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Examining Rapid Depressurization of Honeycomb Panels using Computational Fluid Dynamics through Anisotropic Porous Modeling

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THERMAL & FLUIDS ANALYSIS WORKSHOP

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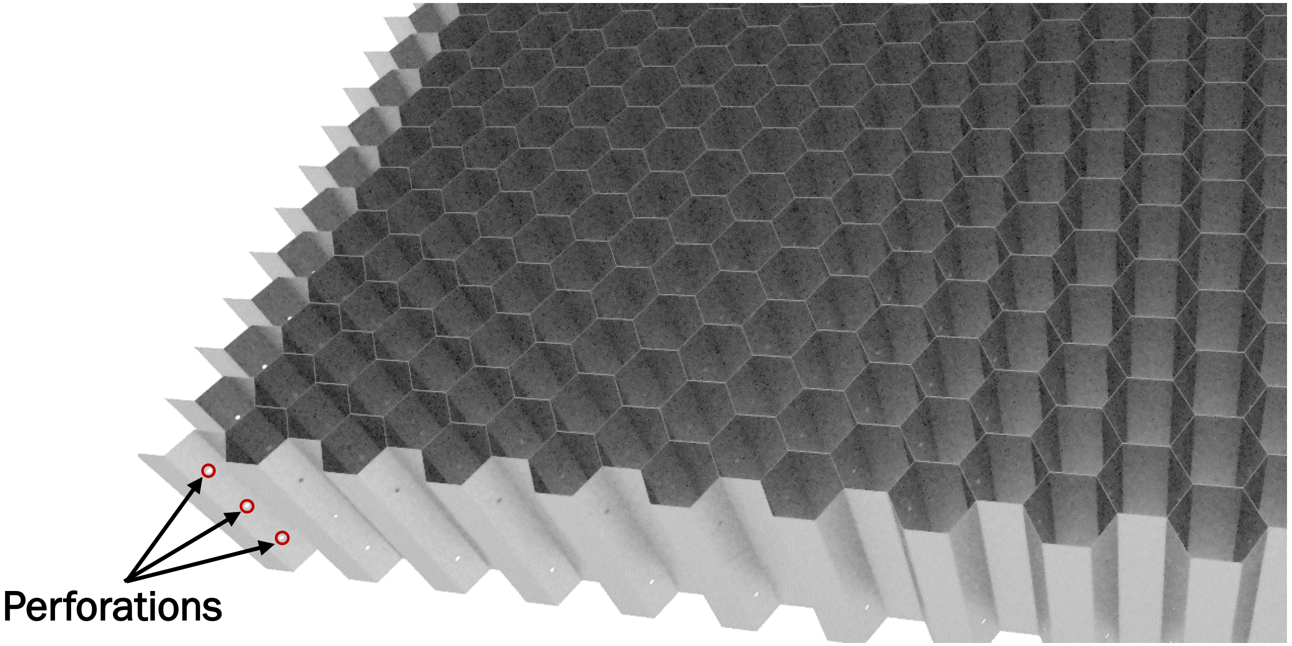
[1] Presenter and corresponding author; mhg@ata-e.com

Background

Honeycomb panels experience rapid depressurization.
Pressure prediction tools are limited

- Composite honeycomb panels used in solar arrays
- Experience rapid depressurization
- Elevated pressure differential causes structural failure
- Cells perforated to reduce differential
- Existing design rule too simplistic
- Limited use of CAE for predicting venting

