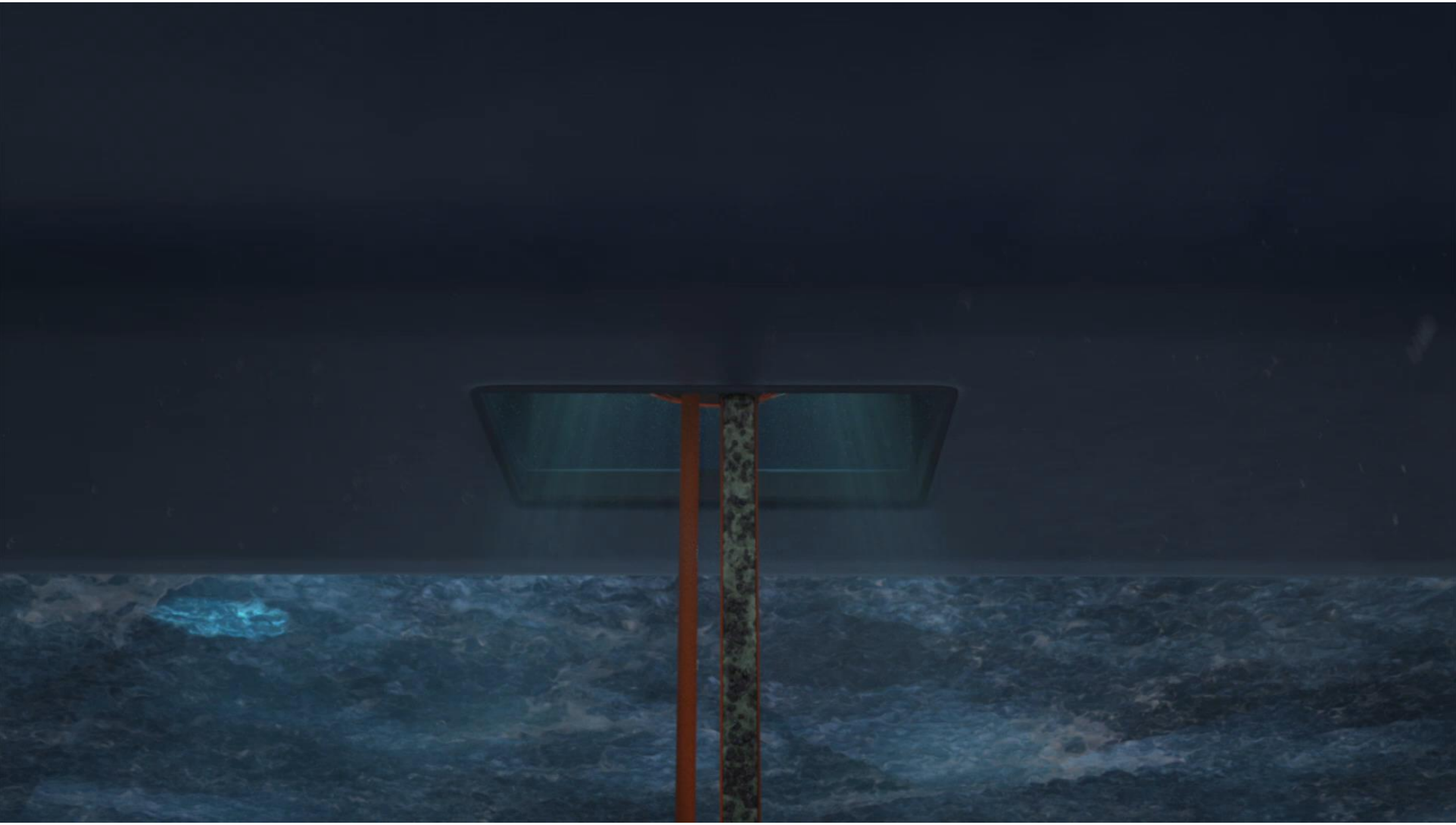
Modeling deep-sea polymetallic nodule mining midwater sediment plumes



Carlos Muñoz-Royo

2.29 Project, 12th May 2020

Outline

1. Intro to Deep-Sea Mining
2. Midwater Sediment Plumes in Nodule Mining
3. Modeling plumes in OpenFoam
    - OpenFoam Solvers
    - Mesh & Boundary conditions
    - Scenarios
    - Results
4. Conclusions
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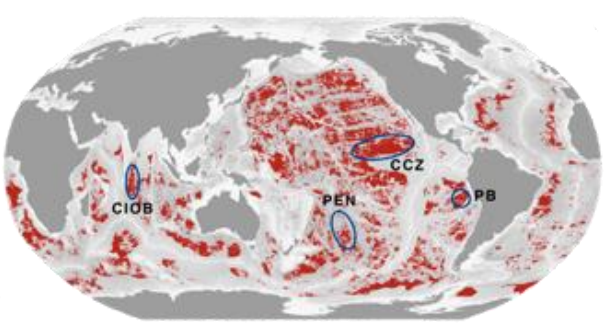
Intro to Deep-Sea Mining

