The Gasdyn code for 0D/1D Simulations of IC Engines Fed with Renewable Fuels

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Acknowledgements: ICEG & Sursum-Mi

Sixth Two-day Meeting on Propulsion Simulations Using OpenFOAM® Technology

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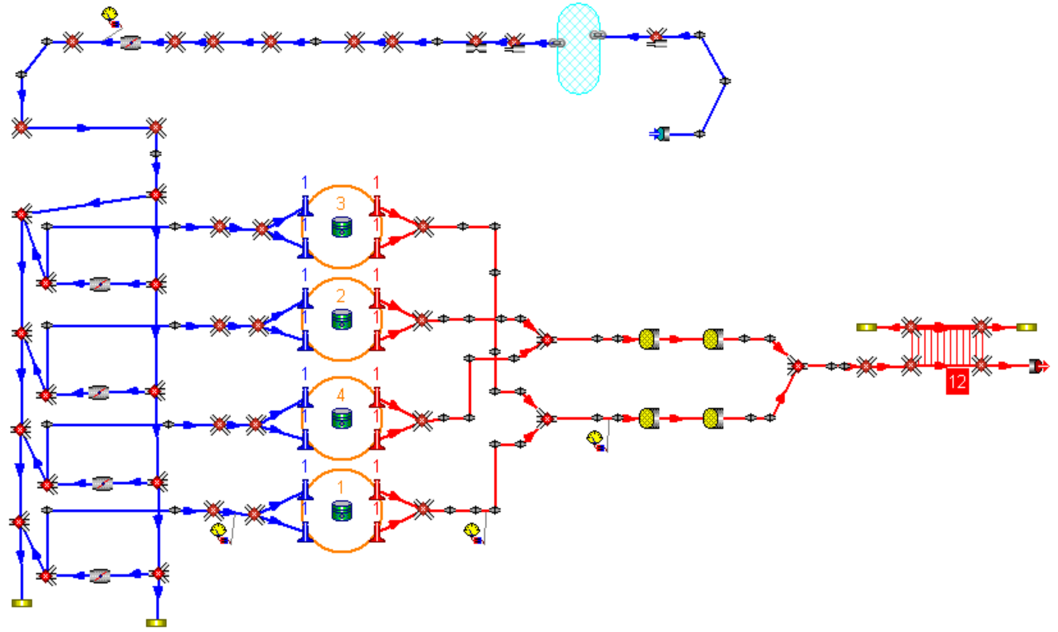
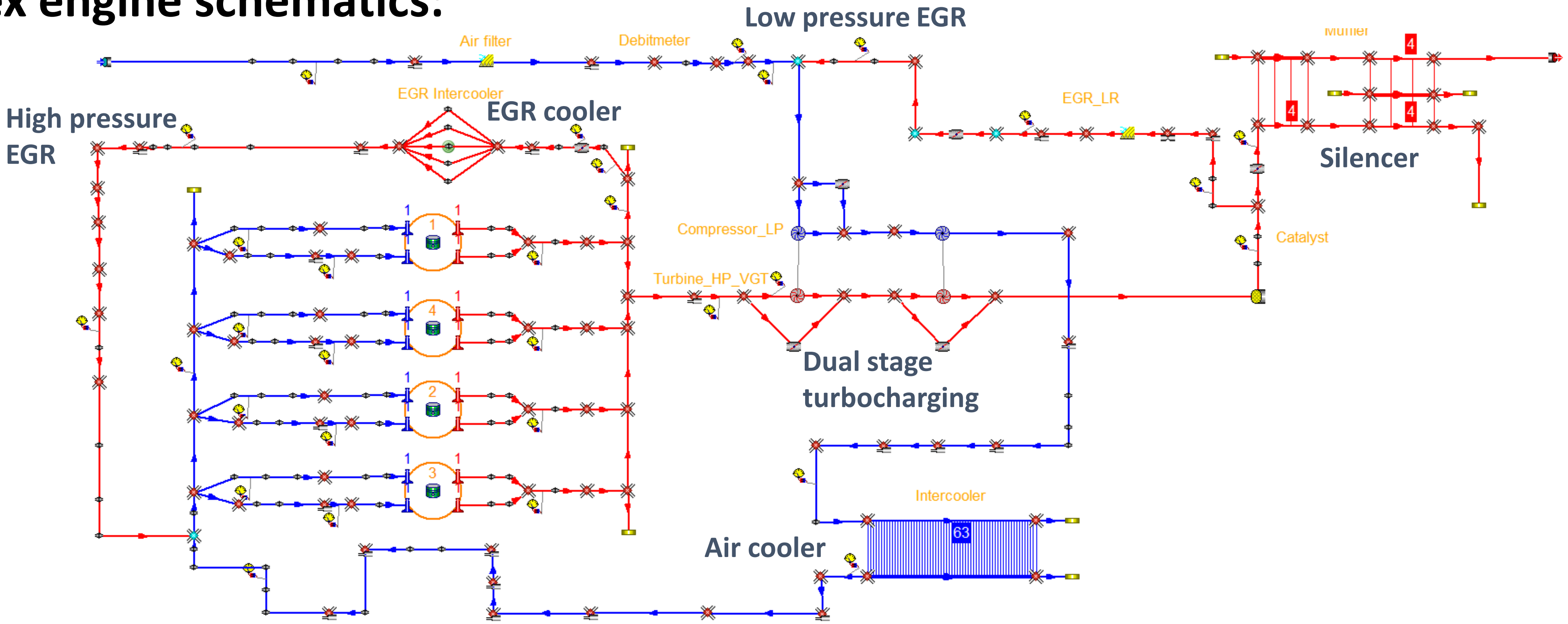
Outline

1. **Gasdyn** brief history.
2. **0D/1D simulation** of a complete IC engine: numerical methods and sub-models.
3. **Applications of Gasdyn** to various configurations.
4. **New engines** fed with renewable fuels: **hydrogen, ammonia**, …
5. **Boundary conditions** for CFD simulations (LibICE).



1D simulation code: Gasdyn

Complex engine schematics:



Developed at PoliMi during the last **25 years**. The name **Gasdyn** was given in 1998.

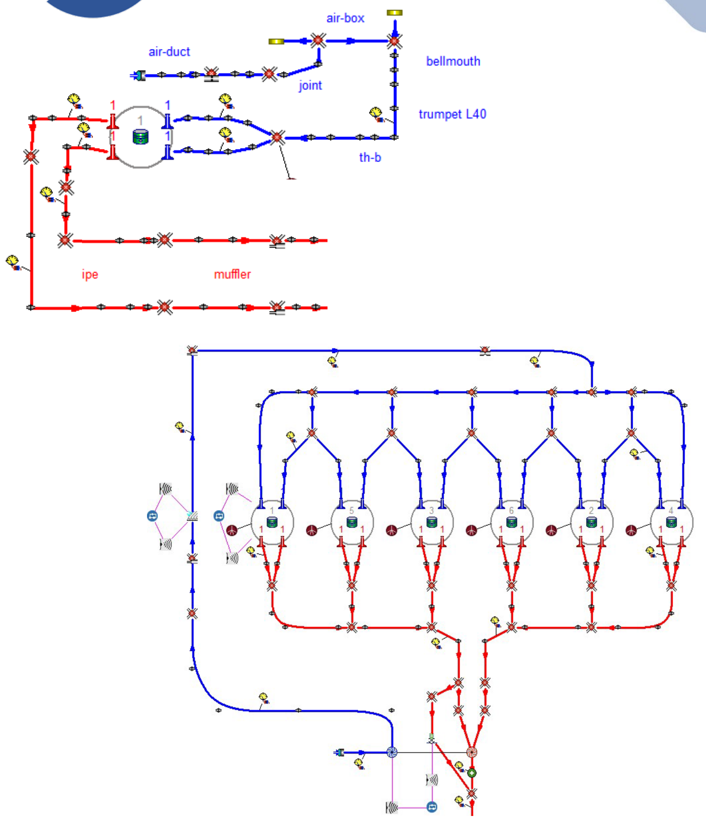
Ref.: Onorati A., Ferrari, «Modeling of 1D unsteady flows in IC engine pipe systems: numerical methods and transport of chemical species». (1998) SAE Technical Papers, DOI: 10.4271/980782

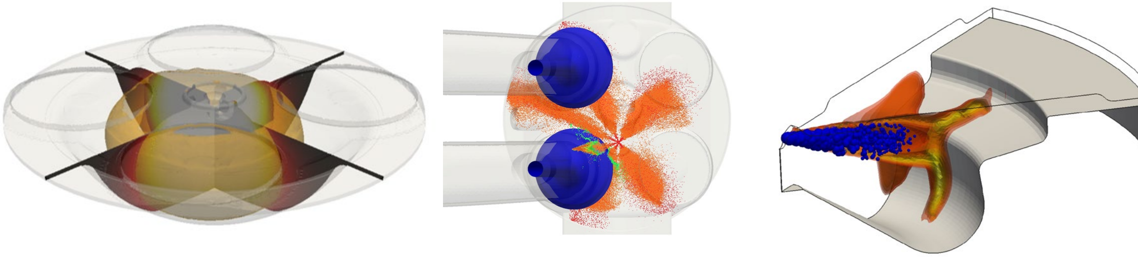
ICEG research activities – numerical modeling

