Thin Film Simulation on a Rotating Wafer

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... your problems flow to a solution!

Topics

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- Motivation
- Finite Area Method
- Thin Film Model
- Impinging Jet
- Polydual Mesh
- Comparison with 3D Solution
- Conclusion
- Outlook & Discussion

Motivation (1)

- **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 (2)

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

Finite Area Method

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- **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 (1)

- Normal velocity component is negligible compared to tangential one
- Pressure is constant across the film thickness
- Laminar flow
- Film thickness is identical with a velocity boundary layer
- Parabolic velocity profile assumed across the film thickness

Thin Film Model (2)

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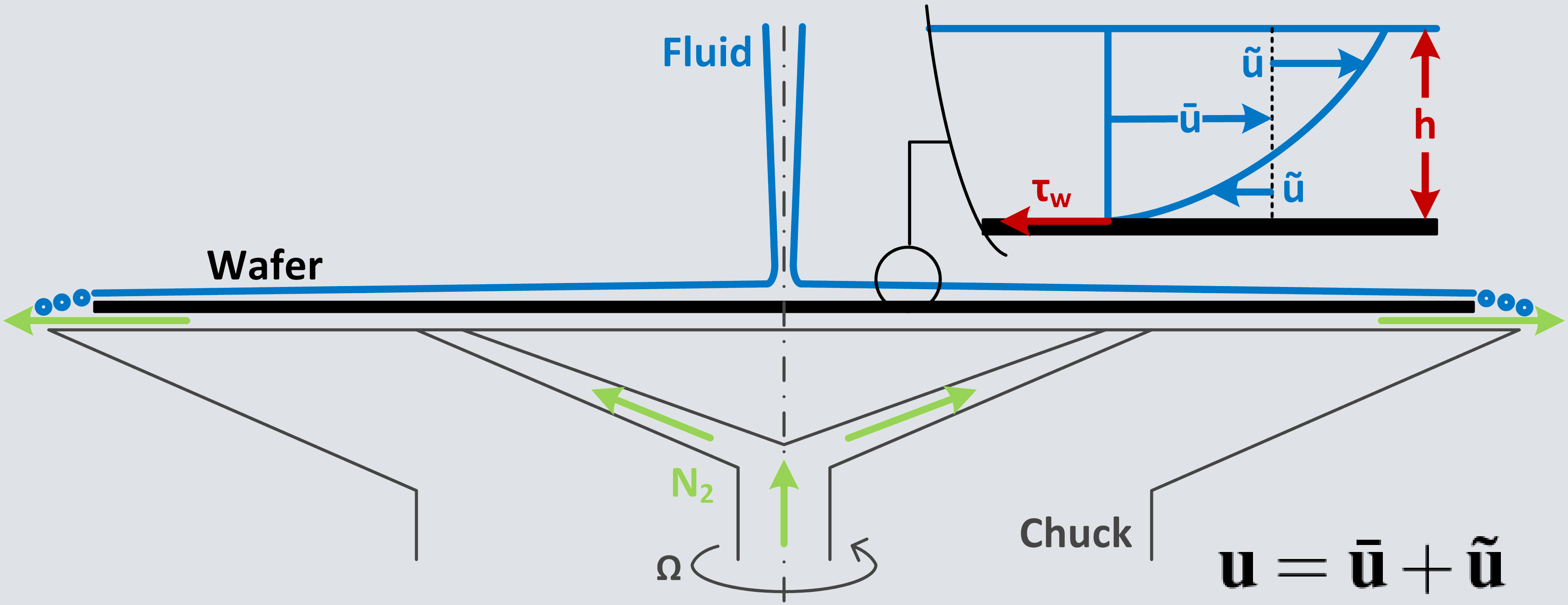

$$\mathbf{u} = \bar{\mathbf{u}} + \tilde{\mathbf{u}}$$

$$\bar{\mathbf{u}} = \frac{1}{h} \int_h \mathbf{u} \, dx_3$$

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

Thin Film Model (3)

- **Continuity Equation**

$$\frac{\partial}{\partial t}h + \nabla\left(h\bar{\mathbf{u}}\right) = 0$$

- **Momentum Equation**

$$\frac{\partial}{\partial t}\left(h\bar{\mathbf{u}}\right) + \nabla\left(h\bar{\mathbf{u}}\bar{\mathbf{u}}\right) + \nabla\left(\int_h \tilde{\mathbf{u}}\tilde{\mathbf{u}}\, dx_3\right)$$

$$= -\frac{1}{\rho}h\nabla p + \frac{1}{\rho}\left(-\tau_{\mathrm{wafer}}\right)$$

Thin Film Model (4)

- where the pressure is expressed by

$$p = \rho |\mathbf{g}| h - \sigma \kappa$$

- with a surface curvature approximated by

$$\kappa \approx \nabla^2 h$$

- and shear stress at wafer is described by

$$\tau_{\mathrm{wafer}} = \mu \frac{\partial}{\partial x_3} \mathbf{u} \Big|_{x_3=0}$$

Thin Film Model (5)

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

$$u(\xi) = \mathbf{a_0} + \mathbf{a_1}\xi + \mathbf{a_2}\xi^2 + \mathbf{a_3}\xi^3$$

$$\xi \in \langle 0, 1 \rangle, x_3 = h\xi$$

- which defines the free surface velocity

$$\mathbf{u}_{\mathrm{fs}} = u(\xi)|_{\xi=1}$$

Thin Film Model (6)

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- **and fulfils following boundary conditions**

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

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

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

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

Thin Film Model (7)

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- **The boundary conditions imposed on the velocity profile function lead to the following solutions**

$$\nabla\left(\int_h \tilde{\mathbf{u}}\tilde{\mathbf{u}}\,dx_3\right) = \nabla\left[\int_0^1 \left(u(\xi)-\bar{\mathbf{u}}\right)\left(u(\xi)-\bar{\mathbf{u}}\right)h\,d\xi\right]$$

$$= \nabla\left[\frac{213}{875}h\left(\bar{\mathbf{u}}-\mathbf{u}_{\mathrm{wafer}}\right)\left(\bar{\mathbf{u}}-\mathbf{u}_{\mathrm{wafer}}\right)\right]$$

$$\tau_{\mathrm{wafer}} = \mu\frac{\partial}{\partial(h\xi)}u(\xi)\Big|_{\xi=0}$$

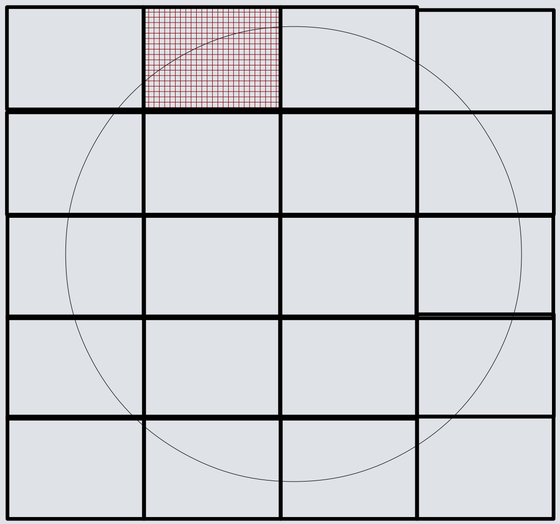
$$= \mu\frac{1}{h}\frac{12}{5}\left(\bar{\mathbf{u}}-\mathbf{u}_{\mathrm{wafer}}\right)$$

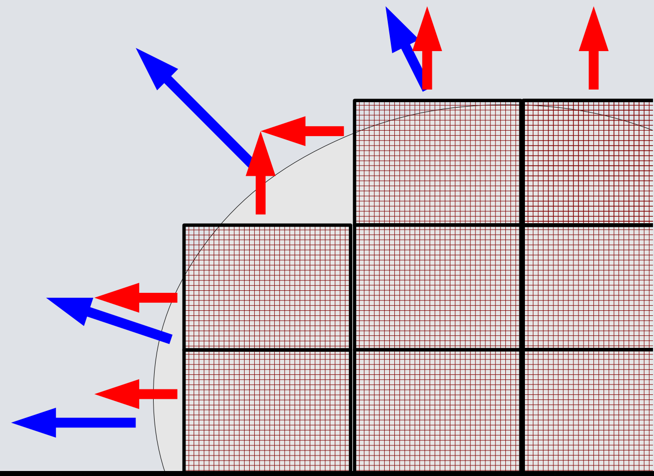
Impinging Jet (1)

- **Impingement area is generally not know**
  - Impinging jet is moving over the wafer
- **Thin film model is not valid in the impingement area and its surrounding**
  - Solution in the impingement area is known from FVM
  - Impingement area is “weakly” influenced from “outside”
- **Possible impingement implementations**
  - Remeshing
    - Impingement area is represented by a circular boundary condition which moves and the mesh is adapted
  - Fixation of solution in faces
    - Impingement faces are selected and solution is prescribed

Impinging Jet (2)

- **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 (3)

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- **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

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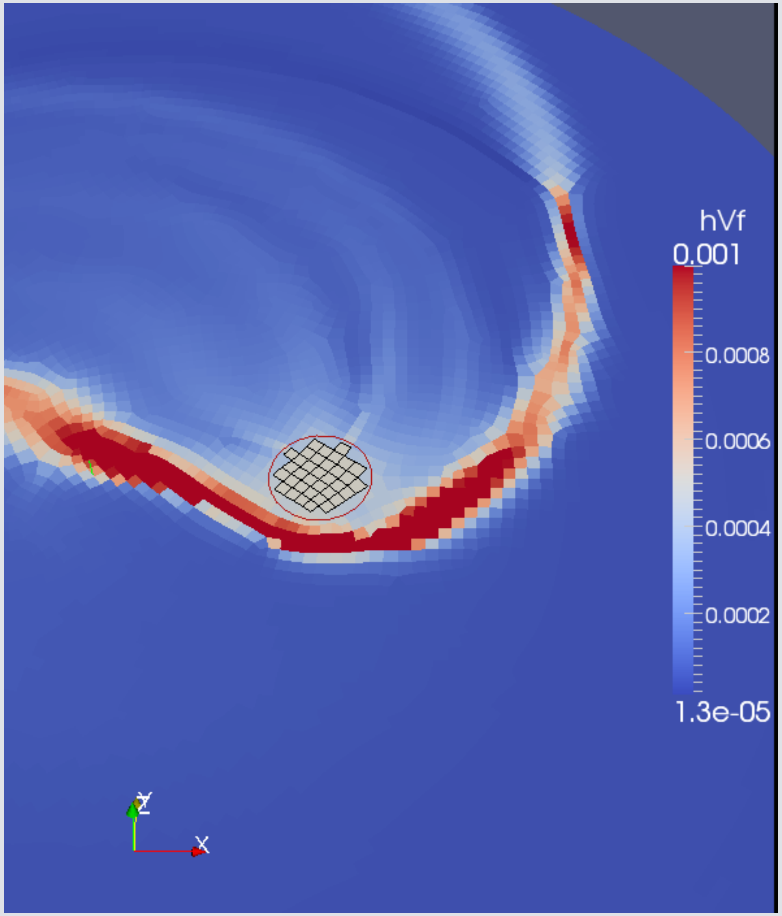
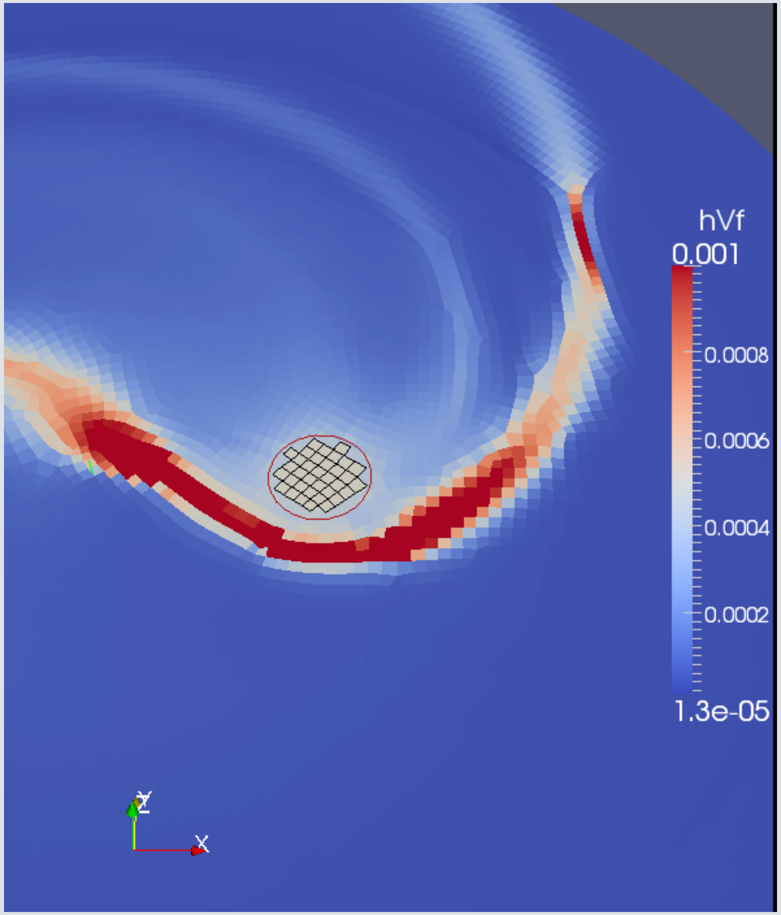
Uncorrected Flow



