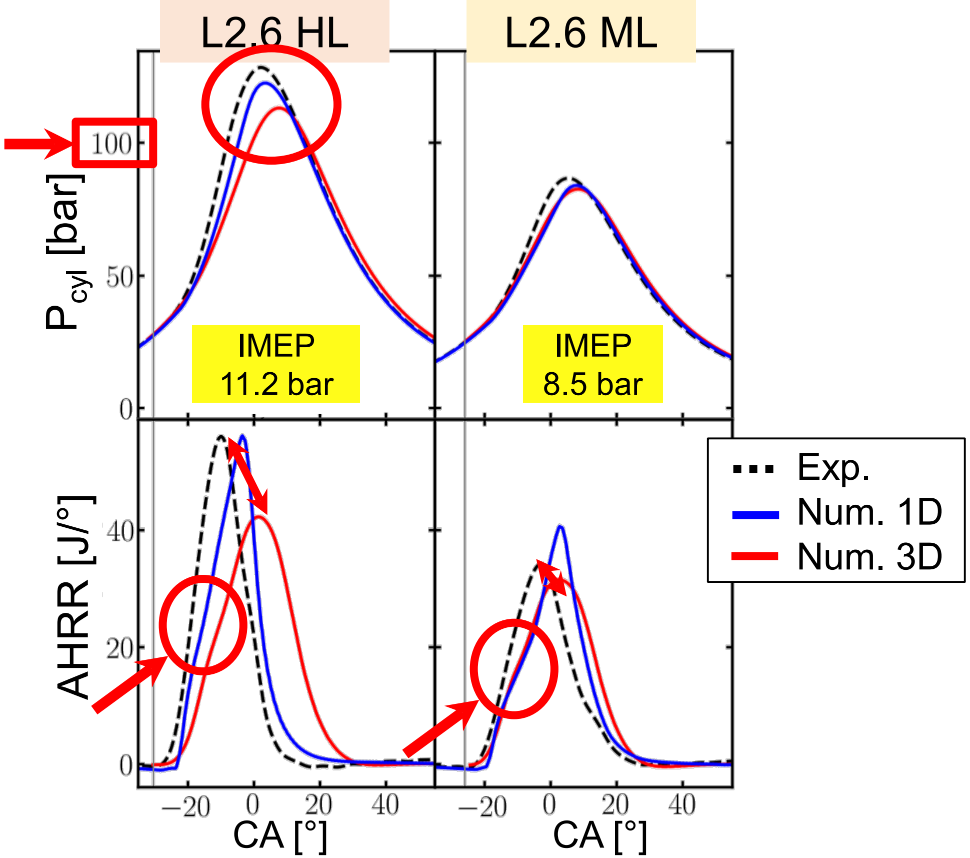
- **AHRR ramp underestimated by ↑ load**

Underprediction of $\boldsymbol{S_u}$?

$$C_0 = 1 + \left(\frac{S_u}{S_{u0}} \bigg|_r - 1 \right) \left(\frac{\phi}{\phi_r} \right)^{\gamma_\phi} \left(\frac{T_u}{T_{u,r}} \right)^{\gamma_{T_u}} \left(\frac{p}{p_r} \right)^{\gamma_p}$$

