Simulation of Oil Jets for Piston Cooling Applications Using Mesh Deformation and the Level Set Method

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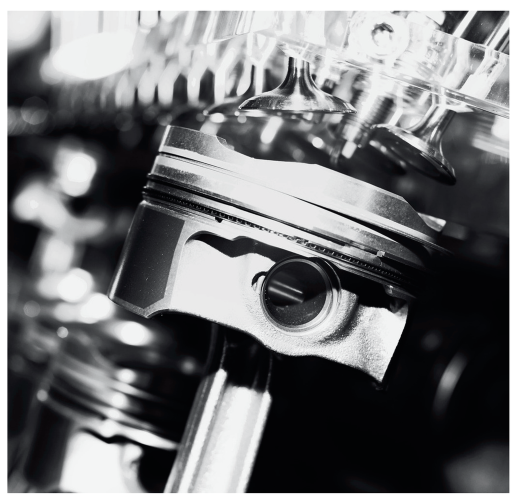
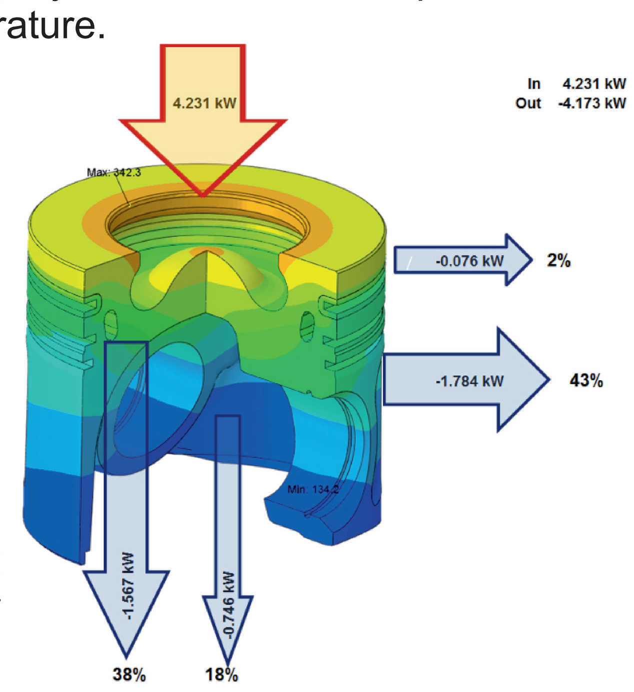
Motivation


Piston in situ

The objective of this project is to develop efficient numerical methods for unsteady multiphase flows applied to jet simulation. The application intended is the cooling of a reciprocating piston inside an Internal Combustion Engine (ICE). Active cooling strategies for pistons are investigated as a way to improve the efficiency of internal combustion engines and reducing harmful emissions. Pistons are notoriously hard to cool because of their high velocity and complex kinematics. This problem can be solved using lubricating oil sprayed underneath the piston as a coolant to regulate the temperature.

The problem when designing such a system is to evaluate beforehand the cooling performance of a particular design. Until recently, it was necessary to use costly test benches and prototypes to evaluate the performance. Furthermore, numerical simulations provide detailed insights into the complex interactions between oil, air and the moving piston.

