Fast Simulation of Liquid Films on a Rotating Disc

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P. Vita, B. Gschaider

... your problems flow to a solution!

Overview

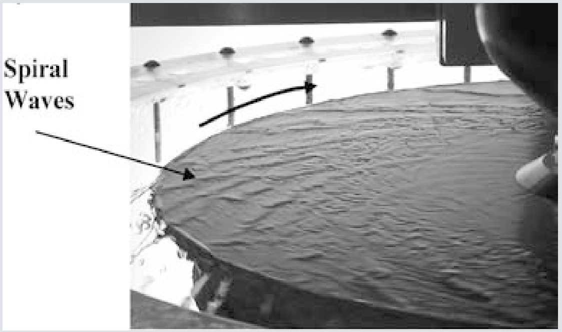
- **Introduction**
  - Problem description
  - Finite Area Method
- **Model development**
  - Thin film model
  - Impinging jet
  - Polydual mesh
- **Results**
  - Comparison with 3D solution
- **Conclusion & Discussion**

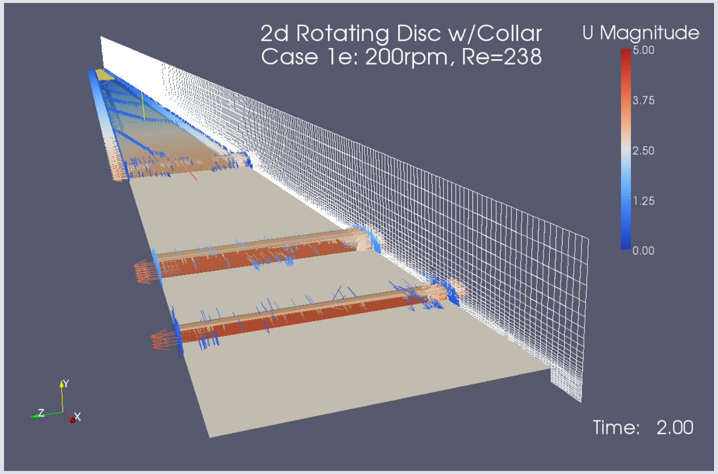
Motivation

- **Our industry partner, LAM Research AG, initiated a project to be able to optimize they product, a spin processor**
  - One-sided single wafer wet processing
  - Patented wafer chuck with floating wafer (N_2 cushion)
  - Vertically arranged process levels
  - Clearly separated chemical lines

Motivation - 2D Simulation

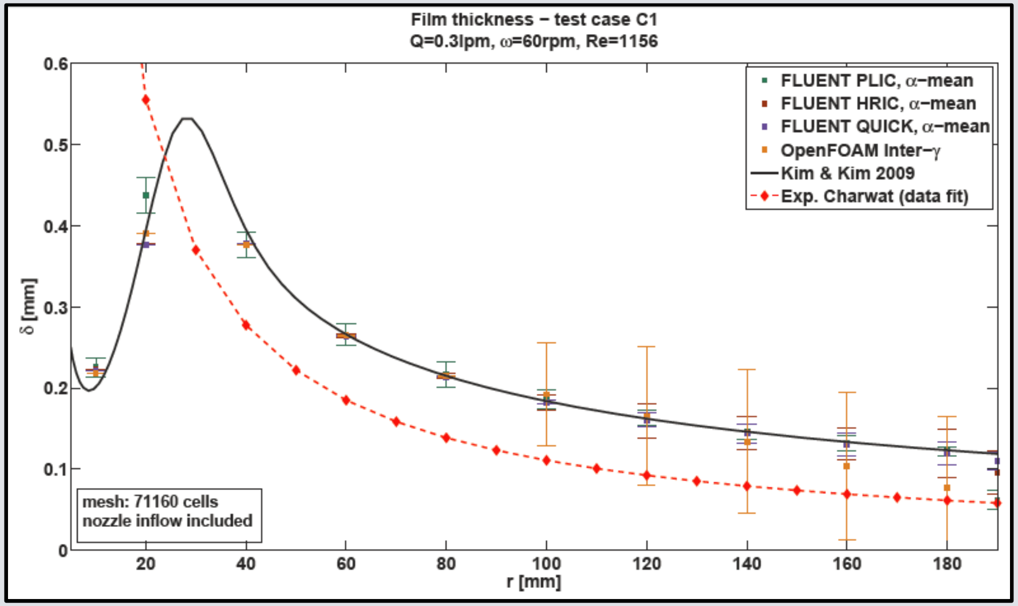
- **2D Simulation (Axial-Symmetric)**
  - Advantages
    - Reasonably small meshes
    - Short computation times in order of hours
    - No additional model assumptions
    - Analytical solutions exists
  - Disadvantages
    - Allows only central impingement
    - Resolve waves only in radial direction





Motivation - 3D Simulation

- **3D Simulation**
  - Advantages
    - Fine resolution only where required
    - No additional model assumptions
  - Disadvantages
    - Huge meshes
      - Still cannot fully resolve all physical aspects
    - Long computation times in order of weeks/months



- **Both 2D and 3D simulations were presented at the 5th OpenFOAM Workshop, Chalmers, Gothenburg**

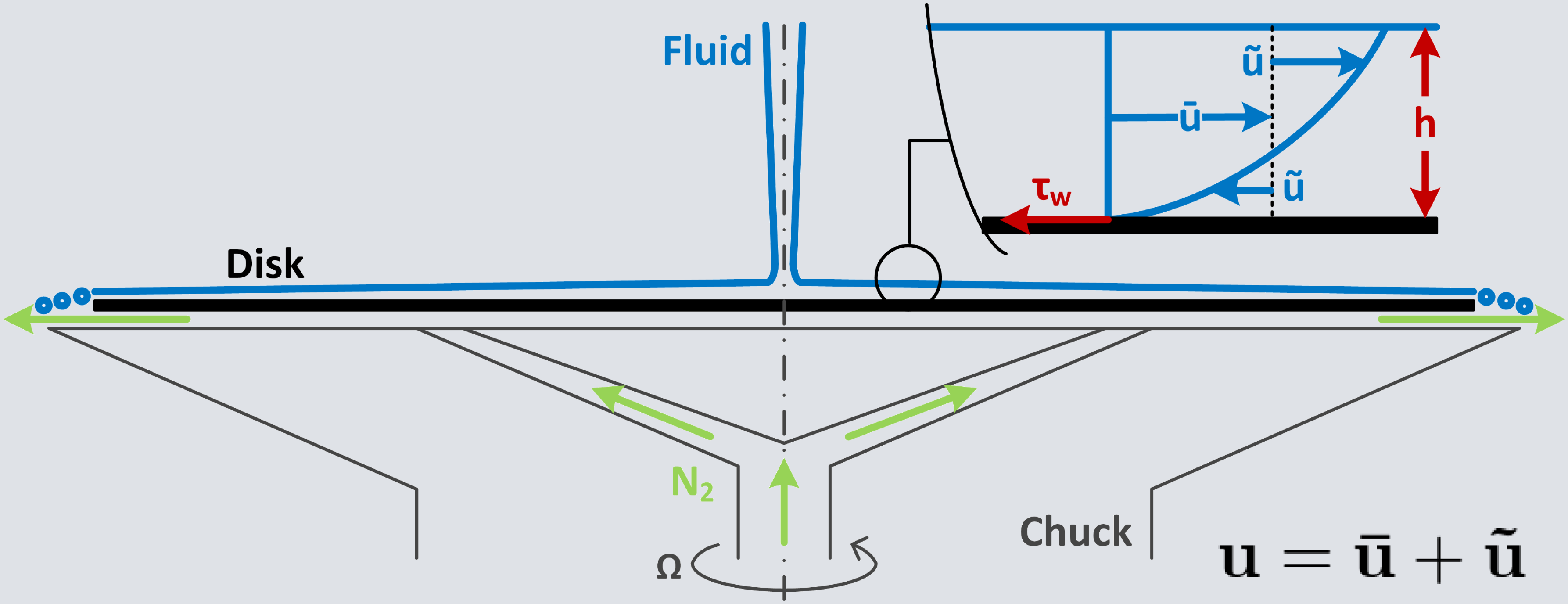
Finite Area Method

- **Specialization of FVM to flows on surfaces-films**
- **Implementation by H. Jasak and Z. Tukovic in OpenFOAM-ext project**
  - Only present in 1.5-dev and 1.6-ext version
- **Demonstration solver models the transport equation on a prescribed velocity field**
  - `surfactantFoam` solver
- **Equations are solved on a boundary patch of the volume mesh**
  - FV-solution can be used as a source term

