TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

Faculty of Engineering

Master's degree in Mechanical Engineering

Multiphysics optimization of an exhaust port using mesh morphing

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A. A. 2022-2023

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***Objectives*:**

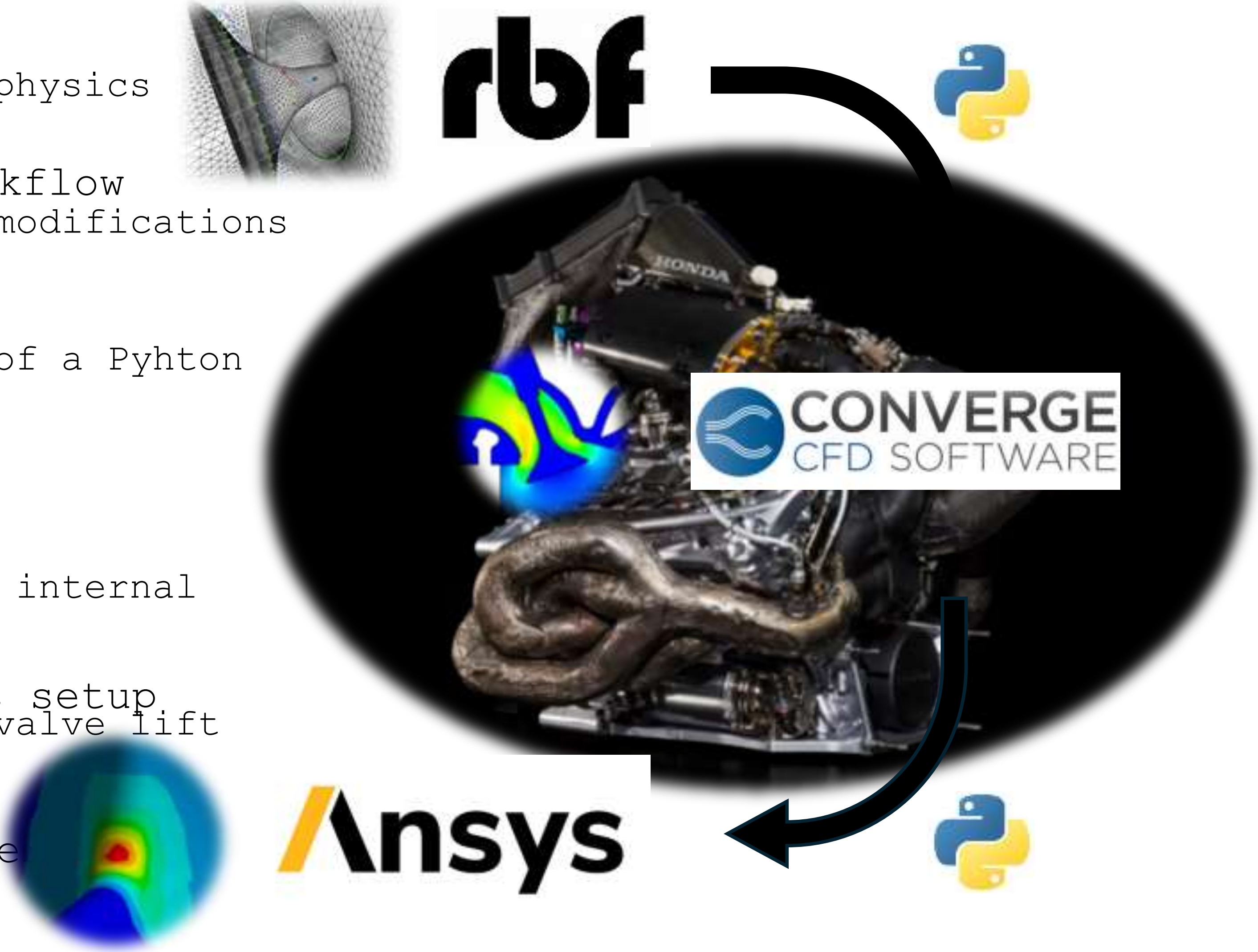
- Development of a workflow for multiphysics simulations
- Integration of mesh morphing shape modifications inside CFD and FEM software
- Process automation through the use of a Pyhton code

Starting point:

- Exhaust port and engine head for an internal combustion engine
- Flowbench simulations with maximum valve lift

Performance parameters

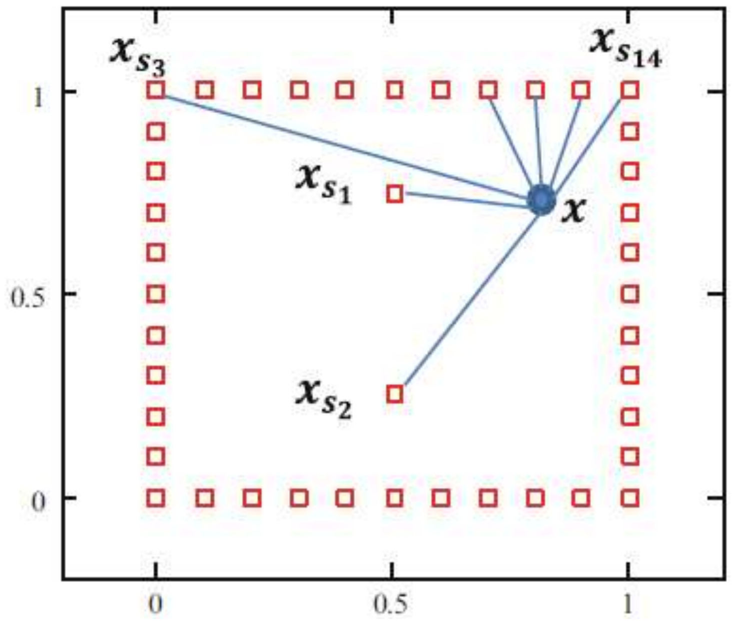
- CFD simulations → Mass flow rate
- CSM simulations → Maximum stress

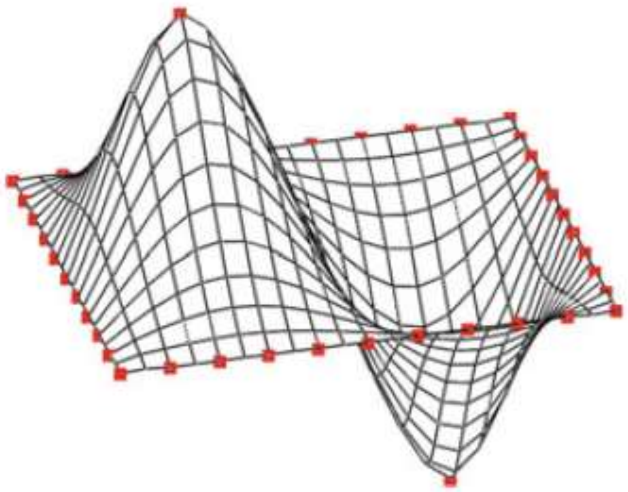


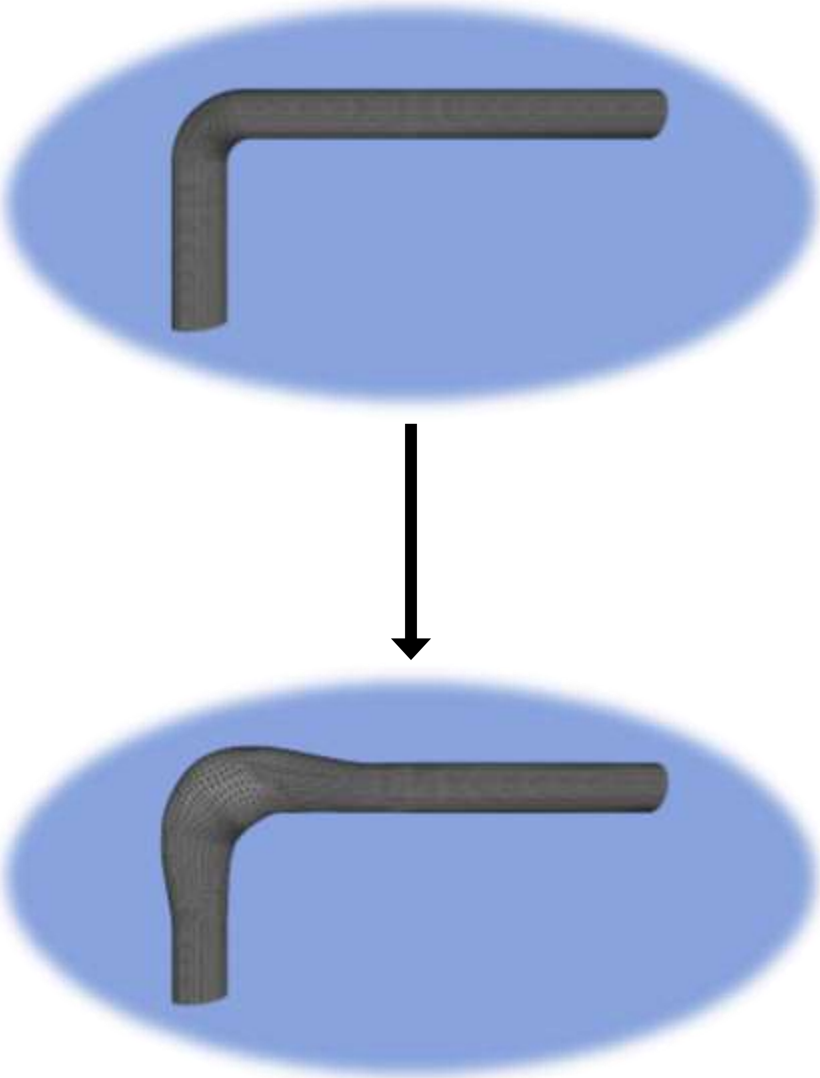
Mesh morphing

$$s(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i \varphi(\|\mathbf{x} - \mathbf{x_{si}}\|) + h(\mathbf{x})$$

- $\boldsymbol{x}$ = Evaluation point
- $\boldsymbol{x_s}$ = Source point
- $s(\boldsymbol{x})$ = Scalar function
- γ_i= Weight of point *i*
- $h(\boldsymbol{x})$ = Polynomial term
- φ = Radial function

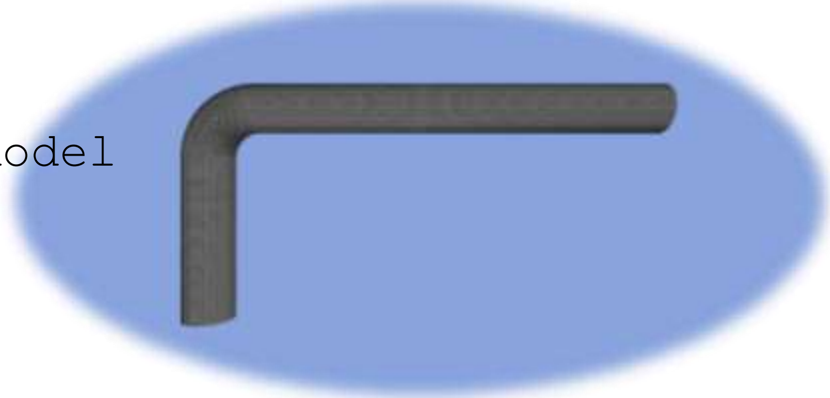






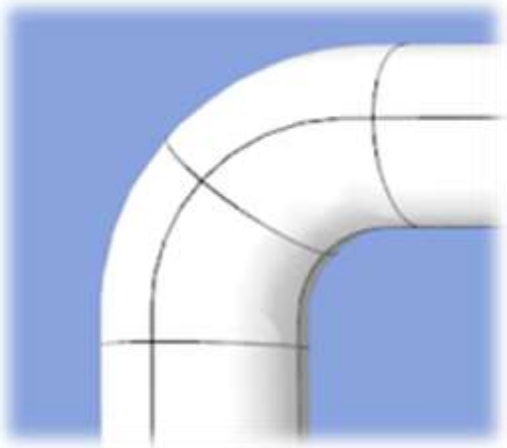
Marco Evangelos Biancolini et al. Fast radial basis functions for engineering applications. Springer, 2017.

