Optimization of Nonlinear, Coupled Fluid-Thermal Systems

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Presentation Outline

- Overview
  - Project Goals
  - Microgravity Research
  - MGFLO
  - Optimization Theory
  - Previous Work
- Code Details
  - Overview
  - Validation
  - Applications
- Conclusions
- Recommendations

Project Goals

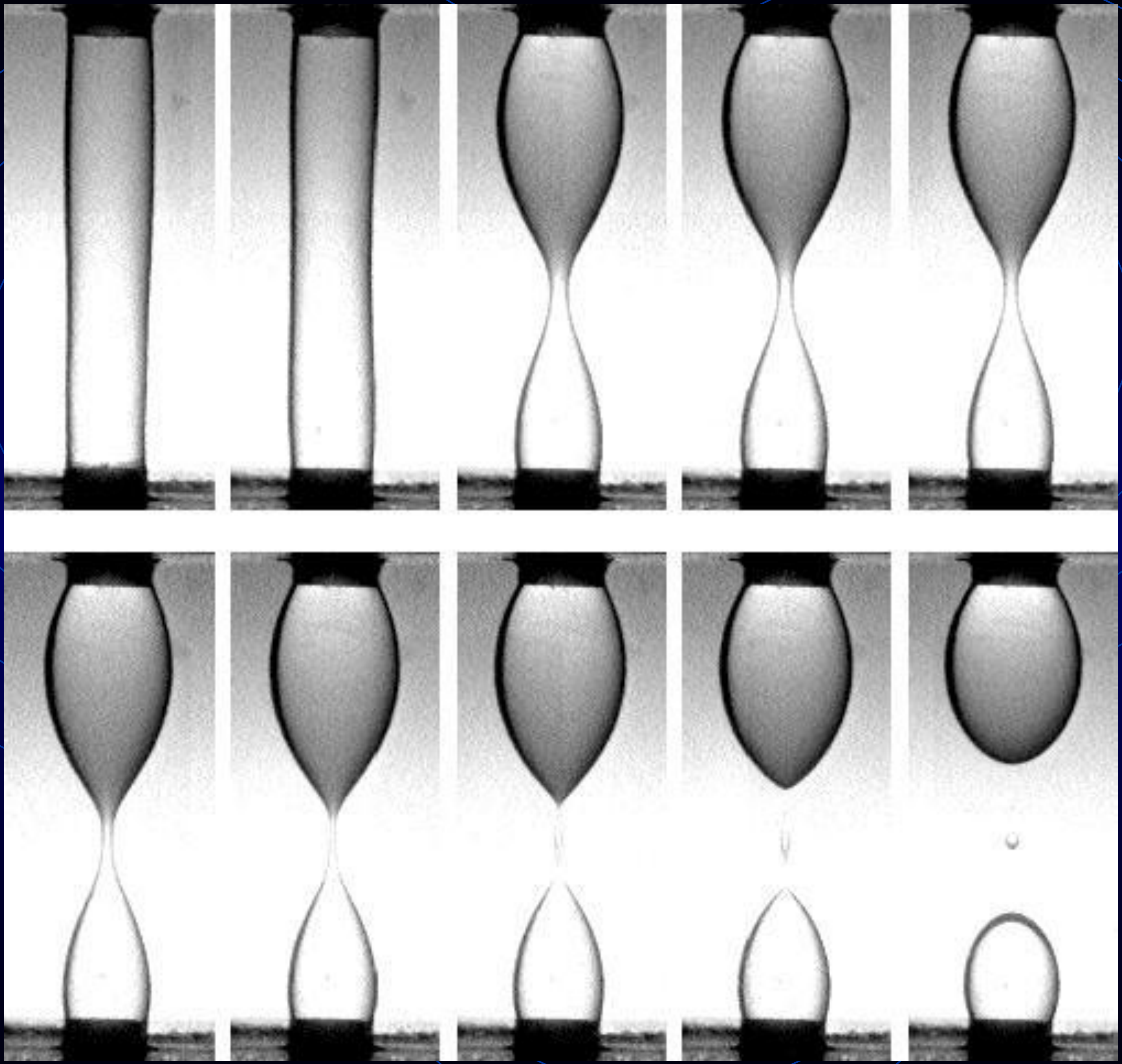
- To Design and Implement an optimization algorithm for a fluid-thermal simulator
  - MGFLO
  - Boundary Condition Manipulation

Microgravity Fluid Research

- Surface Tension
  - Smallest Surface Area Possible
  - Dominated on Earth by Gravity, which Makes Surfaces Flat
- Liquid Bridges
  - ALEX: A Liquid Electrohydrodynamics eXperiment
  - Surface Tension Dominates with Decreased Electric Field

In a microgravity environment, surface tension and thermocapillary effects can be dominant.

Strong Field

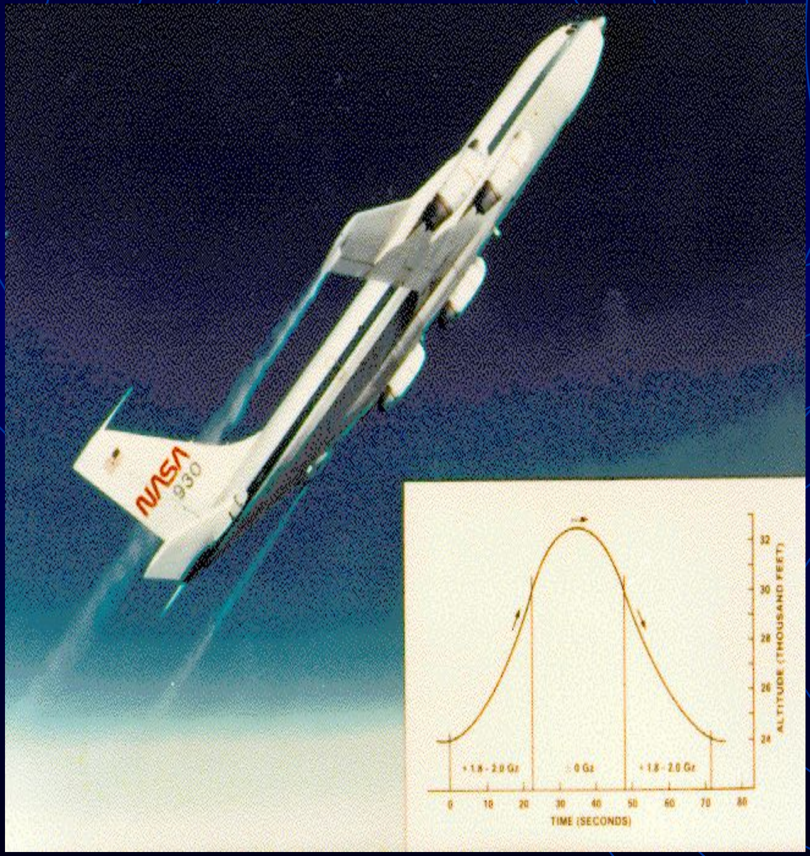


Weak Field

Microgravity Test Facilities

- Drop Towers
  - Evacuated tubes used to expose experiments to several seconds of microgravity
  - Only short durations of microgravity are achieved

Test Facilities



- NASA’s KC-135 “Vomit Comet”
  - Parabolic flight pattern can produce up to 30 seconds of microgravity
  - Several periods of microgravity in one flight

Test Facilities

- Sounding Rockets
  - Also flown in a parabolic flight path to produce microgravity
  - Can provide 6-7 minutes of microgravity

Microgravity Simulation

- Computational Fluid Dynamics (CFD) allows cost-effective microgravity simulation
- Advances in parallel supercomputing allow large problems to be solved

Governing Equations

- Incompressible Navier-Stokes Equations:

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\nabla\vec{u}\right) + \nabla\cdot\vec{\tau} = \vec{f} + \beta\left(T - T_{ref}\right)\vec{g}$$

$$\vec{\nabla}\cdot\vec{u} = 0$$

- Energy Equation:

$$\rho\cdot c_p\left(\frac{\partial T}{\partial t} + \vec{u}\cdot\vec{\nabla}T\right) - \vec{\nabla}\cdot\left(k\vec{\nabla}T\right) = Q$$