Corrected Flow



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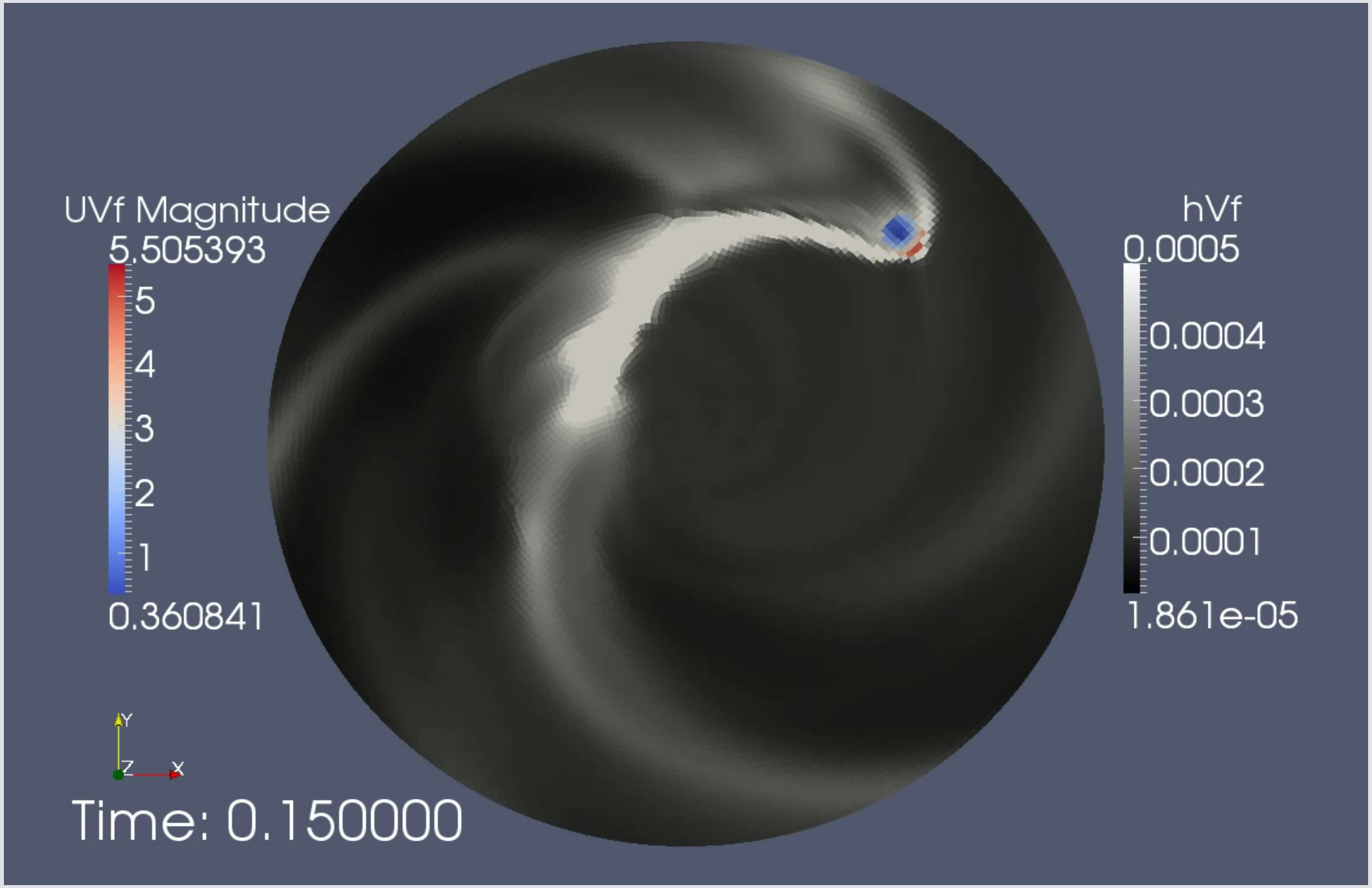
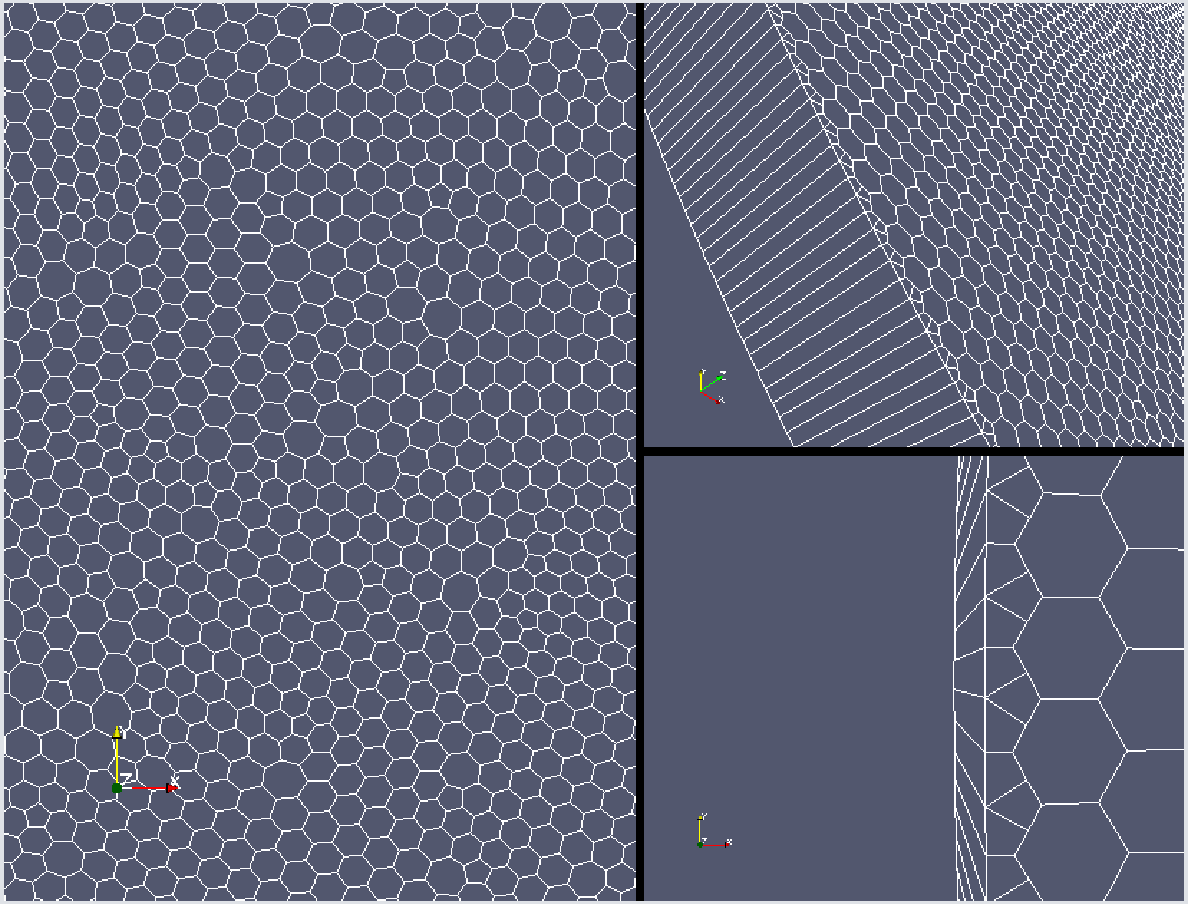
Impinging Jet: Inlet Velocity Profile



Polydual Mesh

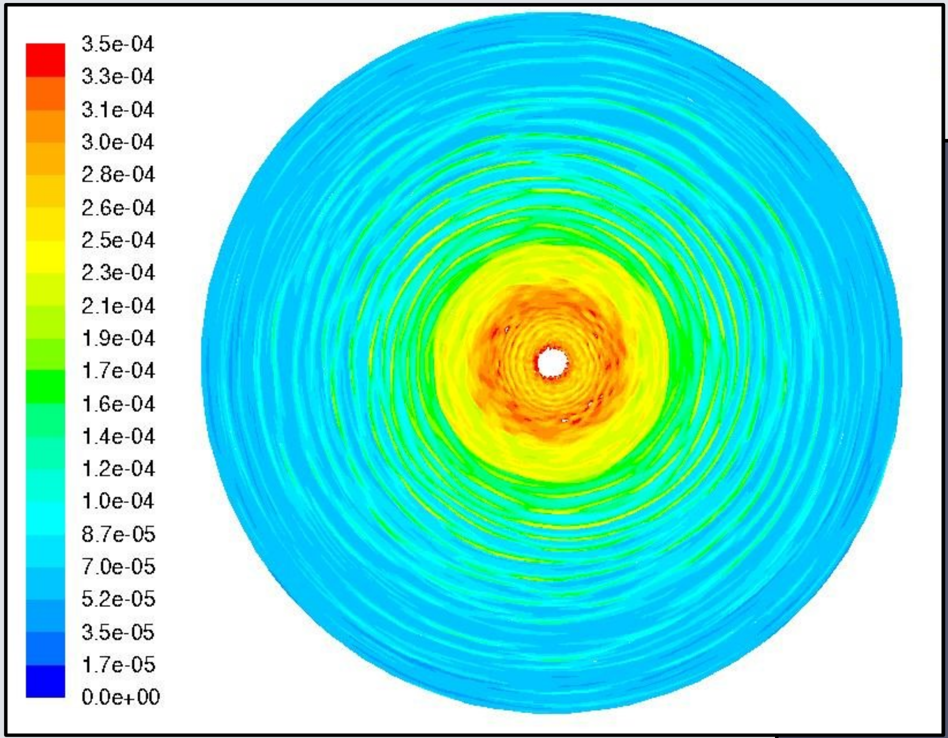
- **Solution is very mesh sensitive**
  - Mesh neutral to flow is needed to avoid artefacts
    - “flow arms”
    - “rose petals”
  - Polyhedral mesh shown the best results
    - **`polyDualMesh`** utility used to convert a tetrahedral mesh into the polyhedral one

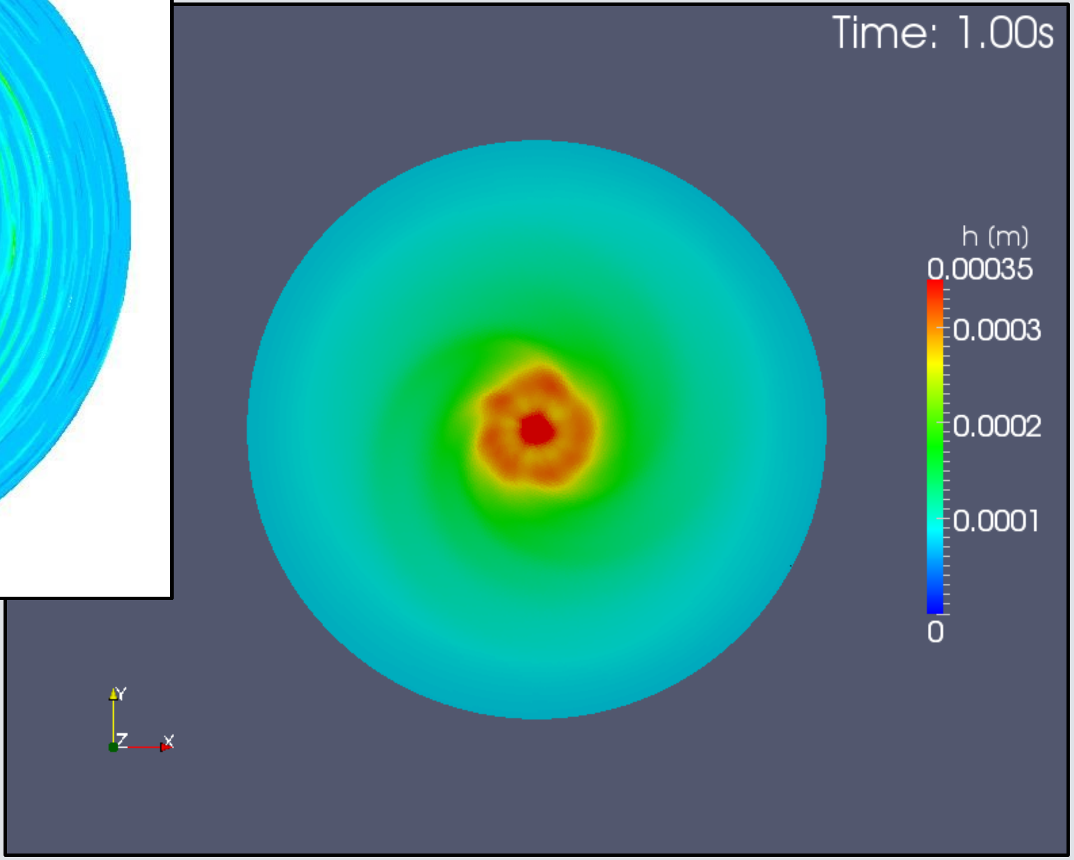


Comparison with 3D Solution

- **3D solution**
  - 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**
  - Ω = 500rpm, Q = 1.5l
  - Spinetch-D ($\nu = 2.87\times10^{-6}$) or water ($\nu = 1\times10^{-6}$)
  - Impingement area
    - Reference Case (central impingement; Spinetch-D)
    - Case 1a (ex-centric case, Δr = 30mm; Spinetch-D)
    - Case 2b (ex-centric case with dry spot, Δr = 50mm; water)
  - No moving inlet was simulated

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





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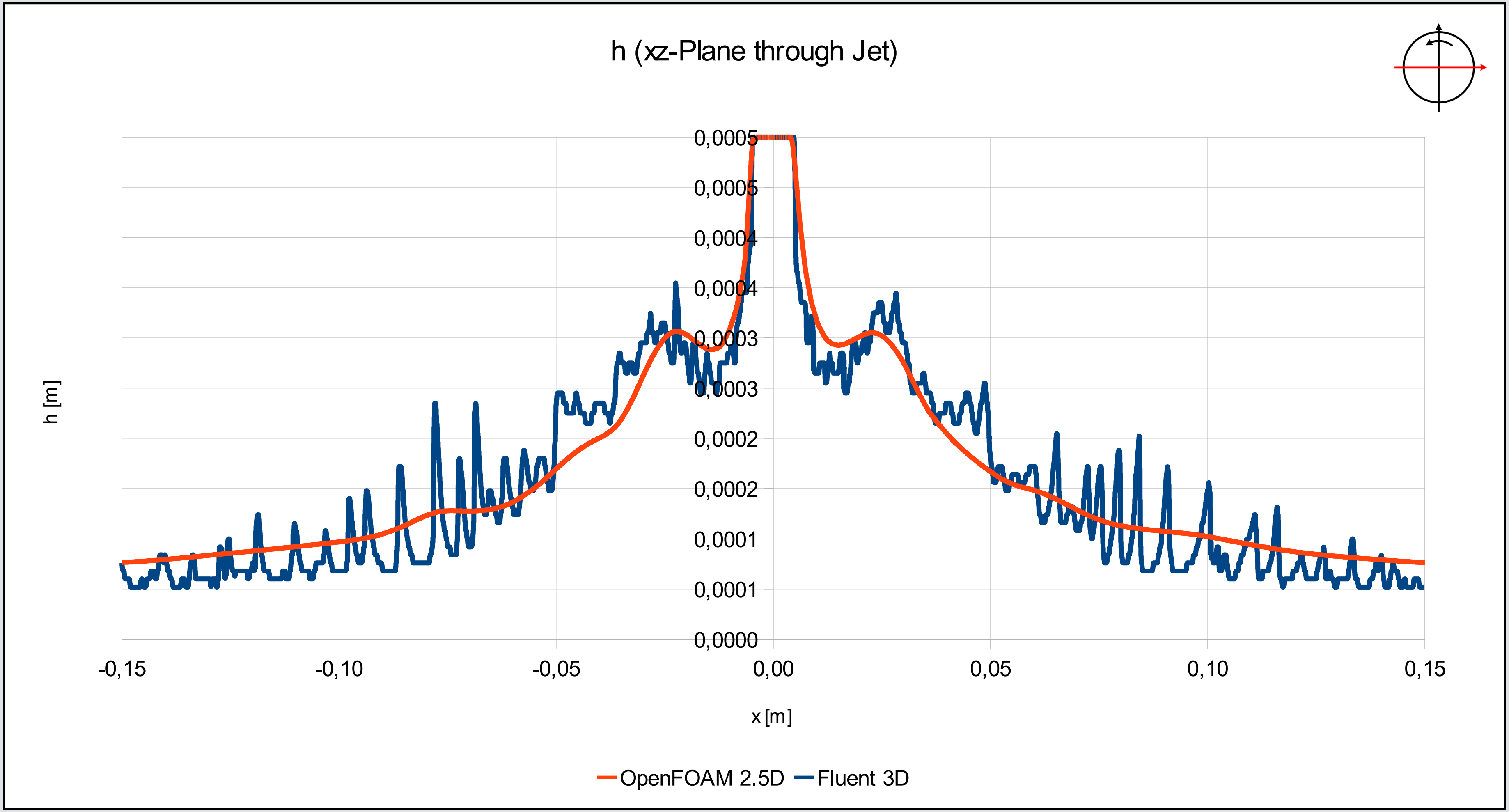