Mesh morphing strategies



CAD based

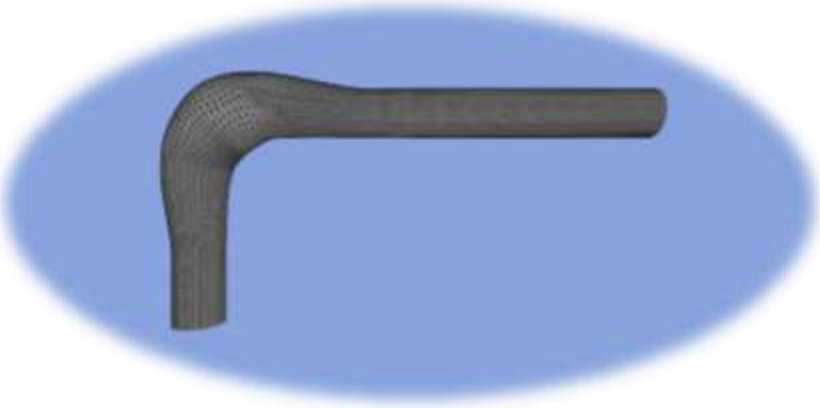
- Full CAD model
- Sources on the starting model



✓ Potentially more precise

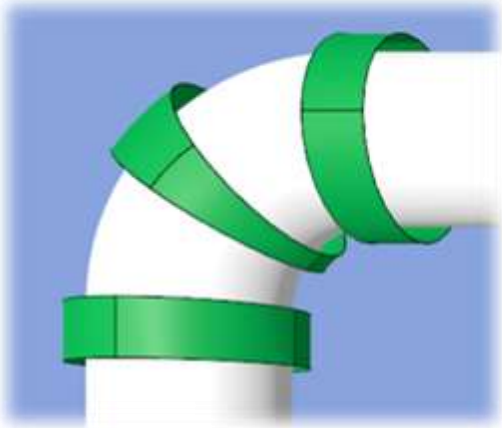
☒ Complexity

Same mesh of target points



Mesh based

- Auxiliary CAD entities
- Sources on virtual geom

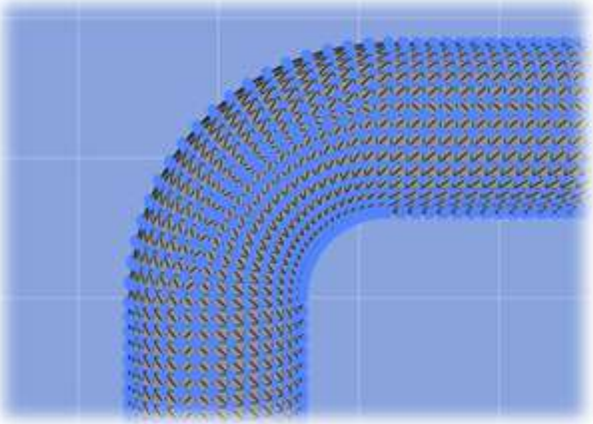


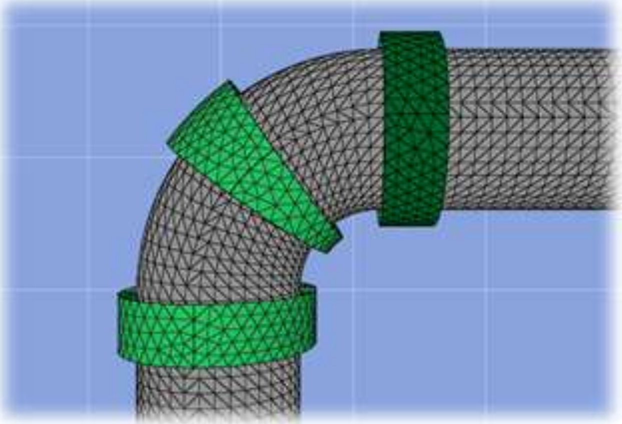
✓ Computational cost

☒ Additional models req

RBF-viewer

RBF Region (file .dat)





RBF Source (file .step)

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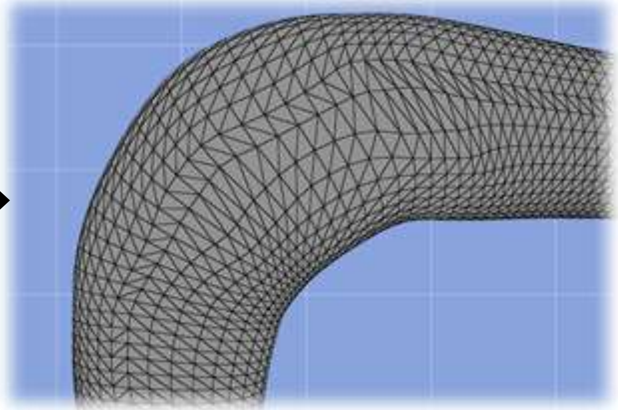
"coord_filtering": false,
"coordinate_system_serialized_id": 0
"function_degree": 3,
"geometry_entities_ids": [
  556
],
"id": 724,
"is_region": false,
"name": "RBF Source 4",
"node_overlap_mode": 1,
"scoping_method": 0,
"serialized_id": 28,
"target_nodes": [
  3698,
  3699,
  3749
],
"transformation_definition_type": 0,
"transformation_id": 0,
"transformation_name": "Translation"
"x": -4.0,
"y": 6.0,
"z": 0.0

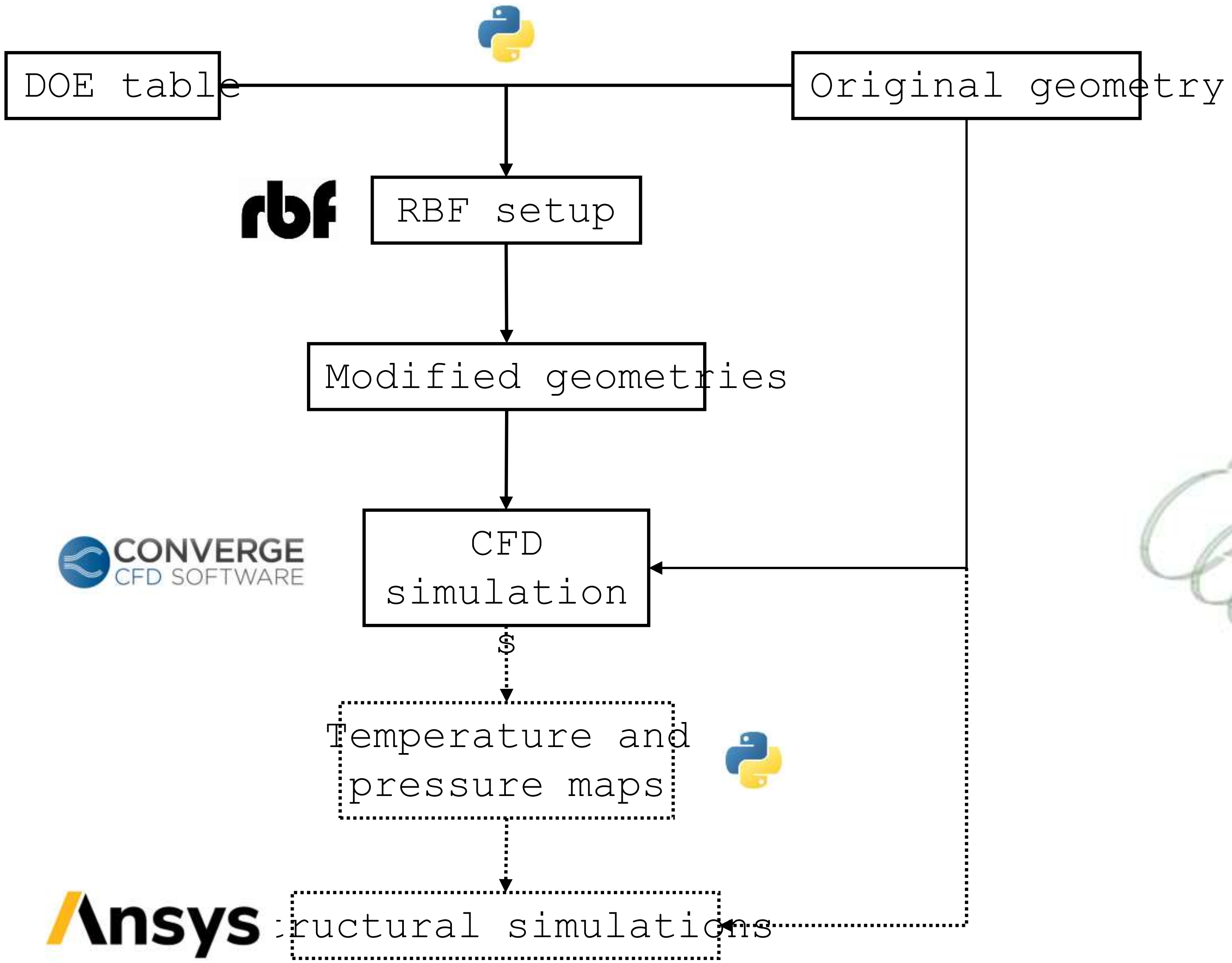
JSON file

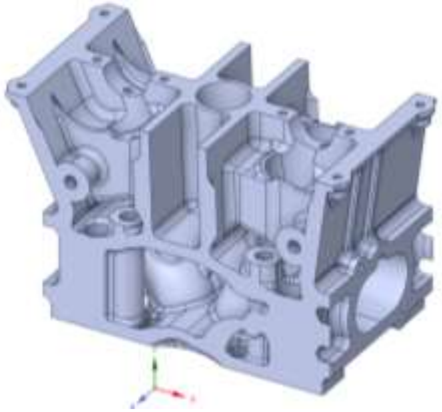
Modified geometry

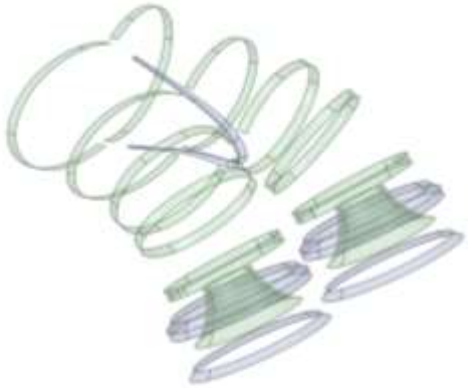


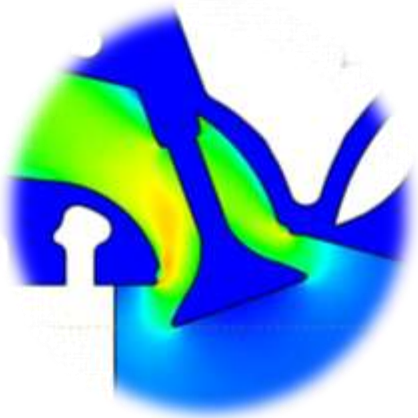
- ✓ Automation
- ✓ Design Of Experiment (D

Workflow

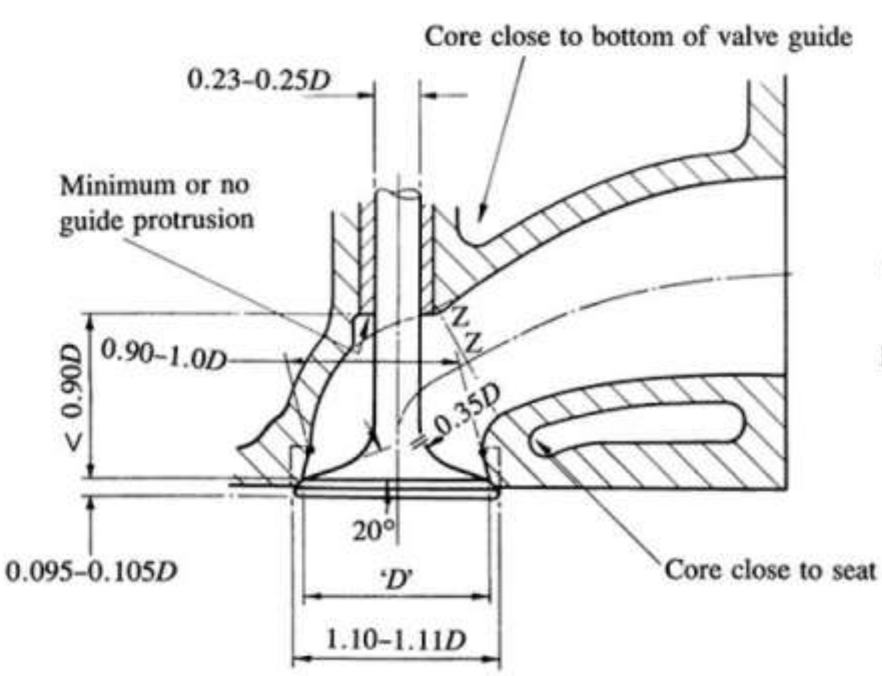

DOE table
Original geometry
rbf
RBF setup
Modified geometries
CONVERGE
CFD SOFTWARE
CFD
simulation
$
Temperature and
pressure maps
Ansys
ructural simulations