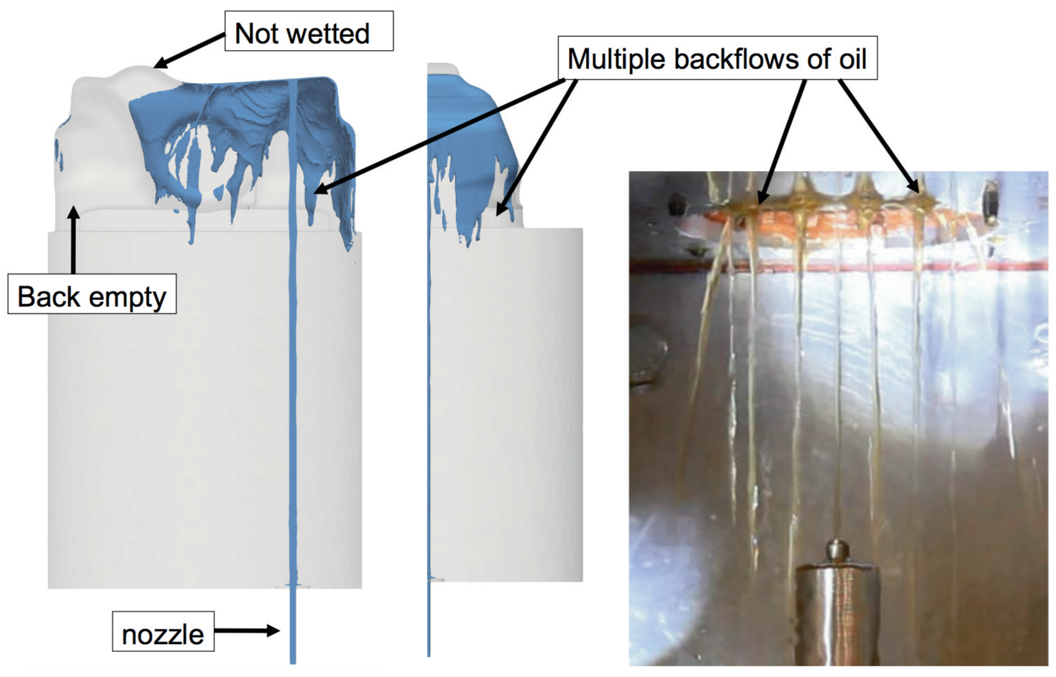
For the first step of this project, our industrial partner, Ford Motor Company, provided us with experimental data. Our task was to build a model capable of replicating those results. Our current model is able to simulate complex piston shapes, atomized jets and jets interacting with moving pistons.



Heat in piston

Standard piston

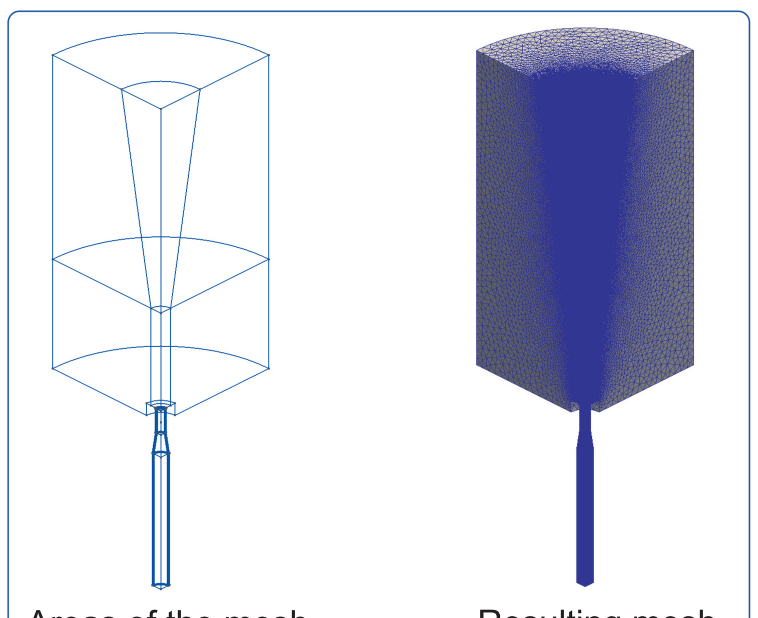
- In the experiments, the heat transfer coefficient was obtained for a fixed piston impinged by an oil jet (Easter, J. et al., Journal of Heat Transfer,136 , 1-4. 2014).
- One of the cases involves a laminar jet (Re = 500) that was simulated with our current implementation.
- The mesh used has 11 million elements and was simulated on 8192 MPI ranks.

