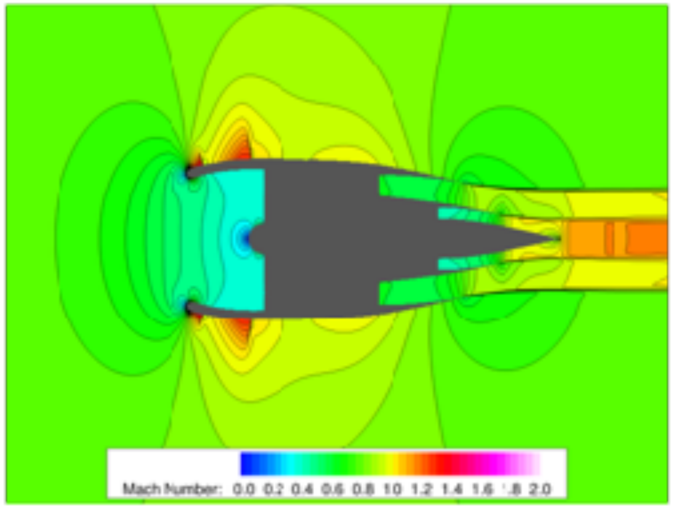
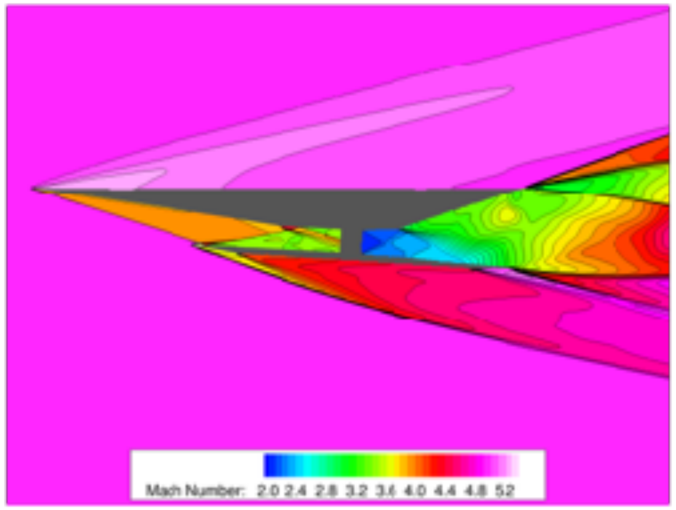
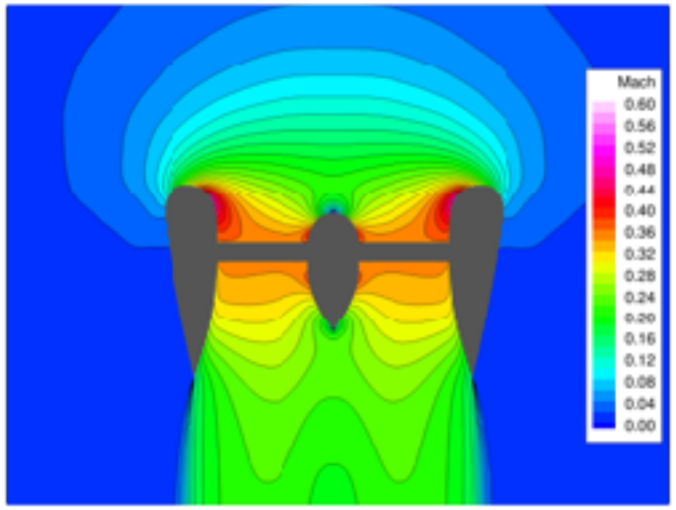




Formulation and Implementation of Inflow/Outflow Boundary Conditions to Simulate Propulsive Effects



David L Rodriguez
Michael Aftosmis
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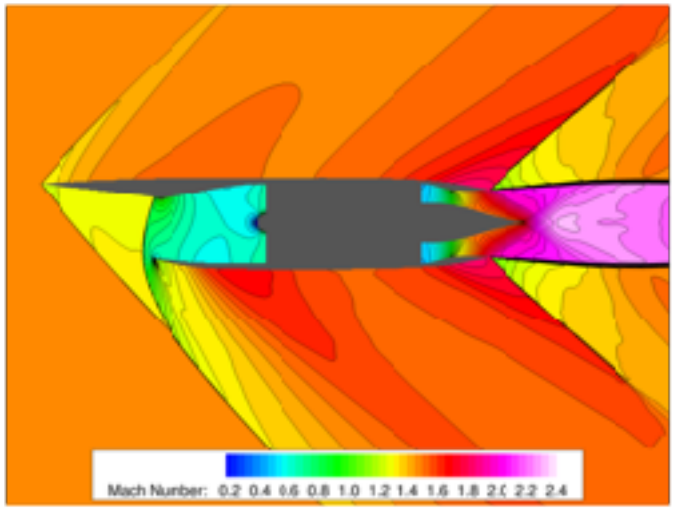
January 8, 2018
SciTech 2018

NASA Ames Research Center

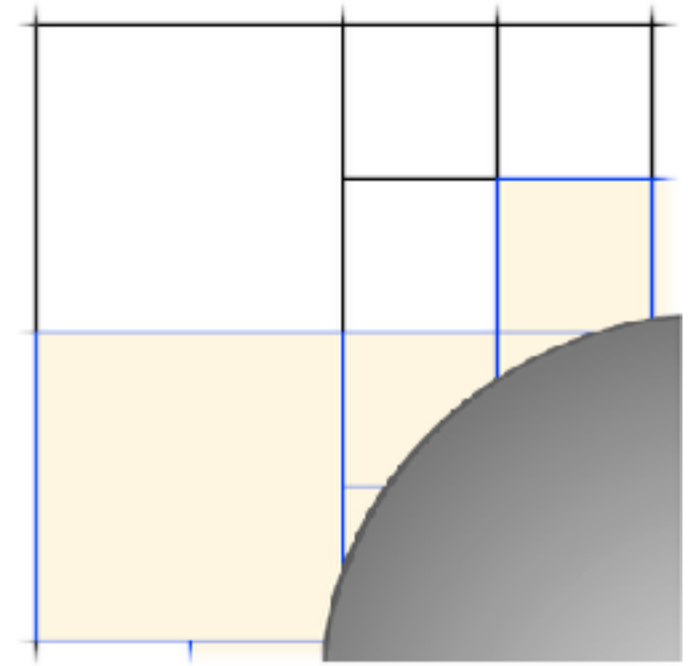


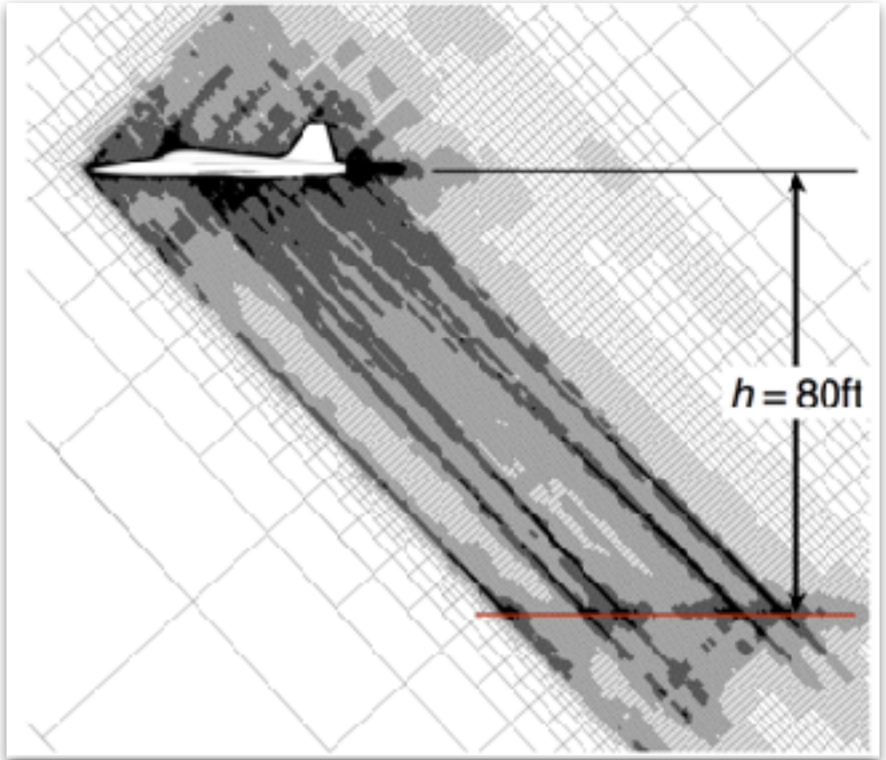
Computational Aerosciences Branch

Advanced Supercomputing Division

Cart3D Aerodynamic Analysis & Design Package

- Automated multilevel Cartesian mesh generation with adjoint-driven adaptive refinement
- Cut-cell approach in cells that include model surface
- Finite volume, 2nd-order accurate Euler solver with explicit Runge-Kutta time stepping and multigrid
- Steady or time-accurate
- Part of a design framework allowing for gradient-based aerodynamic shape optimization of user-specified functional
- Shown to be highly effective for analysis and design of low boom aircraft

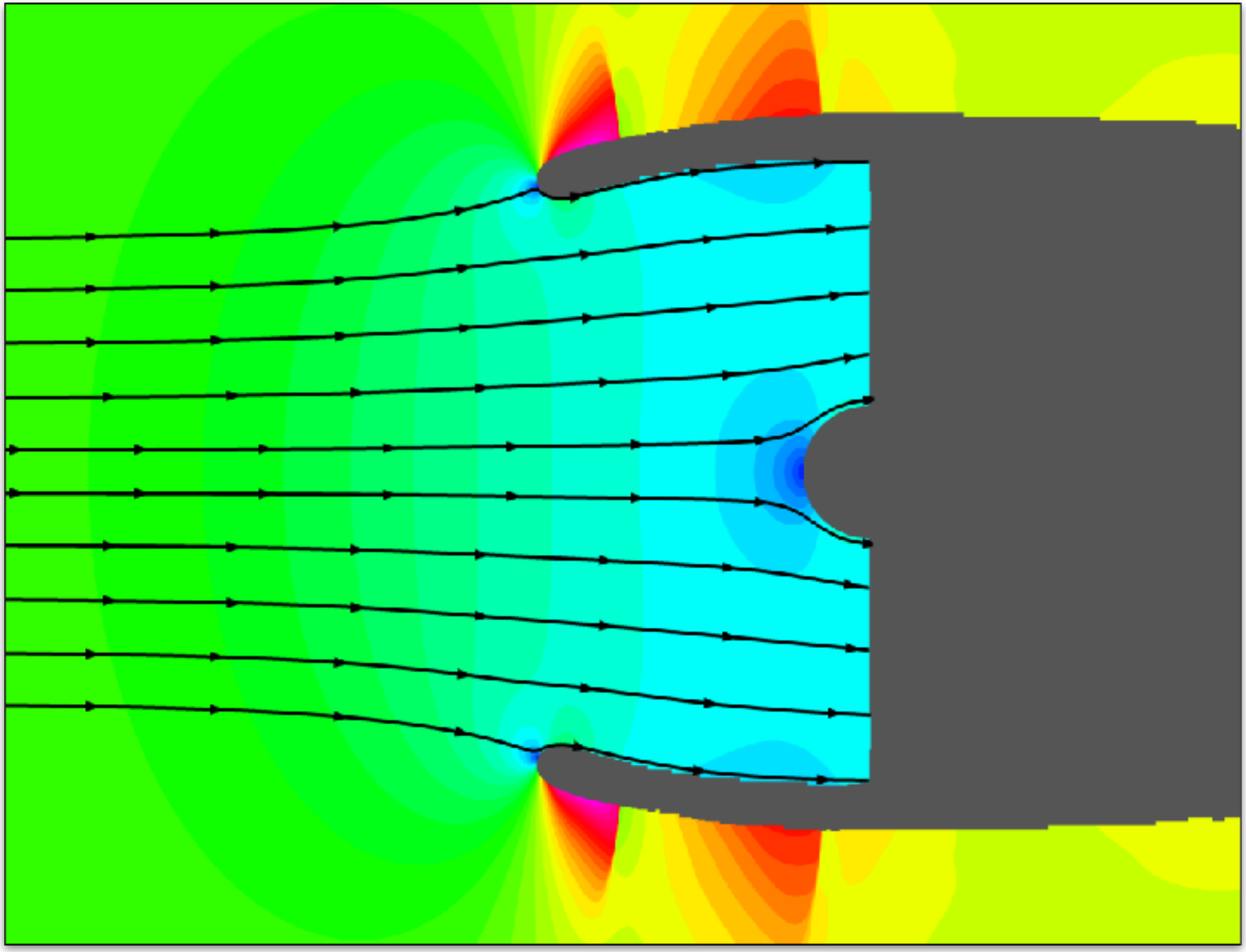




Motivation for New Boundary Conditions

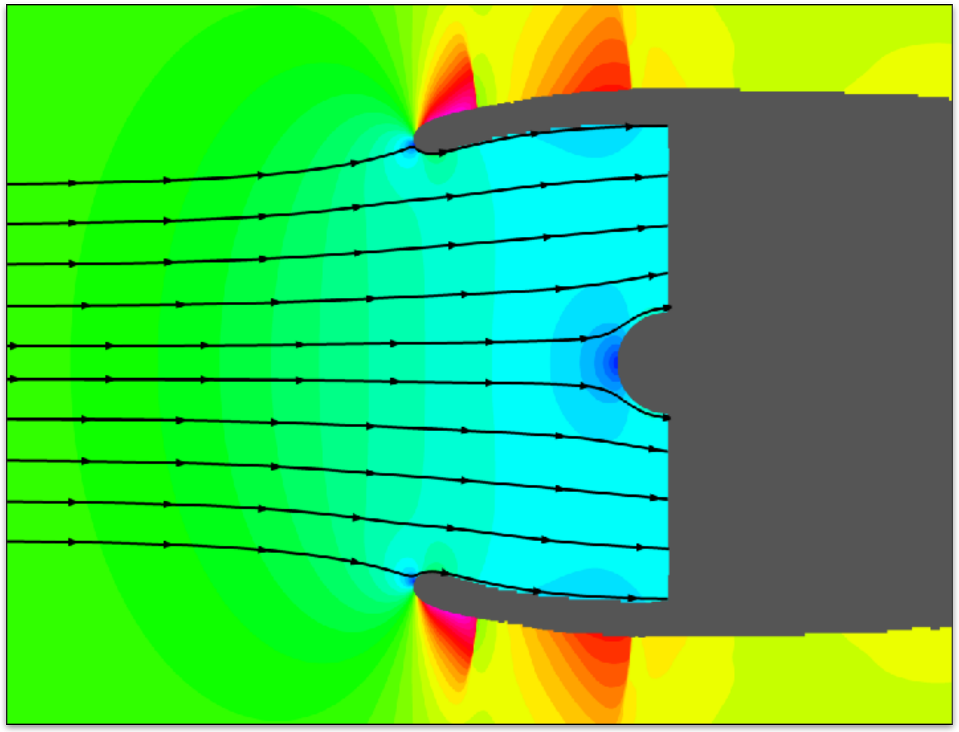
- Current **`SurfBC`** inflow/outflow boundary condition requires user to specify an entire state (ρ, u, v, w, p) at the boundary
  - Riemann solver is applied to compute flux at the boundary and thus boundary condition is always well-posed
  - Robust and flexible since it can be used for both inflow and outflow, subsonic and supersonic
- Inconvenient when user wants to specify inflow or outflow with minimal information
  - for subsonic flow through inlets, most common boundary condition is back pressure
  - for subsonic flow into nozzles, most common boundary condition is specifying total pressure and total temperature (and flow direction)
  - very difficult to specify mass flow rate, particularly in cases where nonlinear flow features are prevalent

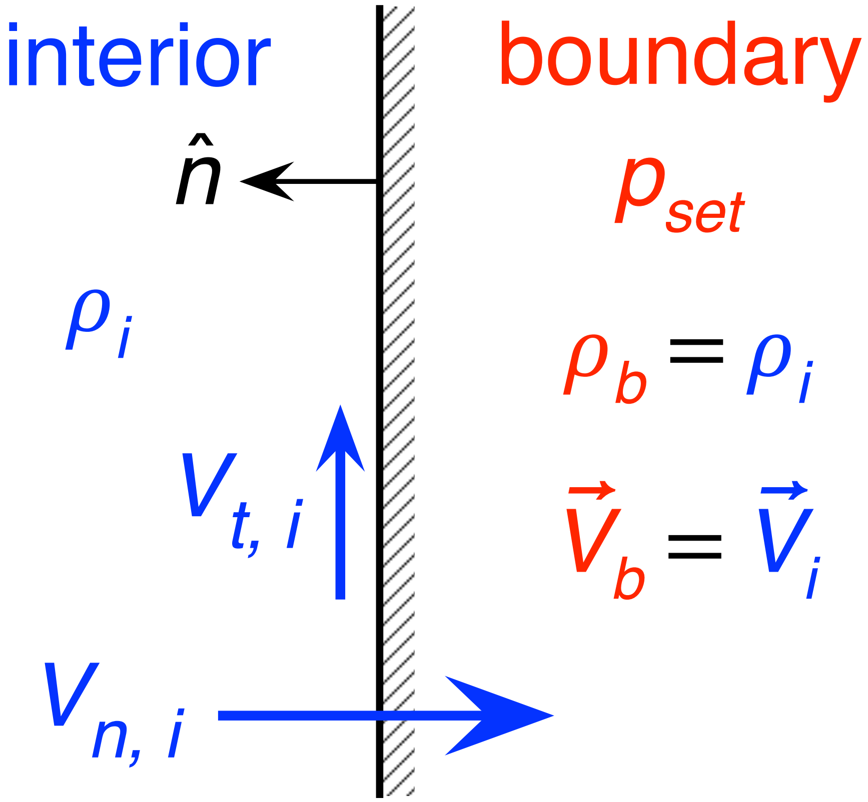
Back Pressure Outflow BC Formulations



Back Pressure Outflow BC Formulations

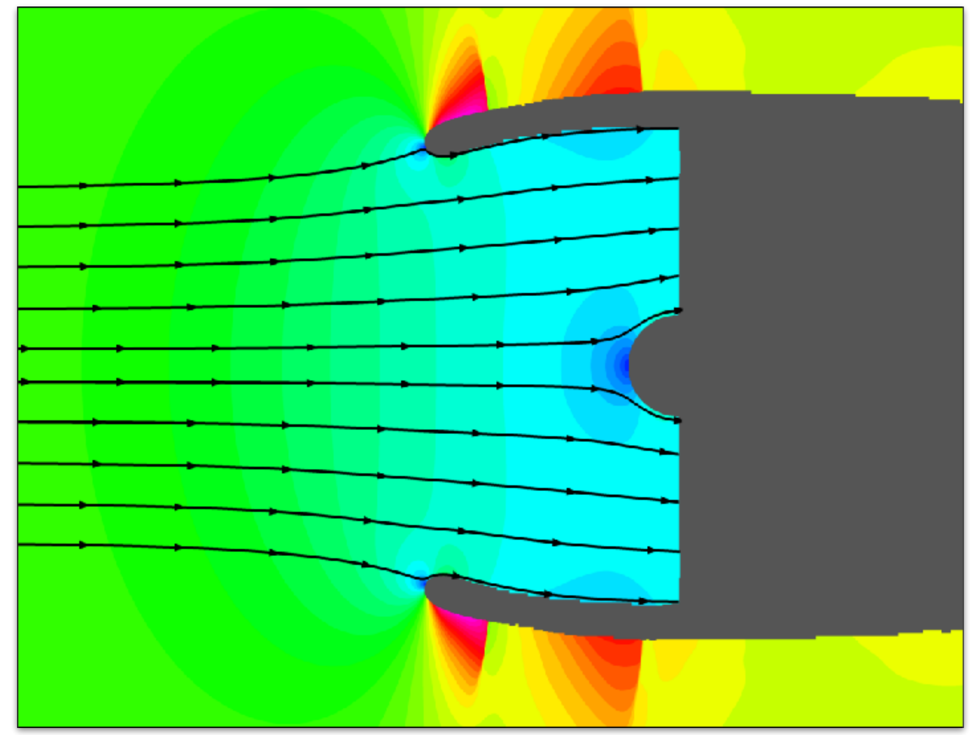
- CFL3D
  - set pressure
  - extrapolate density and velocity

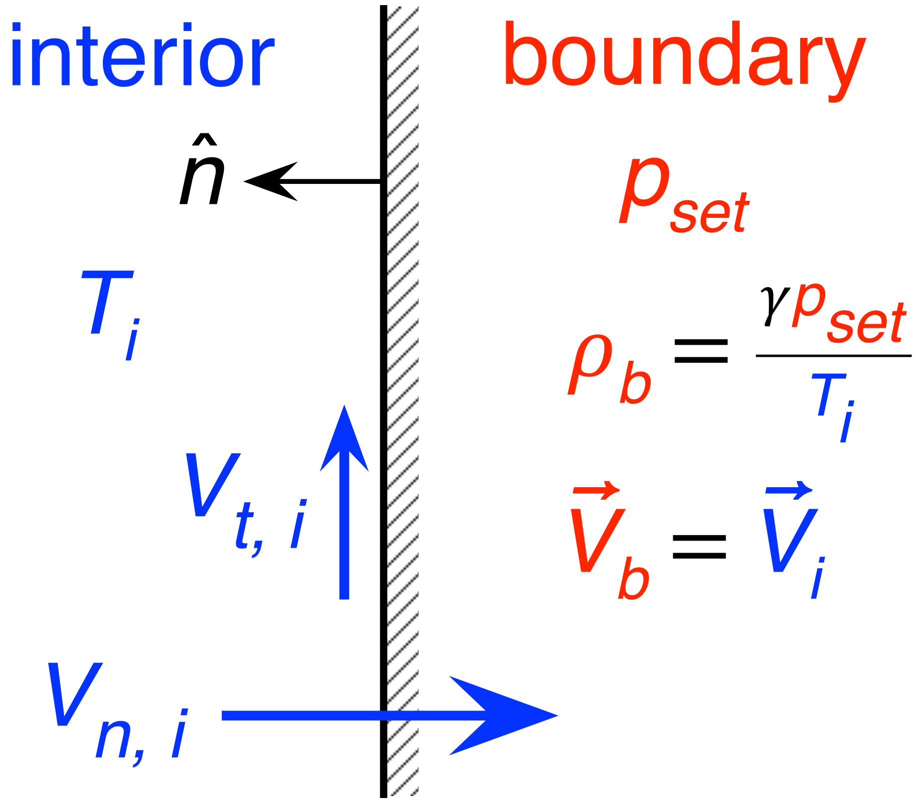




Back Pressure Outflow BC Formulations

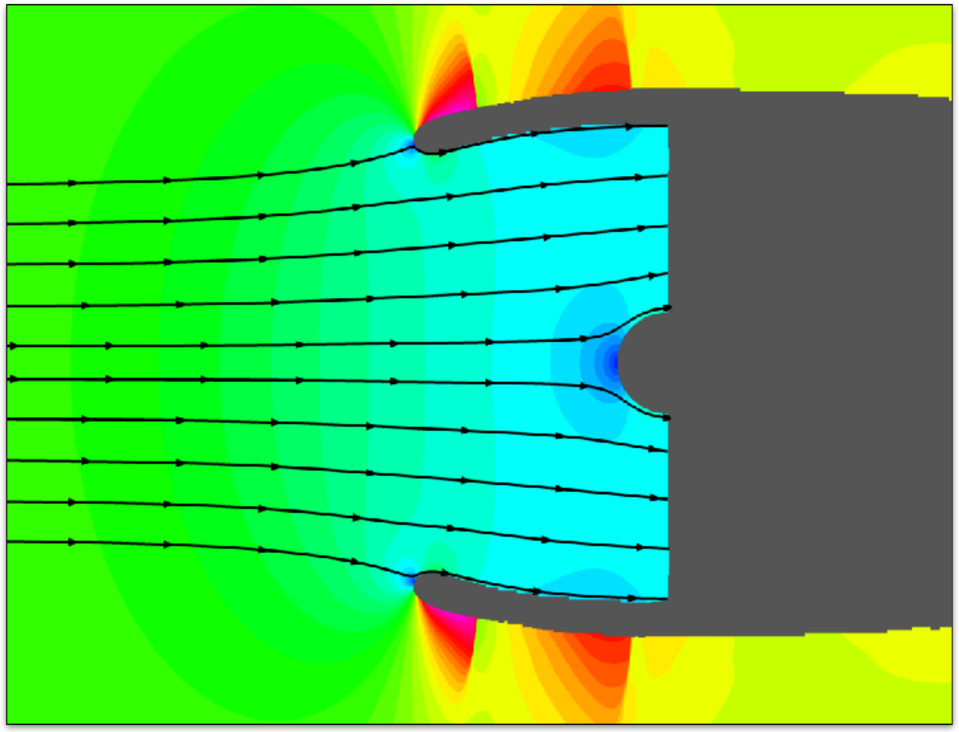
- CFL3D
  - set pressure
  - extrapolate density and velocity
- Fun3D
  - set pressure
  - extrapolate velocity and temperature
  - update density