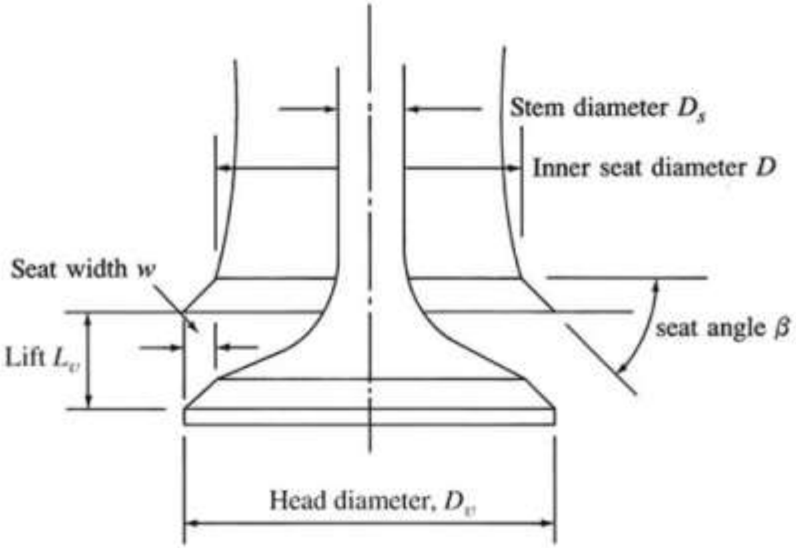






Flow through exhaust valves and ports





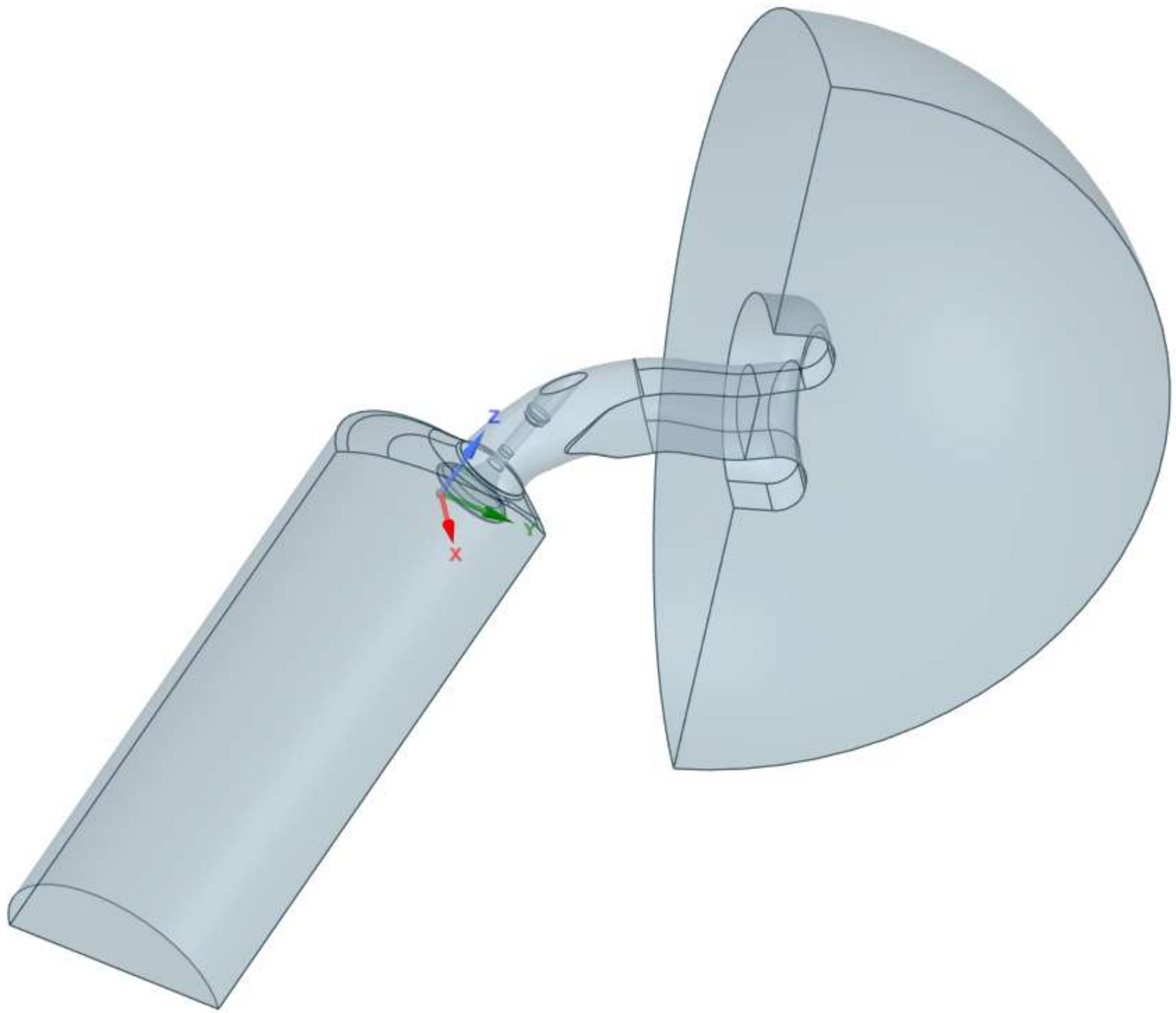
Valve head area	$\frac{\pi D_v^2}{4}$
Port area at valve seat	$\frac{\pi D_p^2}{4}$
Minimum flow area	$\frac{\pi}{4}(D_p^2 - D_s^2)$
Curtain area	$\pi D_v L_v$

$$\dot{m}_r = \frac{C_D A_r P_0}{\sqrt{RT_0}} \left(\frac{p_T}{p_0}\right)^{\frac{1}{\gamma}} \left\{ \frac{2\gamma}{\gamma - 1} \left[1 - \left(\frac{p_T}{p_0}\right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{\frac{1}{2}}$$

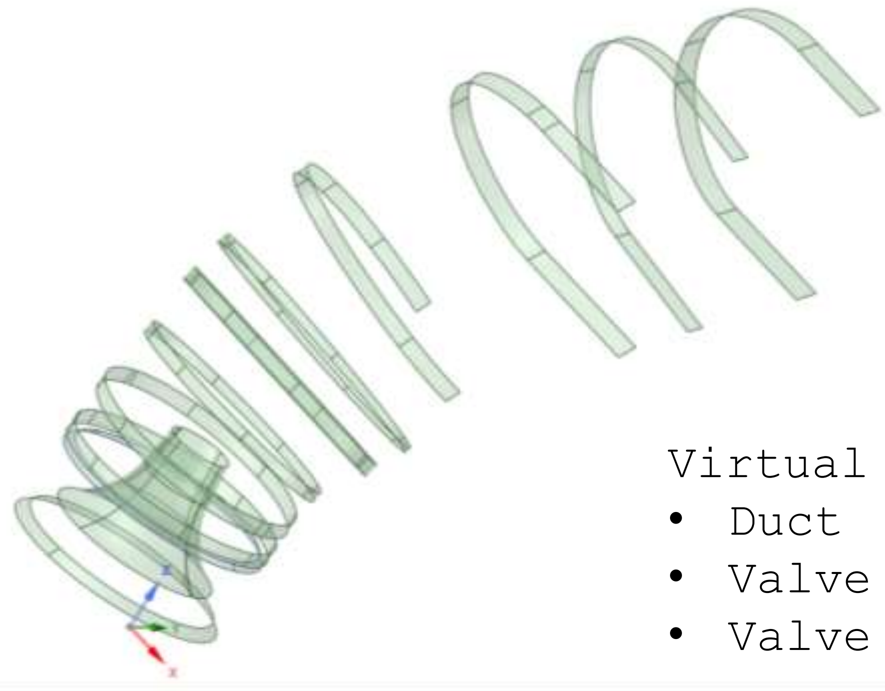
- $p_0 =$ Cylinder static pressu
- $p_T =$ Downstream static press
- $C_D =$ Discharge coefficient
- $A_r =$ Reference area

John B. Heywood. Internal combustion engine fundamentals.

Exhaust - Geometry

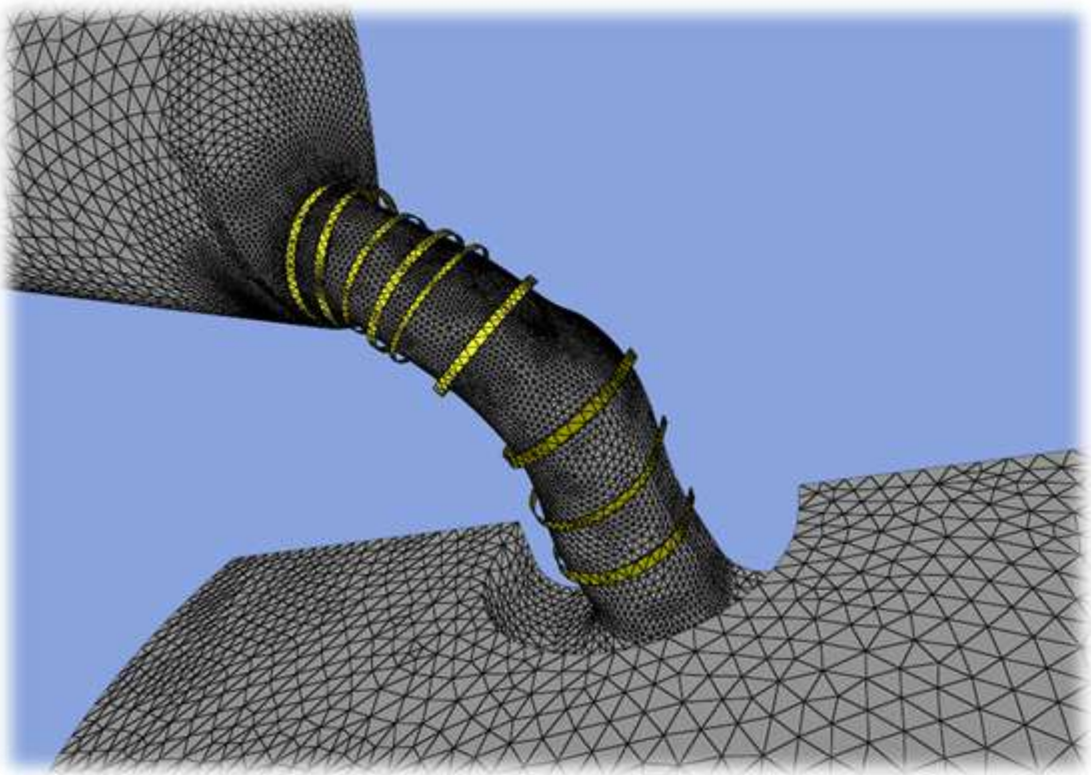


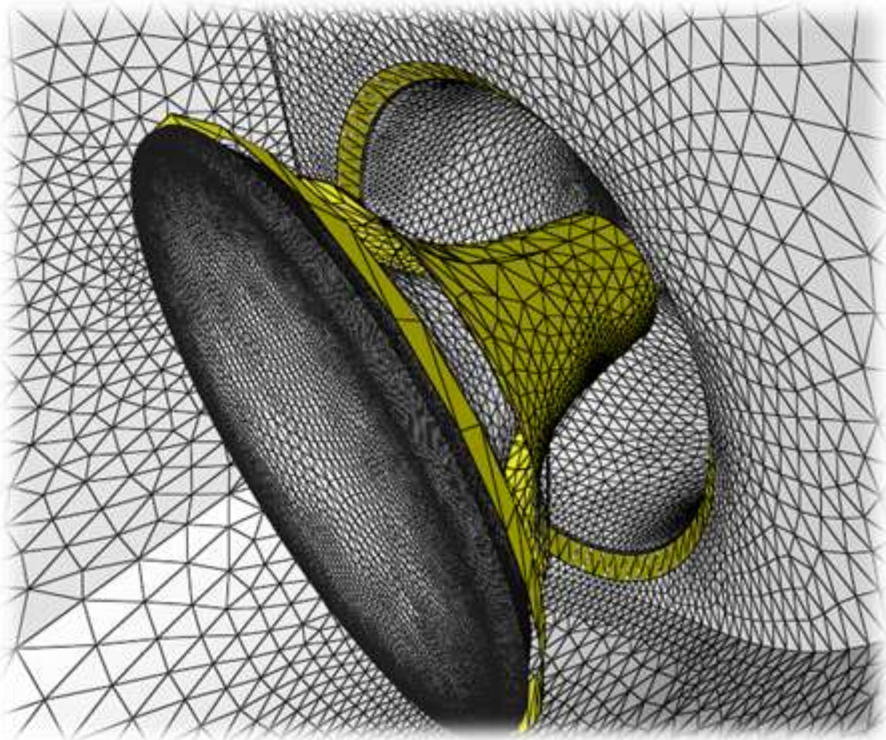
Valve lift	$10\ mm$
Valve diameter	$28\ mm$
Courtain area	$800\ mm^2$
Minimum flow area	$484\ mm^2$
Cylinder bore	$80\ mm$



Virtual geometries:
- Duct
- Valve stem
- Valve seat

Exhaust - RBF setup





Design of Experiment
- Duct (translation)
- Valve seat(scaling)
- Valve seat (scaling, traslation)

Doe table structure

ID	RBF Source 1.T.X	RBF Source 1.S.Z	…
1	2.5	1.1	…
2	5	1.5	…
…	…	…	…

Exhaust – Converge setup

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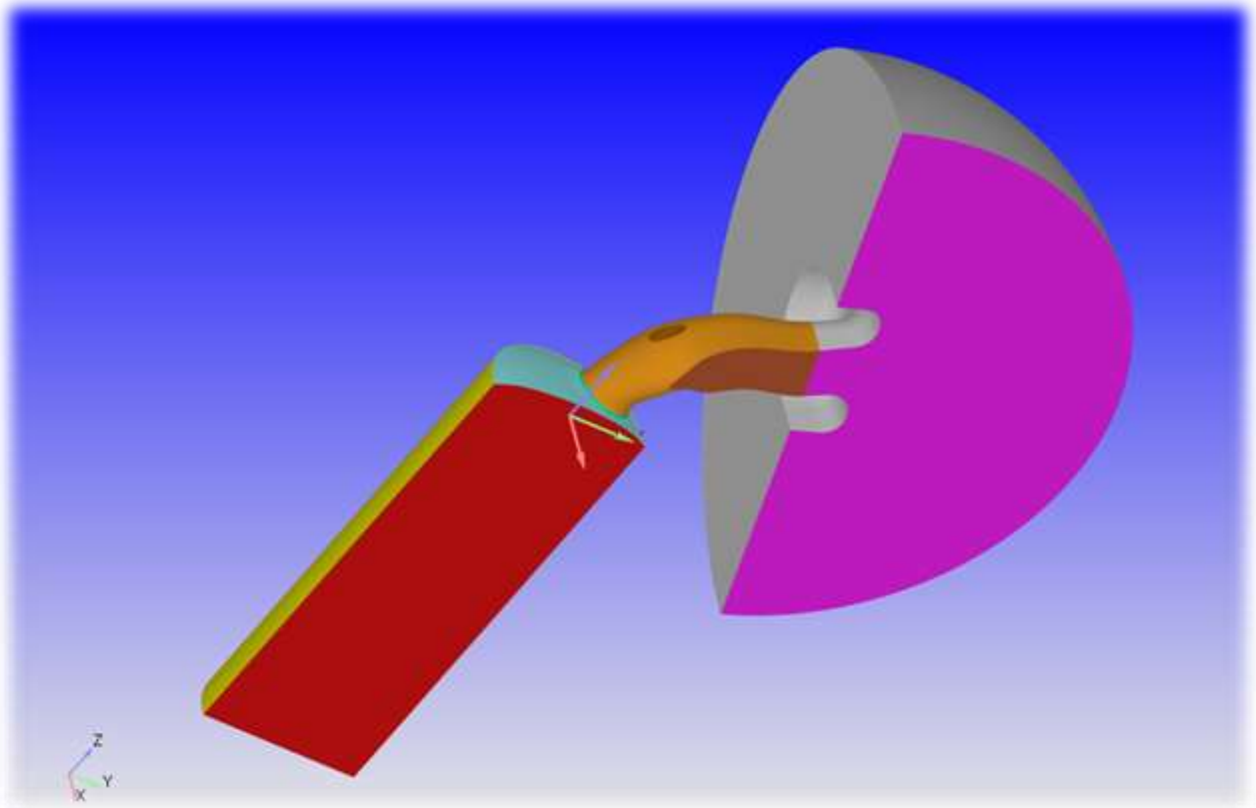