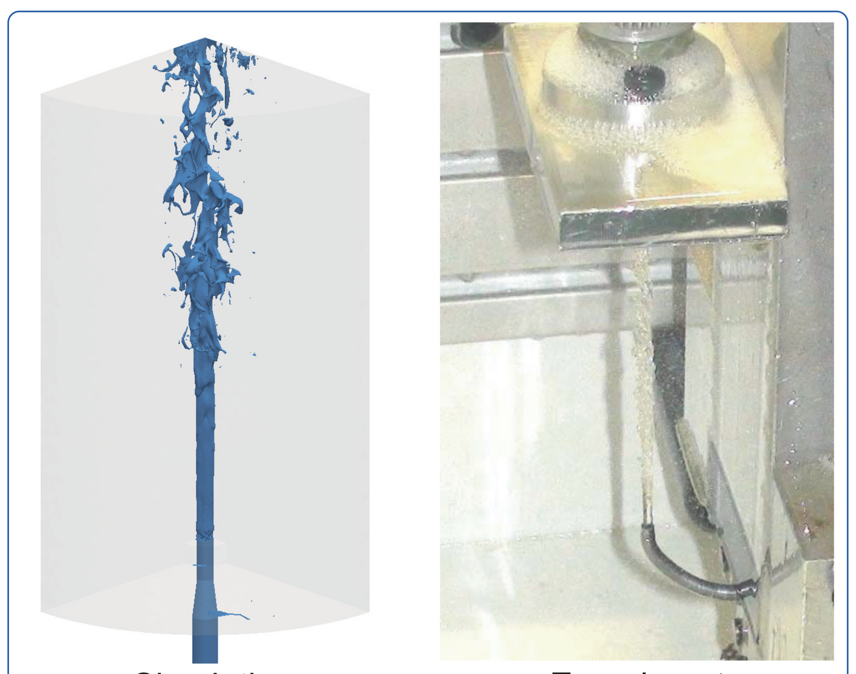


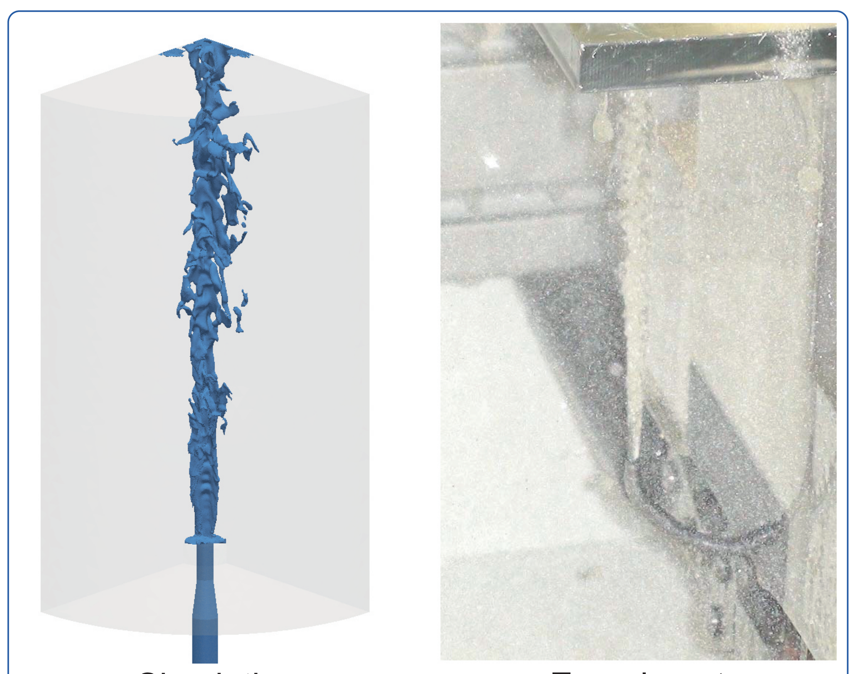
Comparison between simulation and experiment for laminar jet (Re = 500)

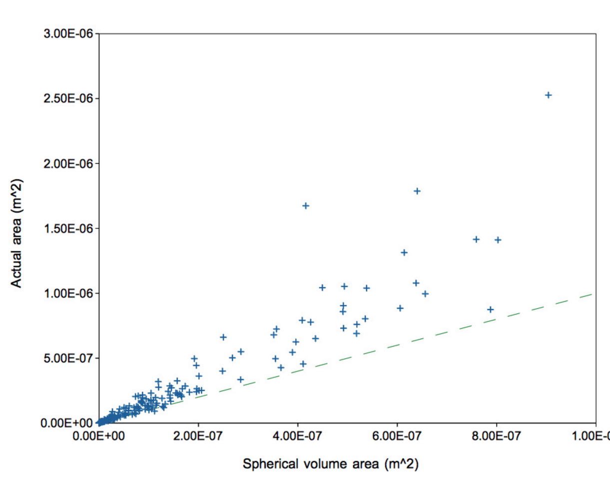
Free oil jet

- The influence of the inflow mass flow rate on the resulting shape of a free oil jet is analysed.
- When the inflow mass flow rate reaches a critical value, the oil jet starts to atomize into numerous droplets.
- In such a case, a 39 million element mesh ran on 32,768 MPI ranks is necessary to capture the atomization.
- It was also observed that the mesh resolution has a significant impact on both the onset of atomization and on the mass conservation of the method.
- An adaptive mesh refinement algorithm will be developed.

