Piston Cooling Jets for High-Performance Engines: development of a simulation strategy based on MPS and CHT

A. Bianco[1], M. Prestifilippo[1], F. Millo[2]

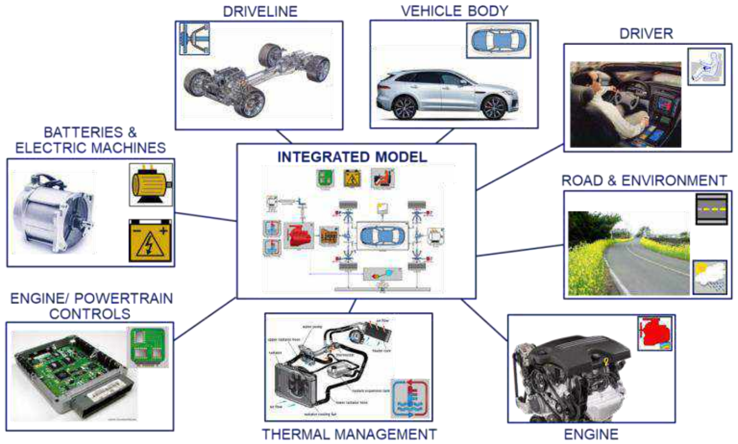
1: POWERTECH Engineering S.r.l., Turin – ITALY
2: Politecnico di Torino, Turin – ITALY

Particleworks experience 2023
June 7 – 8, 2023 – Bergamo, Italy

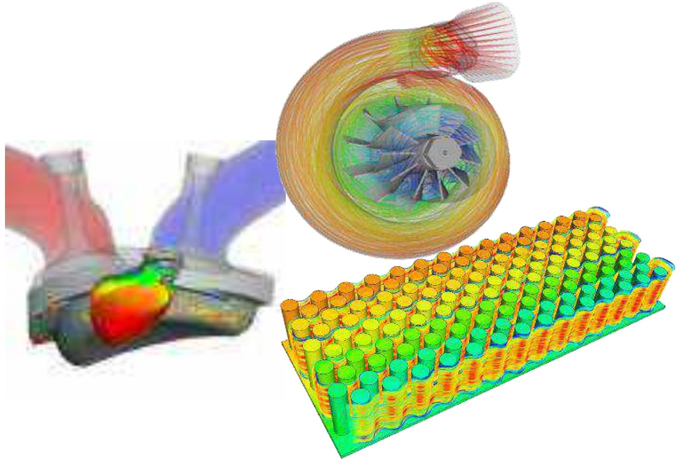
Company overview

- **PWT** is an **independent** consulting **firm** employing **40 engineers**
- Our area of expertise are **Powertrain & Vehicle simulations**

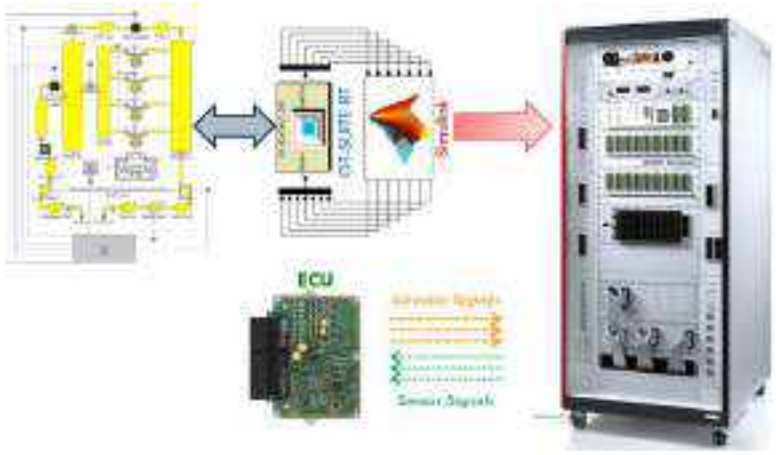
Powertrain & Vehicle 1D



3D-CFD



XiL Applications



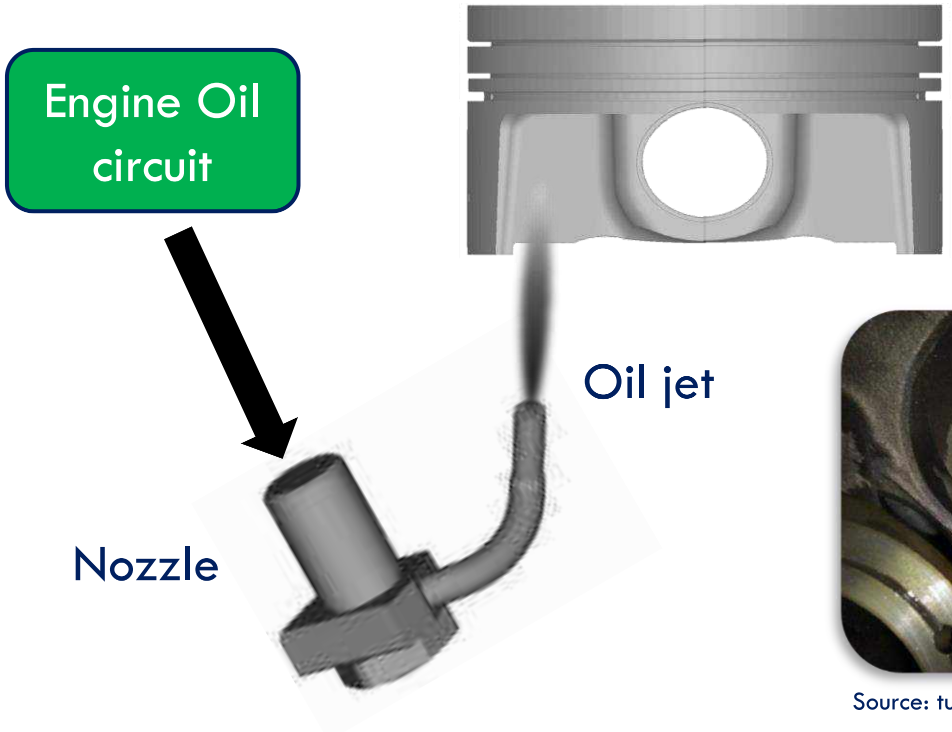
Agenda

- Introduction
- Methodology
- Case studies and results
- Conclusions

Introduction

Piston Cooling Jet (PCJ) is a technology used in internal combustion engines to:

- Remove heat from the piston
- Reduce knock tendency
- Increase power density (kW/L) and reduce emissions



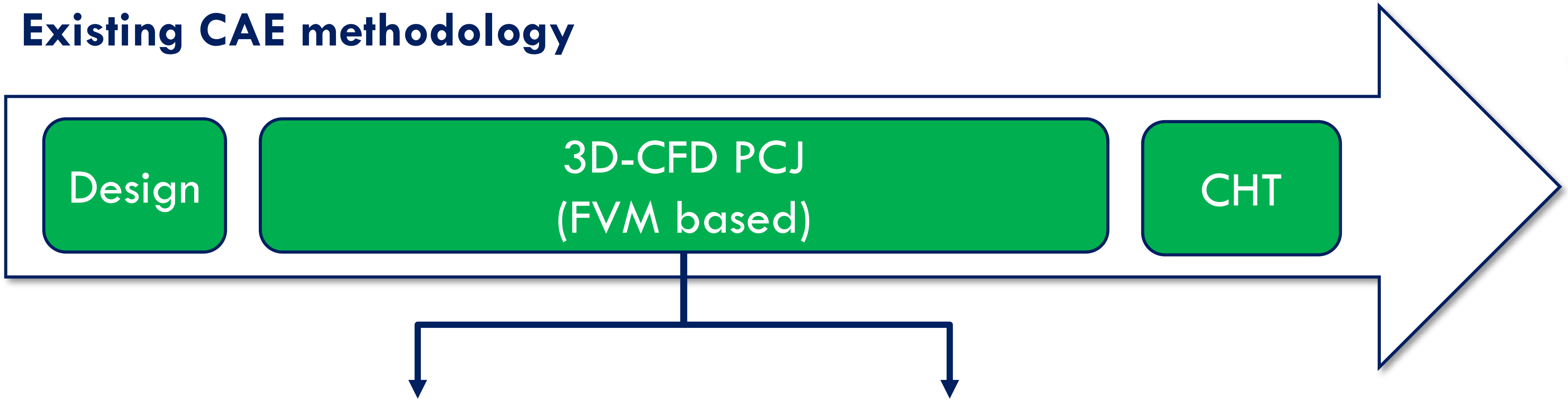
Source: turbo-mopar.com

Peculiarities:

- Very difficult experimental characterization:
  - Moving components
  - Transient phenomena
- Need for CAE models to:
  - Overcome lack of data w/ predictive results
  - Support engine development w/ optimization studies

Introduction

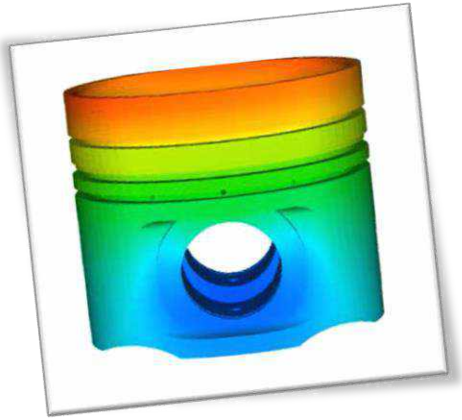
Existing CAE methodology



Design

3D-CFD PCJ
(FVM based)

CHT



Moving mesh

- Overset
- Morphing
- Map/Remesh

Hybrid multiphase

- Jet (VOF)
- Ligaments
- Droplets
- Film

Scope of the work

Evolve current simulation strategy for PCJ to leverage Moving Particle Simulations (MPS) + CHT

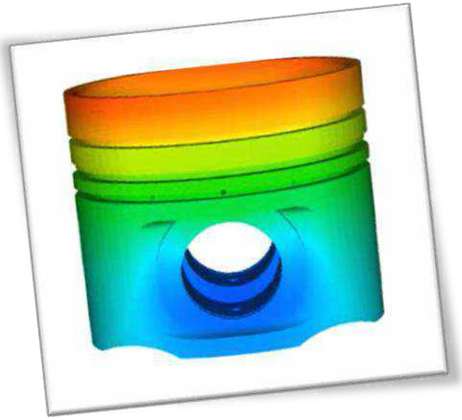
Introduction

Existing CAE methodology

Design

3D-CFD PCJ
(FVM based)