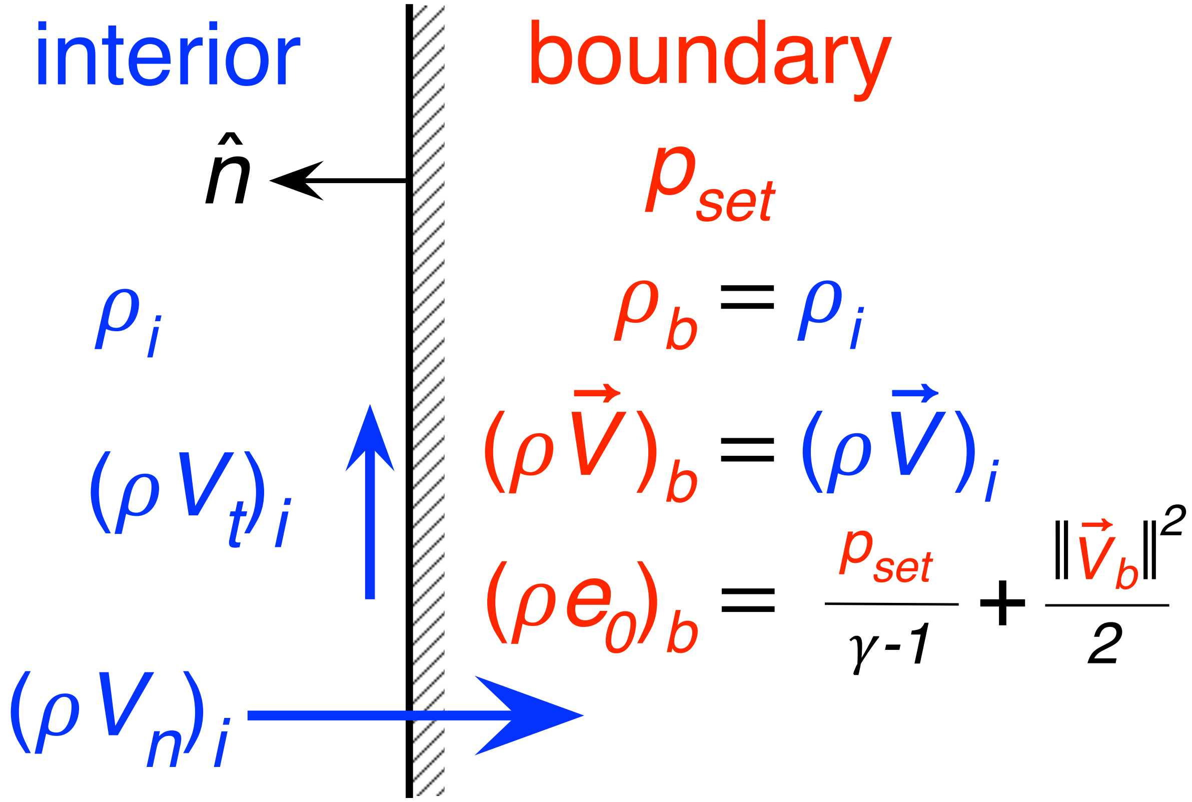




Back Pressure Outflow BC Formulations

- CFL3D
  - set pressure
  - extrapolate density and velocity
- Fun3D
  - set pressure
  - extrapolate velocity and temperature
  - update density
- OVERFLOW
  - set pressure
  - extrapolate density and momentum
  - update total energy





Back Pressure Outflow BC Formulations

- CFL3D
  - set pressure
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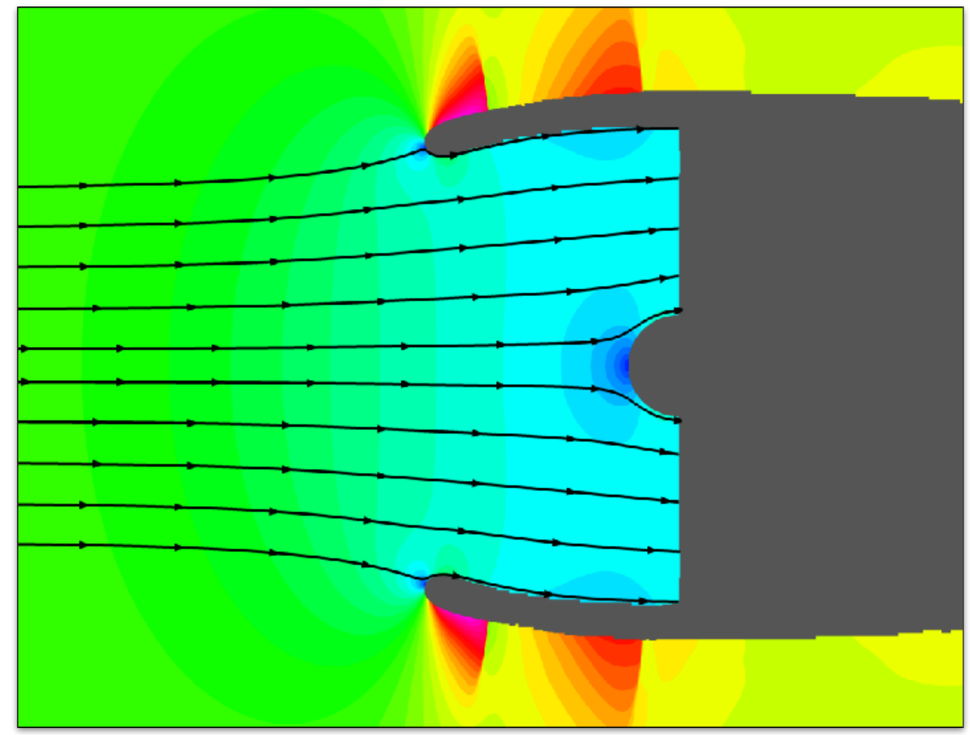
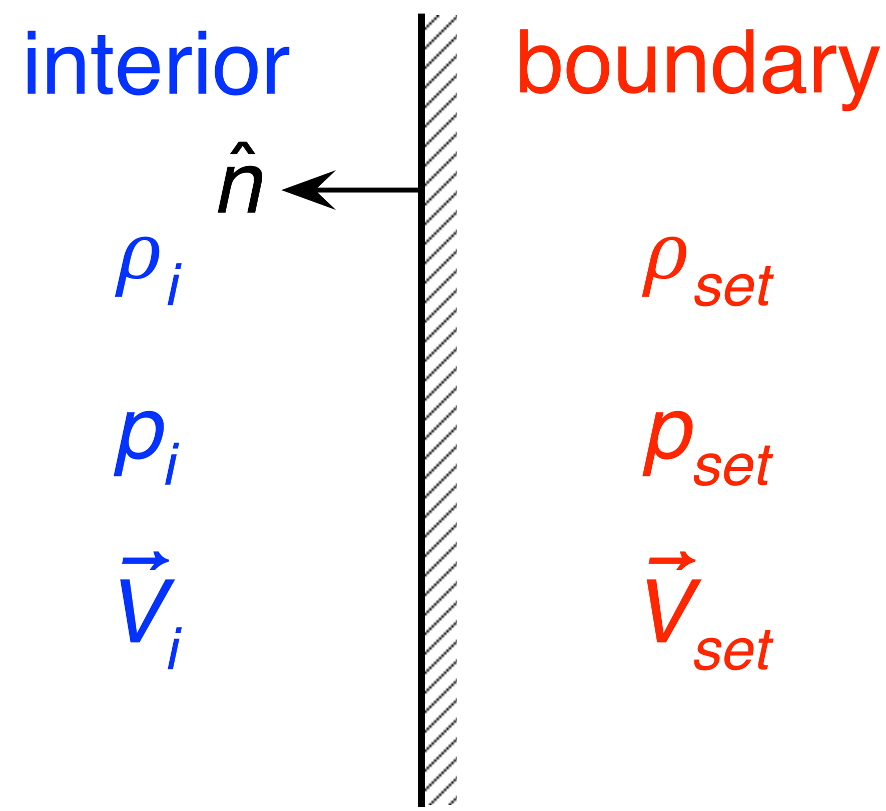
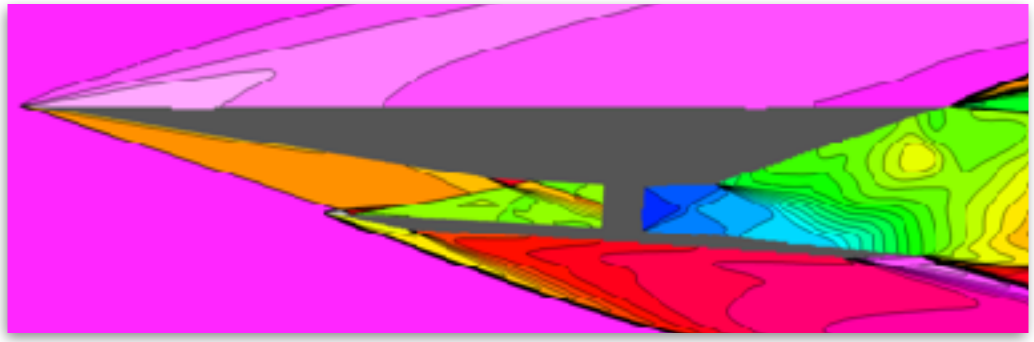
- Fun3D
  - set pressure
  - extrapolate velocity and temperature
  - update density
- OVERFLOW
  - set pressure
  - extrapolate density and momentum
  - update total energy
- Cart3D (since 2004)
  - set entire boundary flow state
  - Riemann solver applied





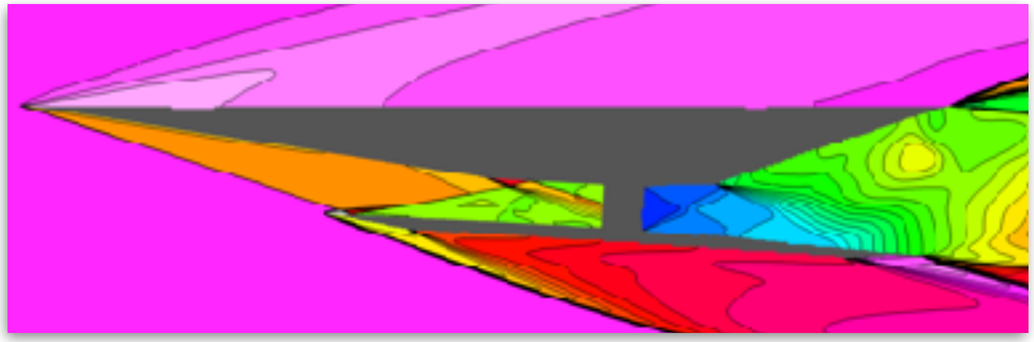
Cart3D Surface Boundary Conditions

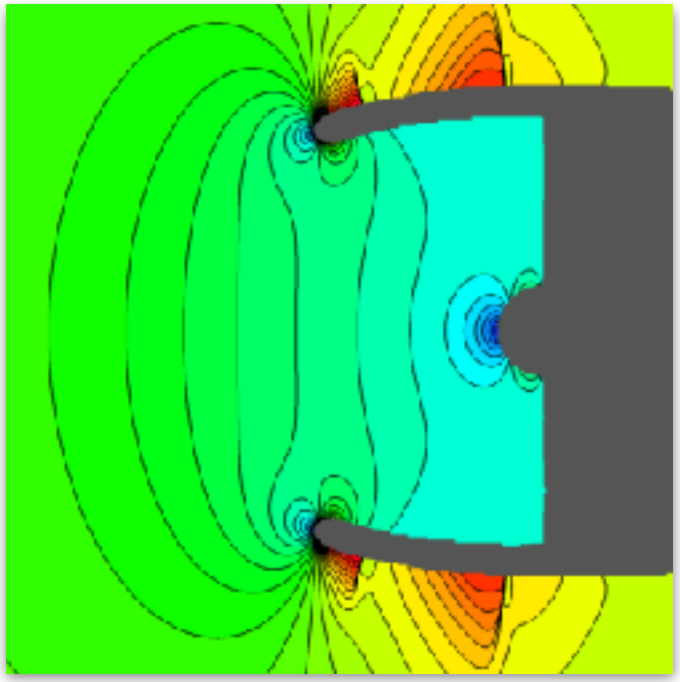
- Solid wall
- Specify full flow state and use Riemann solver (**`SurfBC`**)
  - Pandya, Murman, Aftosmis, 2004
  - for all inflows and outflows



Cart3D Surface Boundary Conditions

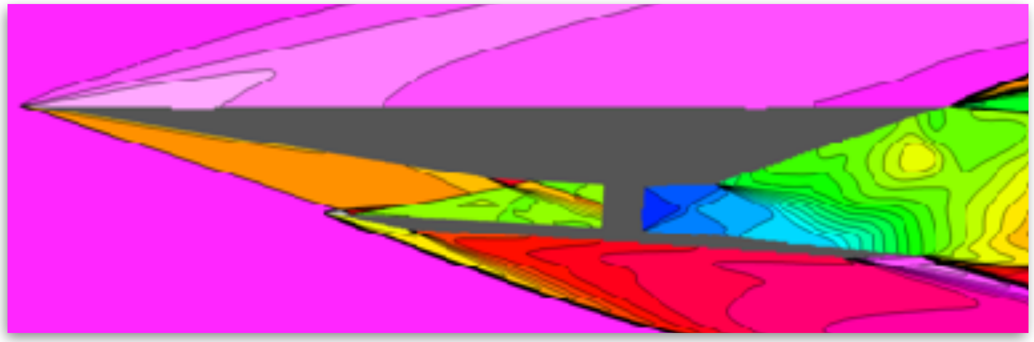
- Solid wall
- Specify full flow state and use Riemann solver (`SurfBC`)
    - Pandya, Murman, Aftosmis, 2004
    - for all inflows and outflows
- Subsonic Outflow
    - back pressure NEW
    - constant normal velocity NEW

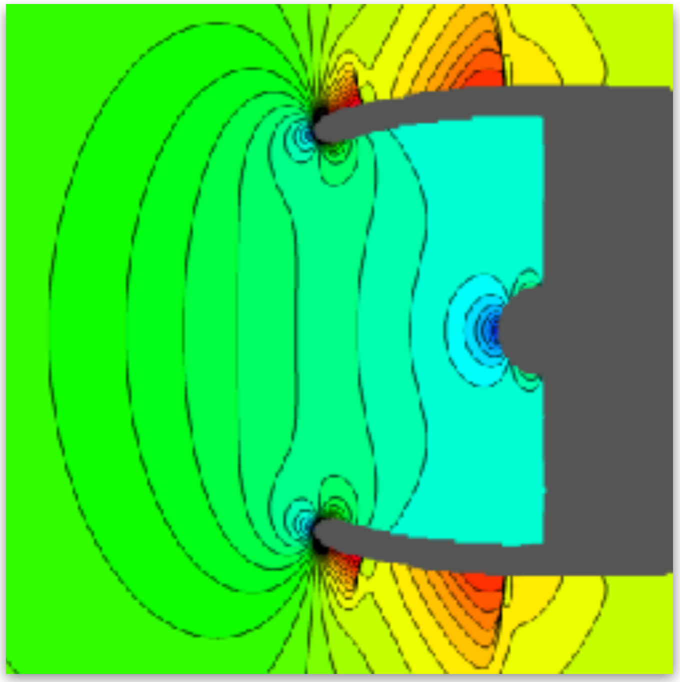


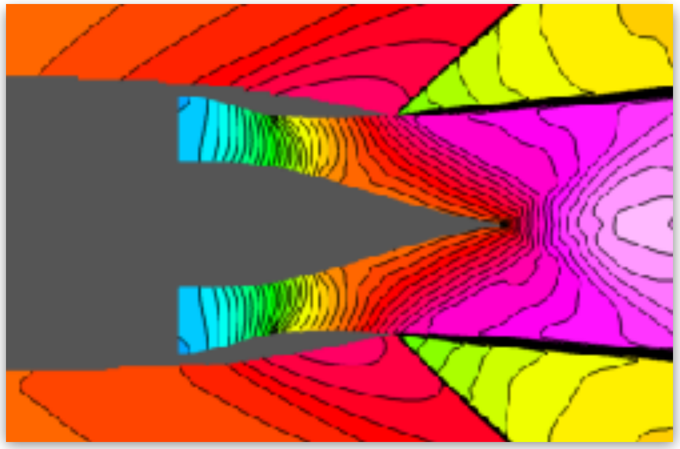


Cart3D Surface Boundary Conditions

- Solid wall
- Specify full flow state and use Riemann solver (`SurfBC`)
  - Pandya, Murman, Aftosmis, 2004
  - for all inflows and outflows
- Subsonic Outflow
  - back pressure NEW
  - constant normal velocity NEW
- Subsonic Inflow
  - total pressure and total temperature NEW
  - mass flow rate and total temperature NEW

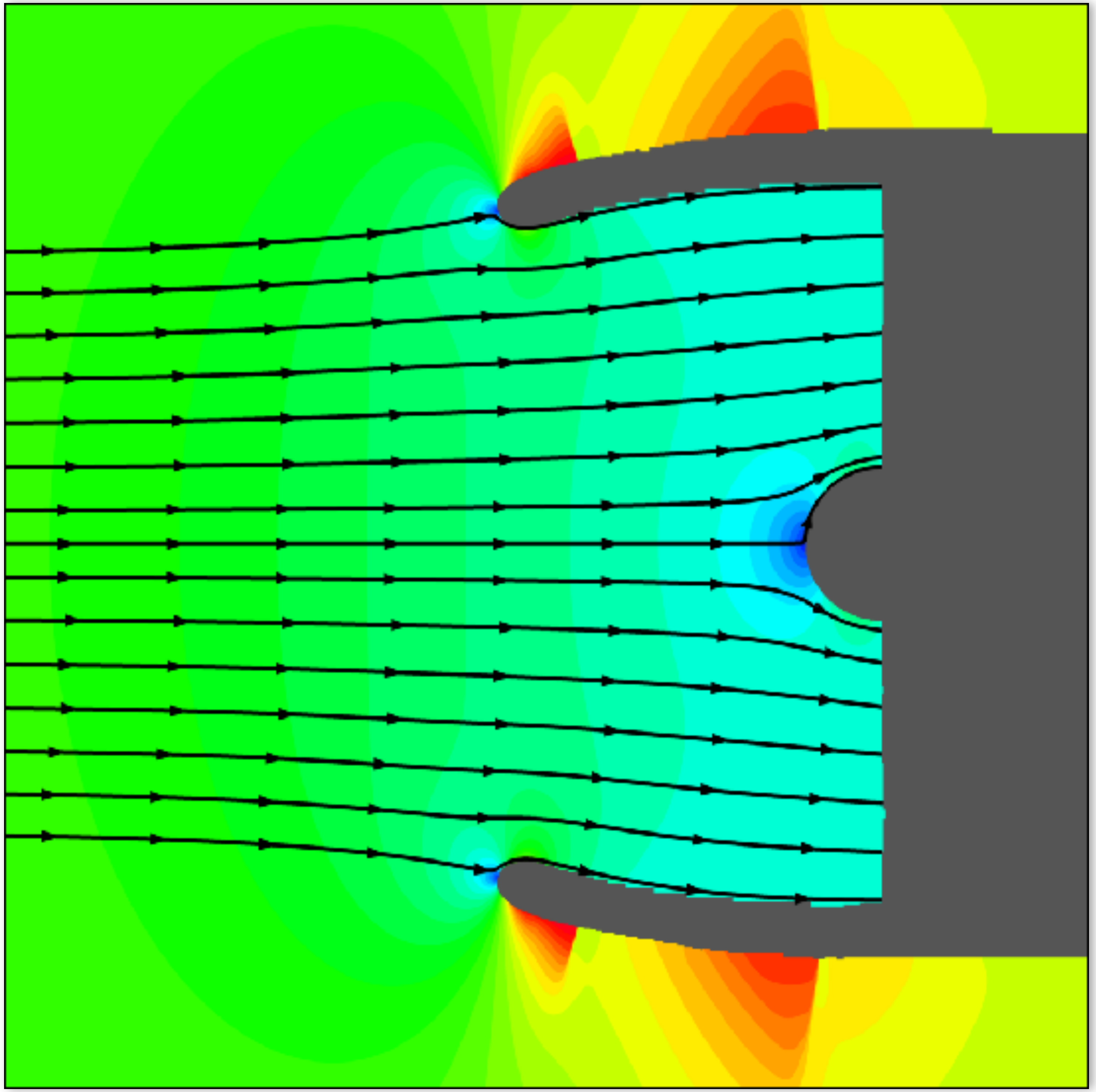






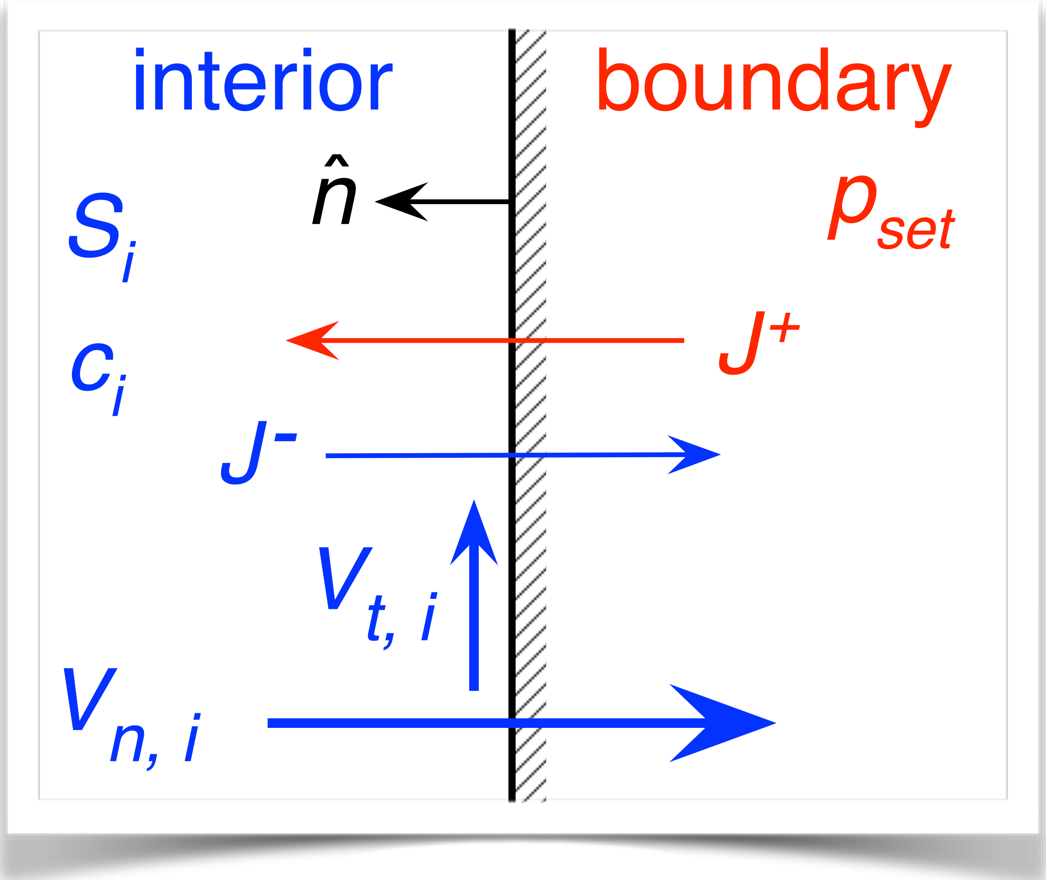
Subsonic Outflow Boundary Conditions

- One flow quantity specified at boundary
  - back pressure
  - normal velocity
- Four flow quantities extrapolated from interior