$$\boldsymbol{S_u} = C_0 \, S_{u0}$$

Validated until: **P ≤ 20 bar**



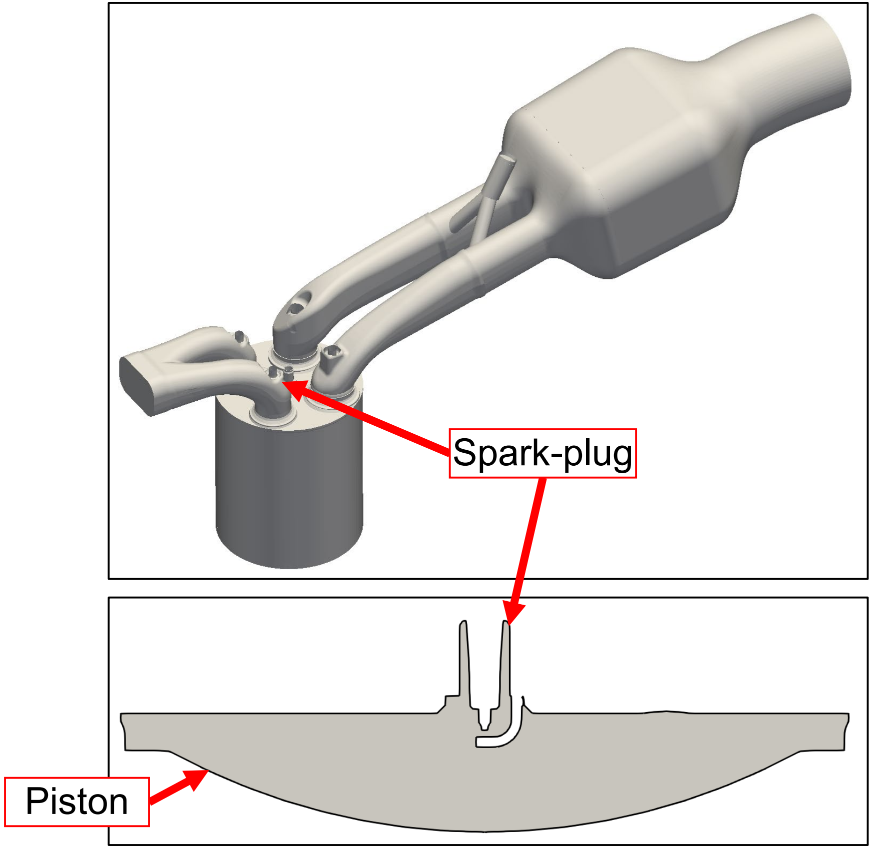
Port-fuel injection H_2 engine

FLHy

Experimental setup – *PFI – FLHy*

- **Central spark-plug**
- **Symmetrical piston bowl**

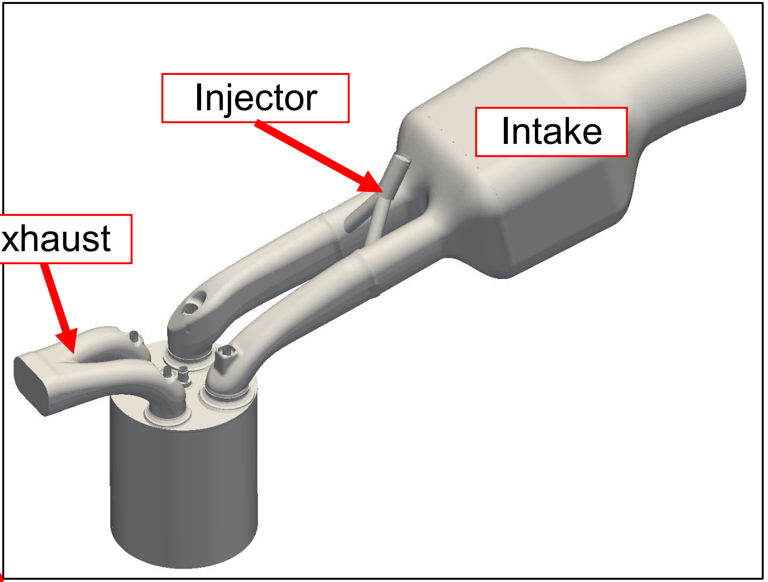
Feature	Value	U.o.M.
Bore	83	[mm]
Stroke	90	[mm]
Conn. rod length	145	[mm]
Compression ratio	12	[-]
IVC	-156.7	[CAD aTDC]
EVO	142.7	[CAD aTDC]

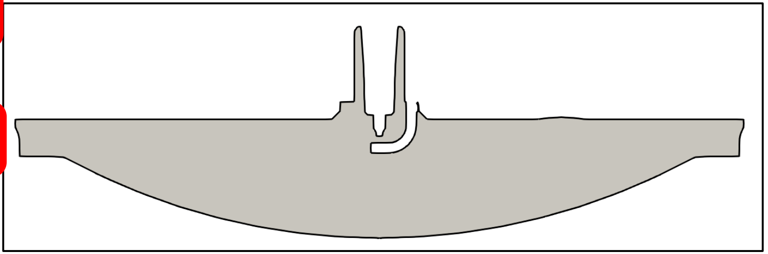


Experimental setup – *PFI – FLHy*

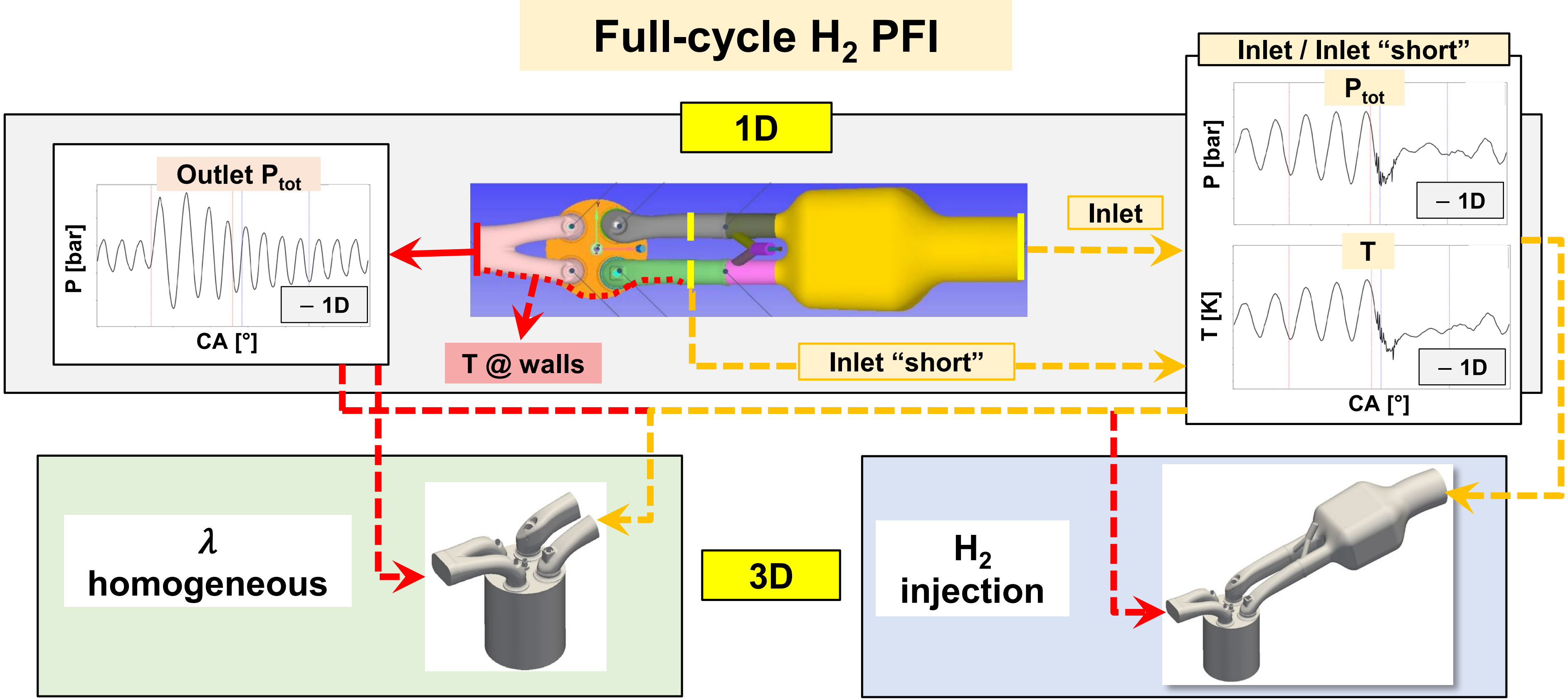
- Central spark-plug
- Symmetrical piston bowl
- **High swirl**
- **H2 injection end ≈ 120° before IVC**
- **Ultra-lean combustion**

Operating condition	λ [-]	Speed [rpm]	SR [-]	IVC	SOI	EOI
				[CAD aTDC]		
PFI	2.0	1500	≈ 1.3	-156.7	-320.8	-273.8