ICEG group: numerical modeling of IC engines, fluid machines and power systems

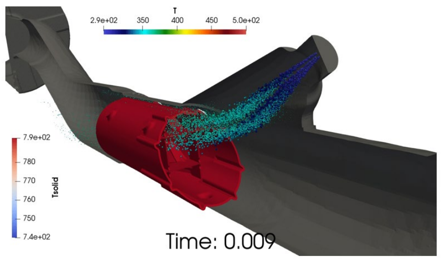
Gasdyn

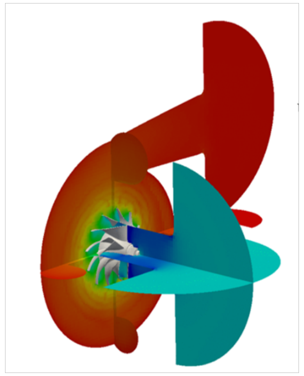
Sursum-Mi
modeling the future

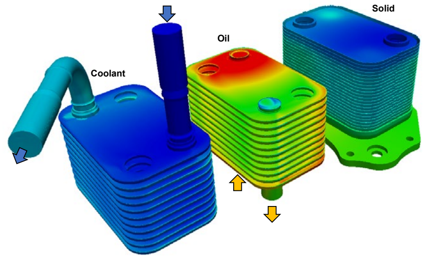




LibICE OpenFOAM®

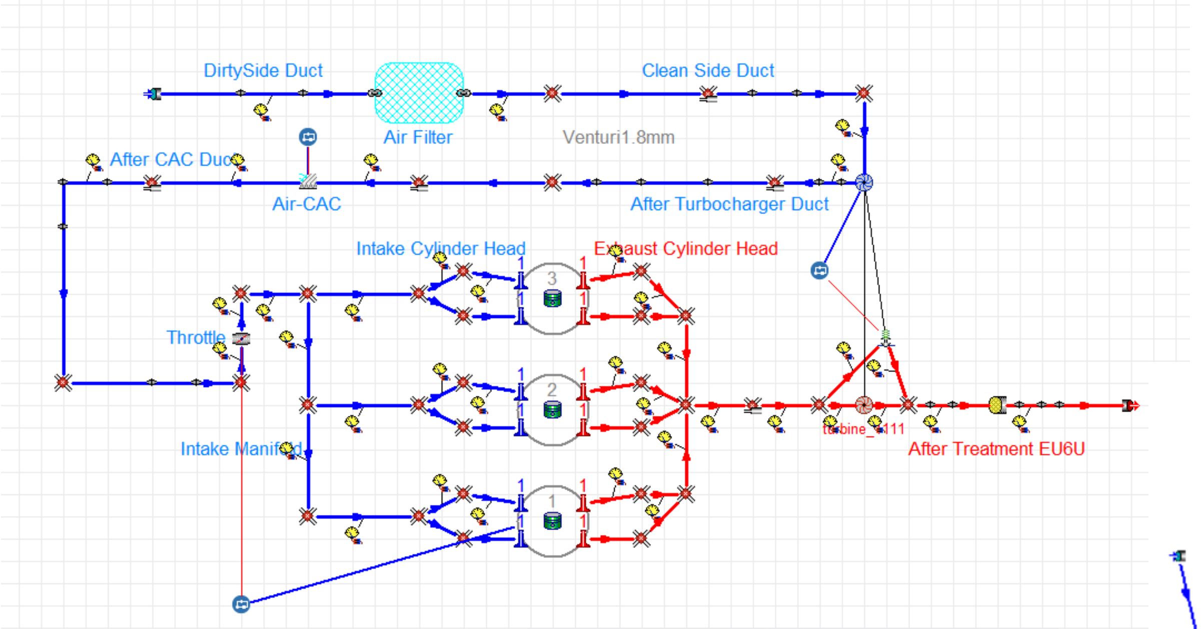


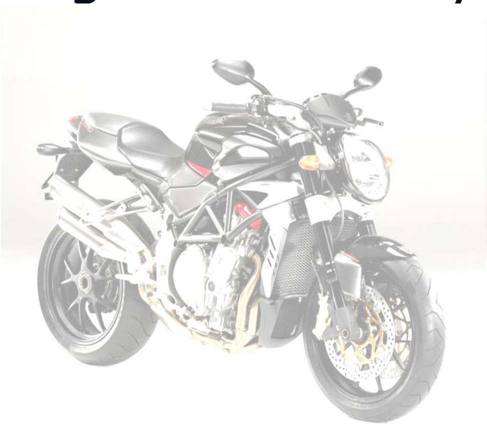




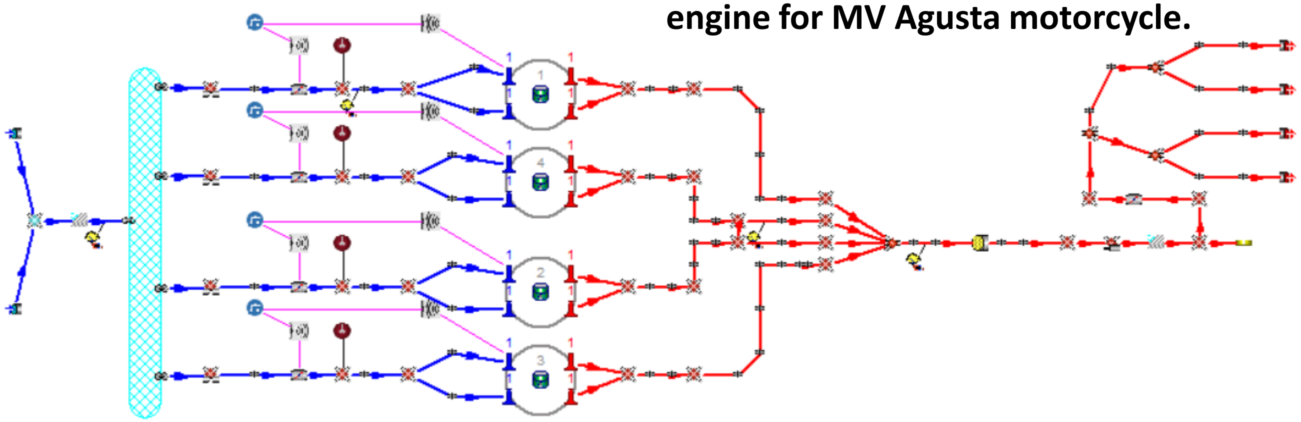
1D simulation code: Gasdyn

1D schematics of Renault 3 cyl. GDI engine (left) and MV Agusta motorcycle, 4 cyl. SI engine (right).





High performance 1L, 4-cyl. SI engine for MV Agusta motorcycle.

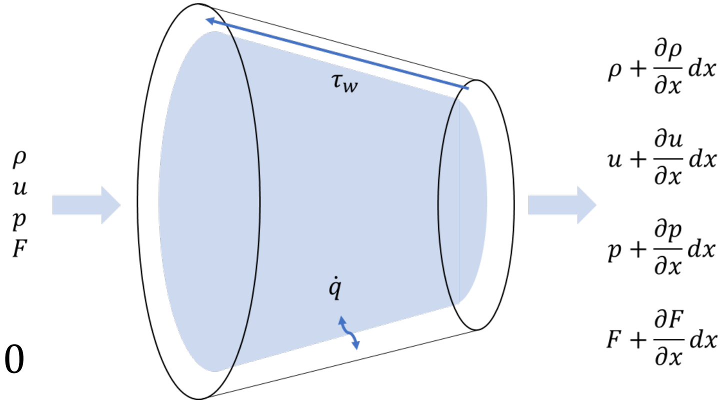


1L 3-cyl. turbo GDI engine for Renault Capture passenger car.

0D/1D simulation: numerical solvers for unsteady flows

One-dimensional, unsteady, compressible, reacting flow with area variations, friction and heat transfer with the walls:

$$
\begin{cases}
\dfrac{\partial(\rho F)}{\partial t} + \dfrac{\partial(\rho u F)}{\partial x} = 0 \\
\dfrac{\partial(\rho u F)}{\partial t} + \dfrac{\partial(\rho u^2 + p)F}{\partial x} - p\dfrac{dF}{dx} + \rho F G = 0 \\
\dfrac{\partial(\rho e_0 F)}{\partial t} + \dfrac{\partial(\rho h_0 u F)}{\partial x} - (\dot{q}\rho + \Delta H_{react})F = 0
\end{cases}
$$

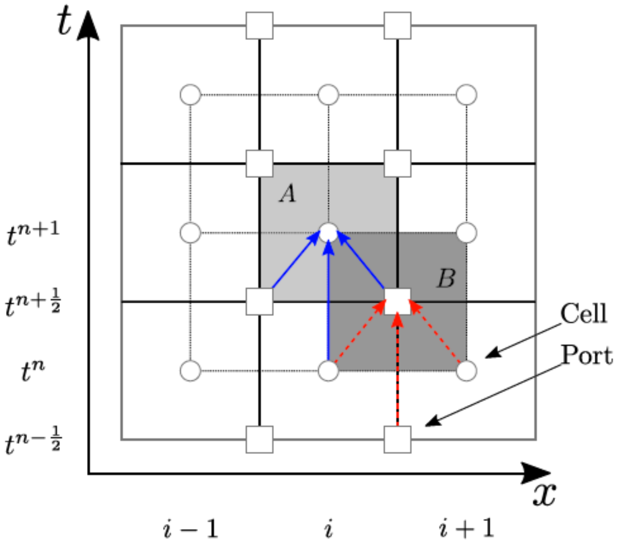


$$
\boldsymbol{W}(x,t) = \begin{bmatrix} \rho F \\ \rho u F \\ \rho e_0 F \\ \rho \boldsymbol{Y} F \end{bmatrix}; \ \boldsymbol{F}(\boldsymbol{W}) = \begin{bmatrix} \rho u F \\ pF + \rho u^2 F \\ \rho u h_0 F \\ \rho u \boldsymbol{Y} F \end{bmatrix};
$$

$$
\boldsymbol{B}(\boldsymbol{W}) = \begin{bmatrix} 0 \\ -p\frac{dF}{dx} \\ 0 \\ 0 \end{bmatrix}; \ \boldsymbol{C}(\boldsymbol{W}) = \begin{bmatrix} 0 \\ \rho G F \\ -(\rho\dot{q} + \Delta H_{react})F \\ \rho \dot{\boldsymbol{Y}} F \end{bmatrix};
$$

Different solvers available, based on:

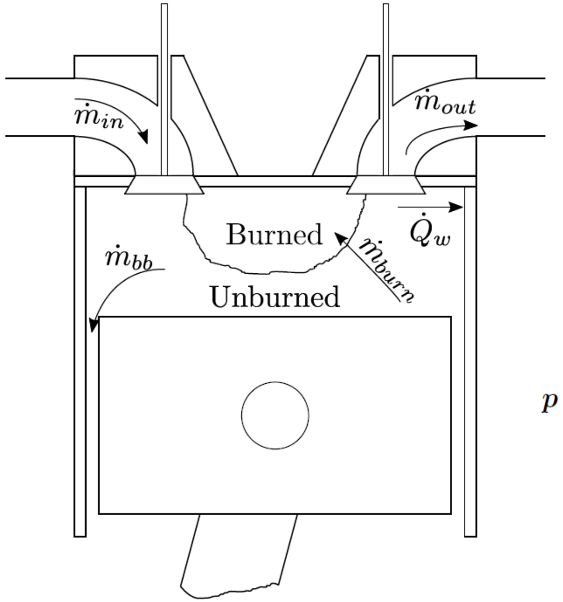
- explicit, staggered space-time **finite volume** method.
- explicit, shock-capturing **finite difference** methods.



$$
\boldsymbol{Y} = \begin{bmatrix} \mathbf{O_2} \\ \mathbf{N_2} \\ \mathbf{Ar} \\ \mathbf{CO_2} \\ \mathbf{H_2O} \\ \mathbf{H_2} \\ \mathbf{CO} \\ \mathbf{NO} \\ \mathbf{C_3H_6} \\ \mathbf{C_3H_8} \\ \vdots \end{bmatrix}
$$

0D/1D simulation: combustion prediction

- The in-cylinder phenomena and combustion are modelled by means of a **multi-zone** approach, solving the **energy and mass balance** of each sub zone.
- Zimont's **correlation** is used to compute **turbulent flame speed** $\Rightarrow$ $S_t = u'^{3/4} L_i^{1/4} \boxed{S_l^{1/2}} k_u^{-1/4}$



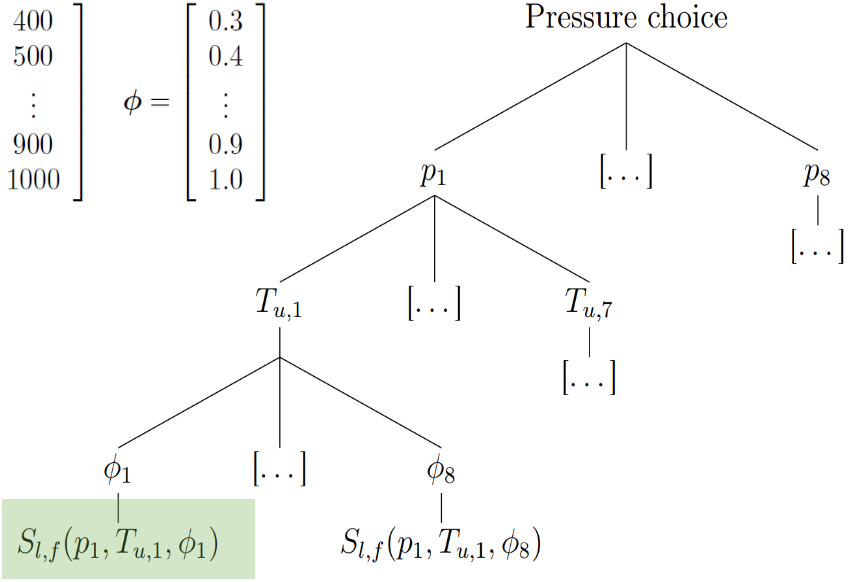
Laminar flame speed evaluation

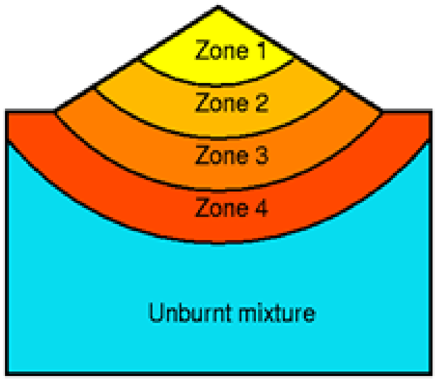
Old method $\Rightarrow$ Empirical correlation $\Rightarrow$ **Strict** validity limits

New method $\Rightarrow$ Tabulated Kinetic approach $\Rightarrow$ **Wider** limit ranges

(3D matrix with around 448 values)

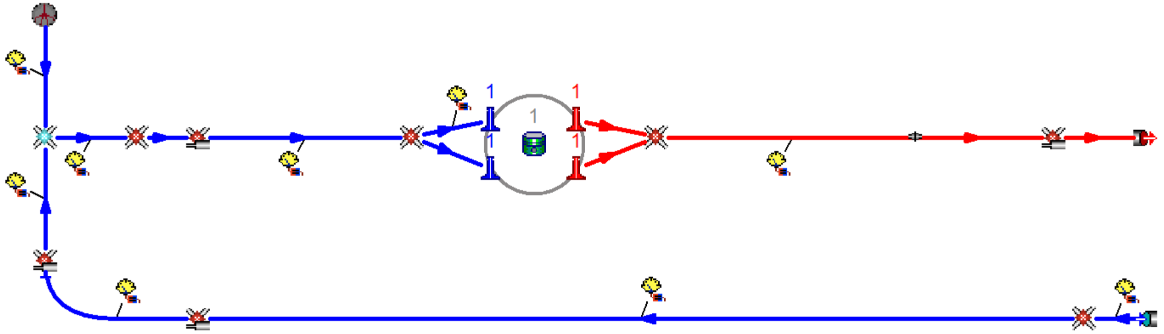
$$\boldsymbol{p} = \begin{bmatrix} 30 \\ 40 \\ \vdots \\ 90 \\ 100 \end{bmatrix} \quad \boldsymbol{T_u} = \begin{bmatrix} 400 \\ 500 \\ \vdots \\ 900 \\ 1000 \end{bmatrix} \quad \boldsymbol{\phi} = \begin{bmatrix} 0.3 \\ 0.4 \\ \vdots \\ 0.9 \\ 1.0 \end{bmatrix}$$



