

*11th OpenFOAM Workshop  
Guimarães, Portugal, June 26th-30th 2016*

## Multiphase VOF Simulation of Gasoline Injectors with Topologically Changing Grids

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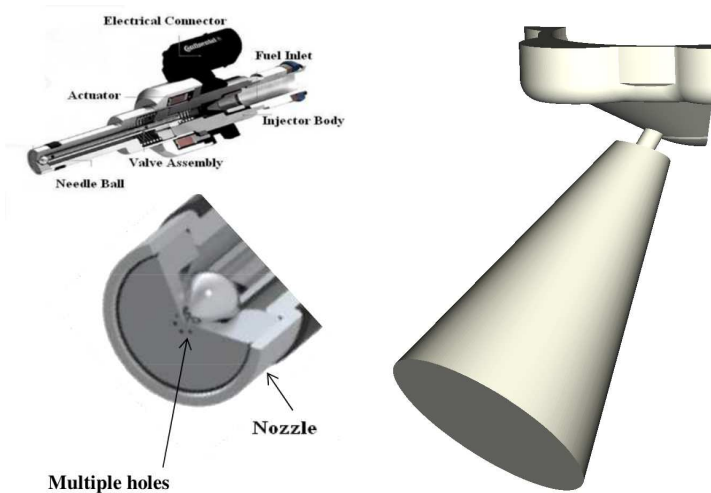
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**OBJECTIVE:** *simulation of primary breakup after injector opening*

# Summary: code development



- ▶ *Dynamic mesh with topological changes*
  - `layerAdditionRemoval`: conservation of intensive quantities with 2nd order discretization *in time*
  - `attachDetach`, `slidingInterface`: improved efficiency
- ▶ *TopoDyM dynamic solver family (compressible/incompressible/VOF)*
  - enhanced formulation of momentum interpolation for solution-independence on under-relaxation factors and time-step advancement
  - consistent pressure-velocity coupling algorithm in inner iteration
- ▶ *Enhanced domain decompositionMethods* for faster simulations on parallel machines:
  - semi-automatic decomposition for full load balancing with topological changes

*References: SAE paper 2015-01-0384, 2013-24-0027, Flow turb & comb. 2016*

All the presented work is compatible with the code released by the OpenFOAM® Foundation. The presented development has been fully tested on the **new releases 3.0.x and dev** of OpenFOAM®.

# incompressible Volume-Of-Fluid solver



- ▶ Solve for **liquid** volume fraction  $\alpha_l$  (vapor is  $\alpha_v = 1 - \alpha_l$ )

$$\frac{\partial \alpha_l}{\partial t} + \nabla \cdot [\alpha_l (\mathbf{U} - \mathbf{U}_m)] + \nabla \cdot [\alpha_l (1 - \alpha_l) \mathbf{U}_c] = \frac{1}{\alpha_l} \dot{m}$$

- ▶ Global momentum equation (with  $\rho$  and  $\mu$  weighted on  $\alpha$ )

$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla \cdot [(\mathbf{U} - \mathbf{U}_m) \rho \mathbf{U}] - \nabla \cdot \mu \nabla \mathbf{U} - \rho \mathbf{g} = -\nabla p - \mathbf{F}_s$$

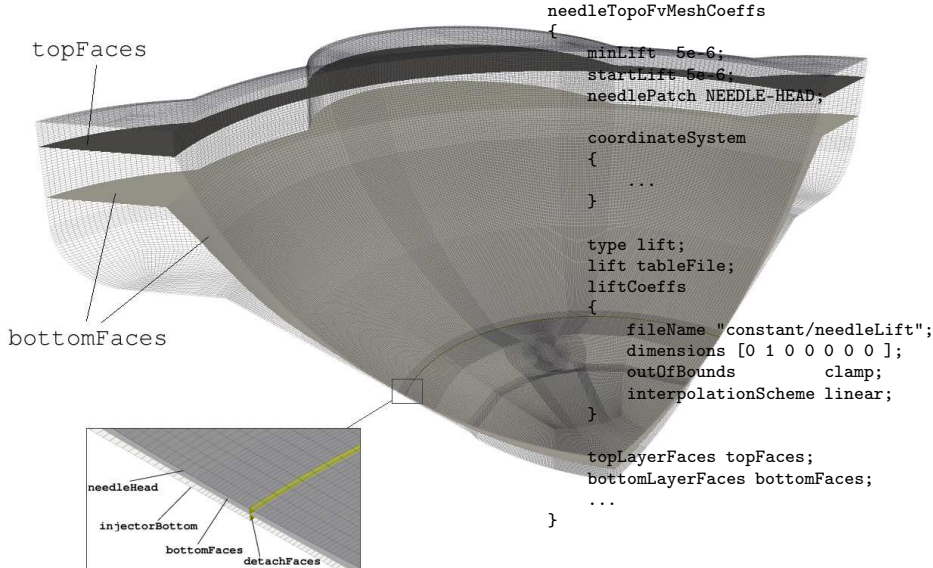
- ▶ Turbulence is modeled using LES
  - Mesh quality is of foremost importance
  - Need high order schemes **in time and space**