Thin Film Model - Assumptions

- Normal velocity component is negligible compared to tangential one
- Pressure gradient is constant across the film thickness
- Laminar flow
- Air/liquid shear stress interactions at the film surface are neglected
- Parabolic velocity profile assumed across the film thickness
- Gravity acts against the disk normal direction

Thin Film Model - Rotating Disk Scheme



$$\mathbf{u} = \bar{\mathbf{u}} + \tilde{\mathbf{u}}$$

$$\bar{\mathbf{u}} = \frac{1}{h} \int_h \mathbf{u}\, dz$$

- **Dependent variables**
  - Film thickness *h*
  - Mean velocity $\bar{\mathbf{u}}$

Thin Film Model - Conservation Eqs.

- **Continuity Equation**

$$\frac{\partial h}{\partial t} + \nabla\bullet\left(h\overline{\mathbf{u}}\right) = S_m$$

- **Momentum Equation**

$$\frac{\partial}{\partial t}\left(h\overline{\mathbf{u}}\right) + \nabla\bullet\left(h\overline{\mathbf{u}\mathbf{u}} + \mathbf{C}\right)$$

$$= -\frac{1}{\rho}h\nabla\left(\rho|\mathbf{g}|h + \sigma\nabla\bullet\nabla h\right) - \frac{1}{\rho}\tau_{\text{disk}} + \mathbf{S}_m$$

Thin Film Model - Velocity Profile

- In order to describe the shear stress at the disk and the differential advection, we introduce a polynomial velocity profile function

$$\mathbf{u}(x, y, z) = u(x, y, \xi) + \varepsilon_u$$

$$u(x, y, \xi) = \mathbf{a}_0 + \mathbf{a}_1\xi + \mathbf{a}_2\xi^2 + \mathbf{a}_3\xi^3$$

$$\xi \in \langle 0, 1\rangle, z = h\xi$$

- where ε_u represents modelling error and ξ is a normalised vertical coordinate

Thin Film Model - Velocity Profile Boundary Conds.

- **and fulfils the following boundary conditions**

$$\int_0^1 u(\xi)\, d\xi = \bar{\mathbf{u}}$$

$$u(\xi)|_{\xi=0} = \mathbf{u}_{\text{disk}}$$

$$\left.\frac{\partial u(\xi)}{\partial \xi}\right|_{\xi=1} = 0$$

$$\left.\frac{\partial^2 u(\xi)}{\partial \xi^2}\right|_{\xi=0} = 0$$

Thin Film Model - Diff. Advection and Shear Stress

- The boundary conditions lead to the following differential advection solution

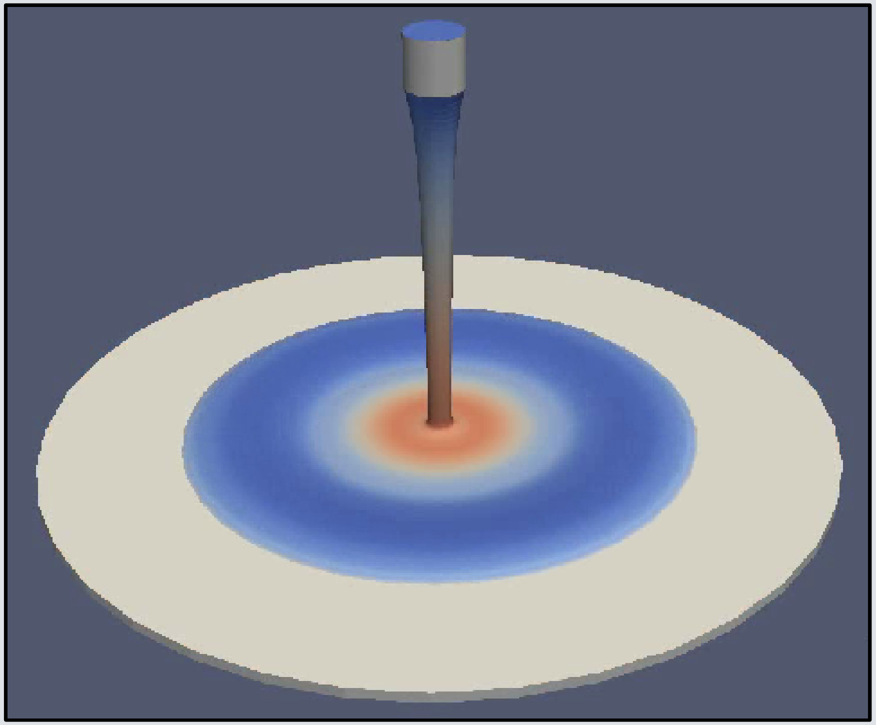
$$\mathbf{C} = \int_h \tilde{\mathbf{u}}\tilde{\mathbf{u}}\, dz = \left[\frac{213}{875} h \left(\overline{\mathbf{u}} - \mathbf{u}_{\text{disk}}\right)\left(\overline{\mathbf{u}} - \mathbf{u}_{\text{disk}}\right)\right]$$

- and the shear stress at the disk

$$\tau_{\text{disk}} = \mu \frac{\partial \mathbf{u}}{\partial z}\bigg|_{z=0} = \frac{\mu}{h}\frac{12}{5}\left(\overline{\mathbf{u}} - \mathbf{u}_{\text{disk}}\right)$$

Impinging Jet

- **Impingement area is generally not know**
  - Impinging jet is moving over the disk
- **Thin film model is not valid in the impingement area and its surrounding**
  - However solution in the impingement area is known from FVM
  - Impingement area is “weakly” influenced from “outside”



Impinging Jet - Solution

- **Remeshing**
  - – Impingement area is represented by a circular boundary condition which moves through the mesh
    - Mesh has to adapted
    - Very computational expensive
- **Fixation of solution in faces**
  - – Faces in the impingement area are selected and solution is prescribed
    - Solution is known from FV-solution
  - – Assumption of the “weak” influence from “outside”
  - – No need of remeshing