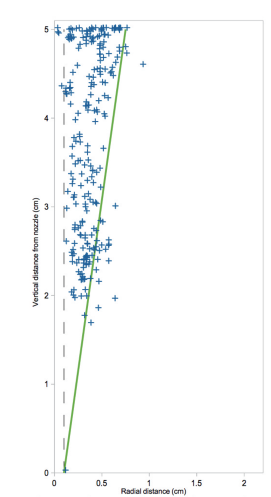

Areas of the mesh   Resulting mesh
Setup


Simulation   Experiment
Semi-turbulent jet (3.0L/min)


Simulation   Experiment
Turbulent jet (4.6L/min)



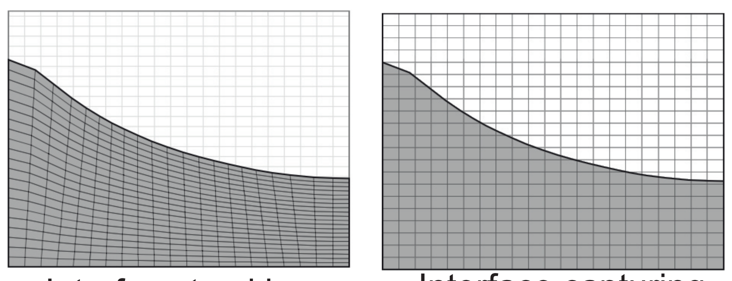
Droplets deformation


Atomization angle

Number of droplets	255	[-]
Minimum droplet volume	1.23×10^{-12}	[mm3]
Maximum droplet volume	1.156	[mm3]
Average droplet volume	1.94×10^{-2}	[mm3]
Minimum element volume	1.824×10^{-8}	[mm3]
Atomization angle	7.41	[mm3]

Atomization statistics

Method


Interface tracking   Interface capturing

- The two main approaches for solving multiphase flows are interface capturing and interface tracking methods.
- The level set method, an interface capturing method is used.
- The multiphase Navier-Stokes equations are solved:

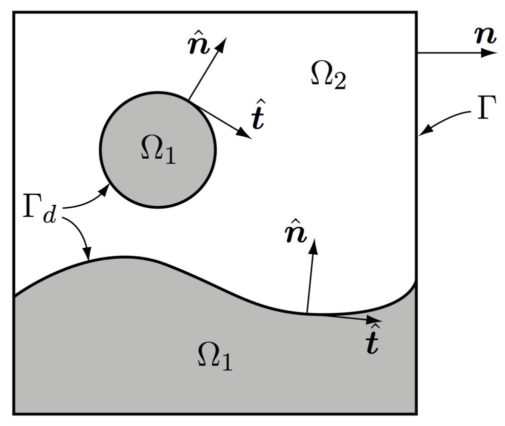
$$\rho(\mathbf{x})\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right) + \nabla p - \nabla\cdot\boldsymbol{\sigma} - \mathbf{f} = \mathbf{0} \quad \text{on } \Omega_t, \quad \forall t \in (0,T)$$
$$\nabla\cdot\mathbf{u} = 0 \quad \text{on } \Omega_t, \quad \forall t \in (0,T)$$

- Both fluids are assumed to be Newtonian immiscible:

$$\boldsymbol{\sigma} = \mu(\mathbf{x})\left(\nabla\mathbf{u} + \nabla\mathbf{u}^{\mathbf{T}}\right)$$

- The source term include the contribution from gravitational effect and surface tension force:

$$\mathbf{f} = \rho\mathbf{g} + \sigma\kappa\hat{\mathbf{n}}\delta(\Gamma, \mathbf{x})$$