MGFLO

- Developed Under NASA-Grand Challenge Support
- Parallel, Finite Element Formulation of Navier-Stokes and Energy Equations
- Allows for Coupled and Uncoupled Solution
- Systems Optimized Through Matlab Using Existing Algorithms

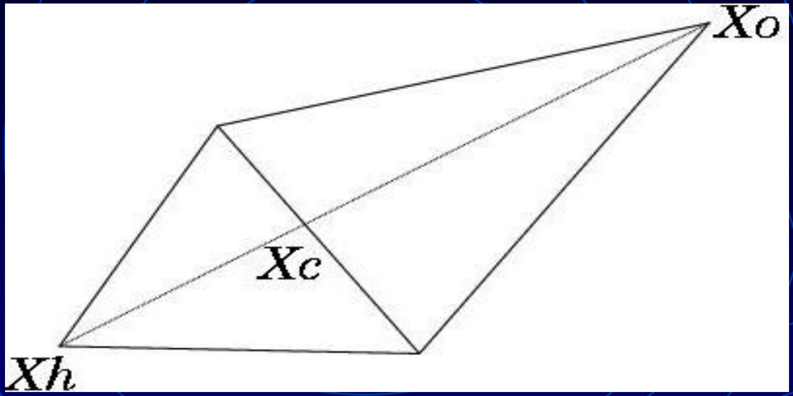
Optimization Theory

- Attempt to find "best value" of a merit function within defined constraints
- Gradient versus non-gradient methods
  - Gradient methods can be complex and require several merit function evaluations
  - Non-gradient methods optimize based on a sample set of merit function values
    - Nelder-Mead Simplex Search Algorithm

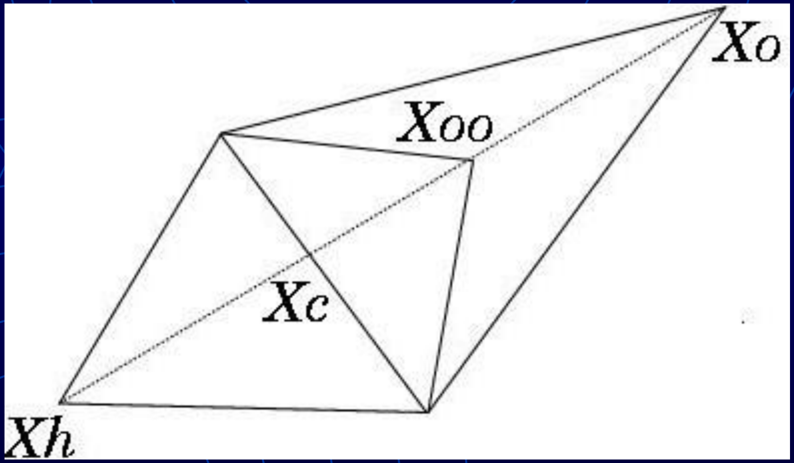
Nelder and Mead's Method

- Efficient search method for minimizing a merit function of up to six variables
- Optimization points are nodes of a polygon
- Optimal solution is determined by:
  - Reflection
  - Expansion
  - Contraction

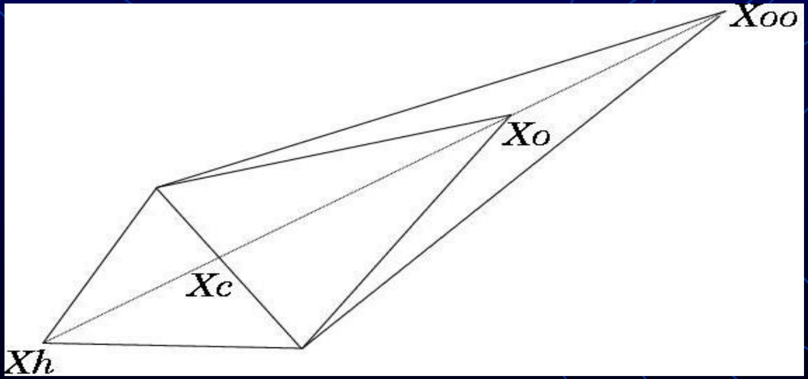
Simplex Steps



Reflection



Contraction



Expansion

Previous Work

- Investigated Operation of the MGFLO Code
- Designed Simple Optimization Routine in Matlab
- Established Algorithms to Optimize Complex Fluid-Thermal Systems

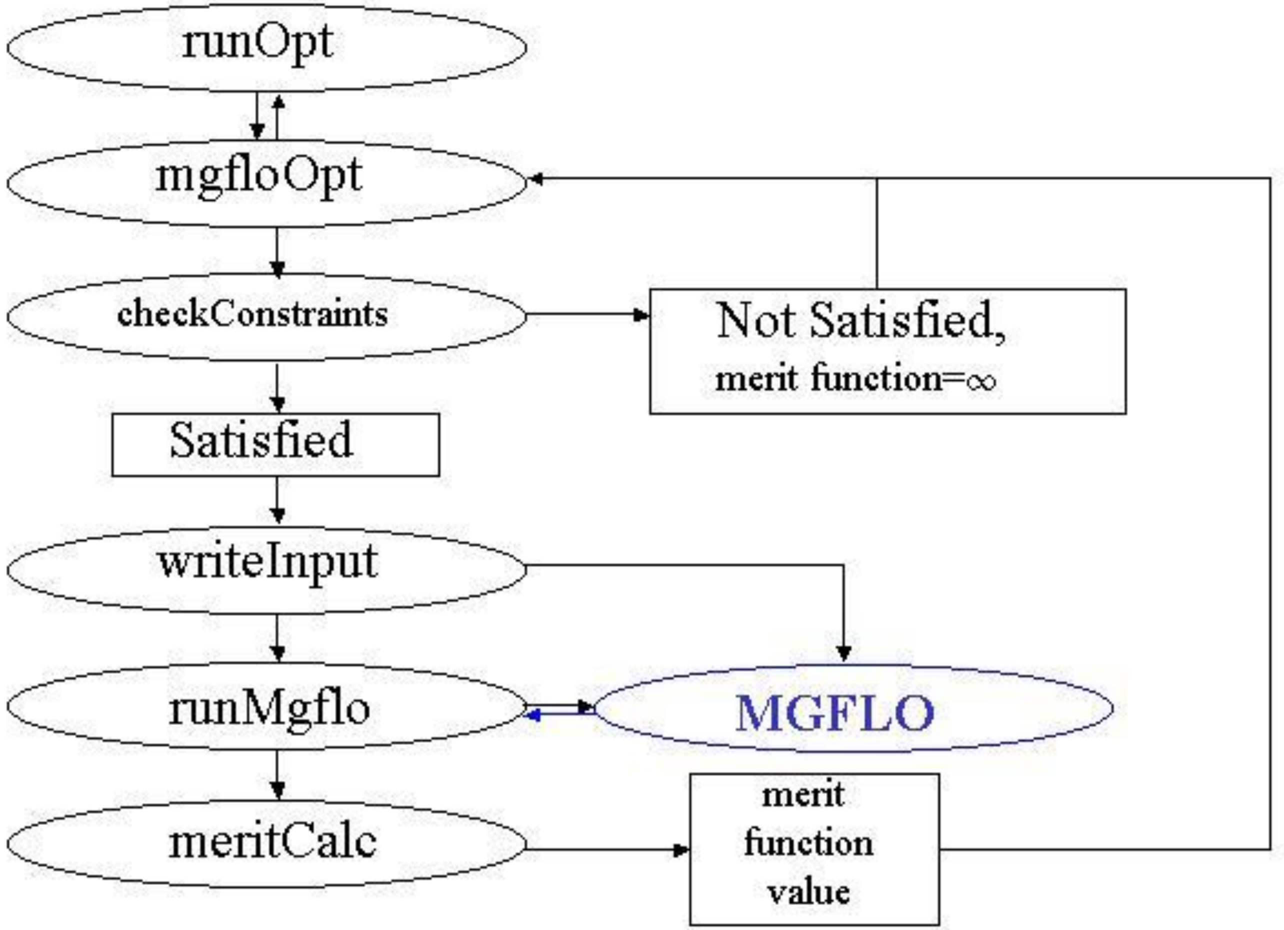
Code Overview

- Developed Matlab Routines to Analyze MGFLO Output.
- Matlab Can Compute Quantities of Interest:
  - Vorticity, Divergence
  - Gradient, Laplacian
  - 0^{th}, 1^{st}, 2^{nd} Order Derivatives Normal to Walls
  - Average Quantities in Large Datasets