Impinging Jet

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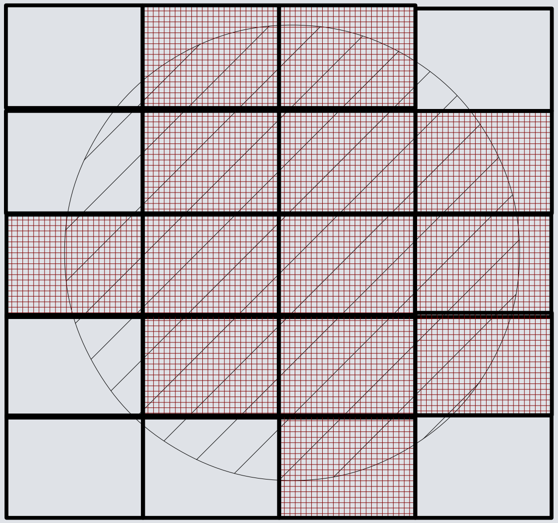
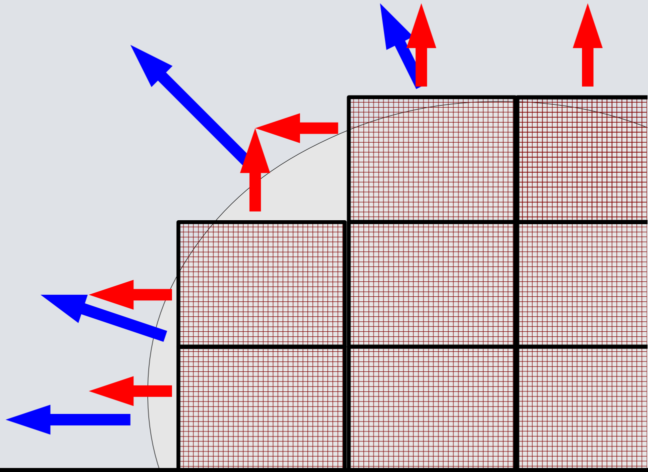
- **Fixation of solution in the faces has significant advantages over remeshing, however it has its own problems**
  - "Crown Cap" effect
    - Faces in the impingement area are not resolving exact circle
    - Face boundaries are not aligned with a circle
  - Total mass-flow correction
  - Inlet velocity profiles
    - Velocities varies along the jet edge



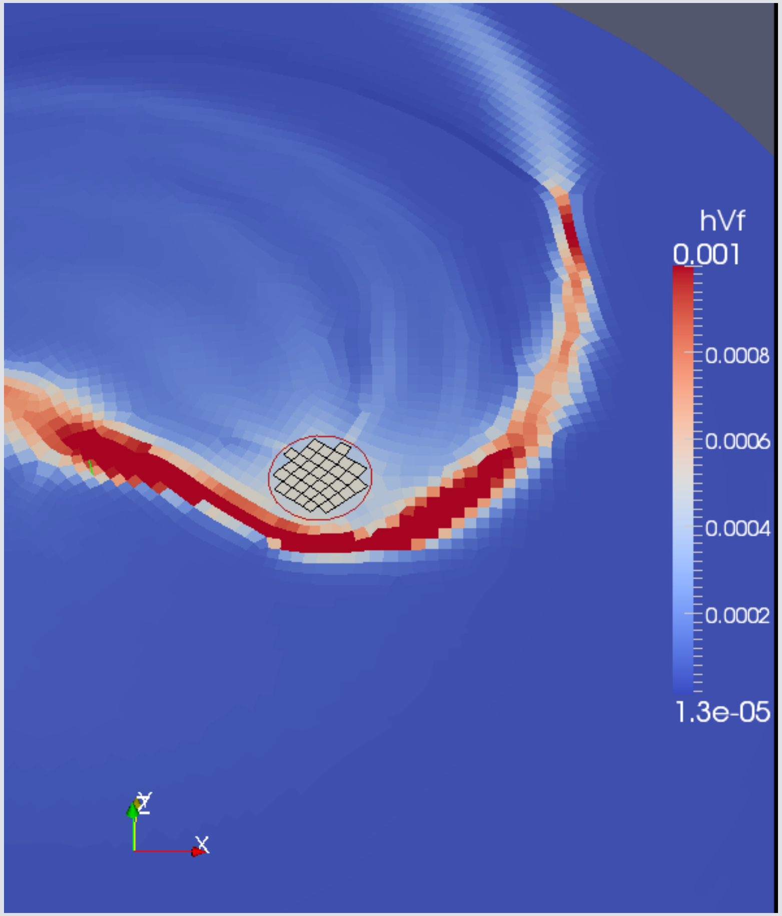


Impinging Jet

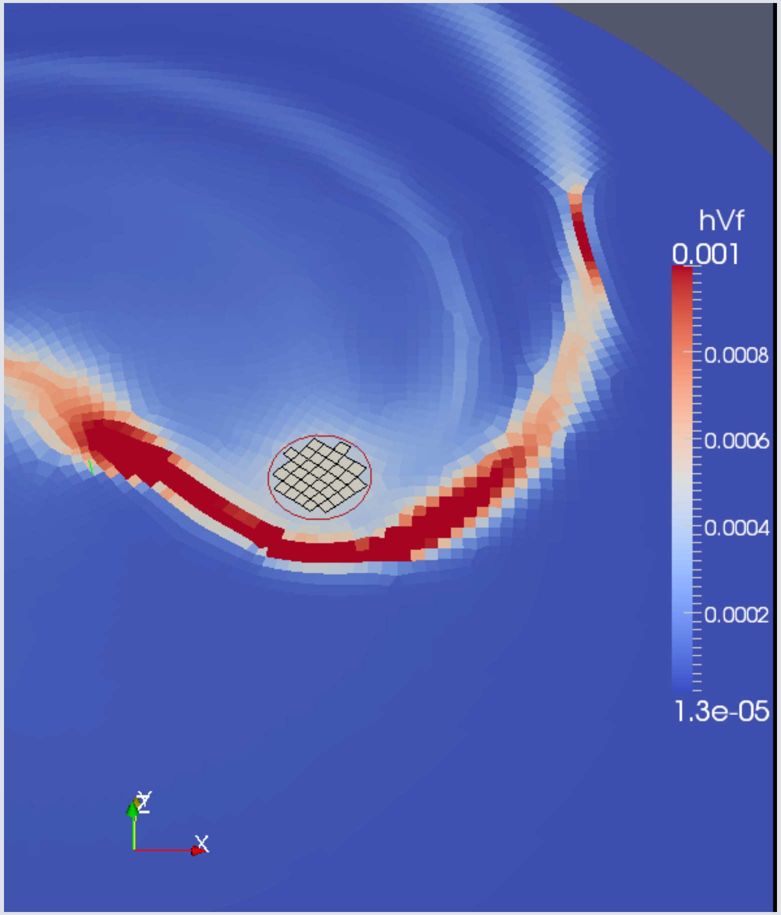
- **Solution to “Crown Cap” effect**
  - Velocity in the outer faces of the fixed area is not only determined by the location of the face centre, but also by the orientation of the edges that separate them from the free region
    - “How much fluid does the next outside face receive?”
- **Solution to total mass-flow correction**
  - Total mass-flow across edges is calculated and the velocities in the faces are normalized accordingly
- **Solution to inlet velocity profiles**
  - Simple models implemented, real data can be read-in