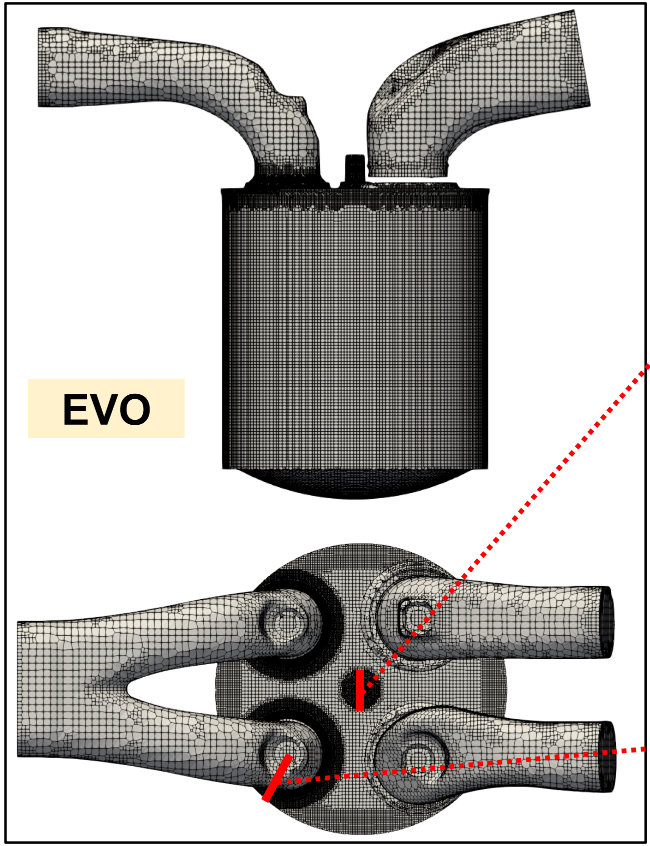


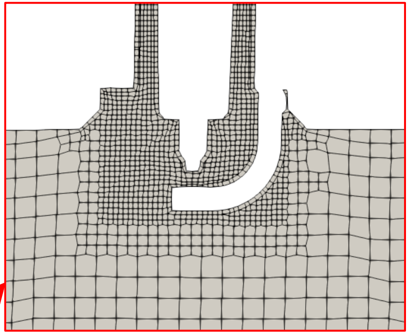


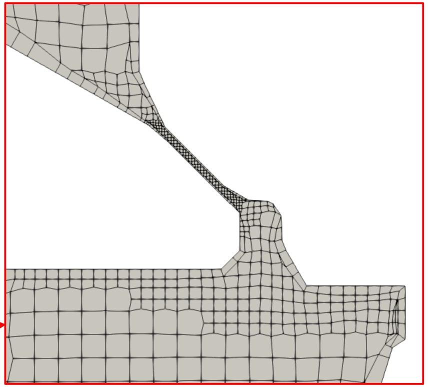
Numerical models – *PFI – FLHy*



Mesh features – λ homogeneous – *PFI – FLHy*



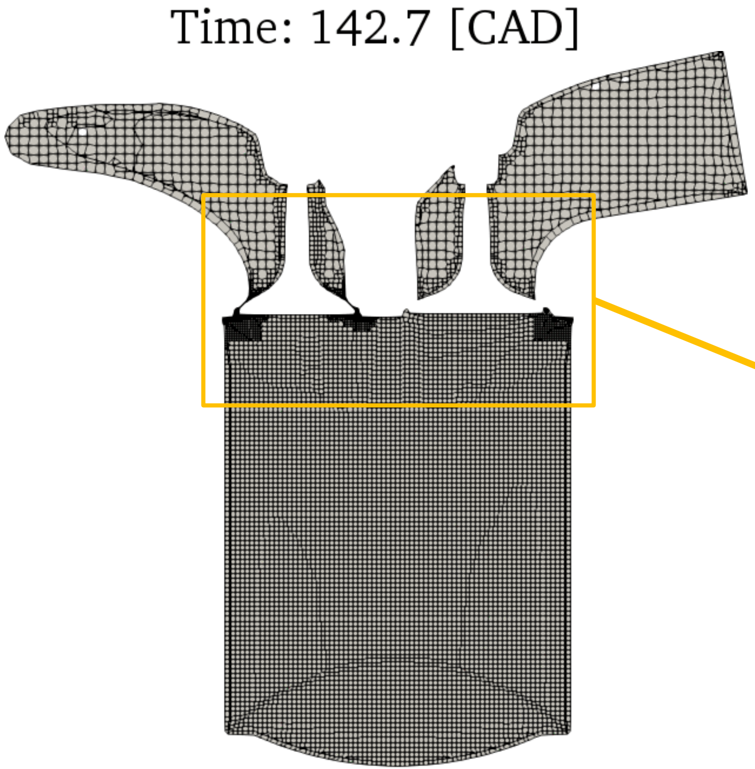




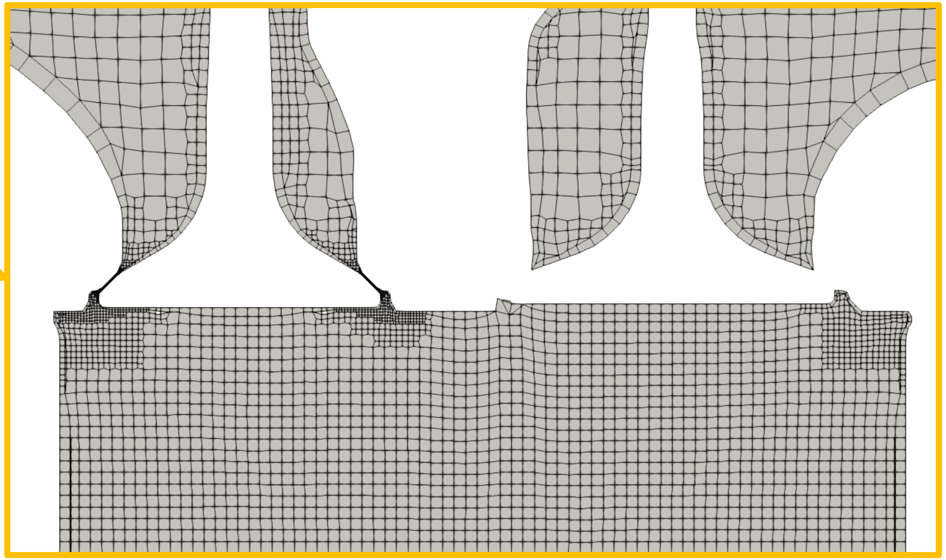
- **Full** engine **domain**
- Non-oriented
- Hexahedral-dominant topology