- ▶ **Additional terms:**

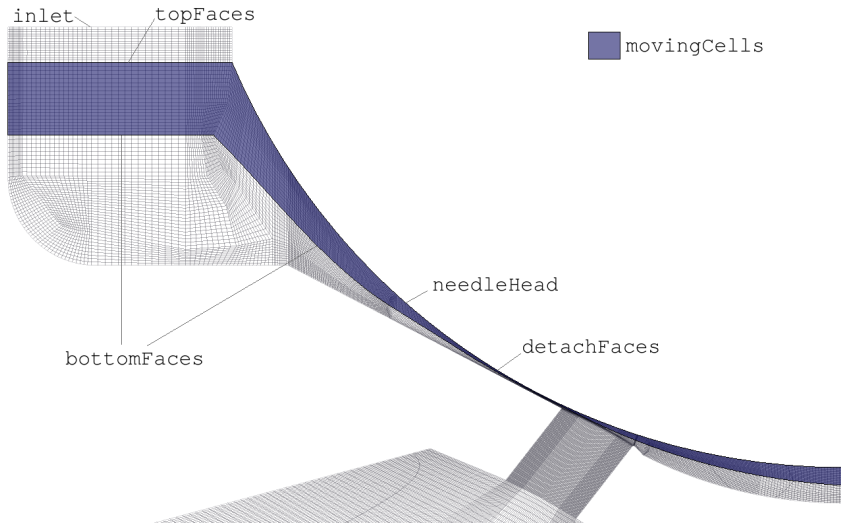
- $\alpha_l (1 - \alpha_l) \mathbf{U}_c$ : interface compression term (prevents smearing)
- $\dot{m}$ : cavitation mass source (according to Schnerr-Sauer<sup>1</sup>)
- $\mathbf{U}_m$ : Mesh velocity: **Must comply with GCL**

<sup>1</sup>G. Schnerr, J. Sauer, Unsteady cavitating flow – a new cavitation model based on a modified front capturing method and bubble dynamics., ASME Fluids Engineering Summer Meeting, June 2011-15, Boston (USA).

# Dynamic mesh with topoChanges



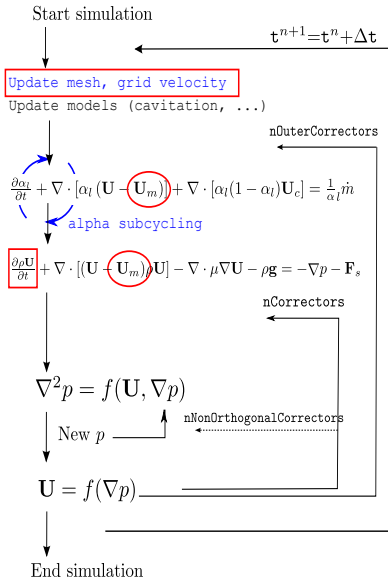
# Mesh motion: class `needleTopoFvMesh`



A. Montorfano, F. Piscaglia, A. Onorati. *An extension of the dynamic mesh handling with topological changes for LES of ICE in OpenFOAM®*. SAE Technical Paper 2015-01-0384.



# Integration solver-dynamic mesh



## ► **Baseline:** interPhaseChangeDyMFoam

- Segregated FV solver
- Multiphase method: VOF
- Dynamic mesh handling **w/o topoChanges**

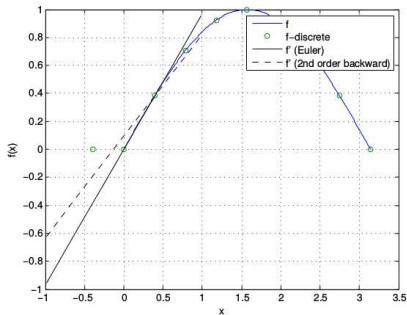
## ► **Novel Development (solver):**

- 2nd order time discretization **(bug fix)**
- Grid Conservation Law (GCL) **(bug fix)**
- Strict coupling pressure/energy coupling
- Interpolative mapping