Impinging Jet - “Crown-Cap” Effect

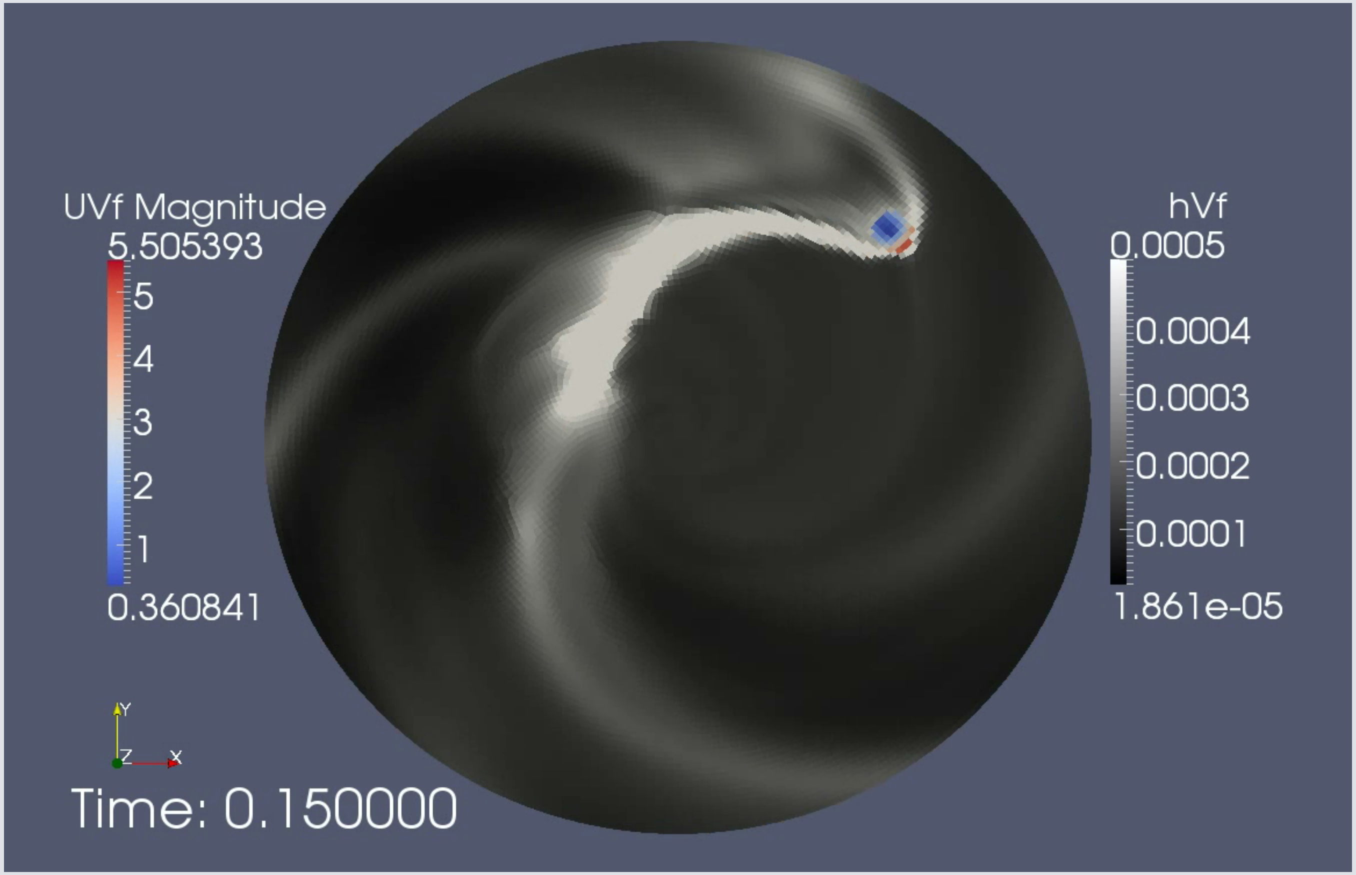
Uncorrected Flow



Corrected Flow

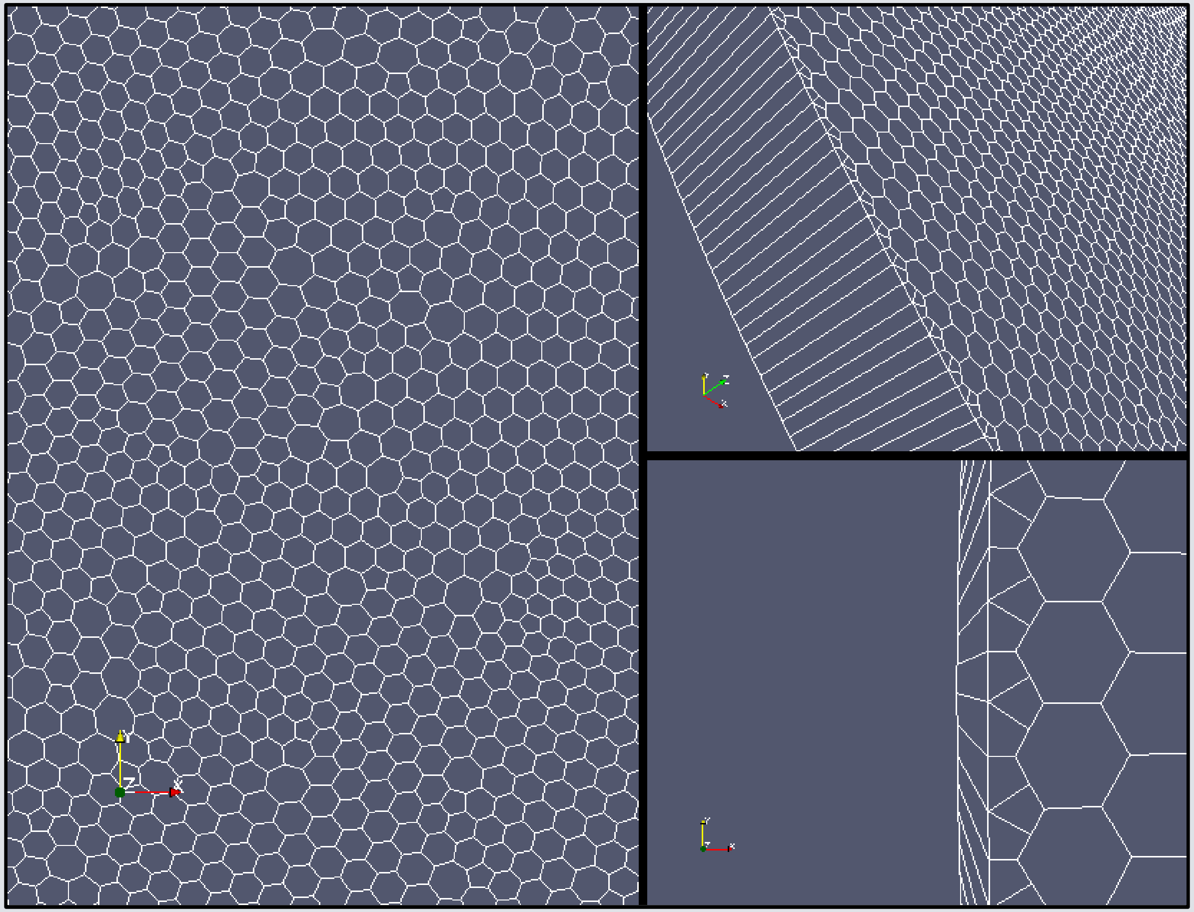


Impinging Jet - Inlet Velocity Profile



Polydual Mesh

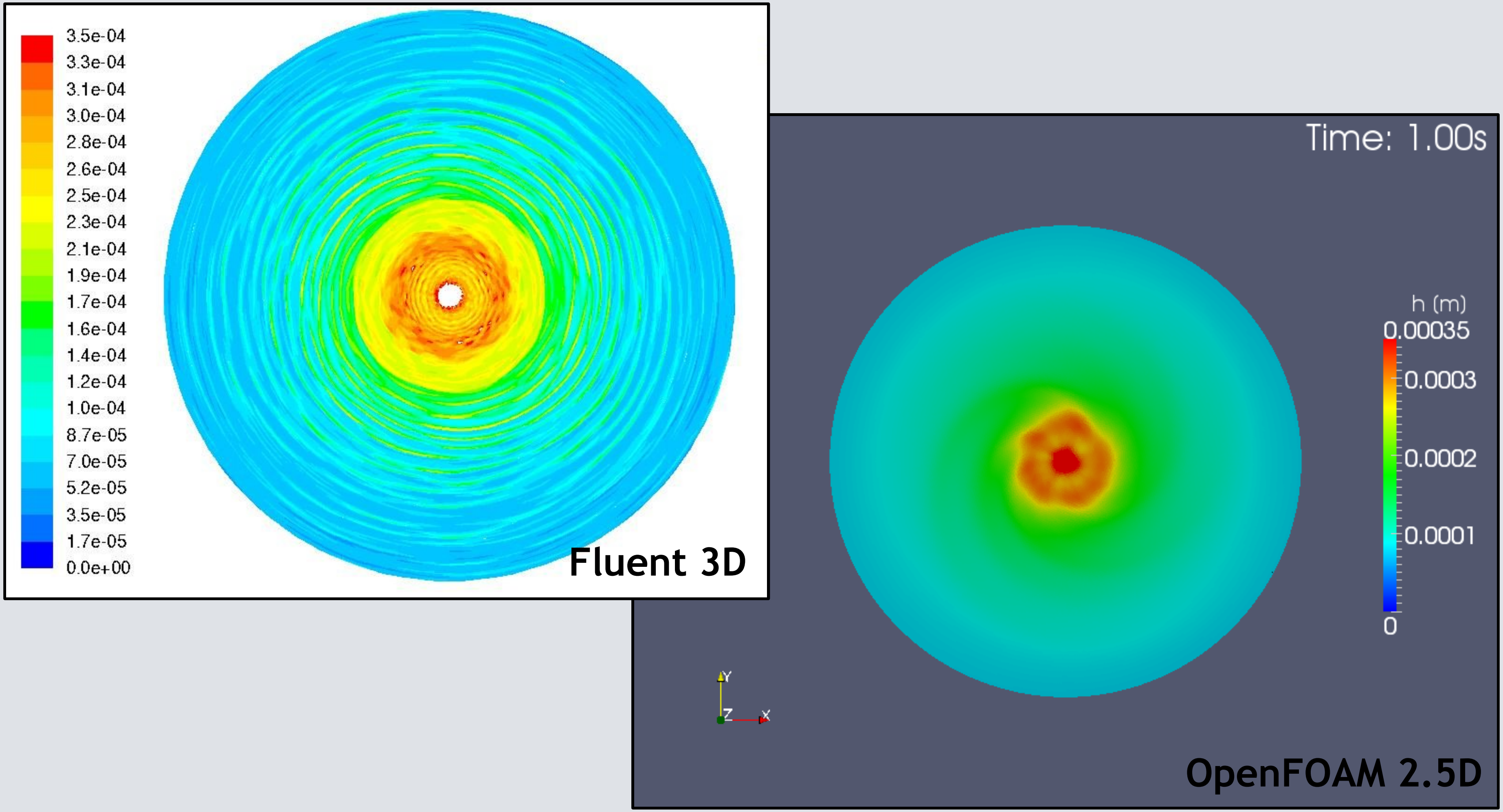
- **Solution is very mesh sensitive**
  - Mesh neutral to flow is needed to avoid artefacts
    - “flow arms”
    - “rose petals”
  - Polyhedral mesh shown the best results
    - `polyDualMesh` utility used to convert a tetrahedral mesh into the polyhedral one