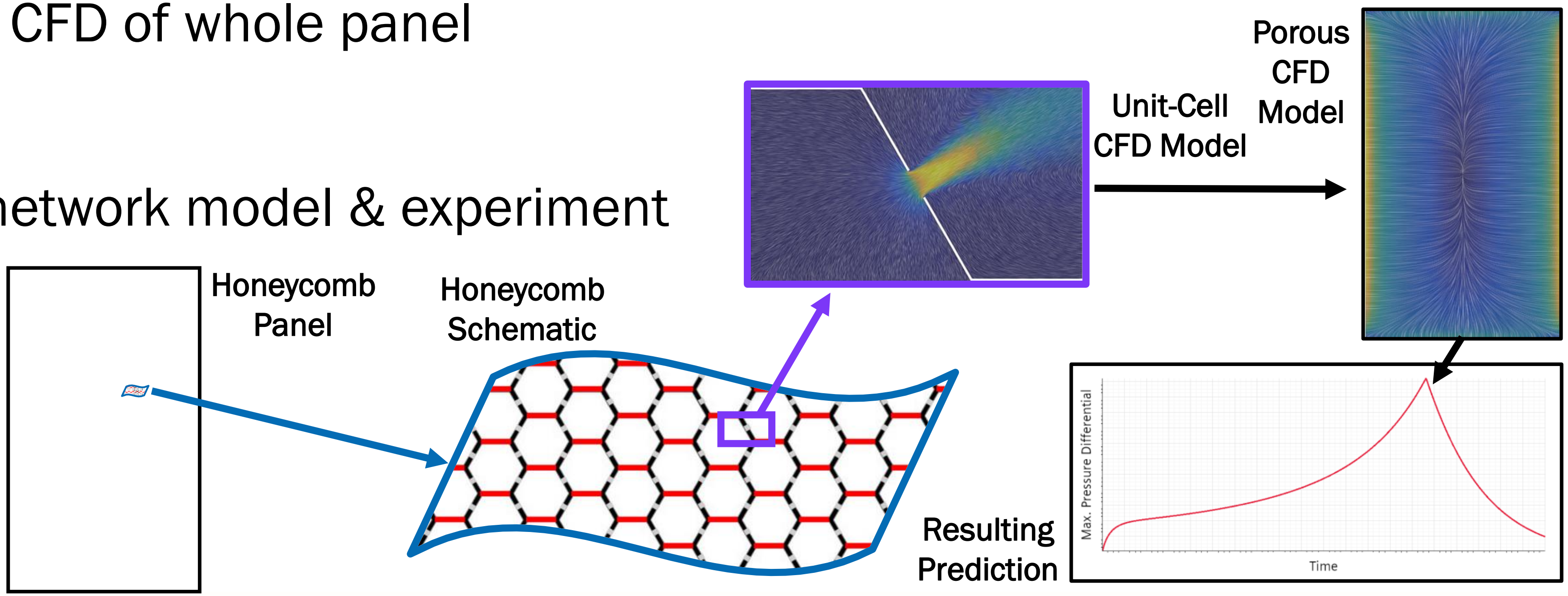
Objective:
Develop method for predicting differential pressures using CFD



Executive Summary

CFD workflow for depressurization of honeycomb panels, validated against test data

- Problem simplified:
    1. Steady CFD of unit cell
    2. Characterize flow to provide porous resistance coefficients
    3. Transient porous CFD of whole panel
- Results in 24 hours
- Validated against 1D network model & experiment