14 boundaries

Flow bench→ Steady-state flow

- Air (Real gas)
- Velocity > 0.3 Ma

} Compressible flow

- Turbulence model: RNG k-ε
- Law of the wall → y+ ∈ [30,100] through A

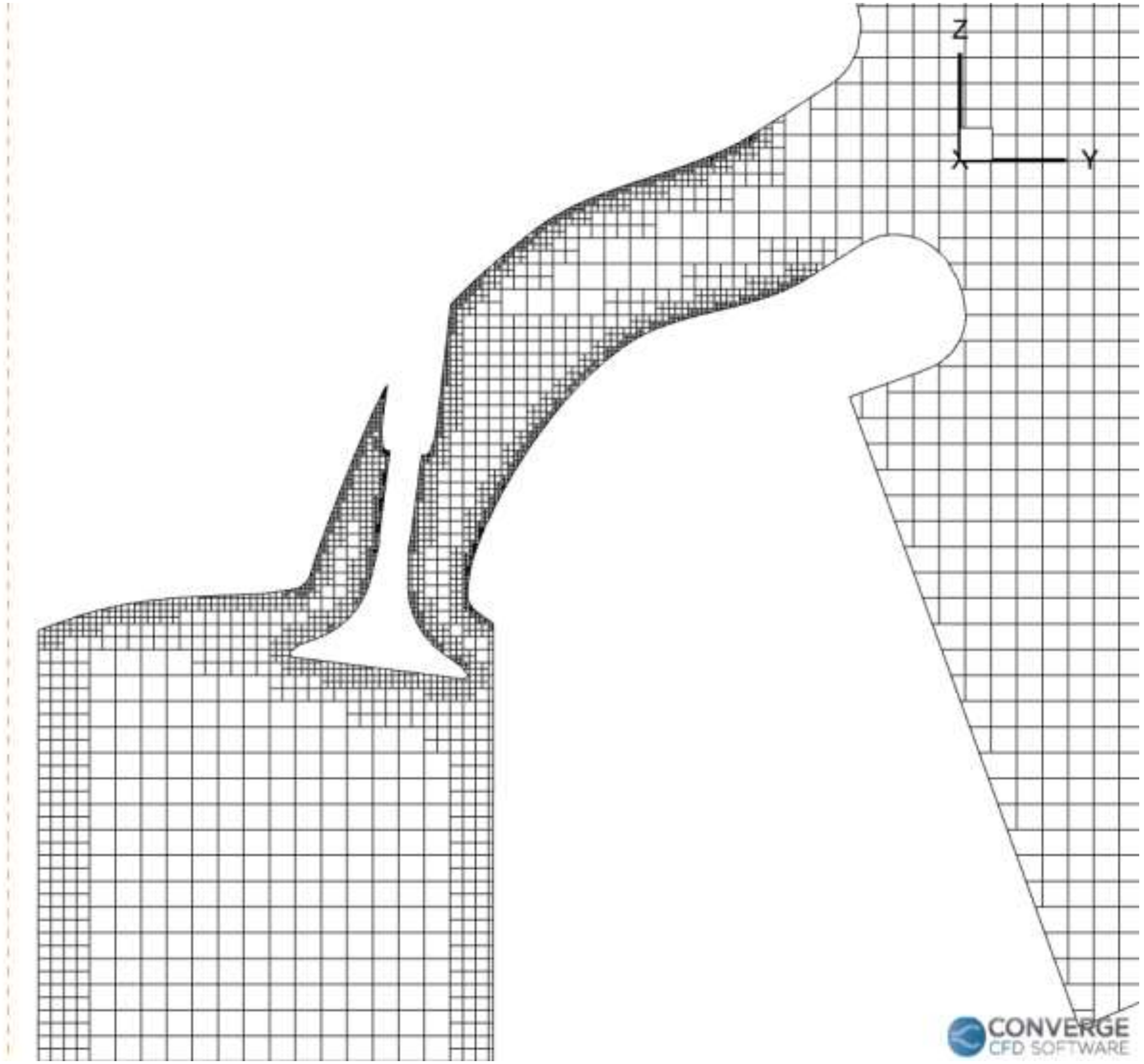
Boundary conditions:

- Inlet total pressure = 111325 Pa
- Outlet static pressure = 101325 Pa

} ΔP ≈ 100 mbar

- Inlet turbulent kinetic energy rate = 0.0
- Inlet turbulent dissipation = 0.008 m

Exhaust – Grid convergence

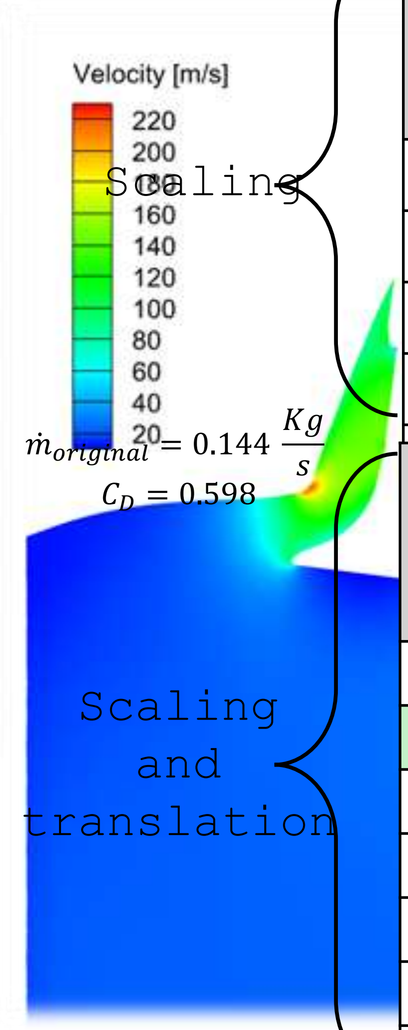


$$\Delta x_{scale} = \frac{\Delta x_{base}}{2^{scale}}$$

Definition		Scale	Layers
Cylindrical fixed embedding		1	\\
Wall embedding	Valve seat	4	2
	Duct, valve	3	2
	Cylinder	1	2

Δx_{base} $[mm]$	Mass flow rate $\left[\frac{Kg}{s}\right]$	Number of cells	Solution time $[s]$	Percentage difference
4	0.14	215000	1726	\\
2	0.147	738000	11307	5 %
1	0.152	4500000	> 24 h	3.4 %

Exhaust – Results



$\dot{m}_{original} = 0.144\ \frac{Kg}{s}$

$C_D = 0.598$

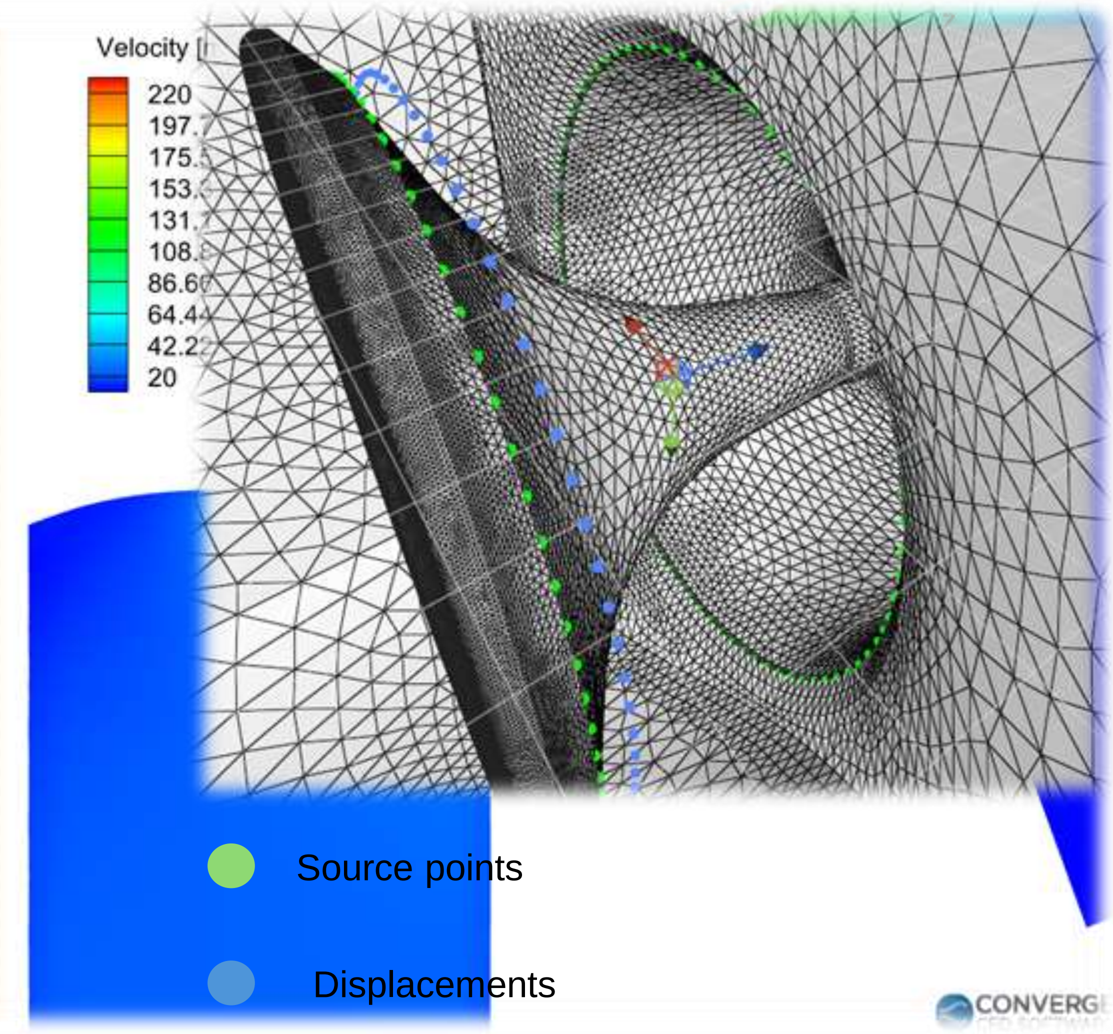
Ori

Scaling

ID	Mass flow rate $\left[\frac{Kg}{s}\right]$	Discharge coefficient	Percentage difference
1	0.146	0.607	1.39%
2	0.140	0.582	-2.07%
3	0.136	0.565	-5.6%
4	0.135	0.603	0.7%

Scaling and translation

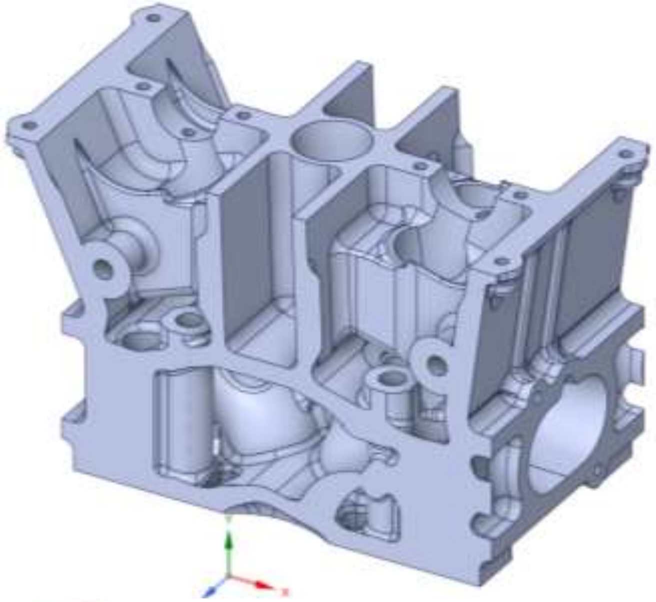
ID	Mass flow rate $\left[\frac{Kg}{s}\right]$	Discharge coefficient	Percentage difference
1	0.1466	0.609	1.81%
2	0.1470	0.611	2.08%
3	0.1468	0.61	1.94%
4	0.1458	0.606	1.25%
5	0.1462	0.608	1.53%
6	0.1452	0.603	0.83%
7	0.1442	0.599	0.14%
8	0.1430	0.594	-0.69%