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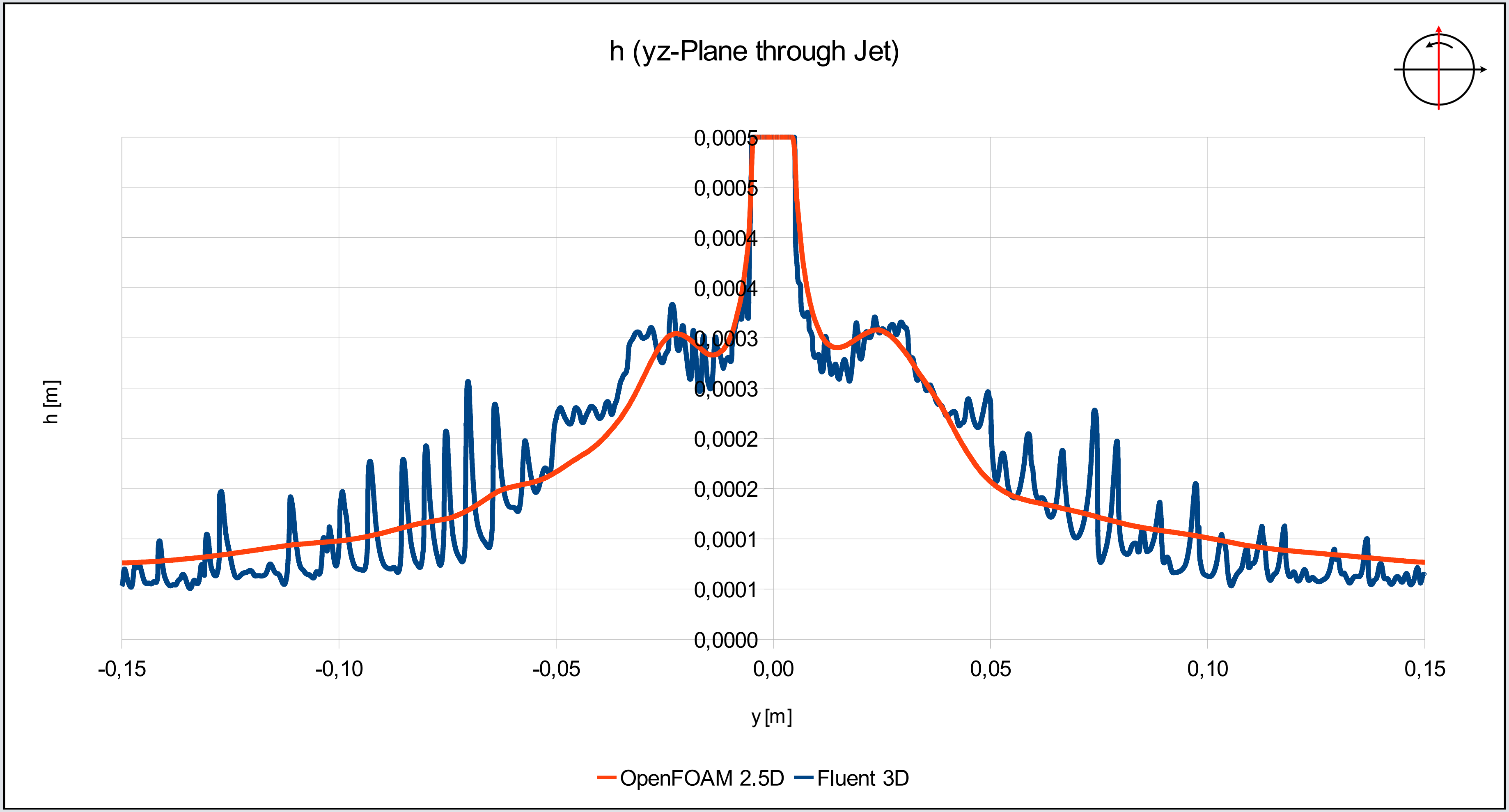

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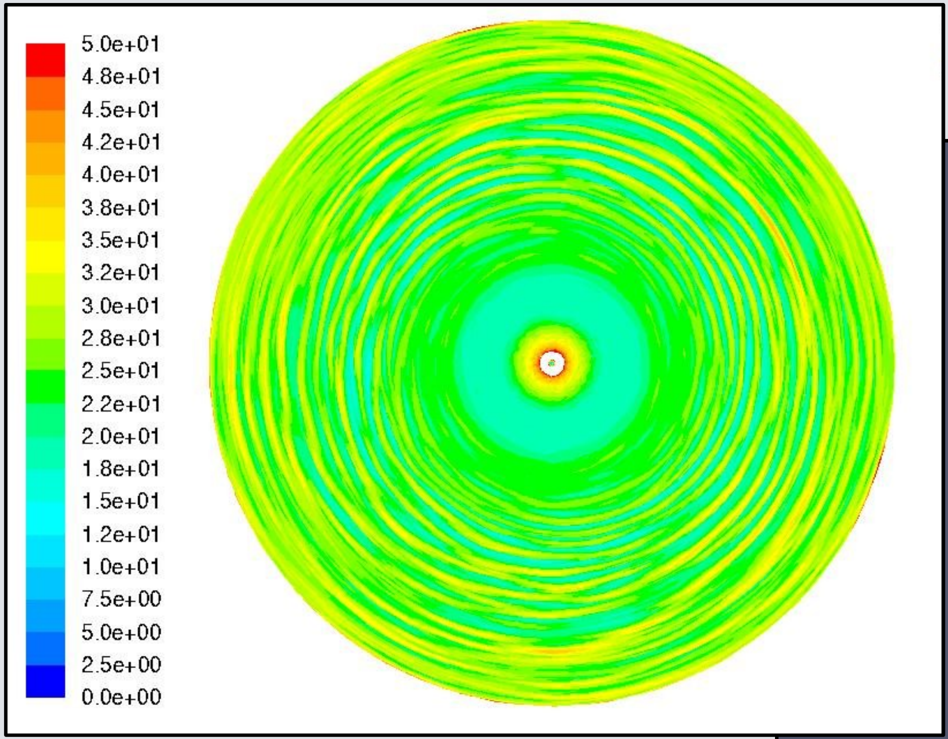

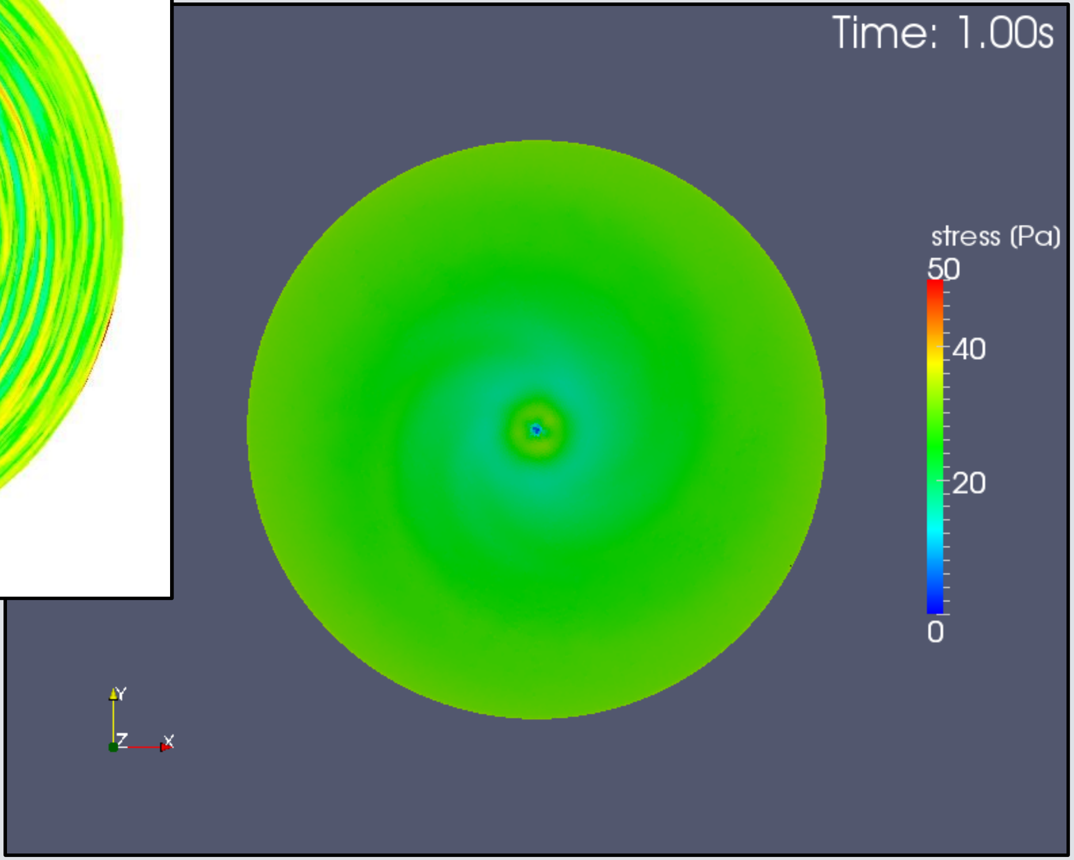

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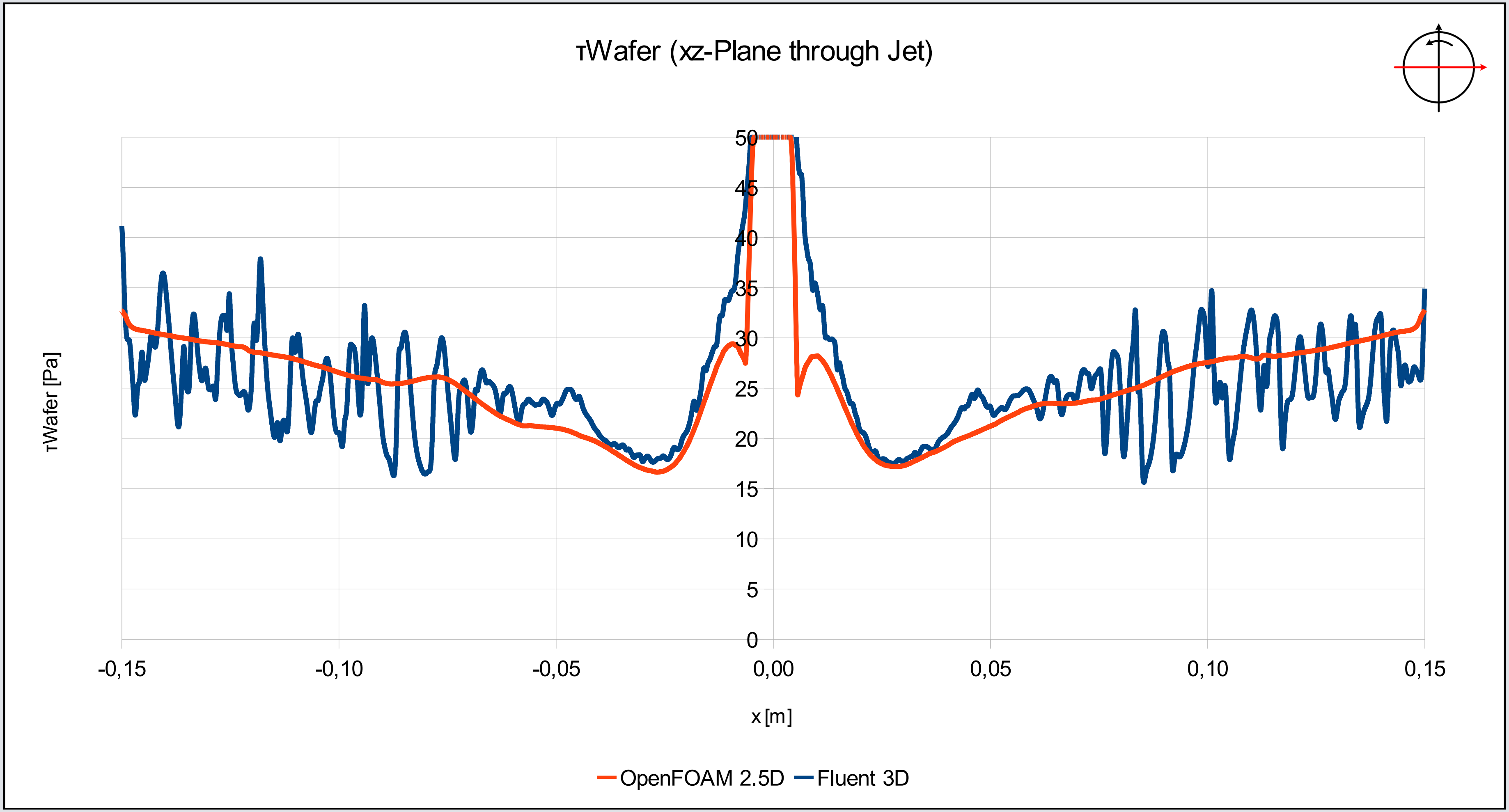