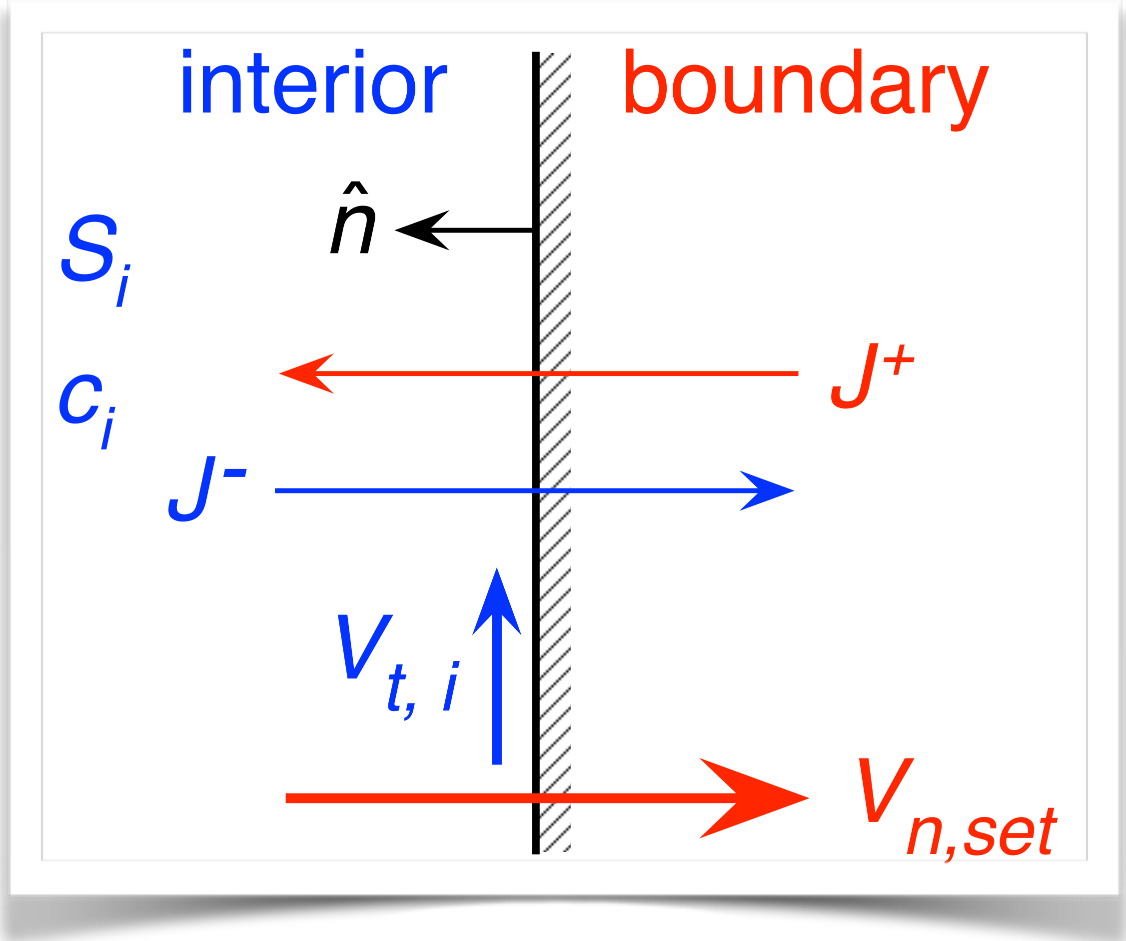
Back Pressure Outflow

- Most other CFD solvers have this common option
- Pressure set to specified value at boundary
- Entropy and tangential velocity extrapolated from interior
- Riemann invariants used to compute boundary state
- Safeguards
  - if flow reverses back into interior (back pressure too high), solid wall boundary enforced
  - if interior flow goes supersonic, compare back pressure to pressure after normal shock occurring at boundary
    - if set back pressure is higher, use after-shock state at boundary, forcing subsonic flow in the interior
    - if set back pressure is lower, extrapolate all flow attributes from interior (supersonic outflow)
- Can be difficult to obtain specific mass flow rate for nonlinear flows



Constant Normal Velocity Outflow

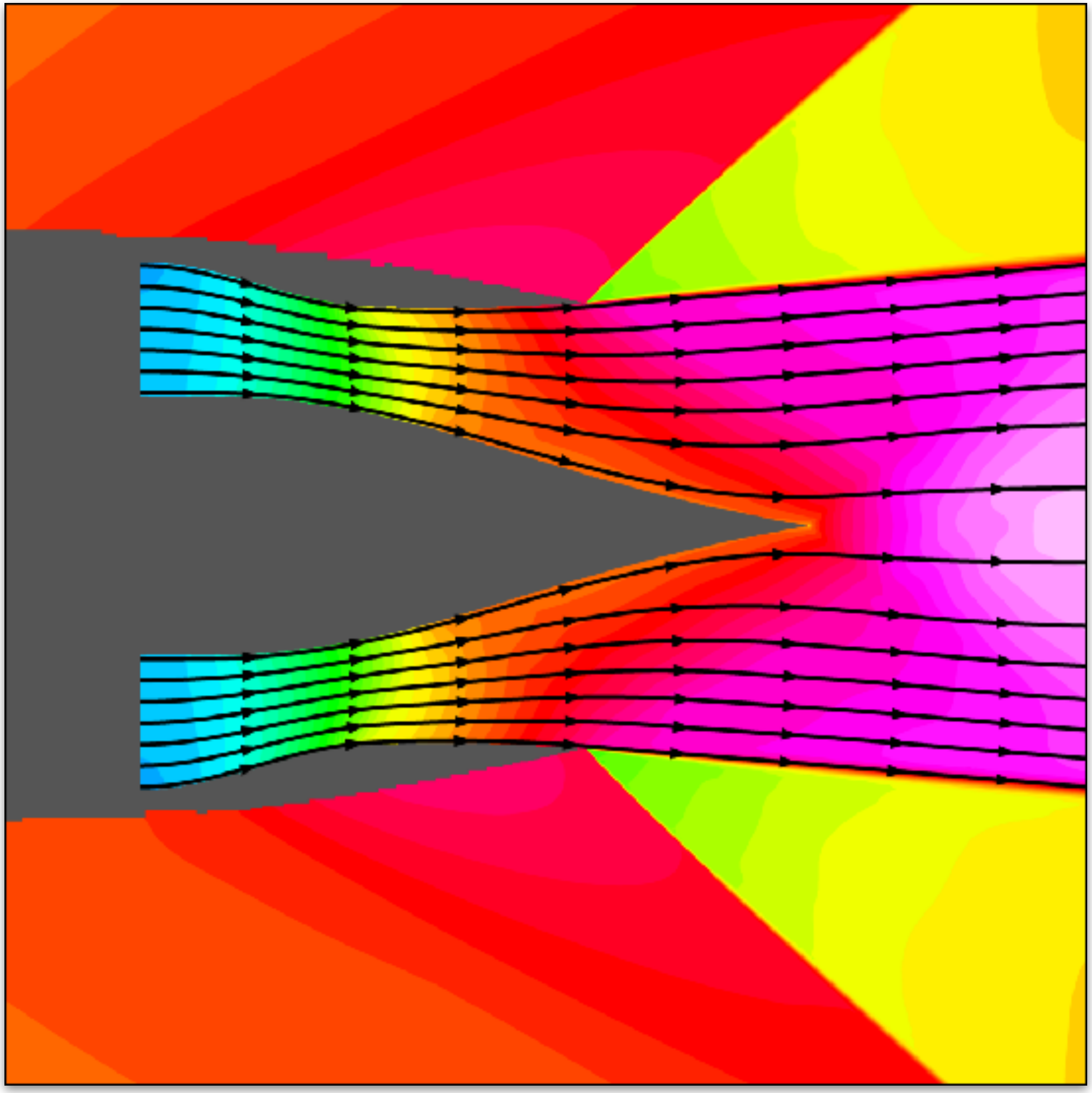
- Allows for robust mass flow rate steering
- Might better represent flow in front of an engine fan face (Pearson ’59, Reid ’69)
- Normal velocity set to specified value at boundary
- Entropy and tangential velocity extrapolated from interior
- Riemann invariants used to compute boundary state



- Safeguards
  - when interior flow is subsonic but boundary flow is supersonic (bad input velocity), flow is forced to be sonic (choked flow)
  - when interior and boundary flow are both supersonic, supersonic outflow is enforced (all interior quantities extrapolated)

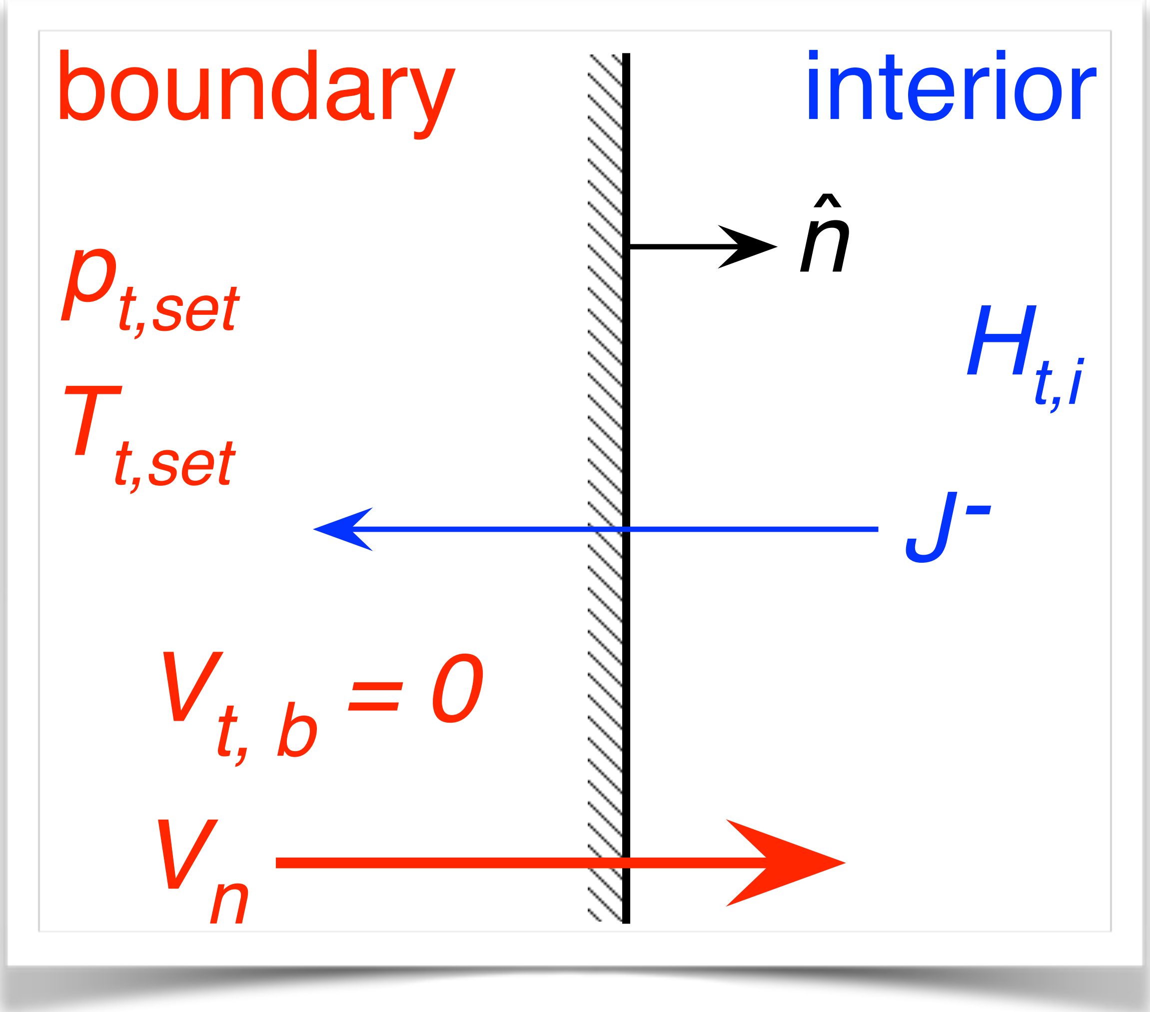
Subsonic Inflow Boundary Conditions

- Four flow quantities specified at boundary
  - velocity set to be normal to boundary (two flow quantities)
  - total pressure and total temperature
  - mass flow rate and total temperature
- One flow quantity extrapolated from interior



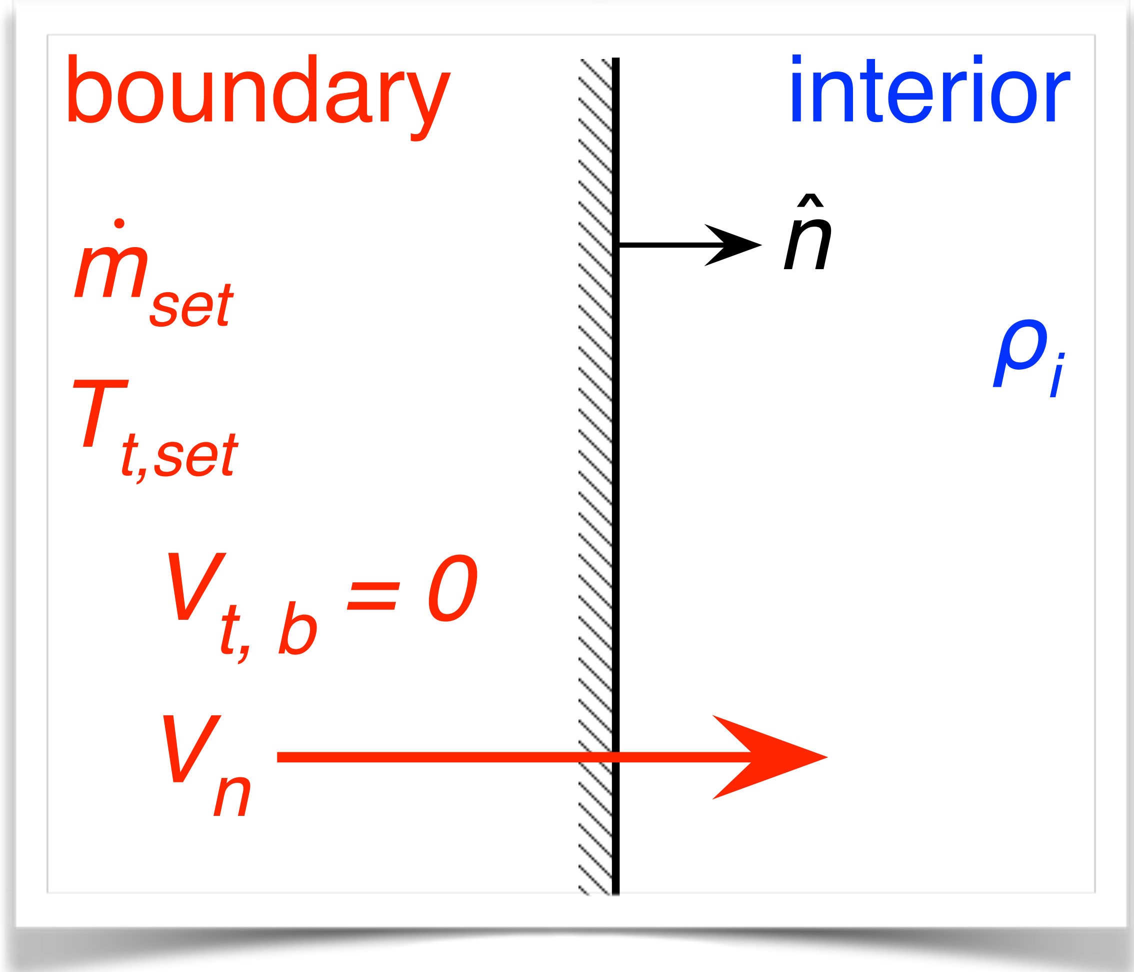
Stagnation Property Inflow

- Most other CFD solvers have this common option
- Total pressure and temperature set to specified value at boundary
- Tangential velocity set to zero, forcing inflow to be normal to surface
- Enthalpy is extrapolated from interior
- Riemann invariant used to computed boundary state
- Safeguards
  - when flow tries to reverse back into boundary, solid wall boundary enforced
  - inflow Mach number is limited to sonic, adjusting stagnation properties accordingly
- Cannot explicitly set a mass flow rate



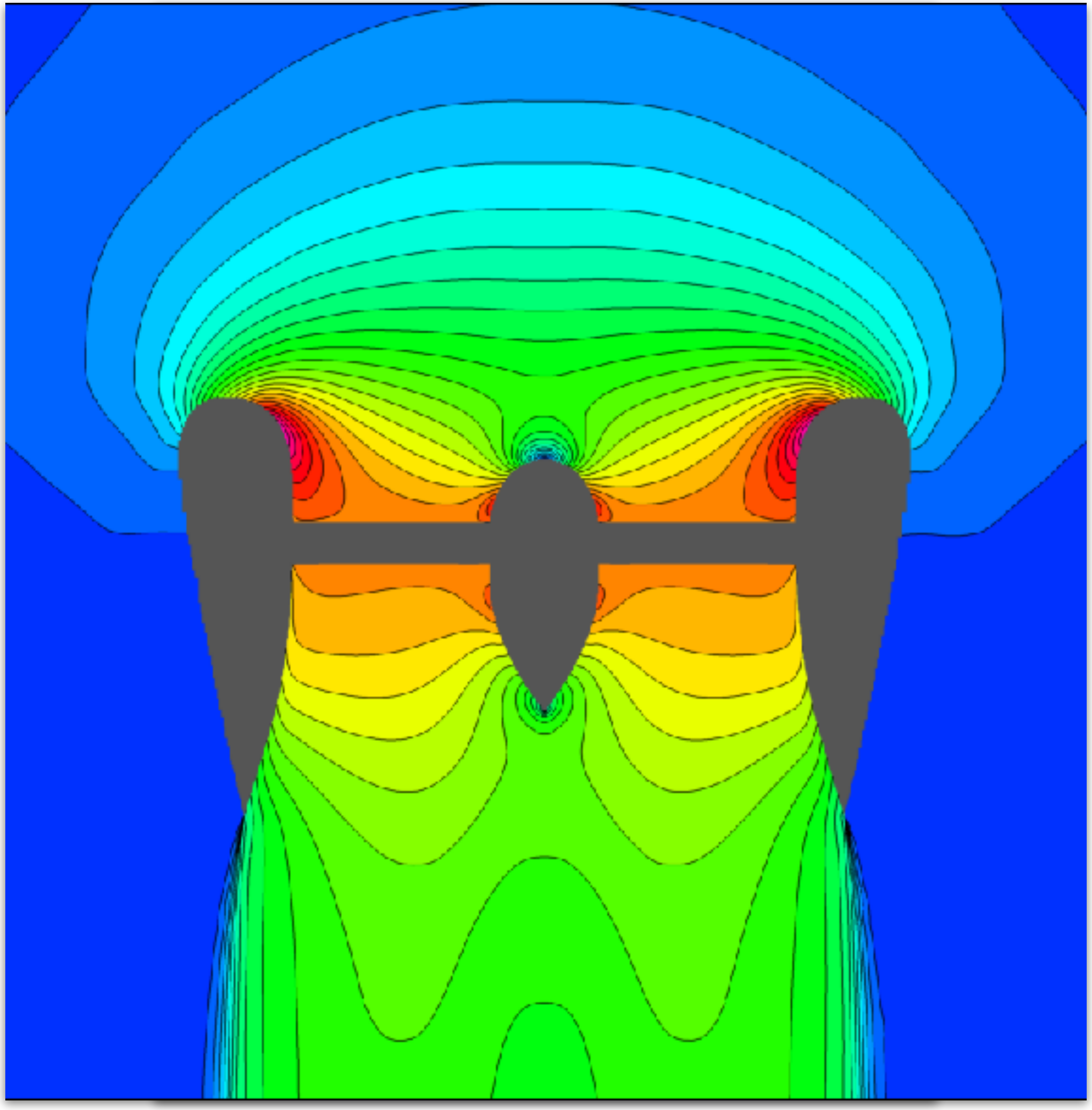
Mass Flow Rate and Total Temperature Inflow

- Allows for explicit mass flow rate control
- Mass flow rate and total temperature set to specified value at boundary
- Tangential velocity set to zero, forcing inflow to be normal to surface



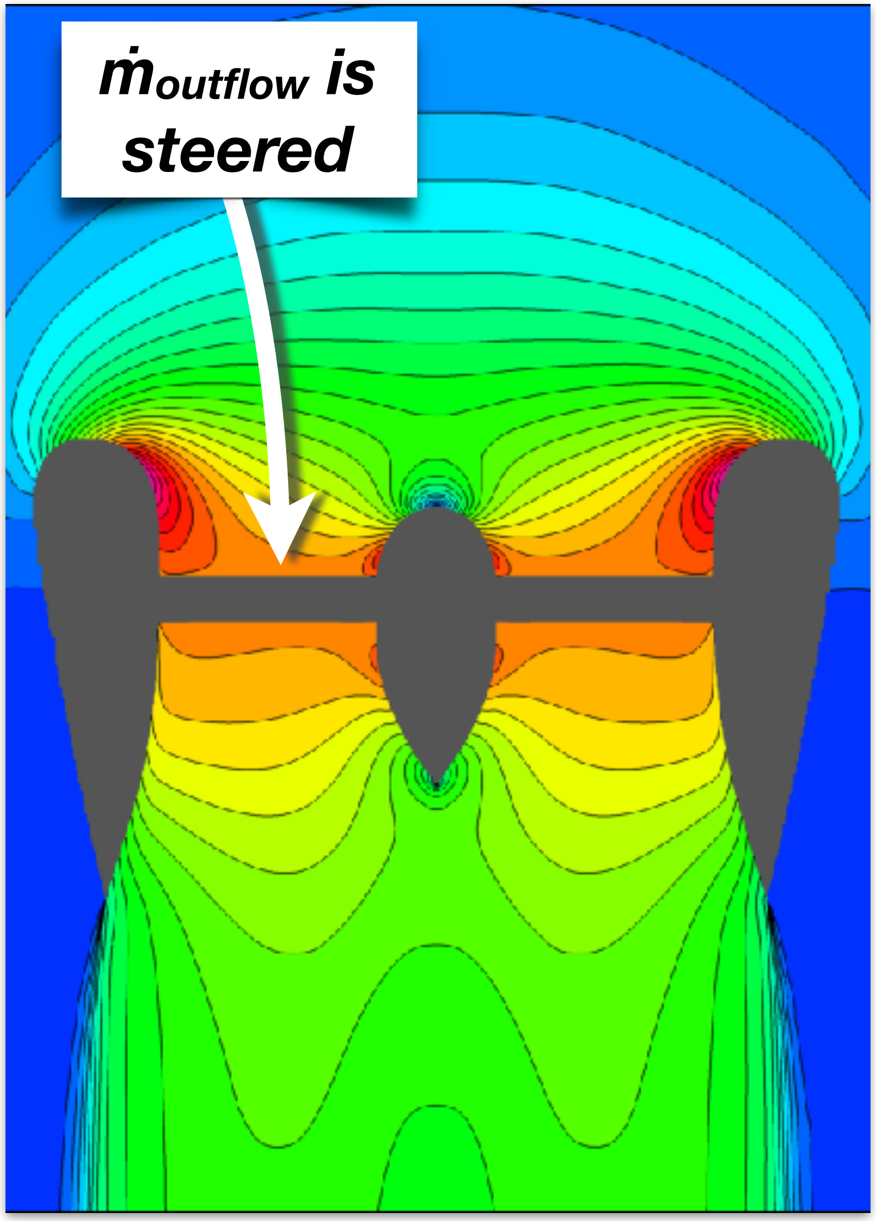
- Density is extrapolated from interior
- Boundary flux computed from boundary state
- Safeguard
  - inflow Mach number is limited to sonic, adjusting boundary values accordingly