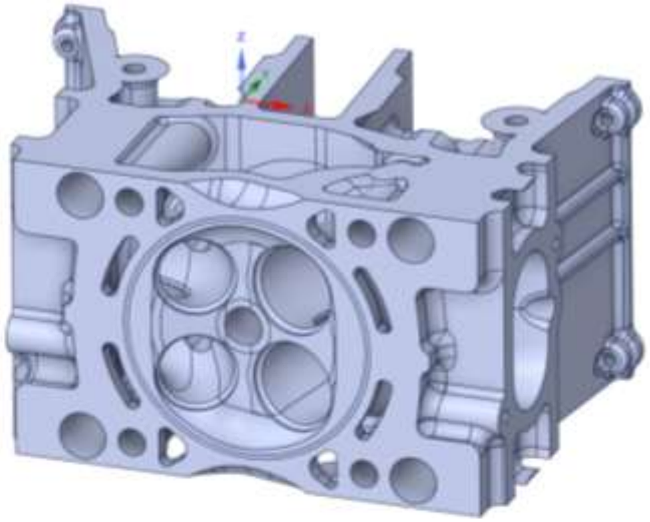


Best variant

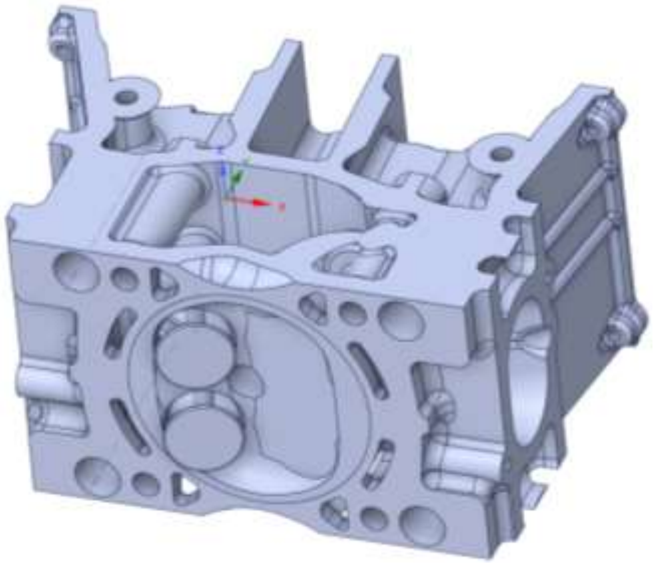
Flow rate referred to both valves, discharge coefficient for single valve, courtain area as reference

Engine head - Geometry



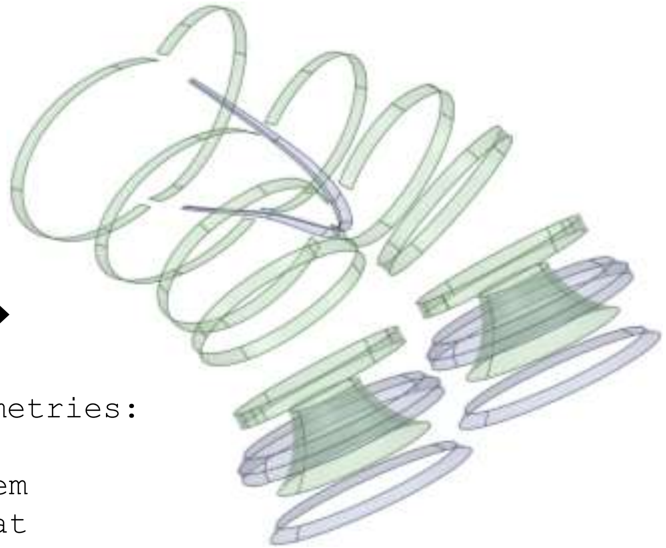


Valve lift	$10\ mm$
Valve diameter	$28{,}5\ mm$
Courtain area	$895\ mm^2$
Minimum flow area	$457\ mm^2$
Cylinder bore	$90\ mm$

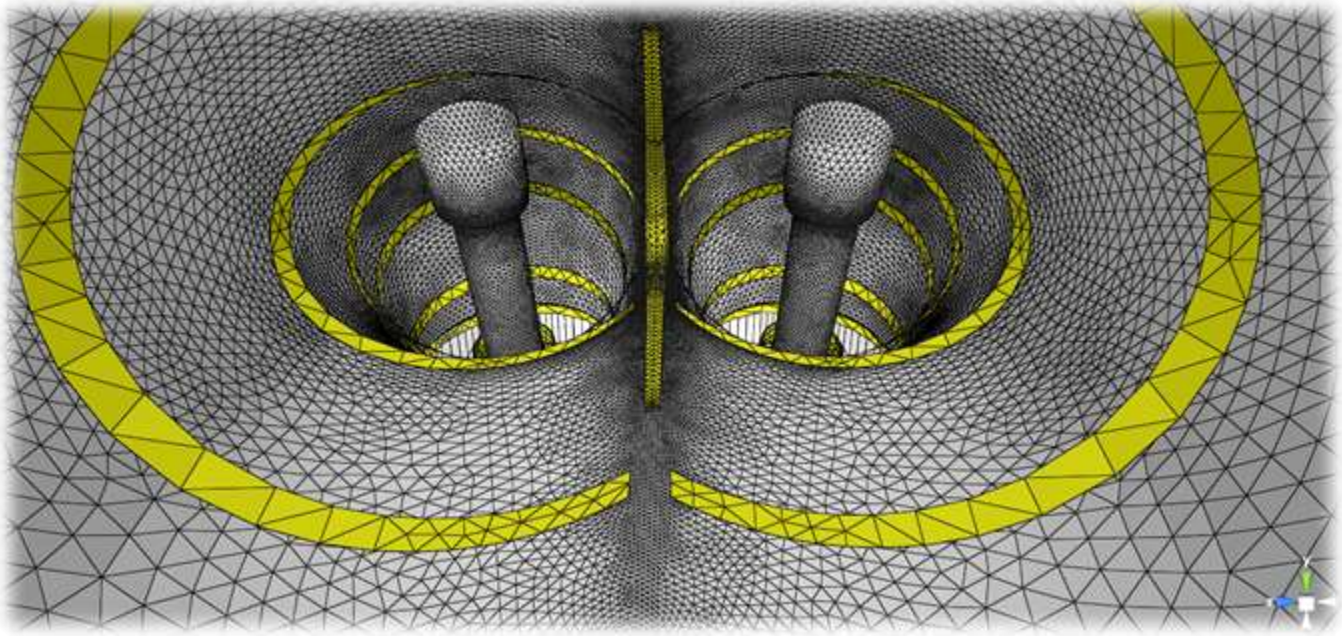


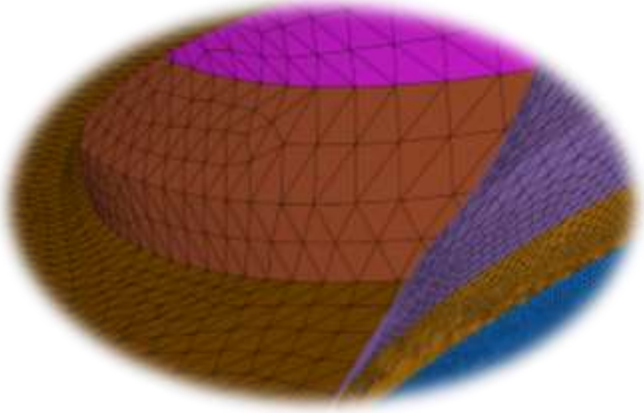
Valves:
- Exhaust → open
- Intake → closed

Virtual geometries:
- Duct
- Valve stem
- Valve seat

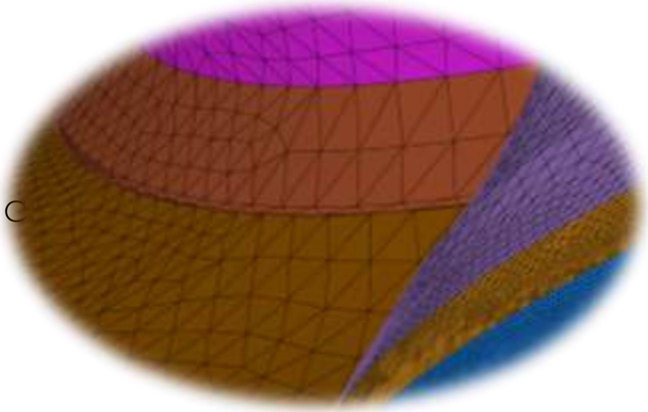


Engine head - RBF setup





Preliminary step:
''Socket'' removal



Design of Experiment

- Valve seat (scaling, traslazione) → Mass flow rate inc
- Duct (traslazione) → Stress reduction

Engine head – Converge setup

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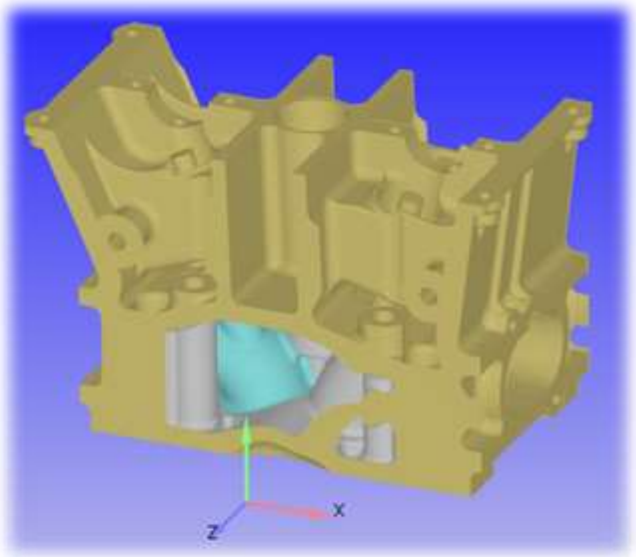
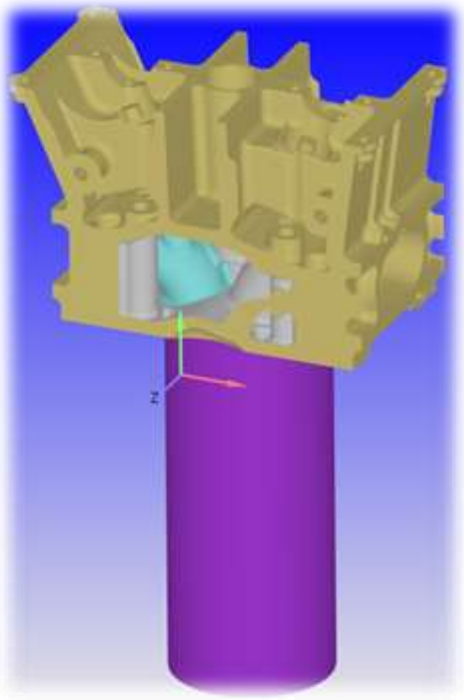




Flow bench→ Steady-state flow

- Air (Real gas)
- Velocity > 0.3 Ma

} Compressible flow

- Turbulence model: RNG k-ε
- Law of the wall → y+ ∈ [30,100] through A

Boundary conditions

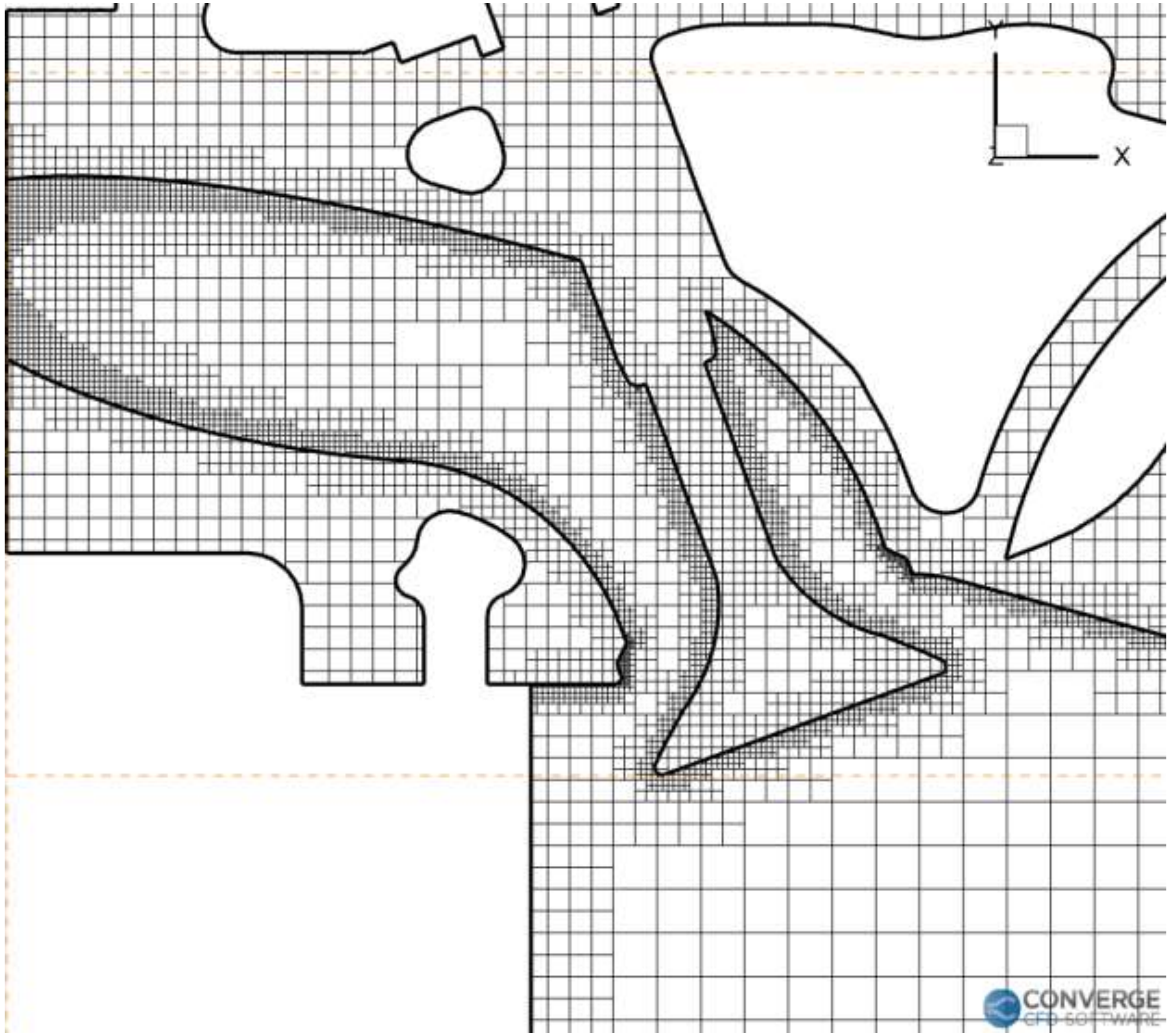
- Inlet total pressure = 111325 Pa
- Outlet static pressure = 101325 Pa