Mesh	Cell size
Base	2 mm
In-cyl	1 mm
Max ref.	5e-2 mm

Mesh features – λ homogeneous – *PFI – FLHy*



Piston / valves motion



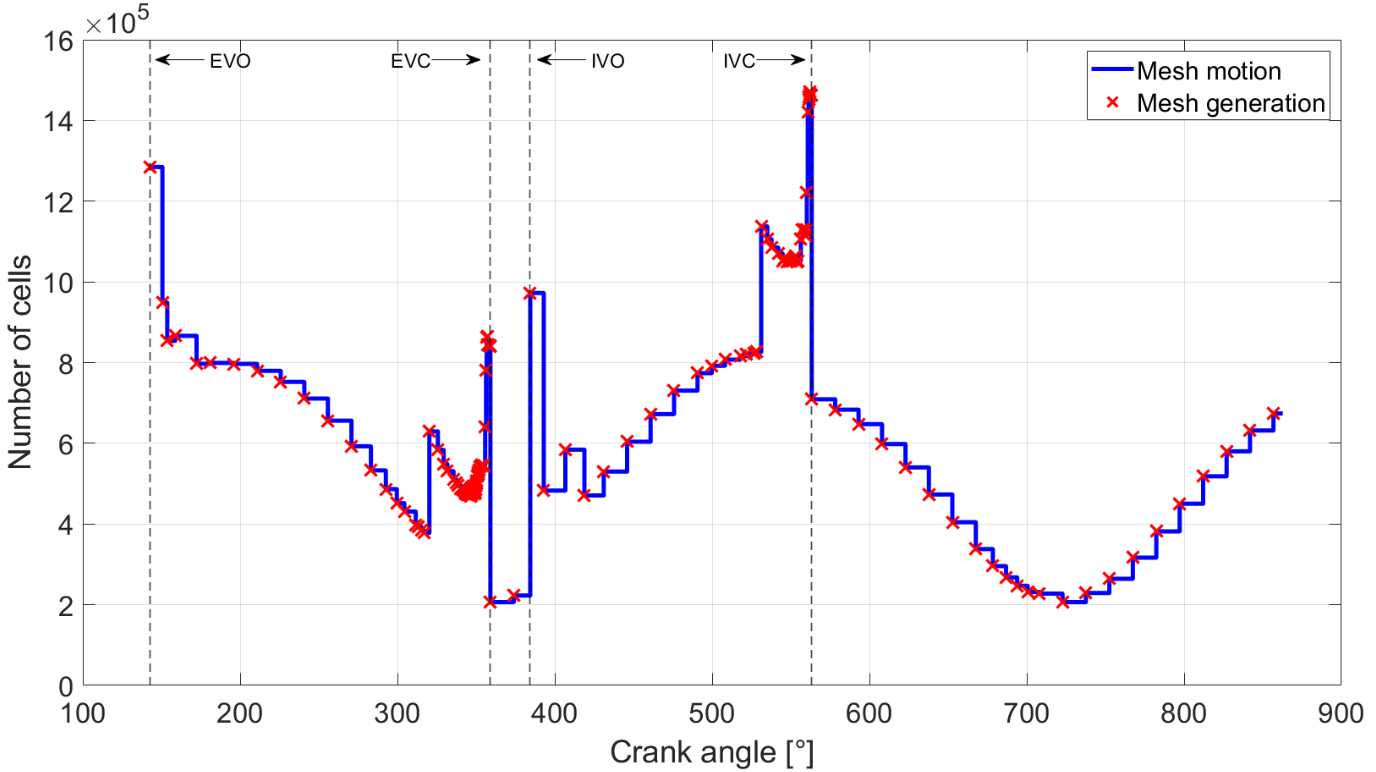
mesh deformation + multiple-meshes

Mesh features – λ homogeneous – *PFI – FLHy*

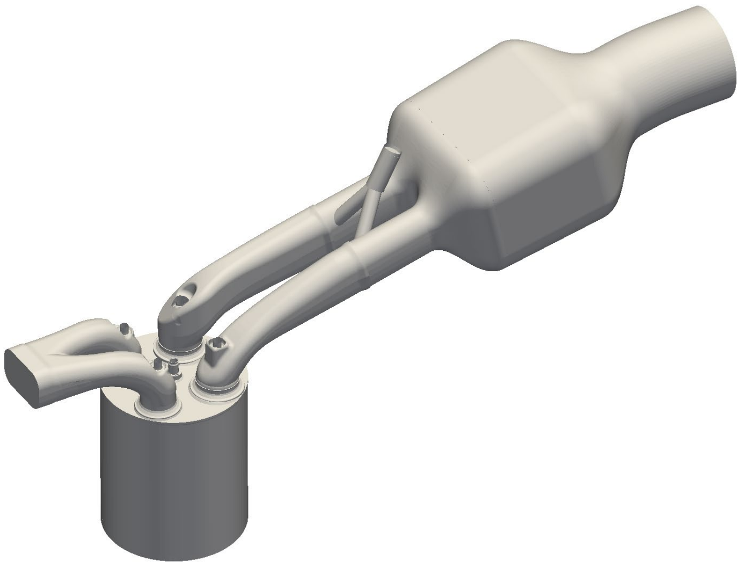
Meshes
n. 84

Average size
≈ 680k cells

Generation time
≈ 8h
with **4 processors**



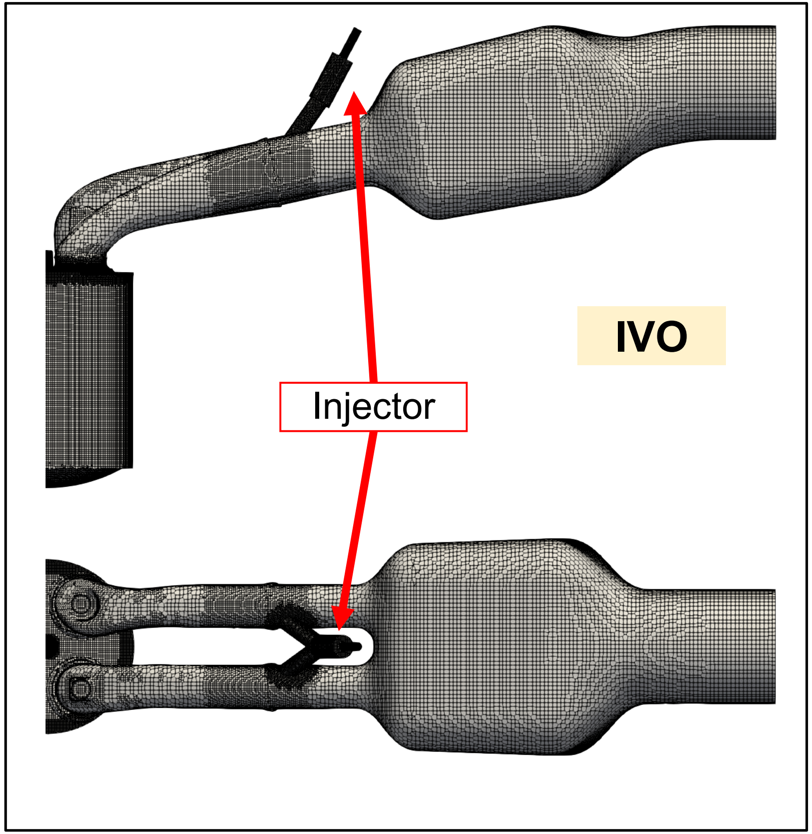
Mesh features – H_2 injection – *PFI – FLHy*