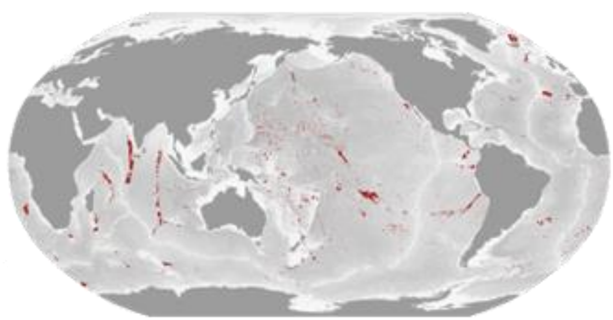
Polymetallic Nodules

Cobalt
Nickel
Copper
Molybdenum
Lithium
Rare Earths



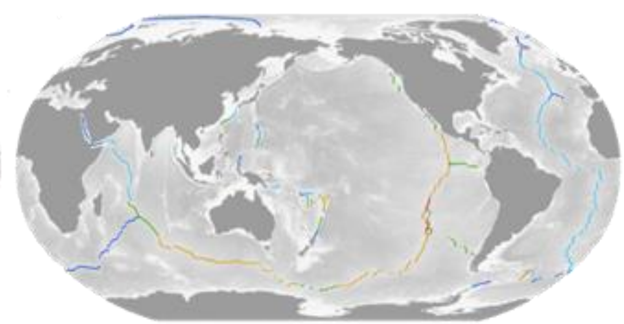
Polymetallic Crusts

Cobalt
Nickel
Titanium
Tellurium
Rare Earths
Platinum



Seafloor Massive Sulfides

Copper
Gold
Silver
Zinc
Lead



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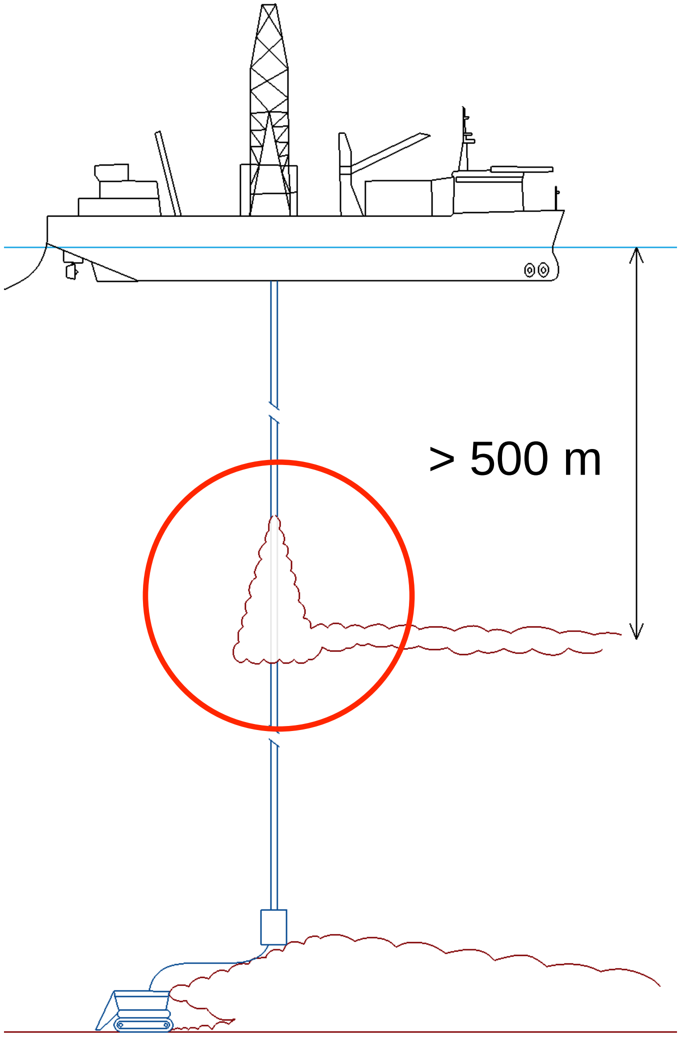
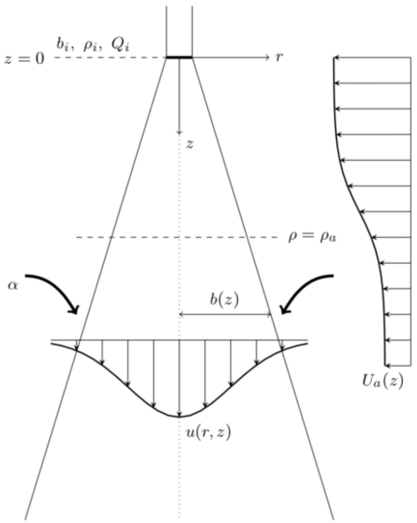
Sediment Plumes in Nodule Mining

Midwater Discharge
Sediment Plume



Sediment Plumes in Nodule Mining

- Semi-Analytical Integral Model
- Main assumptions:
  - Single-phase fluid
  - Gaussian velocity and density deficiency radial profiles (Lee and Chun, 2003)
  - Taylor Entrainment Assumption (Morton et al, 1956; Lee and Chun, 2003)



- Integral Model Governing Equations:

Volume Flux Conservation:

$$\frac{dQ}{dz} = \frac{d}{dz}\left(\pi b^2 \omega_m\right) = 2\pi b \alpha \omega_m$$

Momentum Flux Conservation:

$$\frac{dM}{dz} = \frac{d}{dz}\left(\pi \frac{b^2}{4} \omega_m^2\right) = \pi \lambda^2 b^2 g \frac{(\rho_a - \rho)}{\rho_0}$$

Buoyancy Flux Conservation:

$$\frac{dF}{dz} = \frac{d}{dz}\left(\pi b^2 g \frac{\rho_a - \rho}{\rho_0} \omega_m \frac{\lambda^2}{(\lambda^2 + 1)}\right) = -\pi b^2 \omega_m N^2$$