} ΔP ≈ 100 mbar

- Inlet flow temperature = 500 K
- Heat transfer with air through convection

Thermal properties aluminum alloy (Silafont 30)	
Density	$2700\ \frac{Kg}{m^3}$
Specific heat	$900\ \frac{J}{Kg\ K}$
Thermal conductivity	$140\ \frac{W}{m\ K}$

Engine – Grid convergence



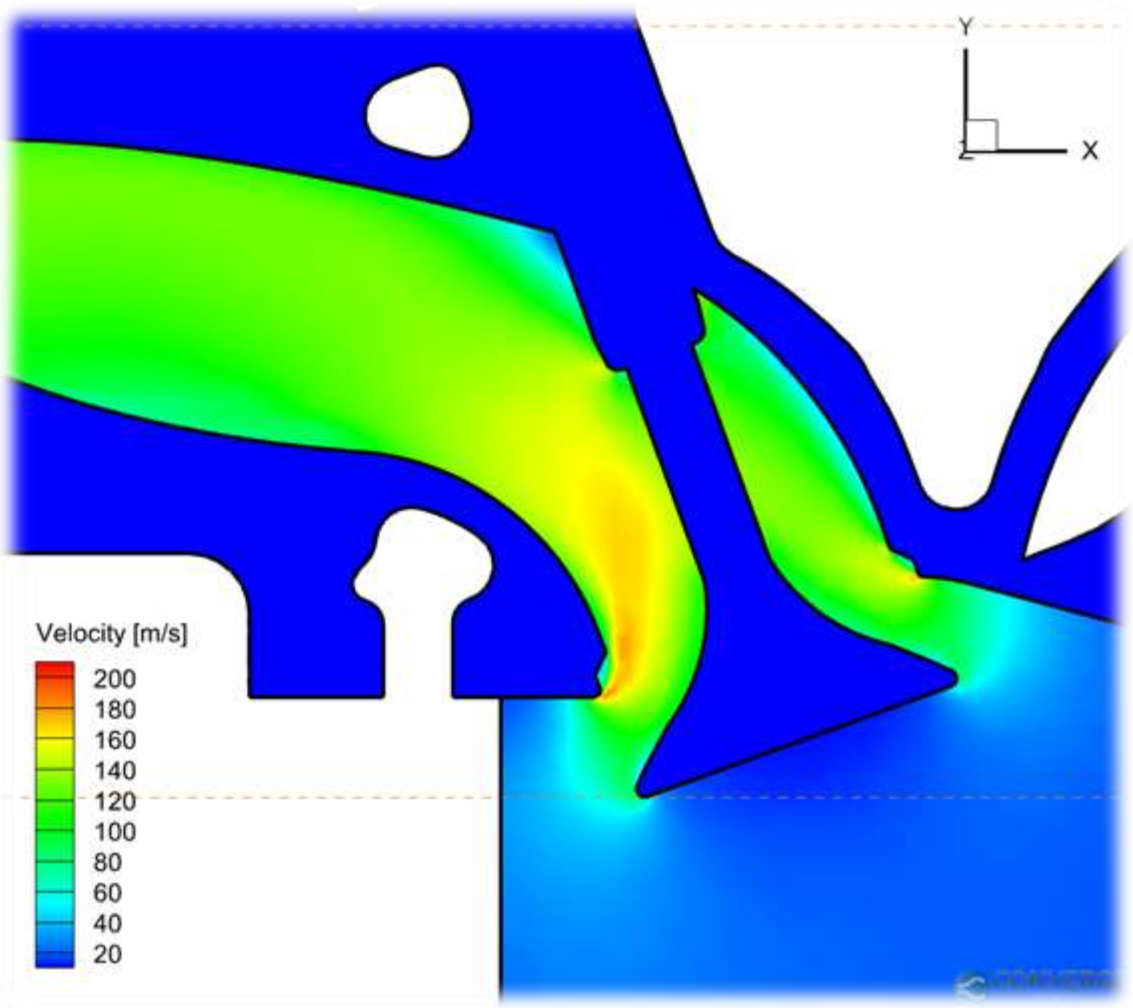
$$\Delta x_{scale} = \frac{\Delta x_{base}}{2^{scale}}$$

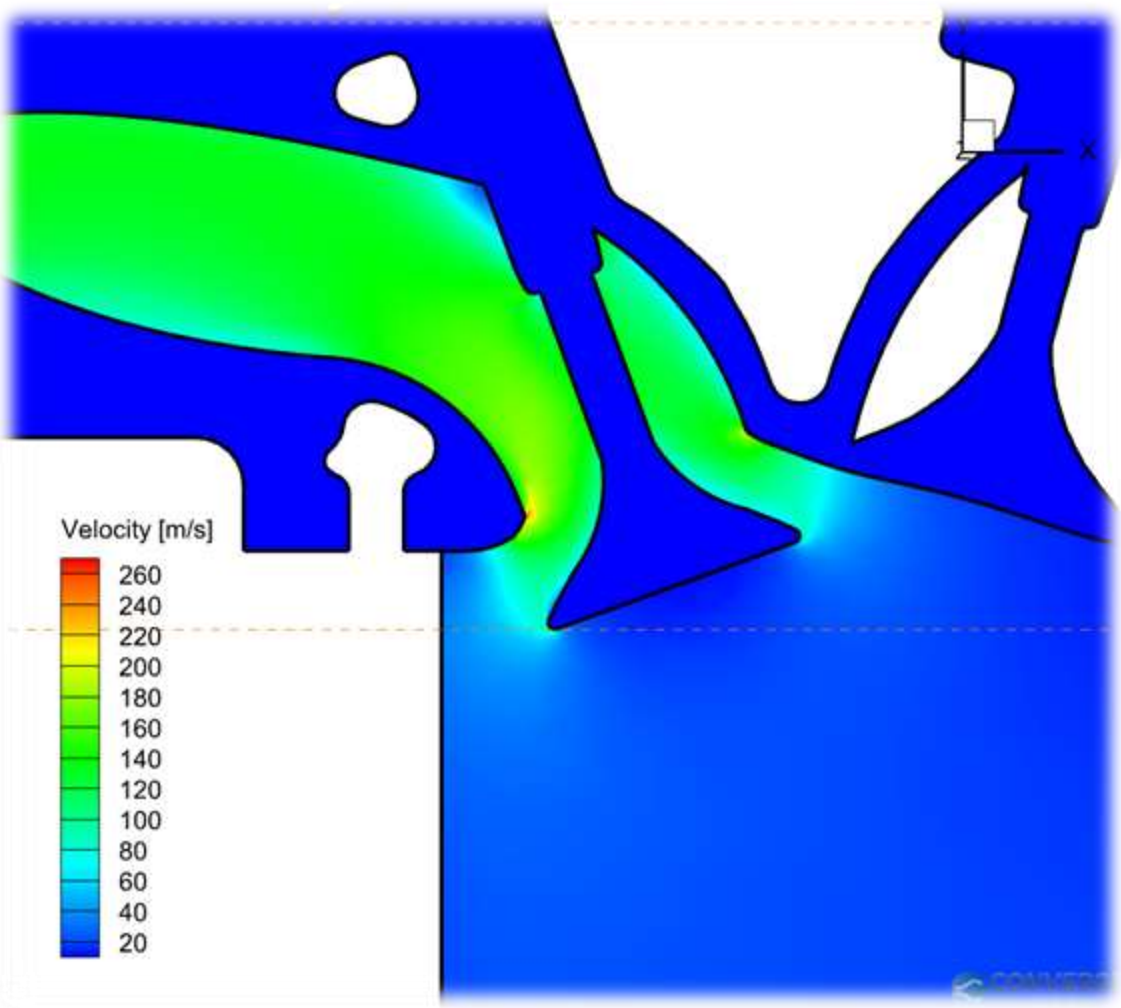
Definition		Scale (Fluid-Solid)	Layers
Solid fixed embedding		1	\\
Wall embedding	Valve seat	4 - 2	2
	Duct, valve	3 - 2	2
	Cylinder	1	2

Δx_{base} $[mm]$	Mass flow rate $\left[\frac{Kg}{s}\right]$	Number of cells	Solution time $[s]$	Percentage difference
4	0.088	645000	1950	\\
4 $(y^+ =$	0.089	1383000	5444	1.14 %
2	0.091	3185000	11300	2.25 %

Engine head - Converge results

1) - ''Socket'' removal → 6.7 % increase of mass flow rate





Original geometry → $\dot{m} = 0.0885\ \frac{Kg}{s}, C_D = 0.421$

After ''socket'' removal → $\dot{m} = 0.0945\ \frac{Kg}{s}, C_D = 0.449$

Engine head – Converge results

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2) – Valve seat DOE

Original geometry

$\dot{m}_{originale} = 0.0885 \, \frac{Kg}{s}$

$C_D = 0.421$

$\Delta \dot{m} \approx 6.7 \,\%$

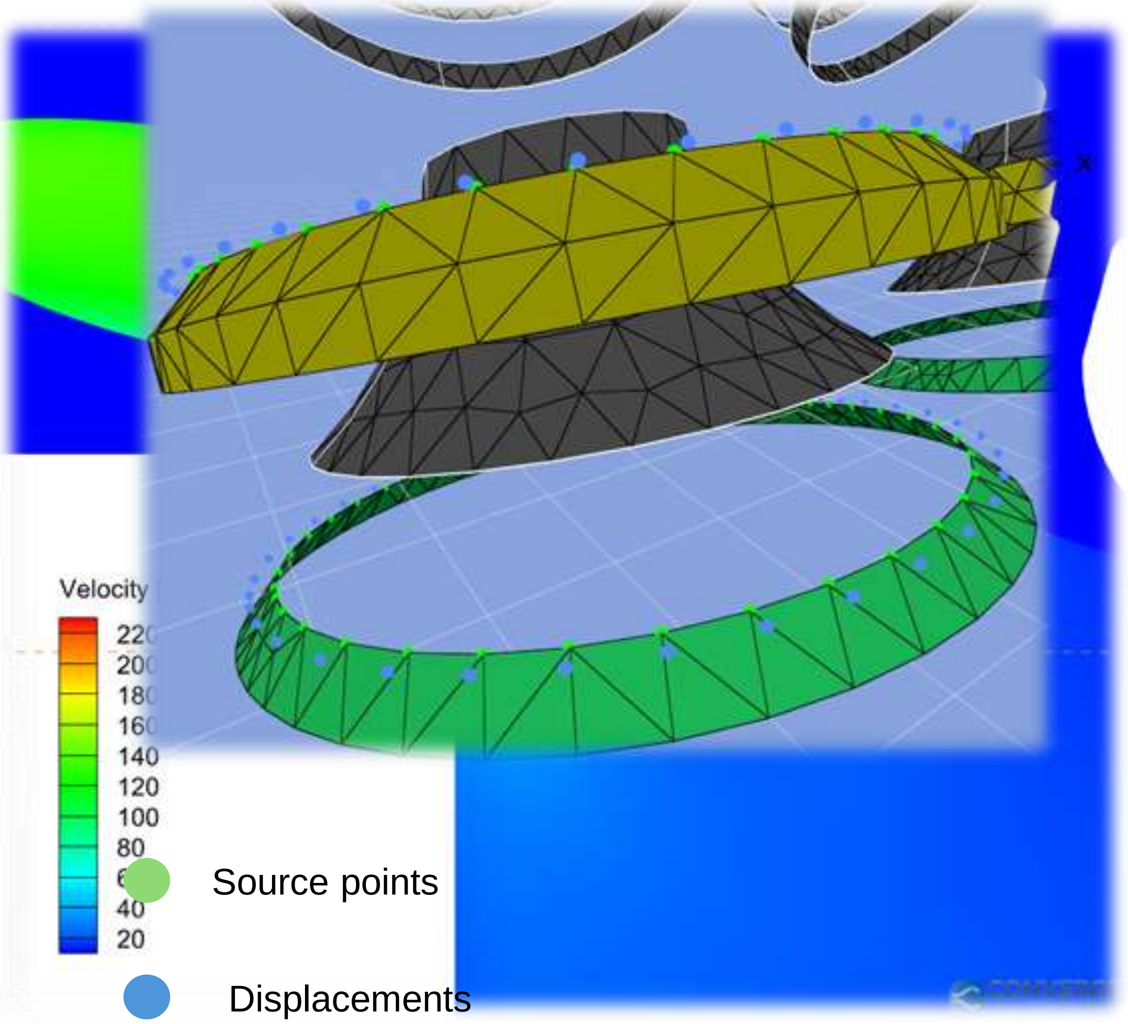
After ''socket'' removal

$\dot{m}_{no\ socket} = 0.0945 \frac{Kg}{s}$

$C_D = 0.449$

ID	Mass flow rate $\left[\frac{Kg}{s}\right]$	Discharge coefficient	Percentage difference
1	0.095	0.452	7.34 %
2	0.0965	0.459	9.04 %
3	0.097	0.461	9.60 %
4	0.0945	0.449	6.78 %
5	0.096	0.456	8.47 %
6	0.097	0.461	9.61 %
7	0.0975	0.463	10.17 %

