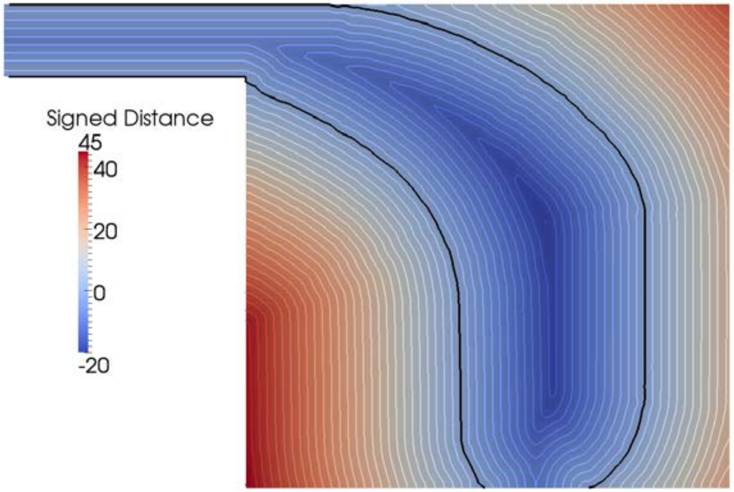
Level-Set based Topology Optimization using Adjoint CFD

8^{th} OpenFOAM Workshop

Jeju, Korea



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AboutFLOW Project

- Adjoint-Based optimization of industrial and unsteady flows
- Research funded by the European Commission – Marie Curie Actions
- Topology Optimization based in OpenFOAM Continuous Adjoint Solver

http://aboutflow.sems.qmul.ac.uk

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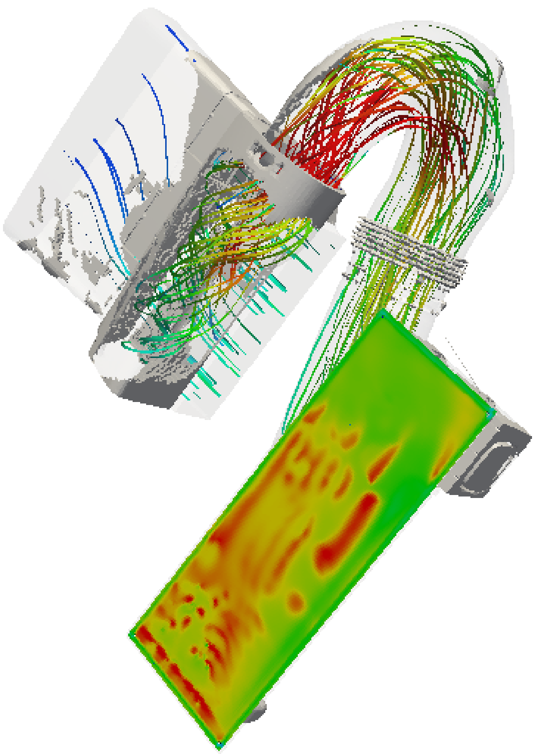
Optimization | Adjoint Method

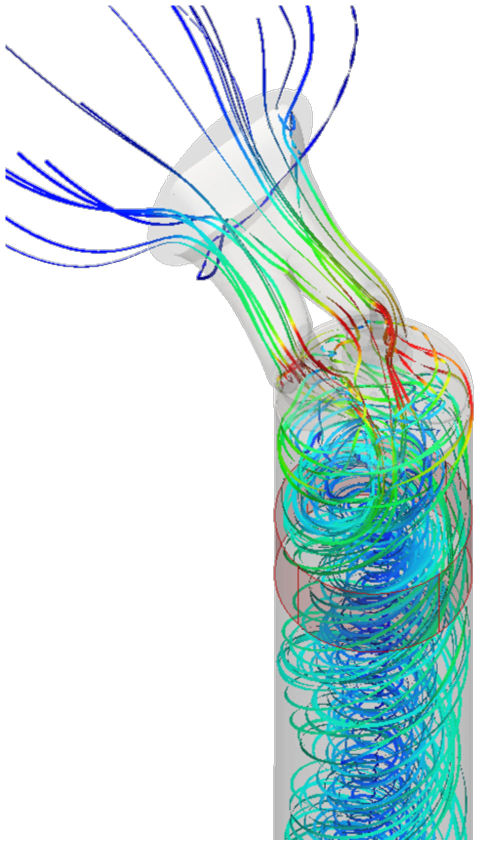
- What is Design Optimization?
  - Design for increased efficiency
  - Better performance, lower operating cost, robustness, increased reliability, etc.
- Continuous Adjoint Method
  - Cost doesn't increase with the number of parameters
  - The calculation of the sensitivity derivatives is approximately equivalent with the solution of one primal problem
  - Can be perfectly implemented on OpenFOAM as the adjoint equations are similar with the equations of the primal problem
  - Is already used for shape, flow-control, robust-design, topology optimization problems

Examples | Topology Optimization

Automotive air intake system



Multi-objective of intake port



Current Problems | Porosity Method

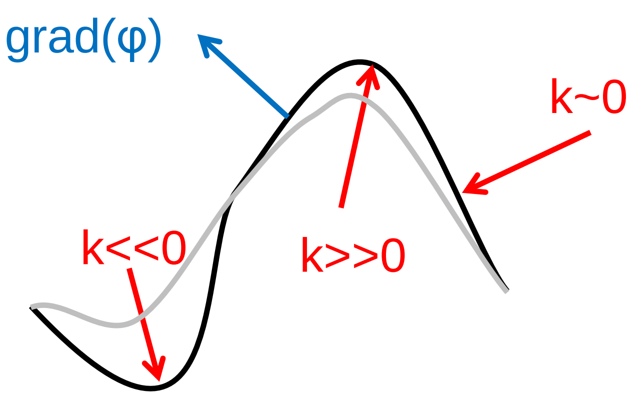
- The Final Shape is rough
- Islands
- Different speed for blocking and unblocking areas
- Lack of accuracy
  - Interface is approximately in the intermediate area
  - Nature of porosity means resistance
  - Bigger problem in turbulent flows
- Optimization slow due to the small sensitivities
- **Not manufacturable**