Code Functions

- Initializes the solution
- Calls MGFLO for each simplex step
- Checks that user-specified constraints are satisfied
- Calculates the user-specified merit function
- Allows user to monitor solution progression

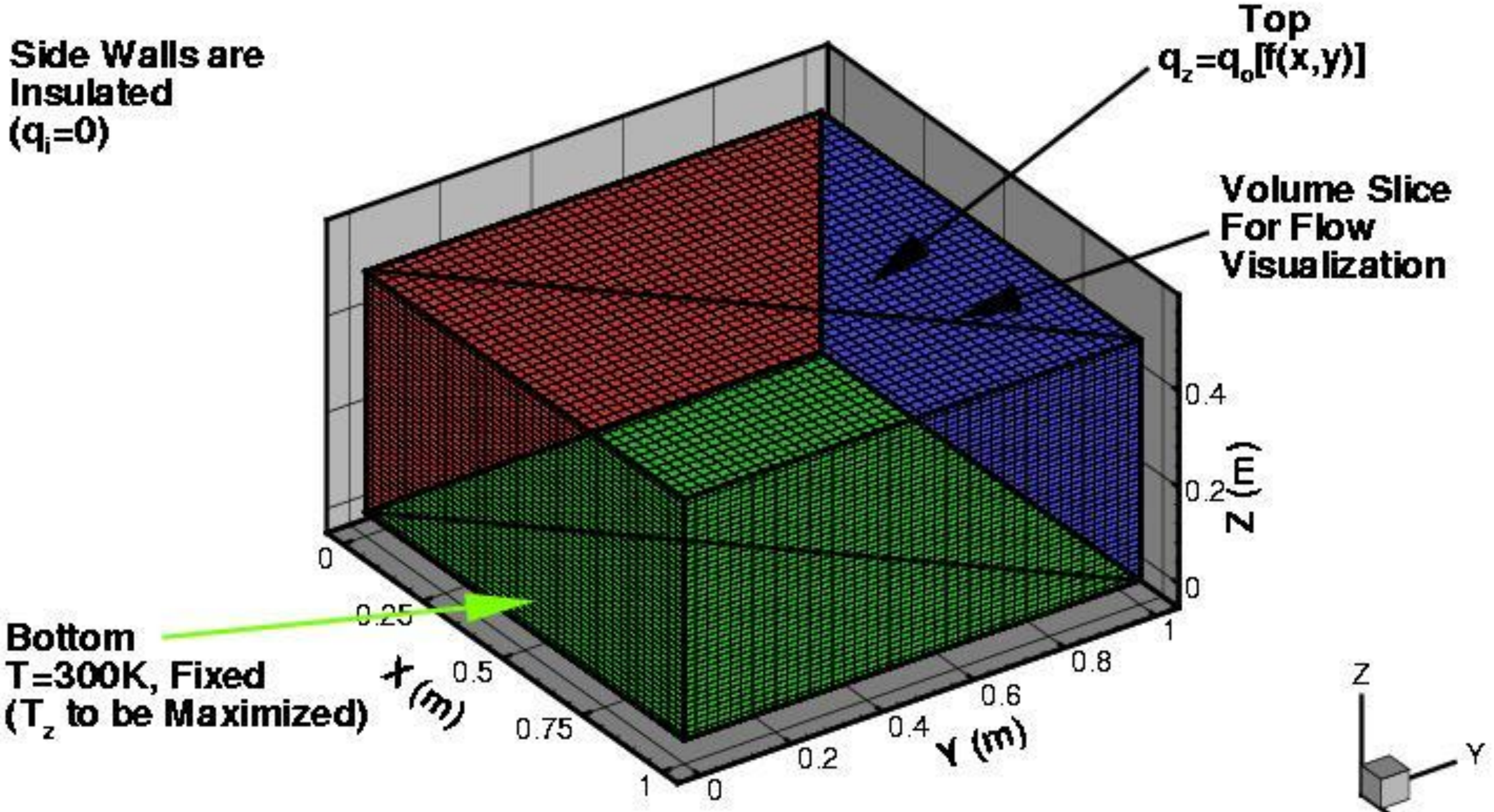
Flow Chart


runOpt
mgfloOpt
checkConstraints
Not Satisfied,
merit function=∞
Satisfied
writeInput
runMgflo
MGFLO
meritCalc
merit
function
value

Debugging & Validation

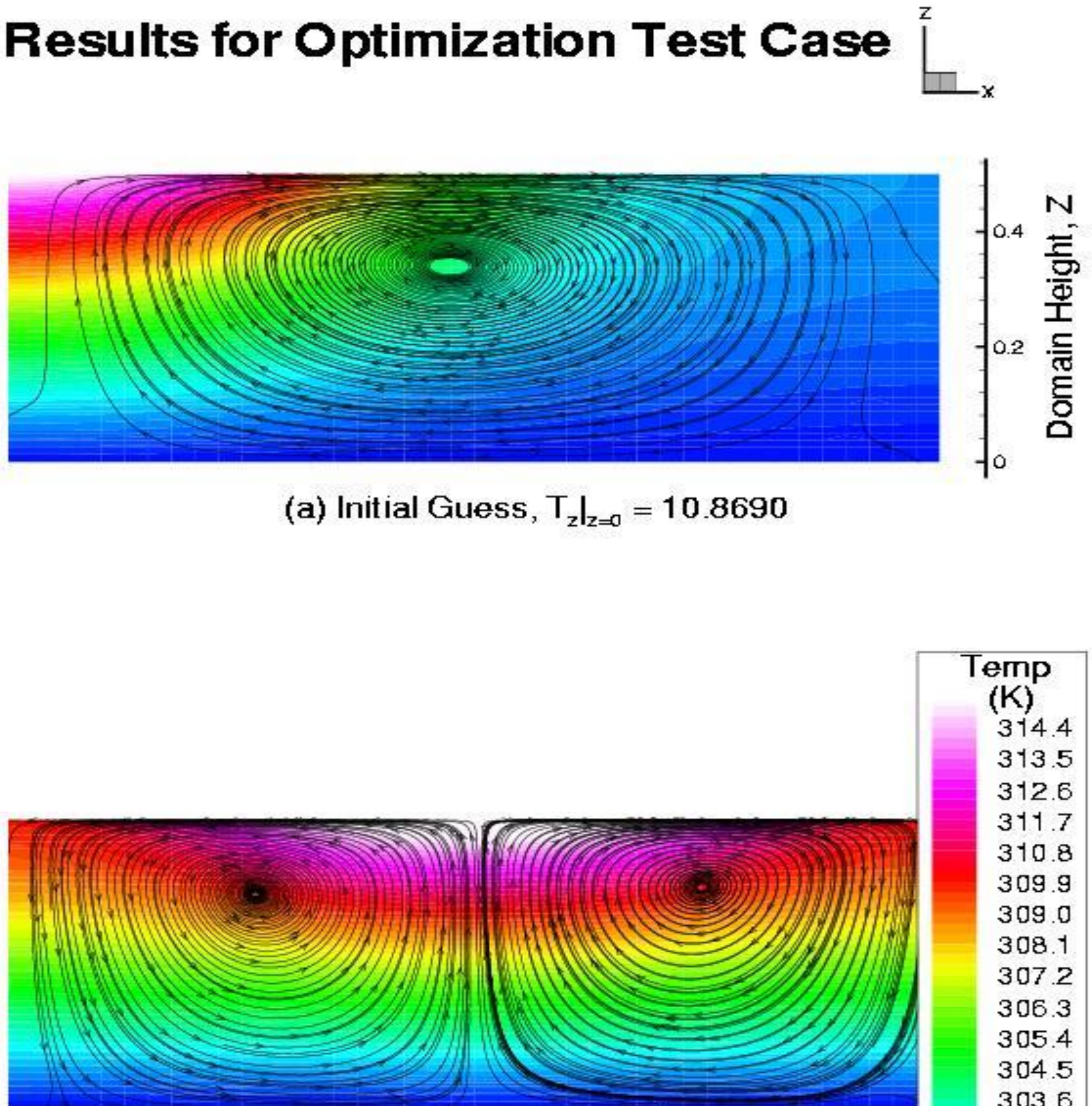
- Attempt to find answer to a known problem
- Position heat source on top surface to maximize heat flux out of the bottom
- Run on the 16-node Beowulf cluster in the CFDLab