Flow rate referred to both valves, discharge coefficient for single valve, courtain area as reference

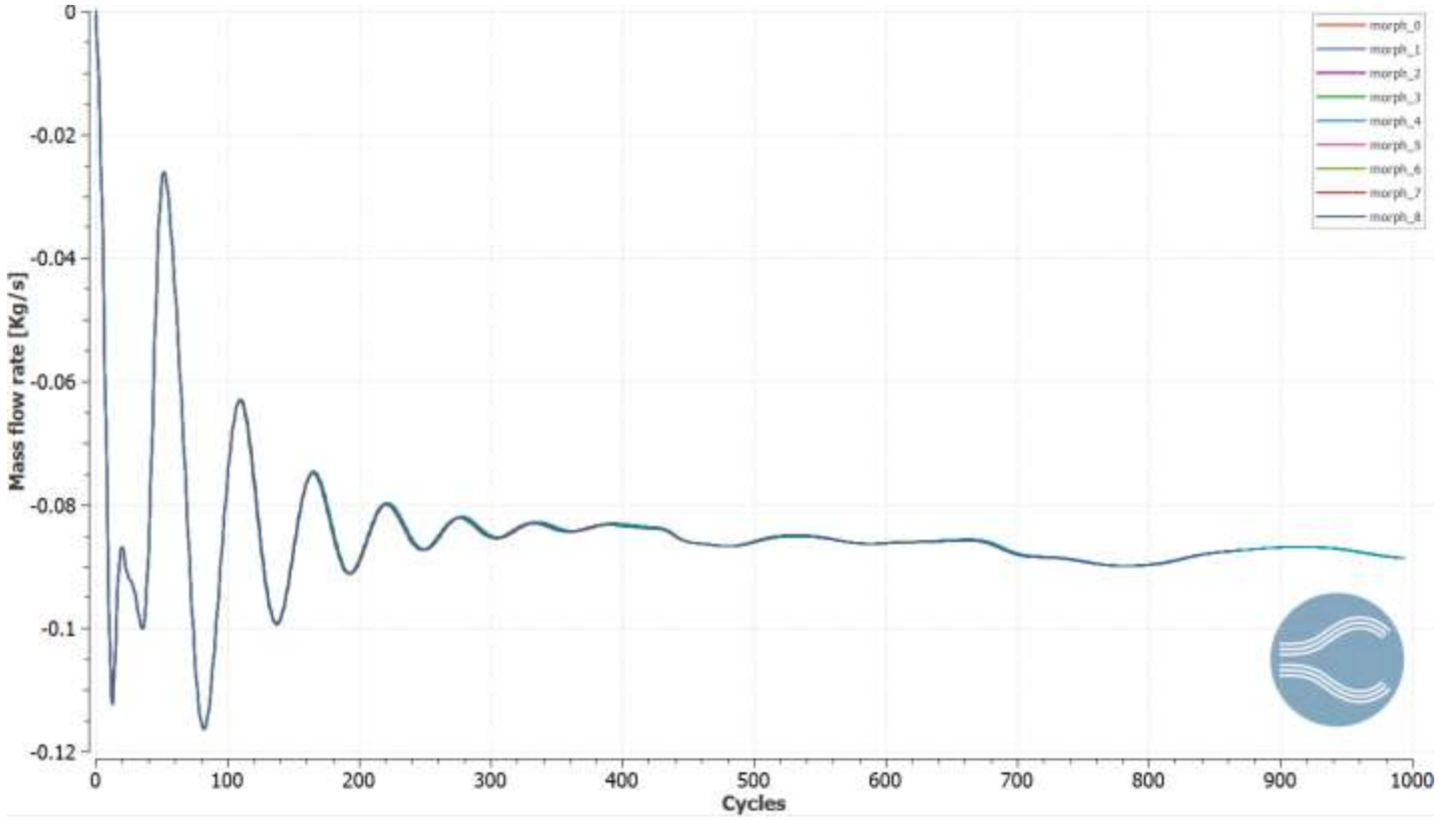


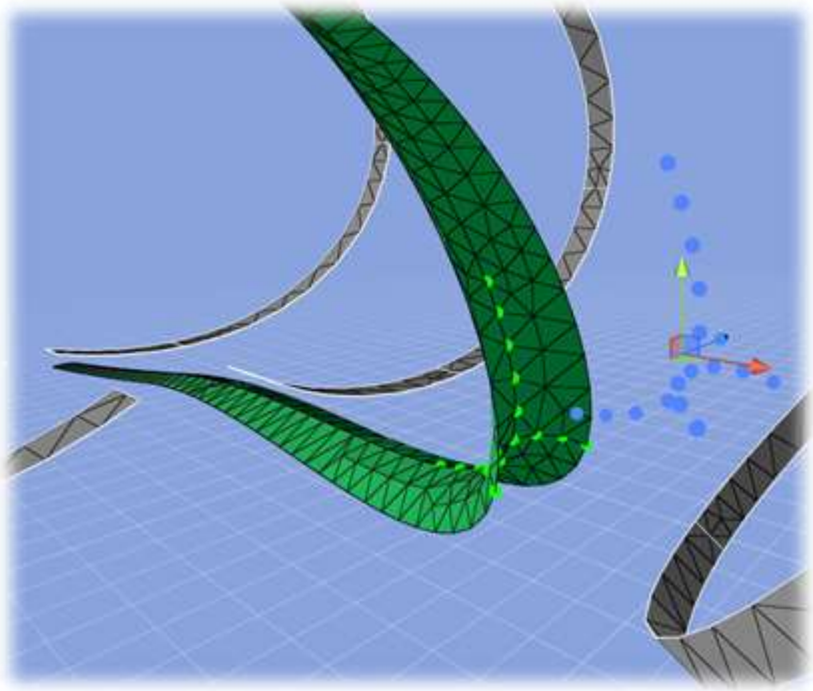
Best variant

Engine head – Converge results

3) – Duct DOE → No effect on mass flow rate

Mass flow rate computed for each cycle





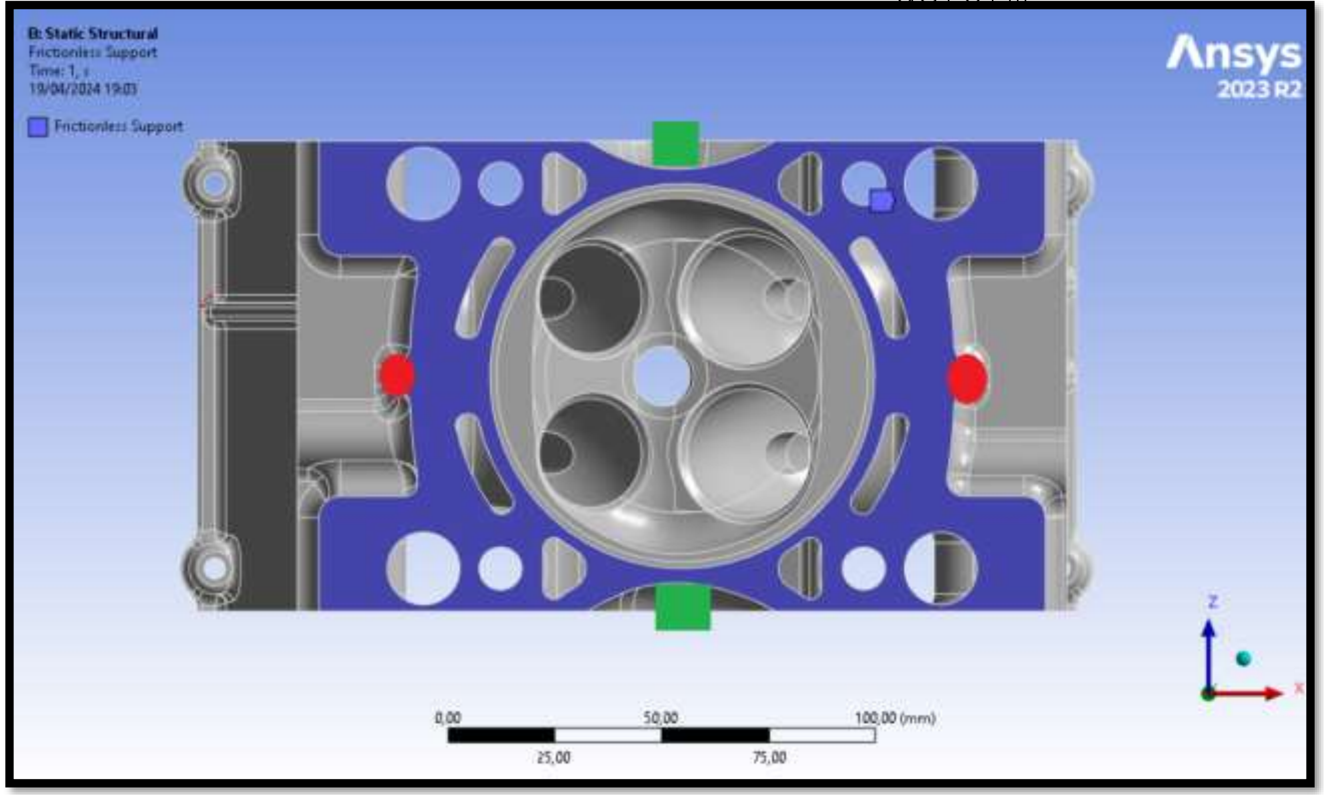
Source points

Displacements

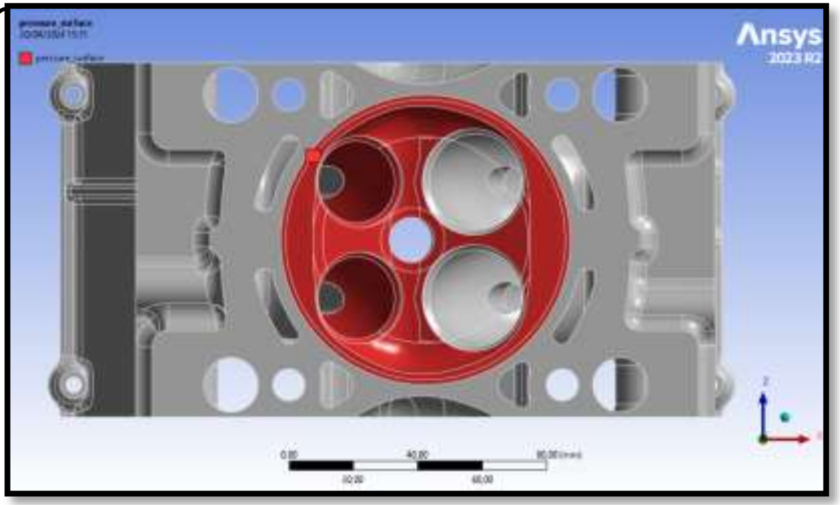
Engine head – Ansys Mechanical setup

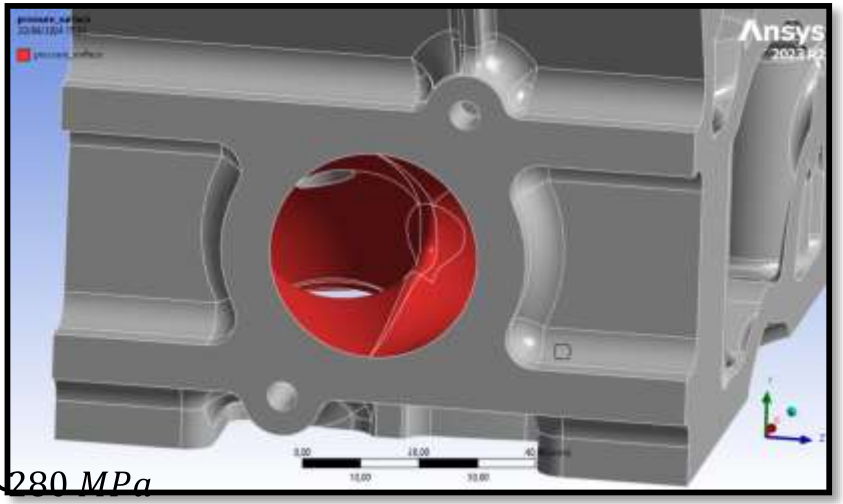
Thermal loads → Structure must be free to deform

Temperature → Mapped on entire domain



Pressure





Constraints

- Blue square → Y = 0
- Green square → X = 0
- Red circle → Z = 0

Aluminum alloy

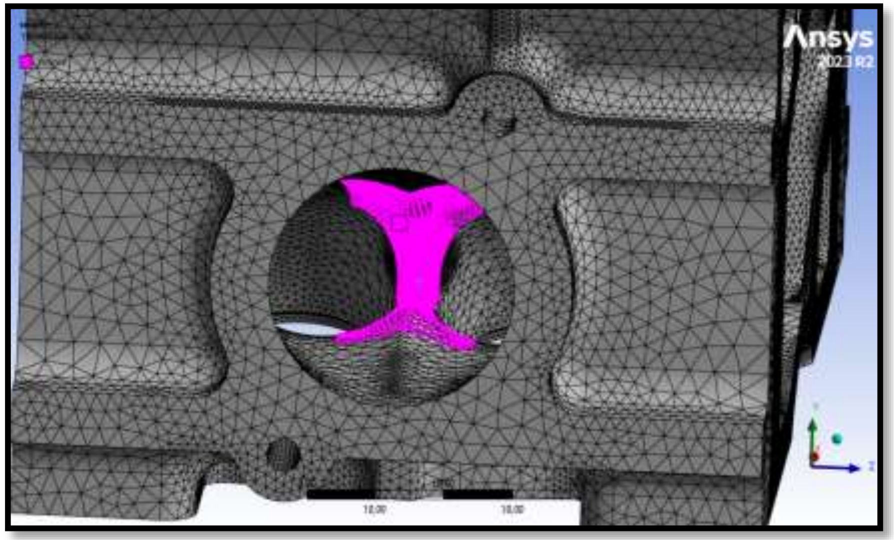
- Density = $2700\ \frac{Kg}{m^3}$
- Young's modulus = $71\ GPa$
- Poisson's ratio = 0.33
- Tensile yield strength = $280\ MPa$