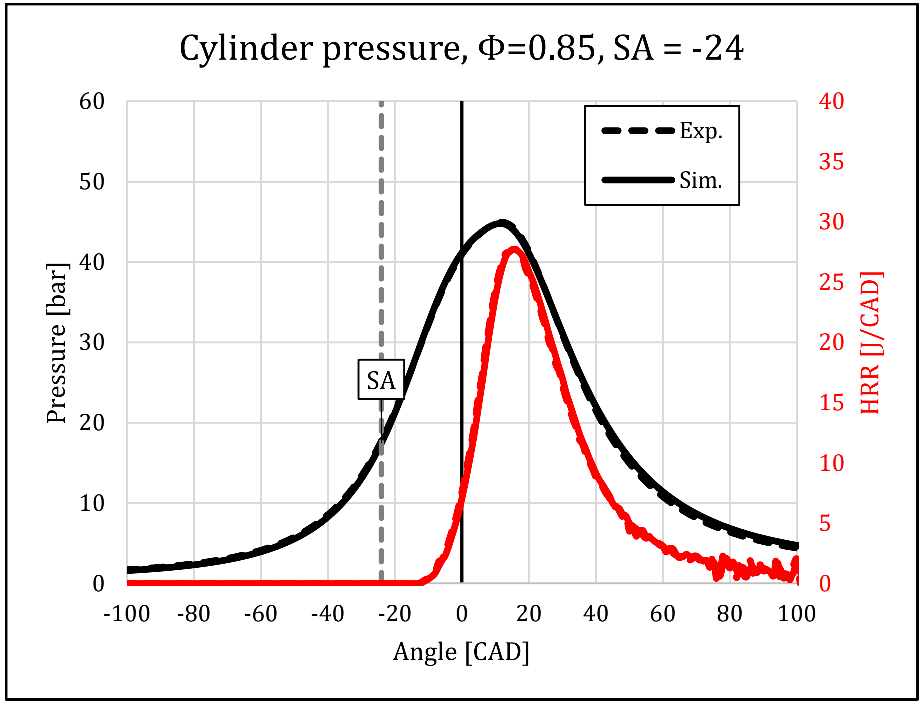


Spark-ignition ammonia-fueled engine

Gasdyn schematic for a single-cylinder engine, experimental setup (at Orleans University):



- **Imposed combustion** from experimental HRR;
- **Predictive models** with <u>specific sub-models</u> (eg. S_L, chemical composition);



- Better evaluation of **pressure**, **temperature** and **composition** <u>at IVC</u> for CFD simulations;
- **Performance evaluation** of heavy-duty engines with **ammonia** as fuel.

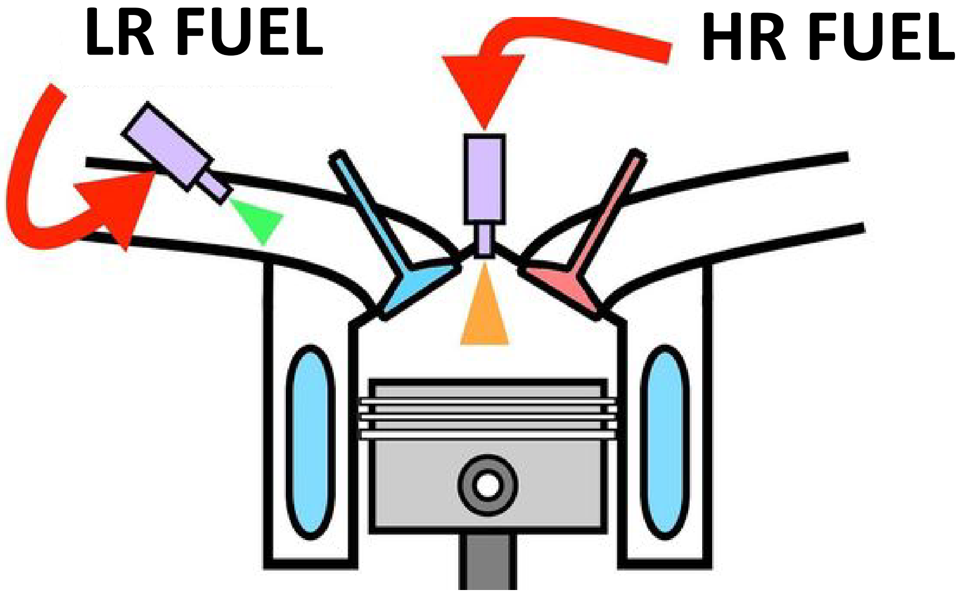
0D combustion model for RCCI simulation

Reactivity Controlled Compression Ignition

Problems linked to NH_3 in SI engines:
- ➢ low combustion rate;
- ➢ high production of NO_x.

RCCI to better control combustion:
- ➢ Low Reactivity fuel (injected in the pipes);
- ➢ High Reactivity fuel to start combustion.

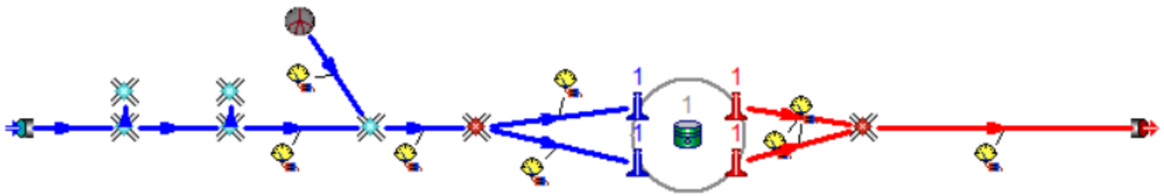
Advantages with RCCI:
- ➢ faster combustion;
- ➢ lower temperatures (less NO_x);
- ➢ higher fuel conversion efficiency.



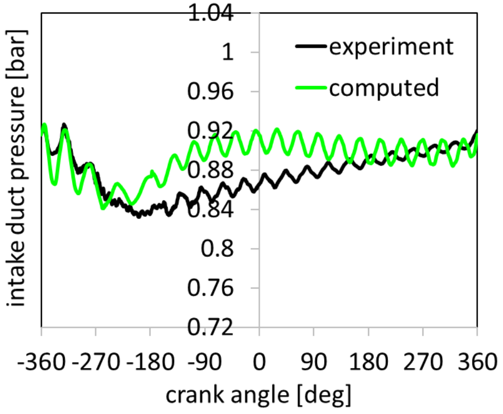
Quasi-Dimensional Model in development phase, main challenges:
- **flame surface** evaluation;
- **local turbulence variation** due to fuel injection.

H2 PFI single cyl. engine

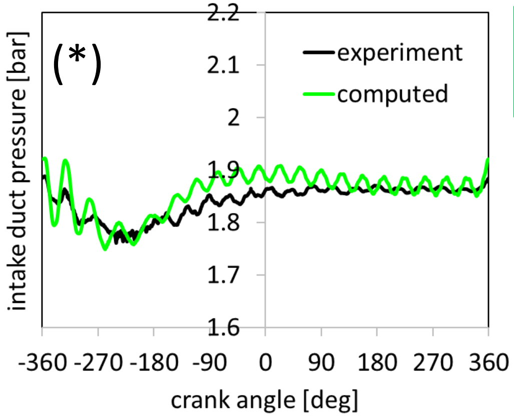
(in collaboration with CMT, Valencia)