Normal definition

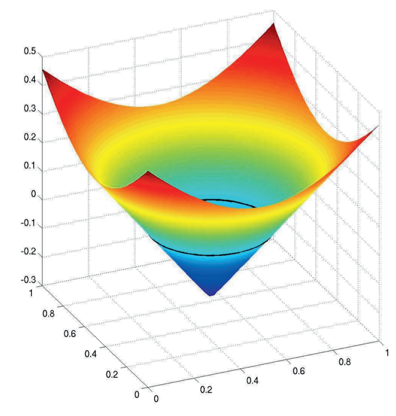
- The level set advection is defined as:

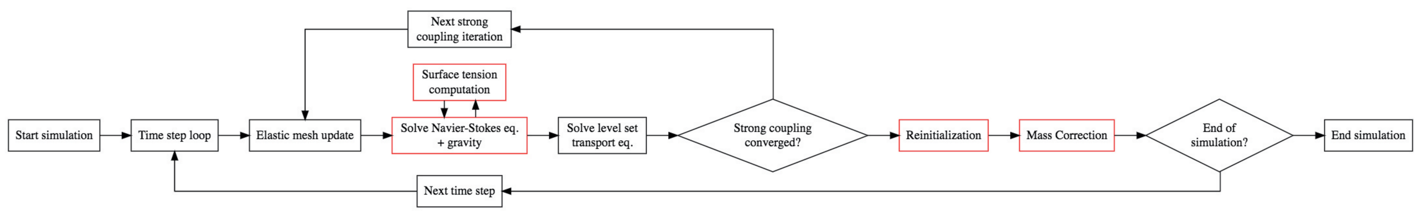
$$\frac{\partial\phi}{\partial t} + \mathbf{u}\cdot(\nabla\phi) = 0 \quad \text{on } \Omega_t, \quad \forall t \in (0,T)$$

- The linear elasticity equations are solved:

$$\begin{aligned}
\nabla\cdot\boldsymbol{\sigma}_{mesh} &= 0\\
\boldsymbol{\sigma}_{mesh}(\boldsymbol{\nu}) &= \lambda_{mesh}(tr\boldsymbol{\varepsilon}_{mesh}(\boldsymbol{\nu}))\mathbf{I} + 2\mu_{mesh}\varepsilon_{mesh}(\boldsymbol{\nu})\\
\varepsilon_{mesh}(\boldsymbol{\nu}) &= \frac{1}{2}\left(\nabla\boldsymbol{\nu} + (\nabla\boldsymbol{\nu})^T\right)\\
\boldsymbol{\nu} &= \mathbf{v}\Delta t
\end{aligned}$$