Domain Description and Boundary Conditions for Optimization Test Problem



NOTE: f(x,y) is a Gaussian distribution

Results for Optimization Test Case

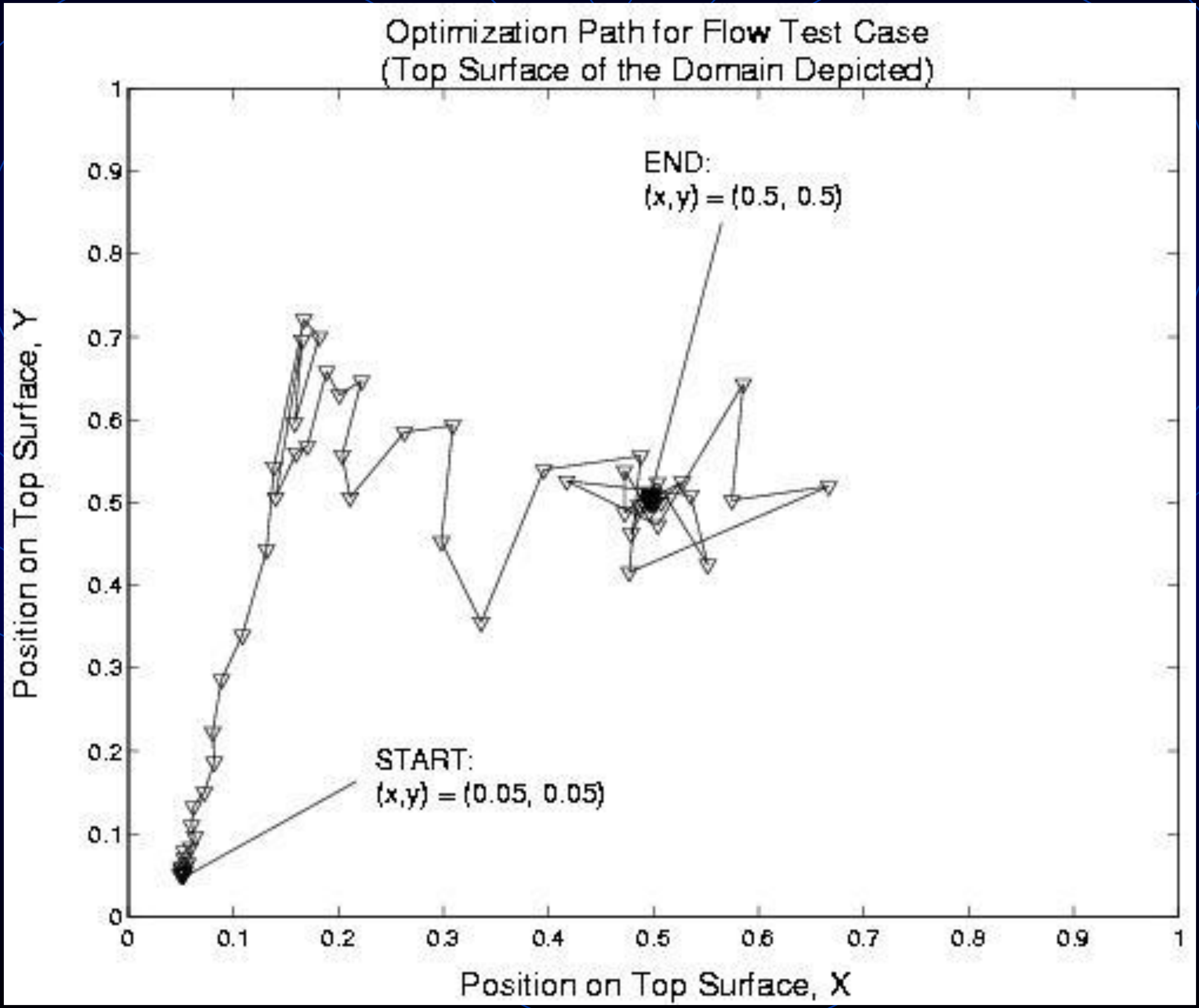


(a) Initial Guess, $T_z|_{z=0} = 10.8690$

(b) Optimized Solution, $T_z|_{z=0} = 26.1445$

Note: Slices Taken Along a Diagonal Plane

Optimization Path



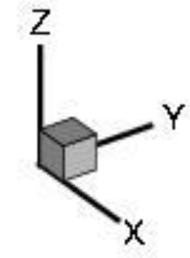
Limitations

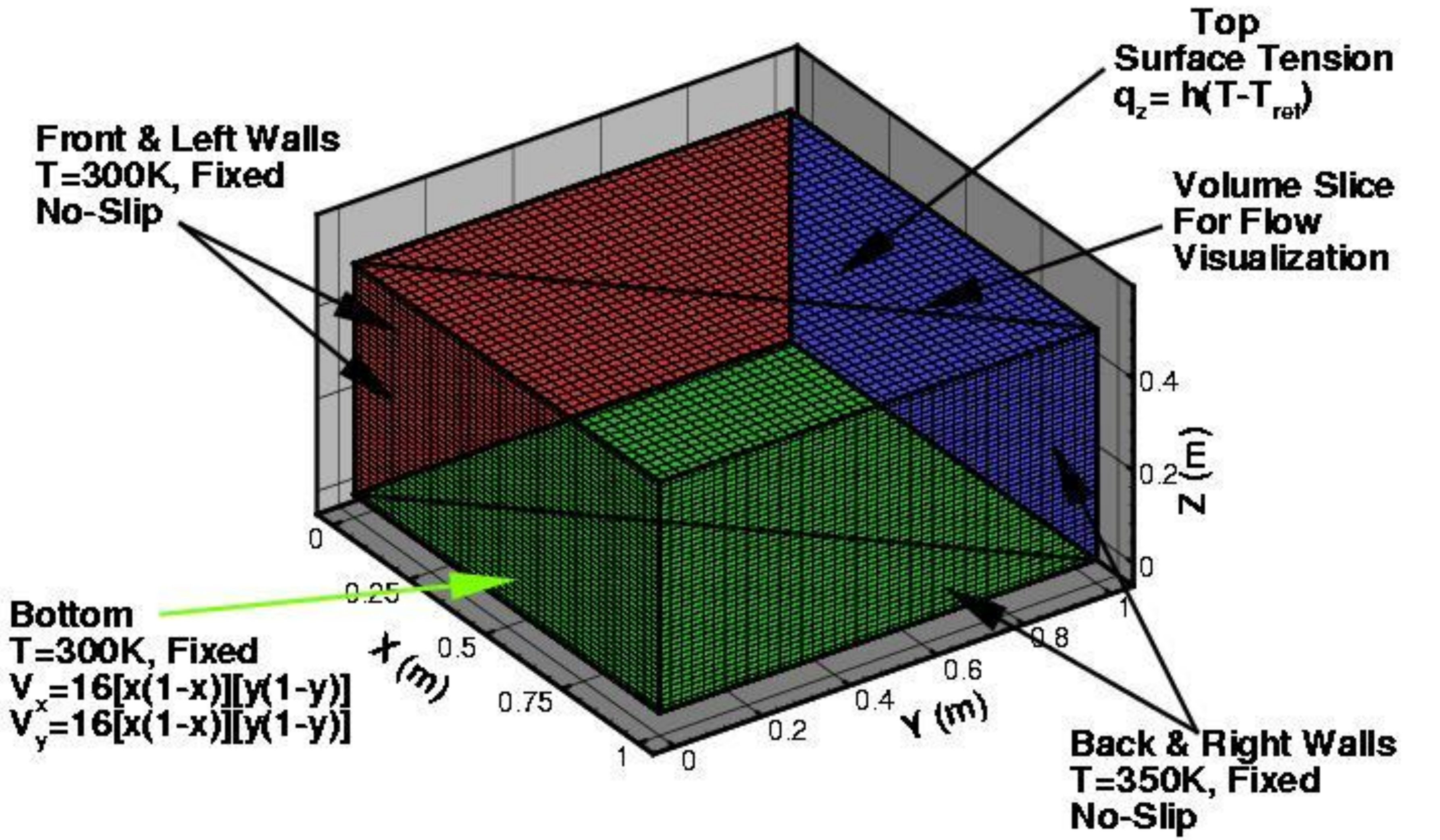
- Merit function dependence for pathological problems
  - Not successful at maximizing vorticity in previous case
  - Non-smooth merit functions (too many local maxima)