## ► **Novel Development (mesh class):**

- Run-time selection of mesh modifiers
- Run-time selection of point motion law
- Proxy class topoManager to handle:
  - modifiers creation/update
  - modifiers activation/deactivation
  - flux correction
  - remapping

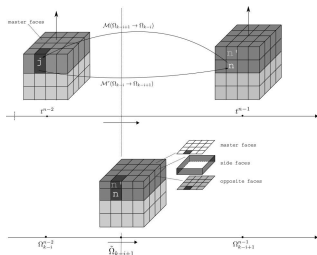
# 2nd order time discretisation



- 2nd order temporal discretization (`backwardDdt`) forces the solution to 0 at  $t^{n-1}$   
→ **accuracy is not fully second order**;

The same happens whenever a `topoChanges` occurs:

- WITHOUT CORRECTION:
  - initial error is accumulated



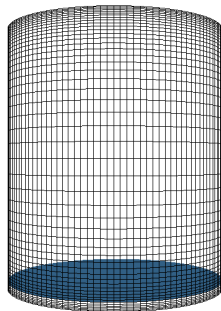
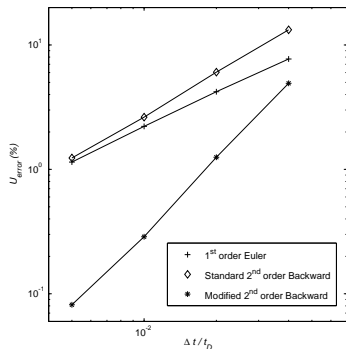
ddtSchemes

```
{  
    default    backward;  
    // default CrankNicolson 0.5;  
}
```

- *Geometric Conservation Law (D-GCL)* is not satisfied with second order discretization in time (backward, CrankNicolson) and layerAdditionRemoval:

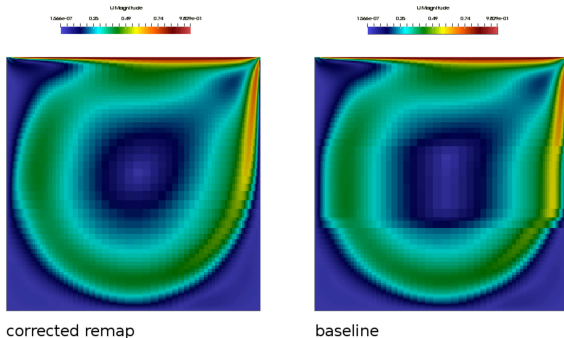
$$\frac{d}{dt} \int_{\Omega(t)} dV = \int_{\Gamma(t)} (\mathbf{v}_{\text{mesh}} \cdot d\mathbf{S}_f)$$

- mesh-to-mesh map of mesh fluxes is not correctly performed
- mesh-to-mesh map of old quantities – in case of topoChanges – is not correctly performed
- **fixed the above points to achieve full 2nd order accuracy**



Test case: cylinder compression

- WITH CORRECTION:
  - second order accuracy in time with topological changes
  - full mass conservation



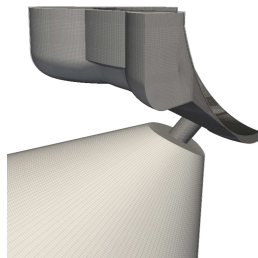
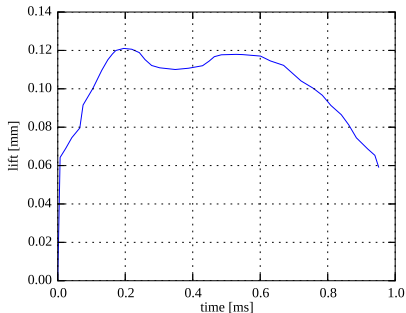
corrected remap

baseline

Novel class topoMapper (in dynamicMesh):

- force correct remapping of fluid-dynamic and transported quantities;
- ensures conservation of the GCL;
- improved overall mass conservation, scalar transport and energy through the topological change with second order TEMPORAL schemes

- ▶ Fuel: n-heptane
- ▶ Cavitation model by Schnerr-Sauer
- ▶ Incompressible 2-phases solver
  - Liquid fuel
  - Fuel vapor
- ▶ In-cylinder air is simulated using fuel vapor