Engine head – Morphing in Ansys Mechanical

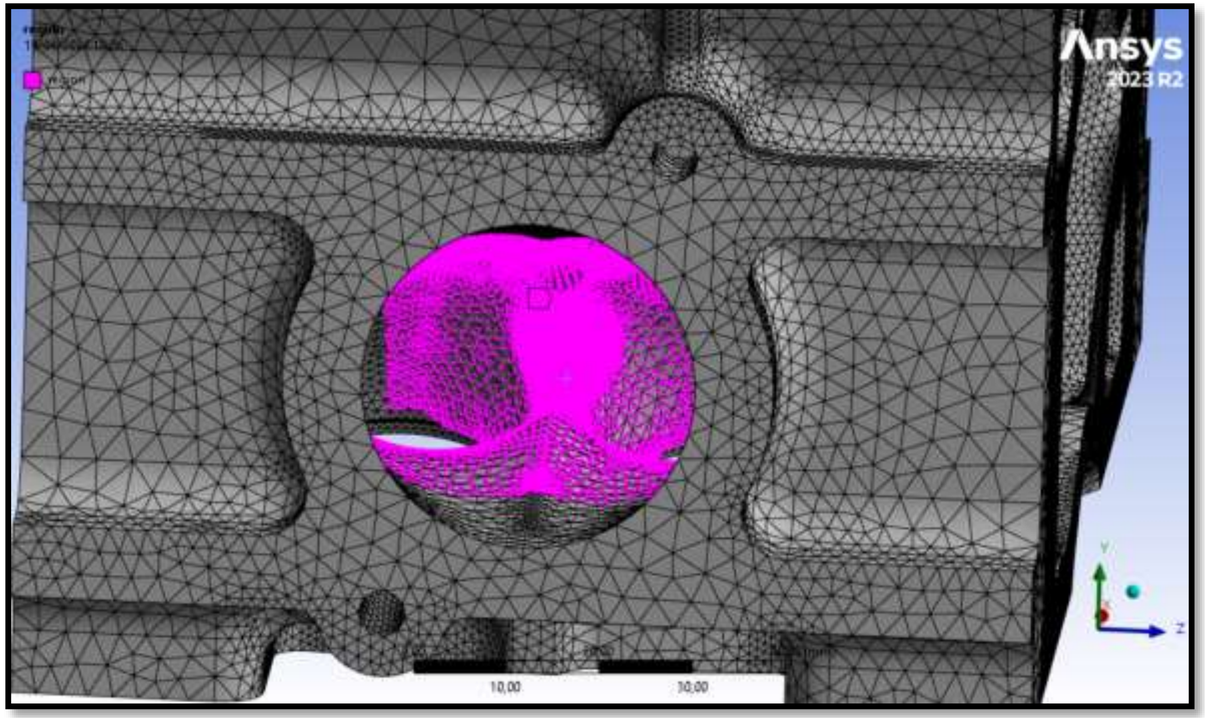
Stress concentration zone

- Reduction in computation cost
- Nodes displacements imported from the previous steps

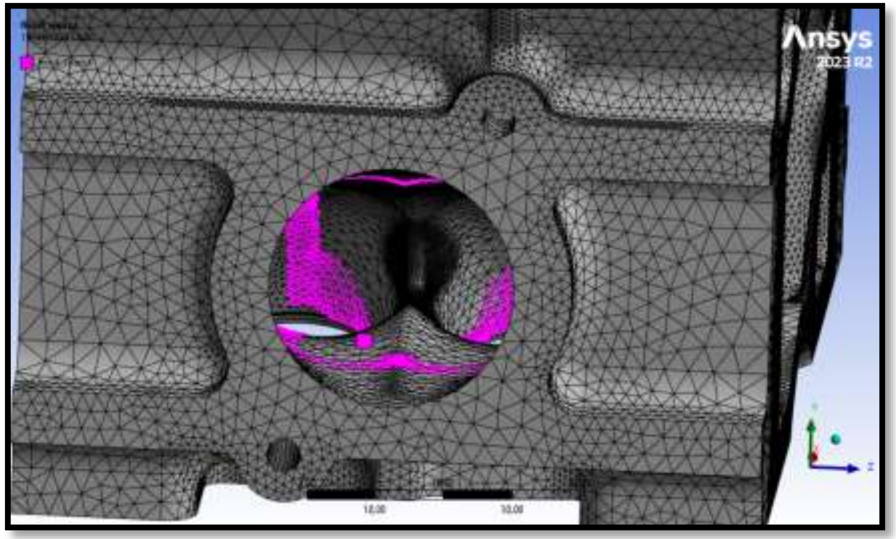
Imported RBF Source



RBF Region



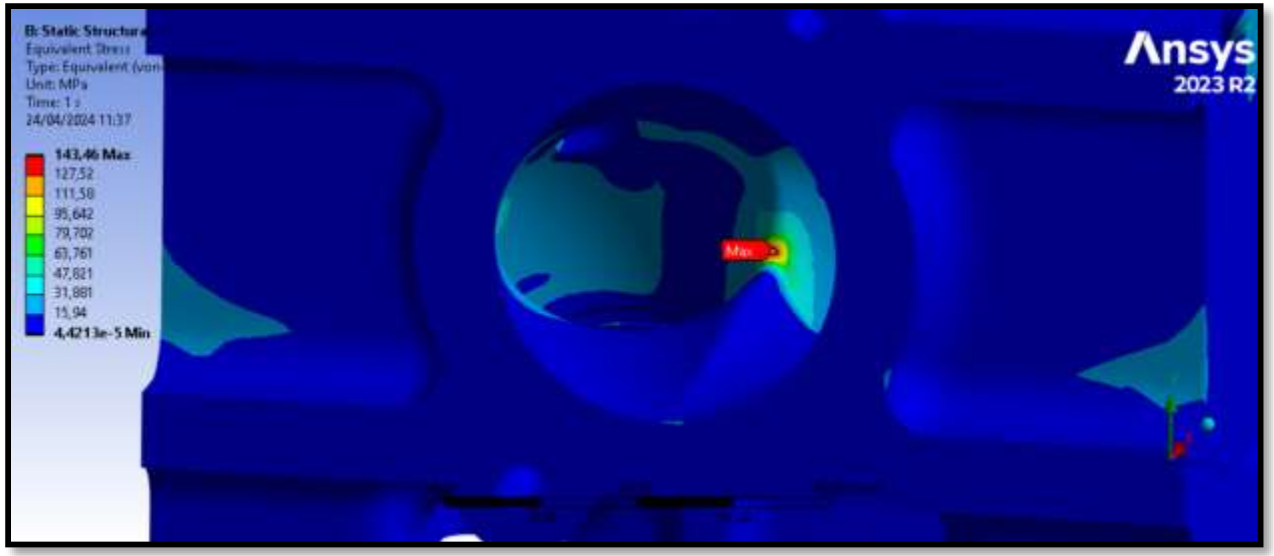
Fixed RBF Source



Engine head – Ansys Mechanical results

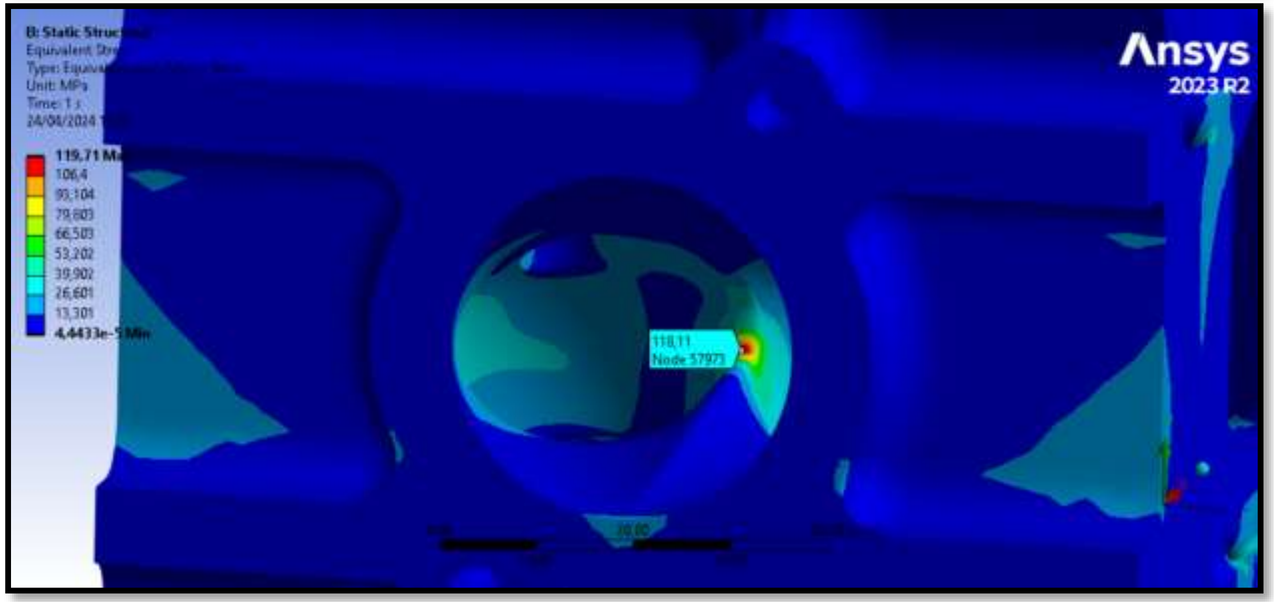
Grid convergence				
Element size [mm]	Number of nodes	Solution time	Maximum stress [MPa]	Percentage difference
1	2426900	1379	131.12	\\
0.5	2443400	1444	143.46	9.41 %
0.25	2504100	1492	148.46	3.39 %
0.1	2971000	1384	148.26	-0.04 %
0.05	4569100	25384	148.28	0.01 %

Original geometry



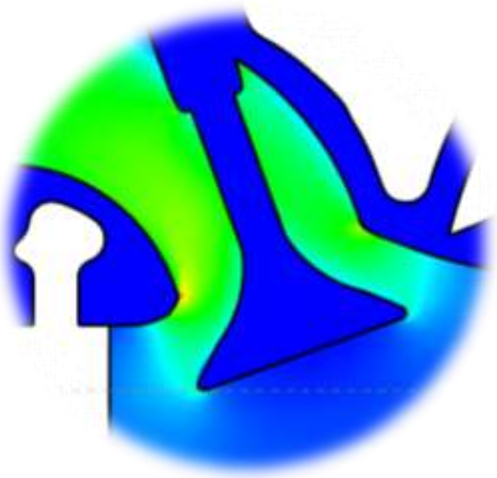
ID	Maximum stress [MPa]	Percentage difference
0	140.40	\\
1	152.49	+8.61 %
2	153.10	+9.05 %
3	136.99	-2.43 %
4	139.44	-0.01 %
5	132.44	- 5.67 %
6	121.20	-13. 68 %
7	125.76	-10.43 %
8	118.11	-15.88 %

Best variant

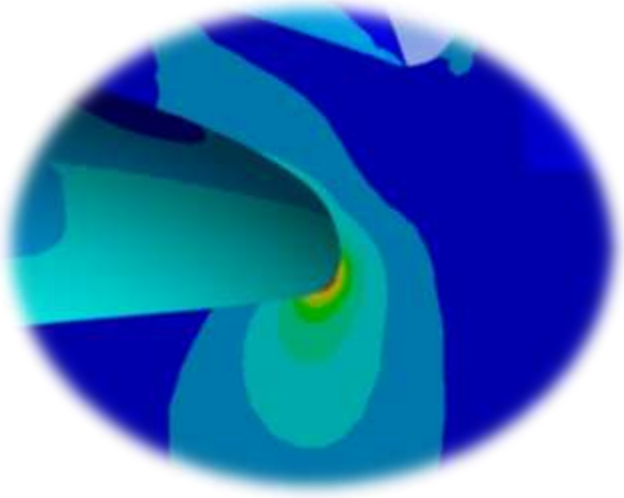


Conclusions

- ✓ Development of a workflow for optimization through the use of multiphysics analyses
- ✓ Implementation of mesh morphing techniques in CFD and CSM simulations within Designs of Experiment
- ✓ Development of a Python code for the automation of shape variations and simulations execution
- ✓ Increase in performance in the proposed flow bench cases

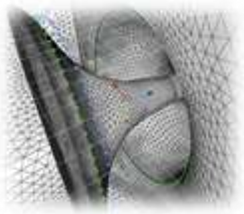


- ✓ Mass flow rate increase of 10%
- ✓ Maximum stress reduction of 15%



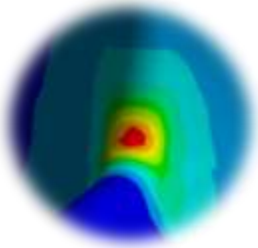
Future developments

- Integration of optimization software in the workflow
- Use of the proposed methodology in more realistic cases → Combustion, transient analysis
- Application of mesh morphing techniques to the new challenges of hydrogen combustion
- Expansion to other engineering fields



rbf → CONVERGE CFD SOFTWARE

→ Ansys



TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

Faculty of Engineering

Master's degree in Mechanical Engineering

Multiphysics optimization of an exhaust port using mesh morphing

Advisor:
Prof. Marco Evangelos Biancolini

Candidate:
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A. A. 2022-2023