CHT



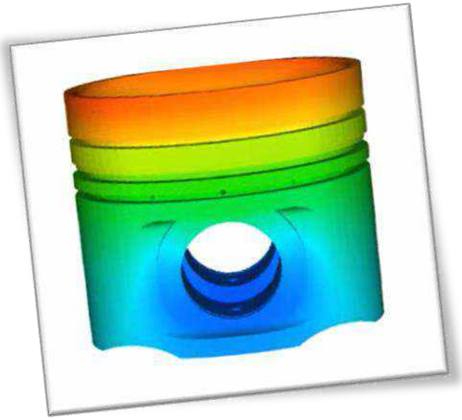
New CAE methodology

Design

CHT

Meshless

Particle-based liquid



- Reduced lead-time (man & CPU/GPU hours)
- Optimization loops enabler

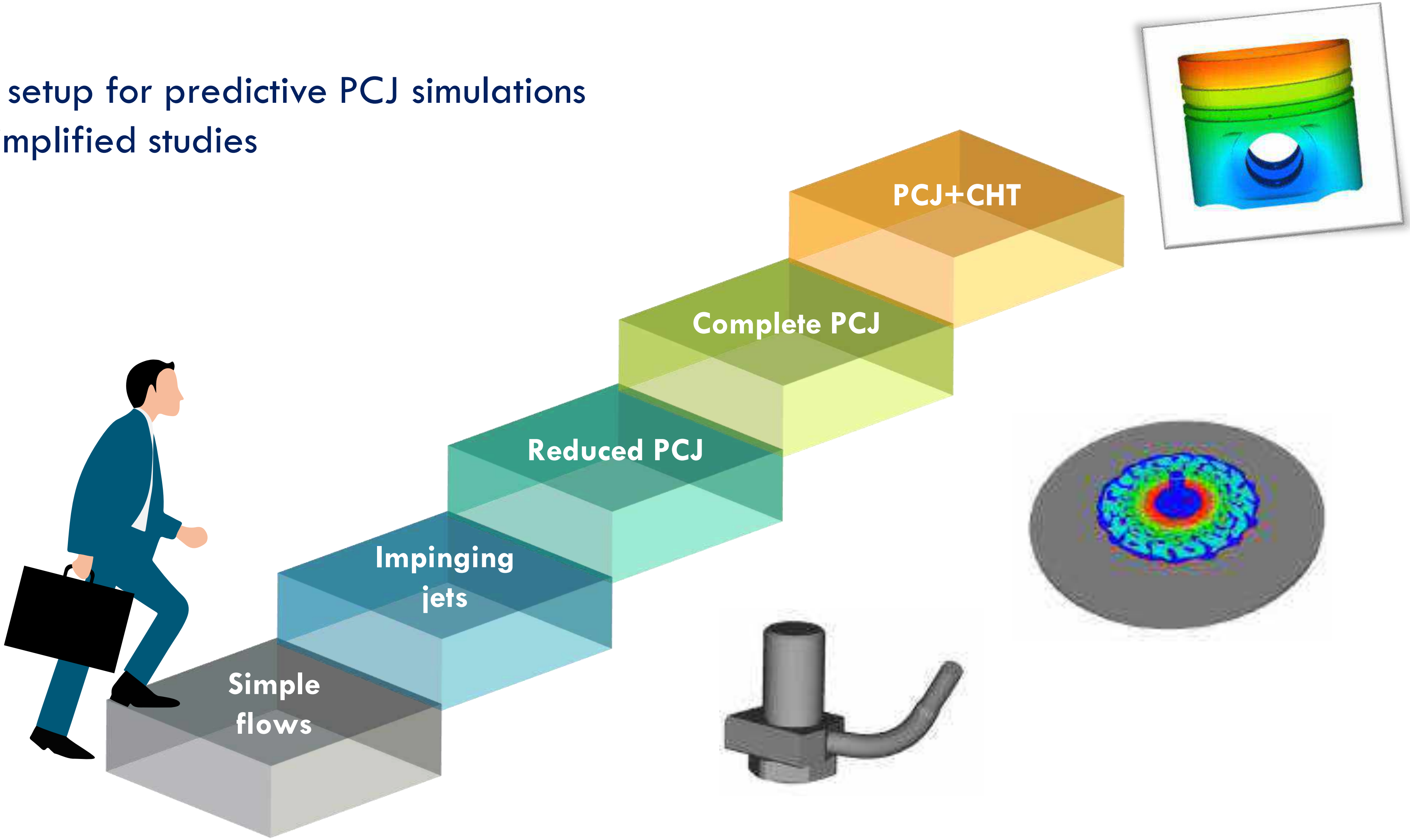
Methodology

Stair-step approach

Objective: develop validated setup for predictive PCJ simulations by leveraging findings from simplified studies

Today's focus:

- Impinging jets simulations
- PCJ + CHT

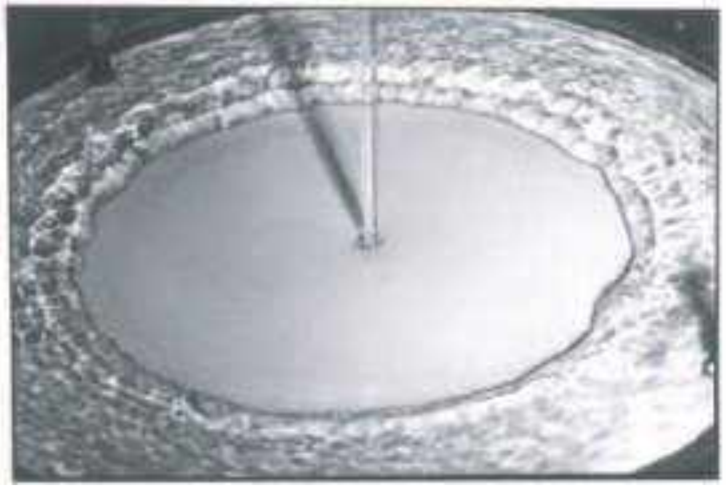


Impinging jets simulations

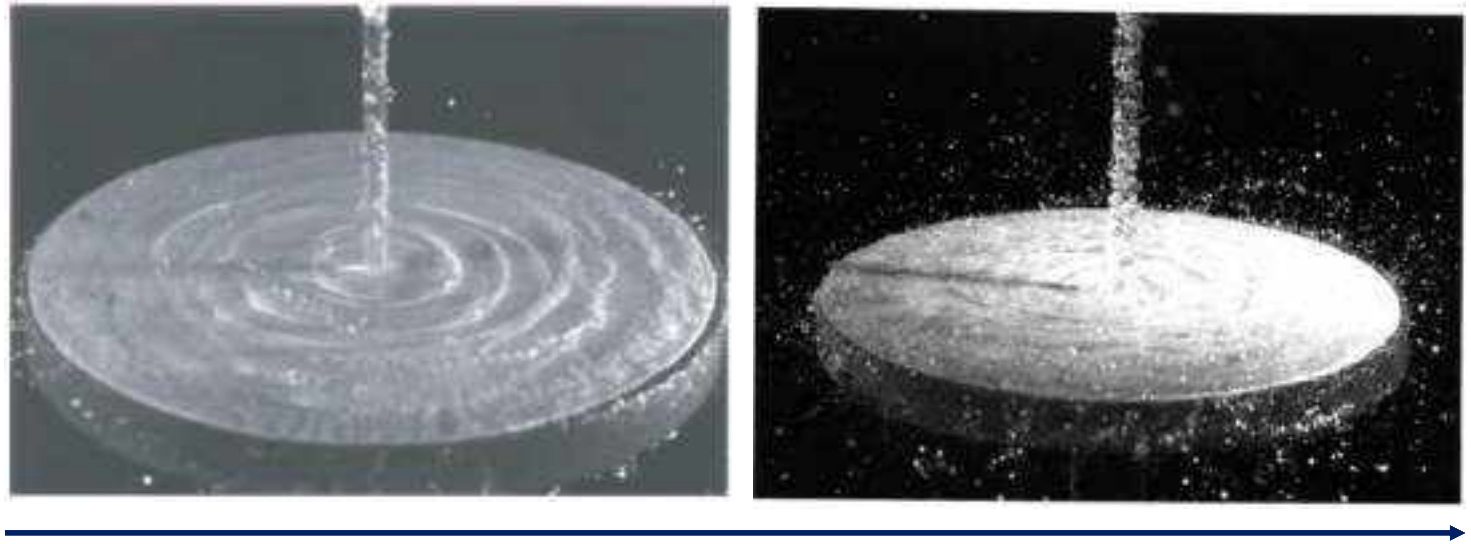
Objective: identify a simulation setup enabling prediction of HTC distribution in impinging jets

Experimental data available in literature show significant changes in jet and film phenomenology w/ flow regime

Laminar



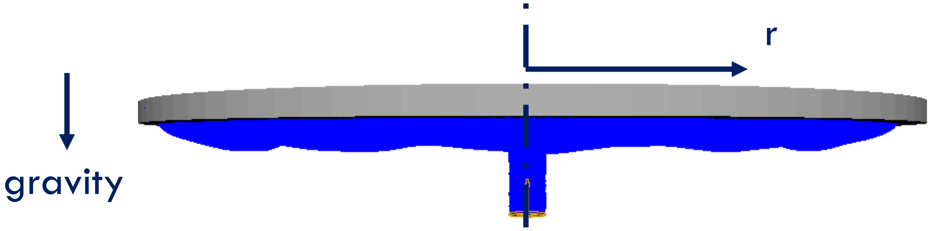
Turbulent (splattering jets)



[1] Lienhard, J., “Heat Transfer by Impingement of Circular Free-Surface Liquid Jets”, 2006

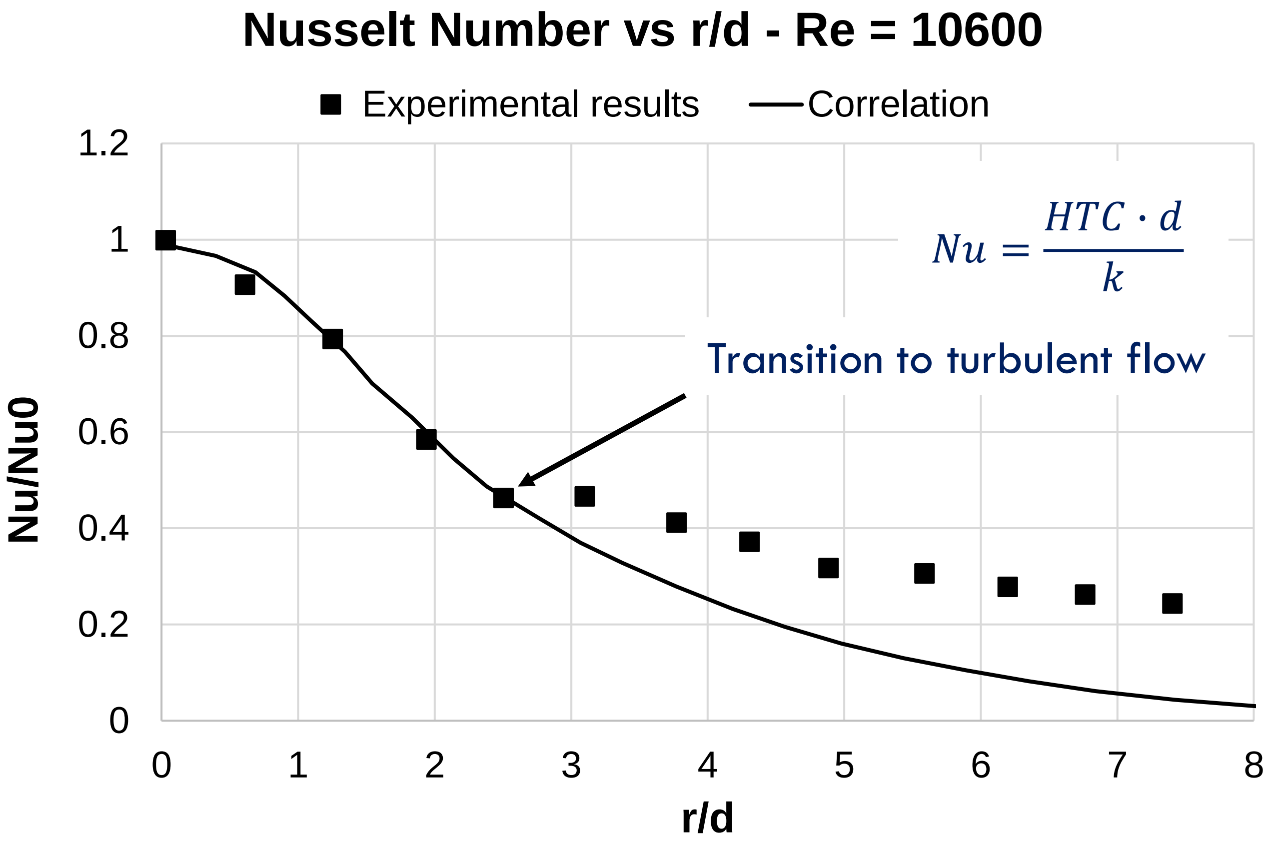
Impinging jets simulations

Experimental data for turbulent water jet [2]:



Nozzle	
Diameter (d)	4.1 mm
Length	380 mm
Nozzle-plate spacing	Z/D=2.5

Flat Plate	
Diameter	82 mm
Thickness	50.8 µm
Material	Stainless Steel



$$Nu = \frac{HTC \cdot d}{k}$$

Transition to turbulent flow

[2] Stevens, J., Webb, B. W., “Local Heat Transfer Coefficients Under an Axisymmetric, Single-Phase Liquid Jet”, 1991

Impinging jets simulations

Simulation setup:

- Inlet jet flow: water
  - Uniform velocity distribution
  - Fixed temperature 20°C
- Solid plate surface:
  - Isothermal boundary
- Gravity
- Solvers:
  - Explicit model for pressure and viscosity
  - Potential model for surface tension
- Simulation time = 0.2s
- Max Courant number = 0.2
- Particle size set w/ sensitivity study