Applications

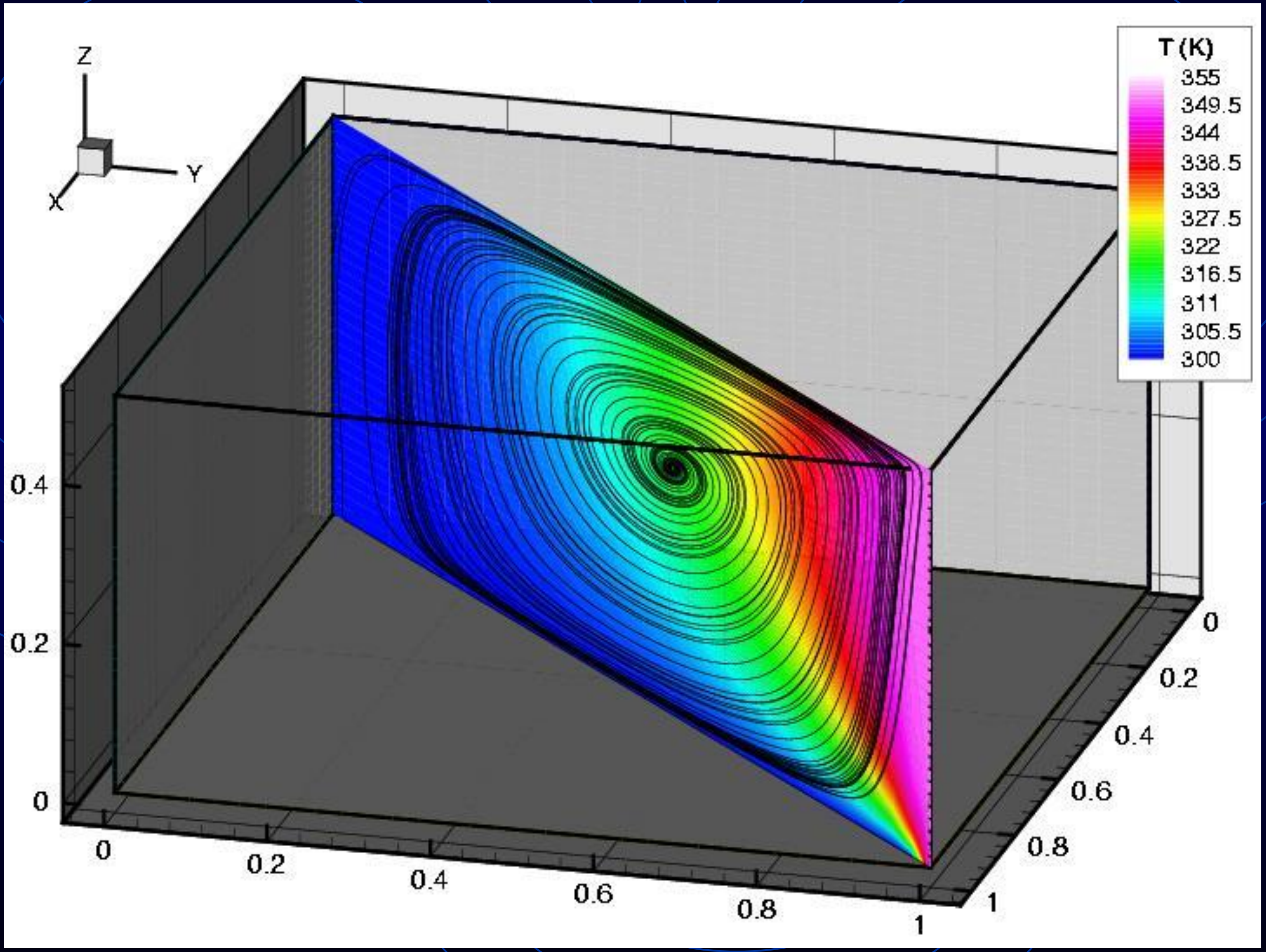
- Solve more complicated problem whose answer is not known *a-priori*
- System exposed to external environment via Newton's law of cooling (mixed boundary condition)
- Use particle tracing as a visualization technique

Domain Description and Boundary Conditions for Optimization Application Problem





Case 1: $T_{desired}$=310K



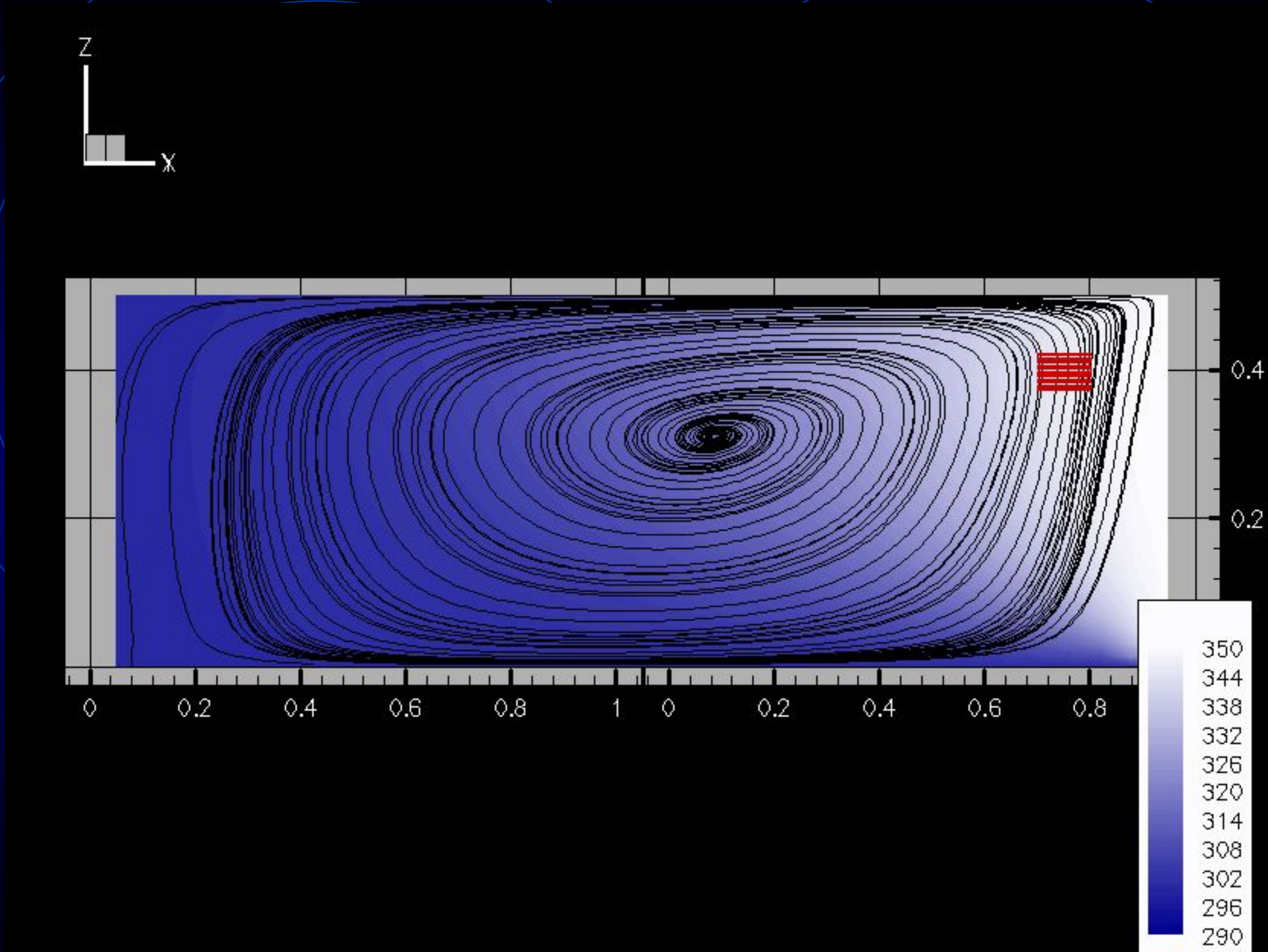
Particle Tracing Algorithm

- Heun predictor-corrector method
- Second-order accurate in time

$$\vec{x}_p^{\,n+1} = \vec{x}_p^{\,n} + \Delta t\left[\frac{3}{2}\vec{u}\left(\vec{x}_p^{\,n}, t^n\right) - \frac{1}{2}\vec{u}\left(\vec{x}_p^{\,n-1}, t^{n-1}\right)\right]$$

$$\vec{x}_k^{\,n+1} = \vec{x}_p^{\,n} + \Delta t\left[\frac{1}{2}\vec{u}\left(\vec{x}_p^{\,n+1}, t^{n+1}\right) + \frac{1}{2}\vec{u}\left(\vec{x}_p^{\,n}, t^n\right)\right]$$