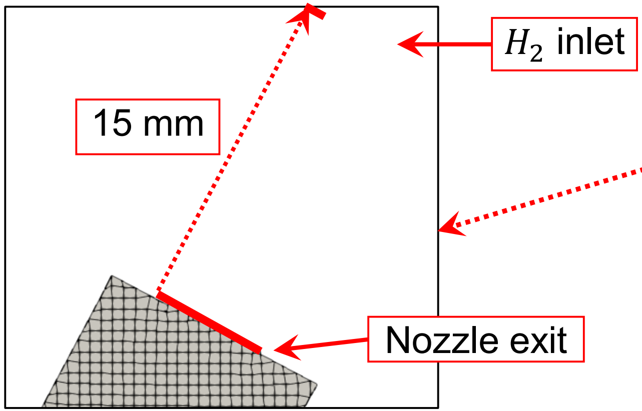
Generation time

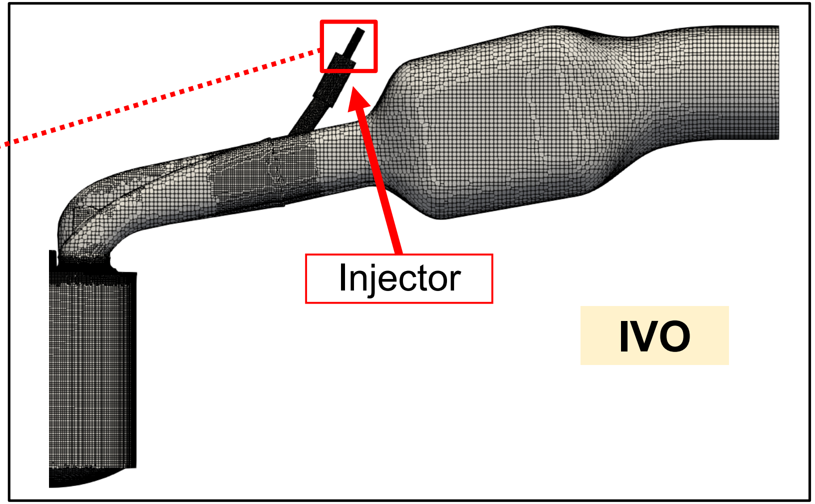
≈ 16h

with **4 processors**



Numerical models – H_2 injection – *PFI – FLHy*





- **Extruded mesh** ⟶ Optimal cell quality

- **Imposed conditions** at **H_2 inlet**

Operating condition	H_2 inlet section	
	$\dot{m}_{H_2}$ [g/s]	T^0 [K]
PFI	2.5	311

Premixed combustion models – *PFI – FLHy*

➢ FAE model

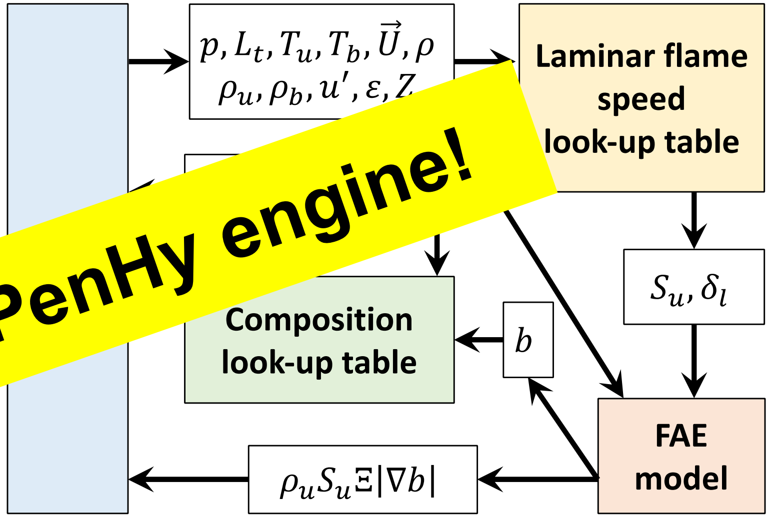
$$\frac{\partial \rho \tilde{b}}{\partial t} + \nabla \cdot \left(\rho \tilde{\boldsymbol{U}} \tilde{b}\right) + \nabla \cdot \left(\mu_t \nabla \tilde{b}\right) = \rho_u \tilde{S}_u \tilde{\Xi} |\nabla \tilde{b}| + \dot{\omega}_{ign}$$

Turbulent flame propagation

Ignition deposition model

LibICE

OpenFOAM



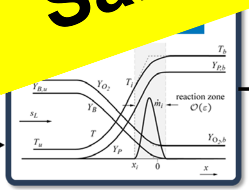
Same models used for PenHy engine!

➢ Tabul...