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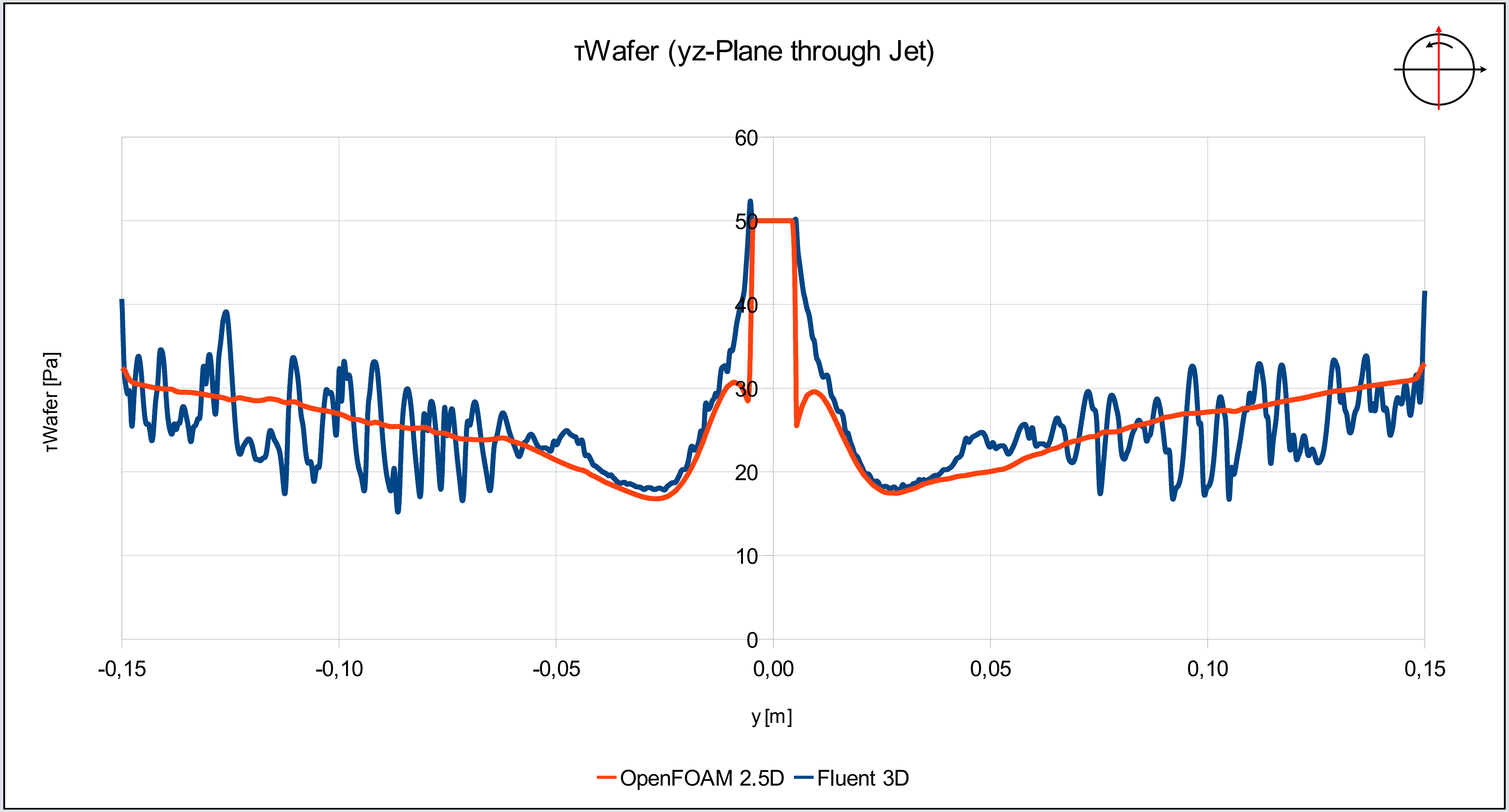

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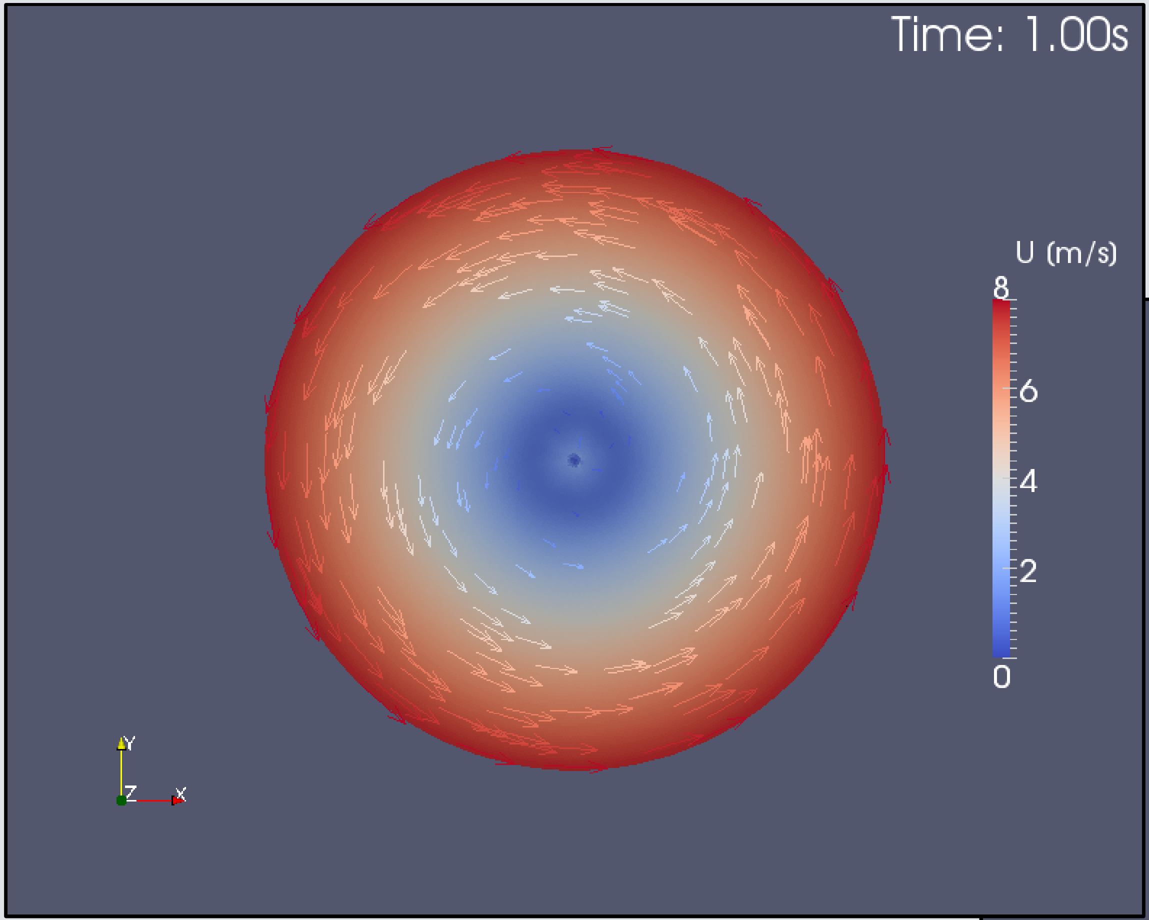
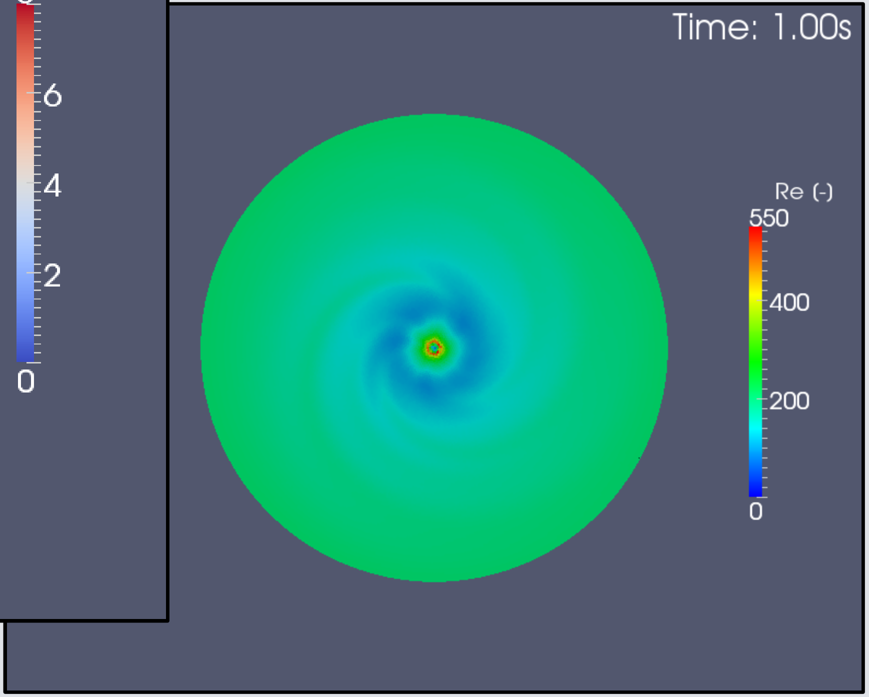
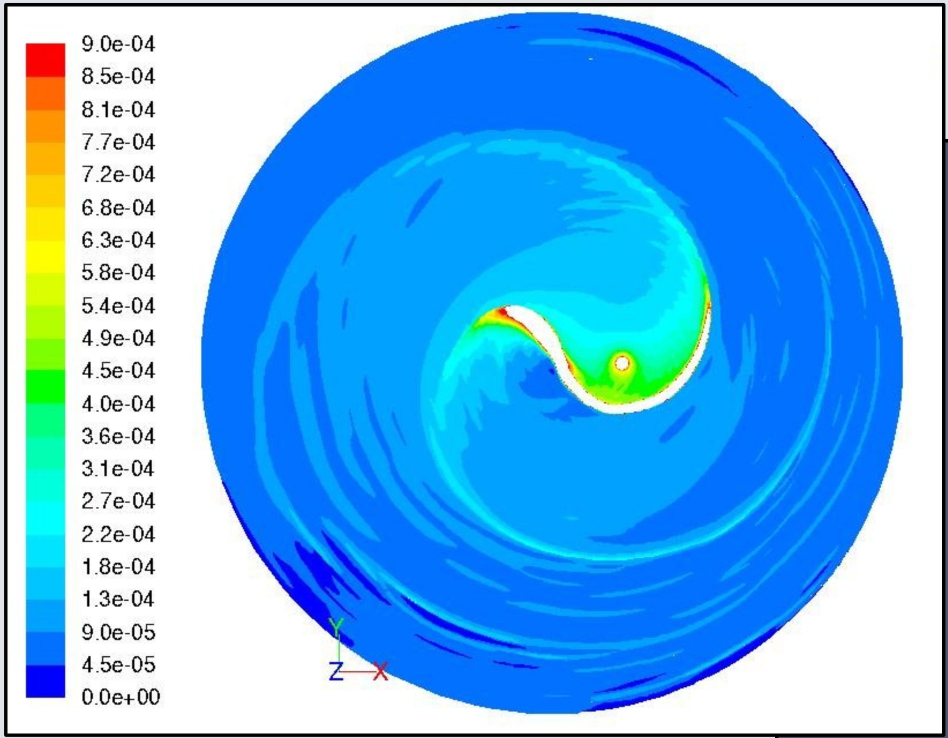
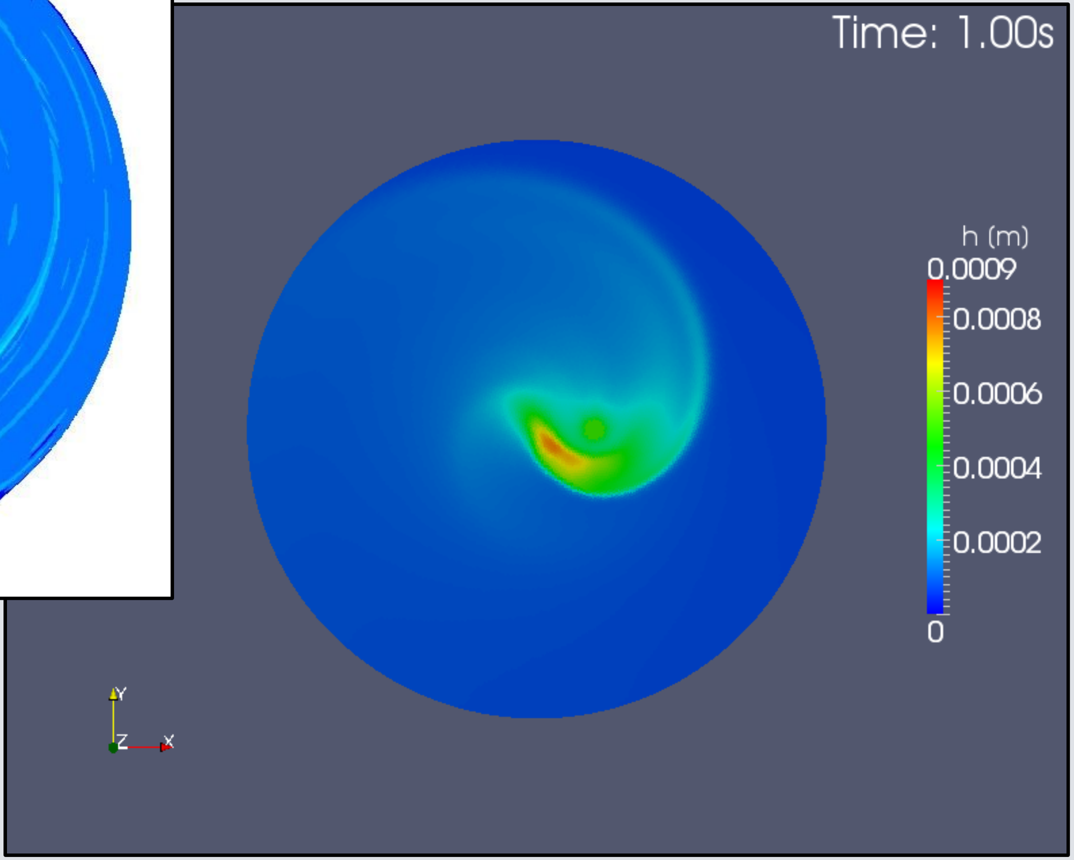