- Lamé-parameters: μ_{mesh} / λ_{mesh}

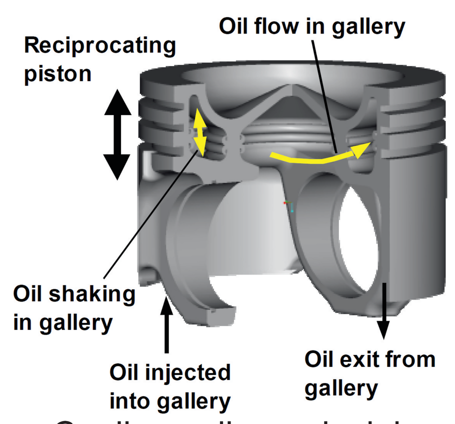

level set function



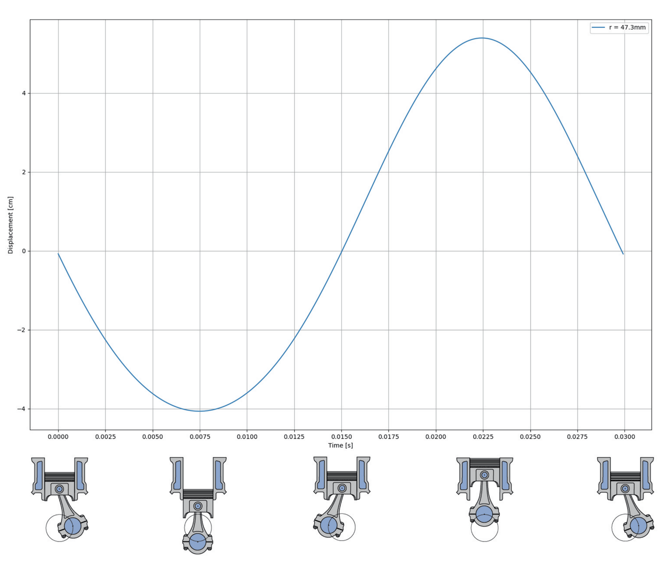
Overview of the procedure

Cooling gallery

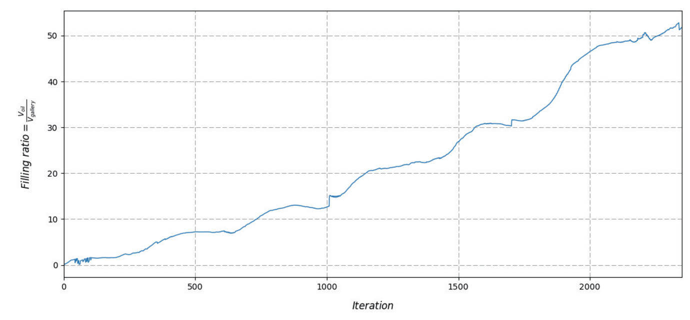
- A laminar jet is injected into a modern piston with a cooling gallery.
- This type of piston is especially efficient because it brings the coolant closer to the combustion chamber and allows more heat removal via the cocktail shaking effect. This effect involves the lubricating oil being trapped and mixed in the cavity inside the piston.
- The jet is here laminar but the periodic movement of the piston is now included.



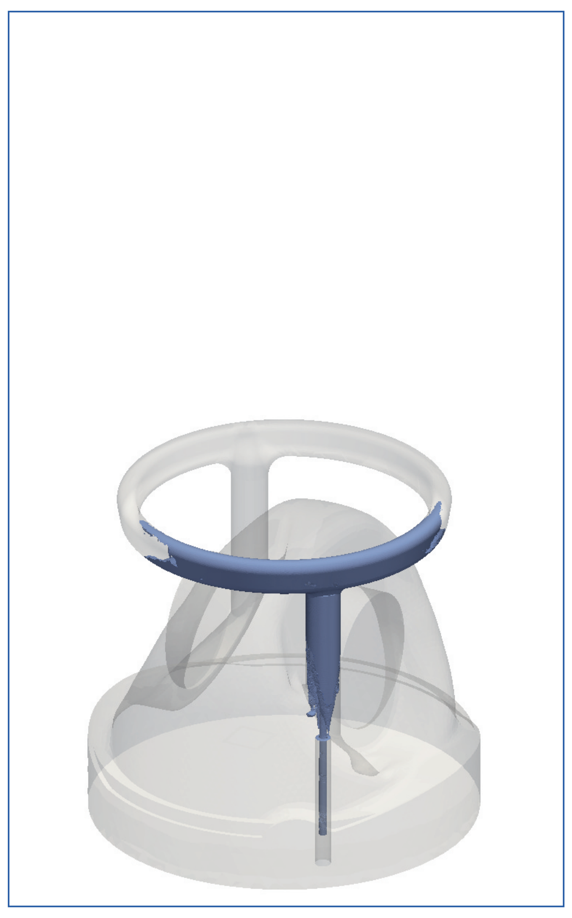
Cooling gallery principle


Curve of piston movement

- It was important in this simulation to accurately represent the interaction between the rising jet and the oscillating piston.
- The mesh used has 8.3 million elements and was run on 3072 MPI ranks on Jureca.
- The resulting interaction on the corresponding figures show the oil sloshing inside the cooling gallery resulting from the movement of the piston.


Oil filling ratio


Initial position


Bottom Dead Center (BDC)


Top Dead Center (TDC)

Conclusion

The level set method proved to be powerful and versatile for complex oil jets. In general, multiphase flow problems are notoriously complex to solve accurately. It was confirmed during this project as we faced many challenges when exploring different approaches (level set method, mesh movement) on various problems (free oil jet, fixed gasoline piston, moving diesel piston with cooling gallery).
New computational capabilities make it possible to simulate such complex flows with an unprecedented amount of detail.

Acknowledgements

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