Proposed Method:

Level-Set based Topology Optimization

Level-Set Method

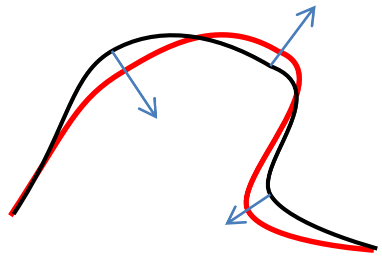
- **Porosity based Topology Optimization**
  - Design variable: Porosity a
    - a = 0 - fluid area
    - a > 0 - solid area
- **Level-Set based Topology Optimization**
  - Design variable: signed distance ϕ from Interface
    - ϕ = 0 - Interface
    - ϕ < 0 - fluid
    - ϕ > 0 - solid
  - The interface propagates using Surface Sensitivities as a velocity in the Transport equation
  - Curvature Limitation $k = \nabla \cdot \left(\frac{\nabla \varphi}{|\nabla \varphi|} \right)$



Level-Set Basic Equations

- **Transport or "Level-Set Equation"**

$$\frac{\partial \varphi}{\partial t} + \frac{\partial (G_i \varphi)}{\partial x_i} - \varphi \frac{\partial G_i}{\partial x_i} = 0 \qquad G_n = \frac{\partial v_i}{\partial n}\frac{\partial u_i}{\partial n} \qquad G_i = G_n \frac{\partial \varphi}{\partial x_i}$$



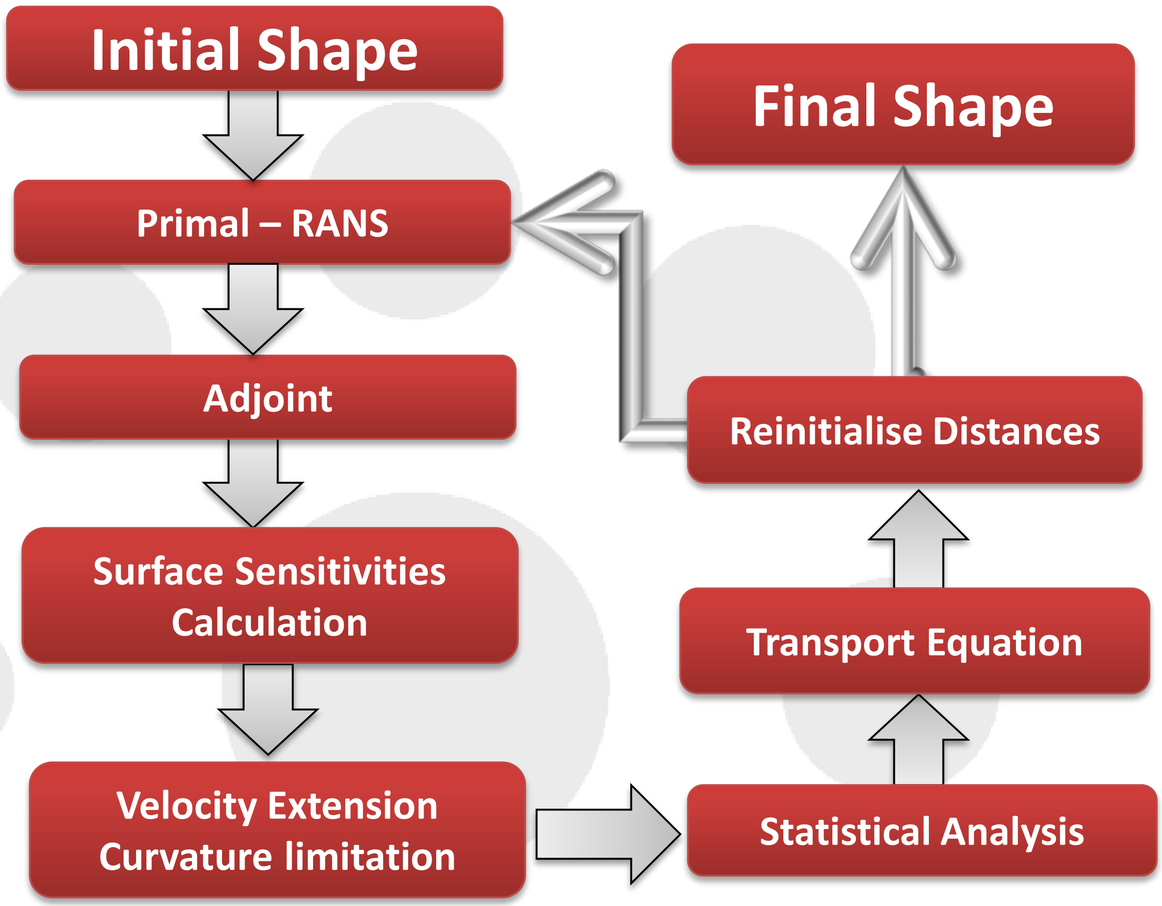
  - v - velocity, u - adjoint velocity
  - G - velocity of the interface resulting from Surface Sensitivities

- **Reinitialization Equation**

$$\frac{\partial \varphi}{\partial t} + \frac{\partial (W_i \varphi)}{\partial x_i} - \varphi \frac{\partial W_i}{\partial x_i} = sign(\varphi_0) \qquad W_i = sign(\varphi_0) \frac{\frac{\partial \varphi}{\partial x_i}}{\left|\frac{\partial \varphi}{\partial x_i}\right|}$$

  - Solve Reinitilization Equation in a narrow band and extend distances with Meshwave

Level Set Adjoint Optimization Algorithm



Design Variables:

Signed Distance φ

φ = 0 Interface

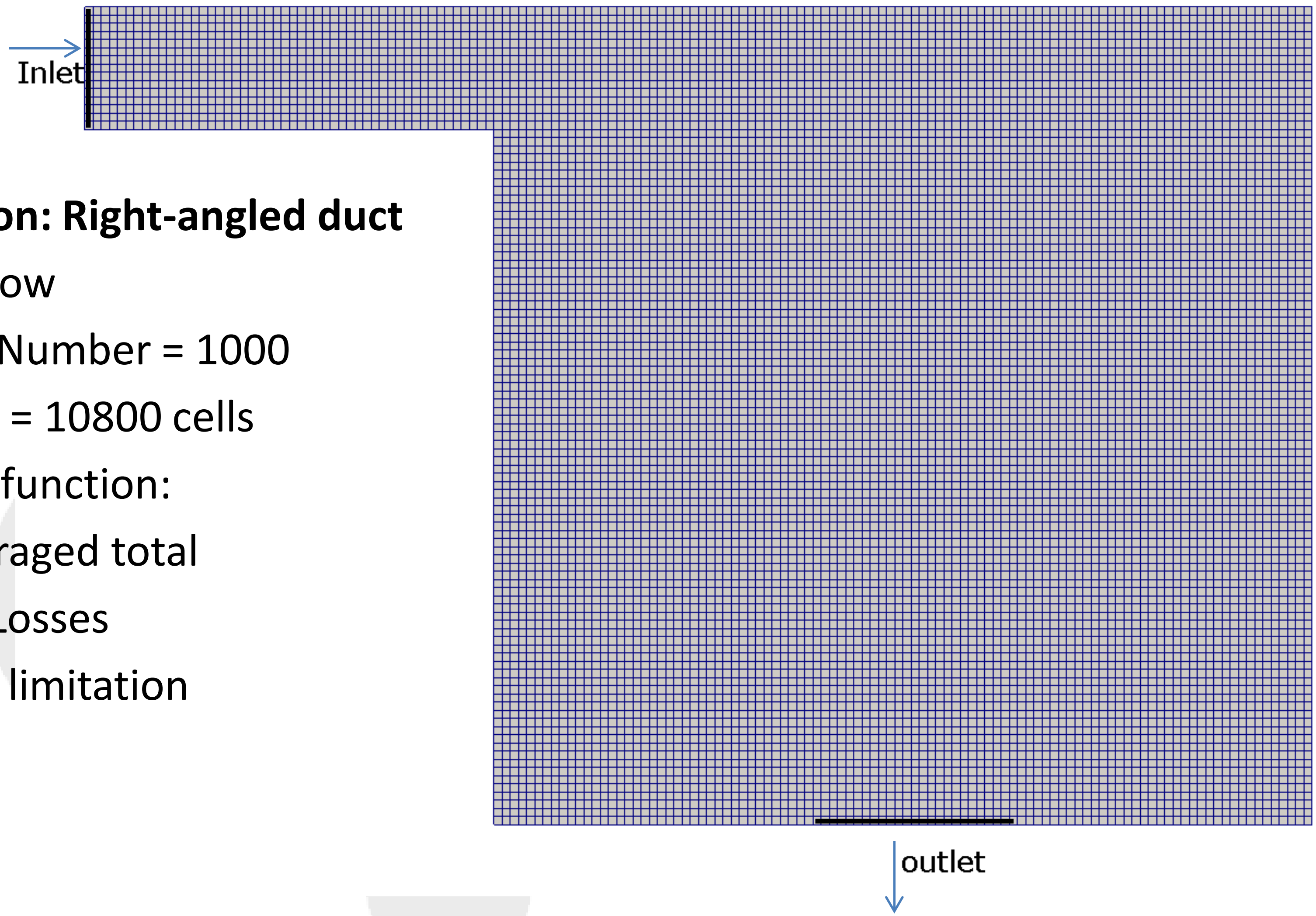
φ > 0 Solid

φ < 0 Fluid

Advantages:

- Smooth Interface
- High Accuracy
- Ability to add Immersed Boundaries

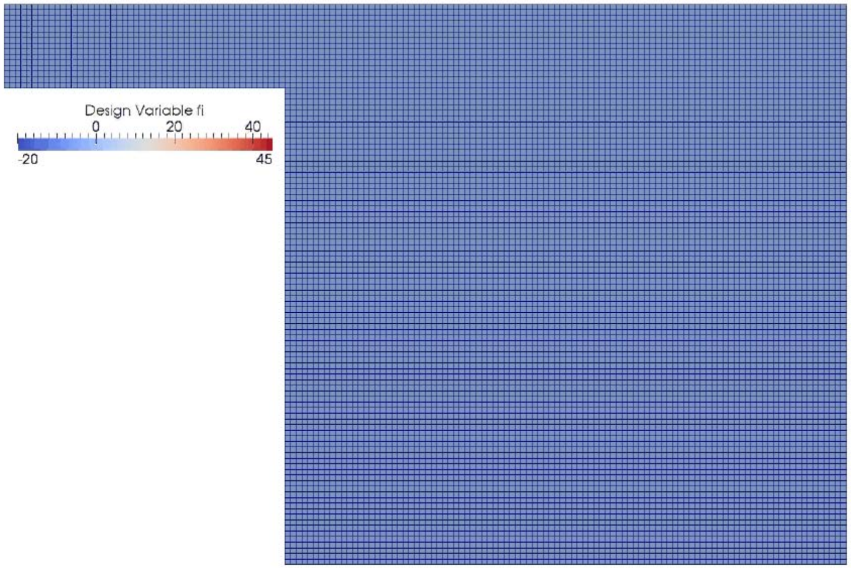
1st Application | Case explanation

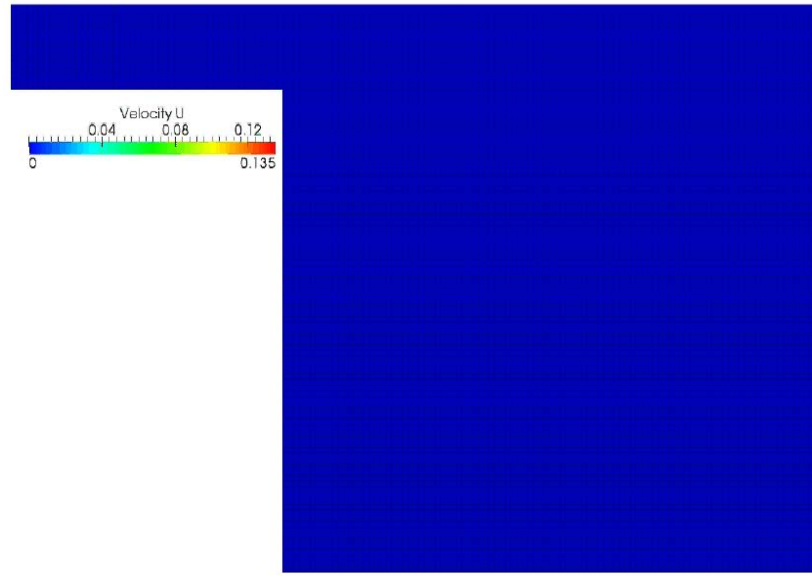


1st Application: Right-angled duct

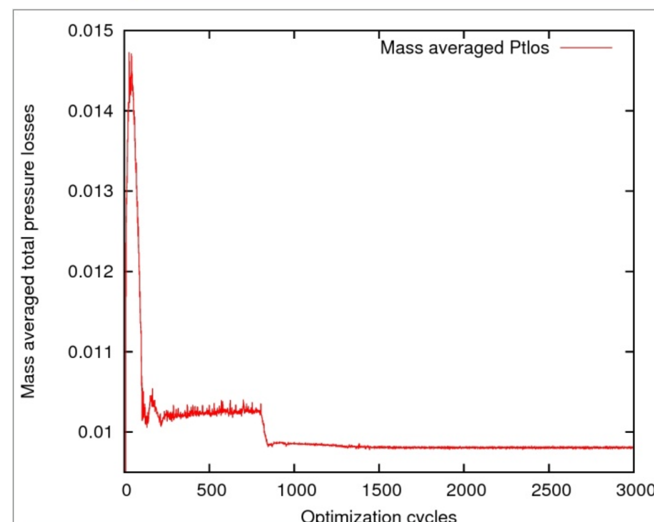
- Laminar flow
  Reynolds Number = 1000
- Mesh Size = 10800 cells
- Objective function:
  Mass Averaged total
  Pressure Losses
- Curvature limitation

2d Right Angled Duct |Optimization





- High curvature limitation in first 800 iterations
- Statistical analysis to cut the sensitivity peaks
- Scaling Sensitivities to make Courant Number = 1
- The final shape is very smooth



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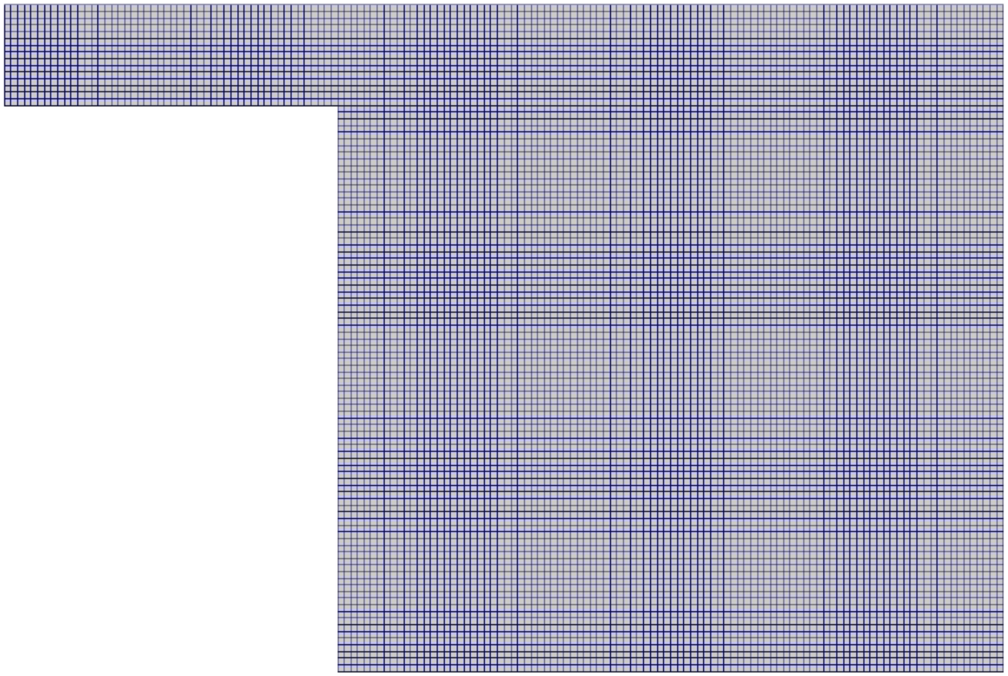
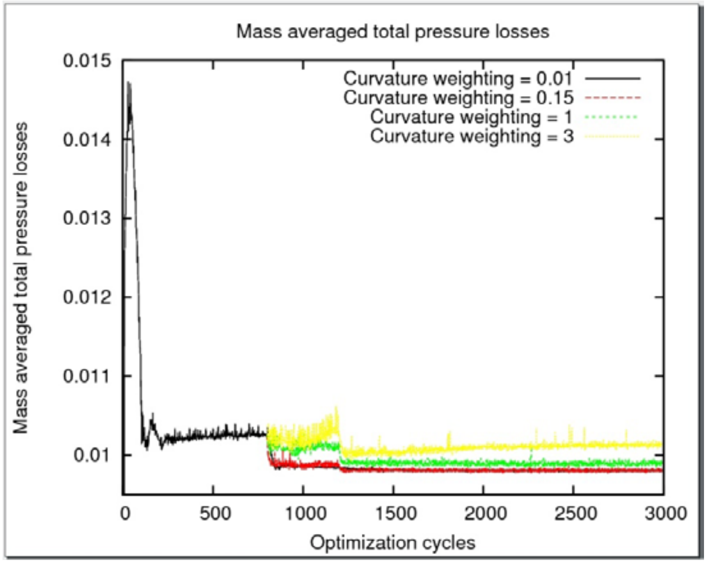
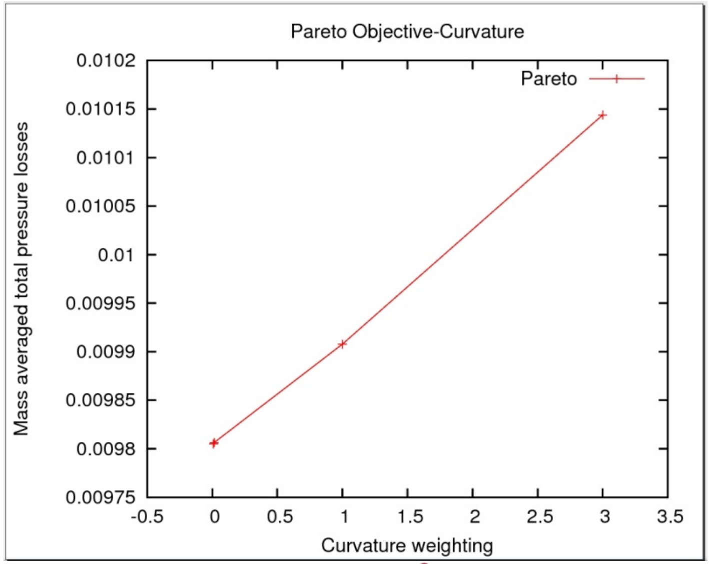
2d Right Angled Duct | Curvature