Case 1a: 500rpm, 1.5lpm, Δr=30mm, Spinetch-D





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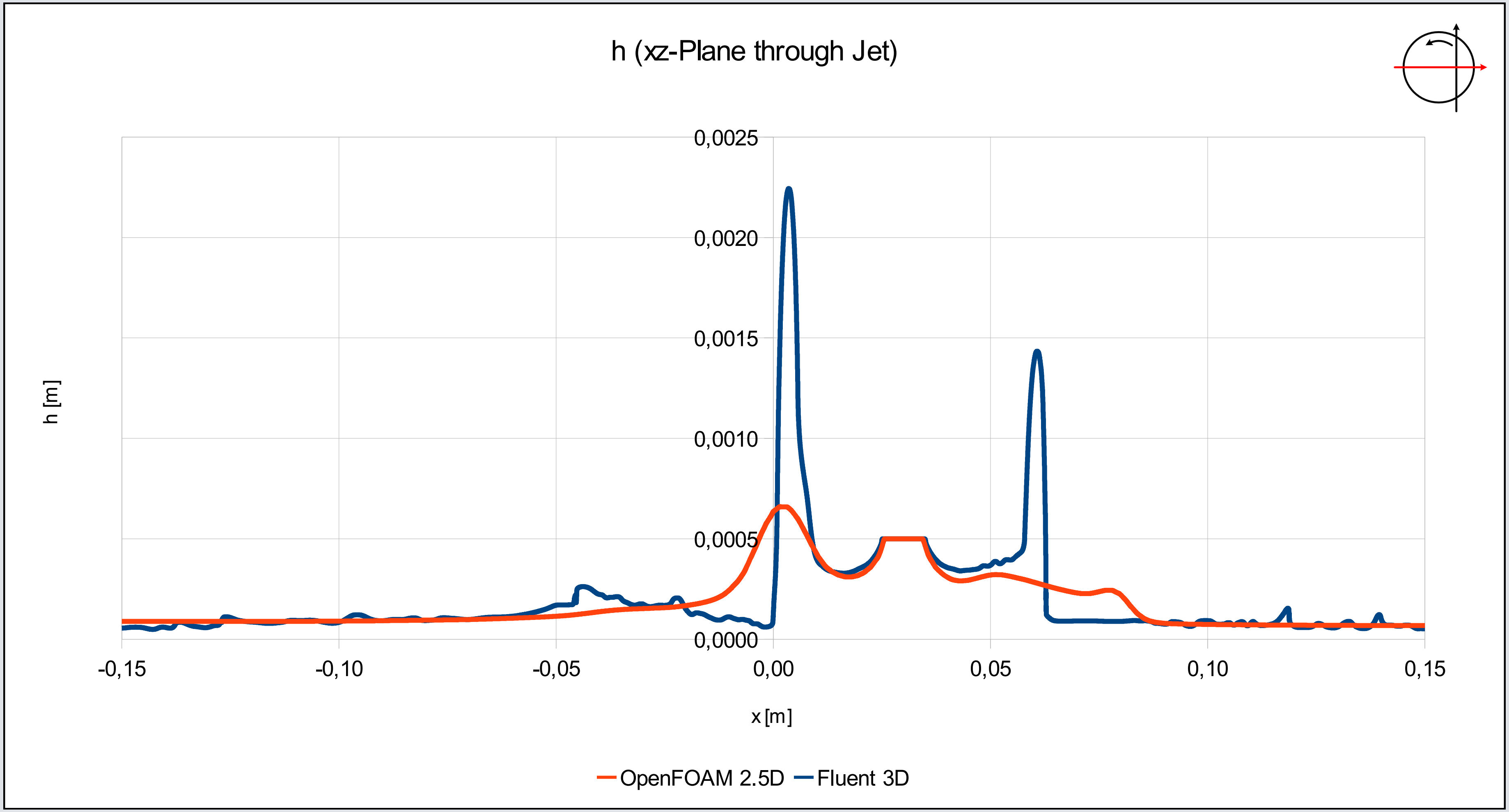

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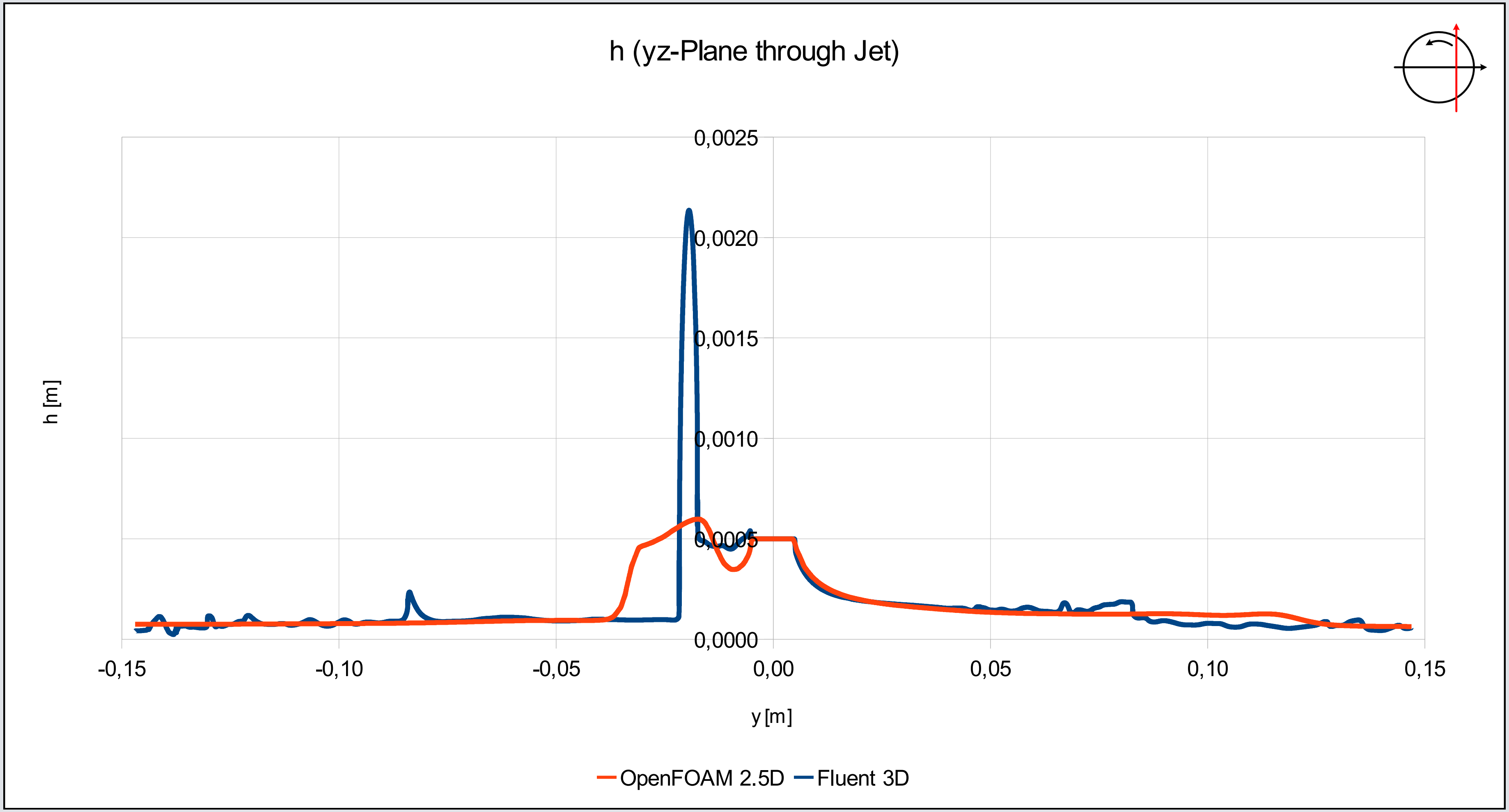

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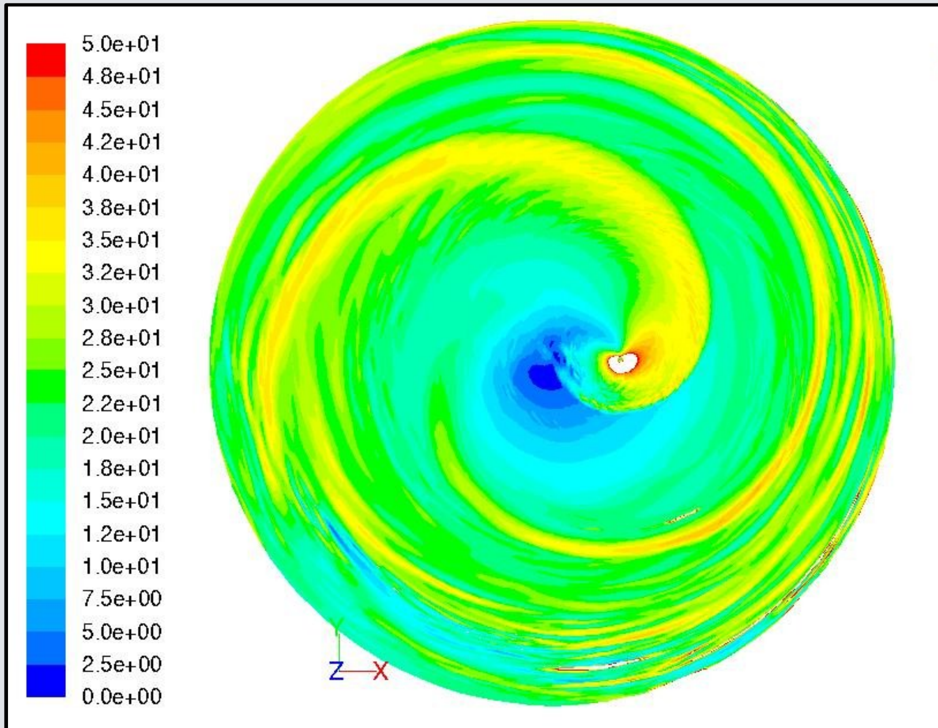