Mass Flow Rate Control



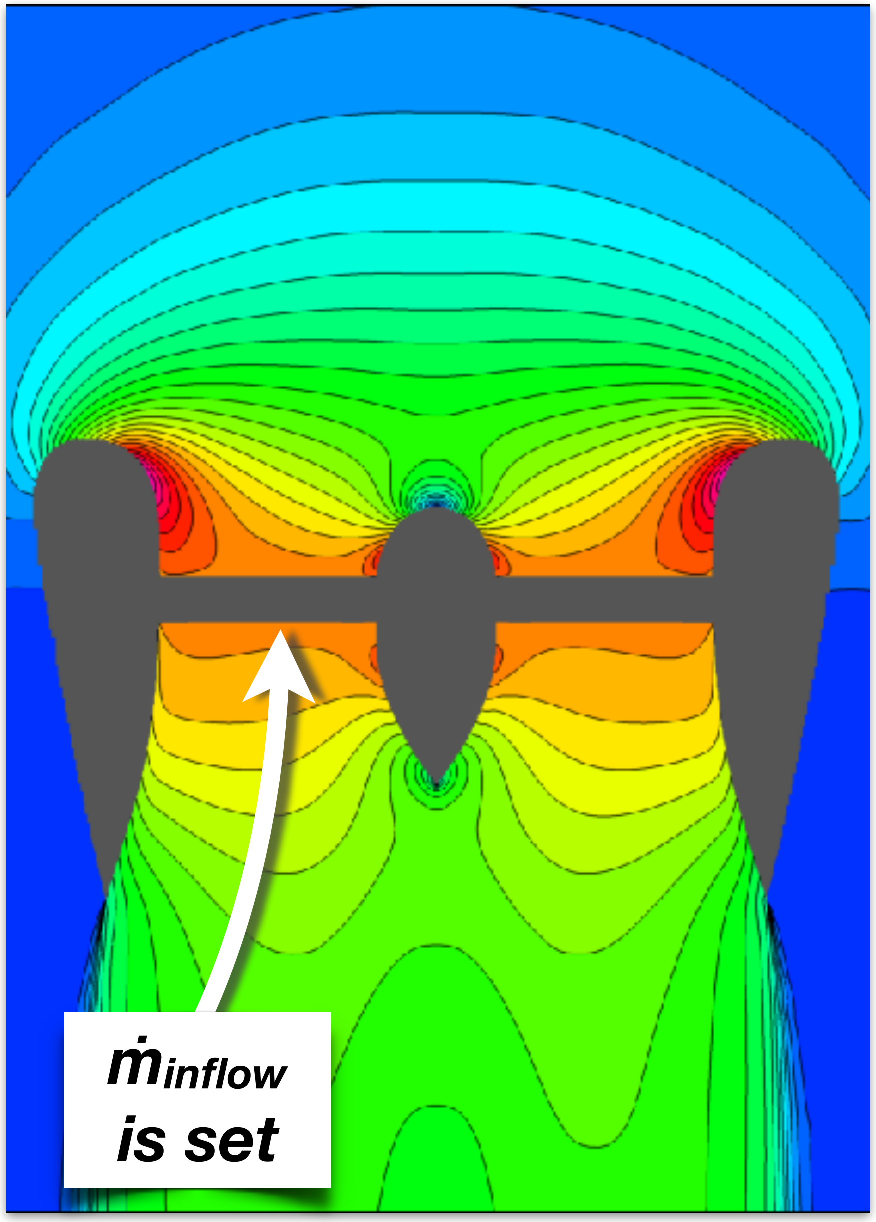
Mass Flow Rate Control

- Constant velocity outflow boundary condition can be steered to obtain specified mass flow rate out of the domain
  - average density over surface is computed
  - velocity out of domain is set based on desired mass flow rate
  - repeat every few iterations until solution converged and mass flow rate within tolerance



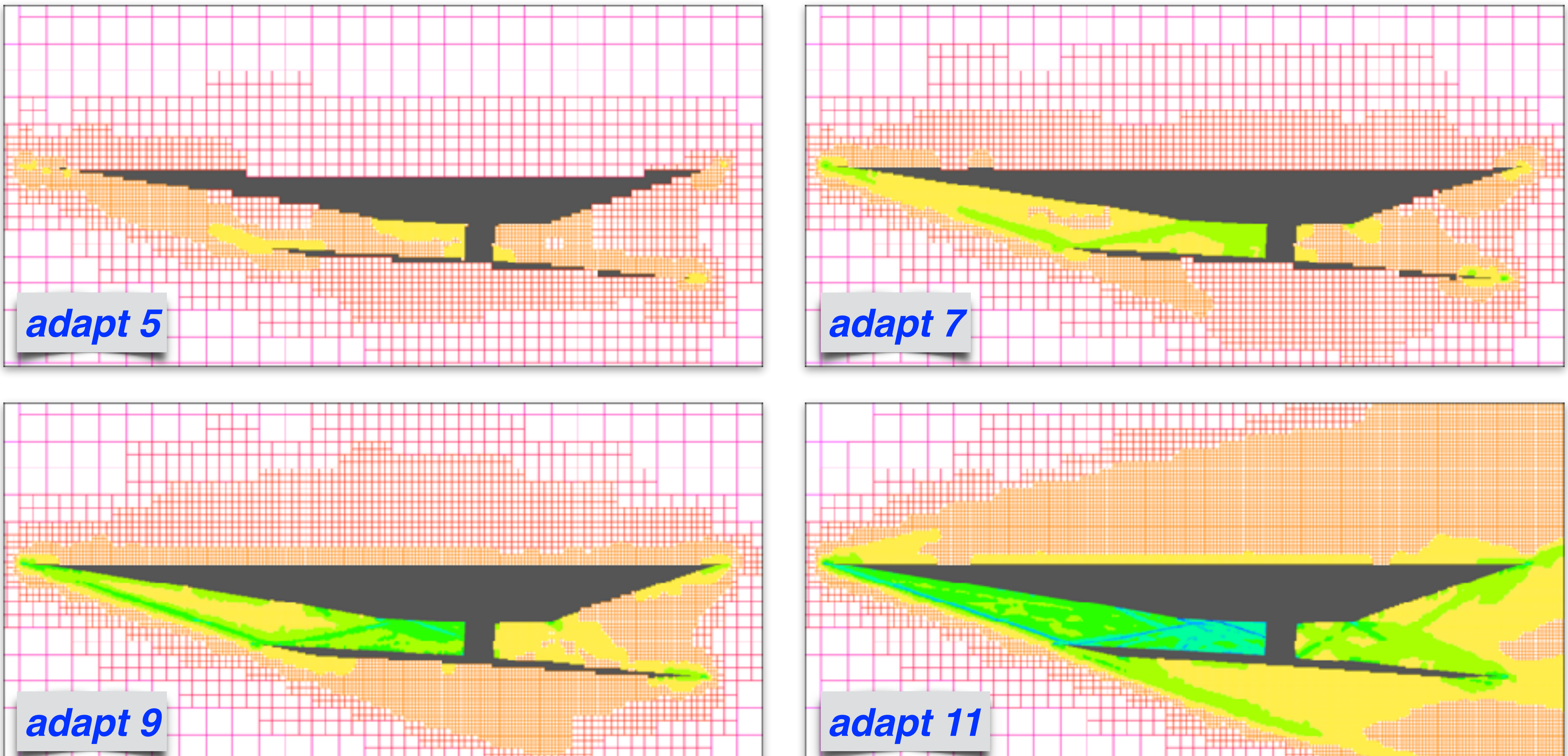
Mass Flow Rate Control

- Constant velocity outflow boundary condition can be steered to obtain specified mass flow rate out of the domain
  - average density over surface is computed
  - velocity out of domain is set based on desired mass flow rate
  - repeat every few iterations until solution converged and mass flow rate within tolerance
- Constant mass flow rate inflow boundary condition explicitly sets mass flow rate into the domain



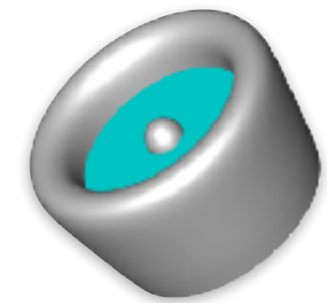
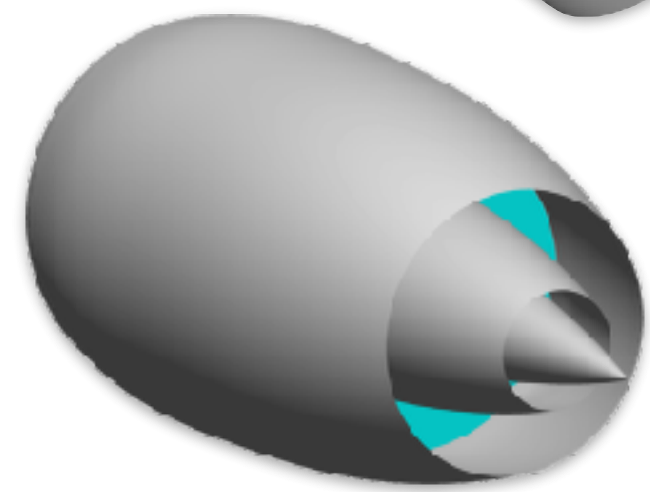
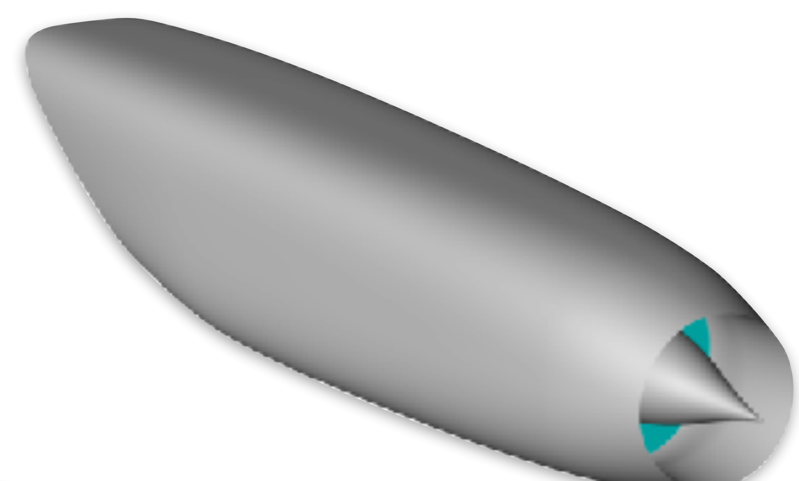
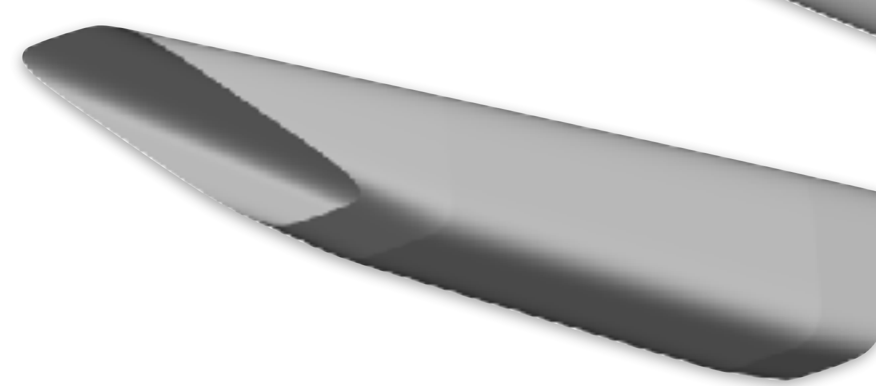
Adjoint-Driven Adaptive Mesh Refinement

- All boundary conditions now implemented in adaptive mesh refinement process
- Updates to `adjointCart`, `xSensit`, `adjointErrorEstQuad`, etc.



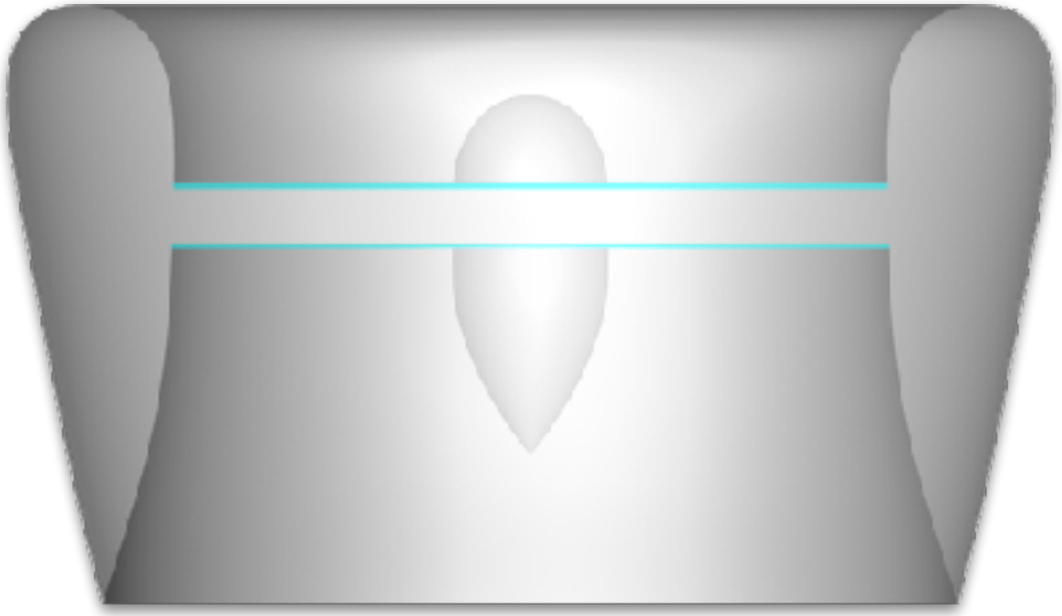
Application of New Boundary Conditions

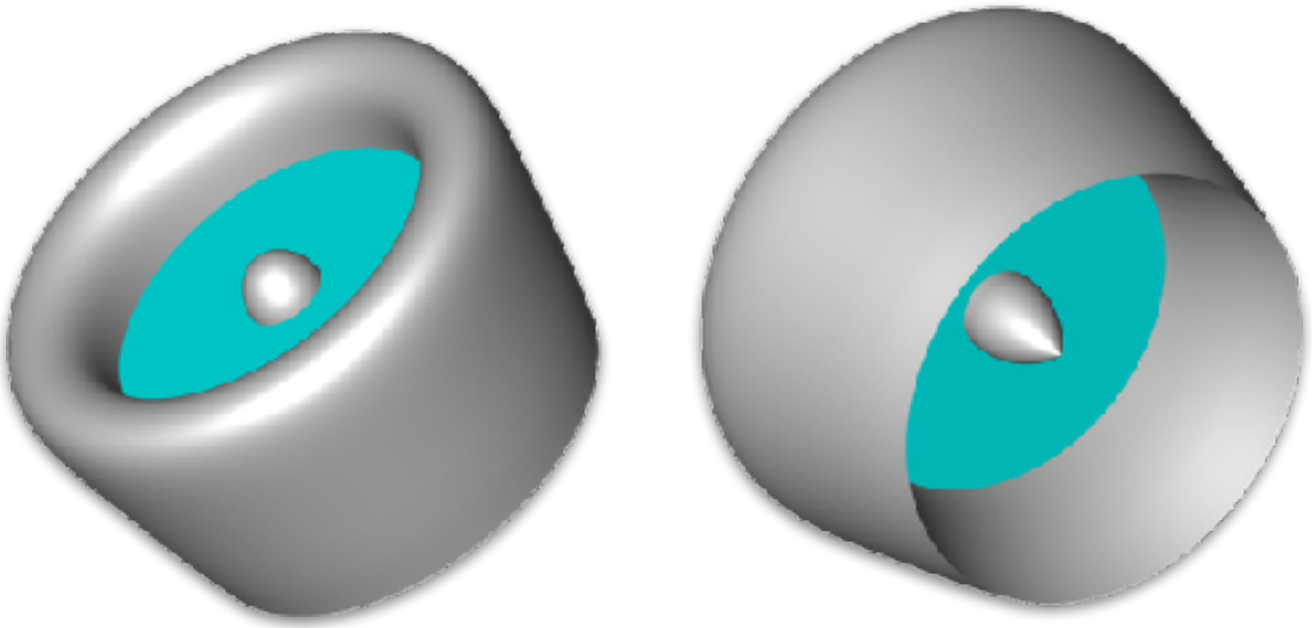
- Ducted fan in near-hover (subsonic)
  - verification of back pressure outflow and mass flow rate inflow boundary conditions
- Turbofan with both fan and turbine exhaust streams (transonic)
  - verification of constant velocity outflow boundary condition
- Turbojet with 2-D ramp inlet (supersonic)
  - mesh convergence through adaptive refinement
  - mass flow rate steering example
- Scramjet (hypersonic)
- Low boom demonstrator

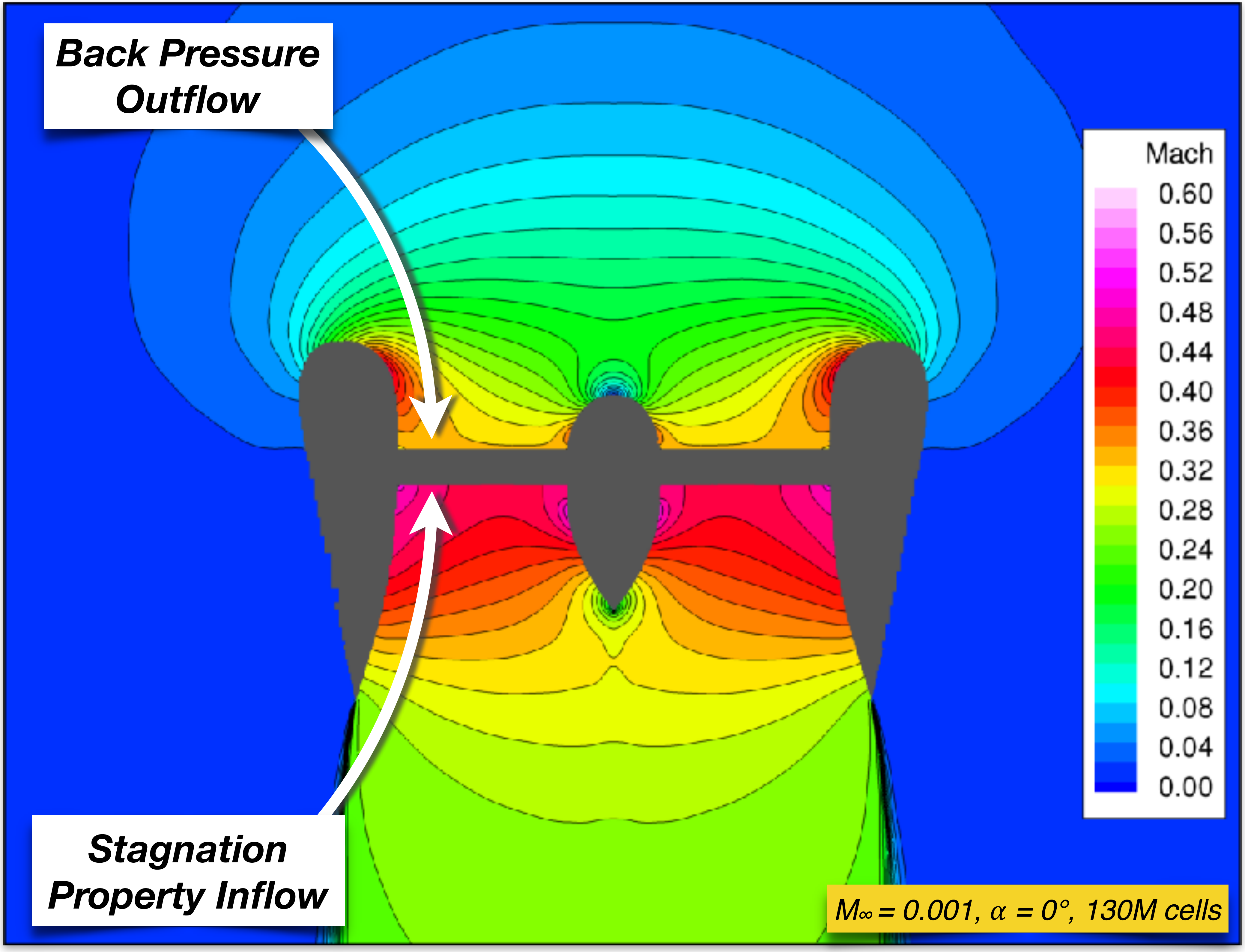
Ducted Fan in Hover

- Duct and center body housing motor to drive fan
- Very low freestream Mach number (0.001) to simulate near hover
- No angle of attack - axisymmetric flow
- Fan modeled as **annular disk**
- Inflow / Outflow boundary conditions enforced on disk to model fan effects