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Modeling plumes in OpenFoam

- Solvers:

  - Initial approach: buoyantBoussinesqPimpleFoam

    Advantage: applies Boussinesq approximation (valid for these plumes)

    Issues: density calculated as function of temperature only

  - **Final approach: twoLiquidMixingFoam**

    Multiphase solver for miscible fluids with different density

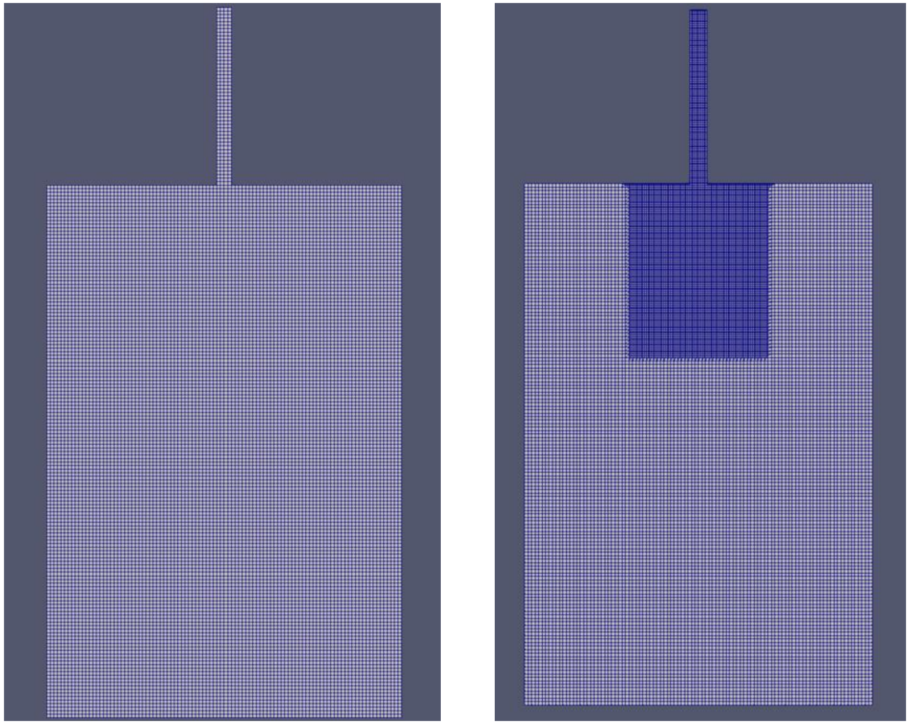
    Adequate for plume near-field: particle settling/dynamics negligible

  - Alternative: driftFluxFoam

    Multiphase solver used in sedimentation/settling problems

Modeling plumes in OpenFoam

- Mesh
  - 3D structured mesh: blockMesh + snappyHexMesh
  - 2 - 1.5 million cells
  - Cell size: 0.05 - 0.1 m
  - Domain: 20D x 20D x 30D + 10D pipe (D: 0.5m)



Modeling plumes in OpenFoam

- Scenarios

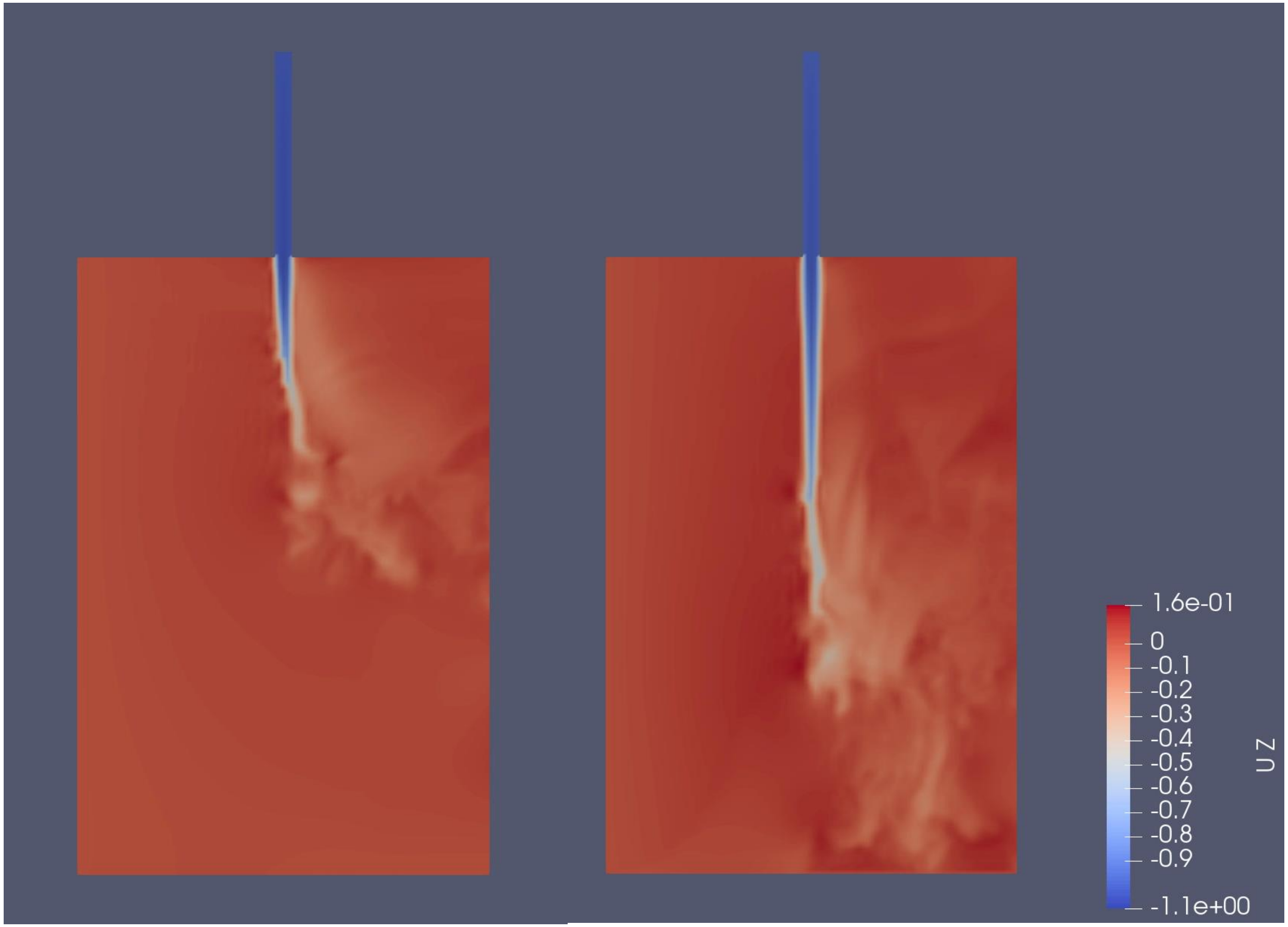
  - Baseline conditions:
    - Discharge Re: $5 \cdot 10^5$
    - Discharge density: 1027 kg/m^3
    - Background stratification: $N^2 \sim 1 \cdot 10^{-4}\ s^{-2}$
    - Background crossflow: 0.1 m/s (x-direction)
    - Turbulence model: LES (k-eqn)