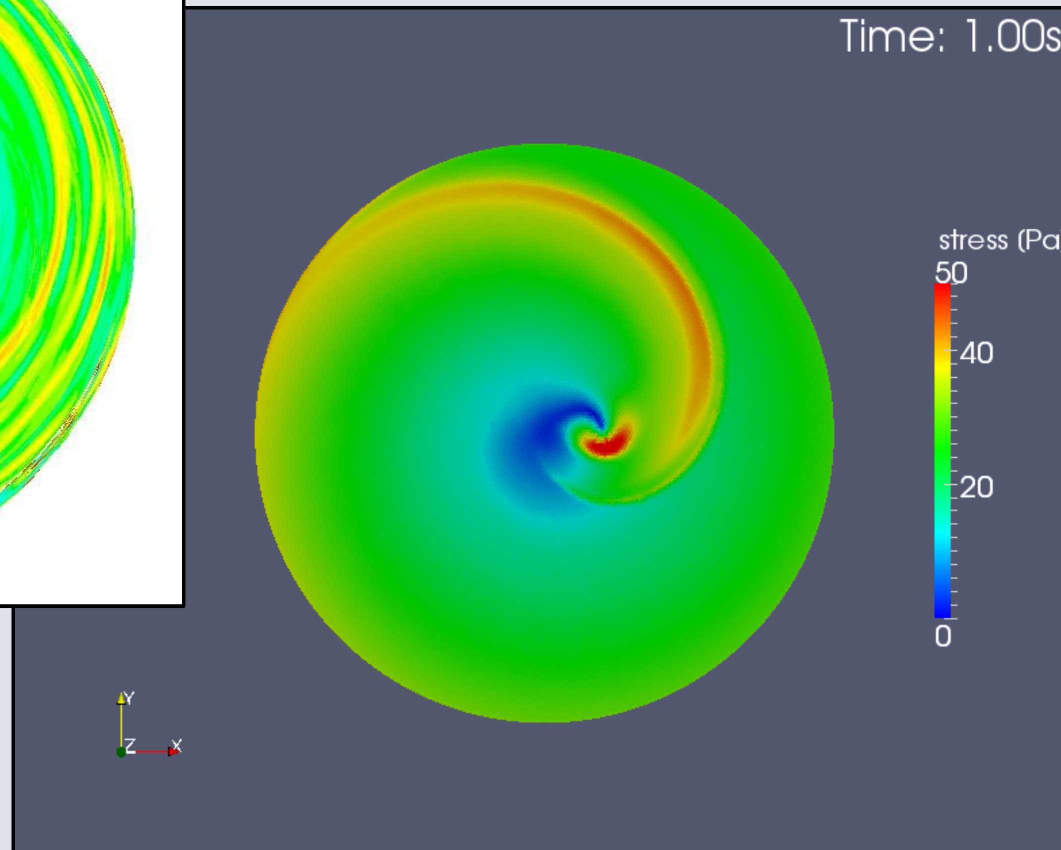

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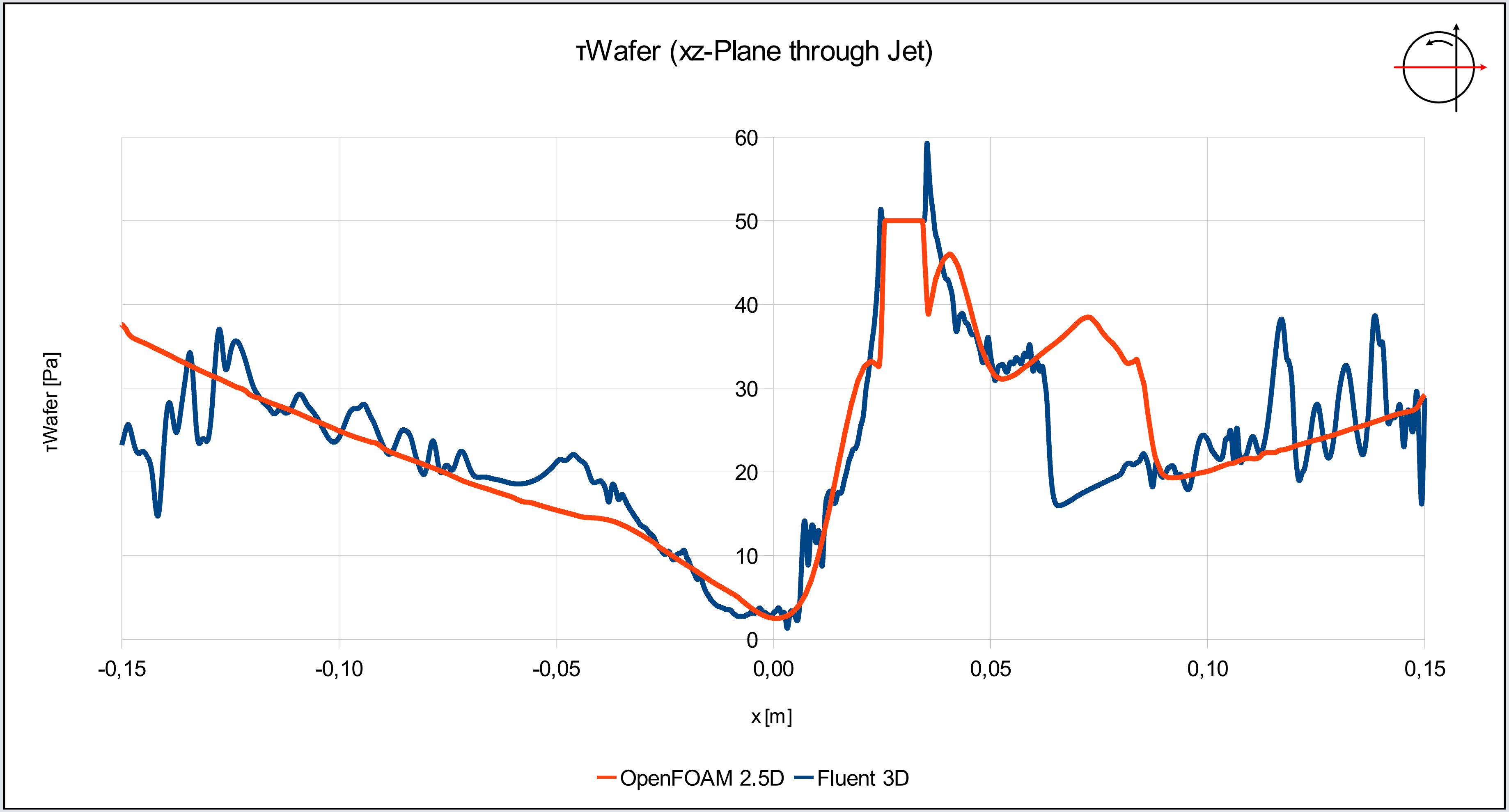

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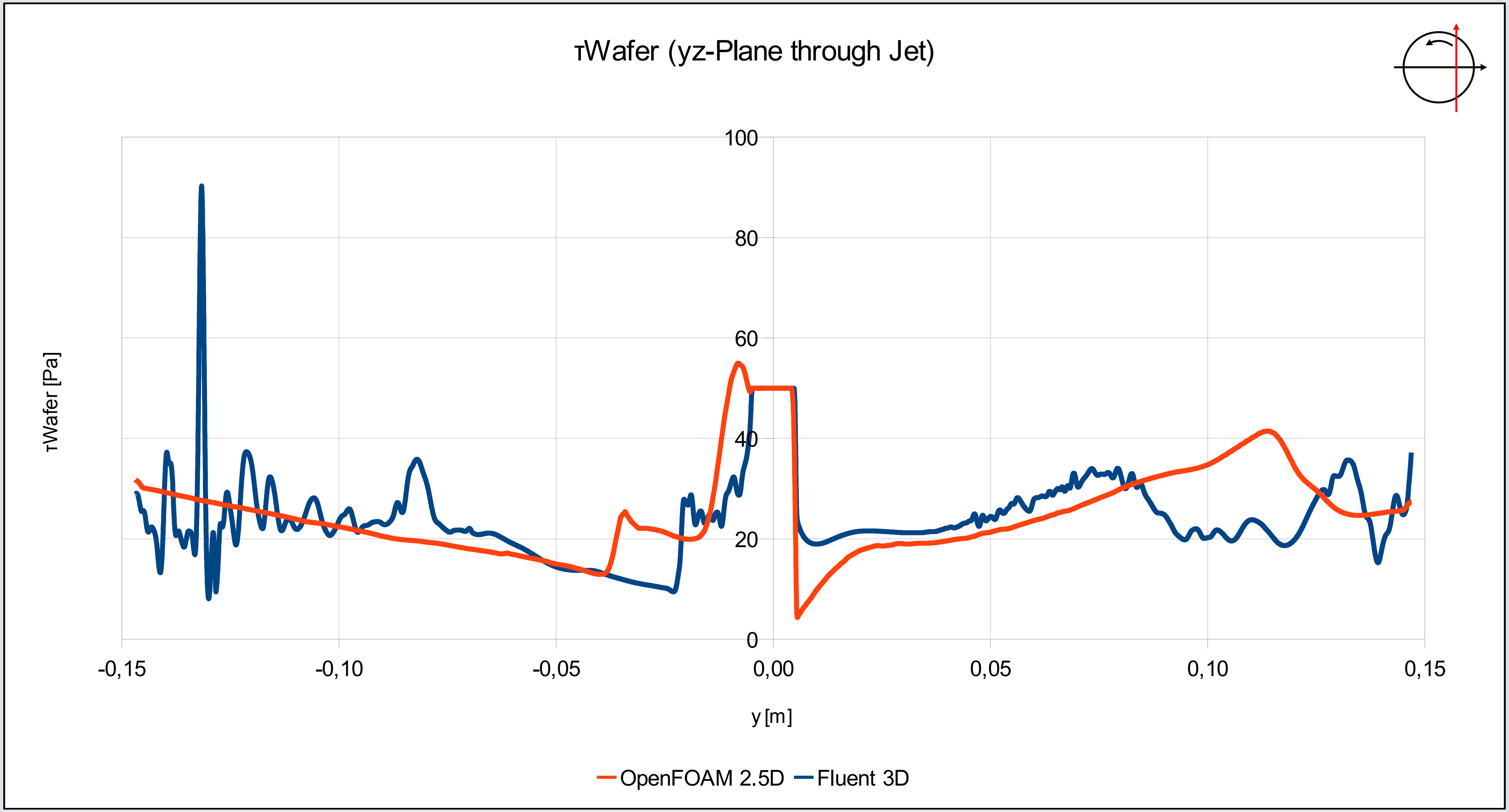

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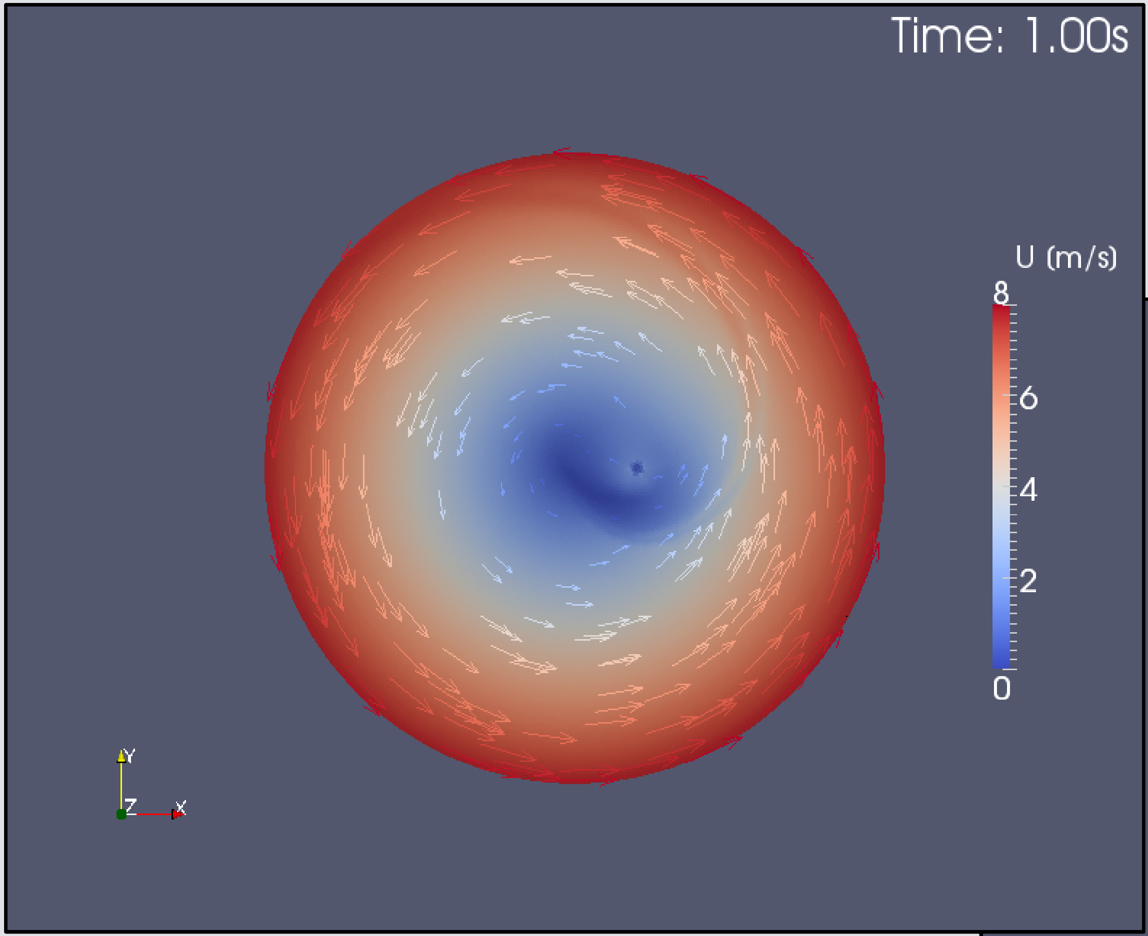
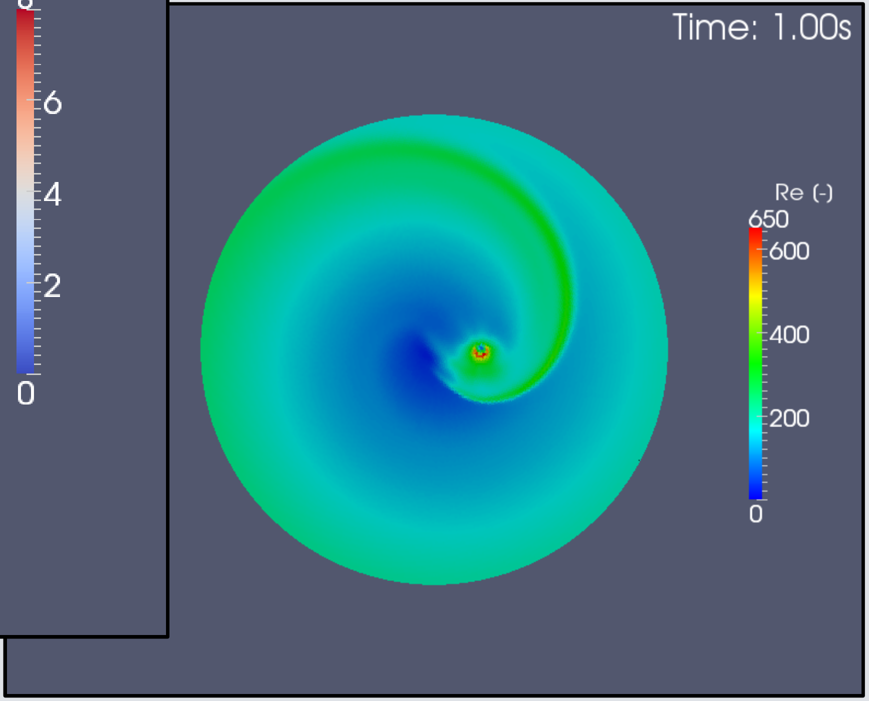
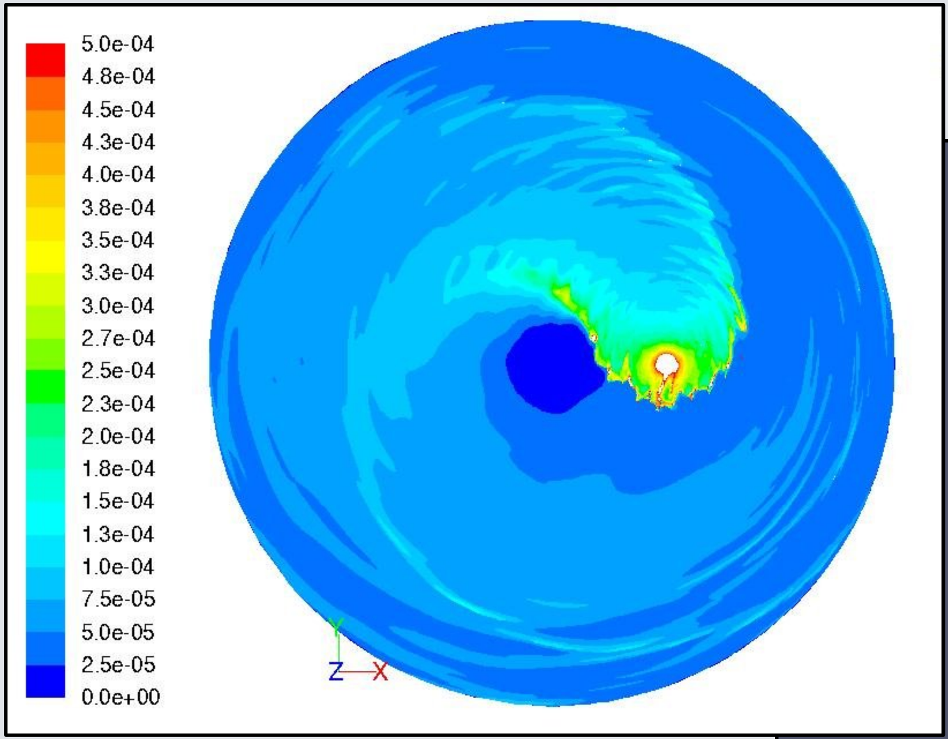
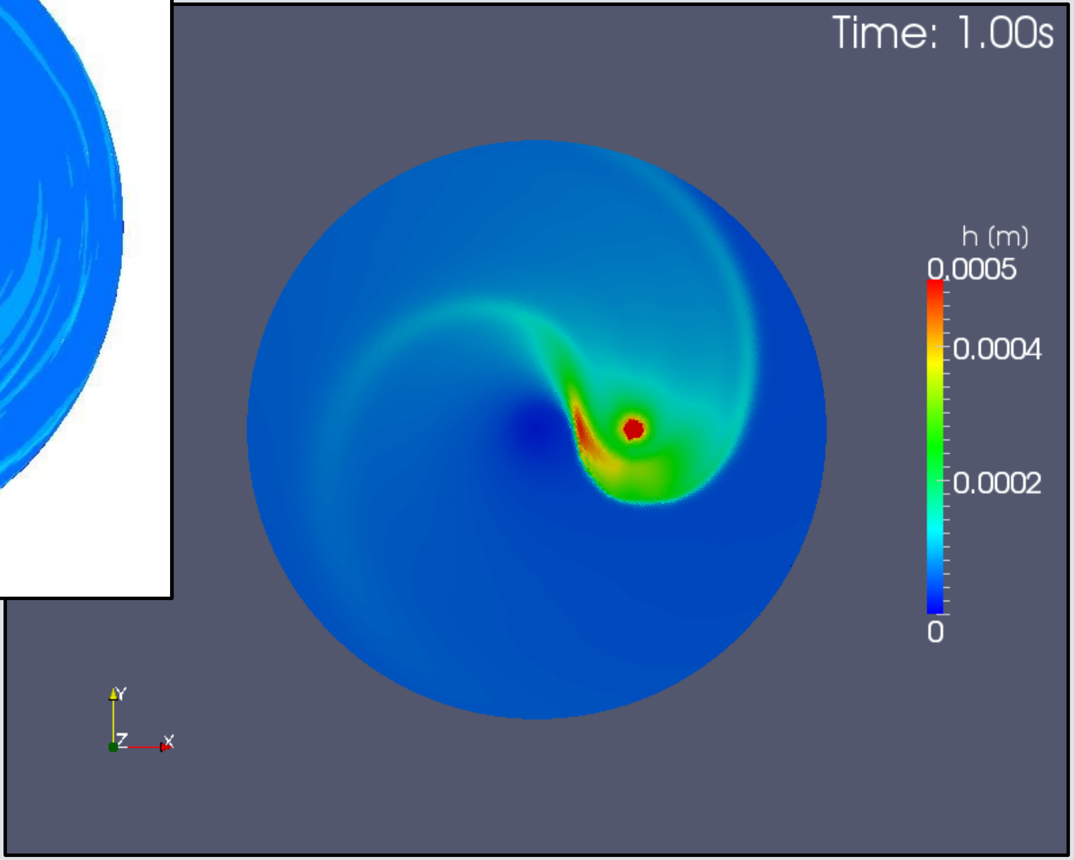