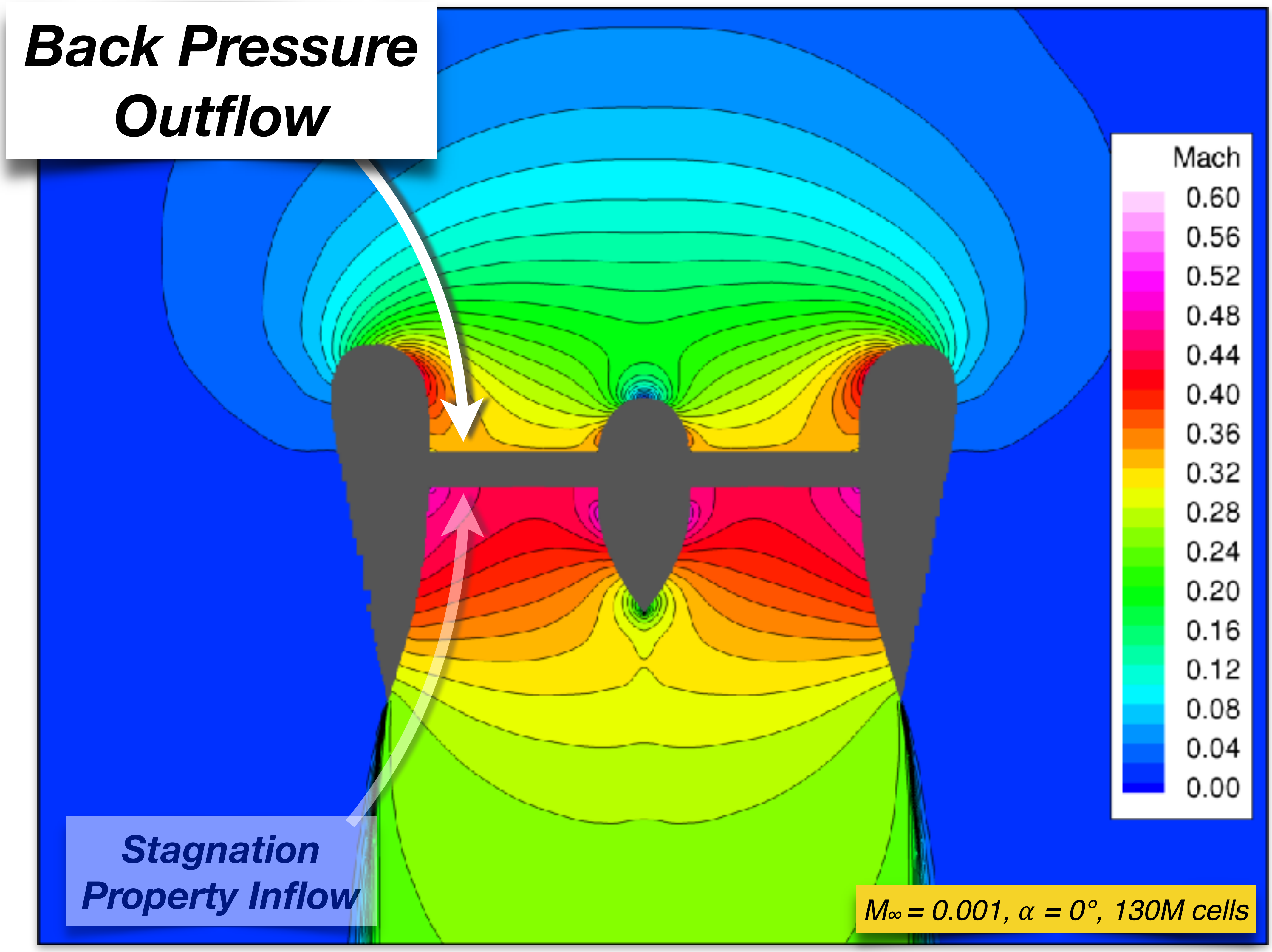




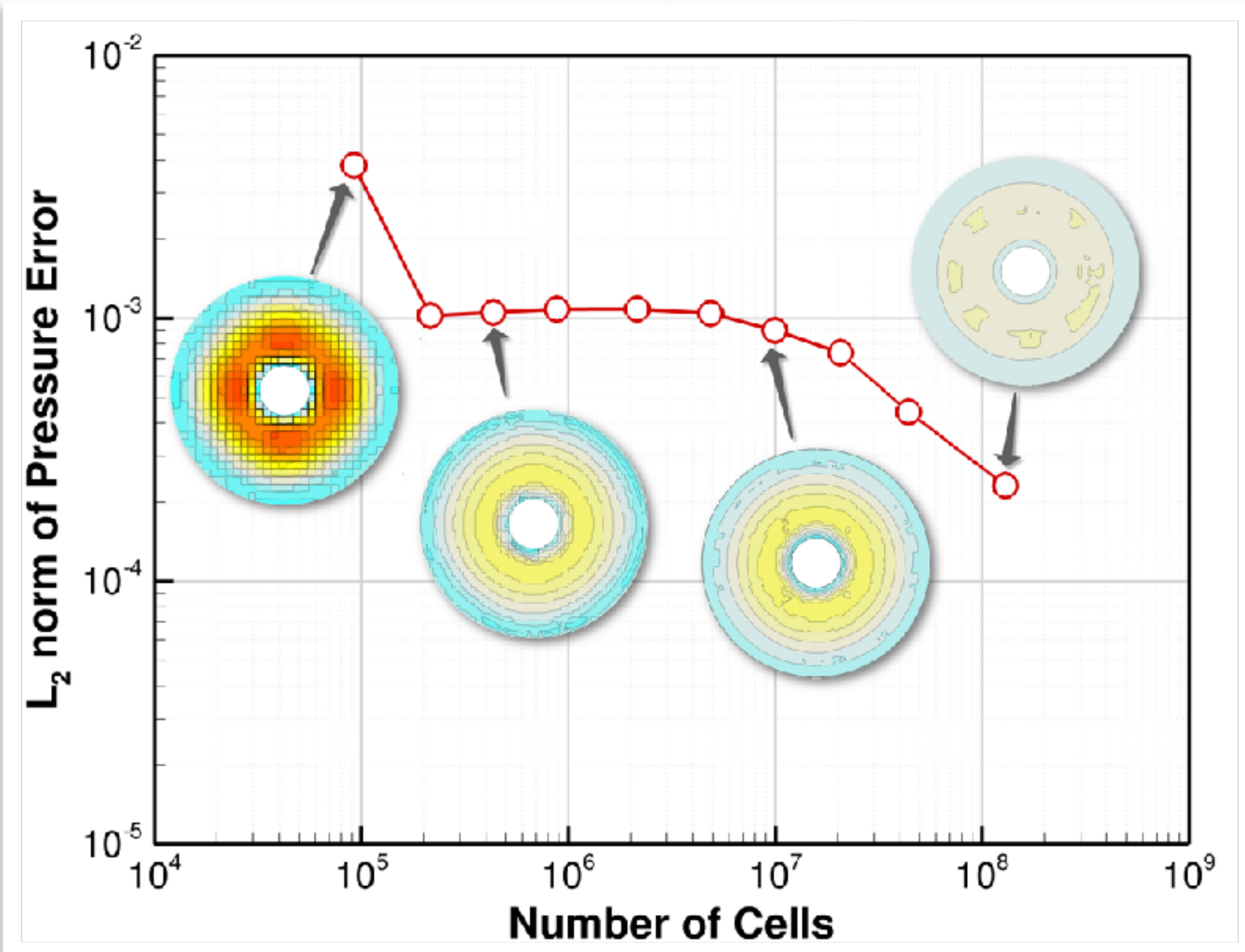
Ducted Fan - Example Solution



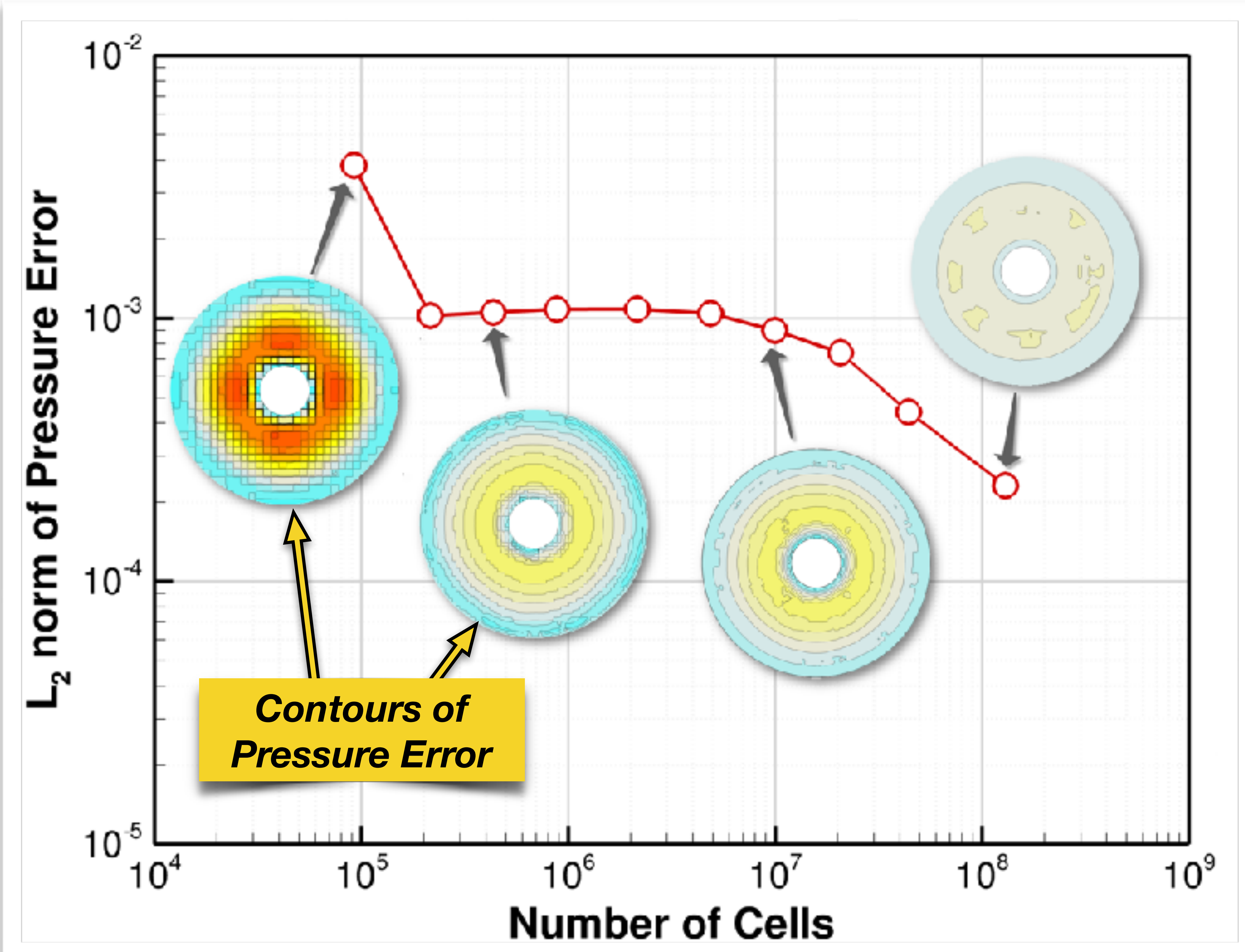
Ducted Fan - Example Solution



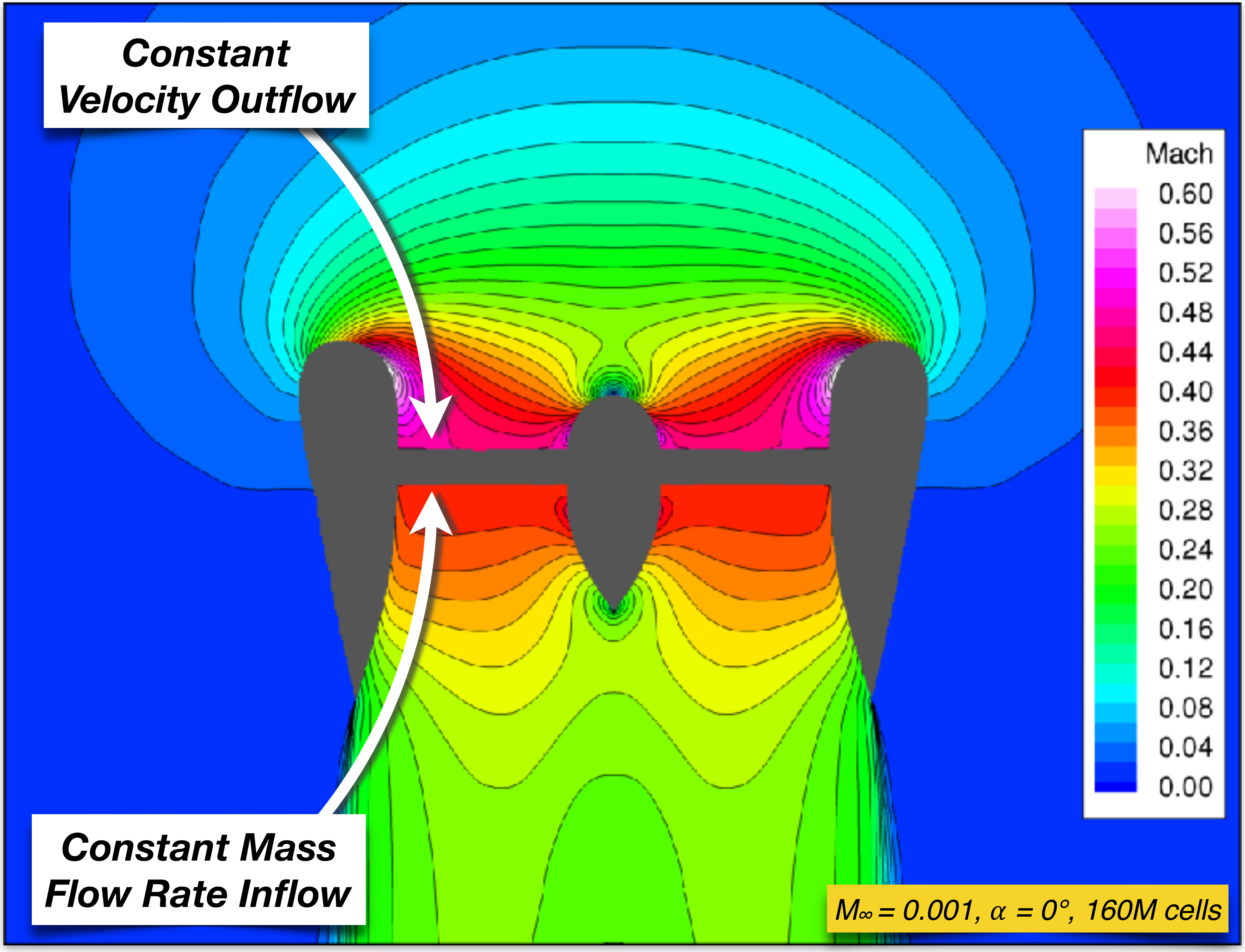
Back Pressure B.C. Mesh Convergence



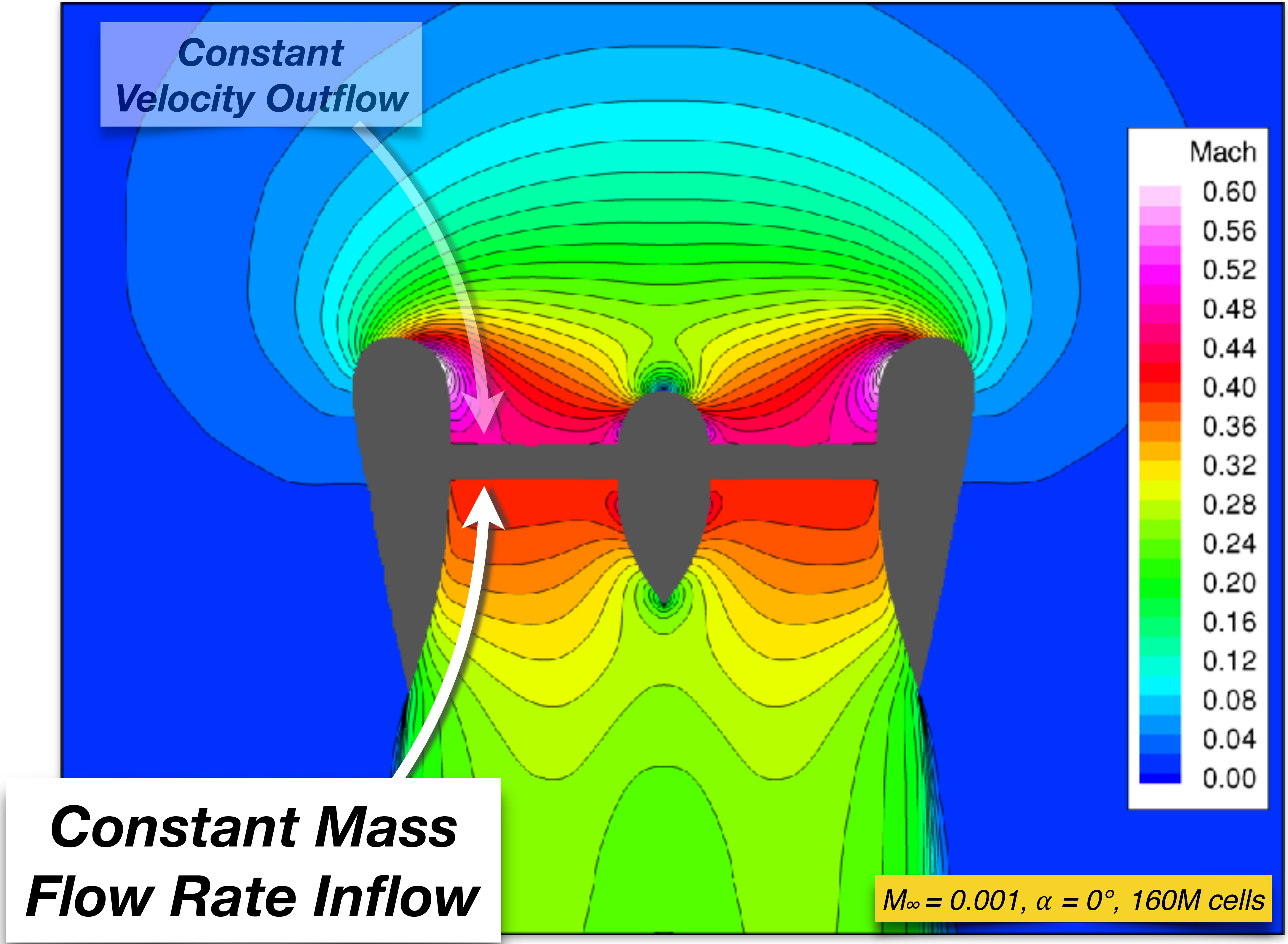
Back Pressure B.C. Mesh Convergence



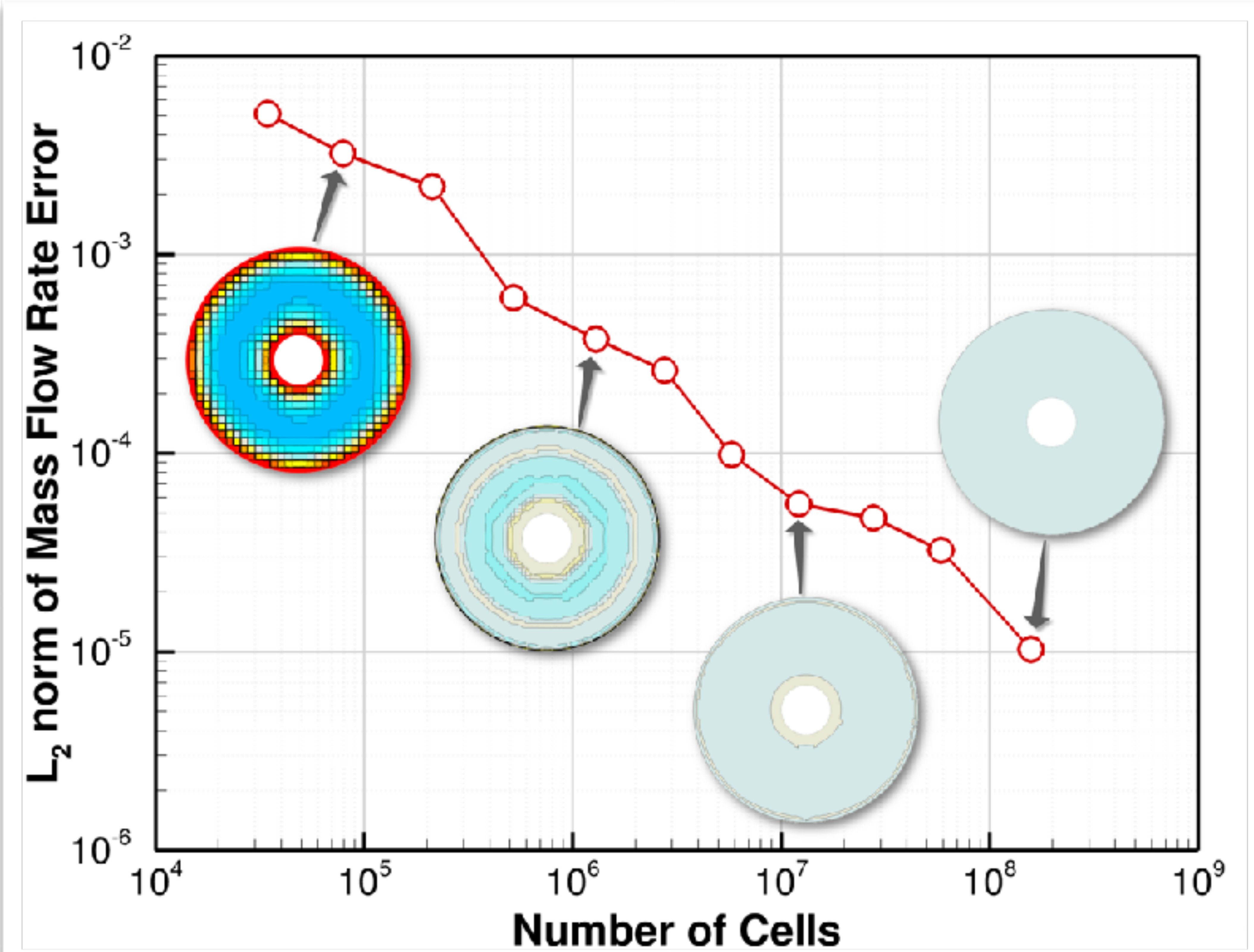
Ducted Fan - Example Solution



Ducted Fan - Example Solution

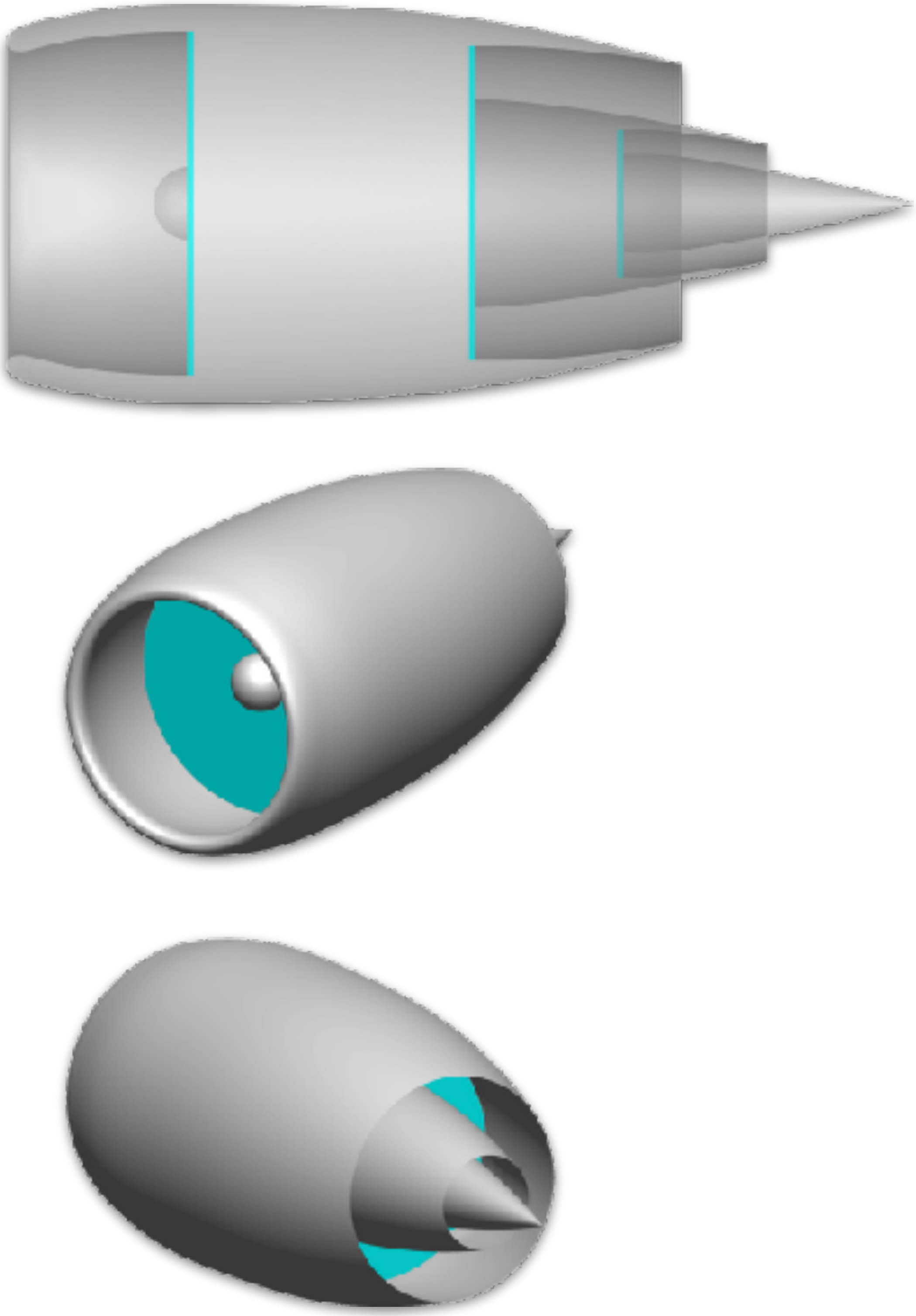


Constant Mass Flow Rate B.C. Mesh Convergence

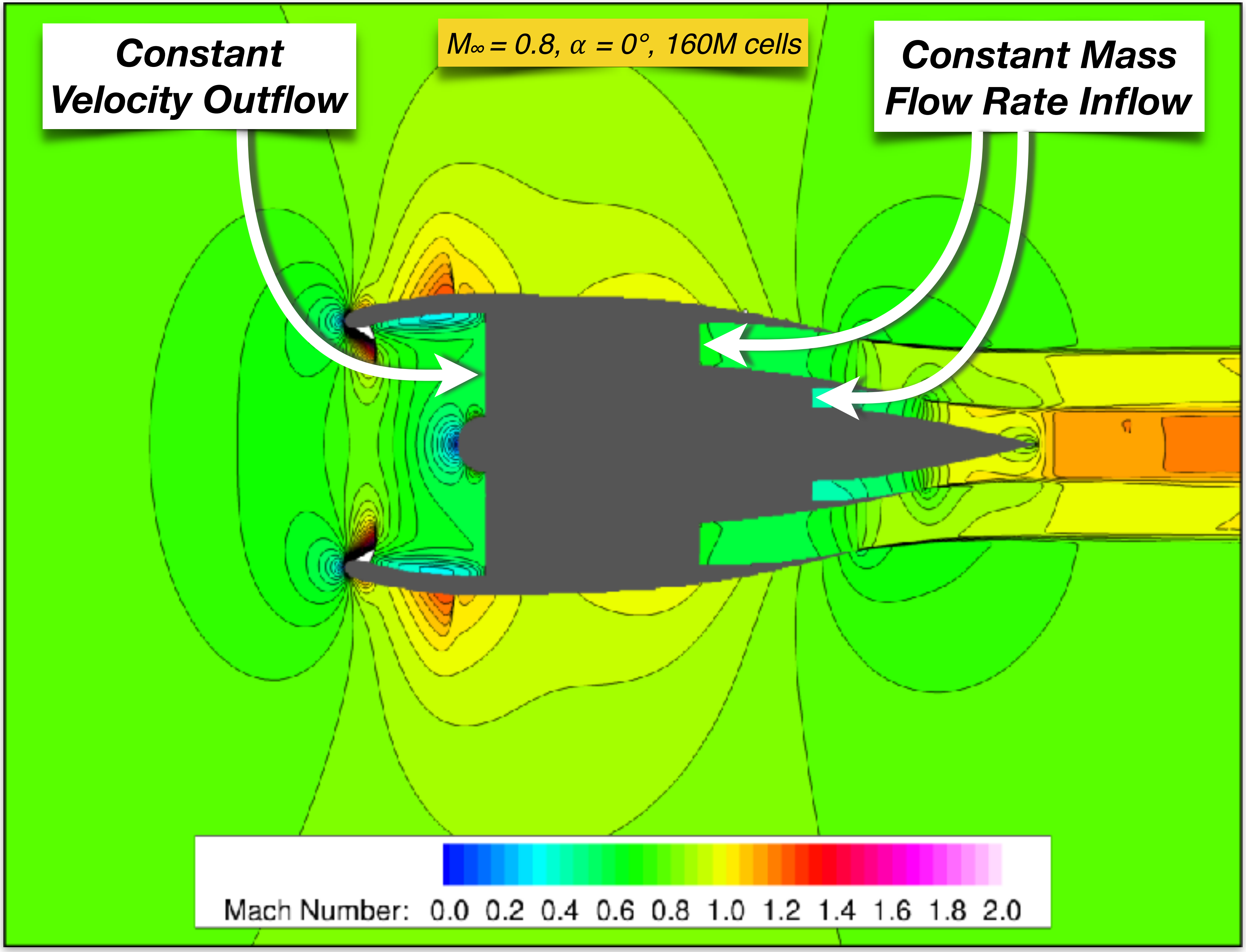


Turbofan in Transonic Flow

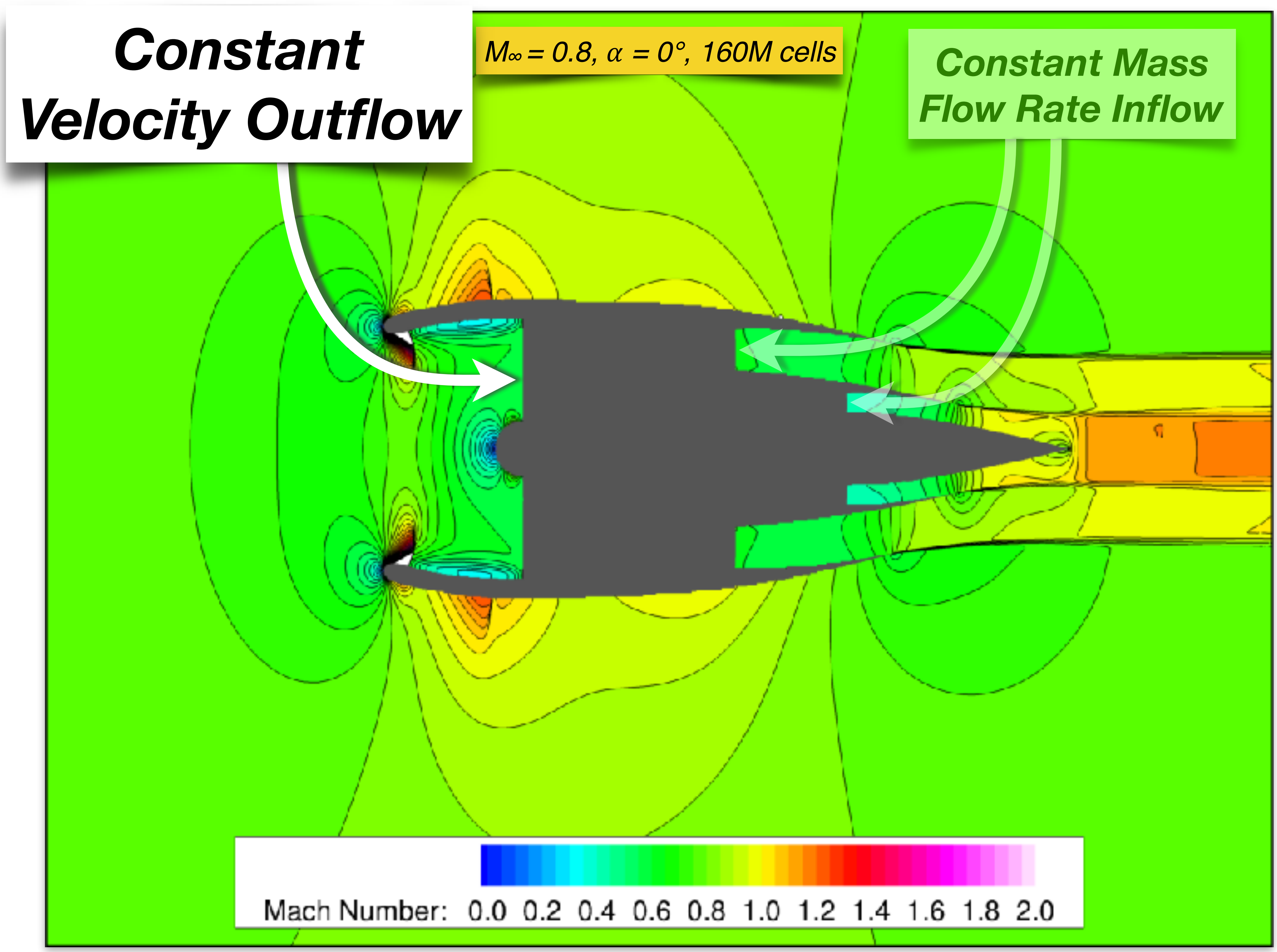
- Transonic diffuser with fan hub
- Two stream exhaust with cone nozzle for turbine flow
- Mach 0.8 freestream, no angle of attack (axisymmetric flow)
- Fan / Compressor face modeled as **annulus**, outflow boundary condition applied
- Fan and turbine exhaust planes modeled as **annuli**, inflow boundary conditions applied



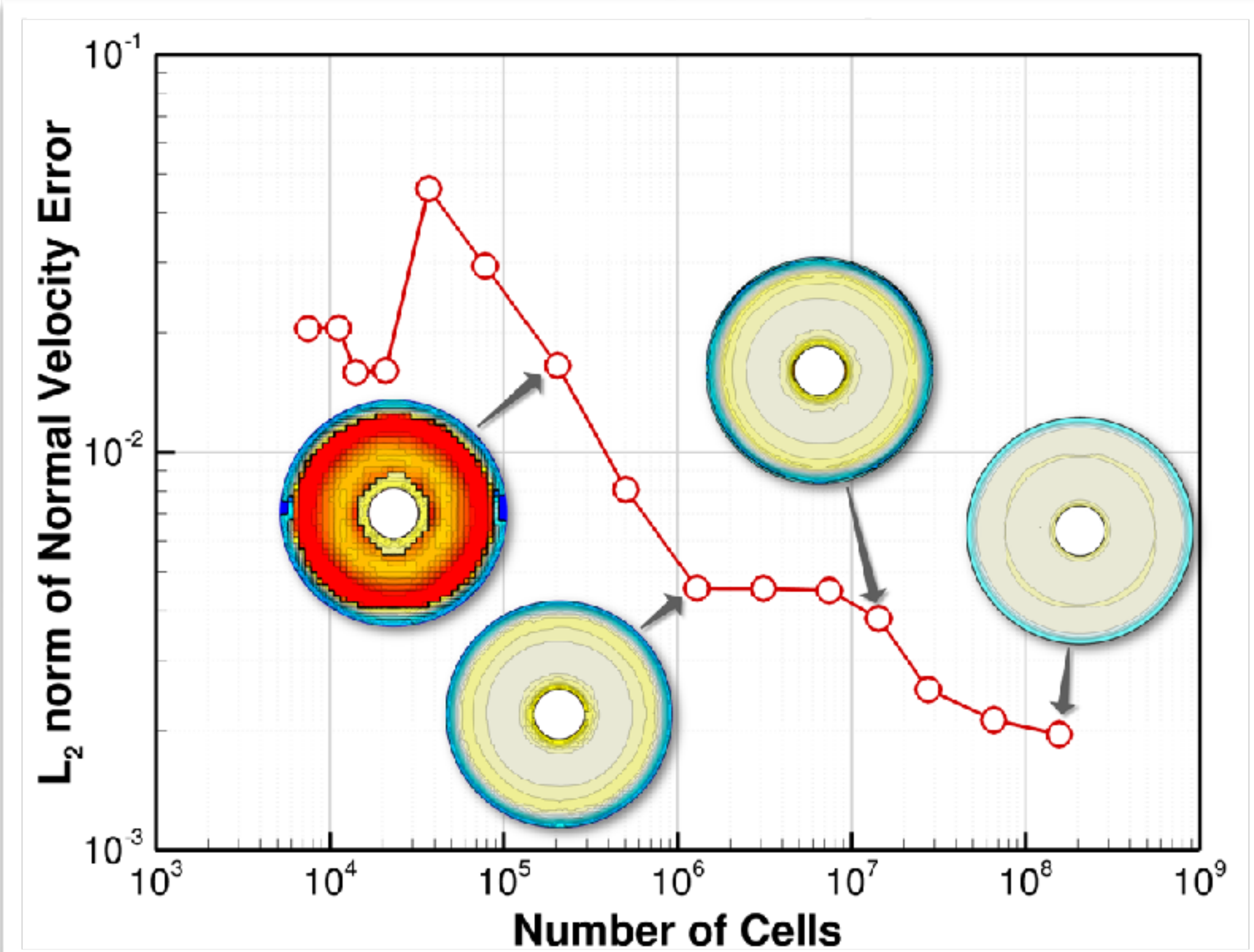