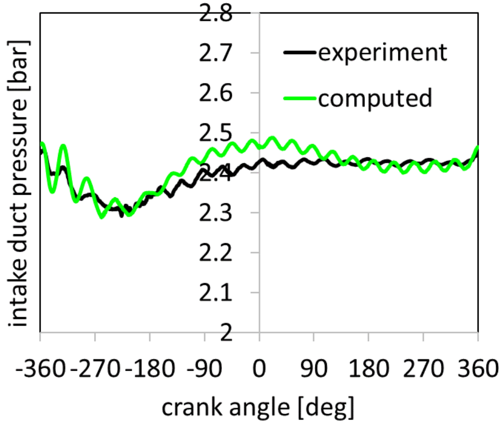
Lambda 1.6, low load

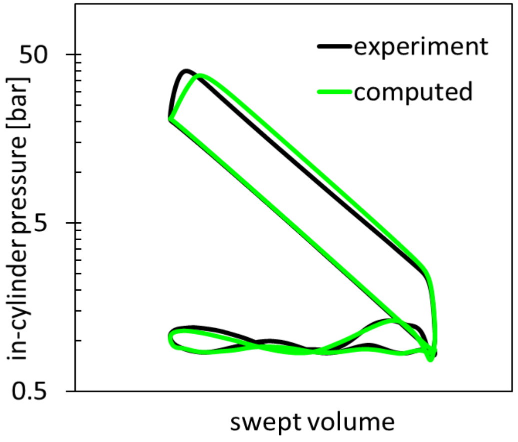


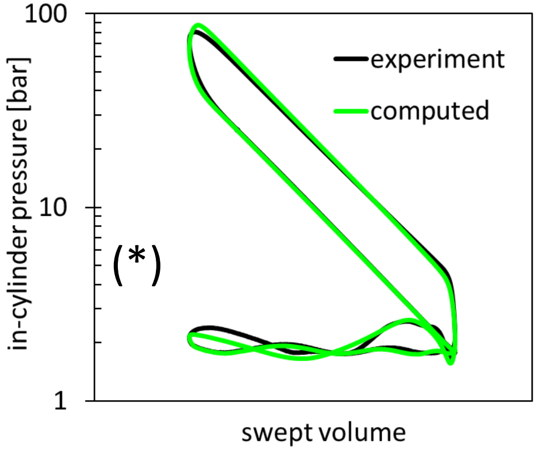
(*) Lambda 2.4, medium load

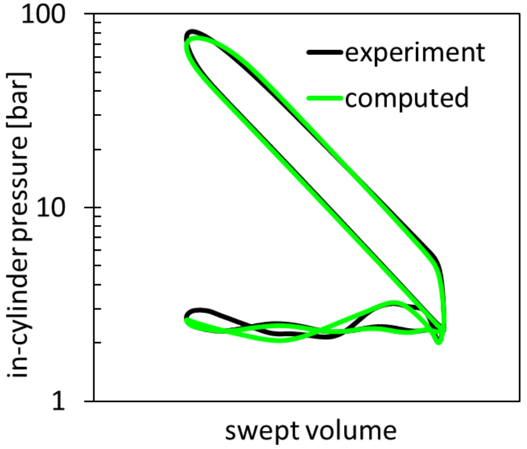


Lambda 3.4, high load



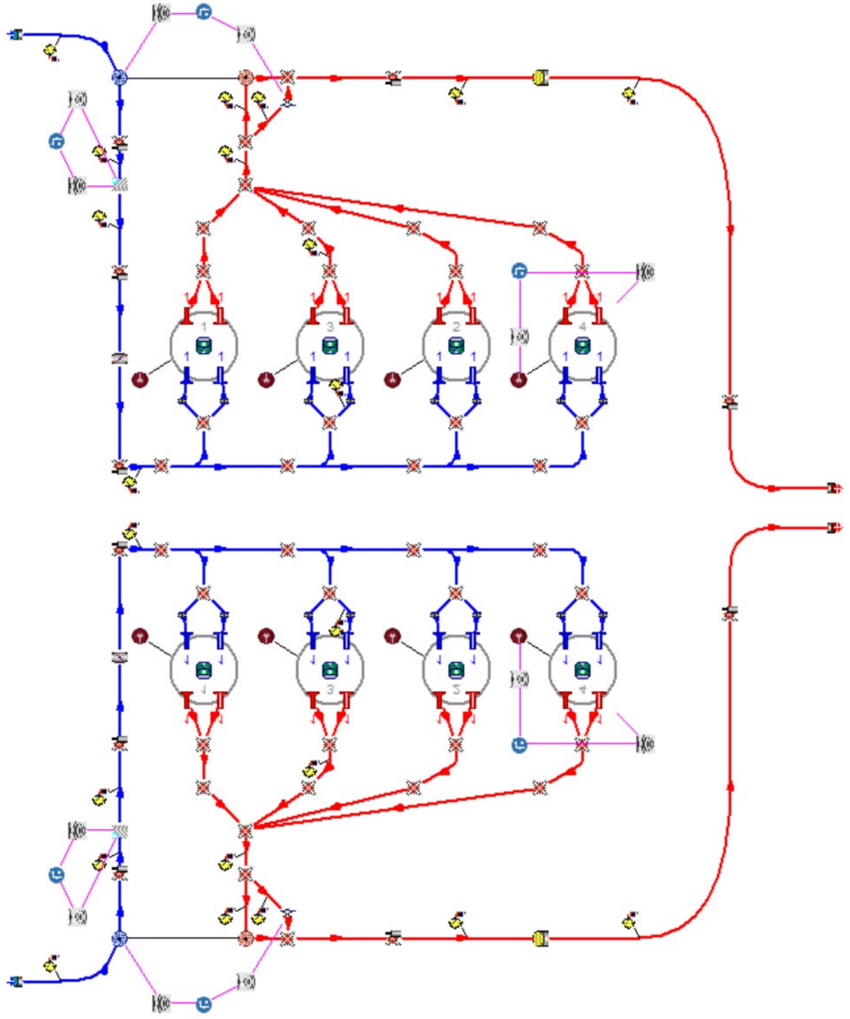


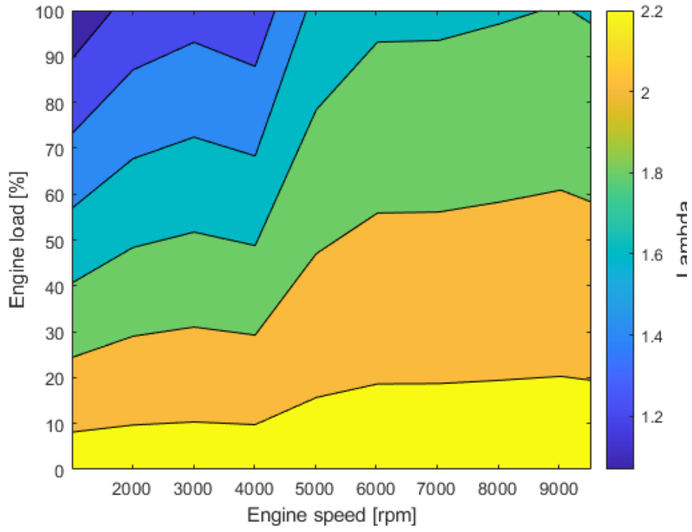


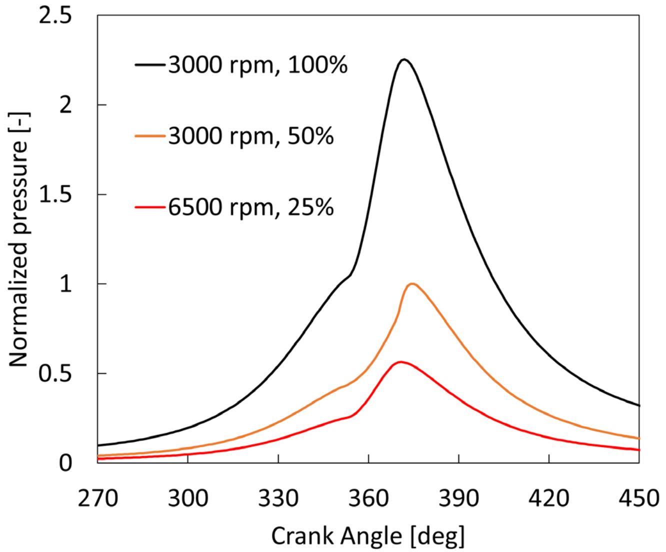


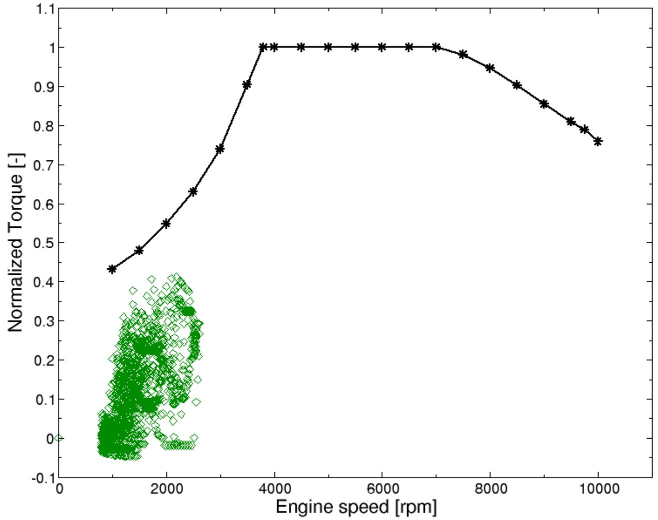
(*) Ref. operating point to calibrate the model

V8 H2 ICE concept with after-treatment system

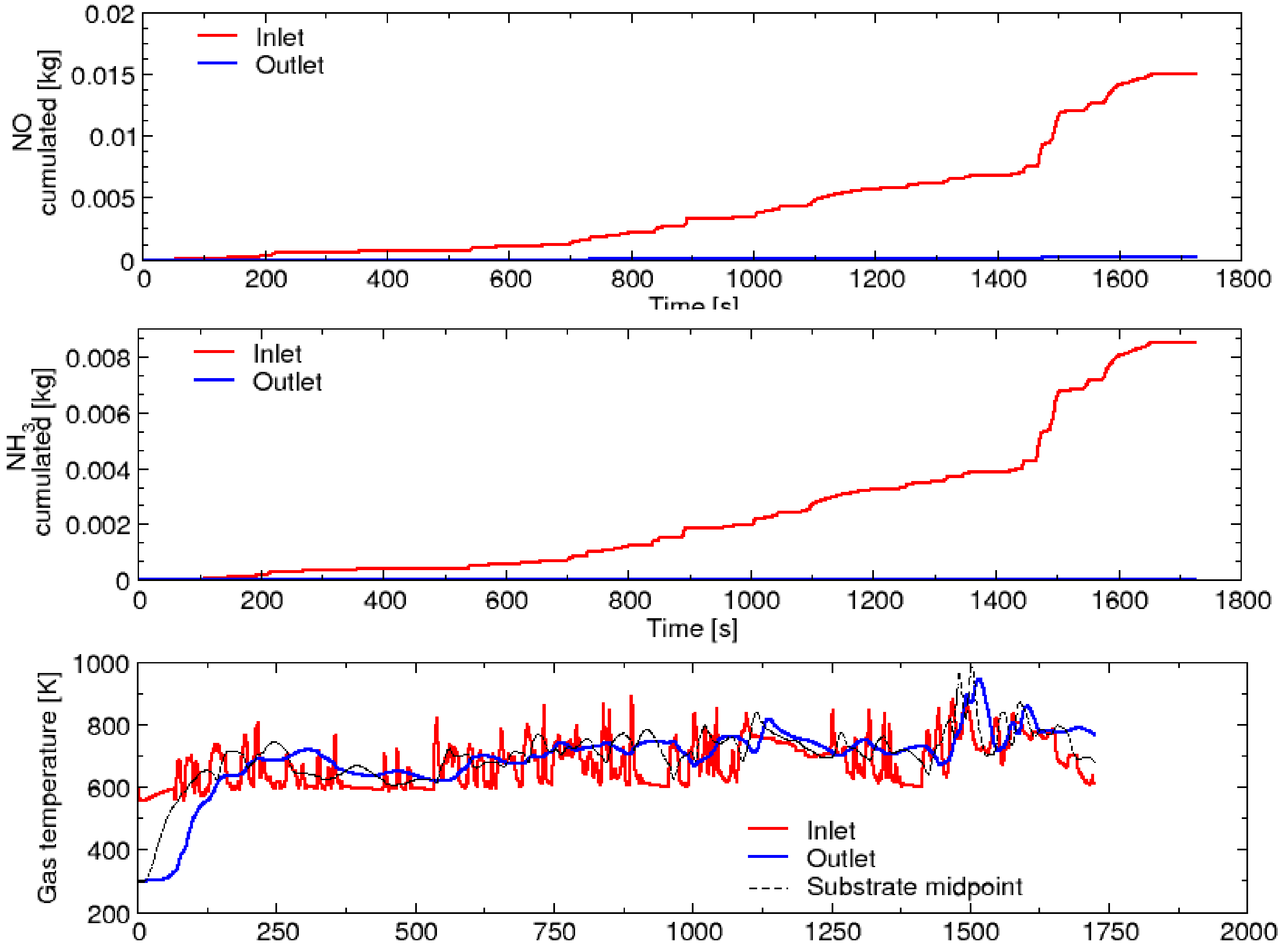








V8 H2 ICE concept with after-treatment system



Reacting flows with chemical species transport in the pipes.

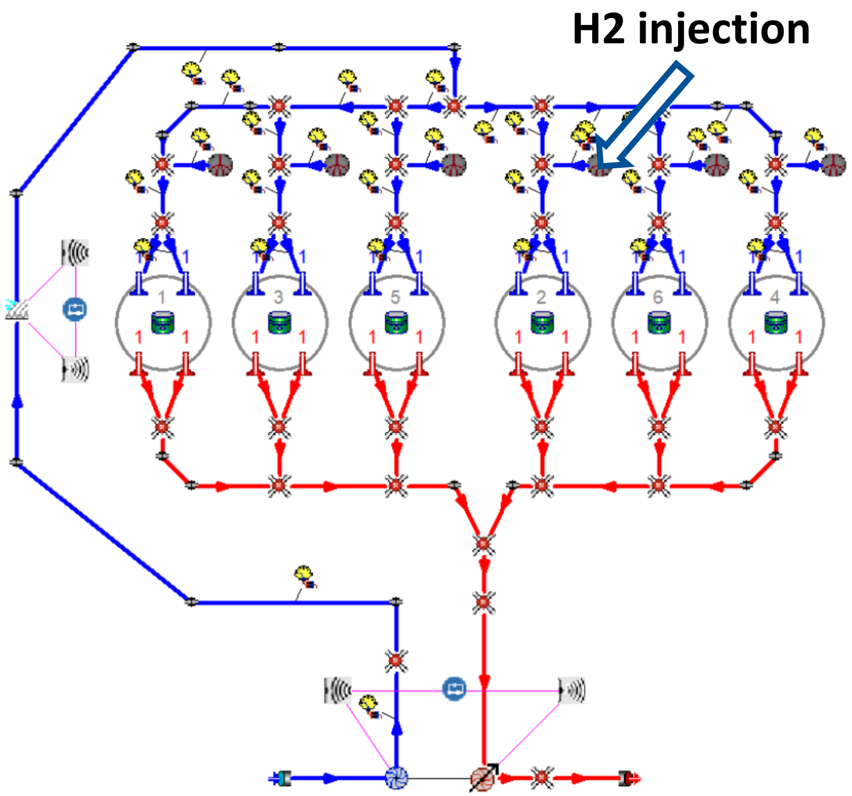
SCR catalyst modeled in **Gasdyn:**

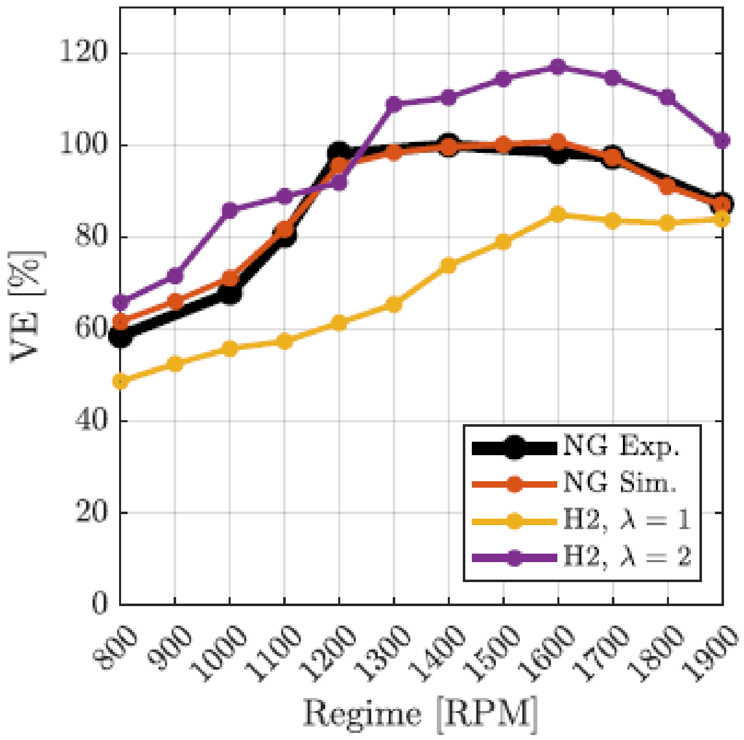
R1	$NO + 1/2O_2 \leftrightarrow NO_2$
R2	$NH_3 + 3/4NO_2 \rightarrow 7/8N_2 + 3/2H_2O$
R3	$NH_3 + 1/2NO + 1/2NO_2 \rightarrow N_2 + 3/2H_2O$
R4	$NH_3 + NO + 1/4O_2 \rightarrow N_2 + 3/2H_2O$
R5	$5/2H_2 + NO \rightarrow NH_3 + H_2O$
R6	$H_2 + 1/2O_2 \rightarrow H_2O$
R7	$H_2 + NO \rightarrow H_2O + 1/2H_2$
R8	$H_2O \leftrightarrow H_2O\,(L)$
R9	$NH_3 \leftrightarrow NH_3\,(L)$