$\{p_0, p_1, \ldots\}$

$\{T_{u0}, T_{u1}, \ldots\}$

$\{\phi_0, \phi_1, \ldots\}$



Look-up table

$Y_{u,i}$

$Y_{b,i}$

S_{u0}

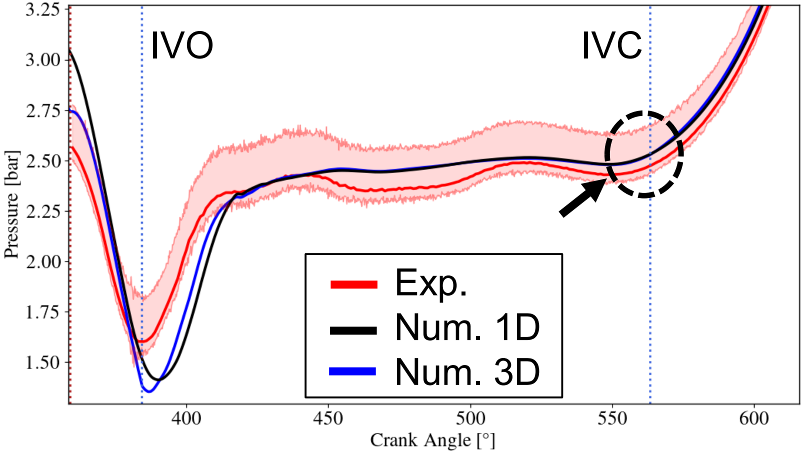
➢ S_{u0} correction *(hydrodynamic instabilities)*

$$C_0 = 1 + \left(\left.\frac{S_u}{S_{u0}}\right|_r - 1 \right) \left(\frac{\phi}{\phi_r} \right)^{\gamma_\phi} \left(\frac{T_u}{T_{u,r}} \right)^{\gamma_{T_u}} \left(\frac{p}{p_r} \right)^{\gamma_p}$$

Results – λ homogeneous – combustion – *PFI – FLHy*

Intake

- **Good 3D-1D match**
- Slight overestimation of P_{IVC}



Intake

- Good 3D-1D match
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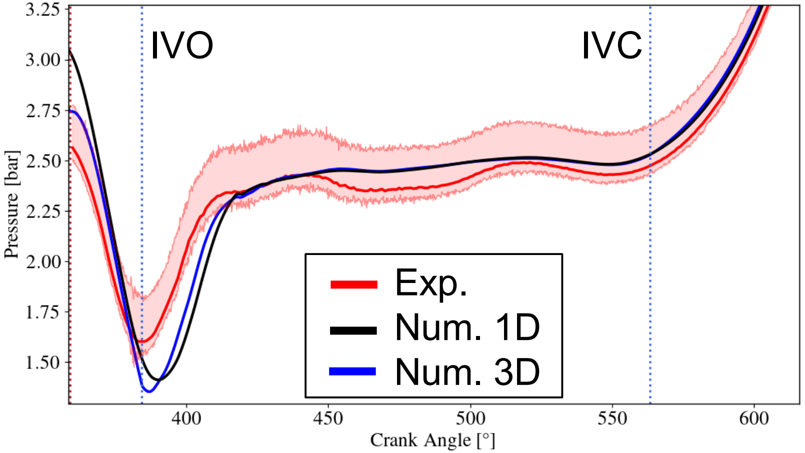
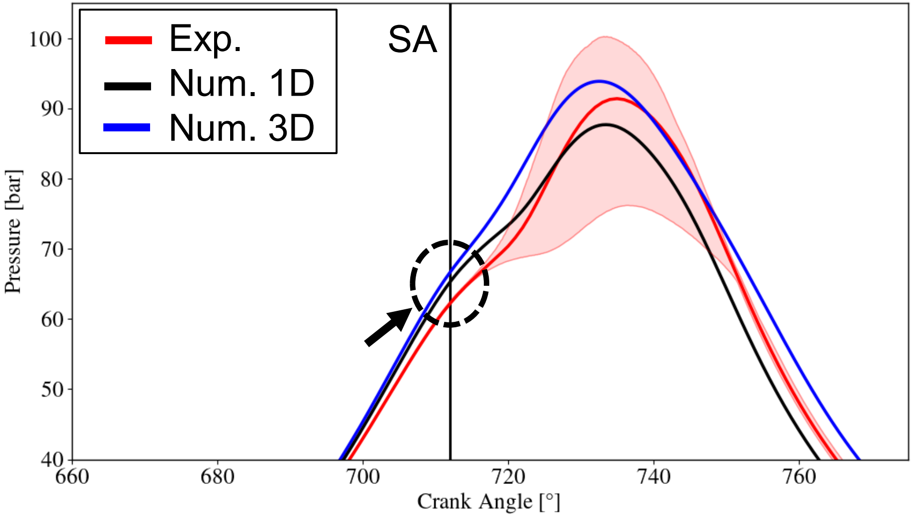
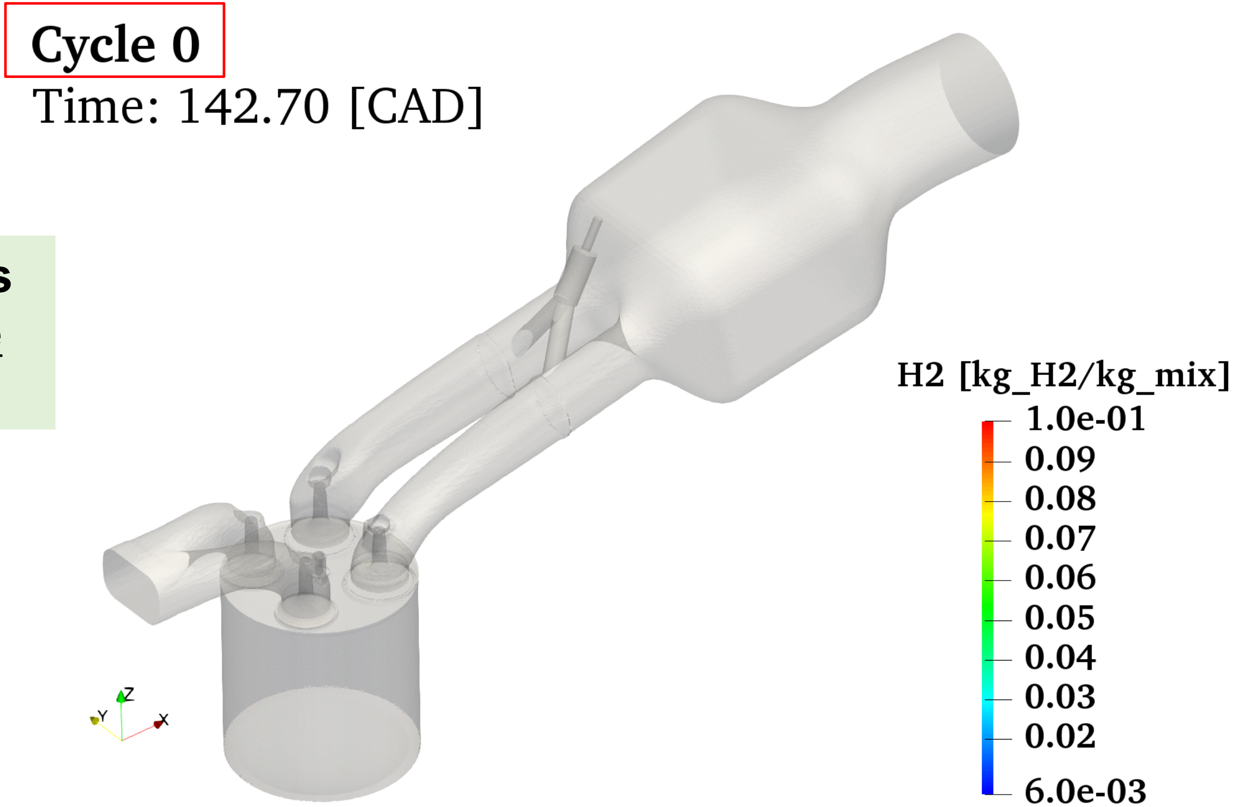