Turbofan - Example Solution



Turbofan - Example Solution

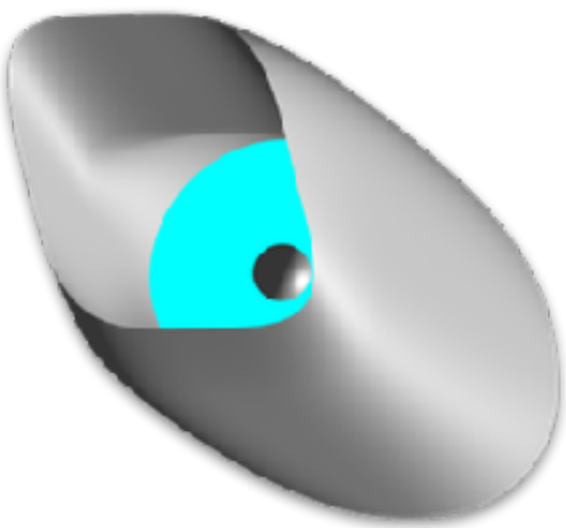


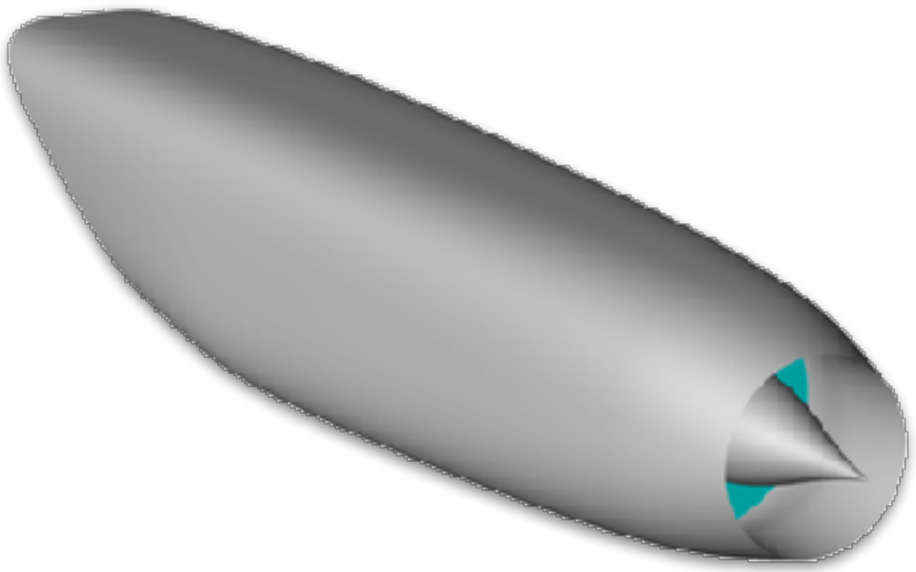
Constant Velocity B.C. Mesh Convergence

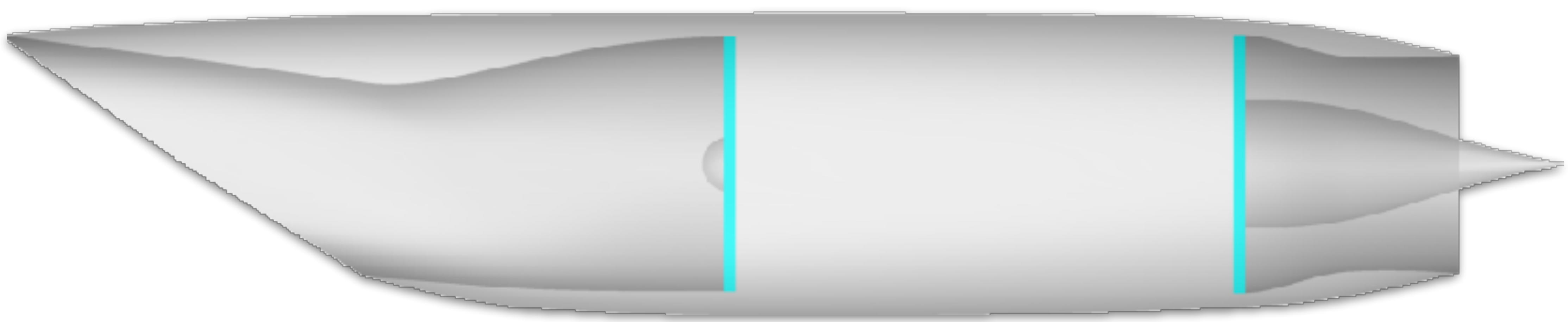


Turbojet in Supersonic Flow

- 2-D ramp inlet design for normal terminal shock
- Converging-diverging duct with cone nozzle
- Mach 1.5 freestream, 1° angle of attack
- Outflow / Inflow boundary conditions applied to **annuli**

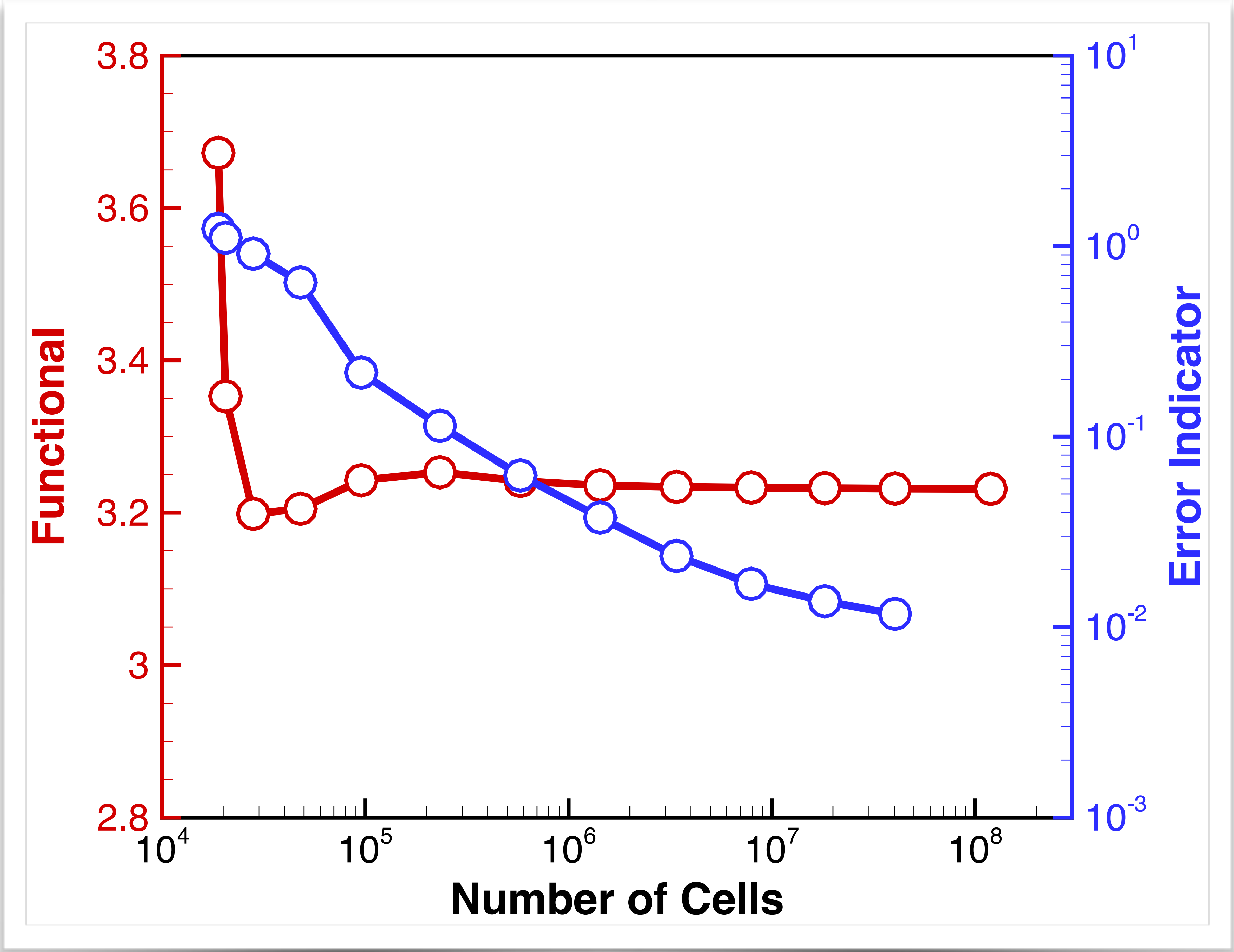






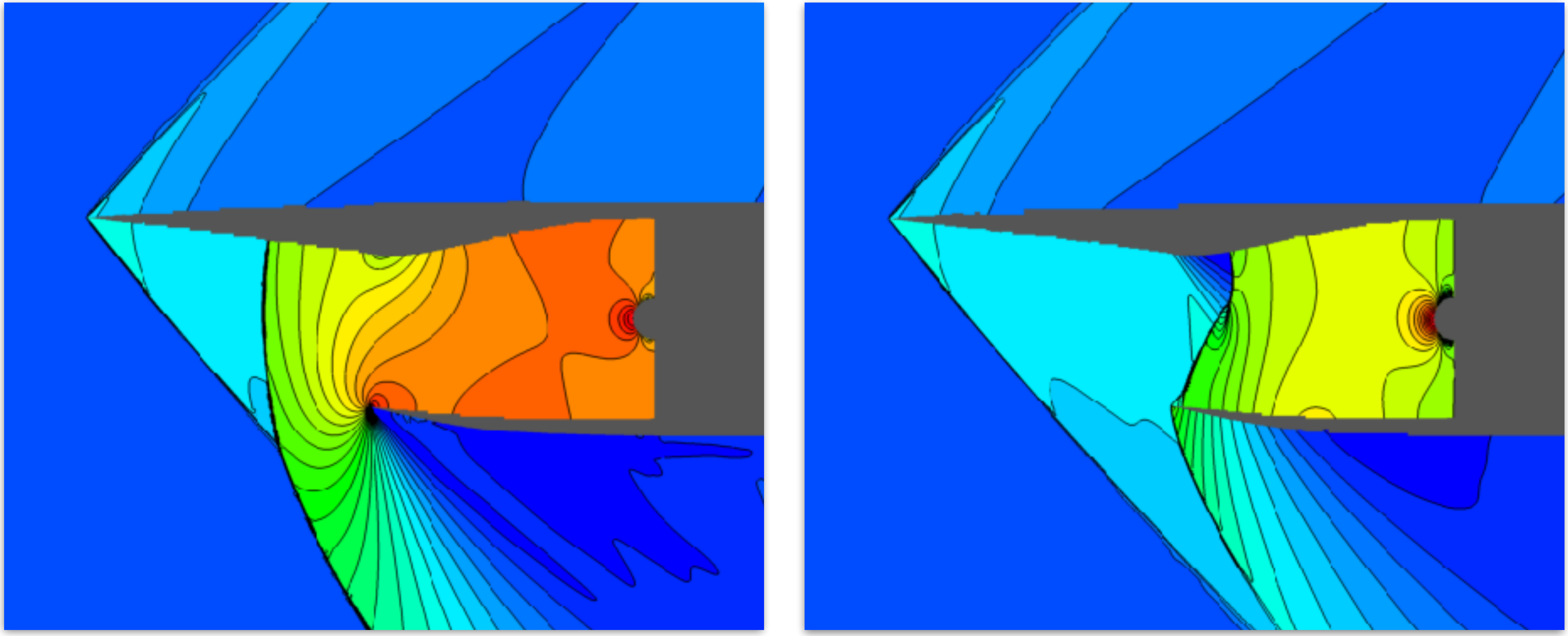
Turbojet - Mesh Convergence

- Good convergence of functional (thrust + lift + plume sensor)
- Steady reduction in error estimate



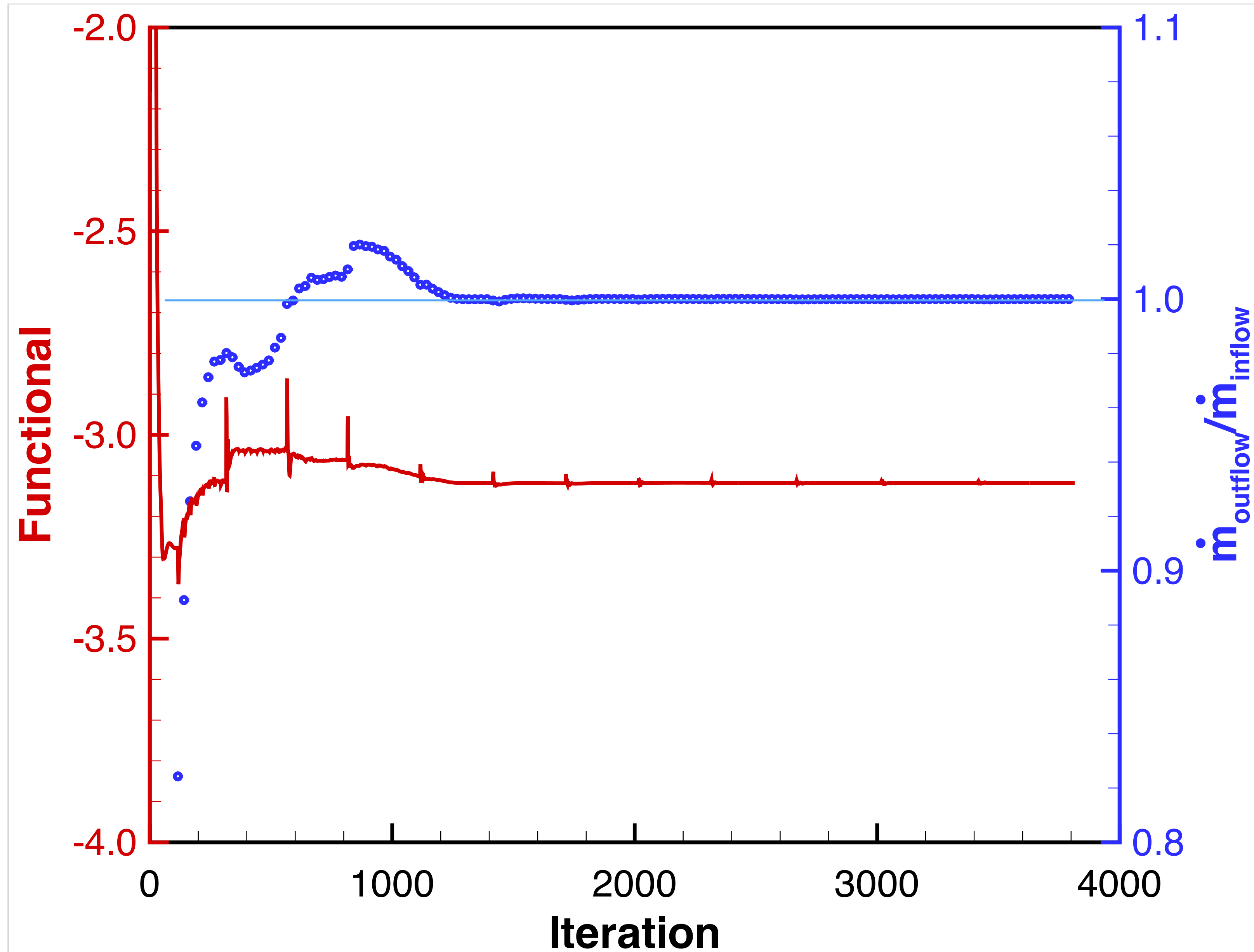
Supersonic Inlet - Mass Flow Rate

- Usually need to specify mass flow rate through an inlet
- Often desirable to match nozzle mass flow rate if modeled
- Highly nonlinear flow features can make mass flow rate steering difficult in supersonic and even transonic inlets