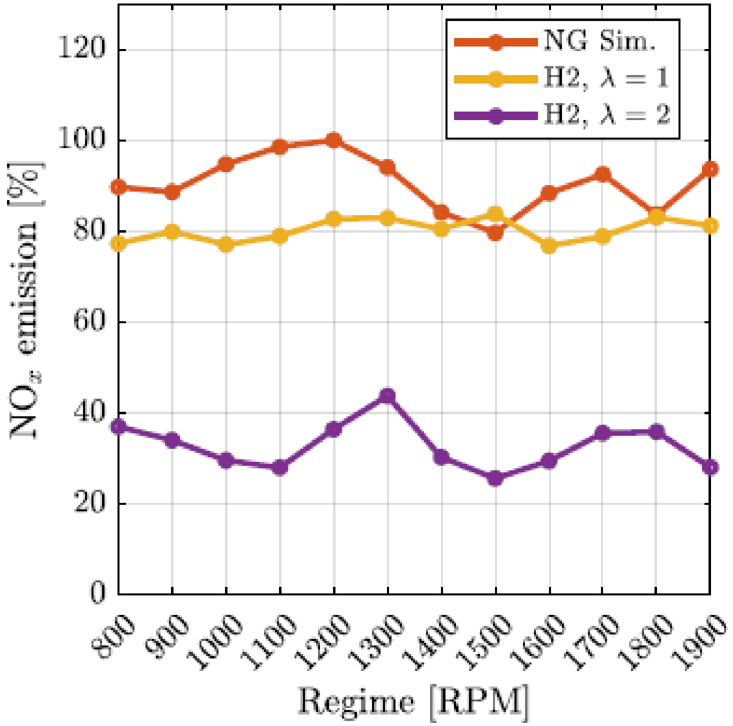
Engine conversion from NG to H2

- Natural gas fuelled **heavy duty** in-line 6 cylinder featuring a **variable geometry turbine**
- λ =1 and λ =2 feeding conditions have been considered

Gasdyn

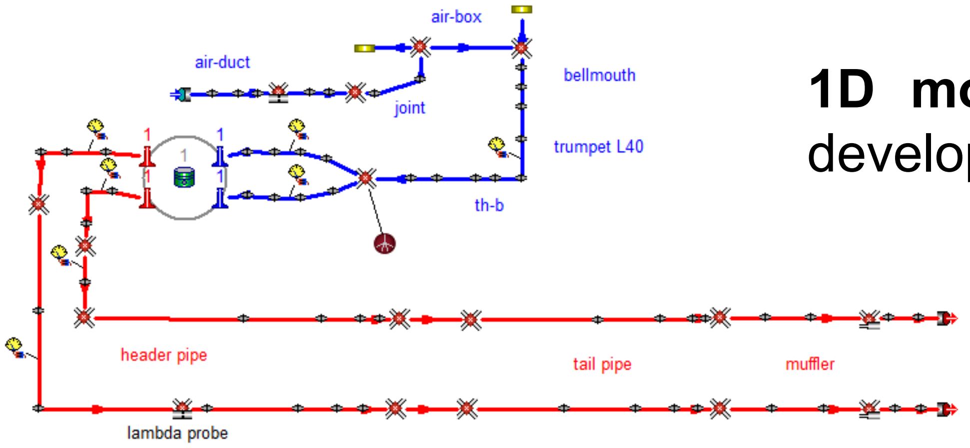




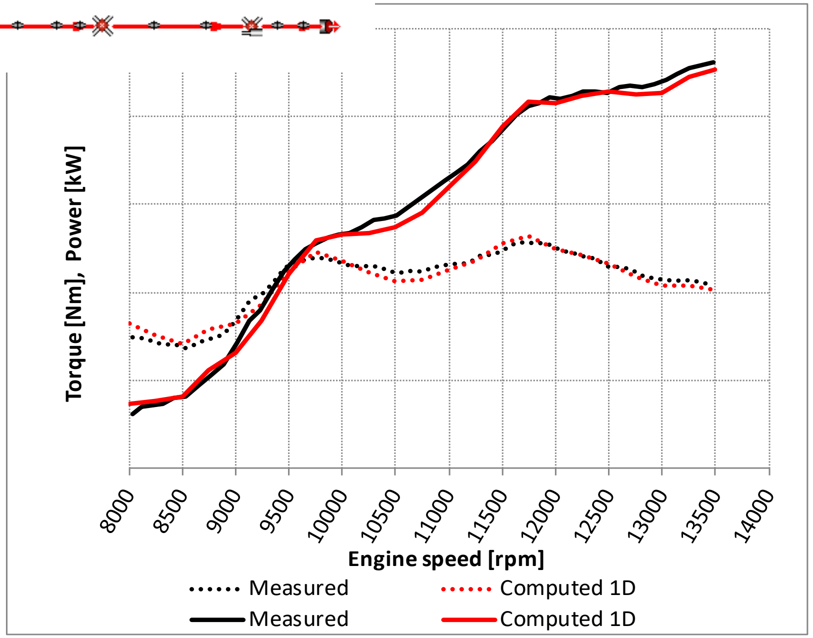


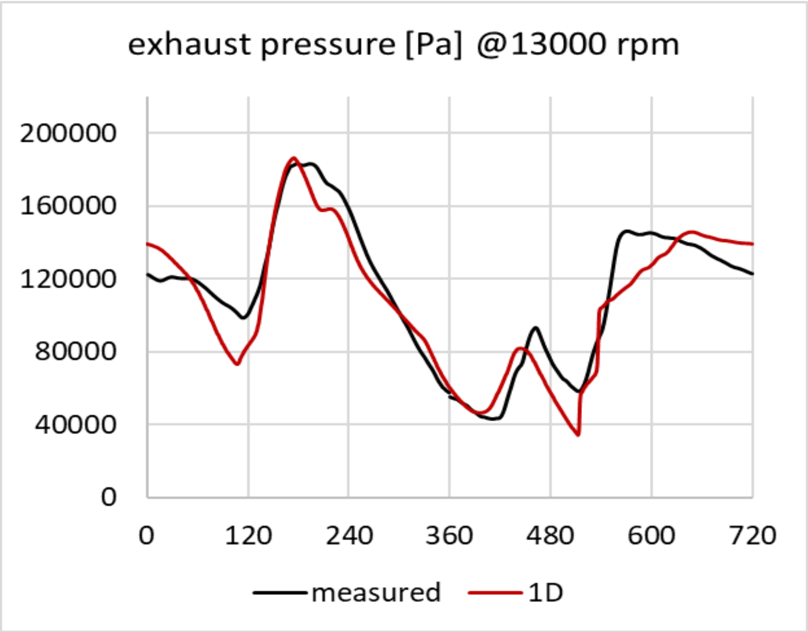
POLITECNICO MILANO 1863

Gasdyn: some application cases



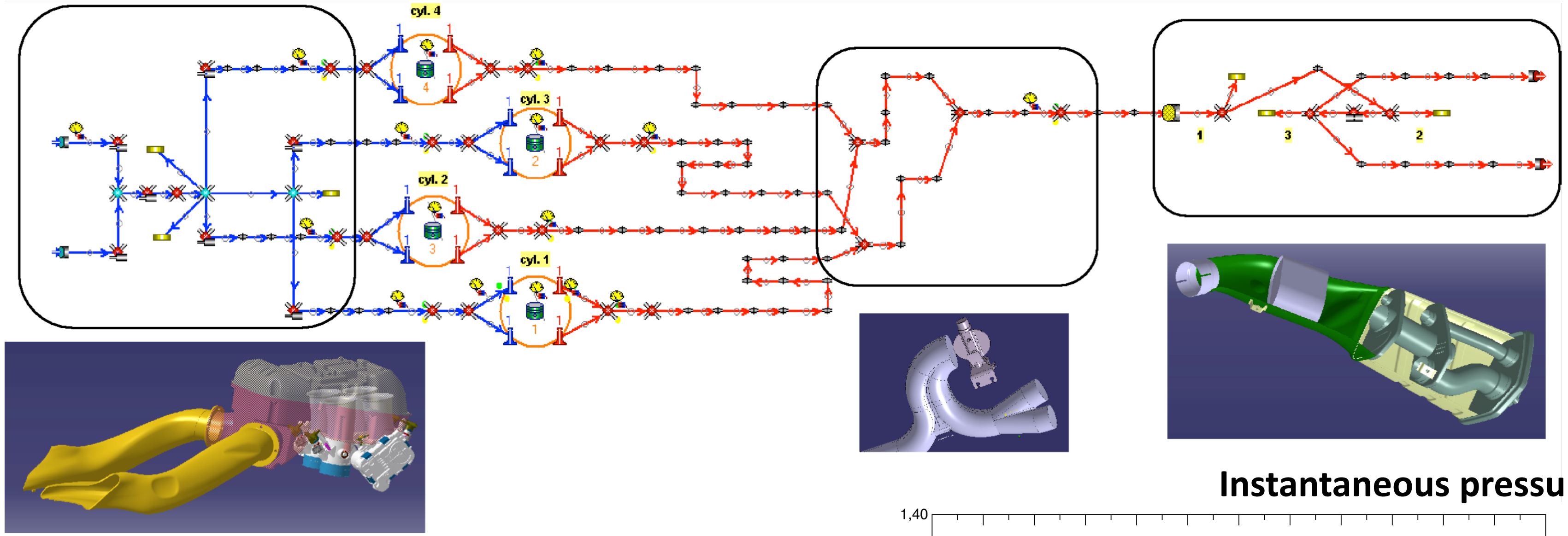
1D model of a single-cylinder, spark-ignition engine developed for a high-performance **Moto3** motorcycle.



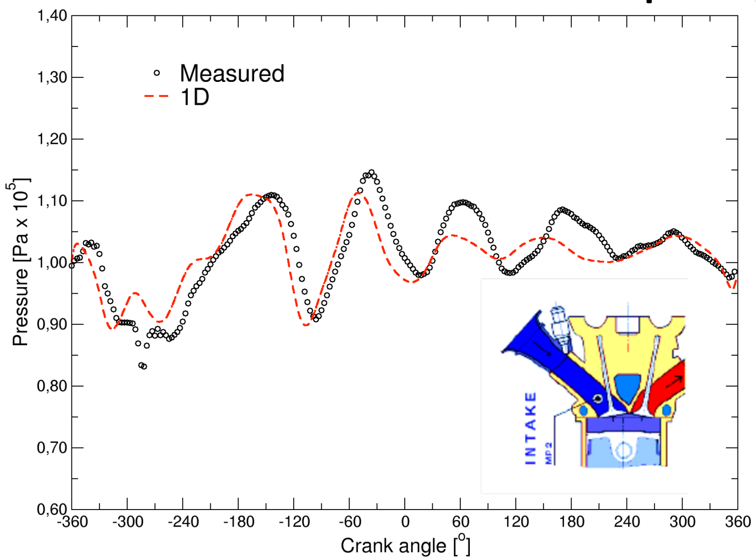


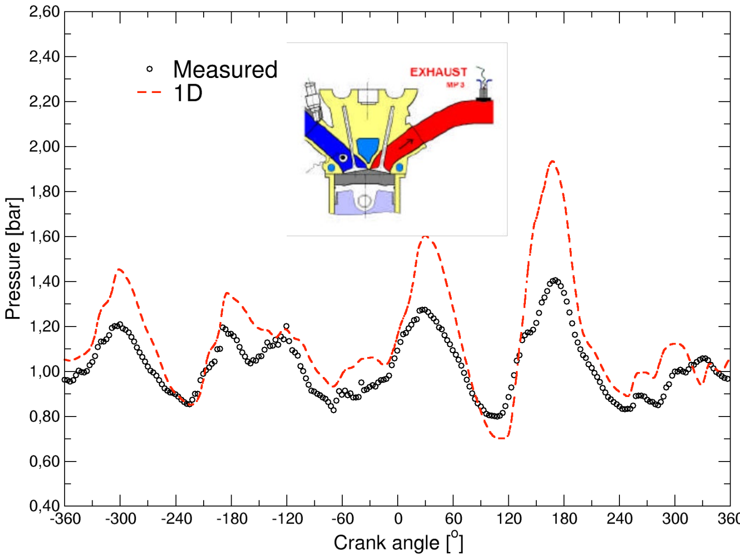
Ref.: Montenegro, G., Cerri, T., Della Torre, A., Onorati, A. et al., Fluid Dynamic Optimization of a Moto3™ Engine by Means of 1D and 1D-3D Simulations, SAE Int. J. Engines 9(1):2016

Gasdyn: some application cases



Instantaneous pressures in the primary ducts

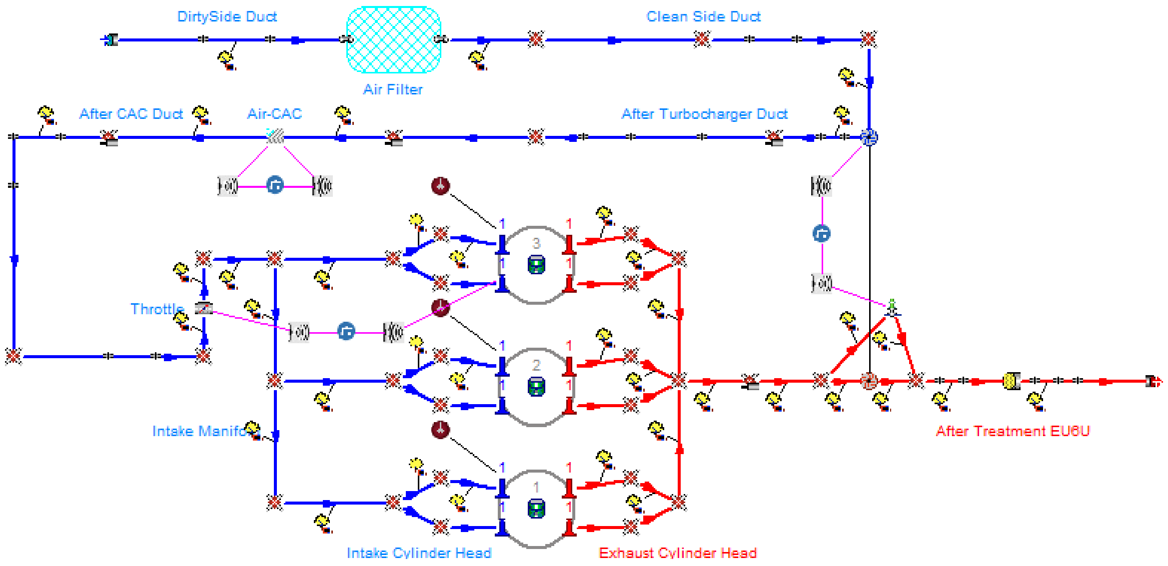




V4 high performance motorcycle SI engine

Ref.: Cerri T., Ferrari G., Montenegro G., Albesiano R., Fabris G., Lombardi C., Zucchi L., 1D-3D Fluid Dynamic Simulation and Experimental Analysis of a High Performance V4 Engine, 65° Congresso Nazionale ATI, Domus de Maria (CA), Italy, 2010.