Heat transfer coefficients

Particleworks assumption: steady flow on planar surface w/ developing boundary layer

$$Nu = \frac{HTC \cdot x}{k} \qquad Re_x = \frac{\rho \cdot x \cdot U}{\mu}$$

Default correlations (parallel flow)

$$Re_x < 10^5 \rightarrow Nu = 0.332\, Pr^{1/3} {Re_x}^{1/2}$$

$$Re_x \geq 10^5 \rightarrow Nu = 0.0296\, Pr^{1/3} {Re_x}^{4/5}$$

↓

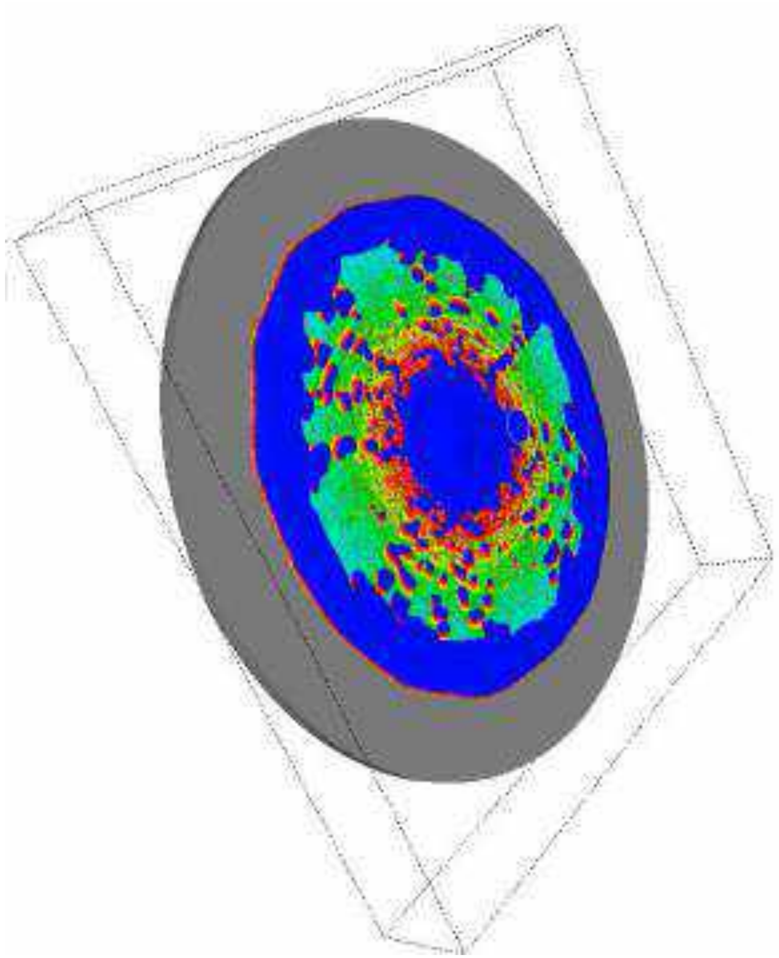
Modified HTC multiplier (normal impinging jet)

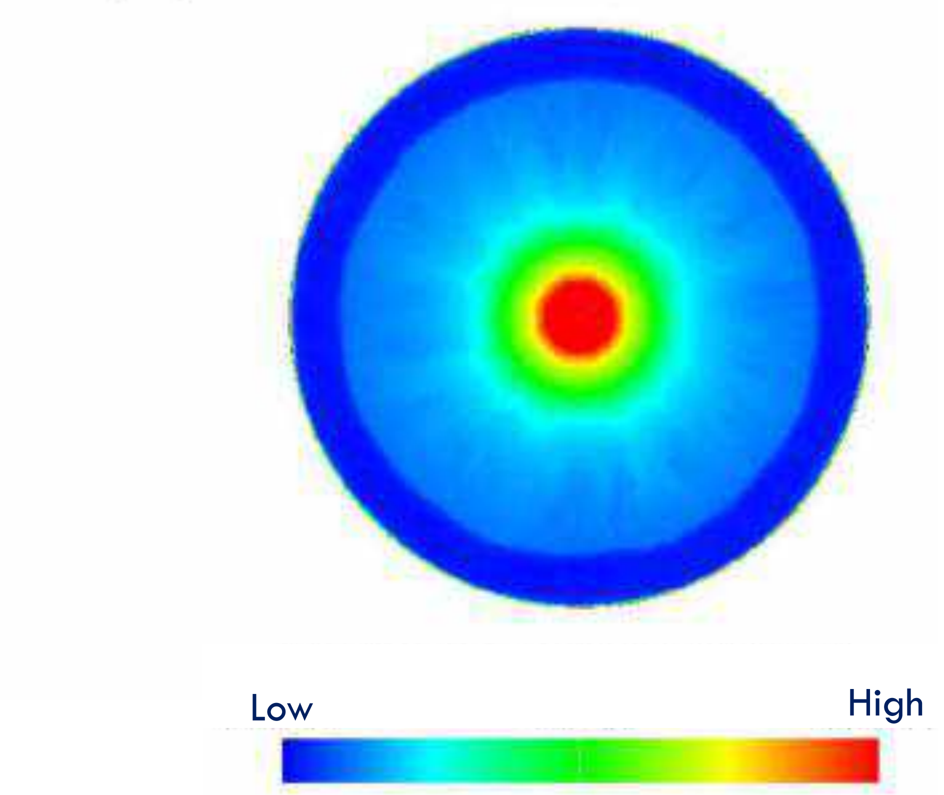
$$Re_x < 10^5 \rightarrow Nu = \mathbf{0.745}\, Pr^{1/3} {Re_x}^{1/2}$$

$$Re_x \geq 10^5 \rightarrow Nu = 0.0296\, Pr^{1/3} {Re_x}^{4/5}$$

Impinging jets simulations

Results





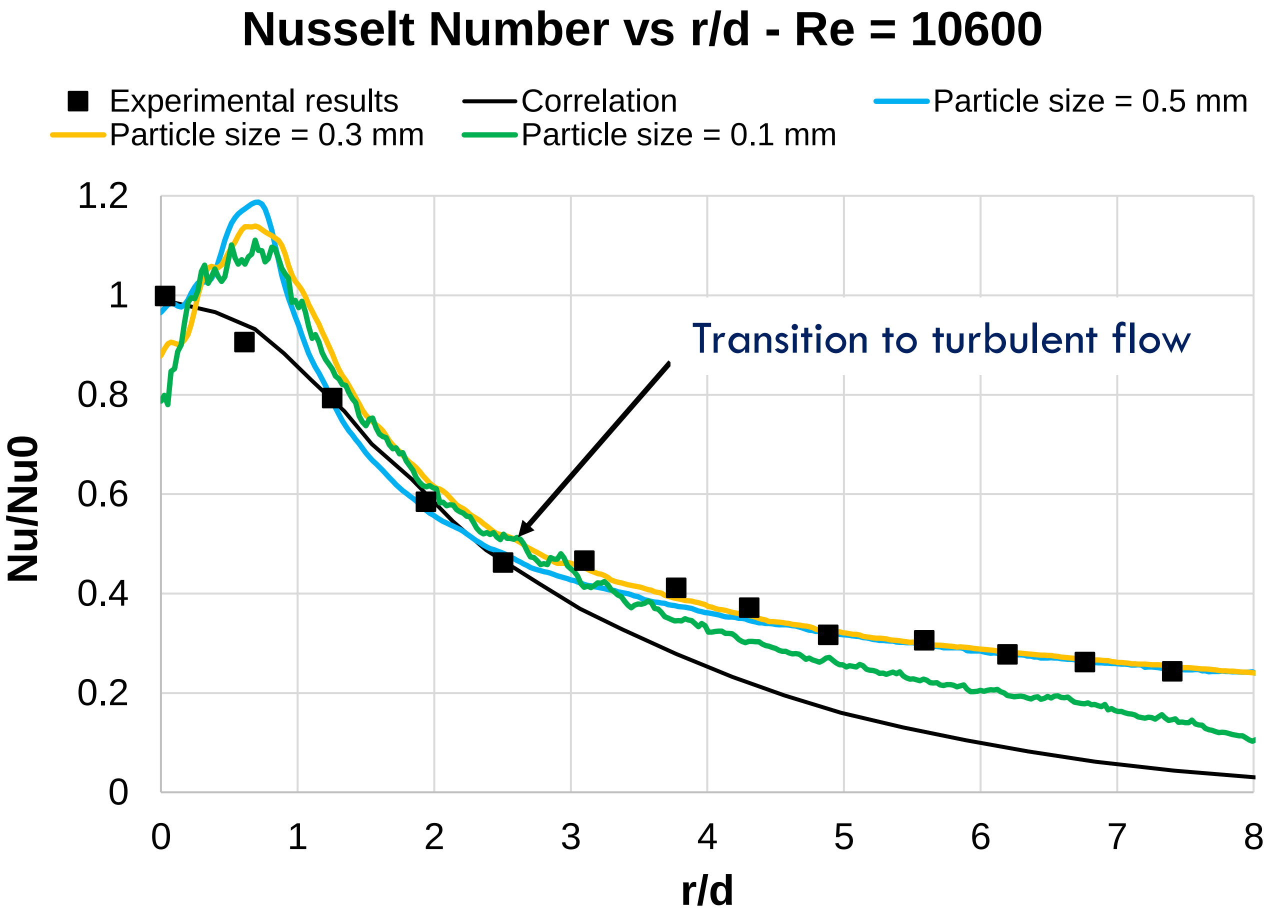
Time-averaged Heat transfer coefficient

[T=0.05s]

Impinging jets simulations

Results w/ modified HTC multiplier

- Sensitivity study showed slight variation of results
- Particleworks results show proper description of transition to turbulent flow
- HTC are always in good agreement w/ experimental data at r/d>1.5 for particle sizes > 0.1 mm
- Major differences are observed close to impingement point and stagnation zone (r/d<1.5)



Impinging jets simulations

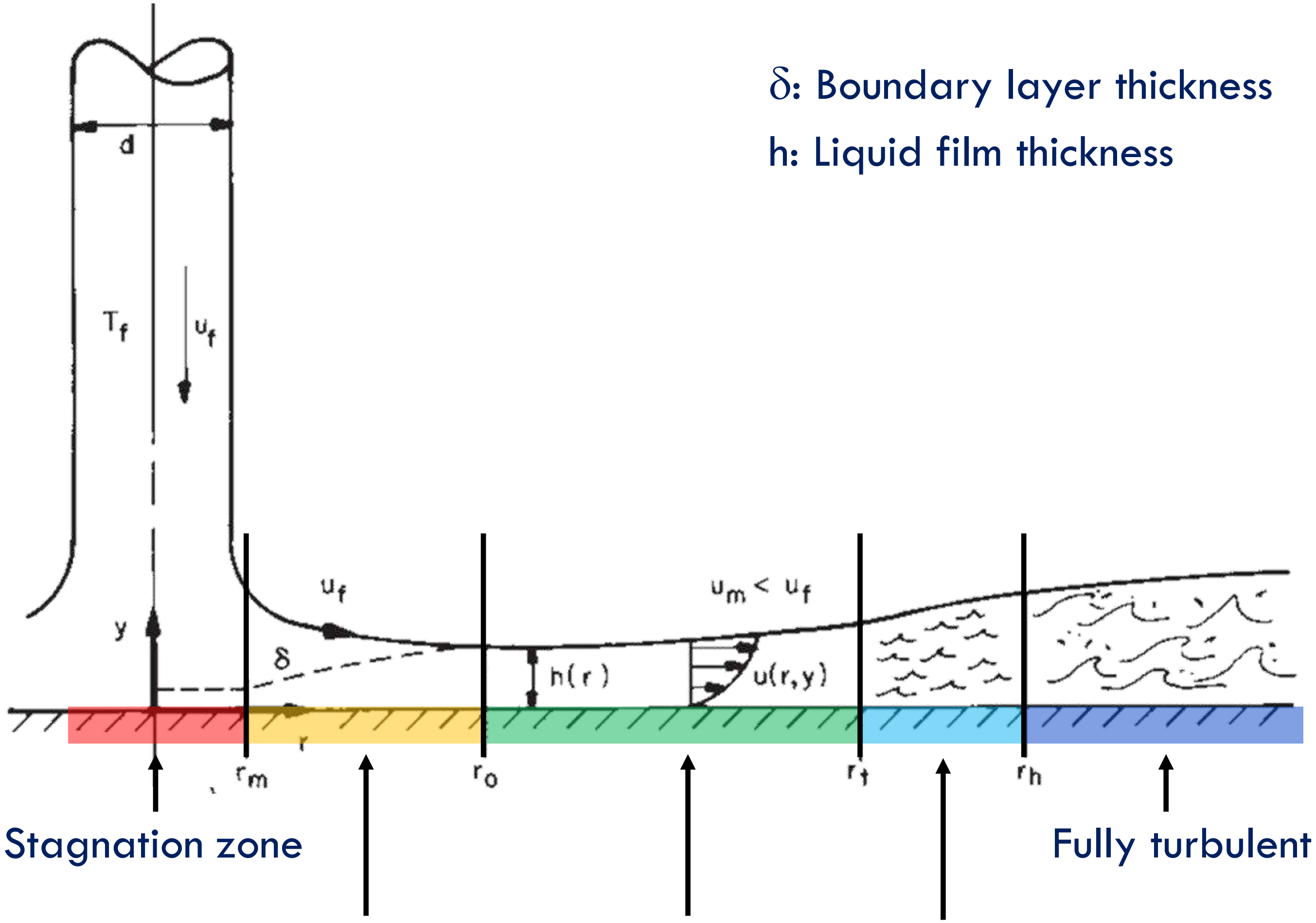
Multi-zone HTC script:

Account for HTC variation in each region according to [1]:

1. Stagnation zone 🟥
2. Laminar boundary-layer region 🟨
3. Viscous similarity region 🟩
4. Developing turbulence region 🟦
5. Fully turbulent region 🟦

Inputs:

- Impinging jet velocity
- Nozzle diameter (d)
- Fluid kinematic viscosity
- Nozzle-to-plate distance



δ: Boundary layer thickness

h: Liquid film thickness

Stagnation zone

Fully turbulent

δ < h

δ = h

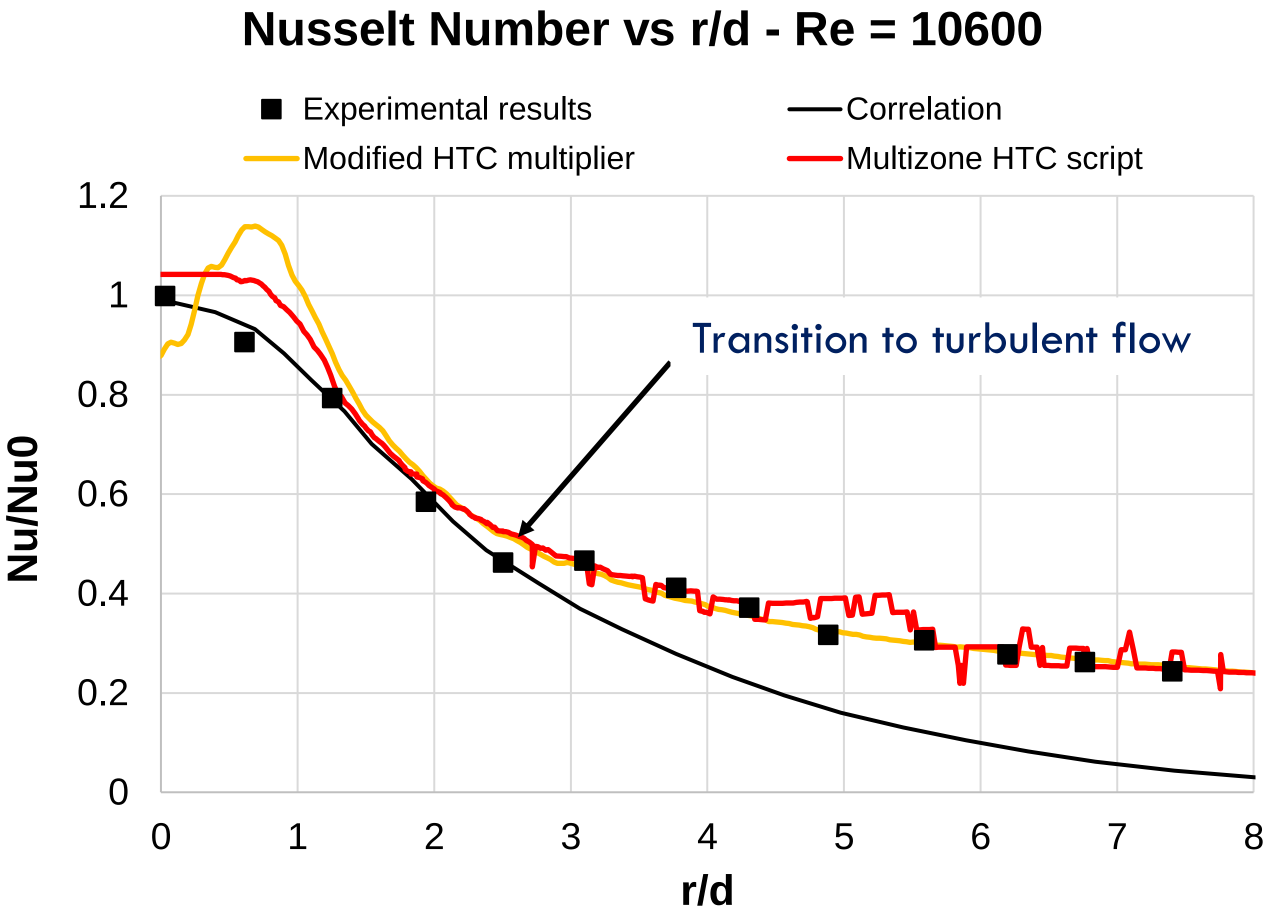
Transition

[1] Lienhard, J., "Heat Transfer by Impingement of Circular Free-Surface Liquid Jets", 2006

Impinging jets simulations

Results w/ multi-zone HTC script

- Results achieved w/ the multi-zone script are aligned to those obtained w/ modified HTC multiplier for r/d>2
- Multi-zone HTC script results shows significative improvement in impingement point and stagnation zone (r/d<1.5)
- Maximum error wrt experimental data is ~10% but is limited to r/d~0.6 and is deemed acceptable
- Simulation time ~15h@32 core

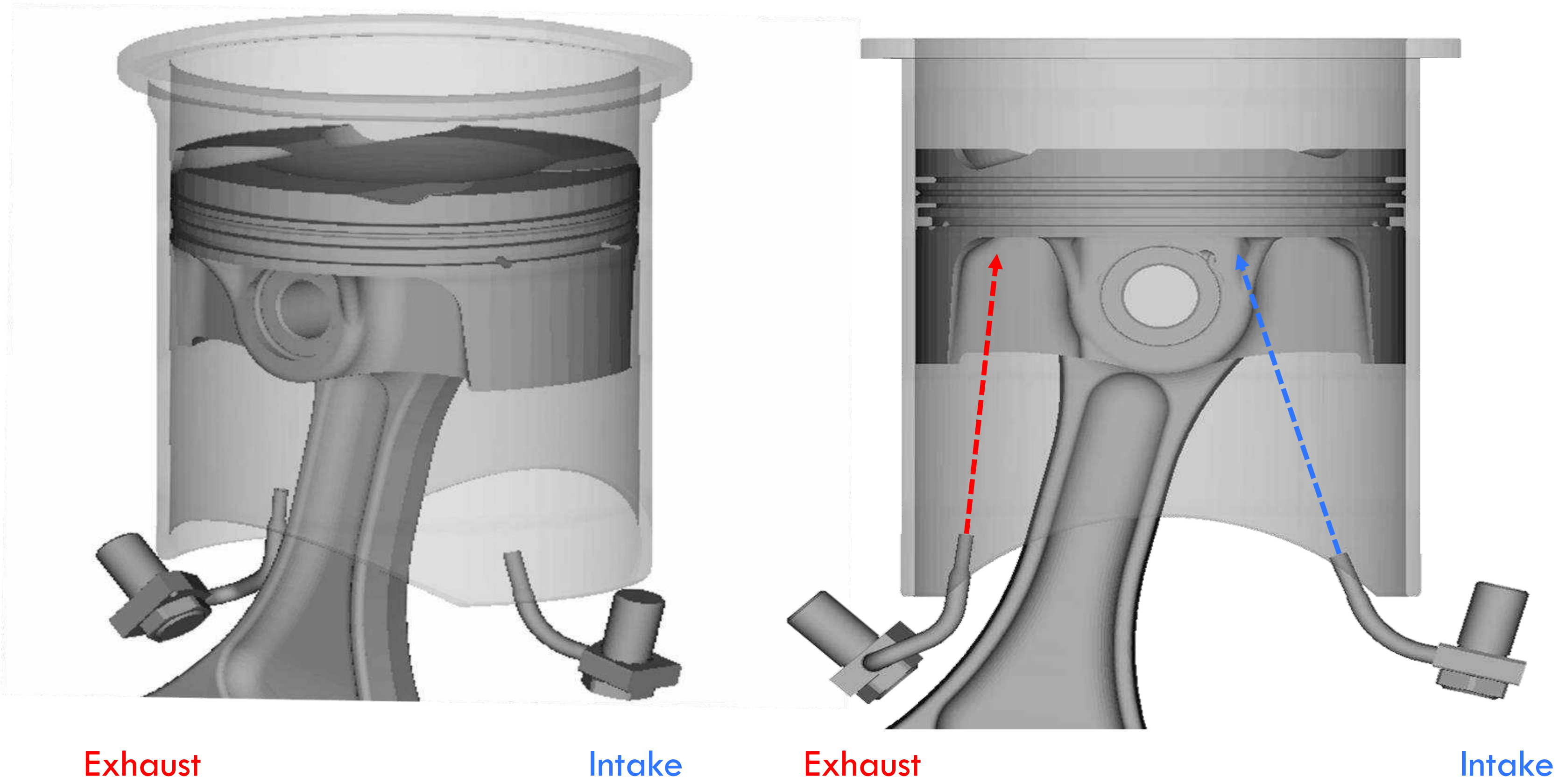


Piston Cooling Jets simulations

Objective: support the development of a new piston design for high-performance engines

Engine target	
Application	4T V-type
Revving speed	>9000 rpm

Oil nozzles	
Diameter	<2 mm
Flow	>6 L/min total
Oil temperature	>100°C

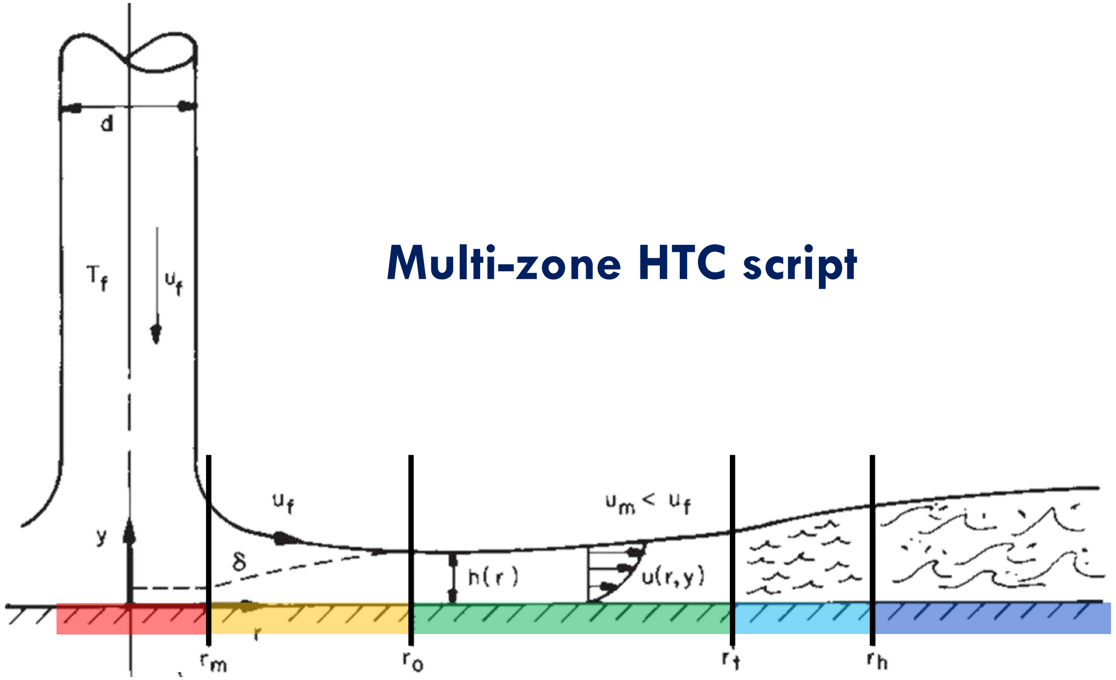


Piston Cooling Jets simulations

Simulation setup:

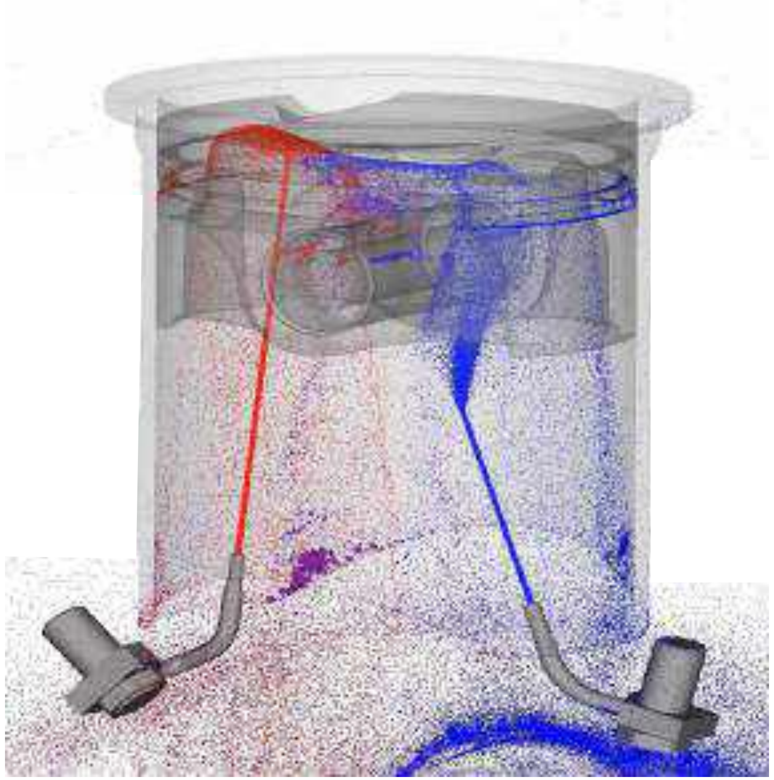
- Inlet jet flow: oil
  - o Uniform velocity distribution
  - o Fixed temperature
- Solid plate surface:
  - Isothermal boundaries (different T for each part)
- Gravity
- Solvers:
  - o Explicit model for pressure and viscosity
  - o Potential model for surface tension
- <u>Simulation time = 3 engine cycles</u>
- Max Courant number = 0.2
- <u>Particle size set w/ sensitivity study</u>
- <u>Particle-air interactions neglected</u>

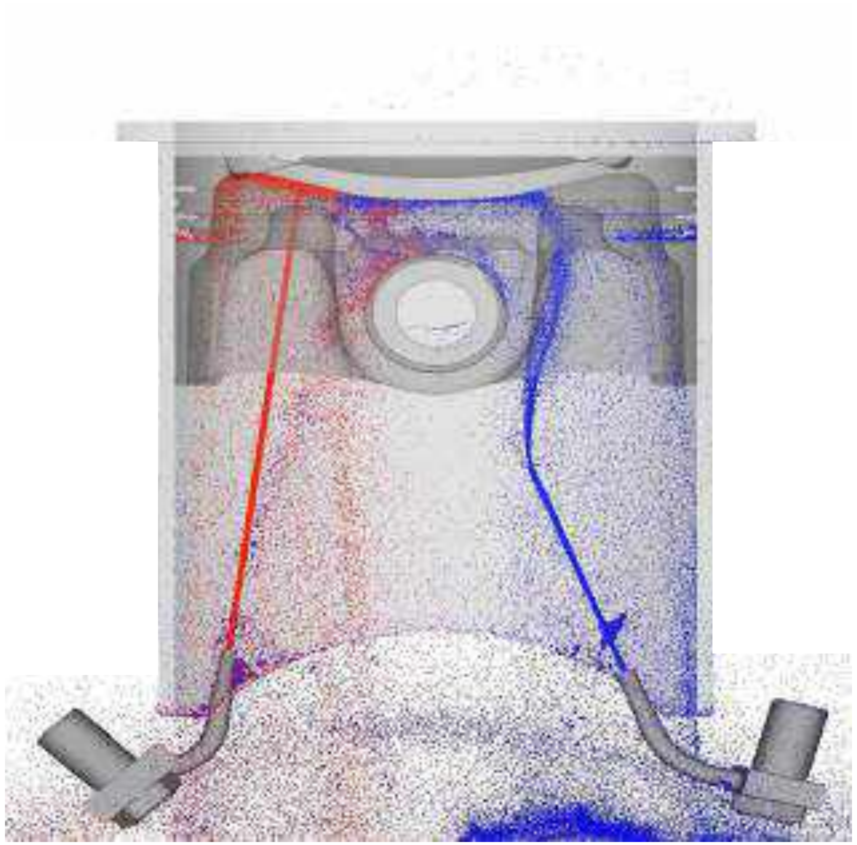
Multi-zone HTC script



Piston Cooling Jets simulations

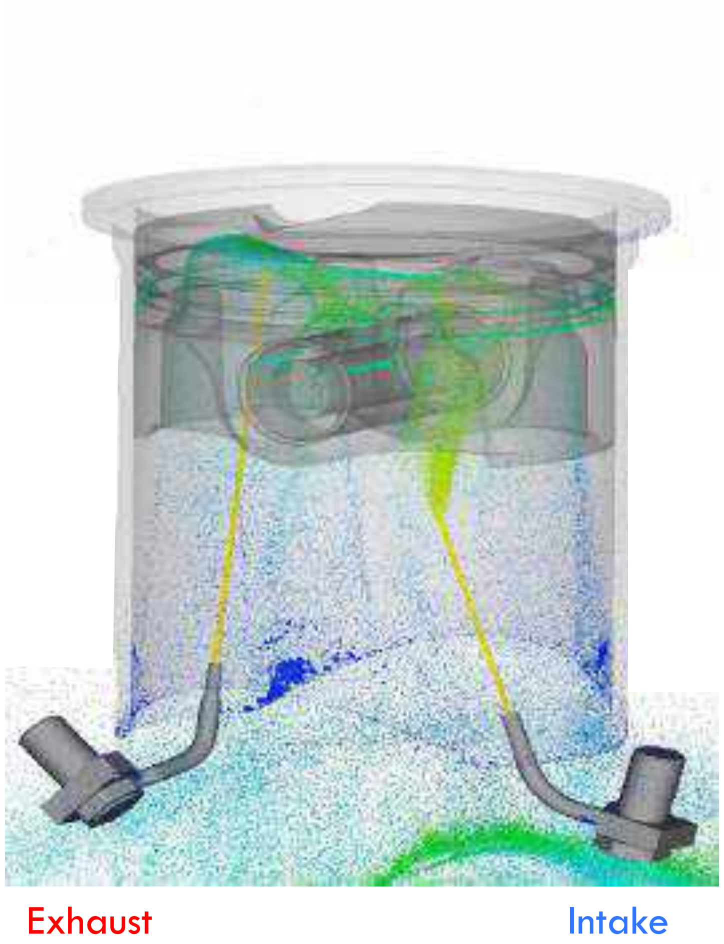
- Simulation w/ complete cranktrain (not shown)
  - Significant interactions of oil jets w/ connecting rod (side + small end)
  - Simulation time ~1 day@32 core (<< FVM)