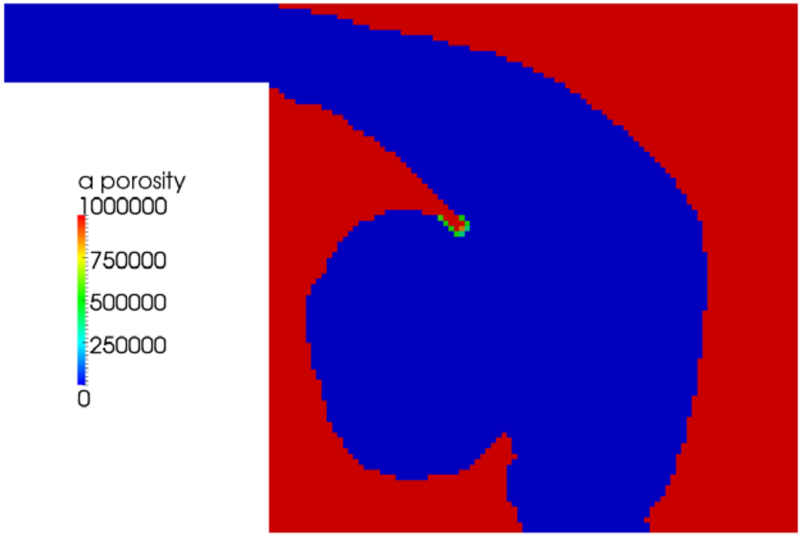


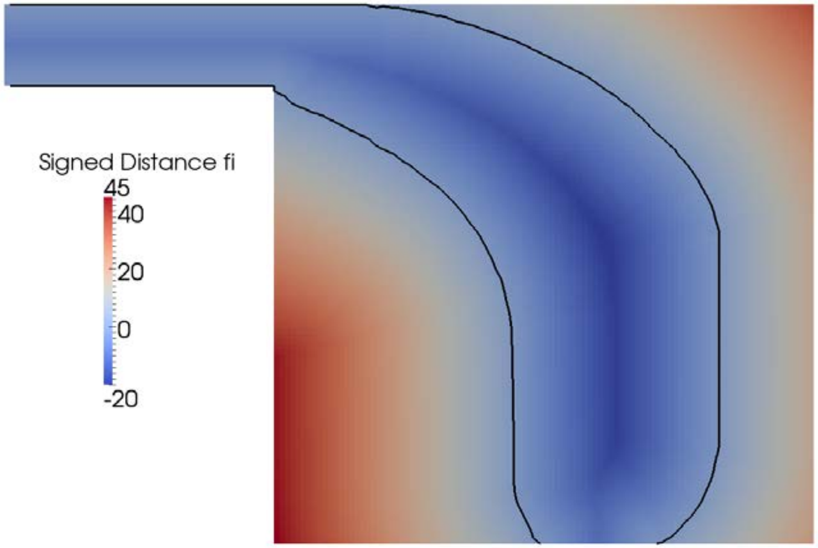




- Pareto Front for different weighting in Curvature limitation
- Higher the weighting the smoother the Interface
- Curvature limitation improves manufacturability

Porosity vs Level Set





Method	Objective - Δptot
Porosity	0.0129 W
Level-Set	0.0098 W

- Porosity method trapped into a local minimum
- Smooth interface using Level Set
- 24% better objective function achieved with level-Set