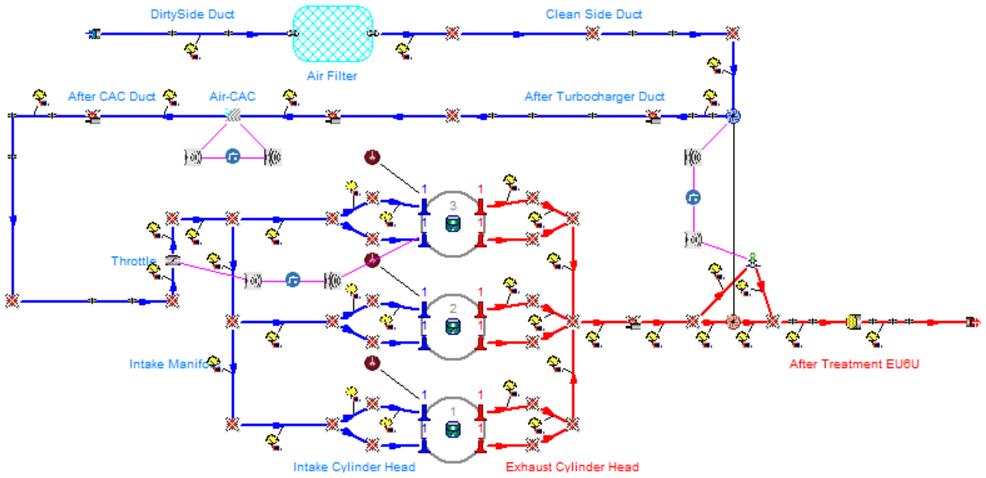
Gasdyn: some application cases



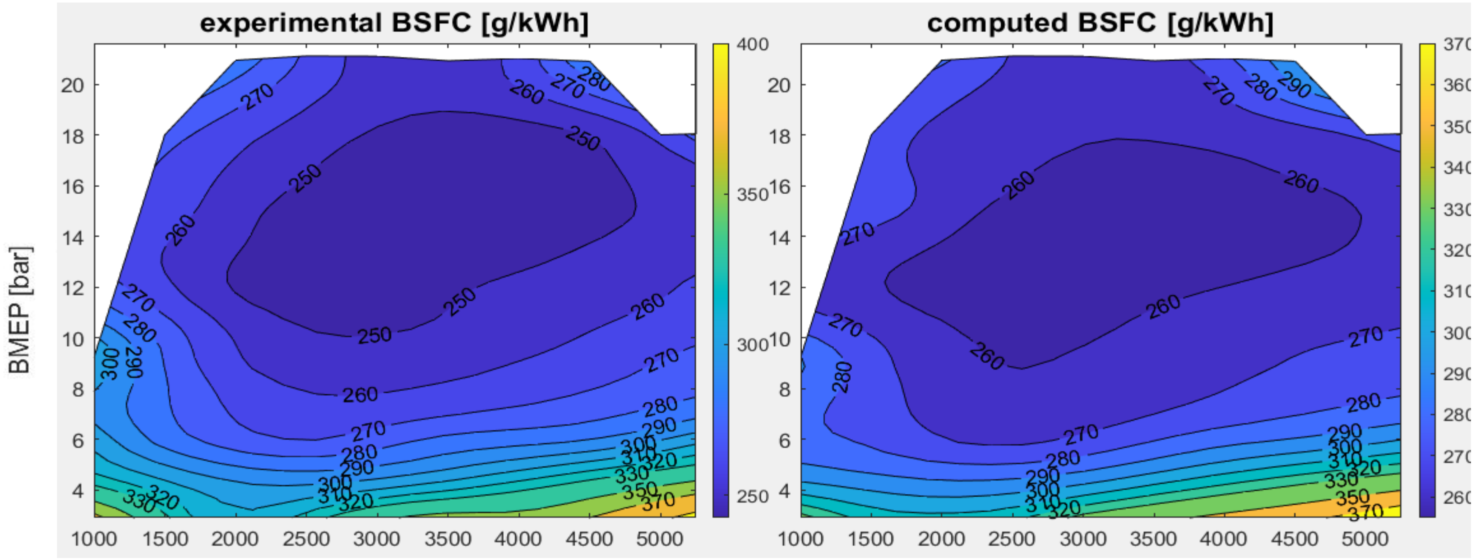
Renault 3-cyl. 1L, GDI engine

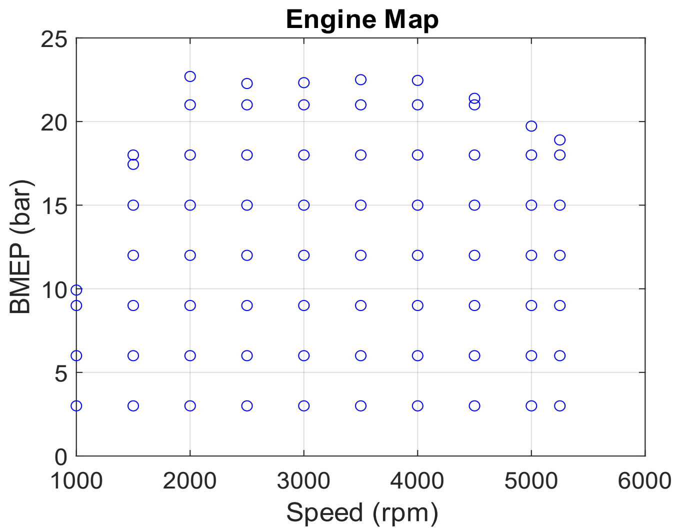
LAYOUT	in-line 3 cylinders
FUEL	gasoline
INJECTION	direct injection (GDI)
DISPLACEMENT	998.55 cm3
TURBOCHARGER	fix-geom turbine + WG + IC
MAX POWER	84 kW
MAX TORQUE	204 Nm
COMPRESSION RATIO	11:01
CYLINDER BORE-STROKE	72.2 cm - 81.3 cm
VALVES	12 (4 per cylinder) with VVA

Gasdyn: some application cases



Measured **Predicted**



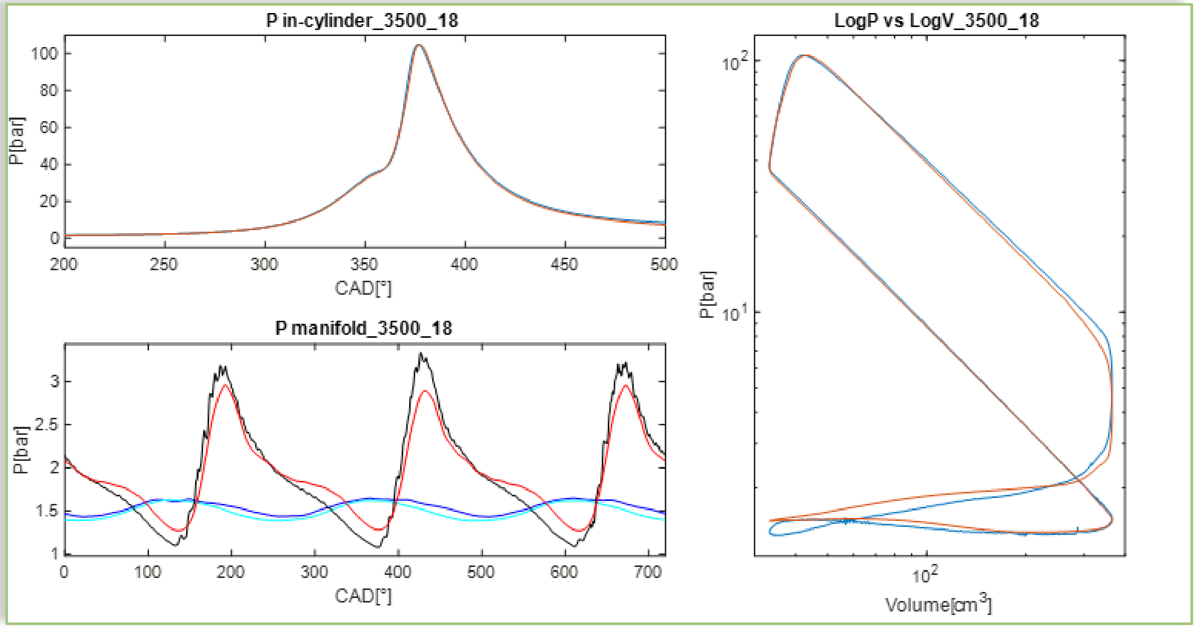


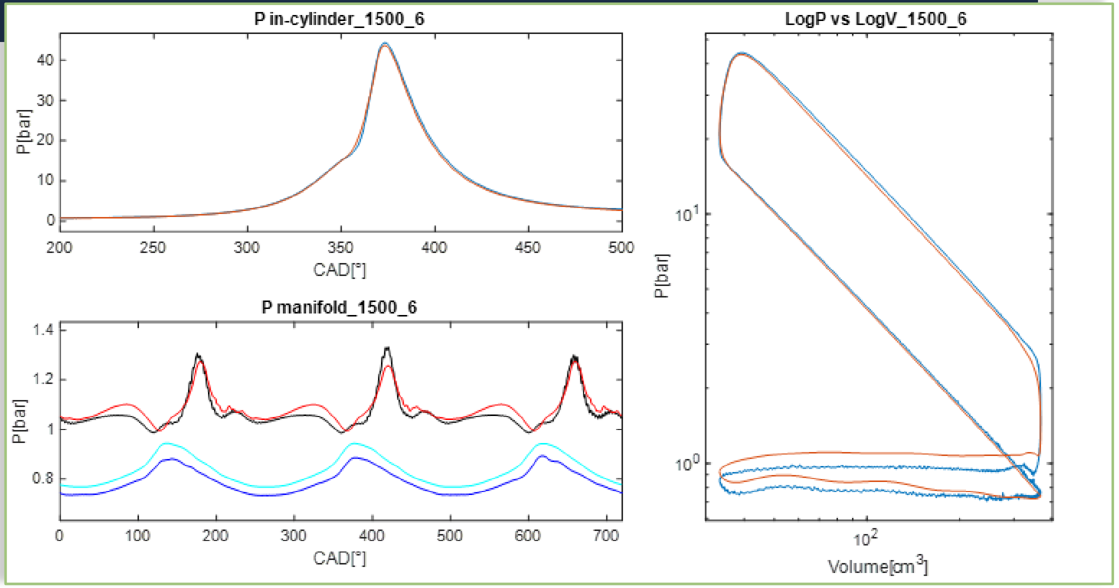
Ref.: Marinoni A.M., Onorati A., Montenegro G., Sforza L., Cerri T., Olmeda P. Dreif A., RDE cycle simulation by 0D/1D models to investigate IC engine performance and cylinder-out emissions, International J of Engine Research, DOI: 10.1177/14680874221141936, 2022.