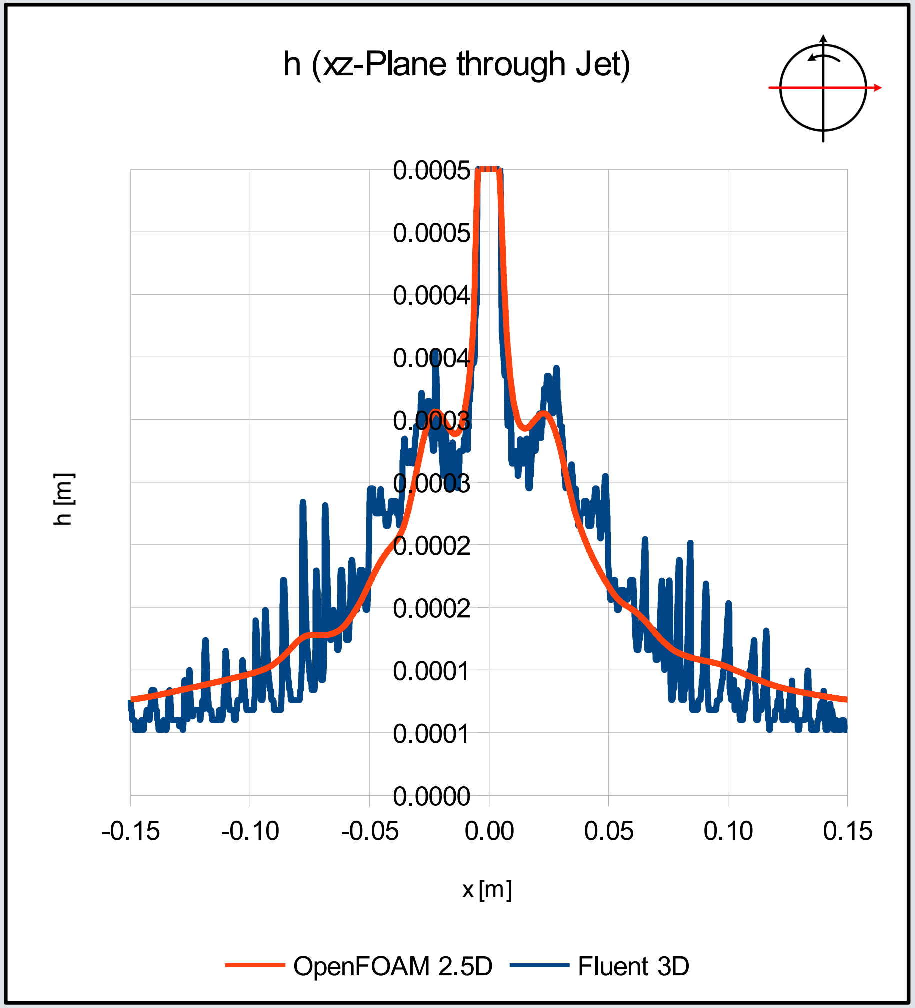
Comparison with 3D Solution

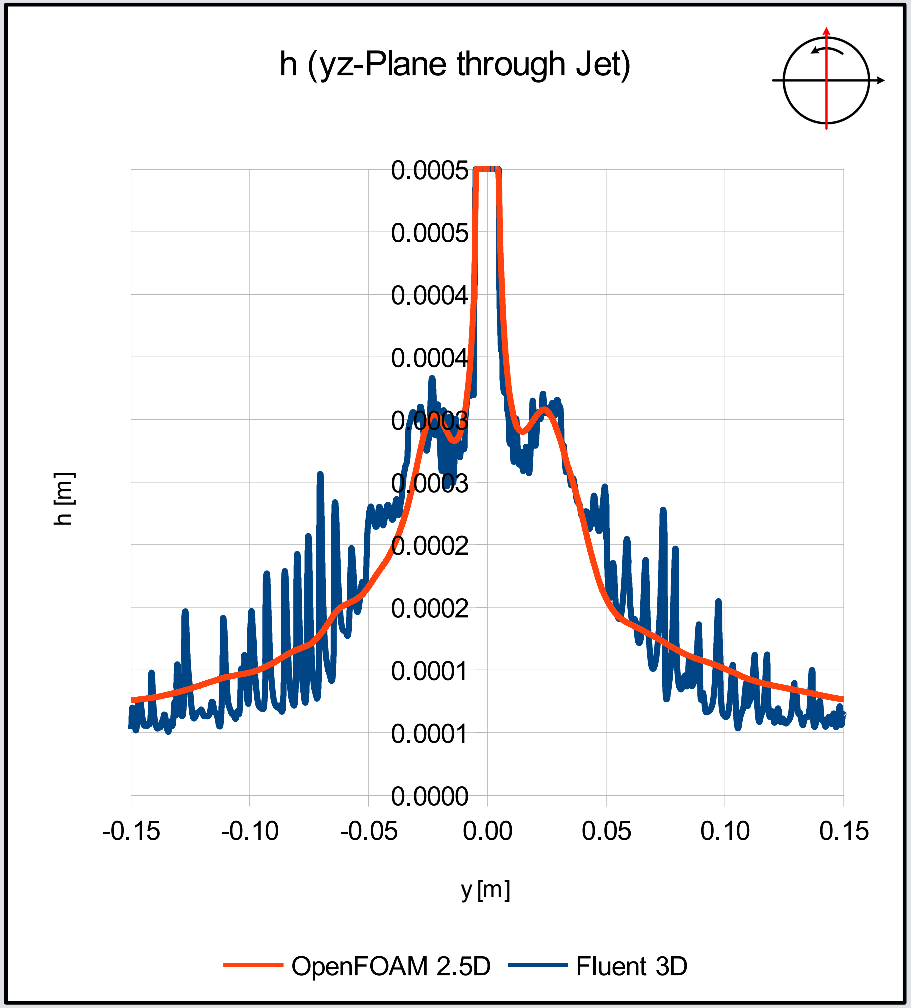
- **3D solution**
  - courtesy of TU Graz
  - Fluent software
  - 5M cells, 4 CPU cores used
  - **1s of process ~ 30days**
- **2.5D solution**
  - OpenFOAM software
  - 36.8k polydual mesh, single CPU core used
  - **1s of process ~ 2hours**
- **Cases**
  - $\Omega = 500$rpm, Q = 1.5l, Spinetch-D ($\nu = 2.87\times10^{-6}$)
  - Impingement area
    - Reference Case (central impingement)
    - Case 1a (ex-centric case, $\Delta r = 30$mm)
  - **No moving inlet due to 3D solution limitation**

Reference Case - 500rpm, 1.5lpm, Spinetch-D



Reference Case - 500rpm, 1.5lpm, Spinetch-D





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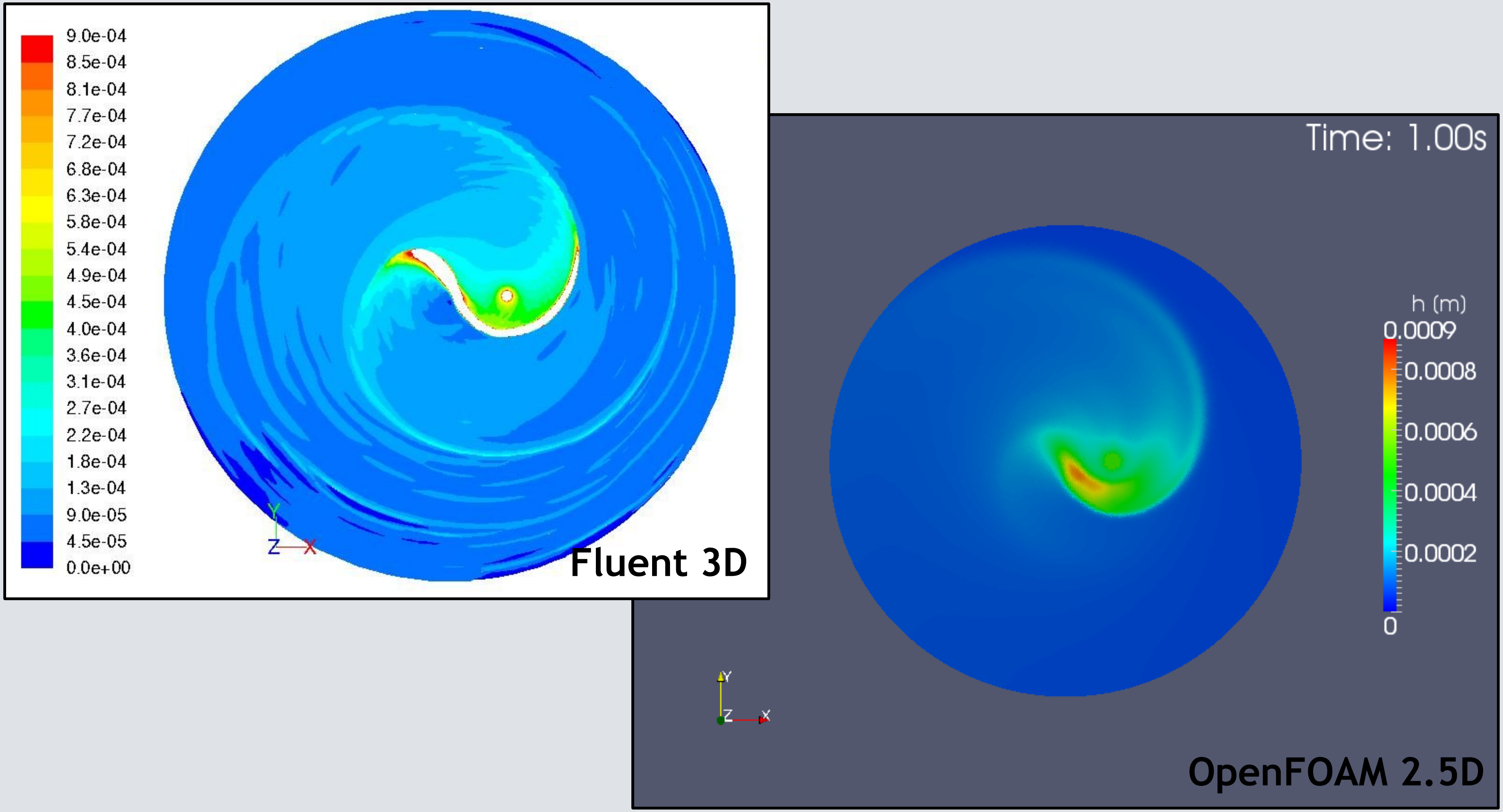
Case 1a - 500rpm, 1.5lpm, Δr=30mm, Spinetch-D