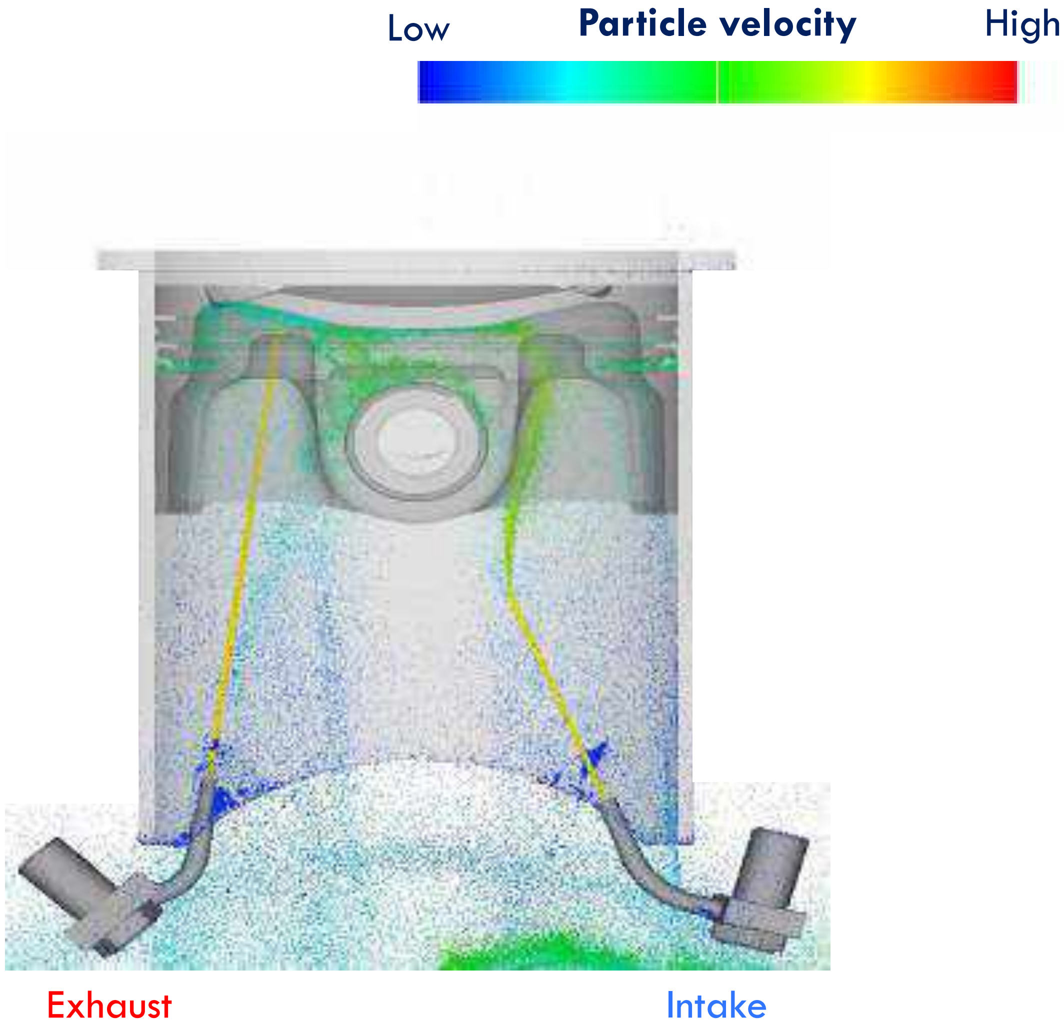




Piston Cooling Jets simulations

- Assessment of velocity distribution

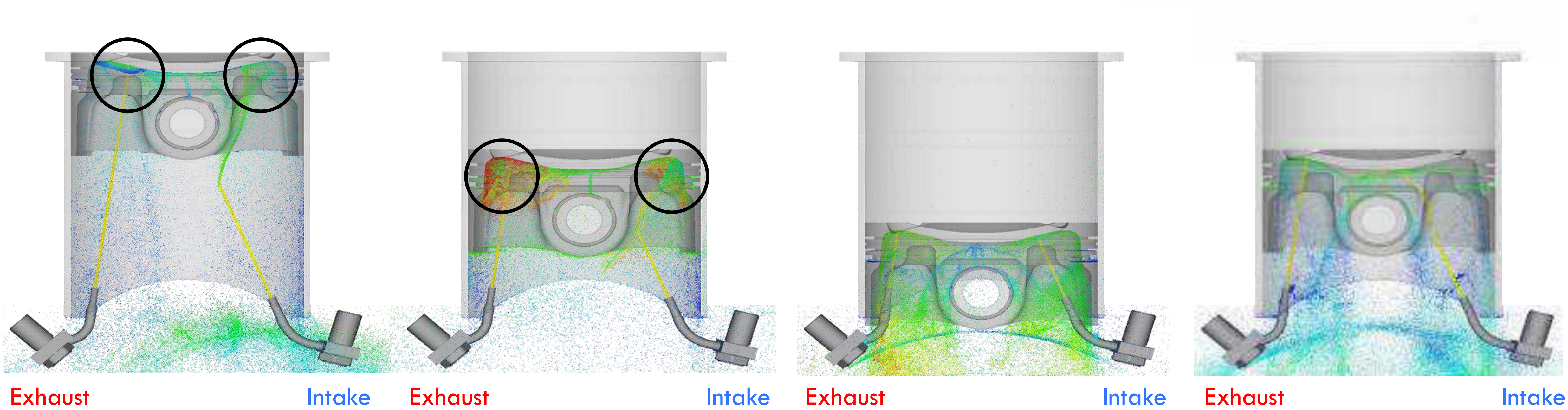




Piston Cooling Jets simulations

- Assessment of velocity distribution

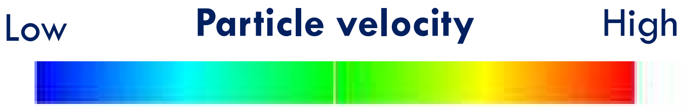
Low **Particle velocity** High

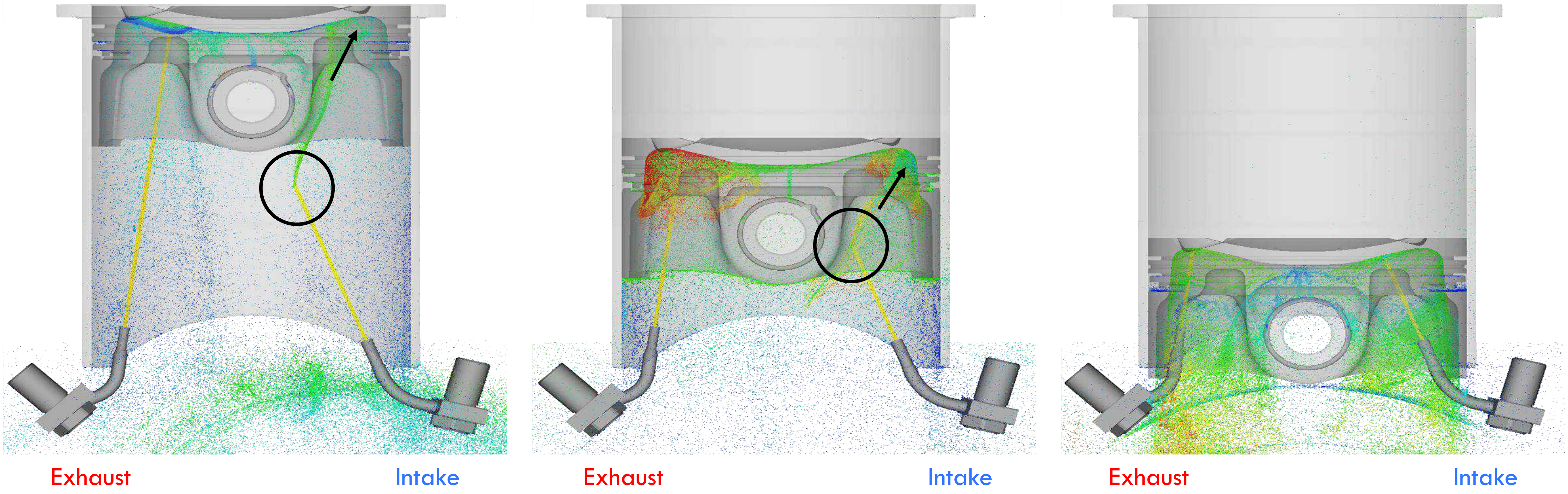


----------→ **TDC** → **Half stroke** → **BDC** → **Half stroke** ---------→

Piston Cooling Jets simulations

- Assessment of velocity distribution
    - Significant interactions of oil jets w/ connecting rod (side + small end)



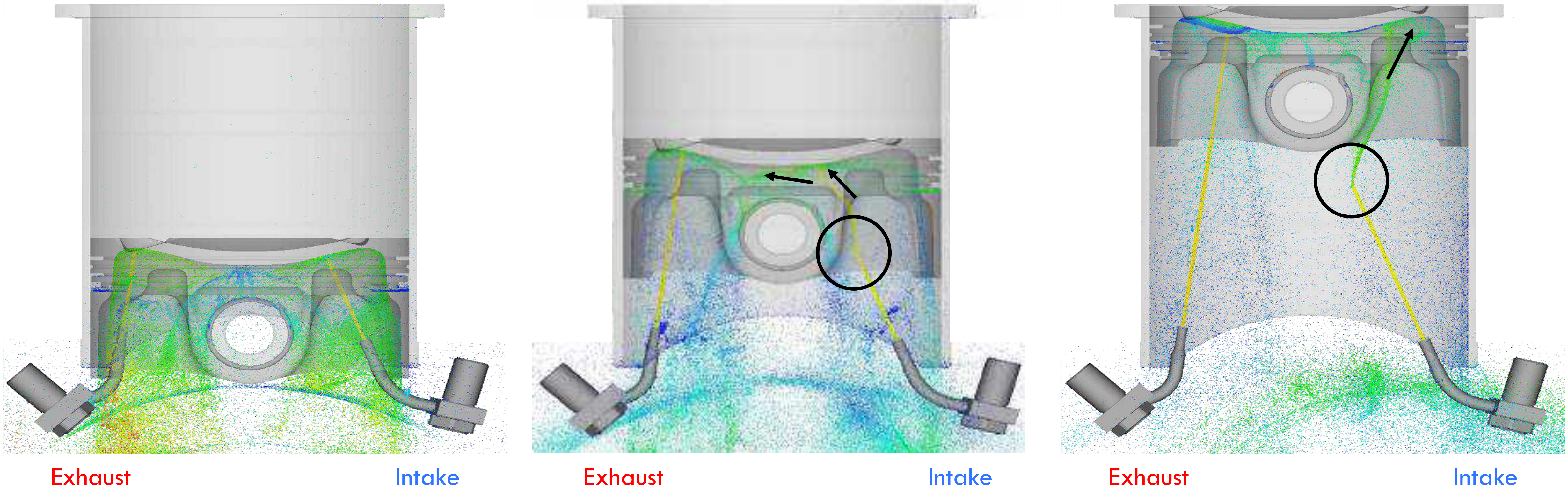


TDC → **Half stroke** → **BDC**

Piston Cooling Jets simulations

- Assessment of velocity distribution
  - Significant interactions of oil jets w/ connecting rod (side + small end)

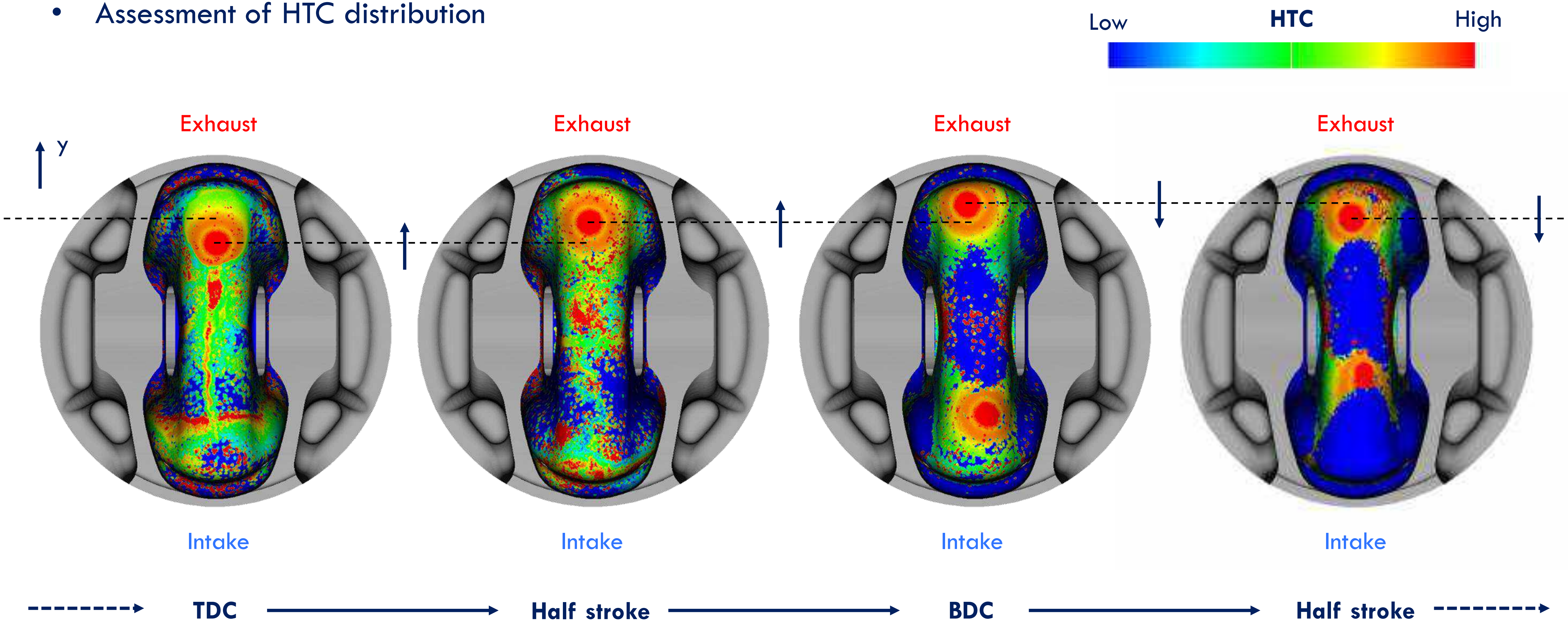
Low **Particle velocity** High



BDC → **Half stroke** → **TDC**

Piston Cooling Jets simulations

- Assessment of HTC distribution



Piston Cooling Jets simulations

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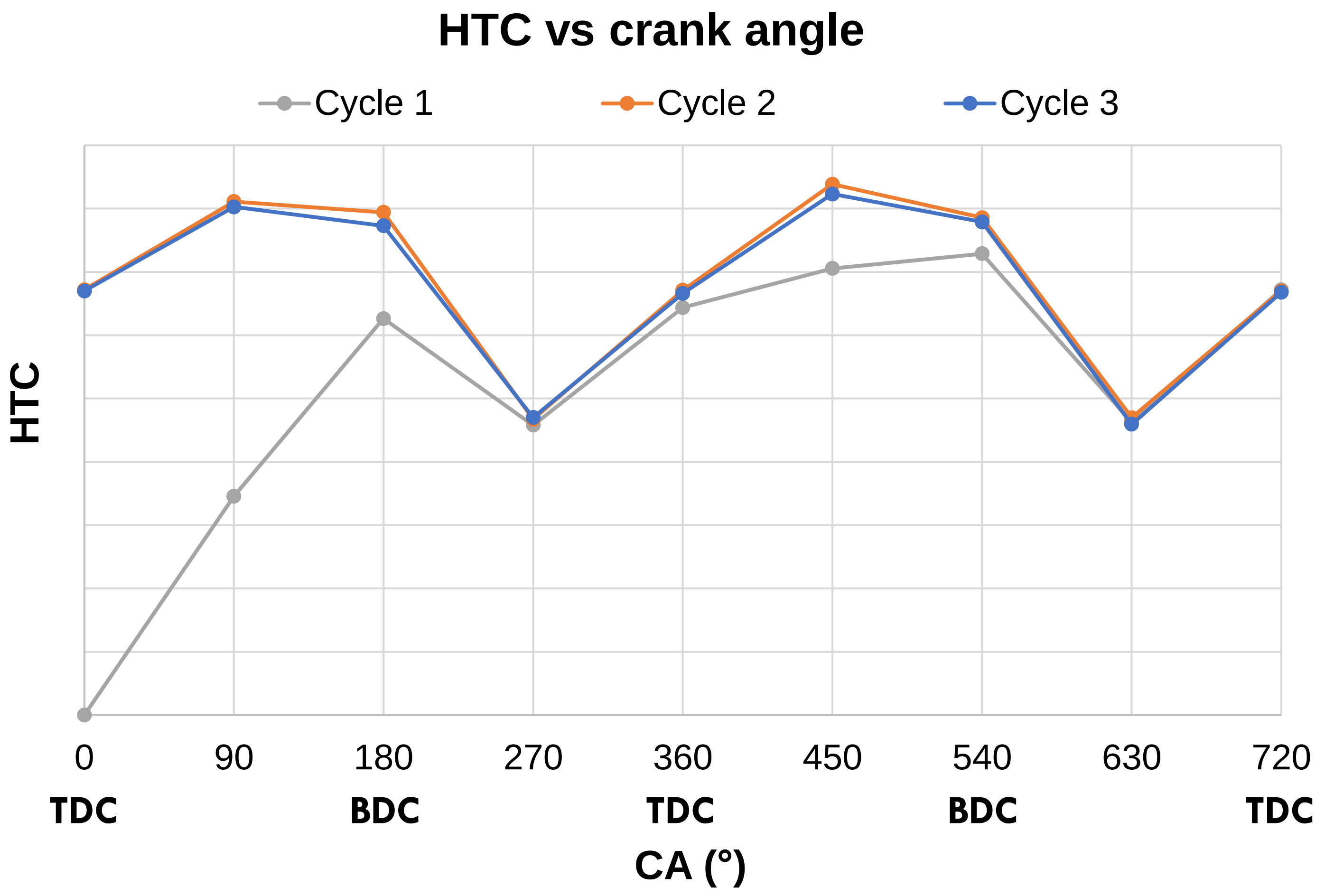
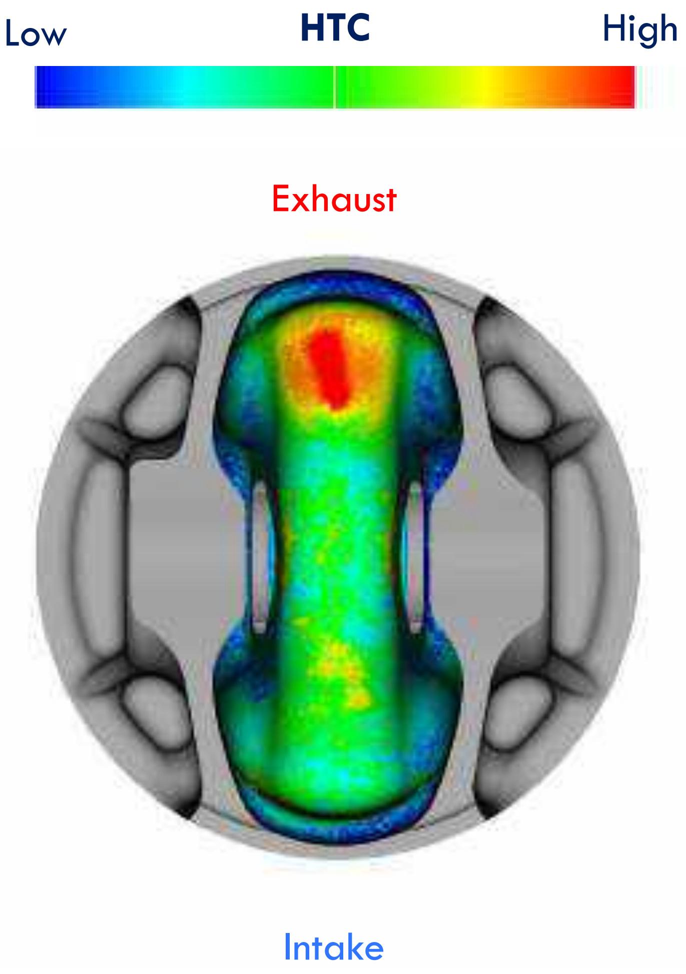
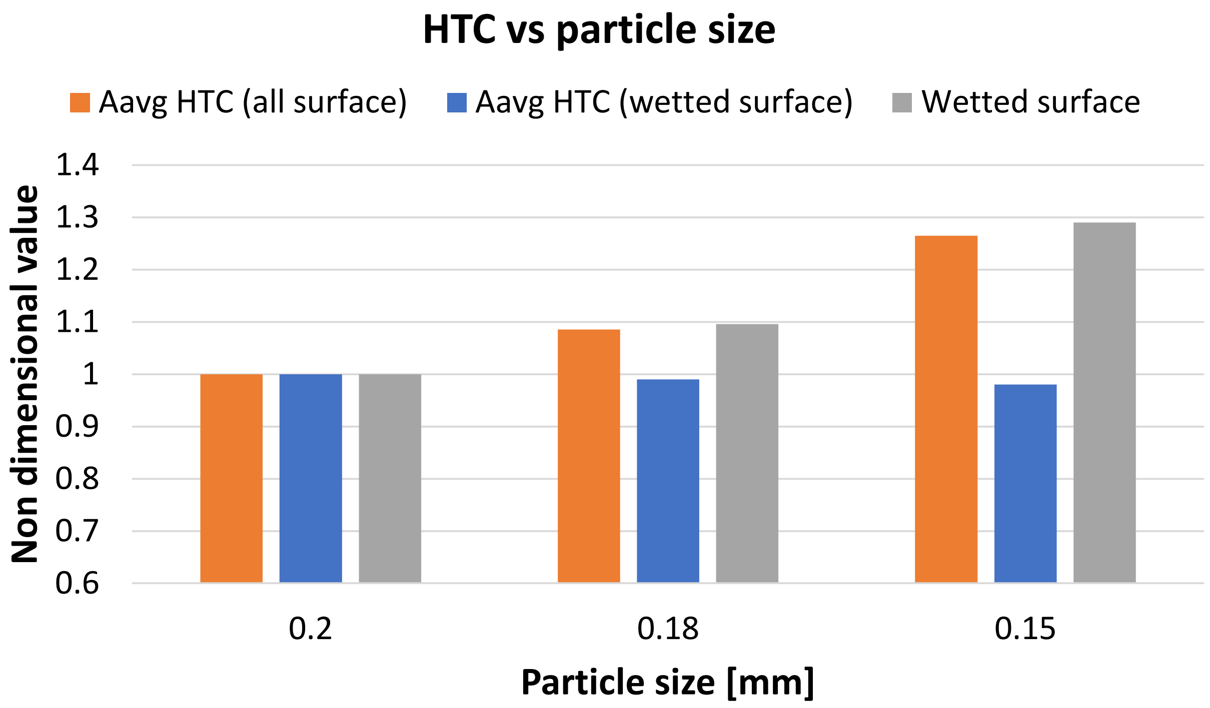