Combustion

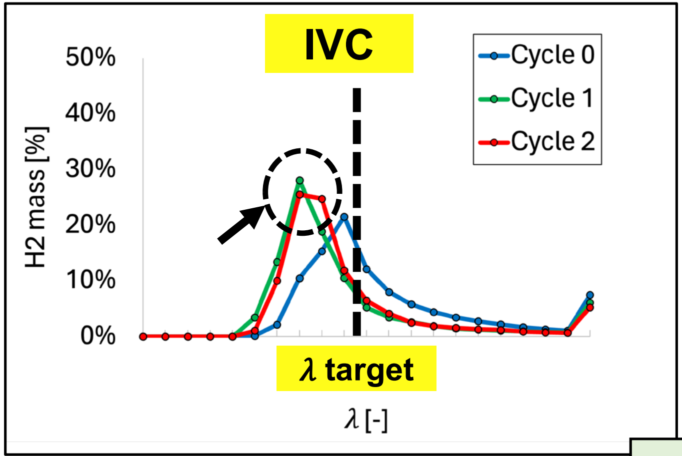
- Overestimation of P_{SA}
- **3D consistent with Exp.**

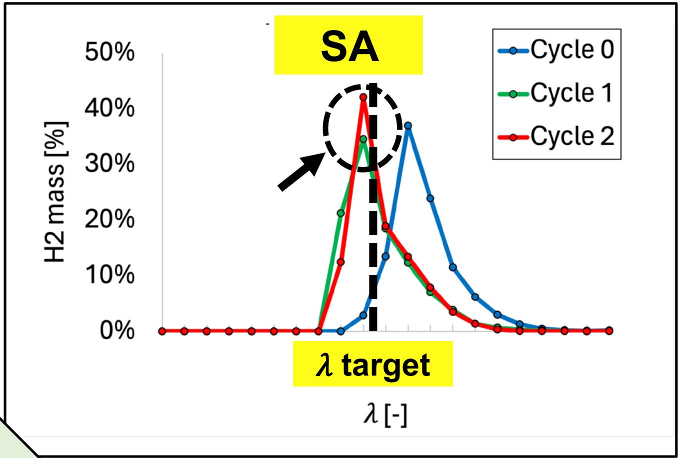
Results – H_2 injection – *PFI – FLHy*



3D multi-cycles
for steady-state injection

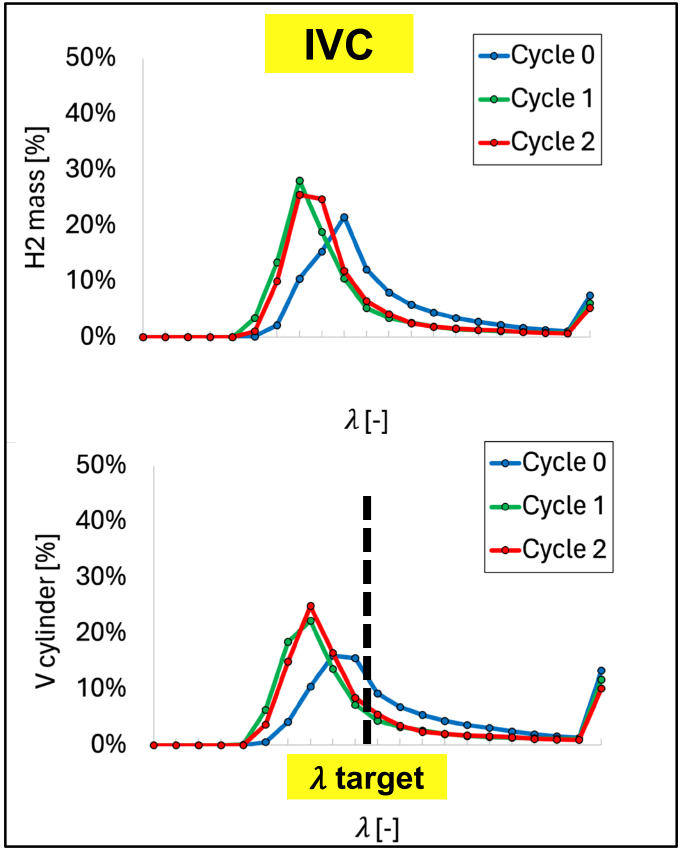
Results – H_2 injection – *PFI – FLHy*





- Cycle 2 almost at steady-state
- **Compression helps homogeneity**

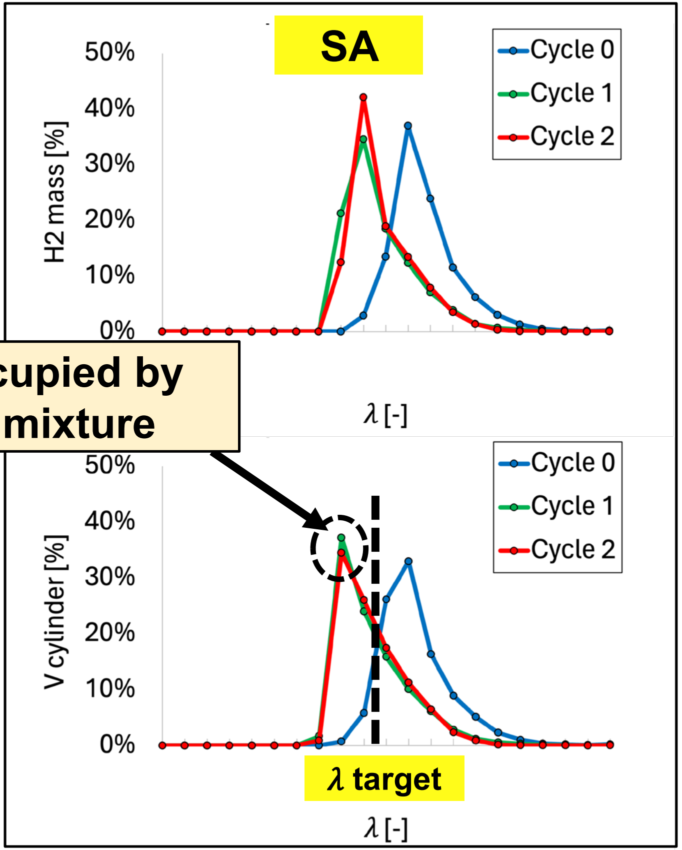
Results – H_2 injection – *PFI – FLHy*



m_{H2} share

↑ V_{cyl} occupied by richest mixture

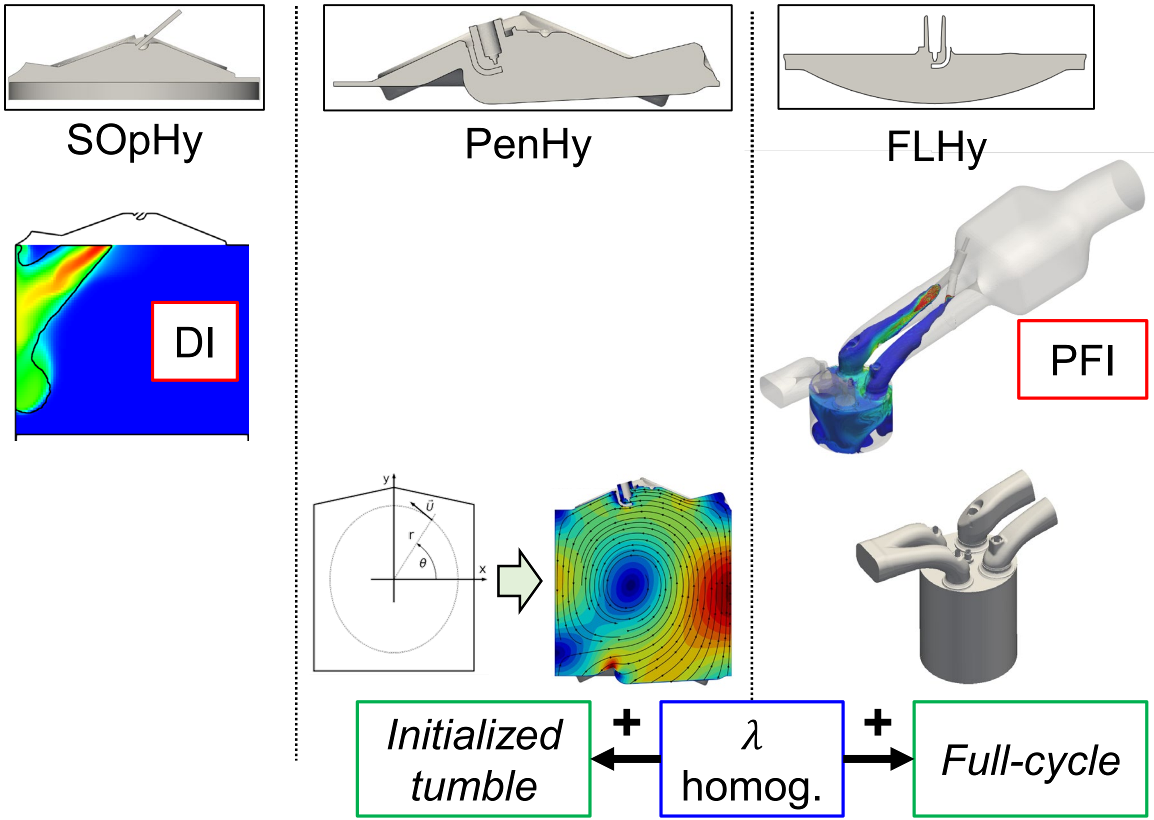
V_{cyl} share



Conclusions

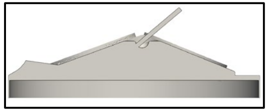