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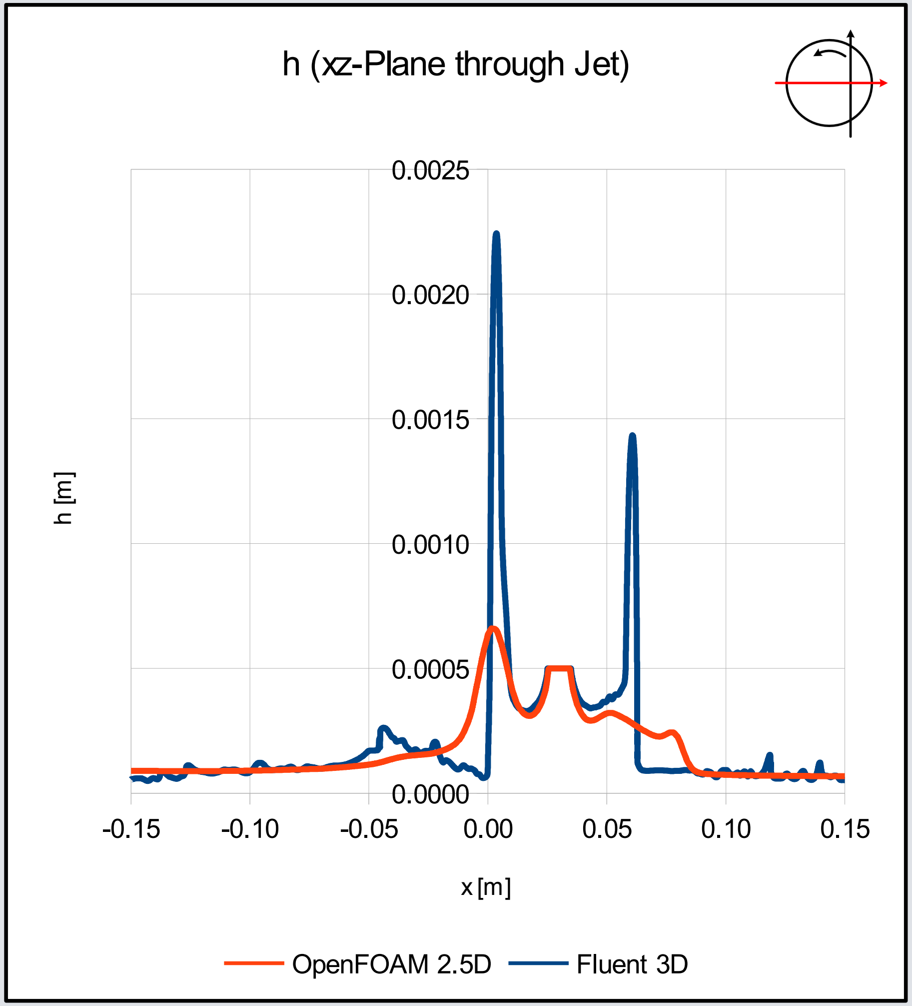
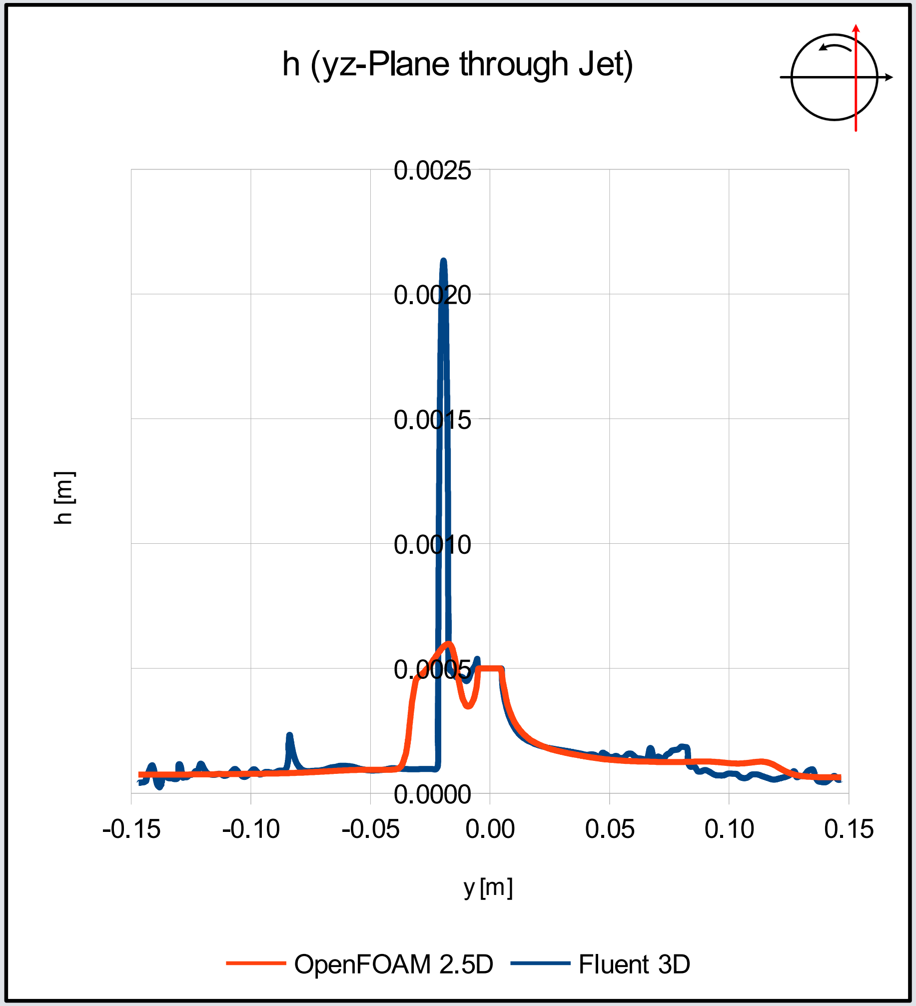
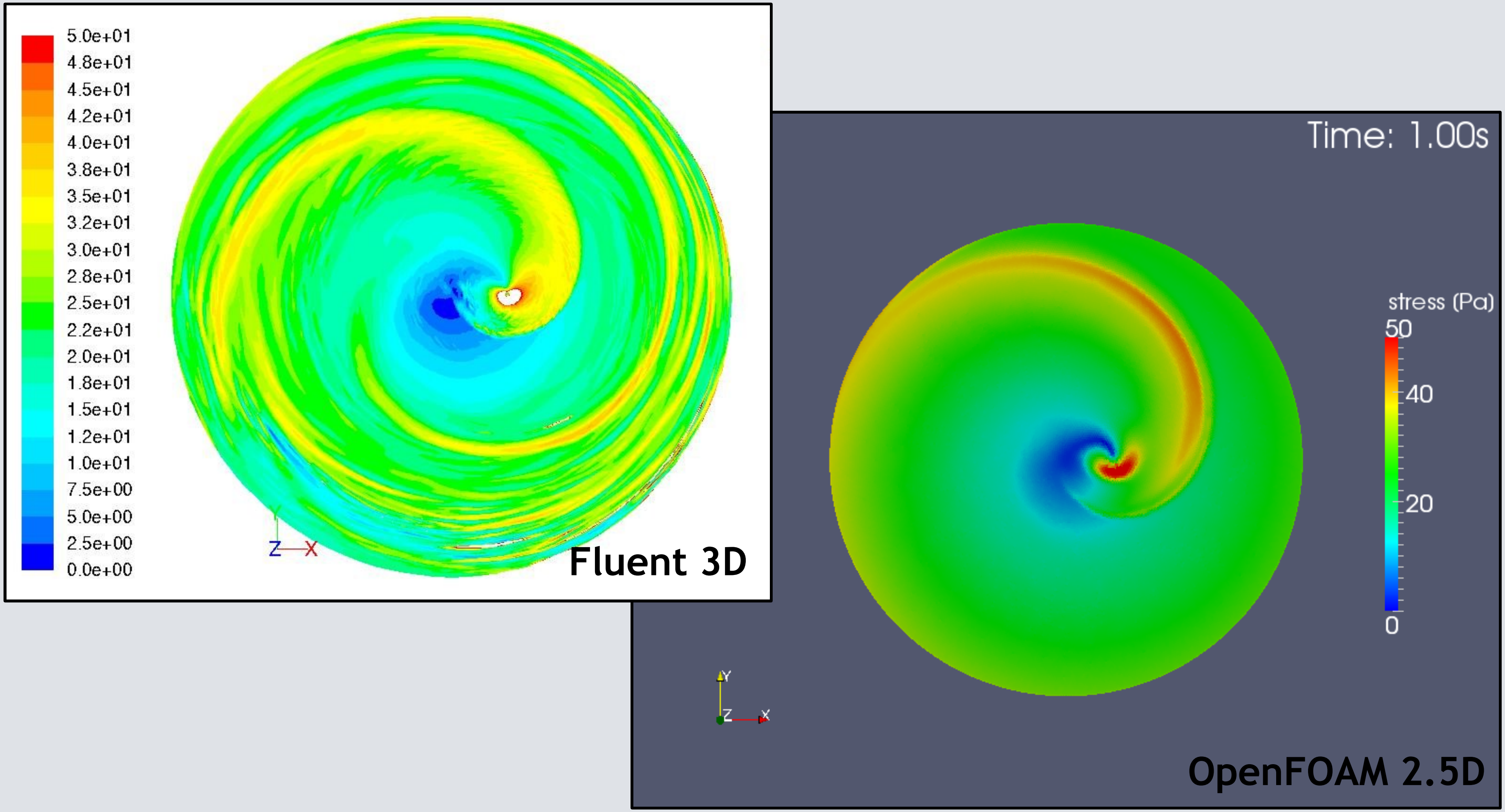