Case 2b: 500rpm, 1.5lpm, Δr=50mm, water





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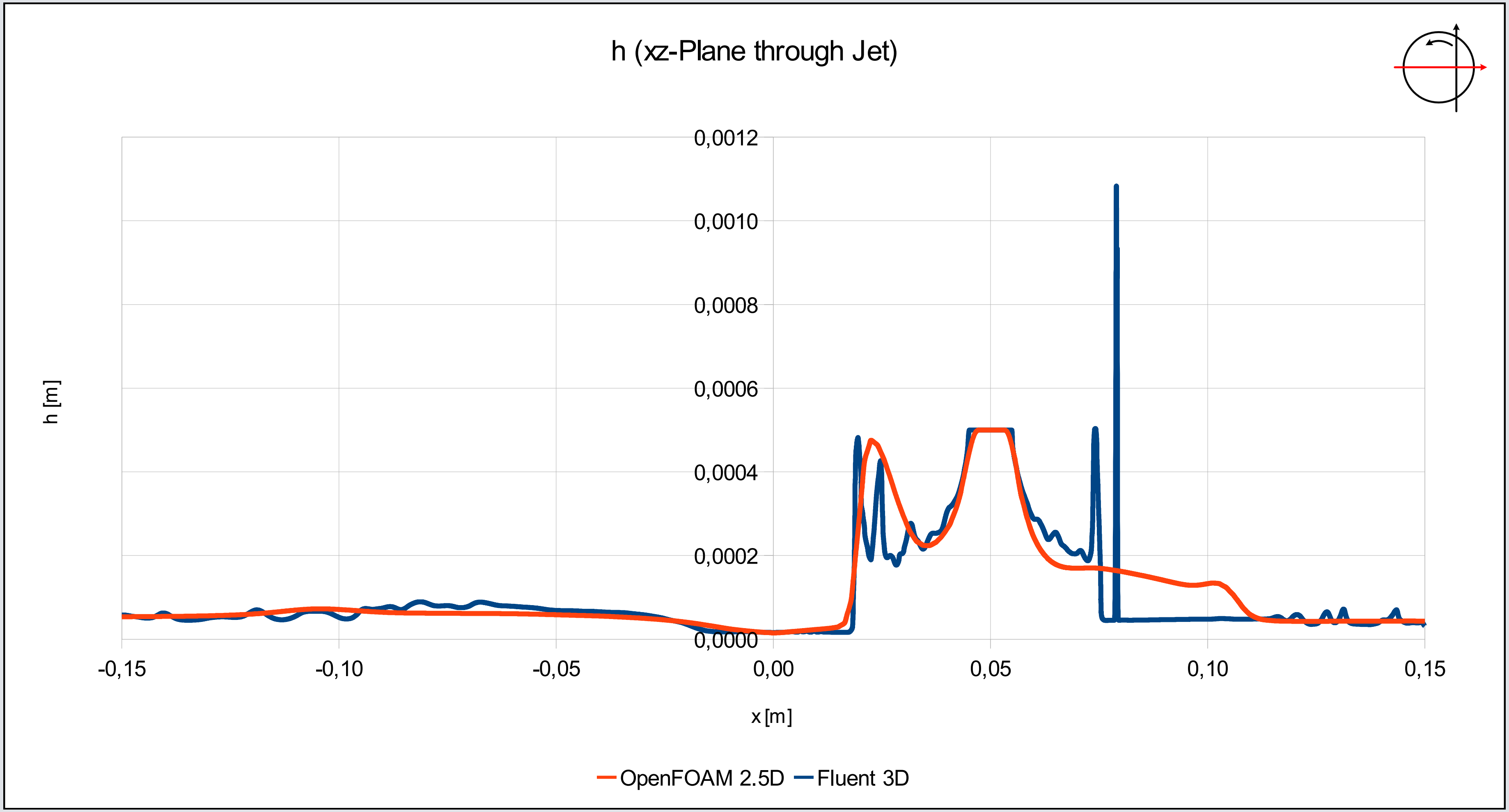

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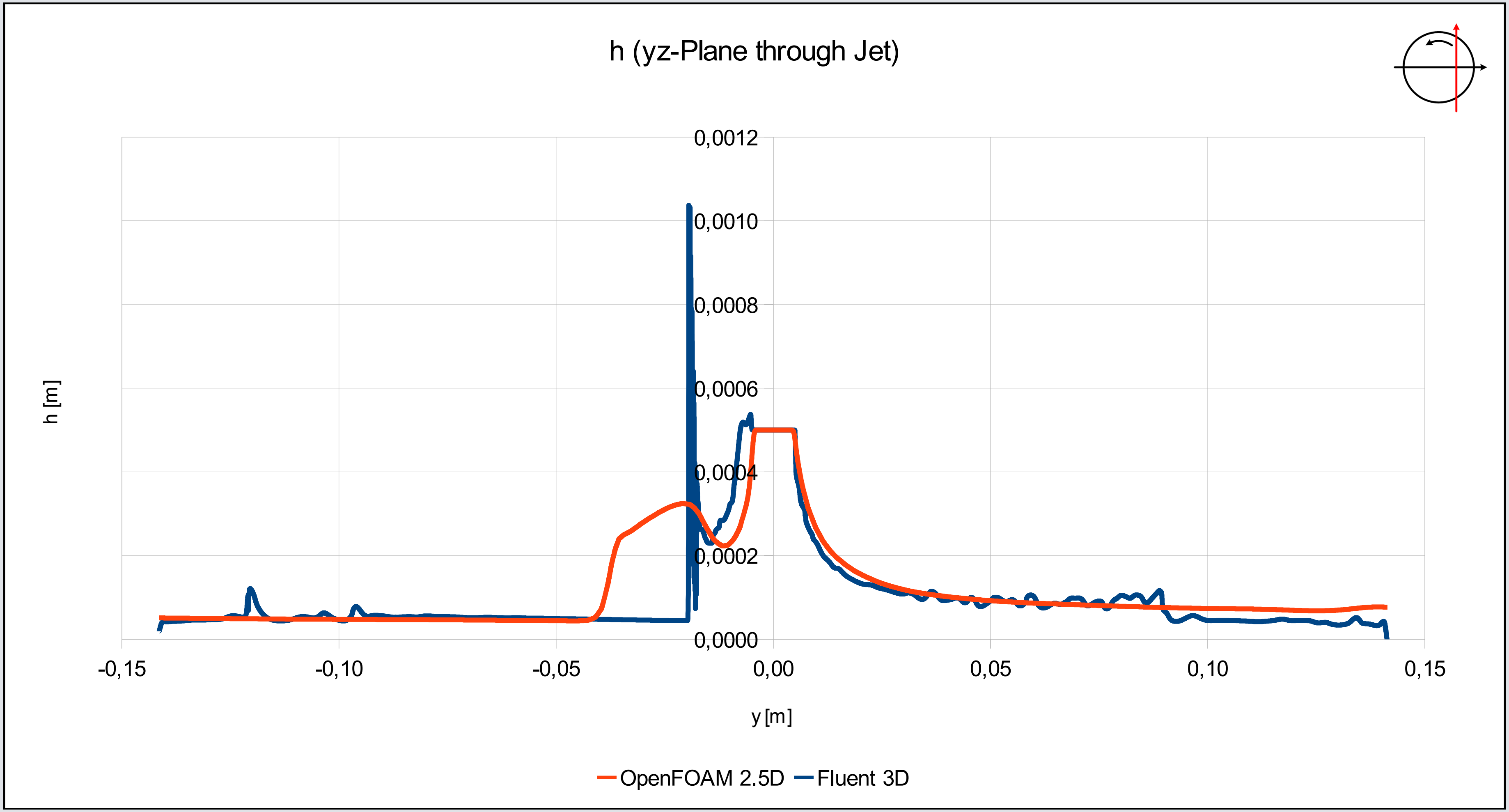

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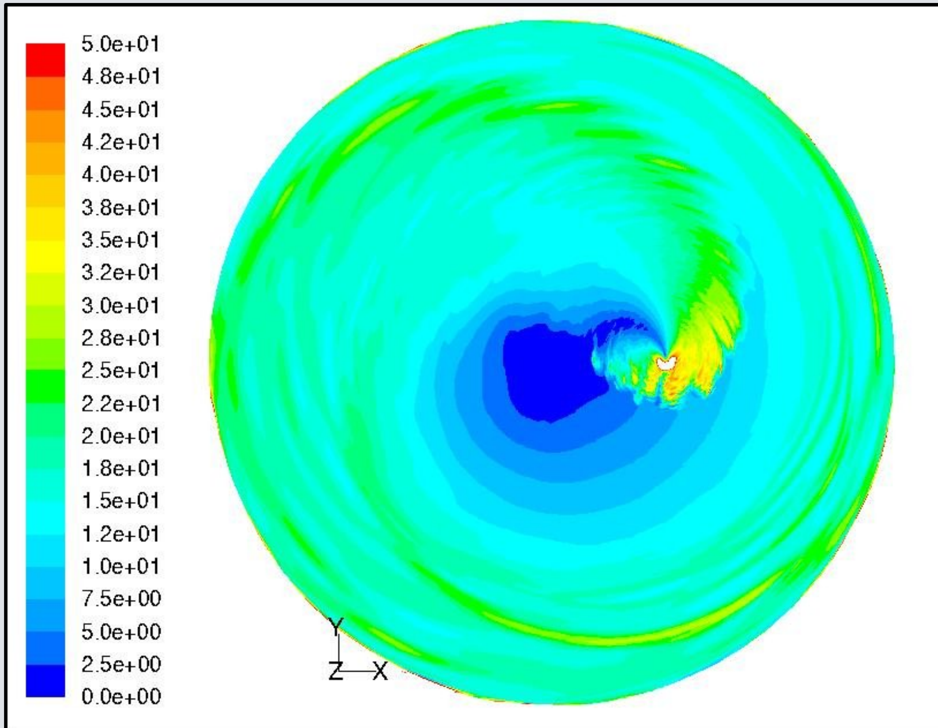