Conclusions

- **3 H_2-ICE configurations**
- **2 H_2 injection strategies**
- **2 simplified techniques** for IVC conditions

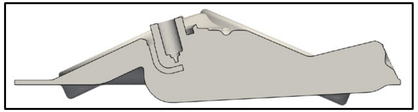


Conclusions

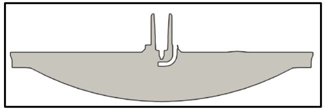
- **3** H_2-ICE **configurations**



SOpHy

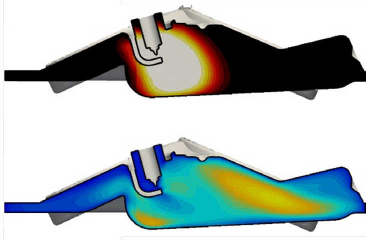


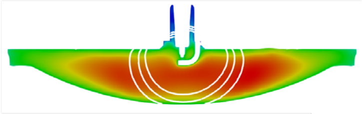
PenHy



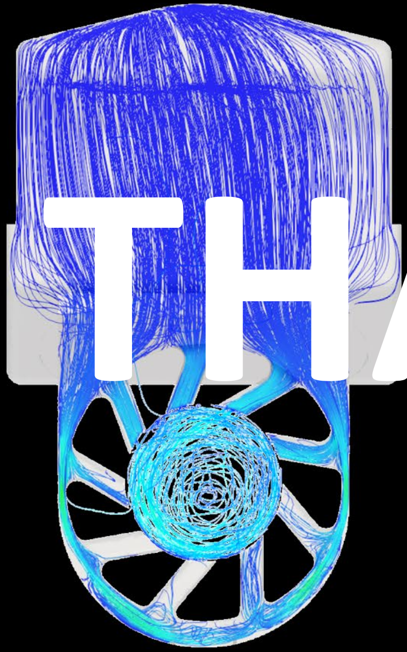
FLHy

- **2** H_2 **homogeneous combustion**





Wide set of validated methods to model SI H2-ICEs!



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THANK YOU

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