Turbojet - Mass Flow Rate Steering

- Inflow mass flow rate ($\dot{m}_{inflow}$) set through boundary condition
- Outflow mass flow rate ($\dot{m}_{outflow}$) steered to match
- Mass flow rate quickly converges and continues to converge through each refined mesh



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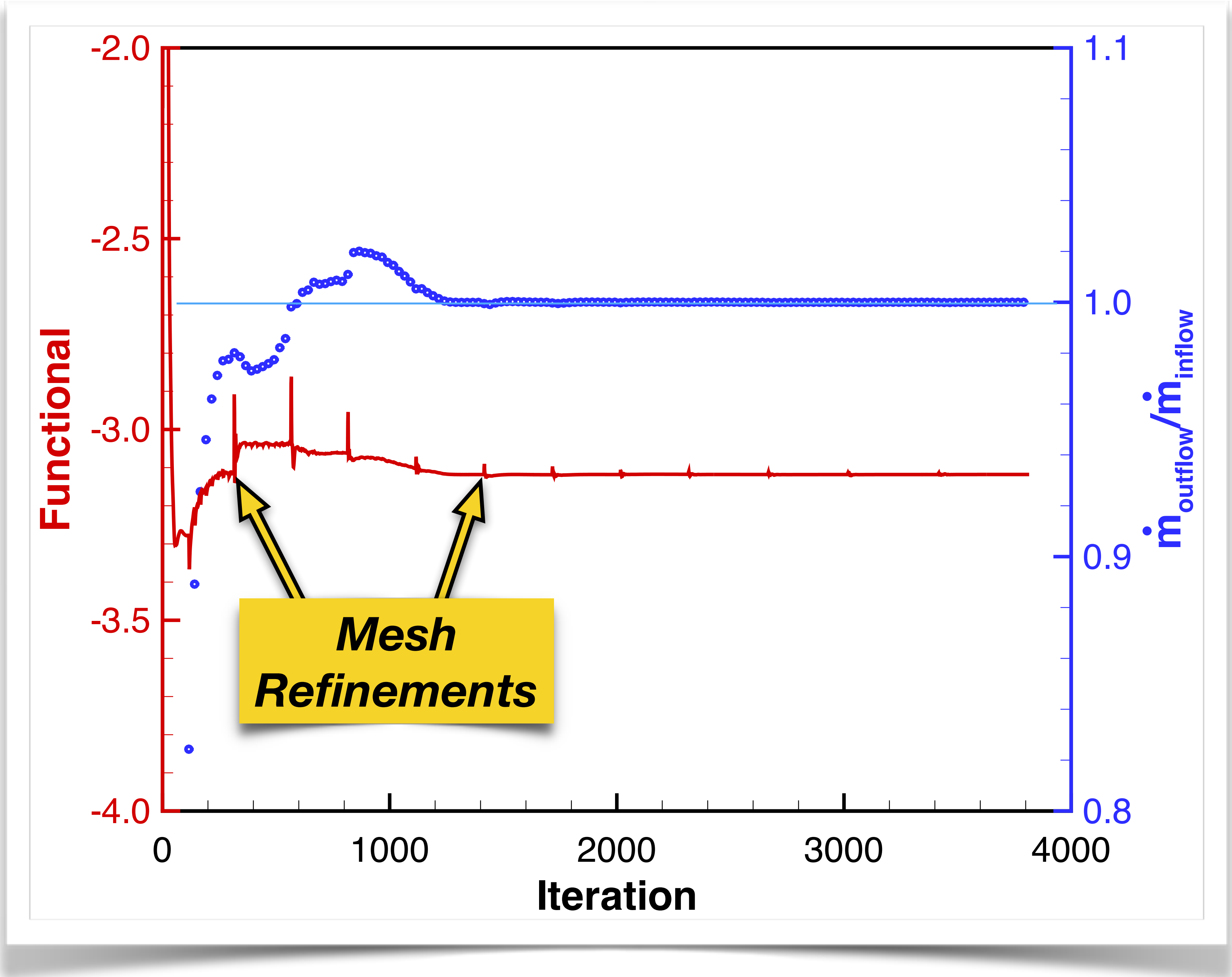
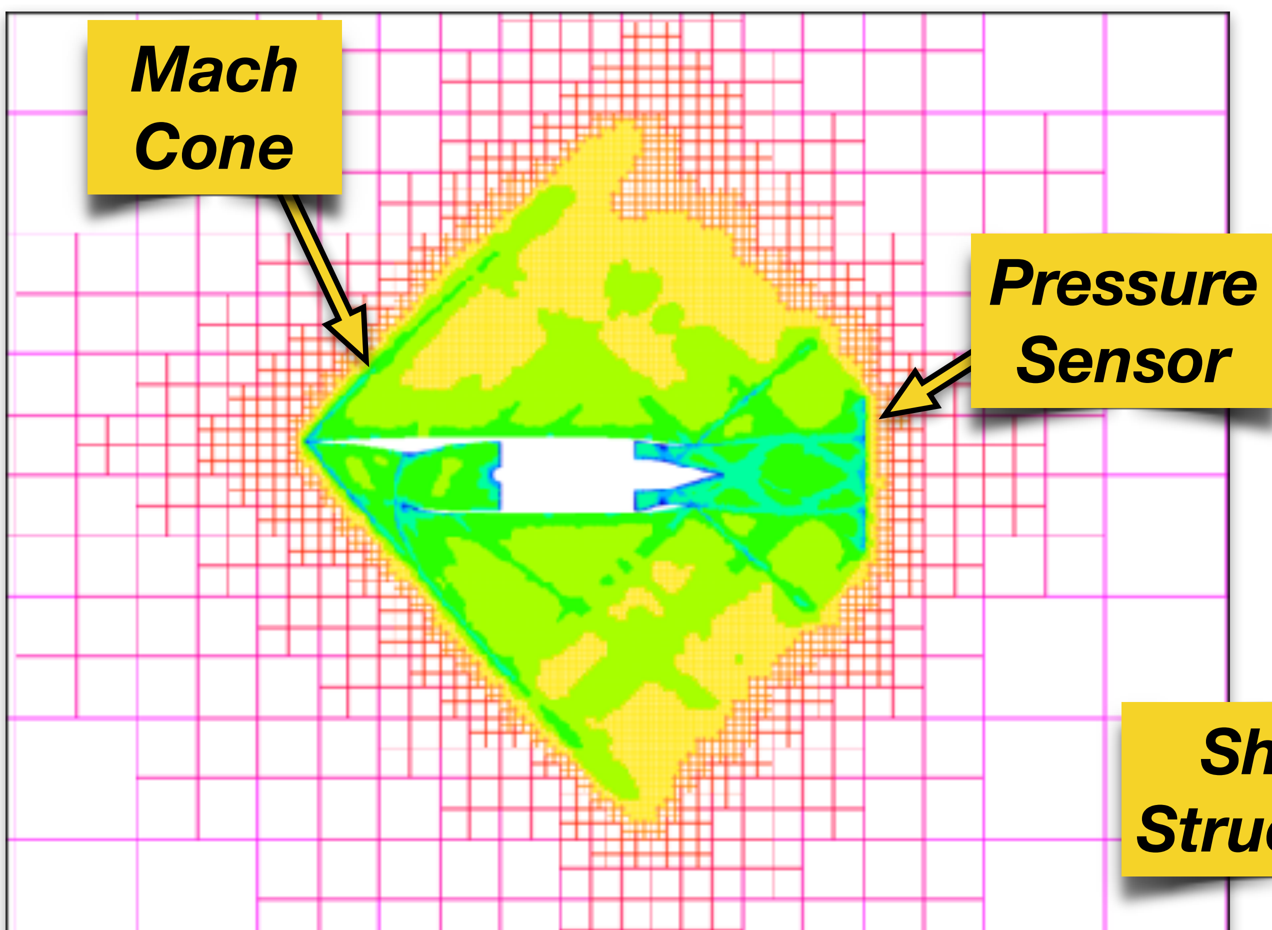
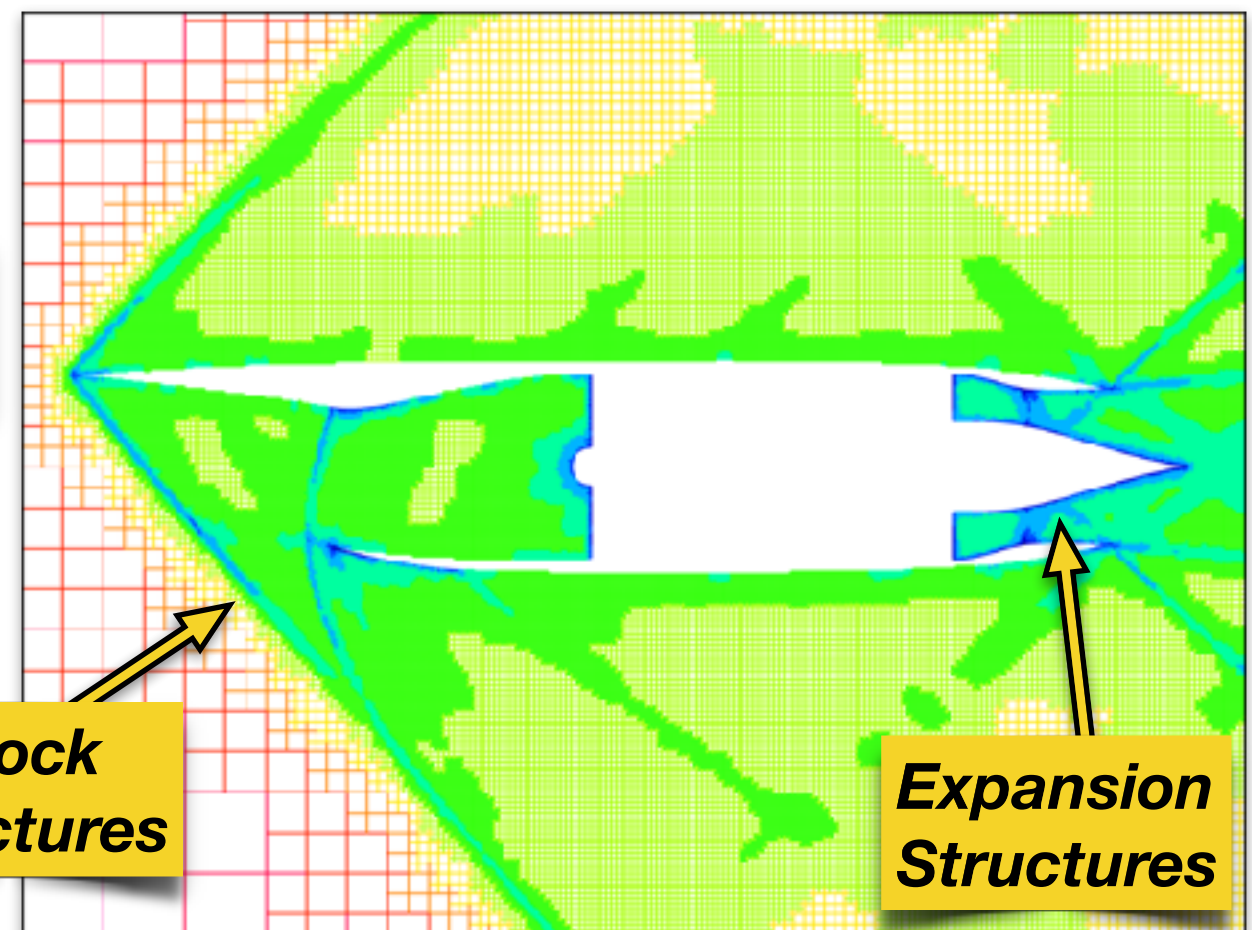


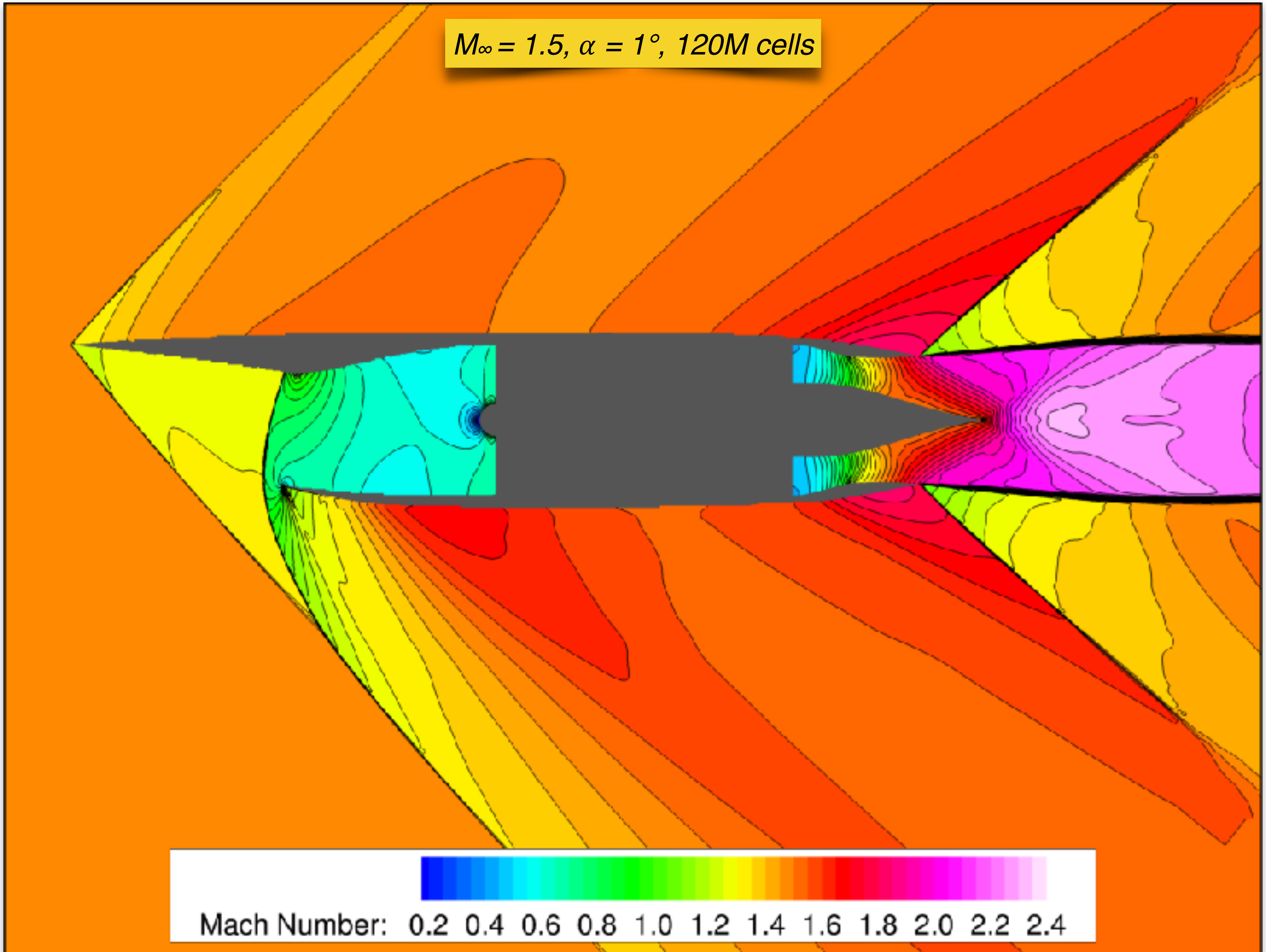
Turbojet - Adaptively Refined Mesh

- Colors represent cells of same level of refinement
- Mesh was refined at surface, within Mach cone of influence, at shock and expansion structures, and at plume shear layer influencing pressure sensor



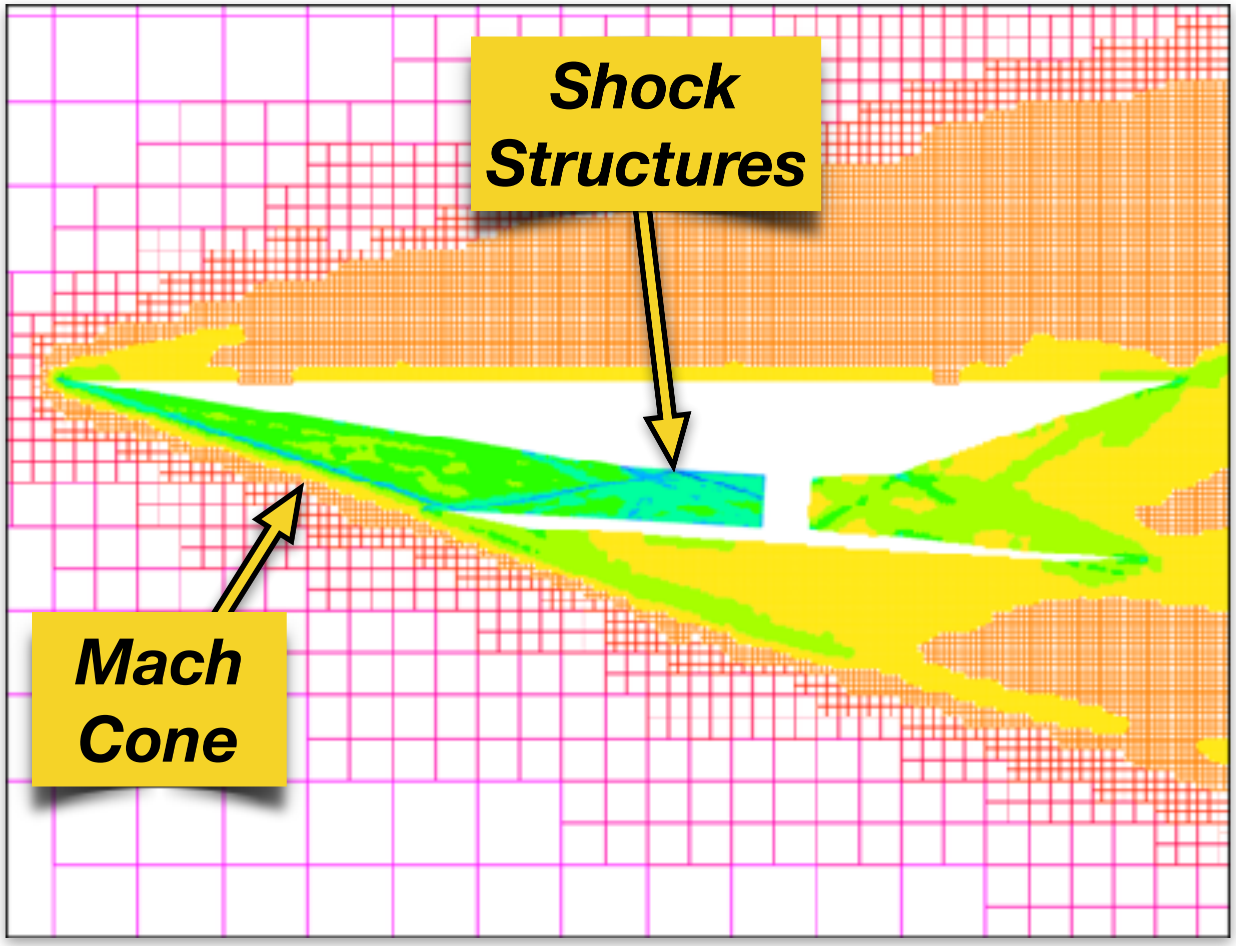


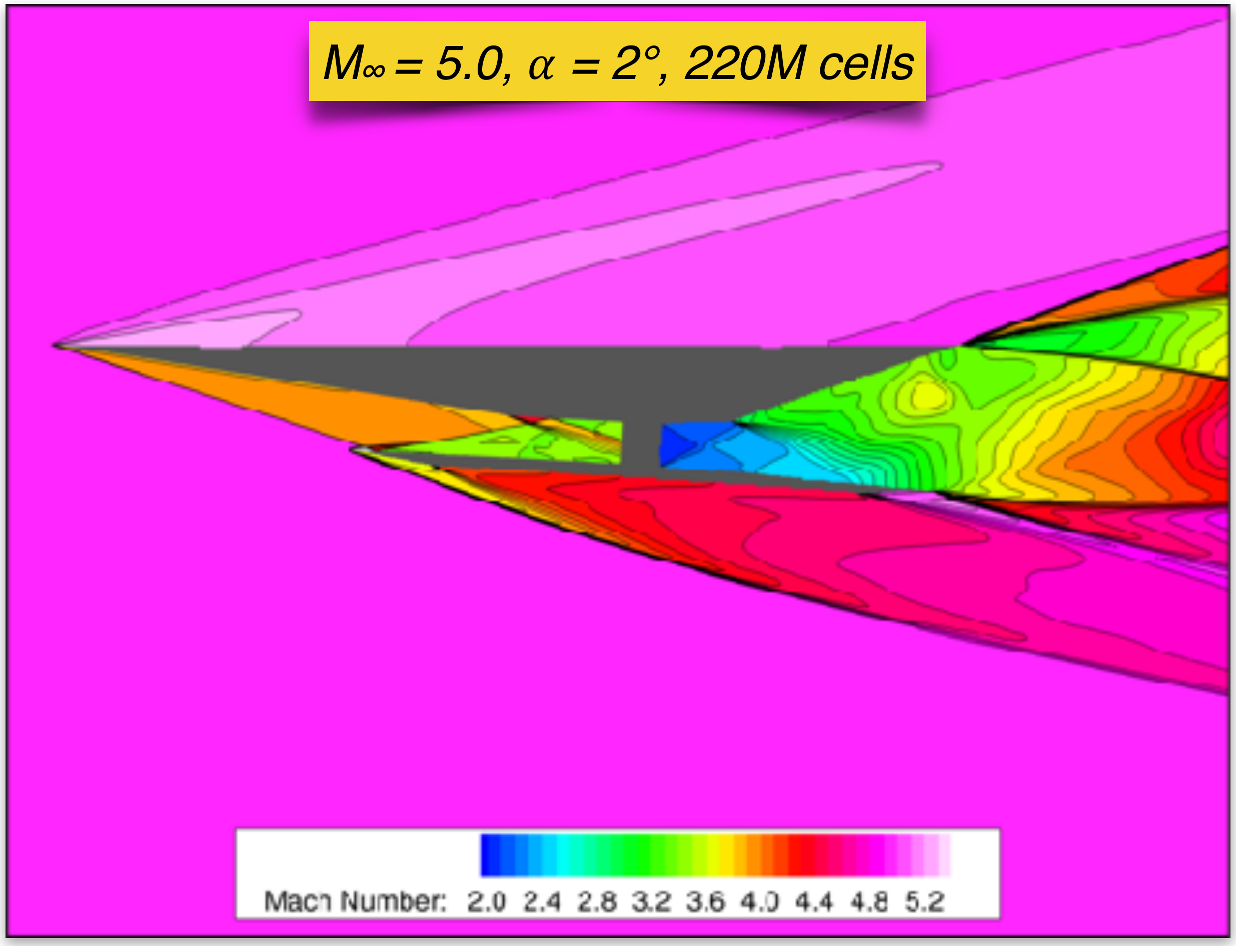
Turbojet - Matched Mass Flow Rates



Scramjet in Hypersonic Flow

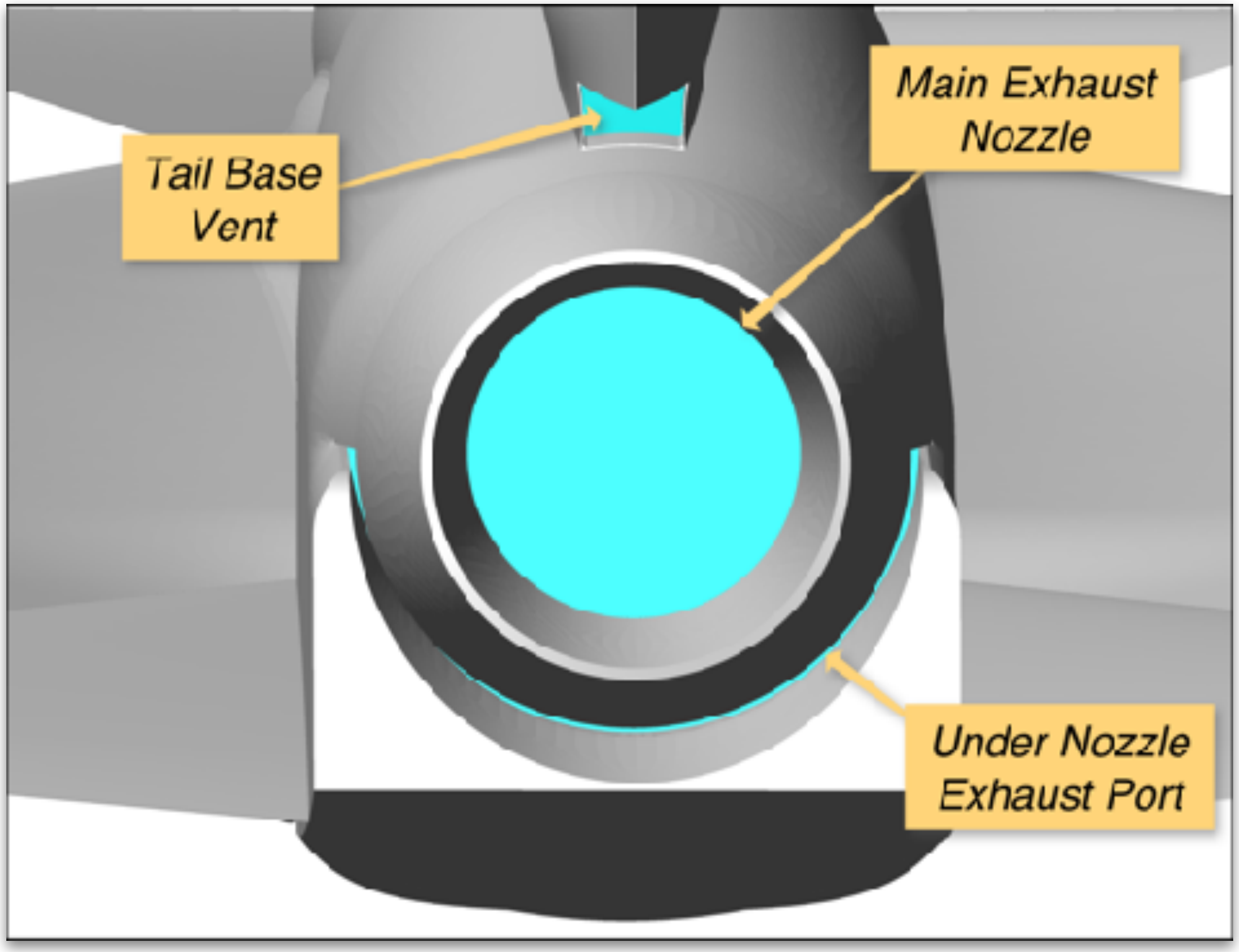
- Multiple ramp inlet and outlet, flow through burner remains supersonic
- Mach 5.0 freestream, 2° angle of attack
- Subsonic inflow / outflow boundary conditions not applicable
- Original full state with Riemann solver (`SurfBC`) boundary condition applied
- Mesh was refined at surface, within Mach cone of influence, shock and expansion structures, and plume shear layer influencing pressure sensor