2nd Application – Case explanation

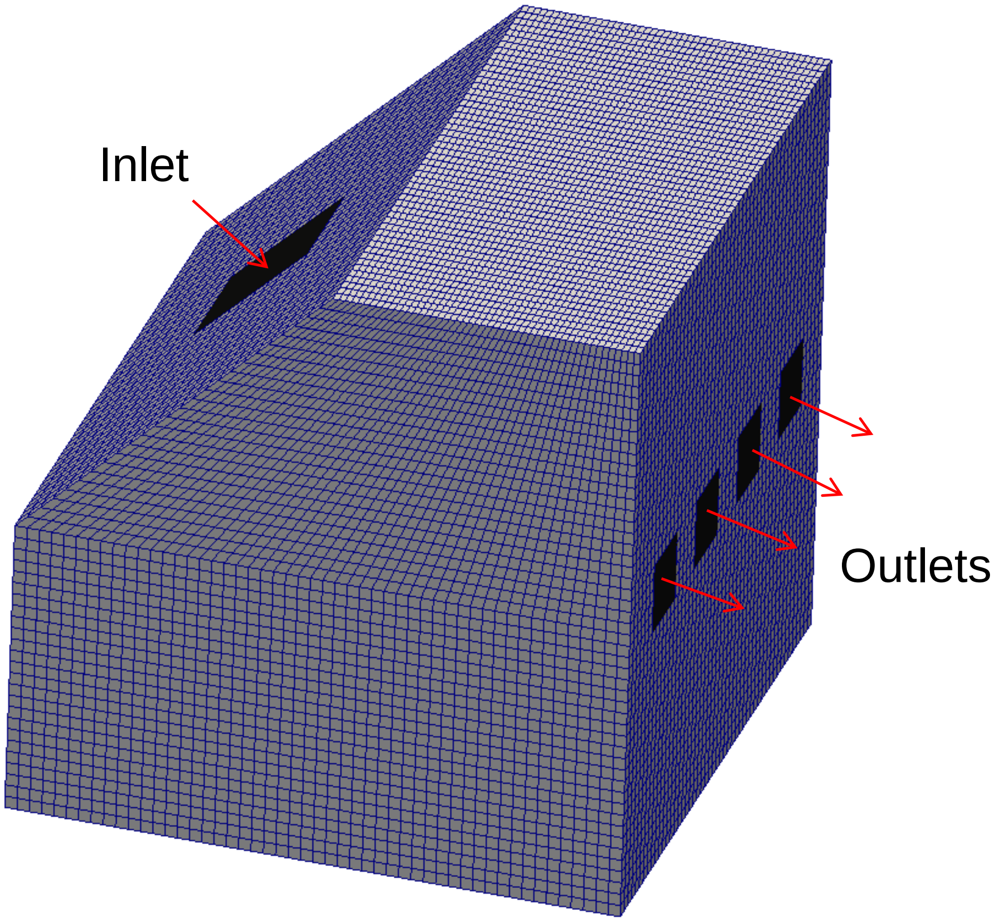
2nd Application: 3d Manifold

- Laminar flow

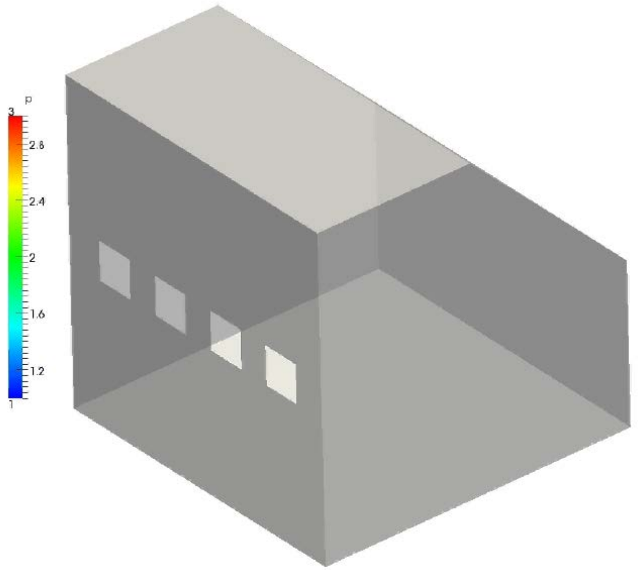
  Reynolds Number = 2000
- Mesh Size = 125000 cells
- Objective function:

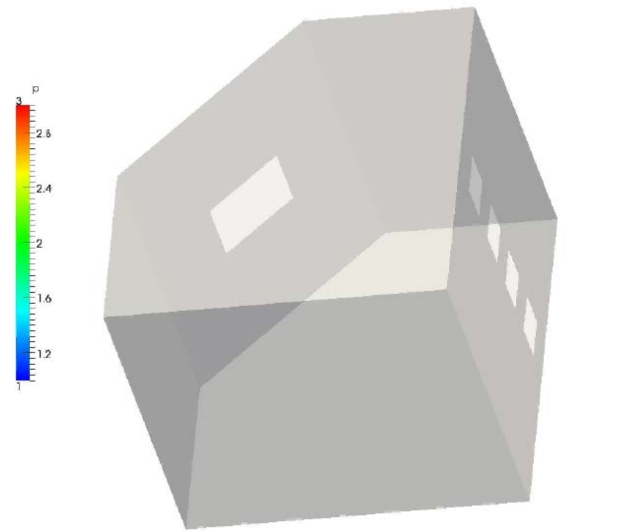
  Mass Averaged total

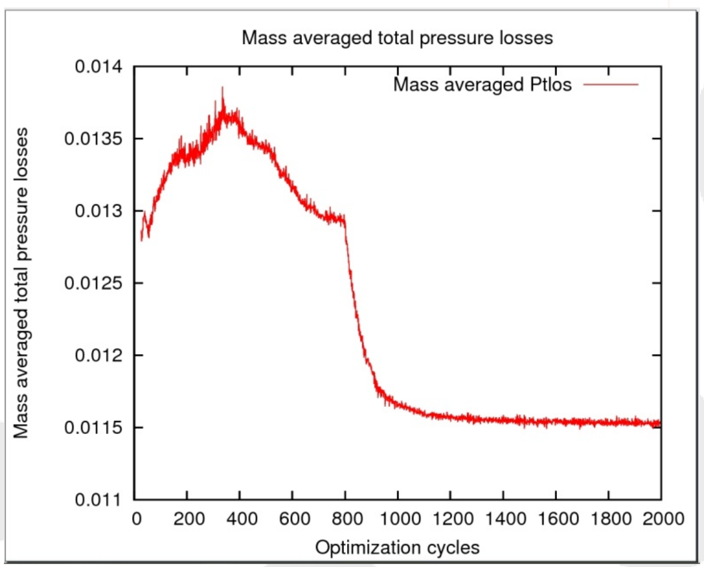
  Pressure Losses
- Curvature limitation