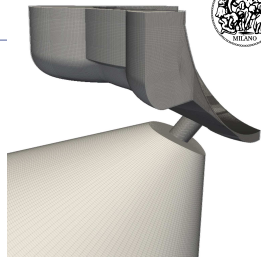


Multi-hole GDI injector geometry: MAGIE by



- Real geometry
- Real needle lift (X Ray in ANL)
- Atomization visualization
- Large spray visualization
- PDA

# Gasoline Injector: opening event



- **COMPUTATIONAL MESH:**

- Fully-hex multi-block grid  $\approx 11$  M cells
- Mesh motion based on topological changes:
  - prescribed needle motion from tabulated data
  - two layer addition/removal zones
  - attach/detach to simulate needle opening/closure

- **SOLVER**

- incompressible **Volume-of-Fluid** (VoF) phase-fraction based interface capturing approach;
  - 2 incompressible, non-isothermal immiscible fluids with cavitation
- Discretization:
  - backward differencing in time (2nd order)
  - LUST on momentum convection
  - limited schemes for  $k$

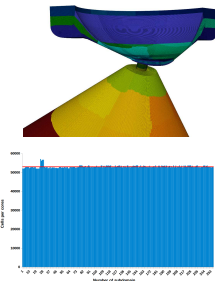
- **TURBULENCE MODELING:** LES dynamic one-equation model

# Decomposition with topoChanges

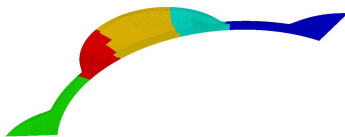


## CONSTRAINED (class structuredSetDecomp)

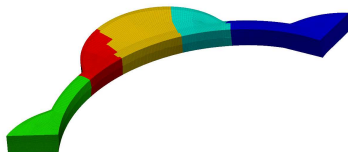
1. mesh is splitted into regions on the basis of layering zones;
2. decomposition of topology modifiers is computed (new class structuredSetDecomp);
3. the remaining zones of the mesh are decomposed;
4. cell-processor assignment is stored and the decomposition of the mesh is performed.



1.



2.

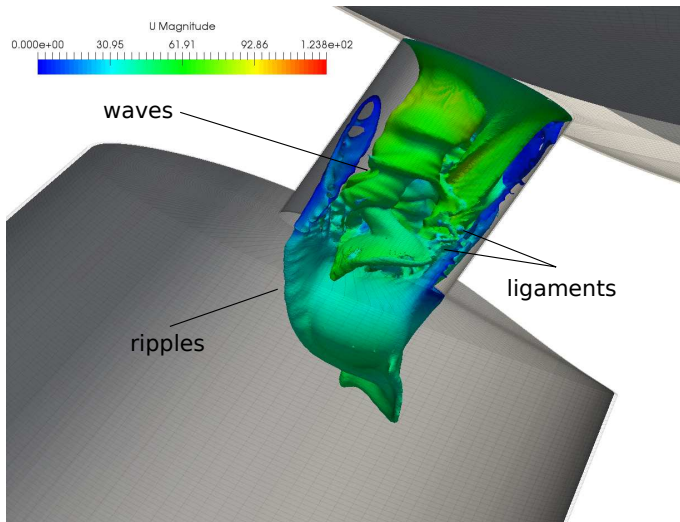


The above steps are fully automated and included in shell scripting.