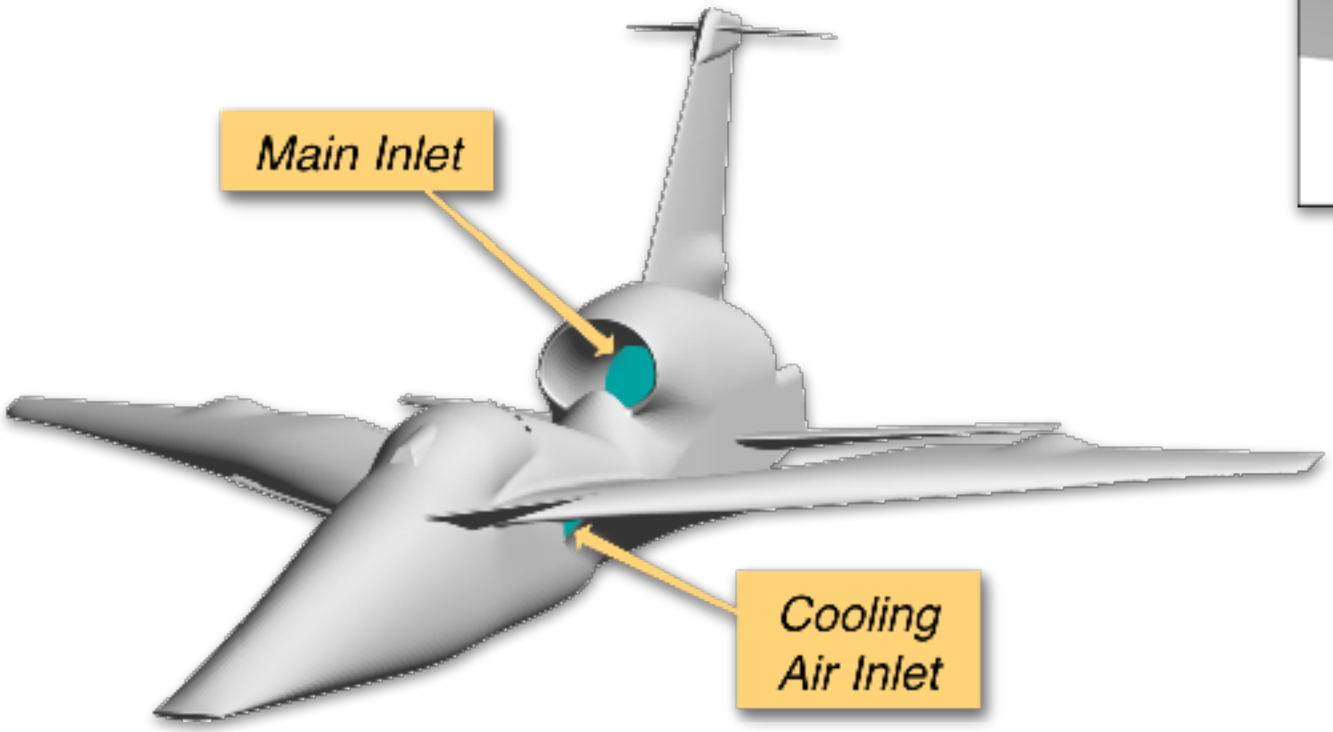


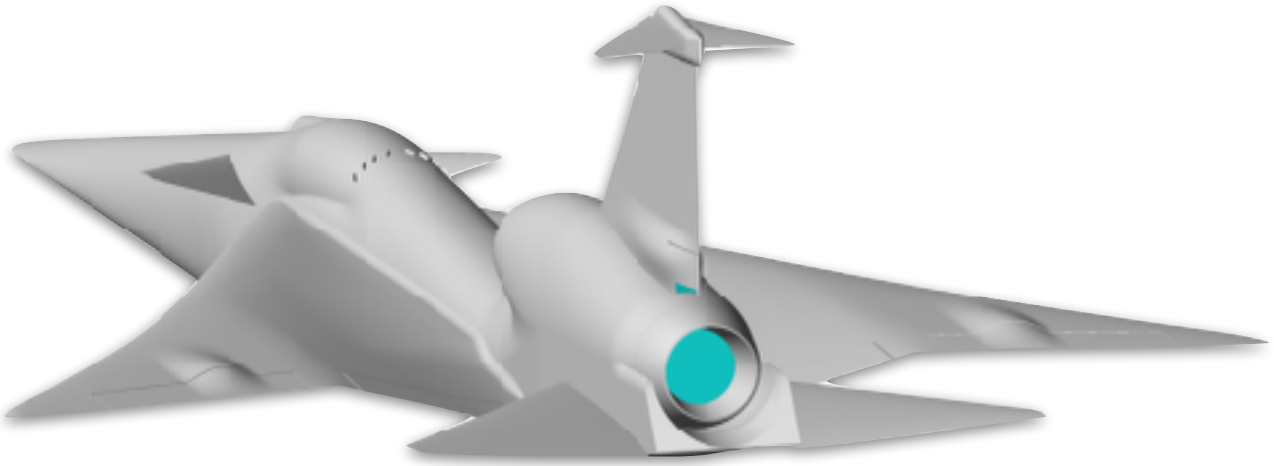


Low Boom Supersonic Demonstrator

- Realistically complex geometry
- Mach 1.4 freestream, 2.15° angle of attack
- 3 inlets and 3 exhausts

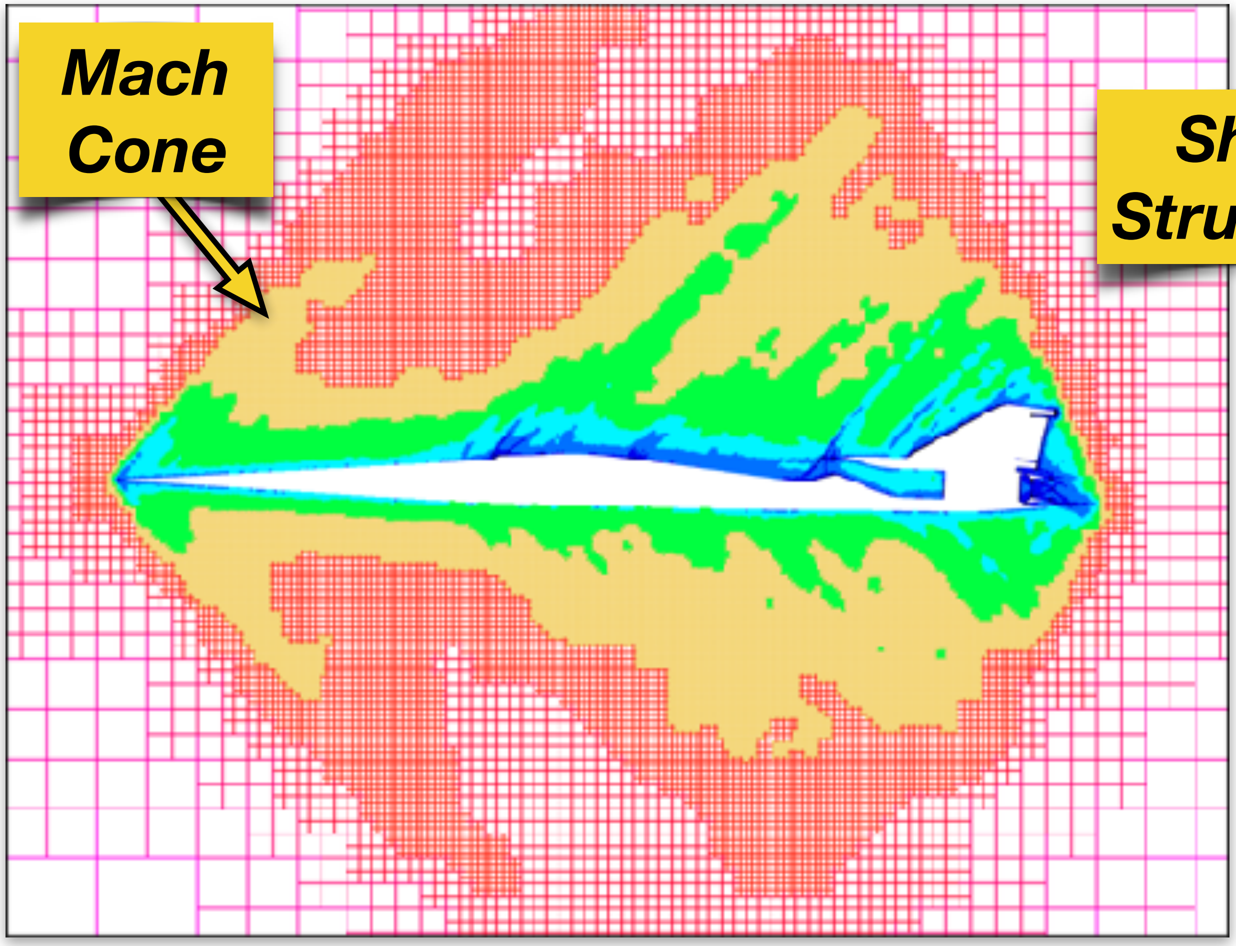


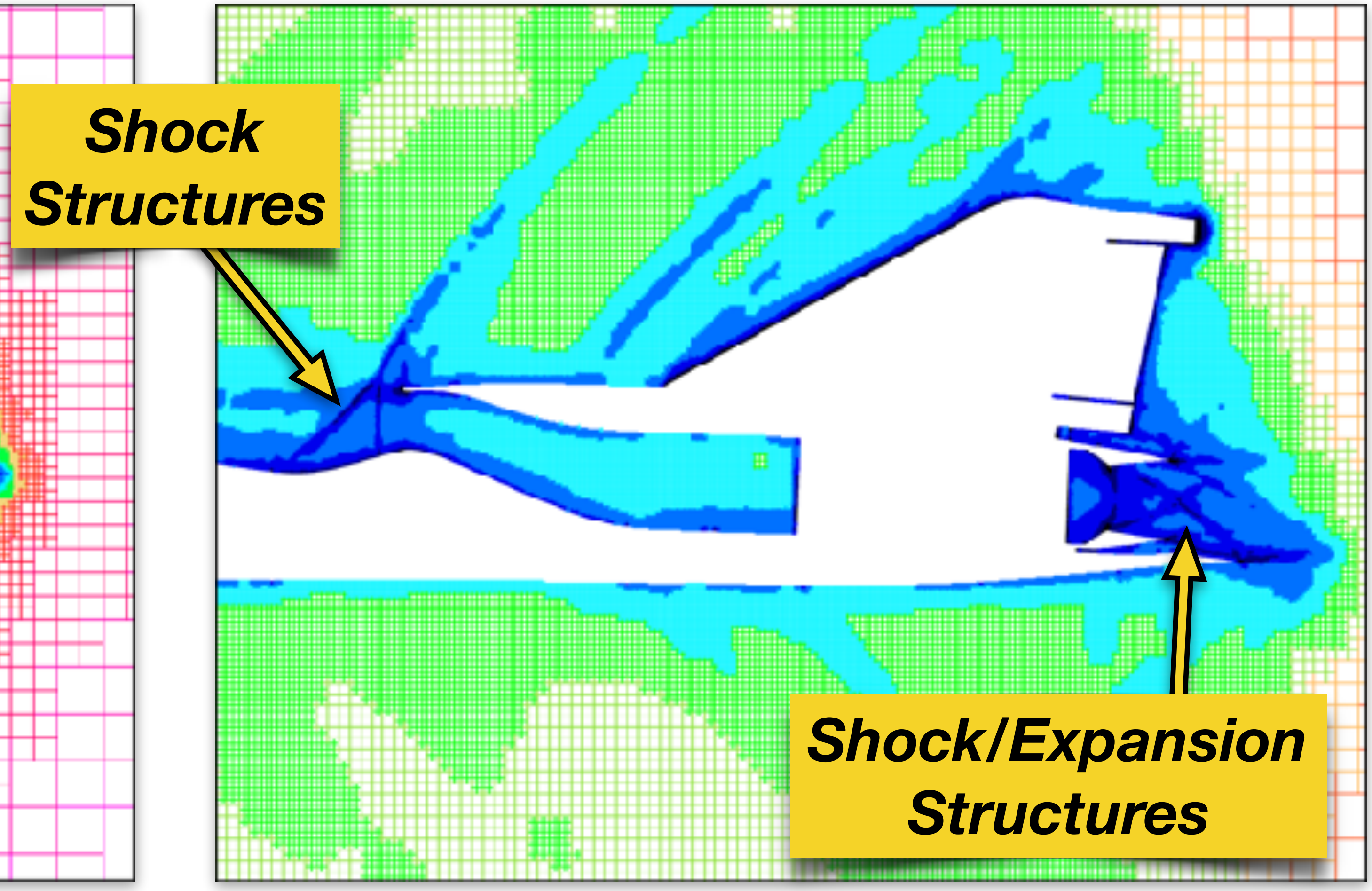




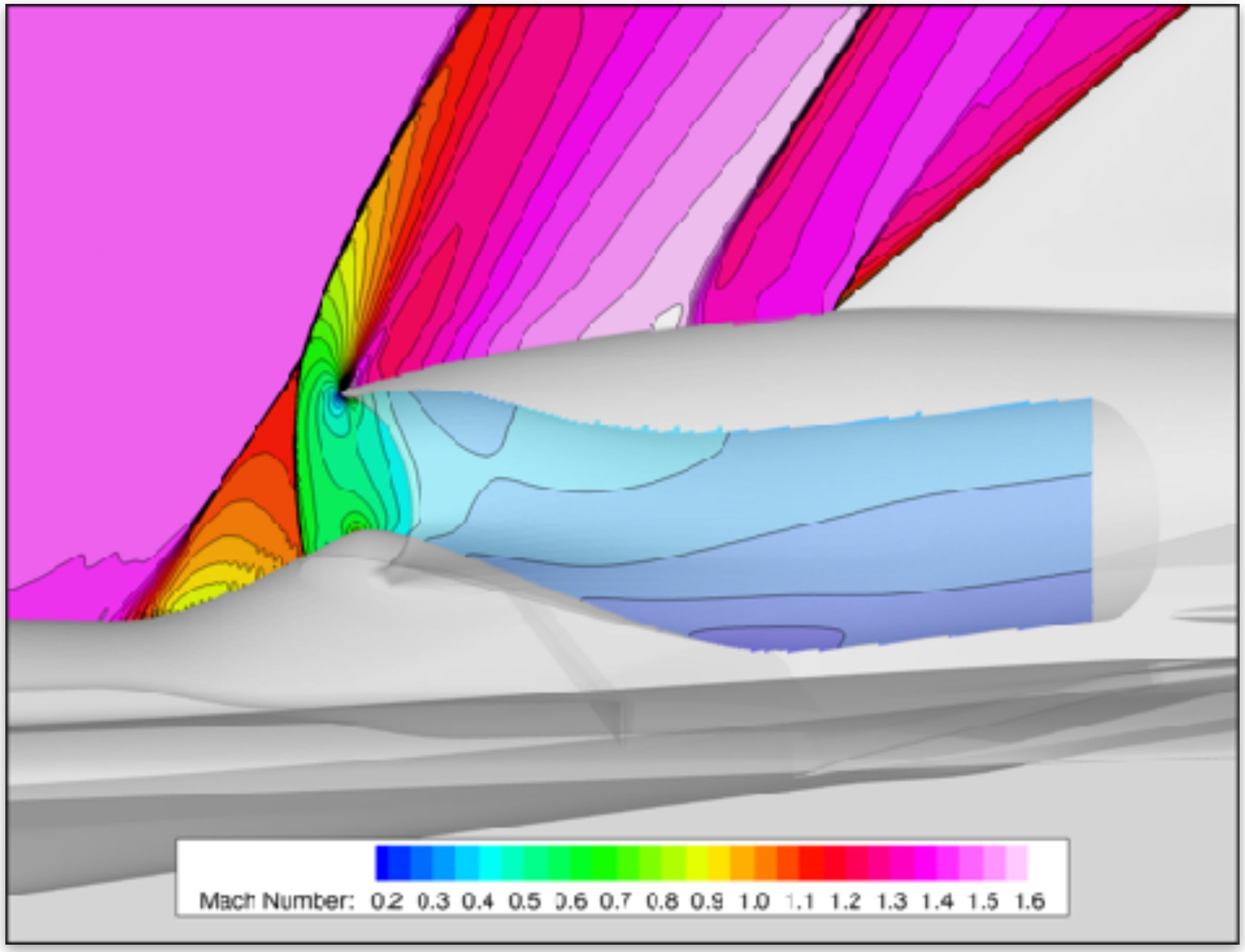
Low Boom Aircraft - Adaptively Refined Mesh

- Functional was aircraft drag
- Colors represent cells of same level of refinement
- Mesh was refined at surface, within Mach cone of influence, and at shock and expansion structures

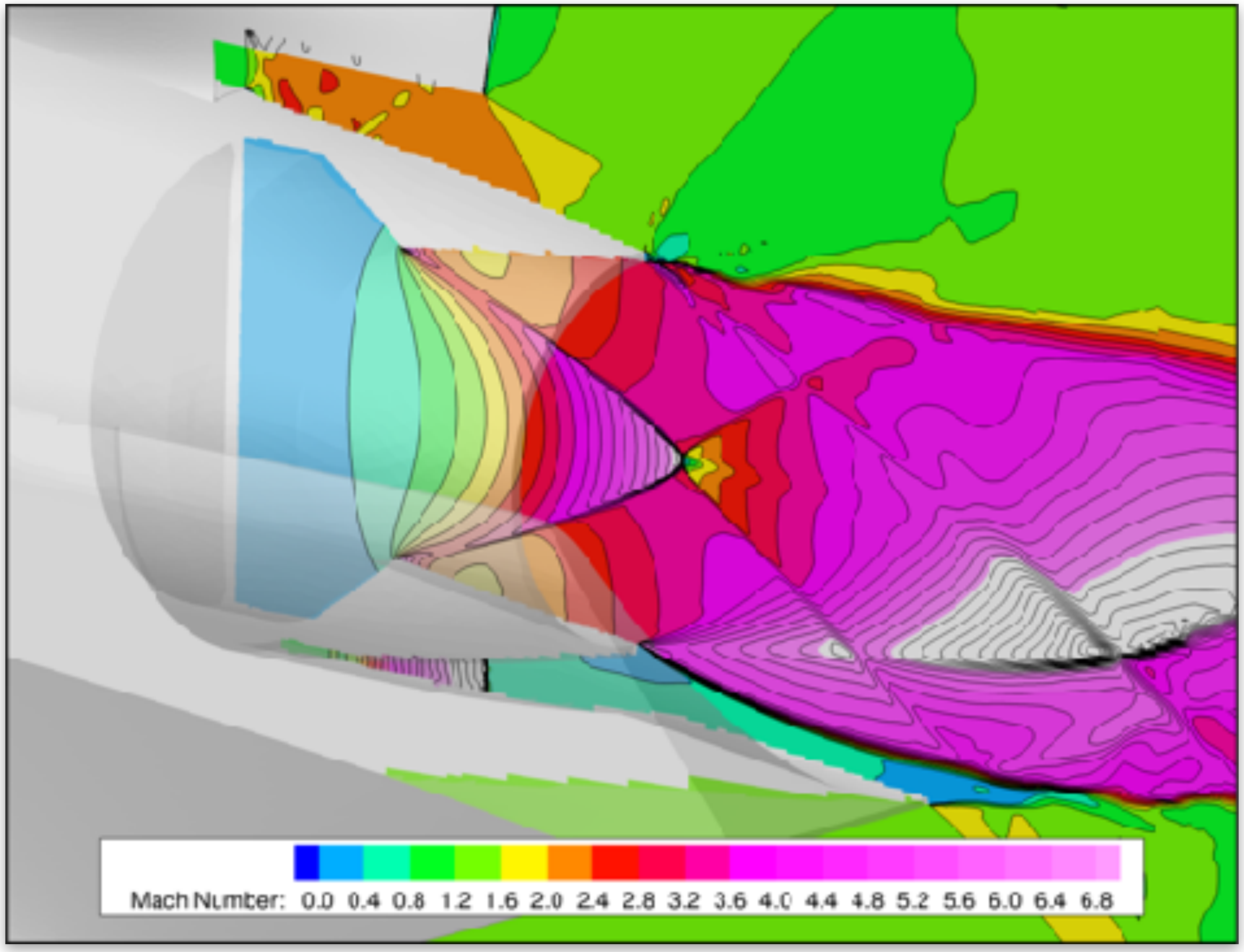




Low Boom Aircraft - Example Solution



$M_\infty = 1.4$, $\alpha = 2.15°$, 70M cells (half-body mesh)



- Underwing inlet geometry is not fully realized
- Safeguards were active in these inlets (solid wall to not allow reverse flow)

Summary and Ongoing Work

- Four new subsonic inflow/outflow boundary conditions implemented to improve modeling of propulsion systems
- Robust mass flow rate control implemented for both inflow and outflow
- Demonstrated on notional propulsion systems in flight regimes ranging from subsonic to hypersonic
  - adjoint-driven mesh refinement demonstrated with all propulsion boundary conditions
  - new boundary conditions verified mesh convergence studies on notional examples
- Demonstrated on realistically complex low boom aircraft
- *Ongoing work*
  - *Implement additional functionals appropriate for propulsion systems*
  - *Extend design framework to include new propulsion boundary conditions and functionals*

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