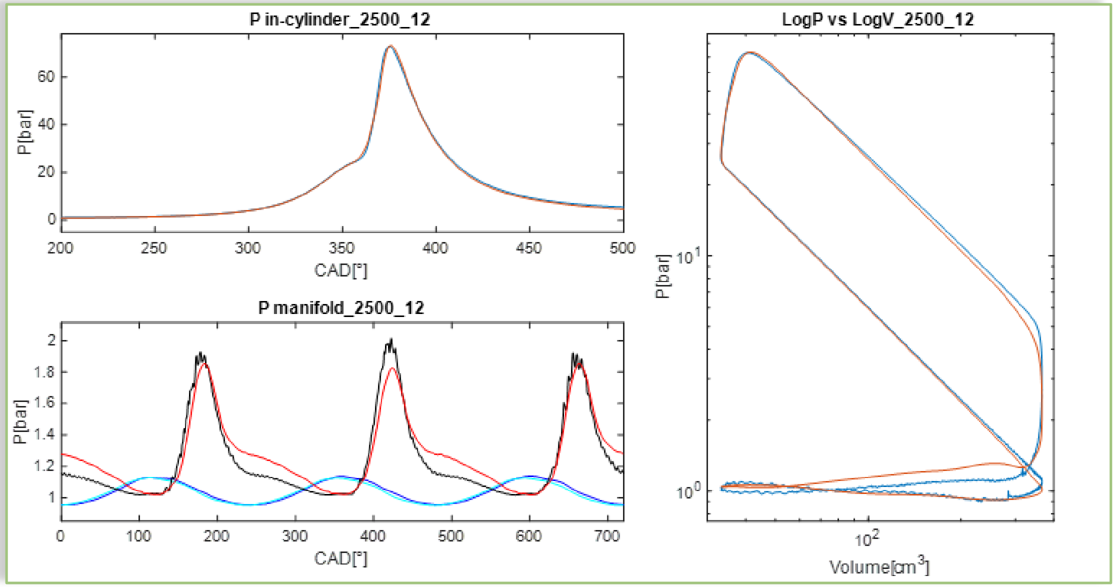
Gasdyn: some application cases

Comparisons of:

- In-cylinder pressure
- Intake and exhaust pressure

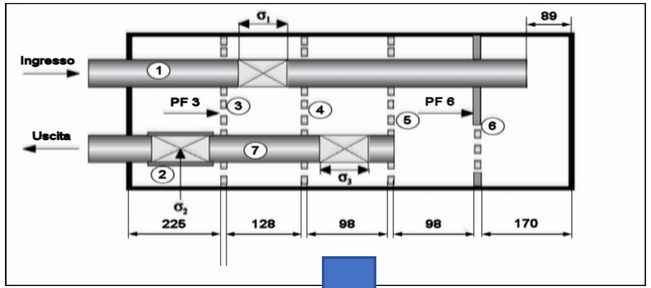


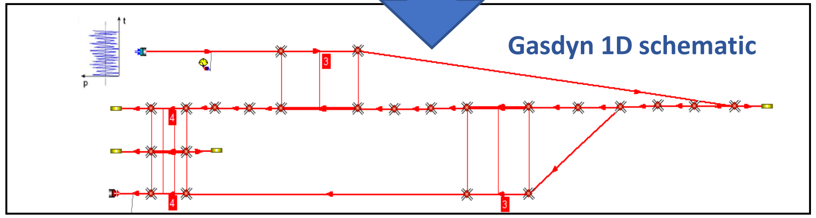




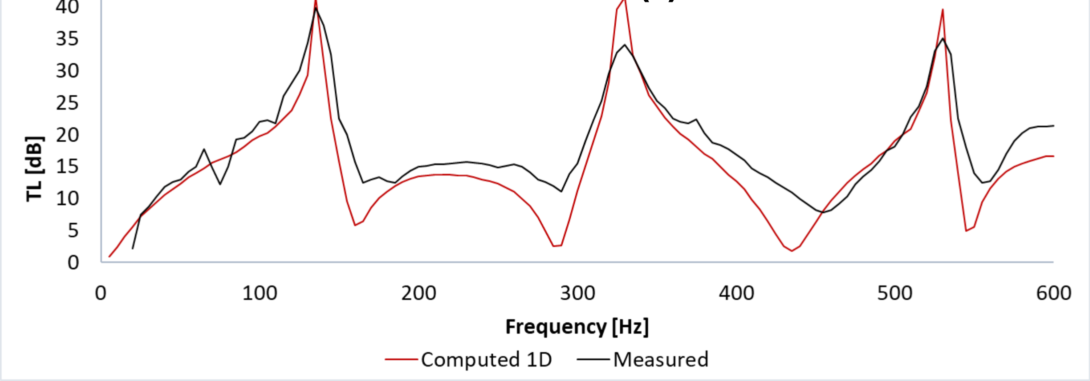
Noise reduction: Transmission Loss and Transfer Function