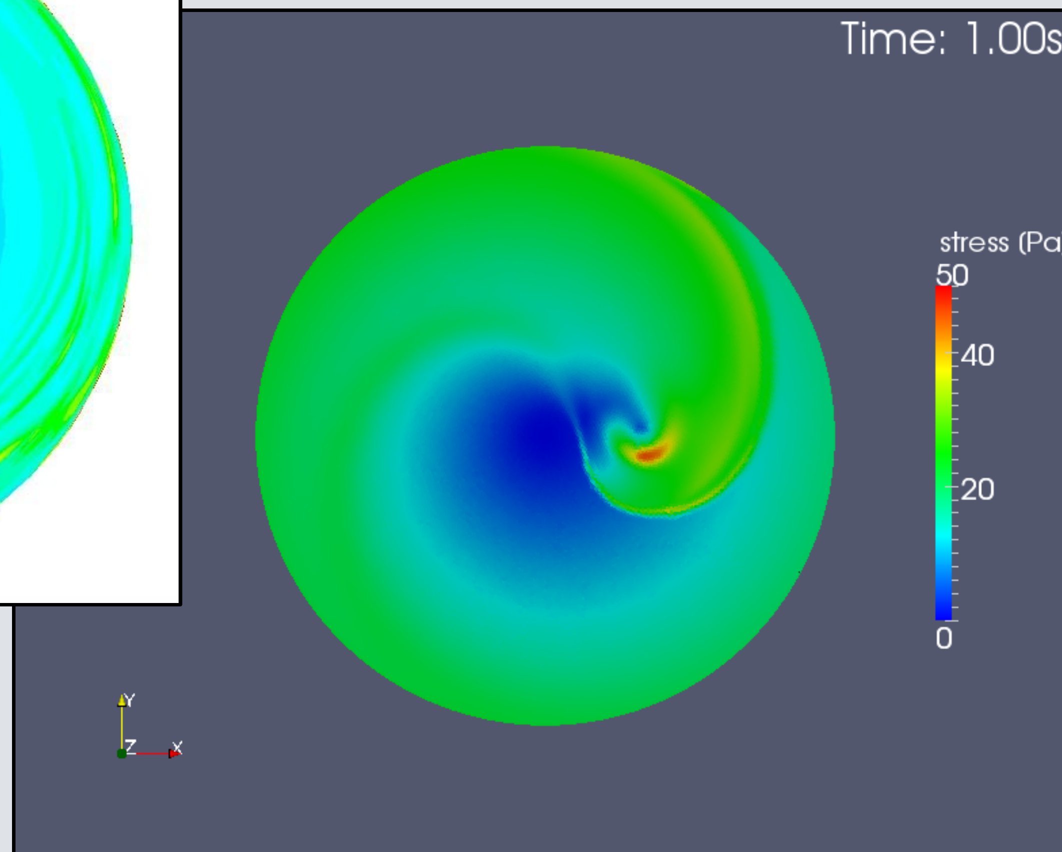

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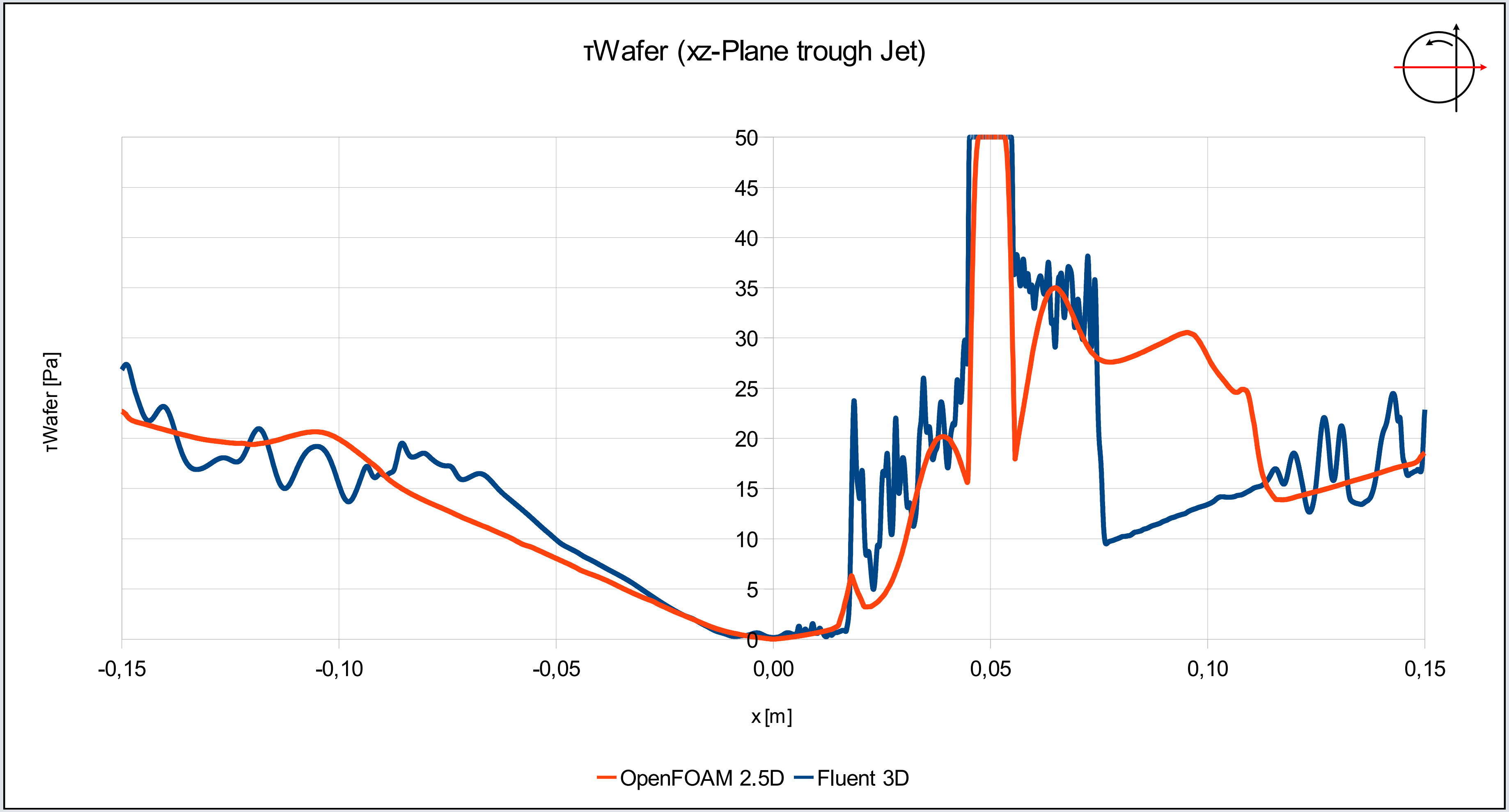

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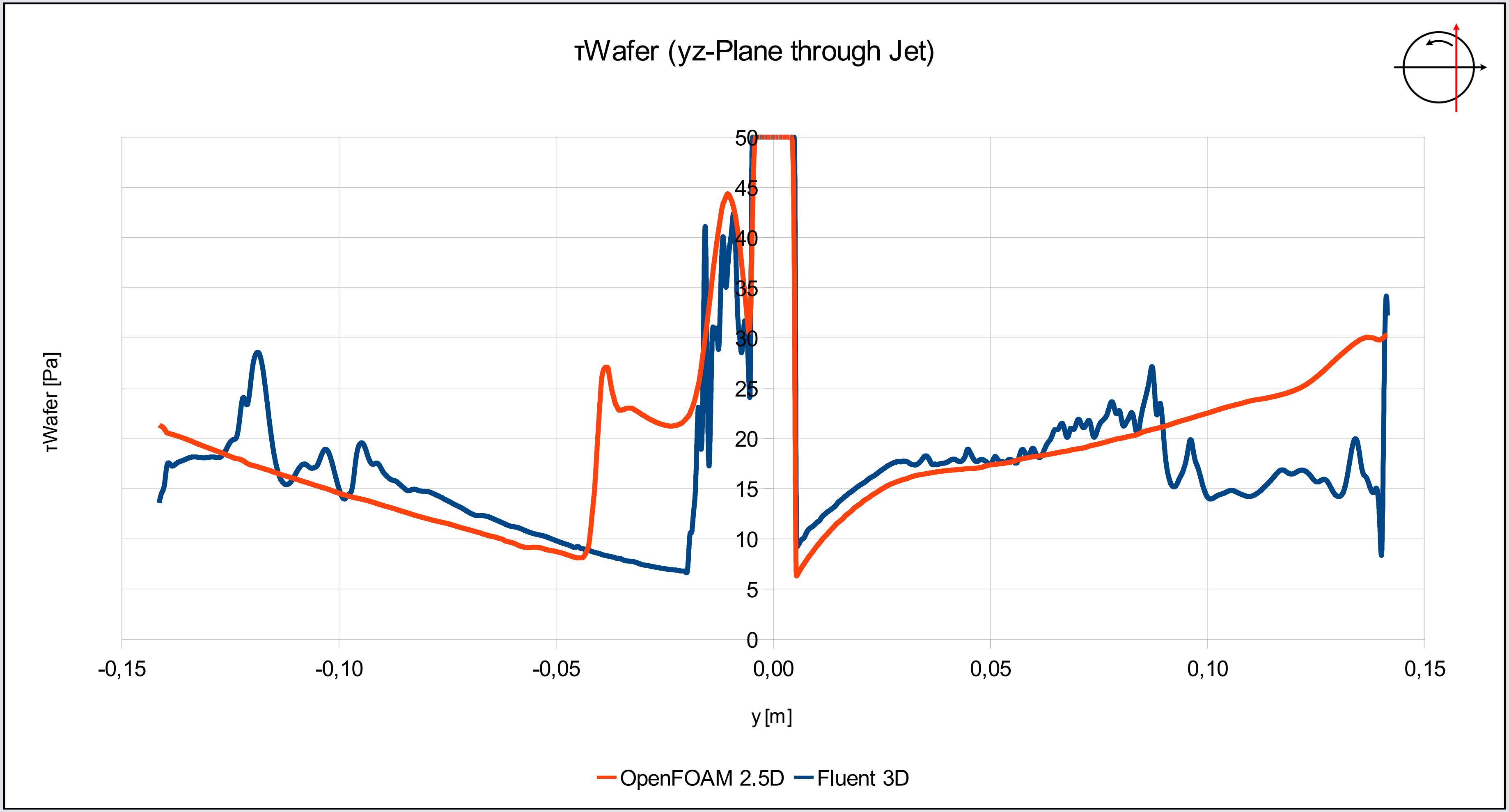

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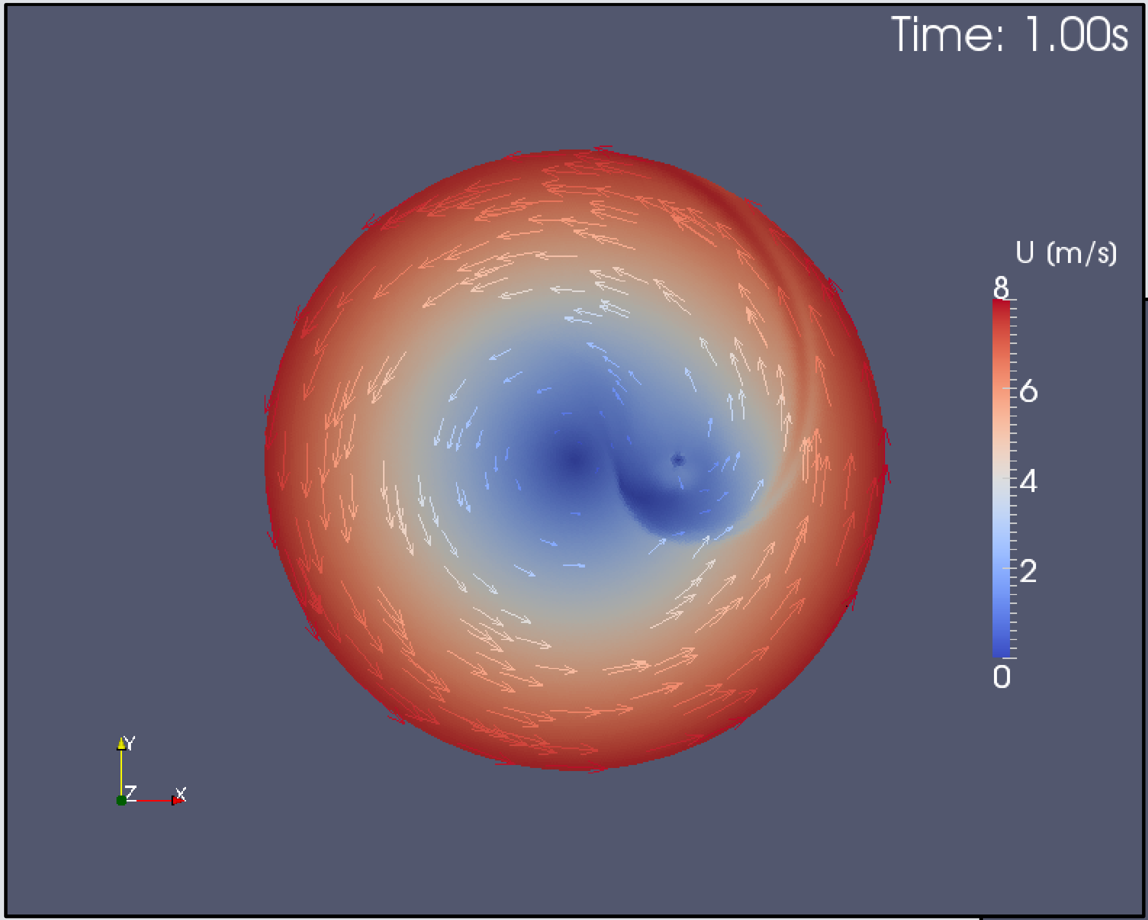

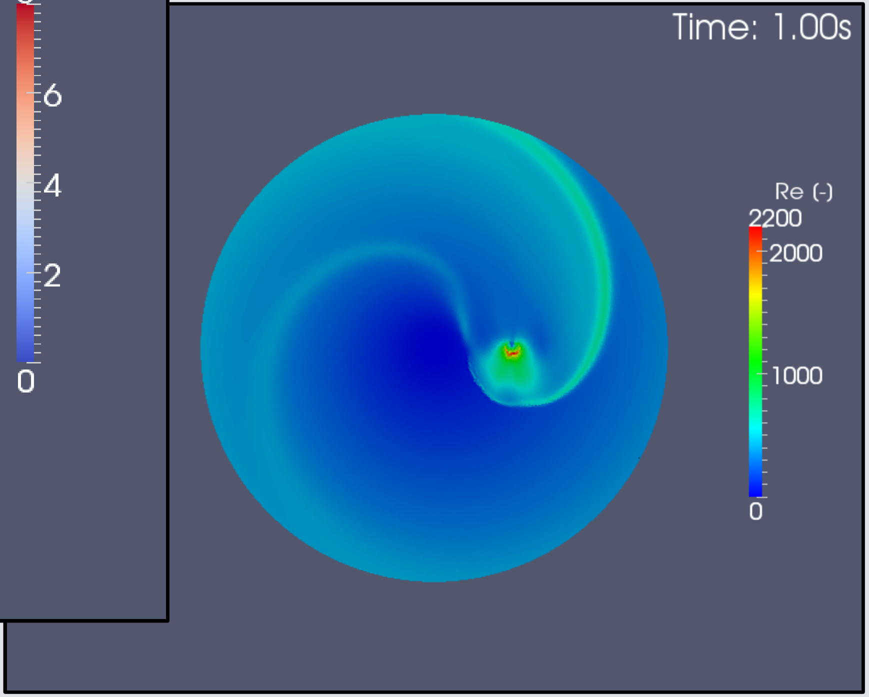

Conclusion

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- **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 there!
  - Zone outside of the impingement influence is showing a very good agreement
  - Shear-stress prediction is good enough
    - Important for a chemistry reactions
  - Smooth solution without fluctuations
  - Small meshes and significantly shorter simulation times

Outlook & Discussion

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- **Outlook**
  - Dry spot handling
  - Impingement area
    - Prescribing not only dependent variables, but as well the velocity profile function itself
  - Velocity profile function
    - Prediction of the velocity boundary
    - Hydraulic jump modelling
      - Would be great for comparison with experiments!
  - Simple etching model
    - Prediction of the concentration boundary
- **Discussion**
  - Thank you for your attention! Questions?