  - Scenarios for qualitative validation:
    - Weaker crossflow: 0.05 m/s
    - Stronger stratification: $N^2 \sim 2 \cdot 10^{-4}\ s^{-2}$
    - Higher initial density: 1030 kg/m^3

Modeling plumes in OpenFoam

- Crossflow scenarios:

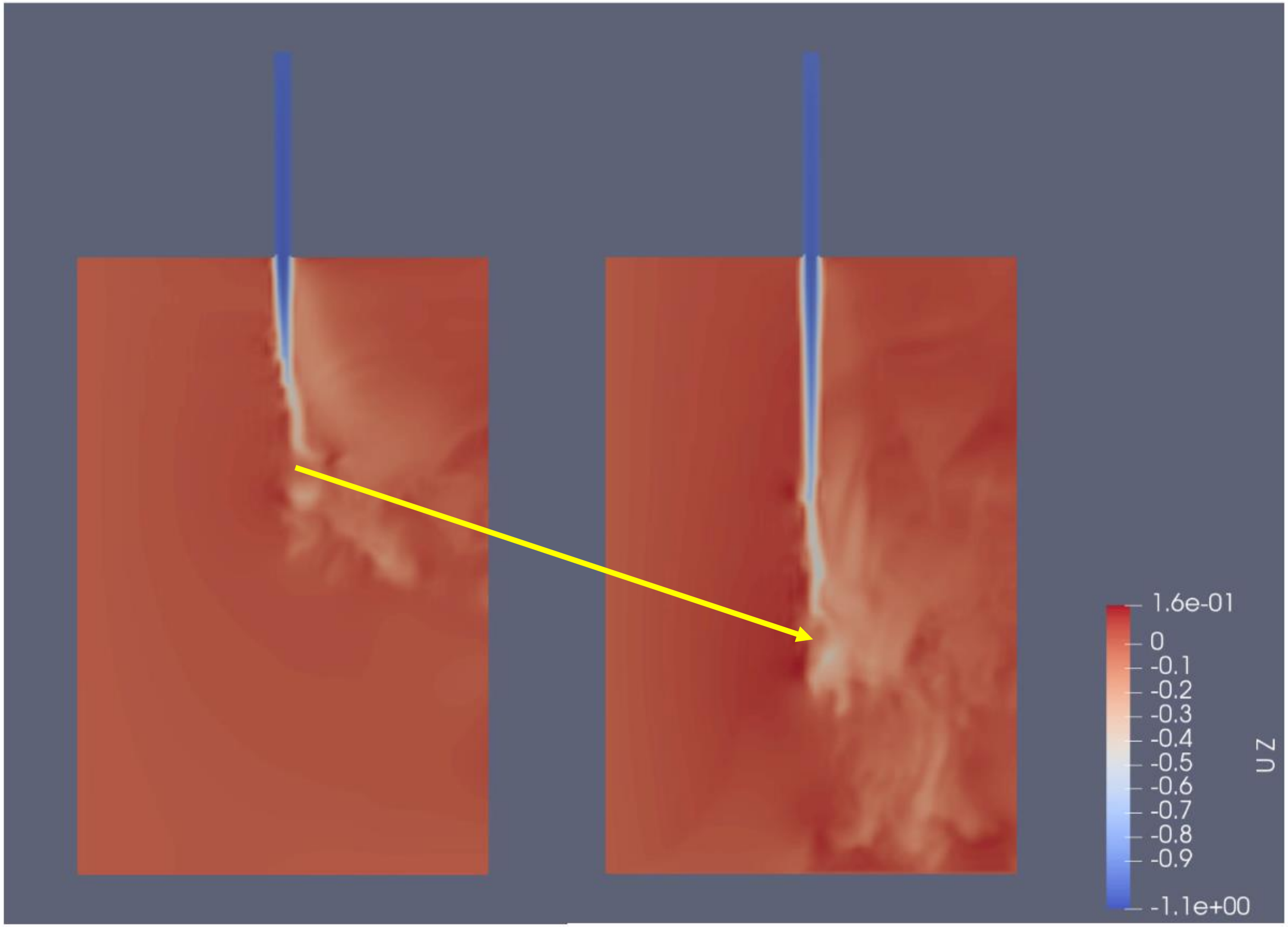
Baseline LES: Weaker Crossflow:



Modeling plumes in OpenFoam

- Crossflow scenarios:

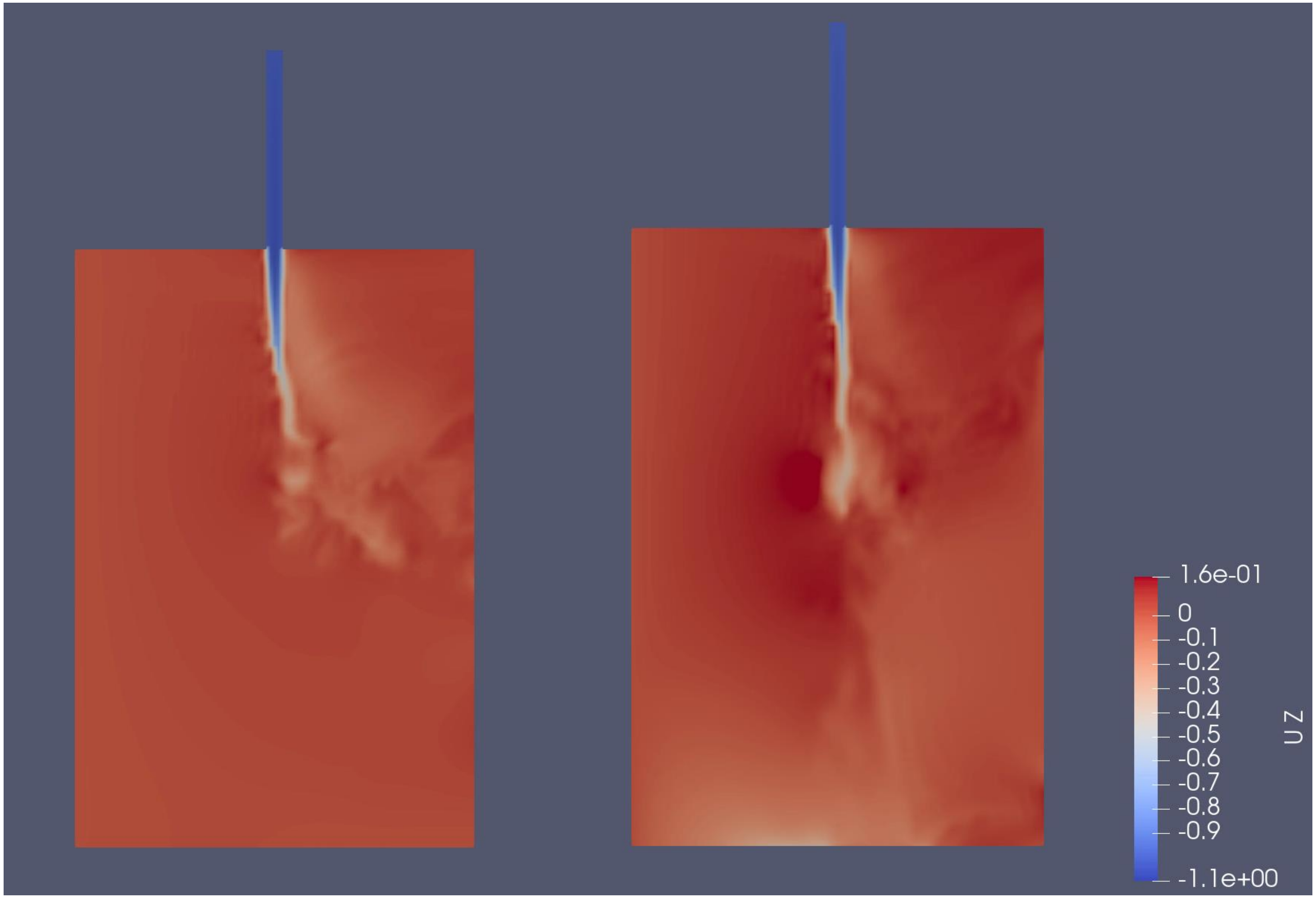
Baseline LES: Weaker Crossflow:



Modeling plumes in OpenFoam

- Initial plume density scenarios:

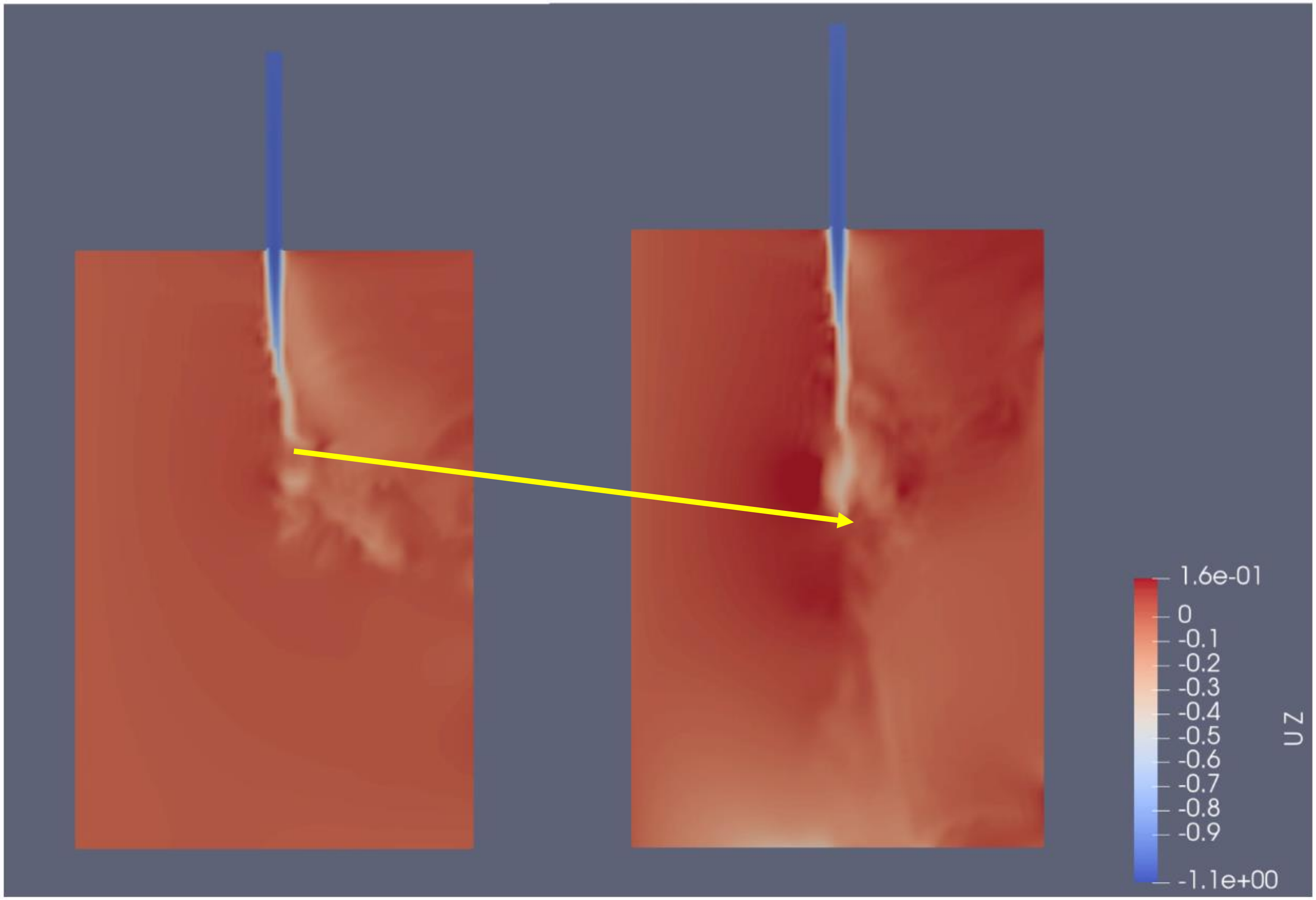
Baseline: Higher initial density:



Modeling plumes in OpenFoam

- Initial plume density scenarios:

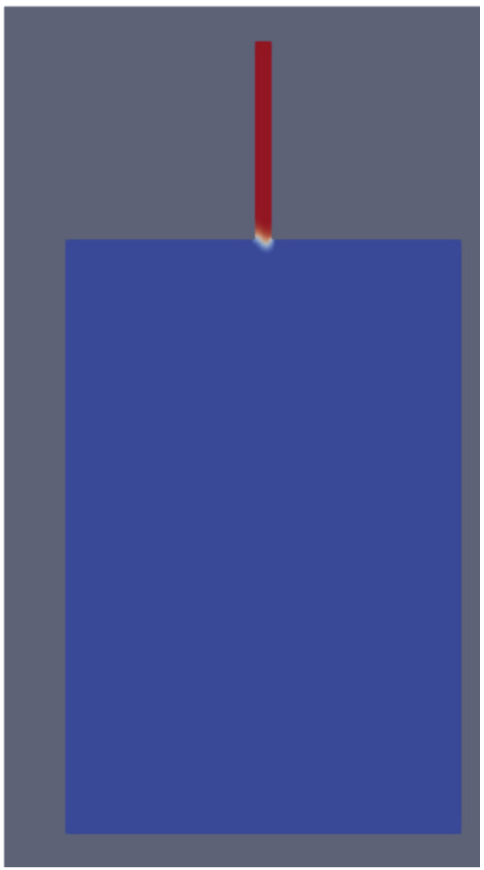
Baseline: Higher initial density:



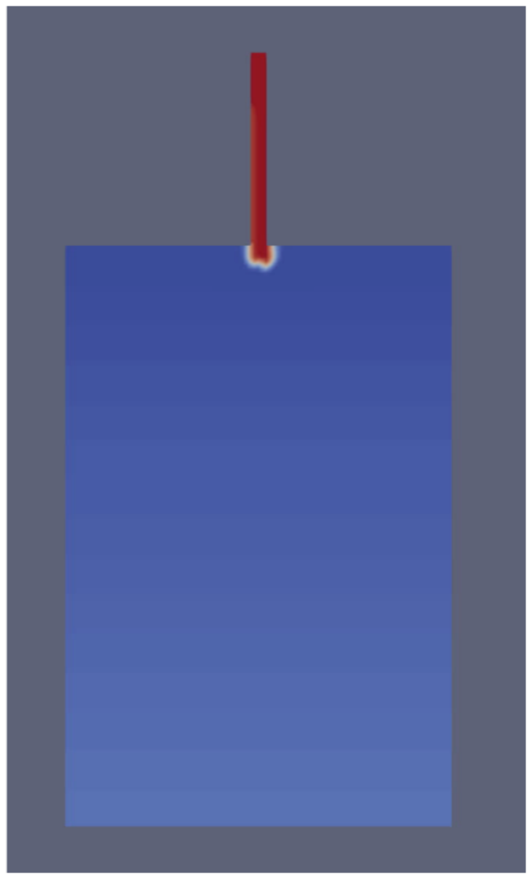
Modeling plumes in OpenFoam

- Stratification

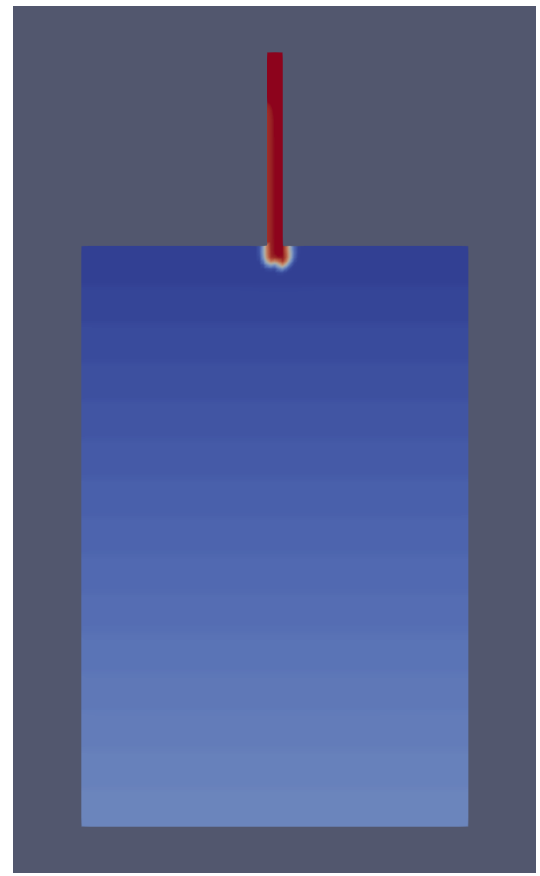
No stratification:



Baseline:



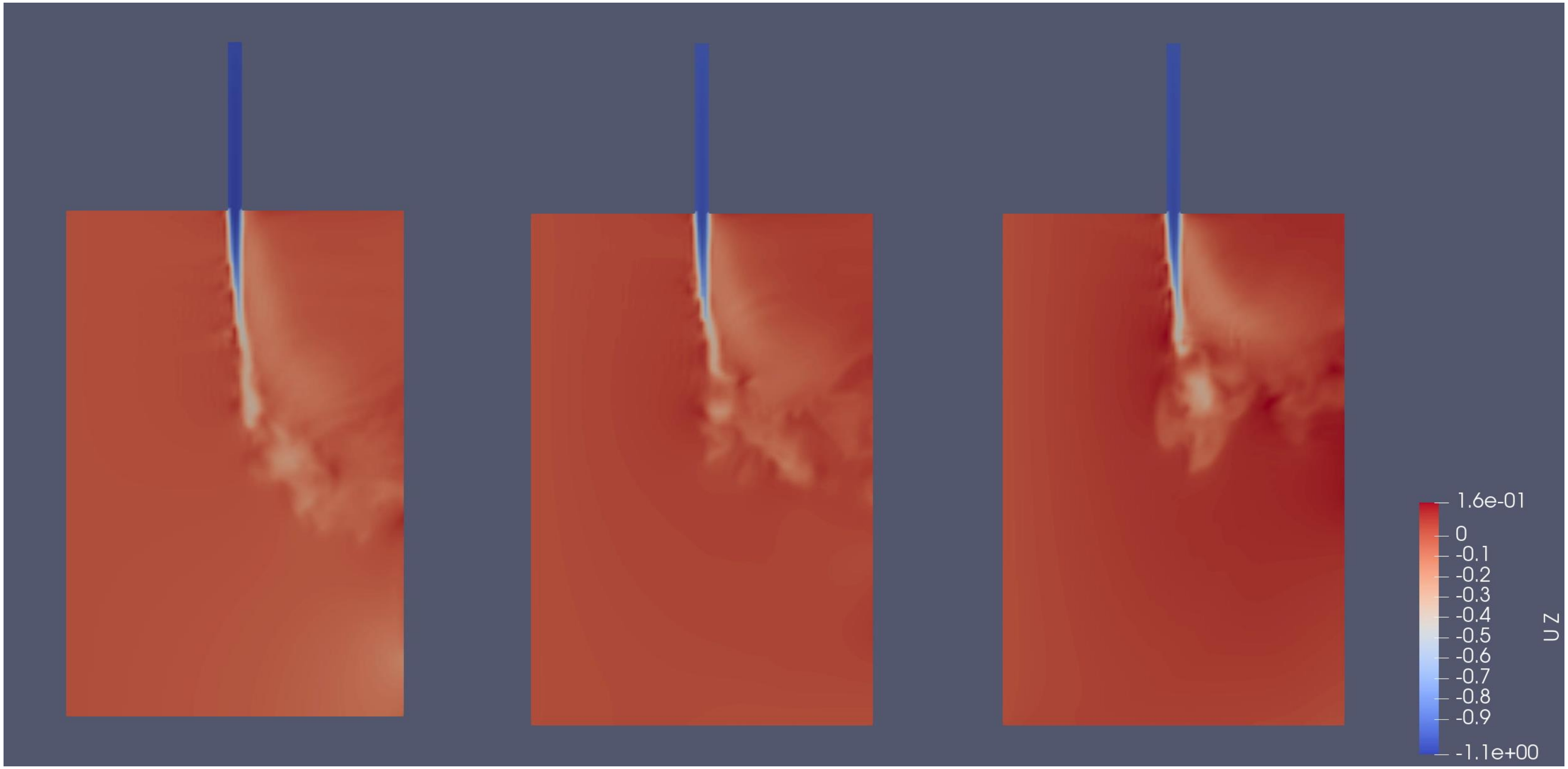
Stronger stratification:



Modeling plumes in OpenFoam

- Stratification

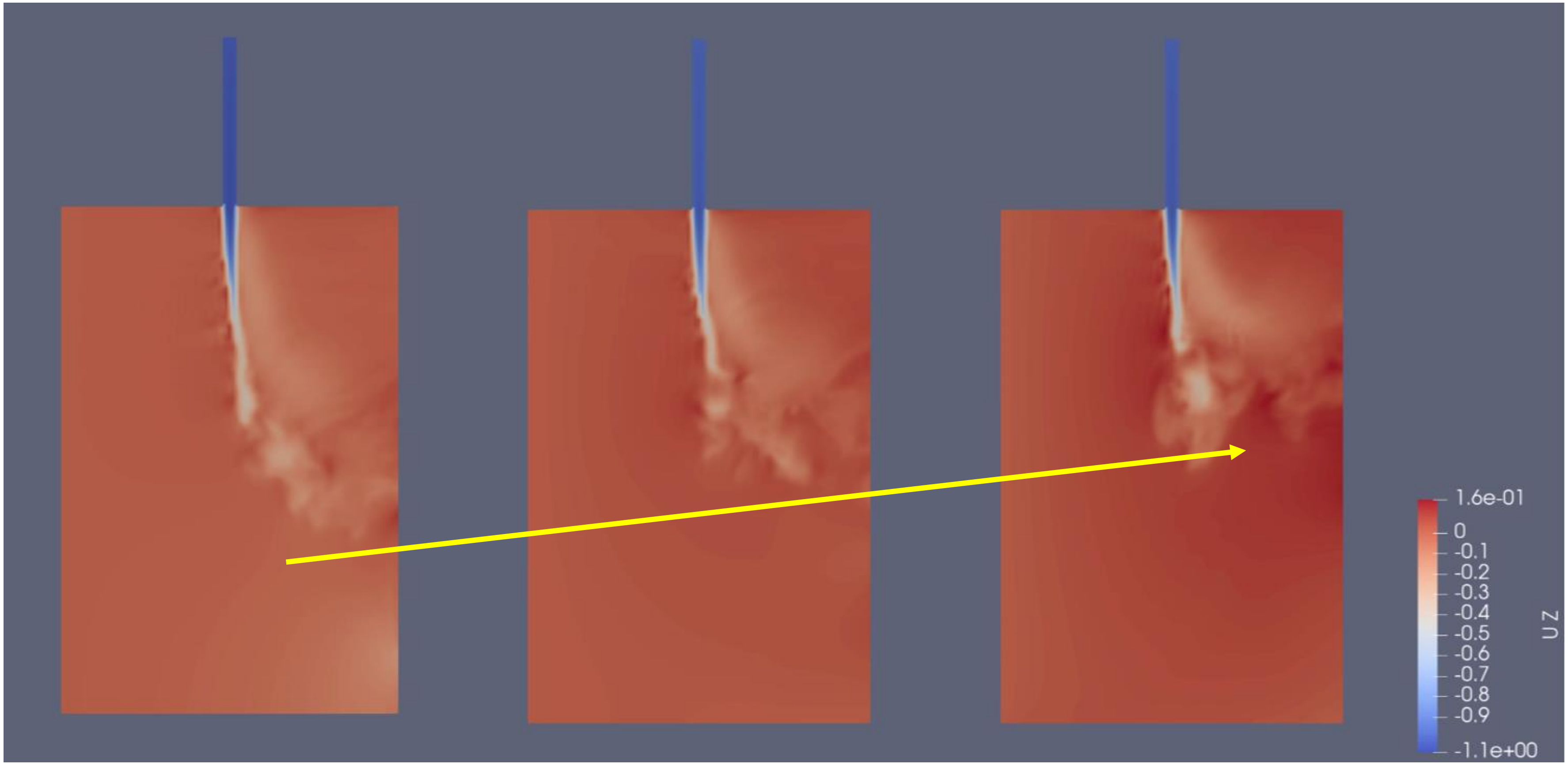
No stratification: Baseline: Stronger stratification:



Modeling plumes in OpenFoam

- Stratification

No stratification: Baseline: Stronger stratification:



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Conclusions

- Model captures plume behavior (only qualitatively for now)

- 3D model with ~2 million cells: demanding for a 7-year old laptop!
    - 7-12 hours for each 100s simulation (~150 hours of computing time)
    - Slows down ability to iterate and update the model

- Good overall experience with OpenFoam:

    Great flexibility to test solvers, turbulence models, boundary conditions

- But: lack of documentation, small online community compared to other open source platforms —> slows down initial ramp-up

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Next Steps

1. Explore other solvers
2. Refine mesh (run in lab workstation!)
3. Explore other turbulence models (LES and RANS)
4. Explore other numerical schemes
5. Validate results:
    - Experimental data
    - Semi-analytic model
    - Dimensional analysis: scaling factors

Thank you!

Thanks 2.29 team!!