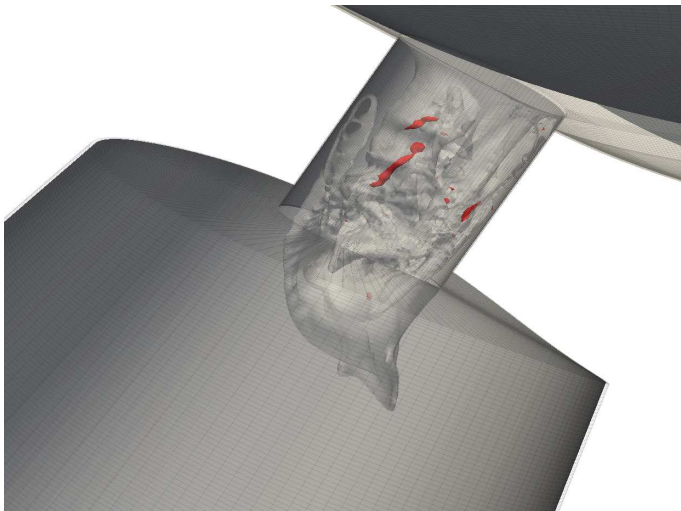
# Preliminary results: alpha



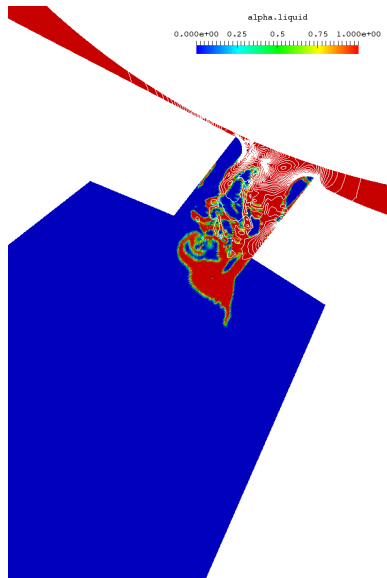
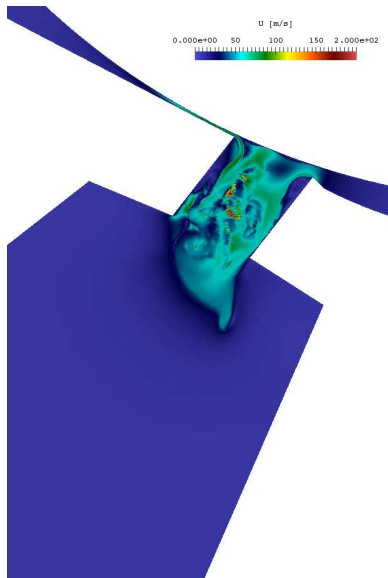
MAGIE injector: injector opening. Simulation ran on 256 cores on Blues HPC machine at Argonne National Lab.



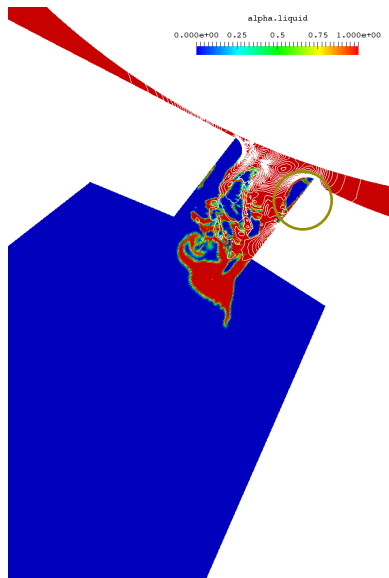
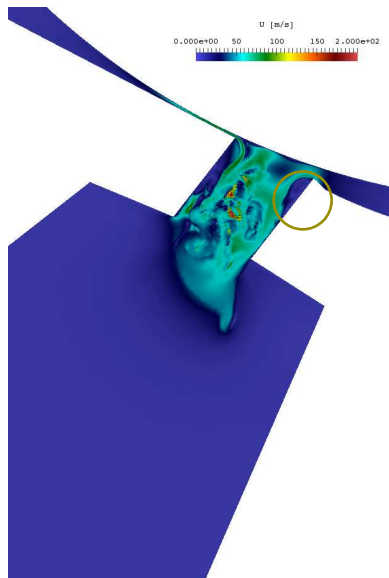
# Preliminary results: breakup



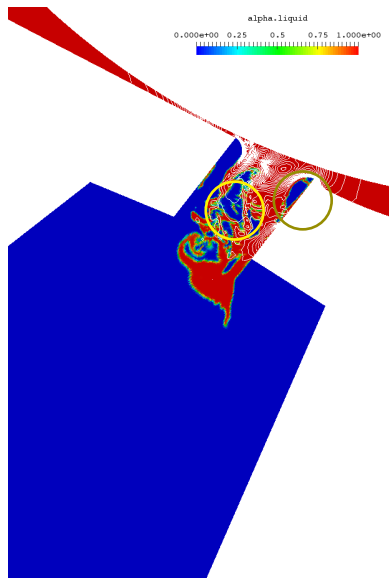
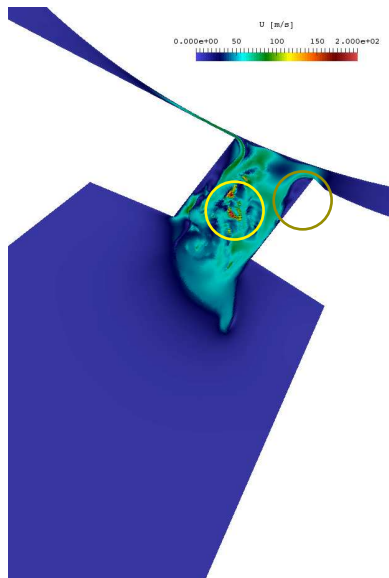
# Preliminary results: cavitation