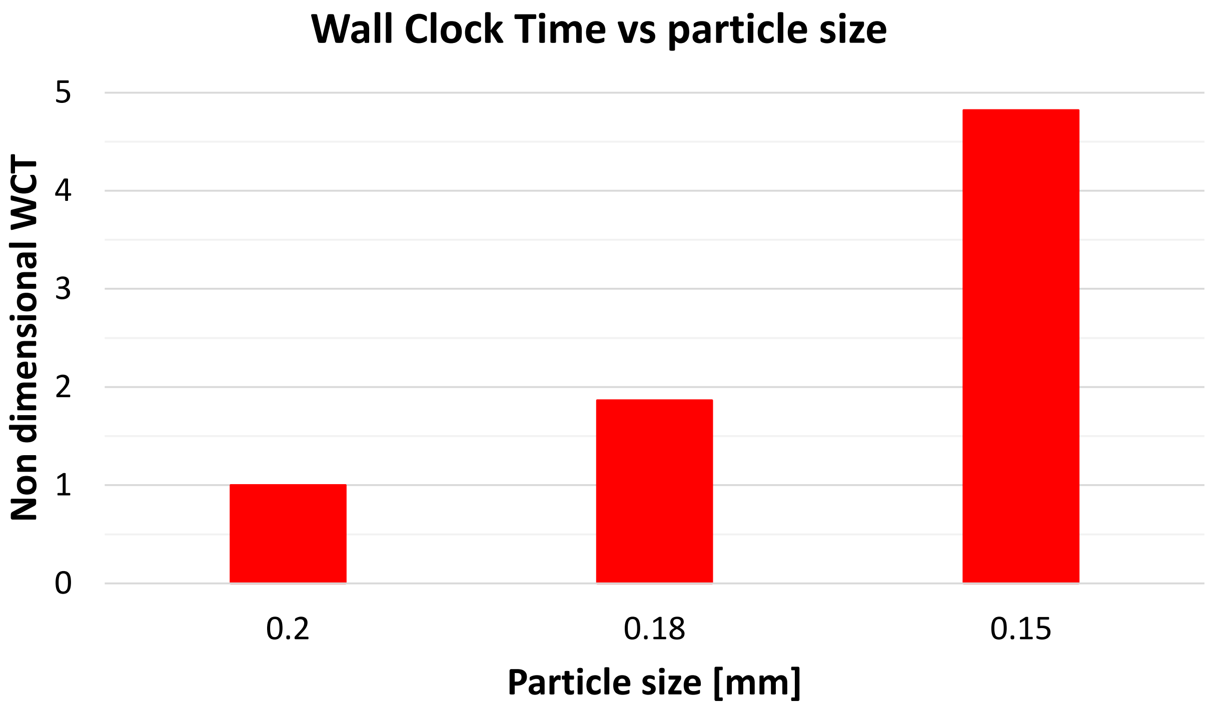


Cycle-averaged HTC distribution (cycle 3)

Piston Cooling Jets simulations

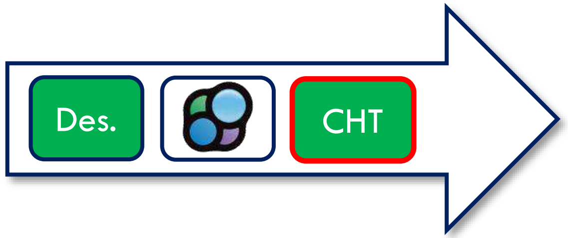
- Particle size sensitivity

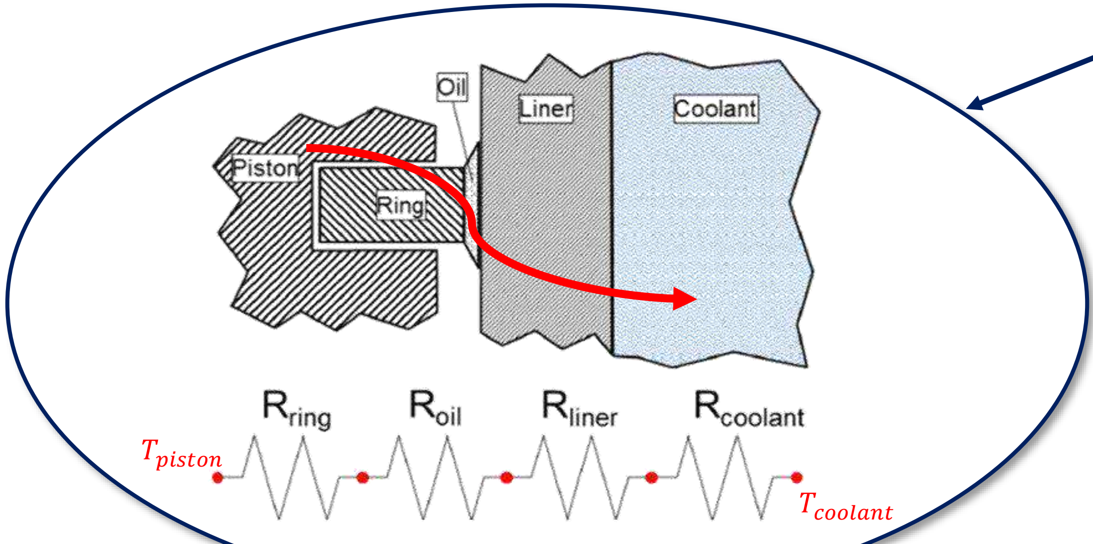




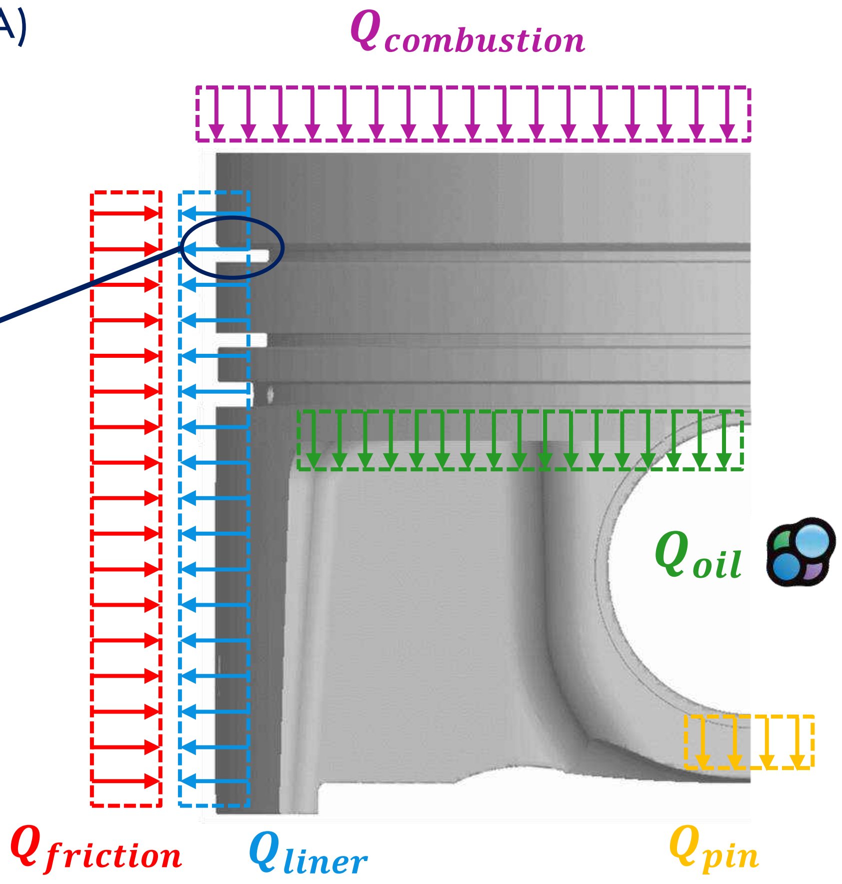
Piston Cooling Jets simulations

- Cycle-averaged piston temperature distribution
  - Integration of Particleworks results in PWT CHT methodology (FVM/FEA)