Case 1a - 500rpm, 1.5lpm, Δr=30mm, Spinetch-D



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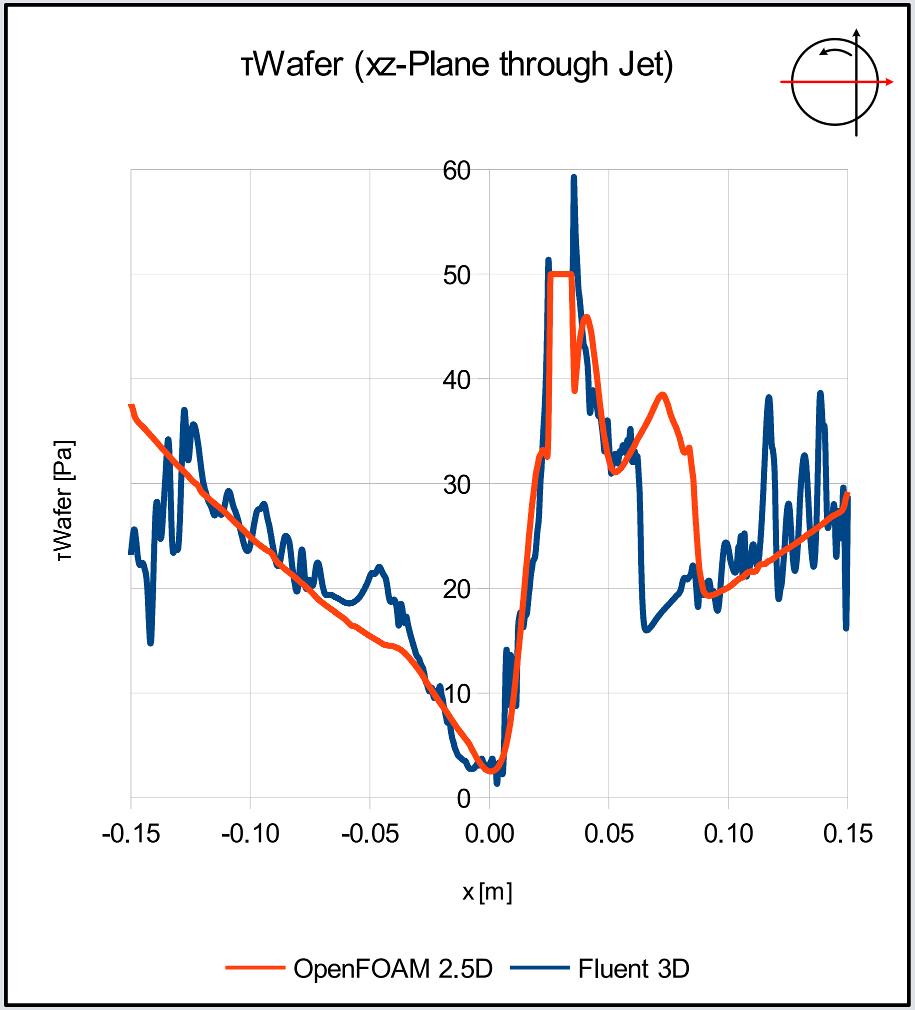
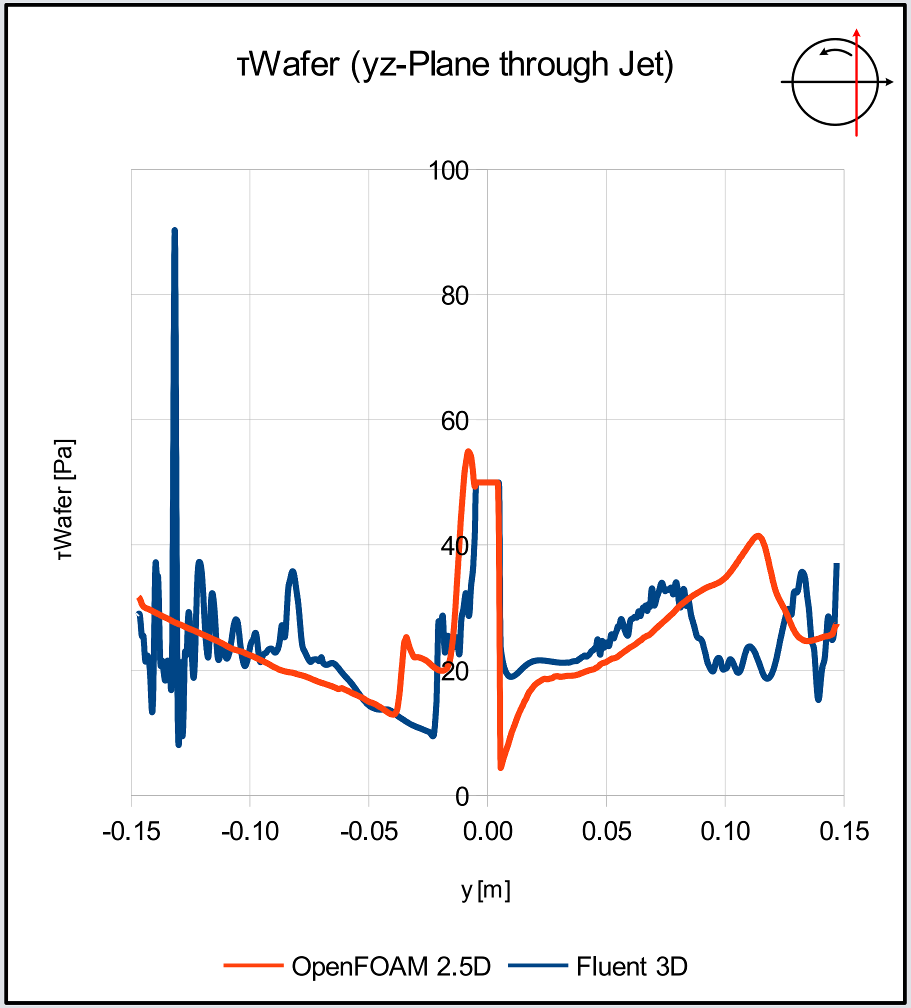

τWafer (xz-Plane through Jet)


τWafer (yz-Plane through Jet)

Conclusion

- **2.5D solution shows a good agreement with 3D solution, while significantly saving on resources**
  - Solution in an impingement area has to be prescribed
  - Zone close to jet, influenced by the impingement, is showing a reasonable agreement and is still able to capture important effects
    - We never promised to be exact here!
  - Zone outside of the impingement influence is showing a very good agreement
  - Smooth solution without waviness
  - Small meshes and significantly shorter simulation times

Discussion

- **Thank you for your attention!**
- **Questions?**