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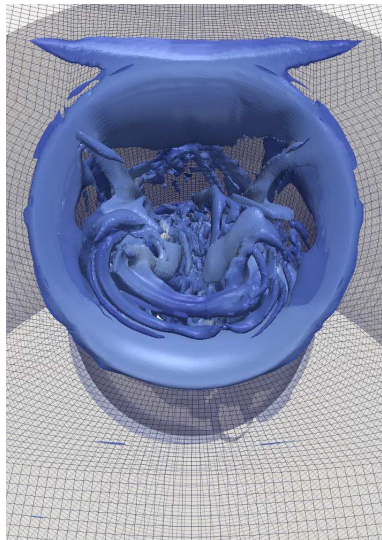
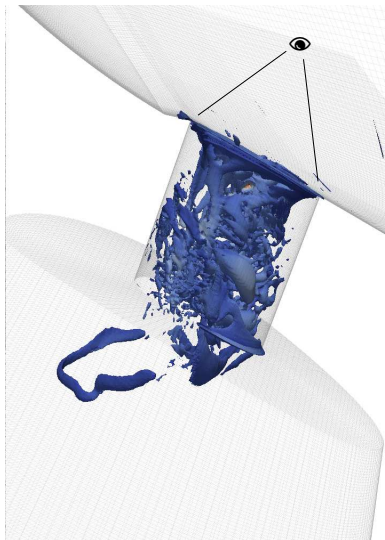
# Preliminary results: cavitation



# Counter-rotating vortices



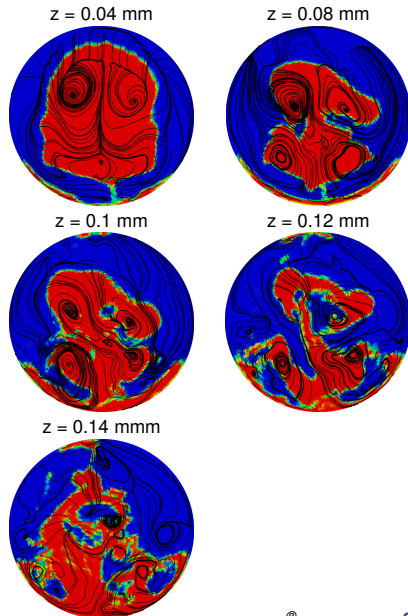
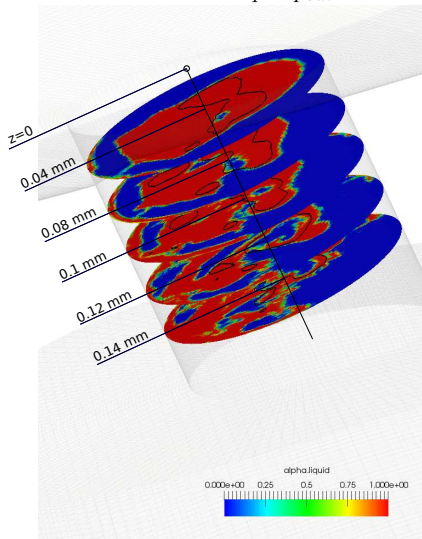
Isosurfaces of Q-criterion



# Counter-rotating vortices



Contour line at  $p = p_{sat}$





## ▶ VOF solver with phase change

- ✓ Implementation of dynamic solver with topochanging mesh
- ✓ Accuracy improvement of time discretization (2nd order)
- ✓ Automatic constrained decomposition

## ▶ Simulation of injector opening (in progress)

- ✓ Case setup with moving mesh



Simulation of injector opening (2 phases, incompressible)



Validation with shadowgraphs

## ▶ Future work

- Implementation of 3-phases, compressible solver

# Acknowledgments



Authors would like to thank:

- ▶ Laboratory Computing Resource Center Argonne National Lab (IL, USA) for providing the computational resources.

Simulations were carried out by the computing resources provided on [BLUES](#), a high-performance computing cluster operated by the Laboratory Computing Resource Center at Argonne National Laboratory (IL, USA).

- Compute – 310 nodes, Each with two Sandy Bridge 2.6 GHz Pentium Xeon (hyper threading disabled.) 4960 available compute cores
- Memory – 64GB of memory
- Storage – 110TB of clusterwide space provided by GPFS (shared with Fusion) 15GB on node Ramdisk
- Network – Infiniband Qlogic QDR





**Thank you for your attention!**

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