- Allows visualization/quantification of mixing


Z
X
0.4
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0.4
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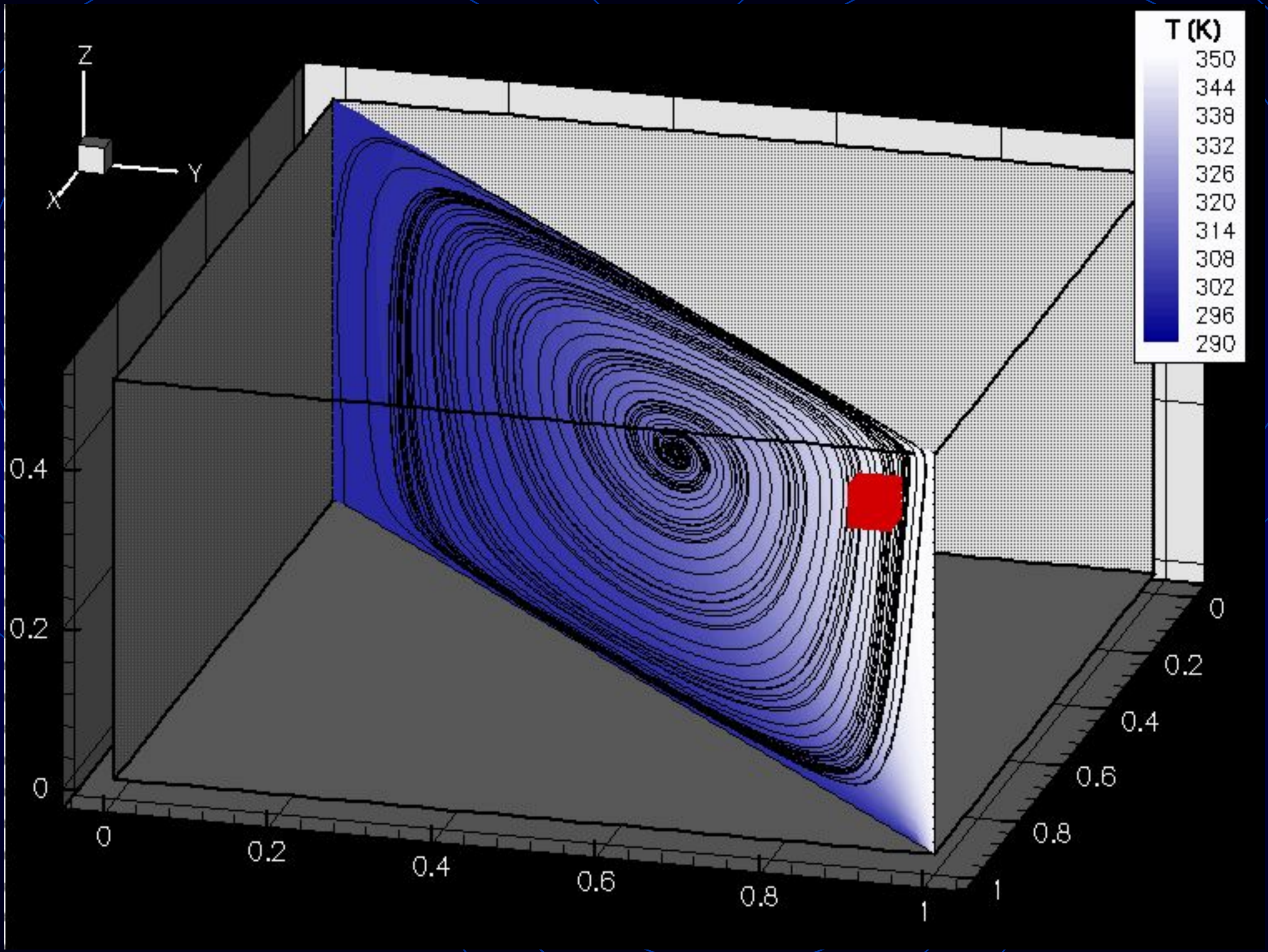