Manifold | Optimization







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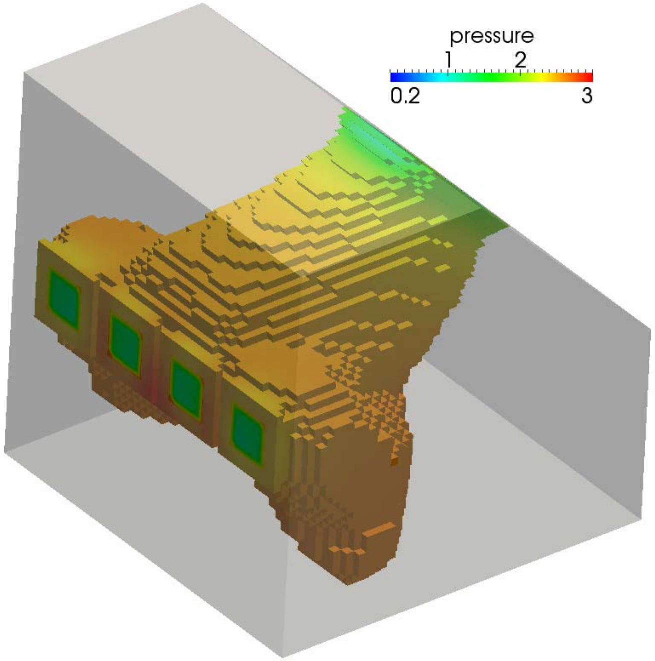
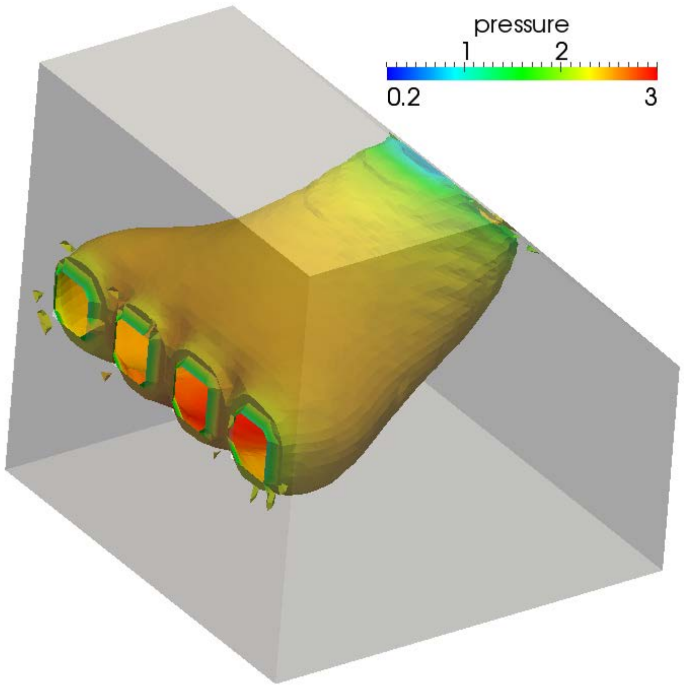
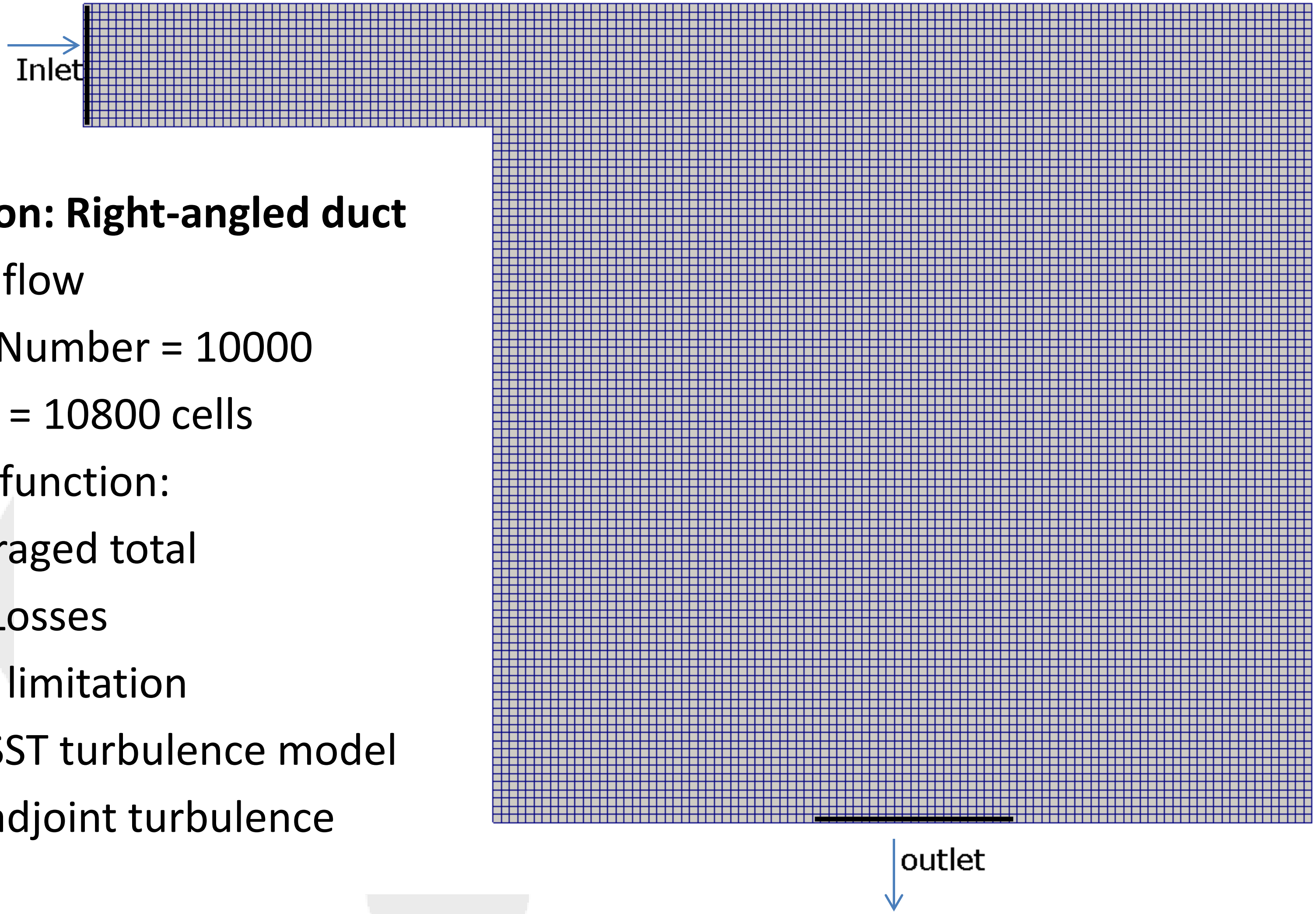
Porosity vs Level set