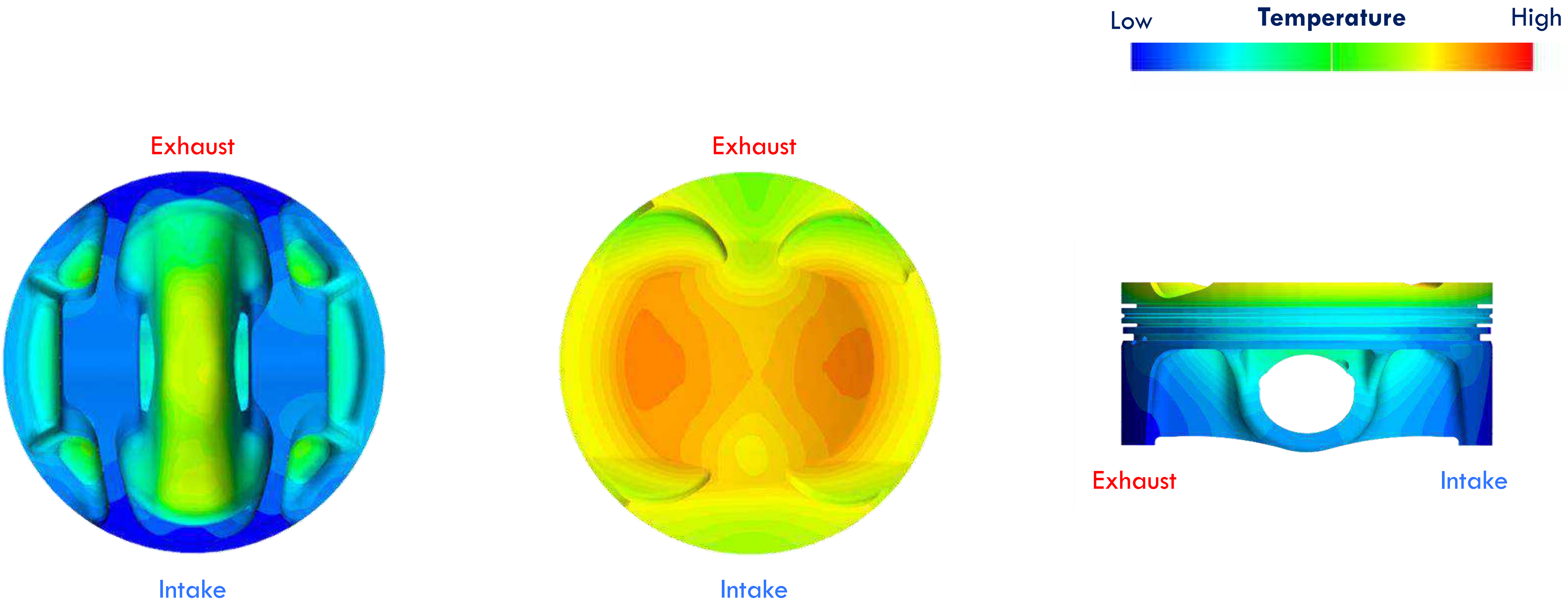
Source: [3]



[3] Giovannoni, N., et al., “Effects of Fuel-Induced Piston-Cooling and Fuel Formulation on the Formation of Fuel Deposits and Mixture Stratification in a GDI Engine”, SAE Technical Papers 2015

Piston Cooling Jets simulations

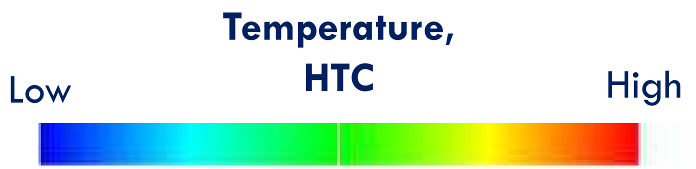
- Cycle-averaged piston temperature distribution

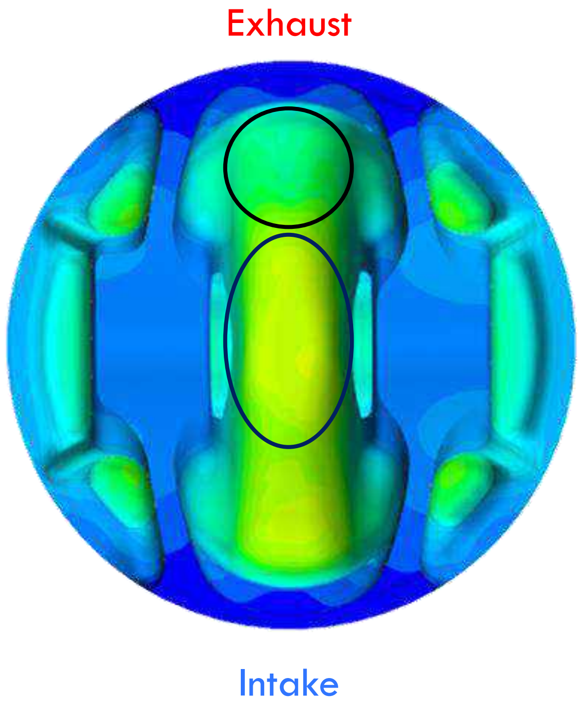


Bottom view **Top view** **Side view**

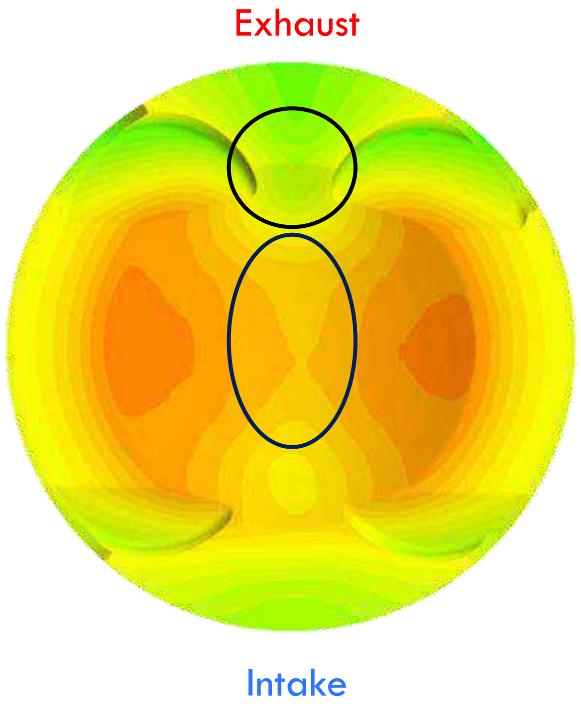
Piston Cooling Jets simulations

- Cycle-averaged piston temperature distribution

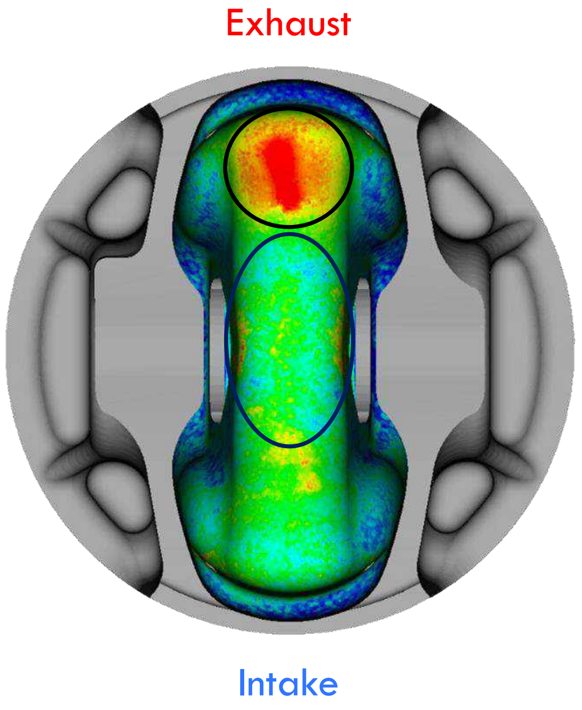




Bottom view



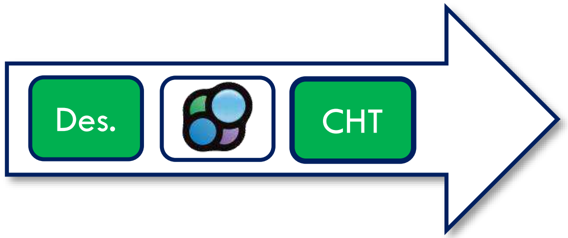
Top view



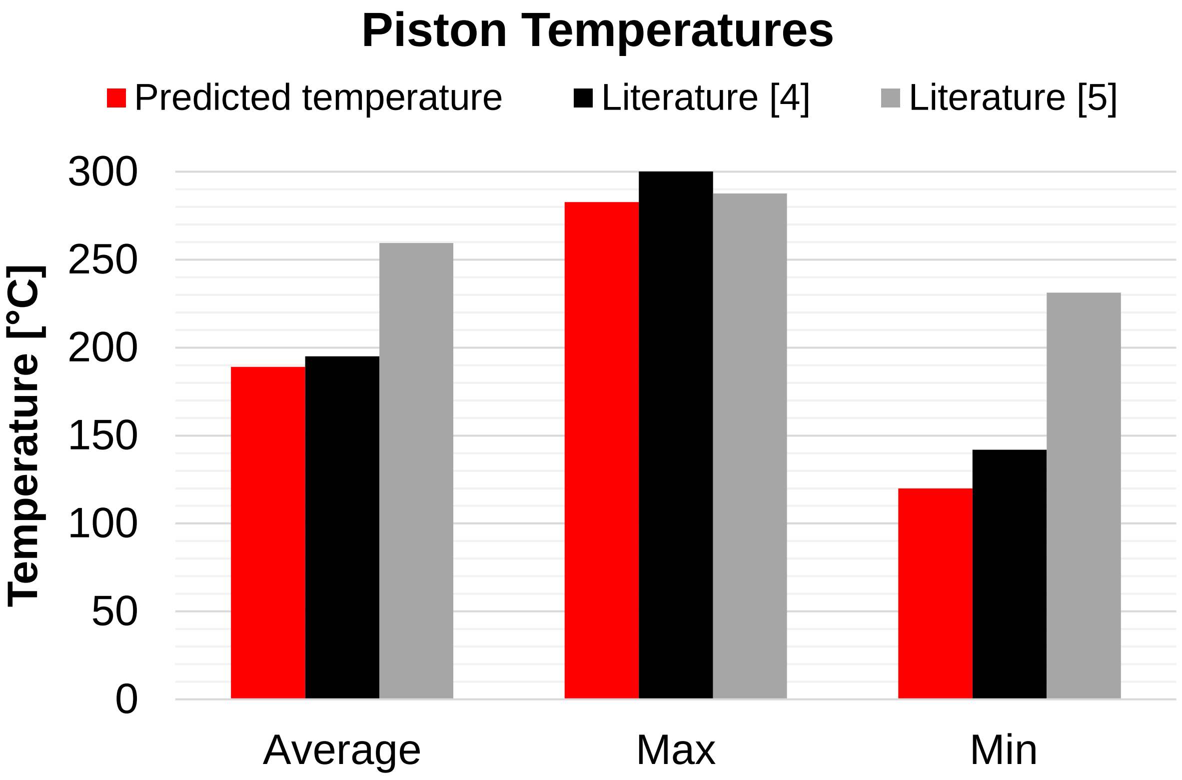
Cycle-averaged HTC distribution (cycle 3)

Piston Cooling Jets simulations

- Cycle-averaged piston temperature distribution



- Results achieved leveraging Particleworks simulations are well aligned to literature data for high-performance engines
- Results are very well aligned in terms of maximum temperature prediction (critical for thermal resistance, knock, etc.)
- Average and minimum temperature results lies in the ballpark of literature data



[4] Mahle, 2012. “Pistons and engine testing”, Vieweg + Teubner Verlag, doi:10.1007/978-3-8348-8662-0

[5] Fontanesi, S., Cicalese, G., and Tiberi, A., "Combined In-cylinder / CHT Analyses for the Accurate Estimation of the Thermal Flow Field of a High Performance Engine for Sport Car Applications," SAE Technical Paper 2013-01-1088, 2013

Conclusions

- A **simulation strategy was developed for PCJs by leveraging Moving Particle Simulations (MPS) + CHT,** with the aim of substitute conventional FVM-based simulations, reduce turnaround time and obtain predictive results
- Stair-step approach:
  - **Impinging jets:**
    - **Particleworks** results **showed good agreement w/ experimental data** w/ the multizone HTC script
    - **Simulation setup extremely easy** wrt conventional FVM methods
  - **Piston Cooling Jets** (PCJ+cranktrain)
    - **Easy setup** (~carry-over of impinging jet case + moving parts)
    - **Reduced computational time** allows for optimization loops (overnight runs possible)
    - **Particleworks + PWT CHT methodology** led to **piston temperatures aligned w/ literature data** for high-performance engines
- Future works:
  - Experimental validation of piston temperatures in real engines
  - Further optimization (alternative designs, PCJ performance vs oil flow rates, engine speeds, etc.)

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Contact:
Andrea Bianco
POWERTECH Engineering S.r.l.
Italy – Turin, Via Carolina Invernizio 6
+39 011 0709964
a.bianco@pwt-eng.com
https://www.linkedin.com/in/andrea-bianco
https://pwt-eng.com

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M. Prestifilippo, POWERTECH Engineering S.r.l.
F. Millo, Politecnico di Torino

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