T (K)
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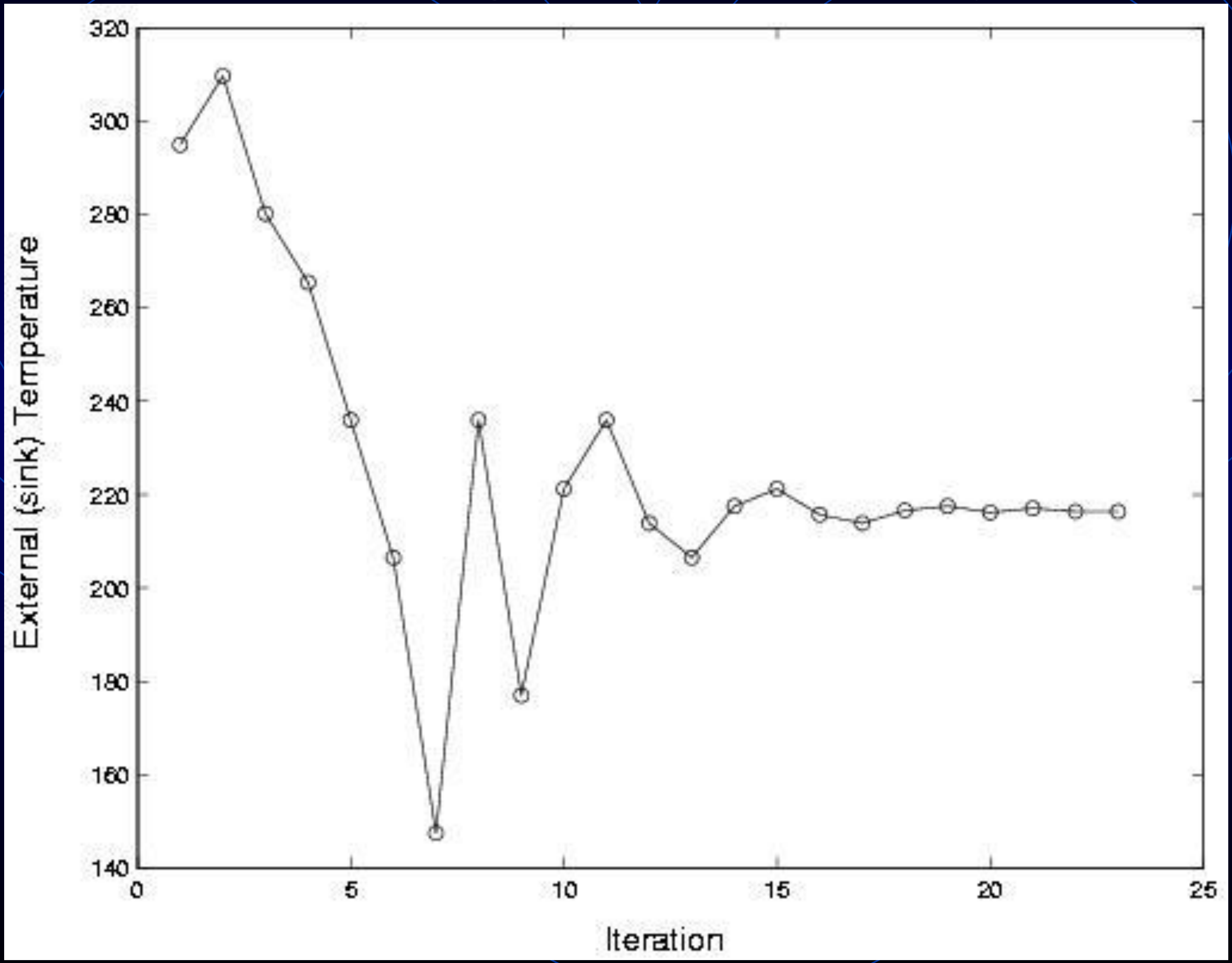
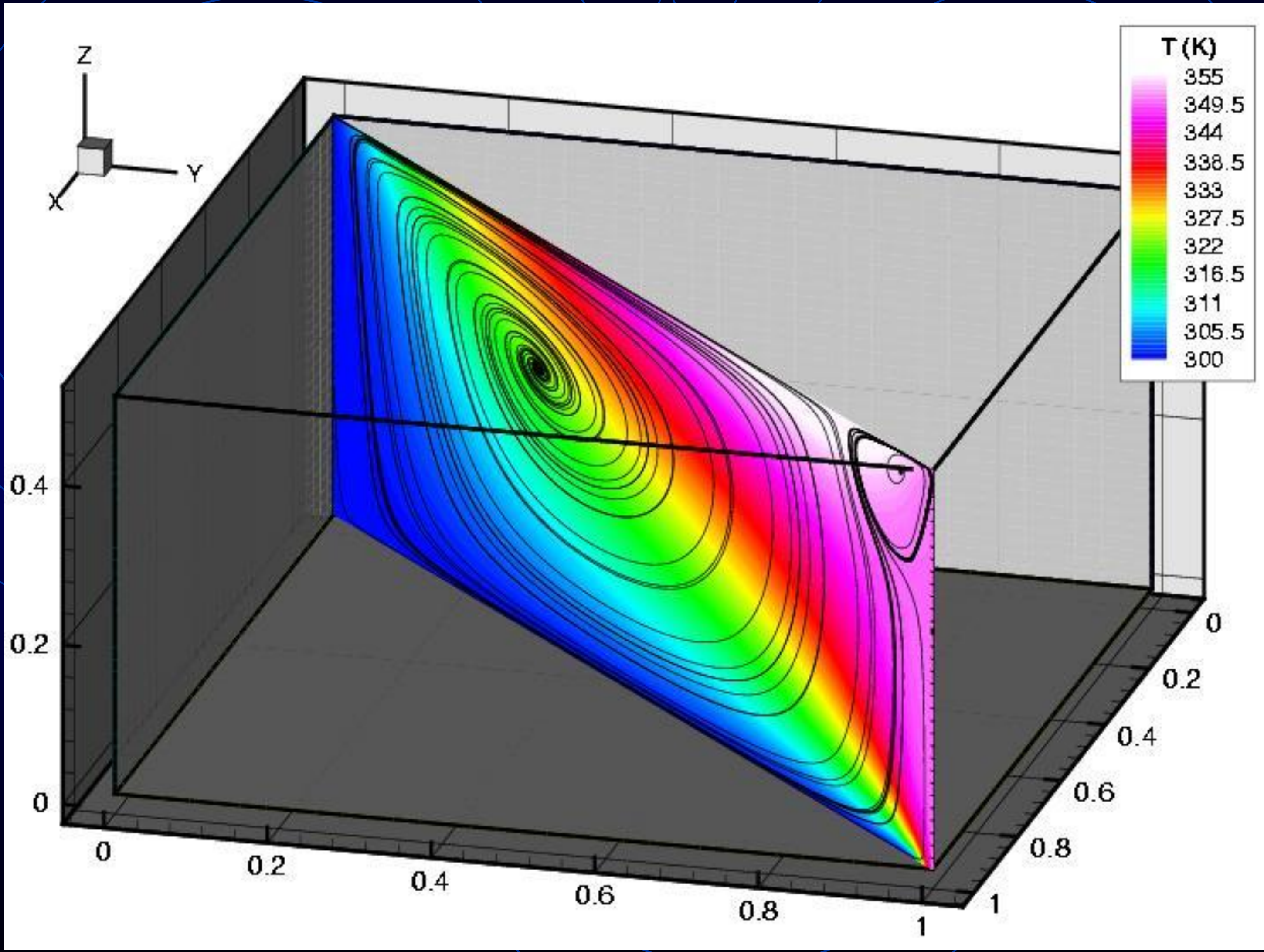
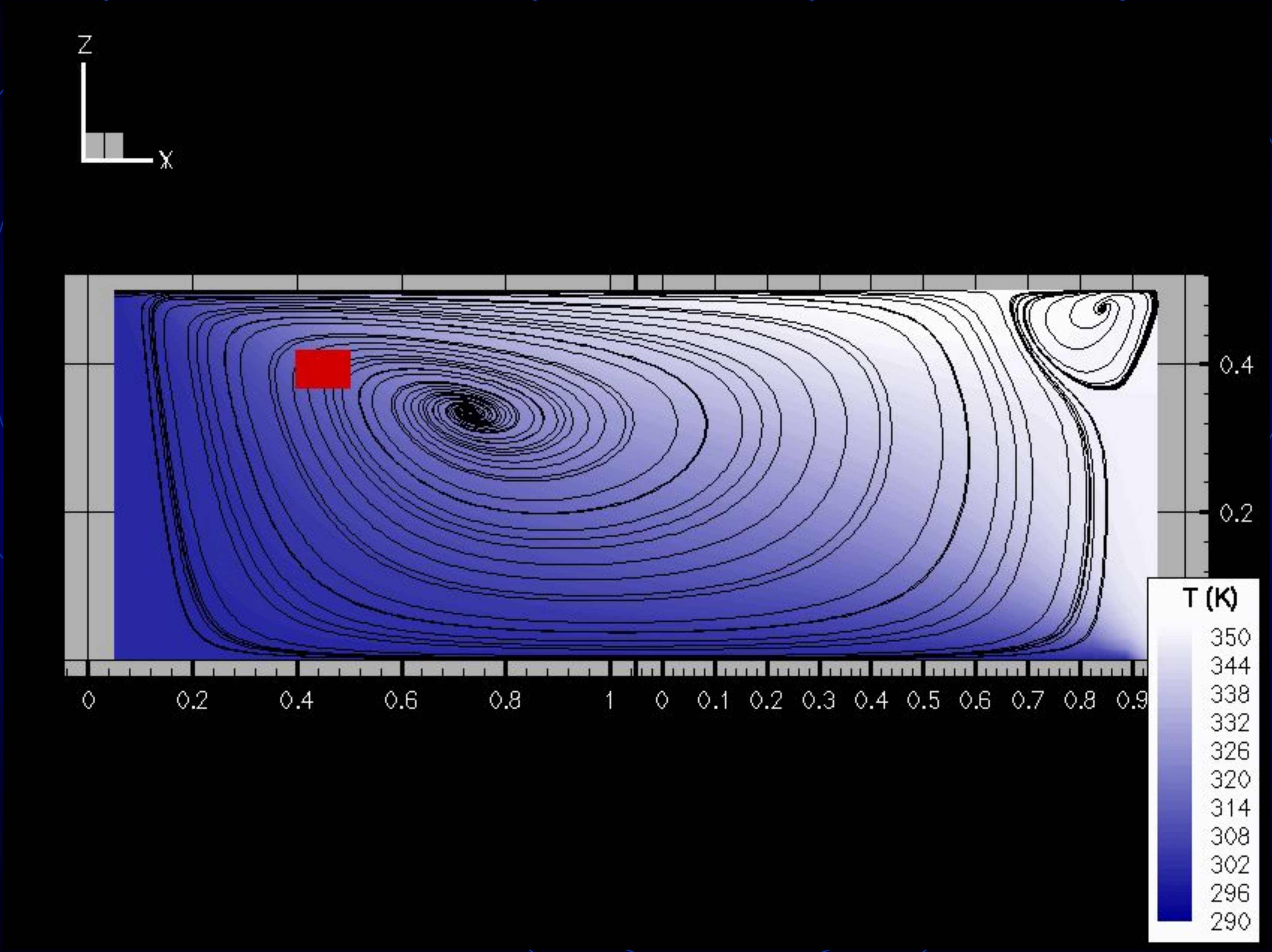
Convergence History