Method	Objective - Δptot
Porosity	0.0122 W
Level-Set	0.0115 W

3rd Application | Case explanation



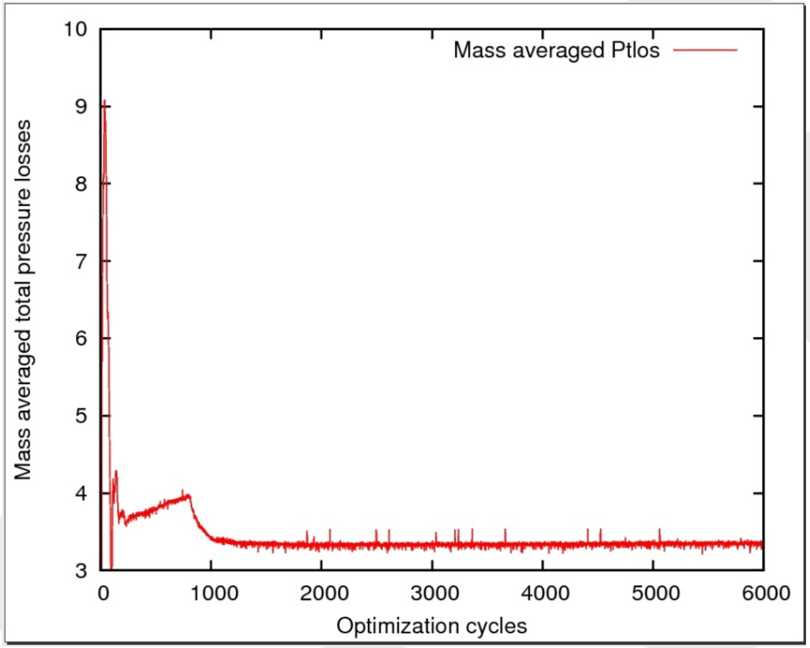
3rd Application: Right-angled duct

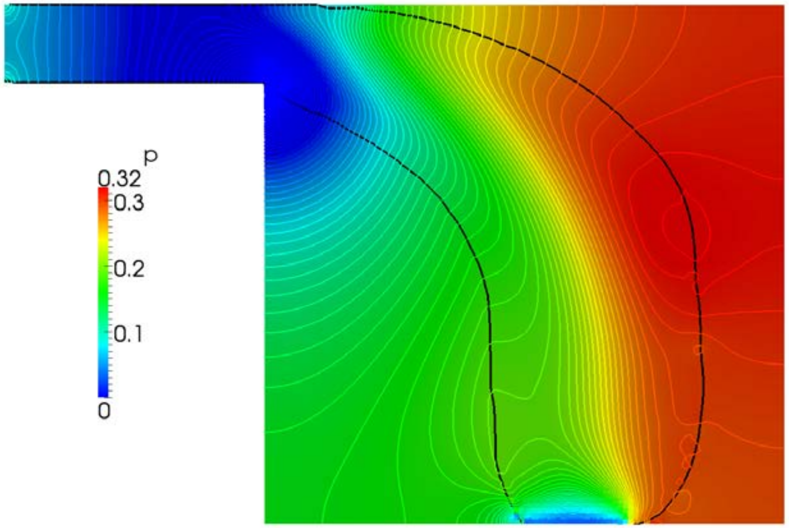
- Turbulent flow
  Reynolds Number = 10000
- Mesh Size = 10800 cells
- Objective function:
  Mass Averaged total
  Pressure Losses
- Curvature limitation
- k-omega SST turbulence model
- “Frozen” adjoint turbulence

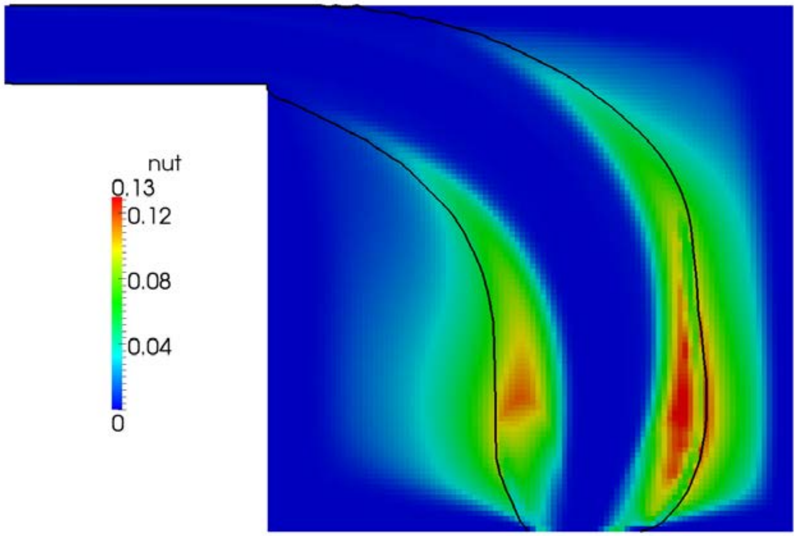
3rd Application |Turbulent case

- Frozen Adjoint turbulence
- Knowledge of distances from walls (Interface)

  Major advantage of level-set in wall functions for turbulent flows
- Next step: Implementation of Immersed boundaries







Conclusions | Summary

- Very smooth final shape
- High accuracy
- Knowledge of the exact distances from interface
- Quick optimization convergence
- Cost does not increase with number of parameters

Conclusions | Future Work

- Implementation of immersed boundaries to improve accuracy especially in turbulent flows
- Statistical analysis to boost optimization speed and convergence
- Intelligent management algorithms for effective multi-objective weighting
- Implementation of tools for extracting the final shape
- Implementation of Adjoint turbulence
- Second order Sensitivity Derivatives using Truncated-Newton method
- High order schemes to improve accuracy
- Multi-point optimization for pseudo-transient cases

The End

Thanks for your time!

Any questions?