Multiple expansion chamber + perforated

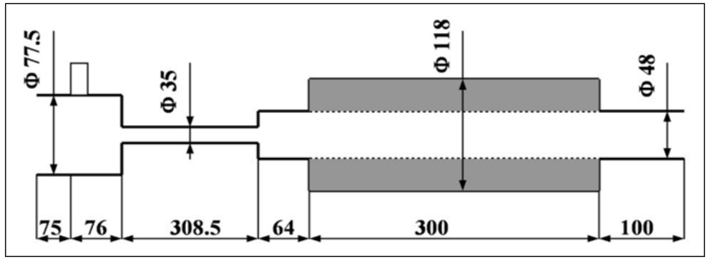


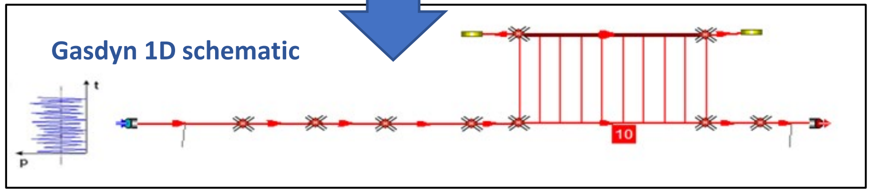


(*) Transmission Loss

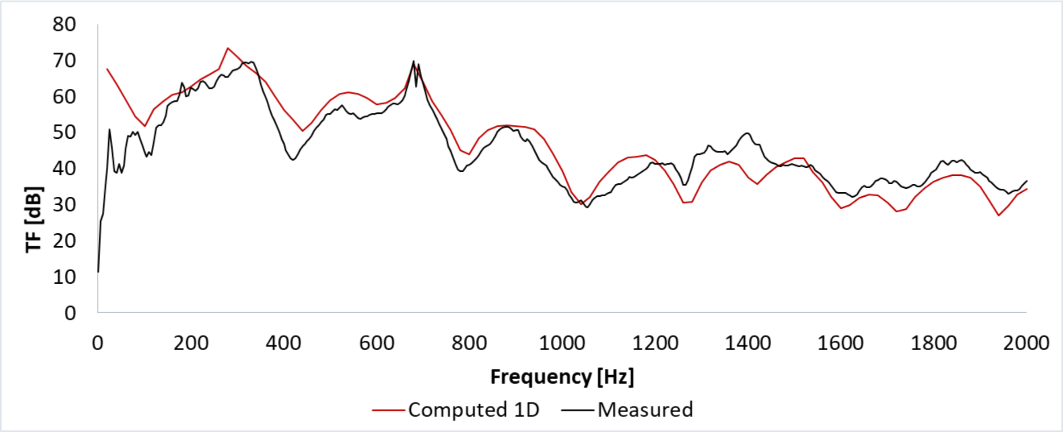


Dissipative + perforated



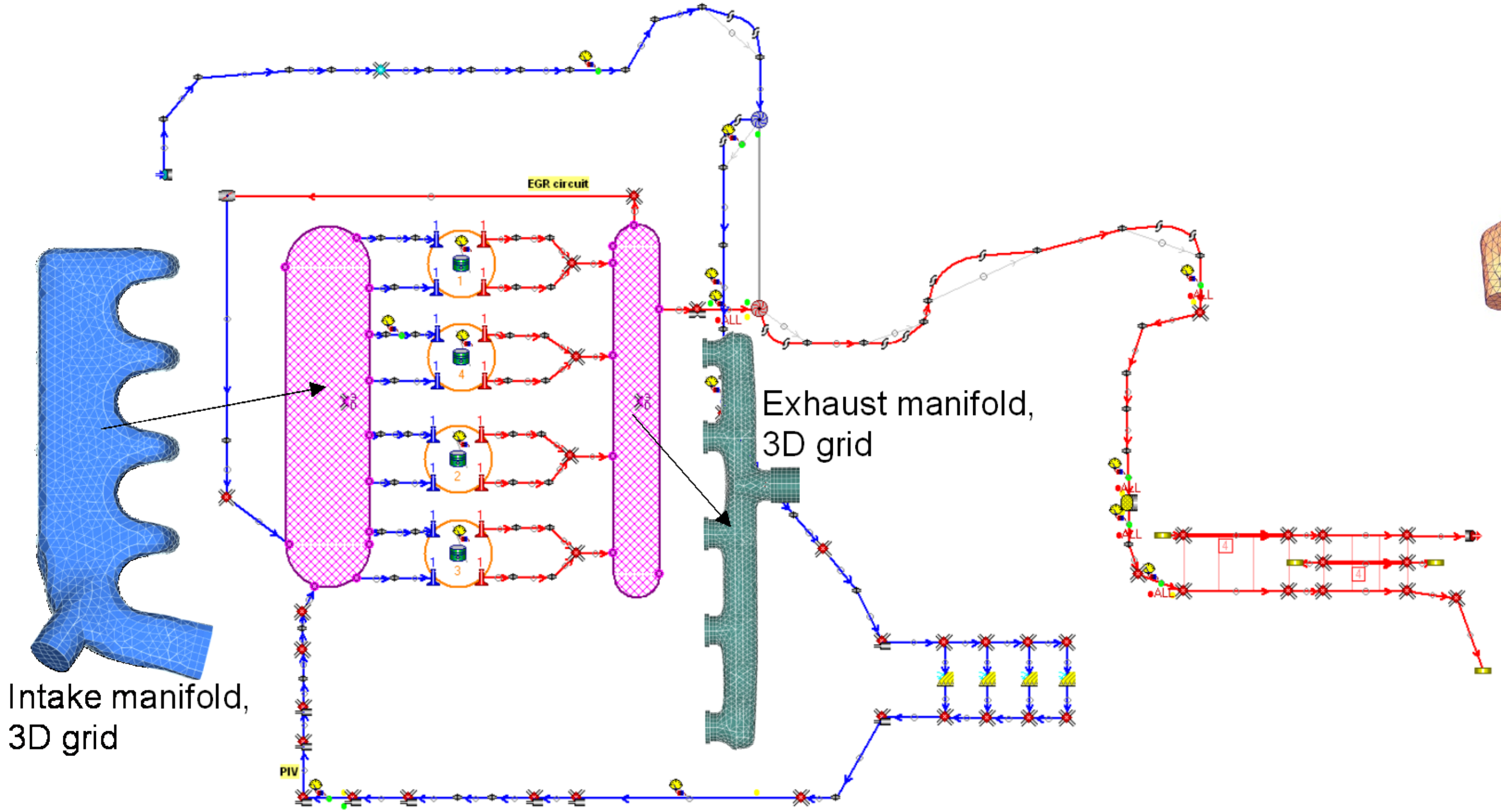


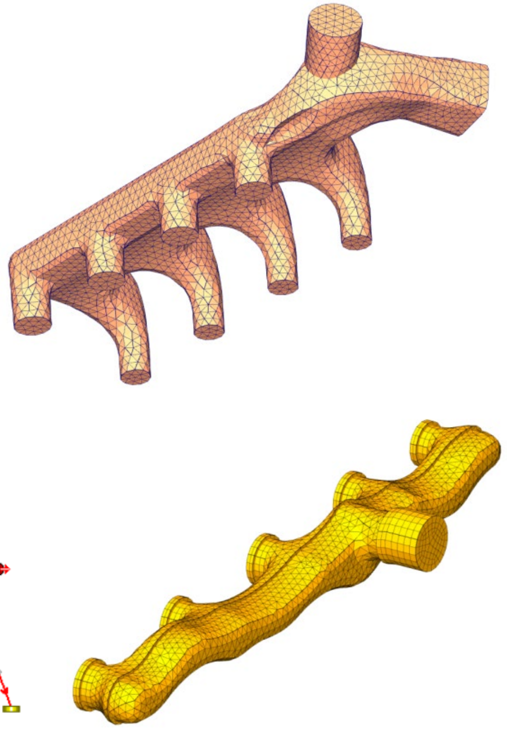
(*) Transfer Function



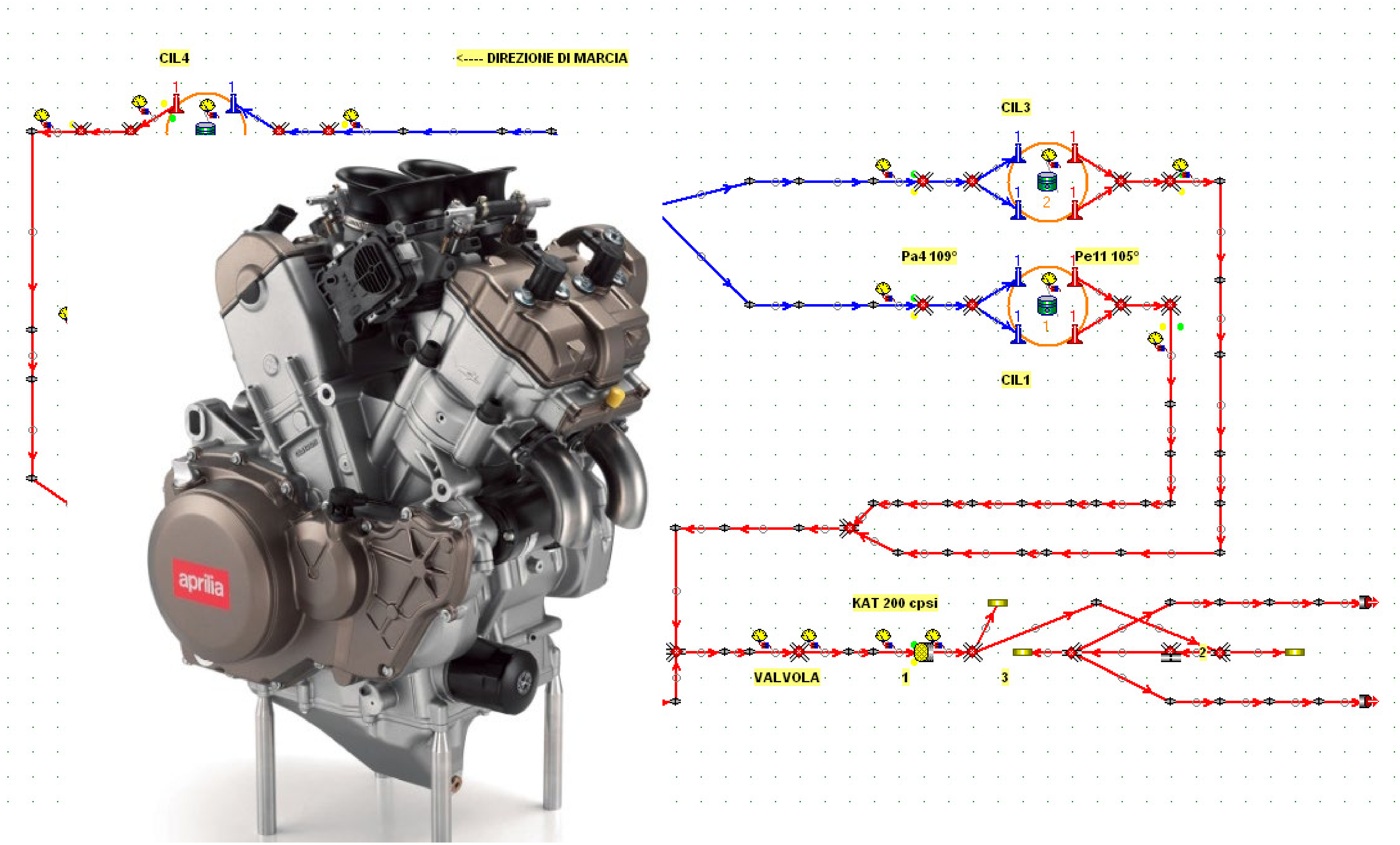
Coupled 1D-3D simulations

Unsteady flows in intake and exhaust systems: 1D-3D coupling



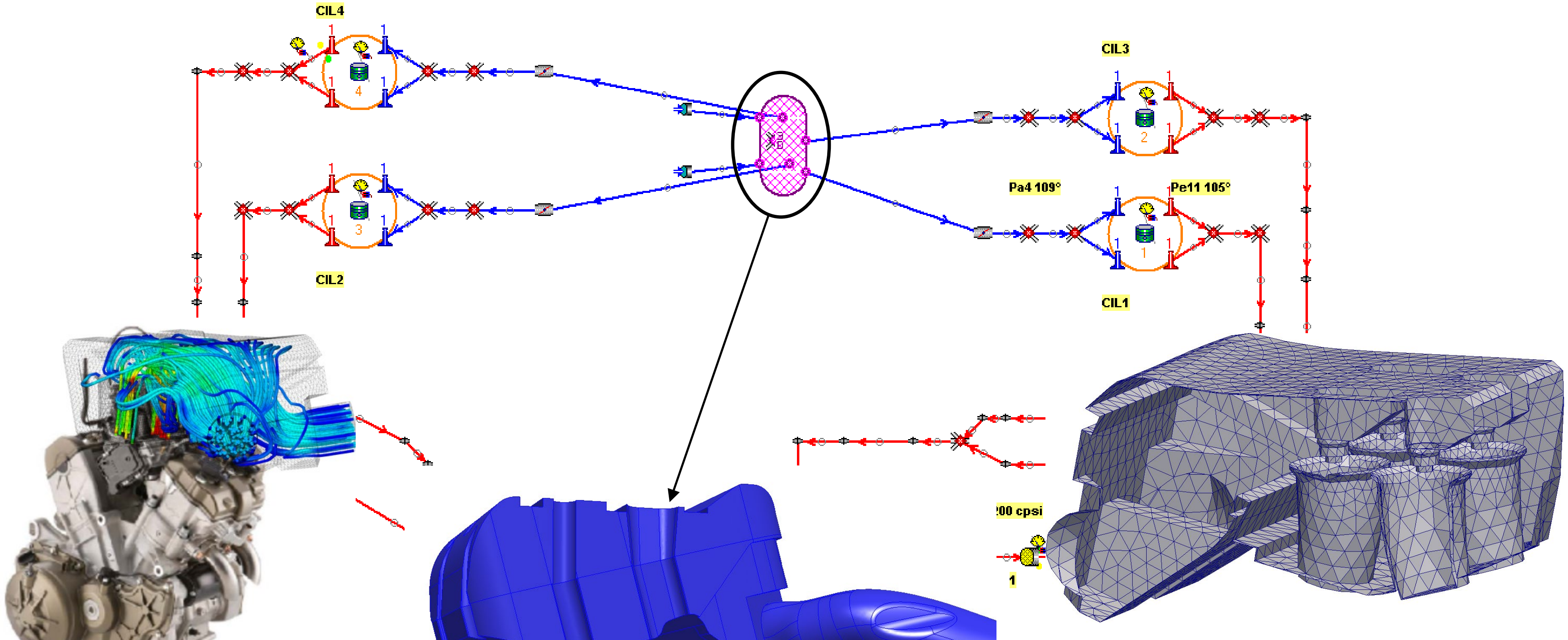


1D-3D simulation of an Aprilia V4 engine



1D-3D simulation of an Aprilia V4 engine

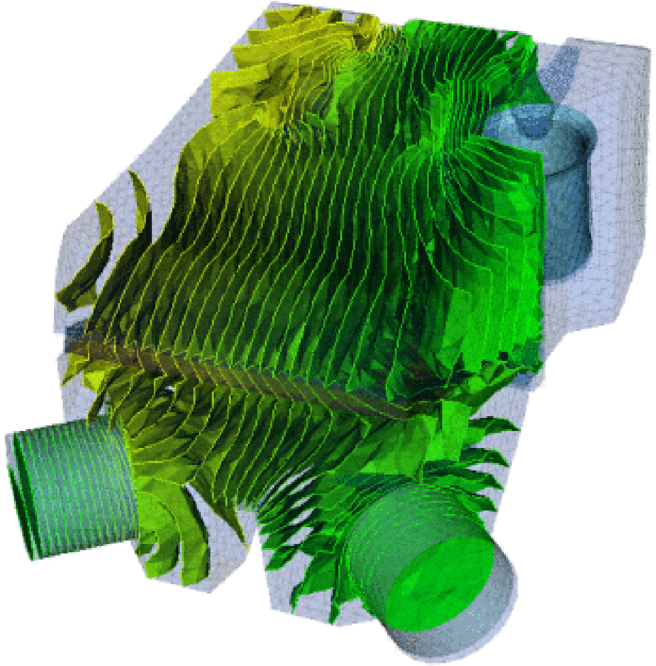
1D code GASDYN coupled to OpenFOAM: intake air-box, 3D domain

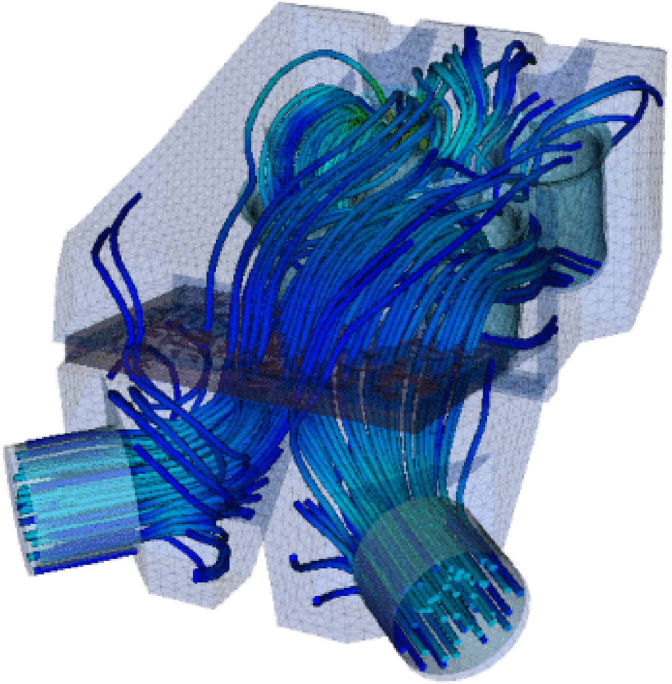


Fully tetrahedral mesh,
18000 cells

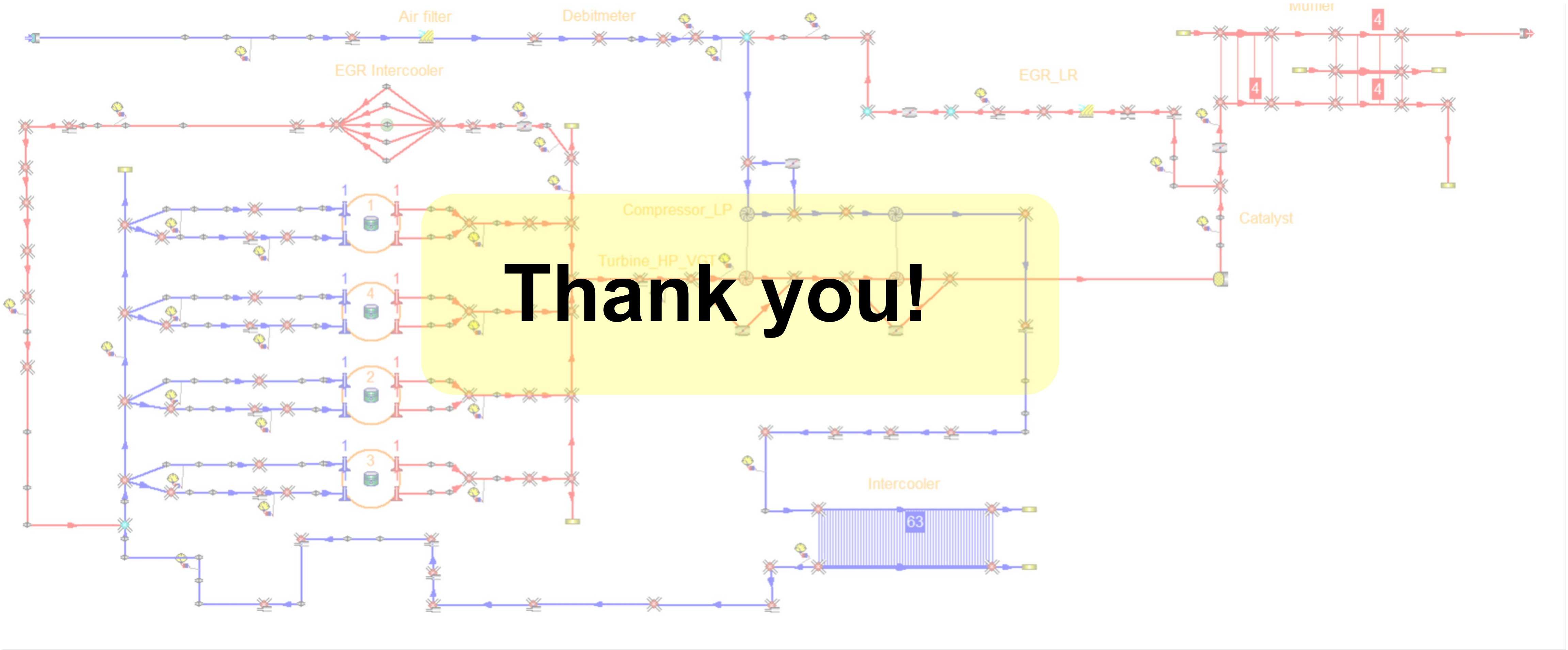
1D-3D simulation of an Aprilia V4 engine

Pressure waves and gas velocity field in the air-box:





The Gasdyn code for 0D/1D Simulations of IC Engines



Thank you!