Case 2: $T_{desired}$=340K





Z
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T (K)
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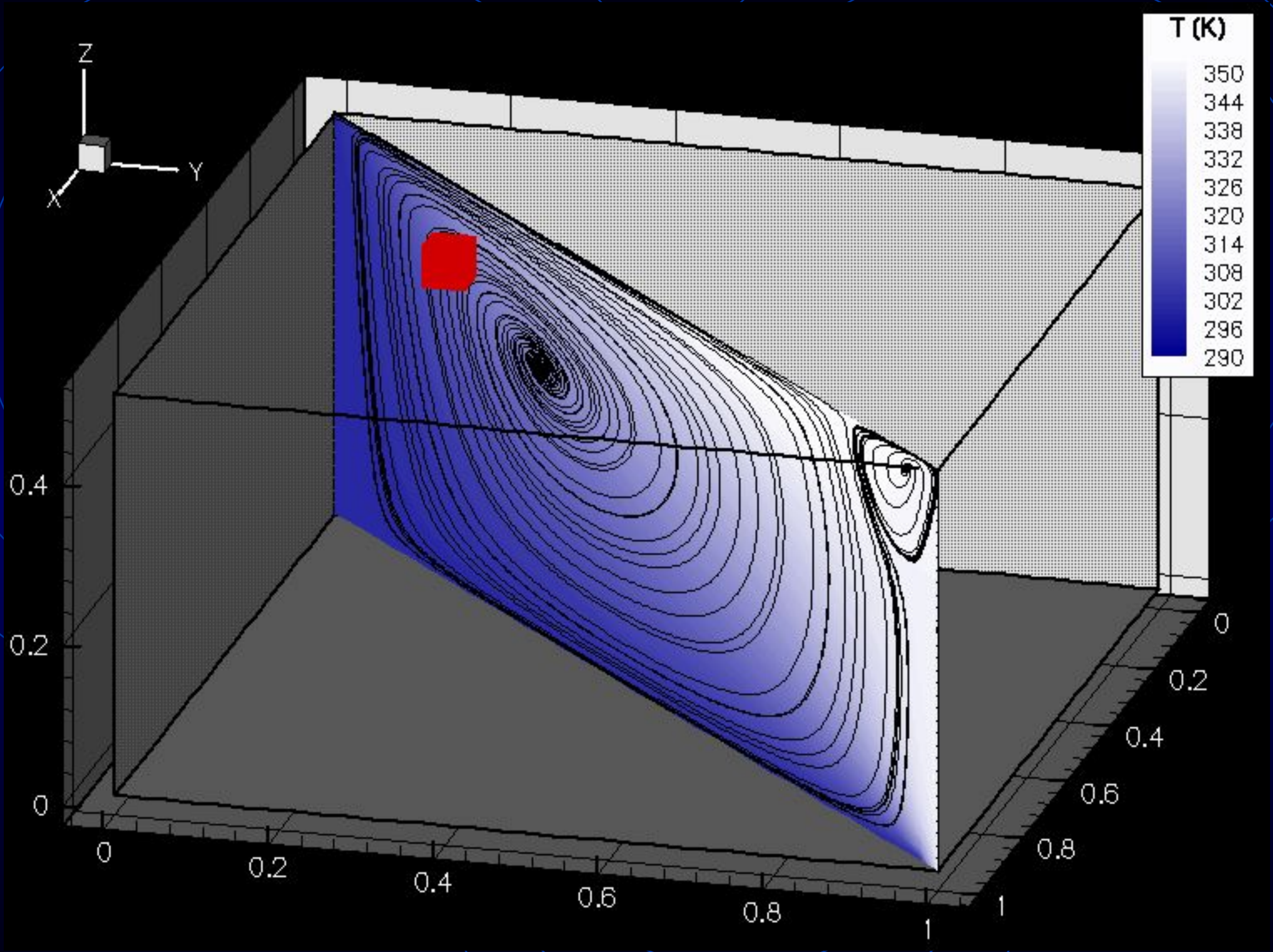
T (K)
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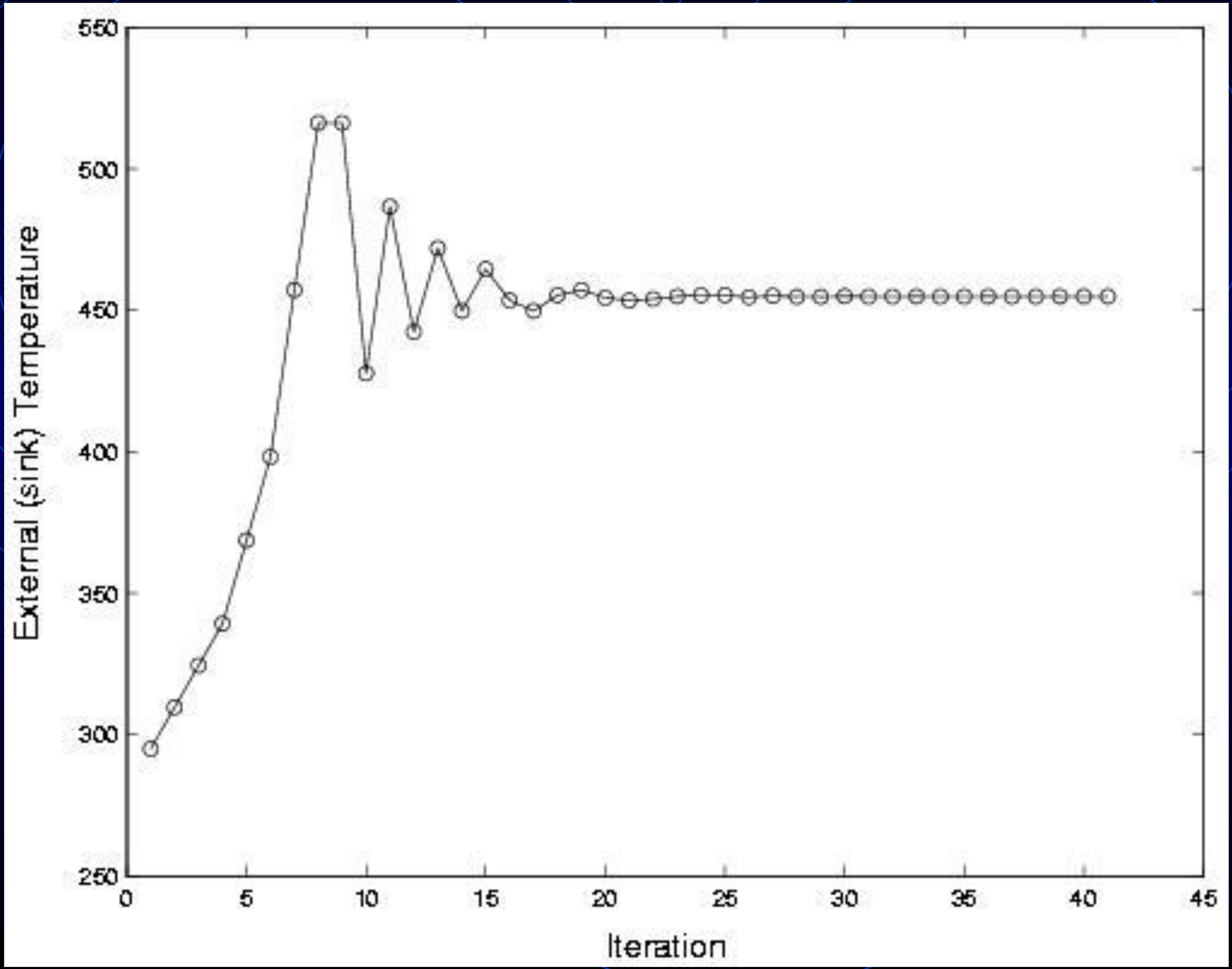
Convergence History



Conclusions

- We became familiar with the CFDLab and the MGFLO code
- Successfully developed a method to optimize nonlinear fluid-thermal systems
- Implemented a particle tracing algorithm in Matlab to visualize fluid mixing

Recommendations

- Use particle tracing algorithm to optimize system mixing (currently takes a long time!)
- Implement feedback control for time-varying systems
- Calculate merit function interior to MGFLO
  - Faster
  - More accurate
  - Support unstructured grids

Questions?