Honeycomb Panel

Honeycomb Schematic

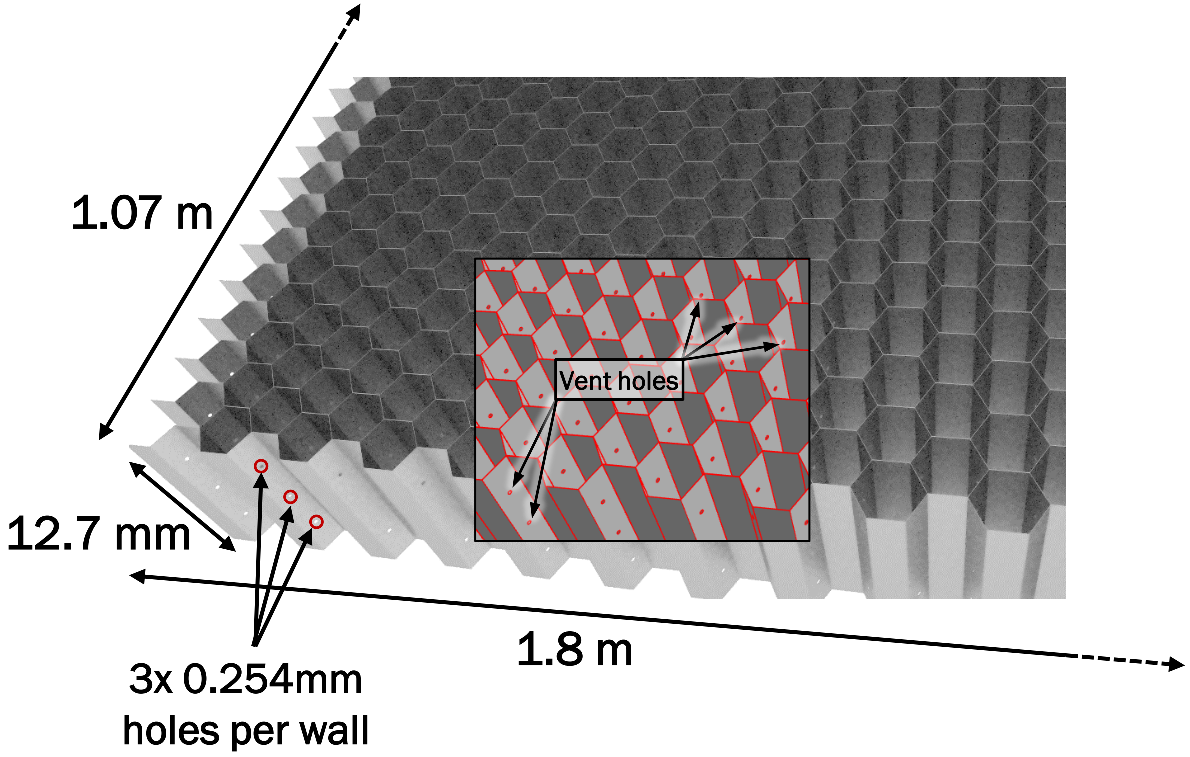
Unit-Cell CFD Model

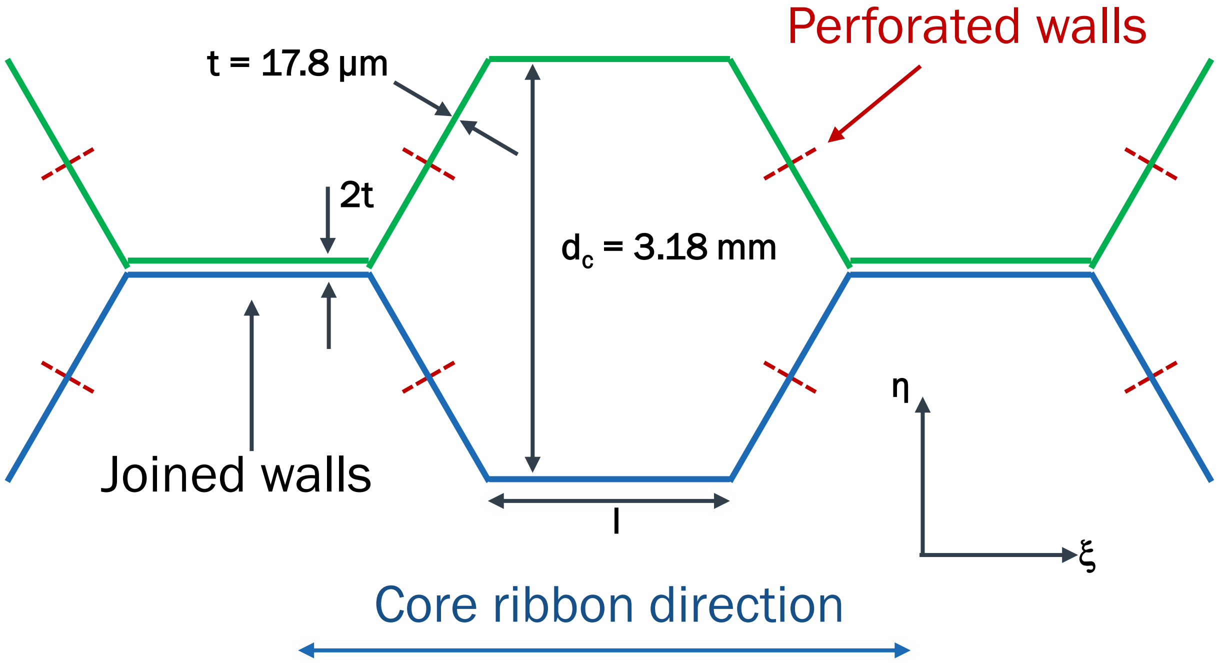
Porous CFD Model

Resulting Prediction

Typical Composite Honeycomb Panel Geometry

Industrially-representative panel



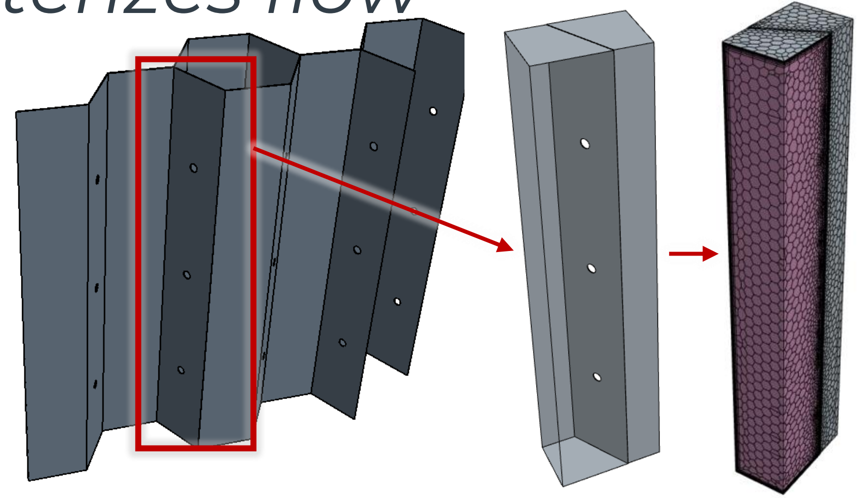


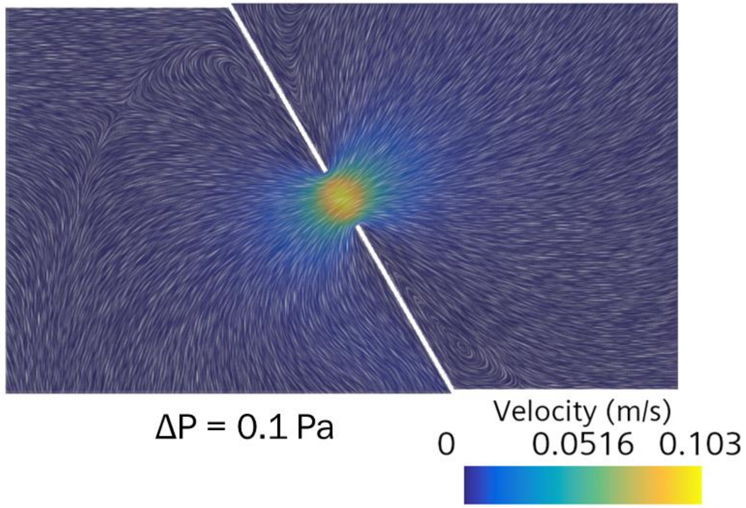
≈220k hexagonal cells

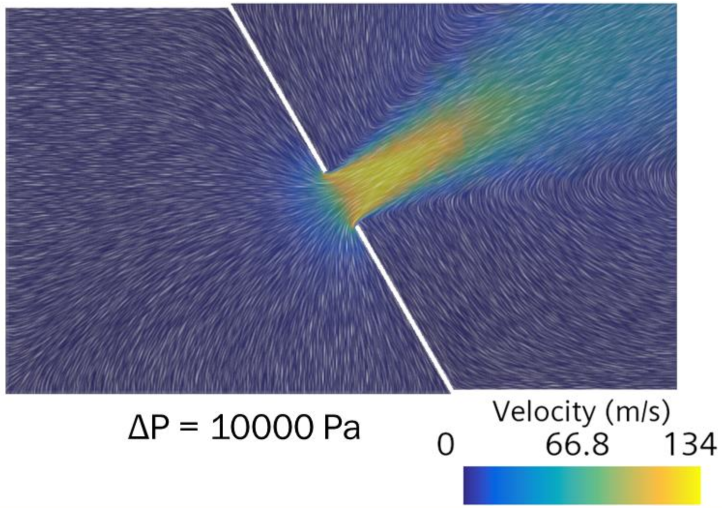
Unit-Cell CFD Model

Fully resolved geometry, characterizes flow

- Unit-cell ***steady*** CFD model (*Siemens Simcenter STAR-CCM+*)
- Two quarter cells, single perforated wall
- Automated polyhedral wall-resolved mesh
- 3D RANS, ideal gas, k-ω SST turbulence
  - 45 min run time
- Range of driving pressures
- Record mass flow rates




ΔP = 0.1 Pa


ΔP = 10000 Pa

Porous Resistance Coefficient Calculation

Fit unit-cell results to polynomial to determine resistance coefficients

- Fit results to:

$$\frac{\Delta p}{\Delta L} = P_{iL} u_{sL}^2 + P_{vL} u_{sL}$$

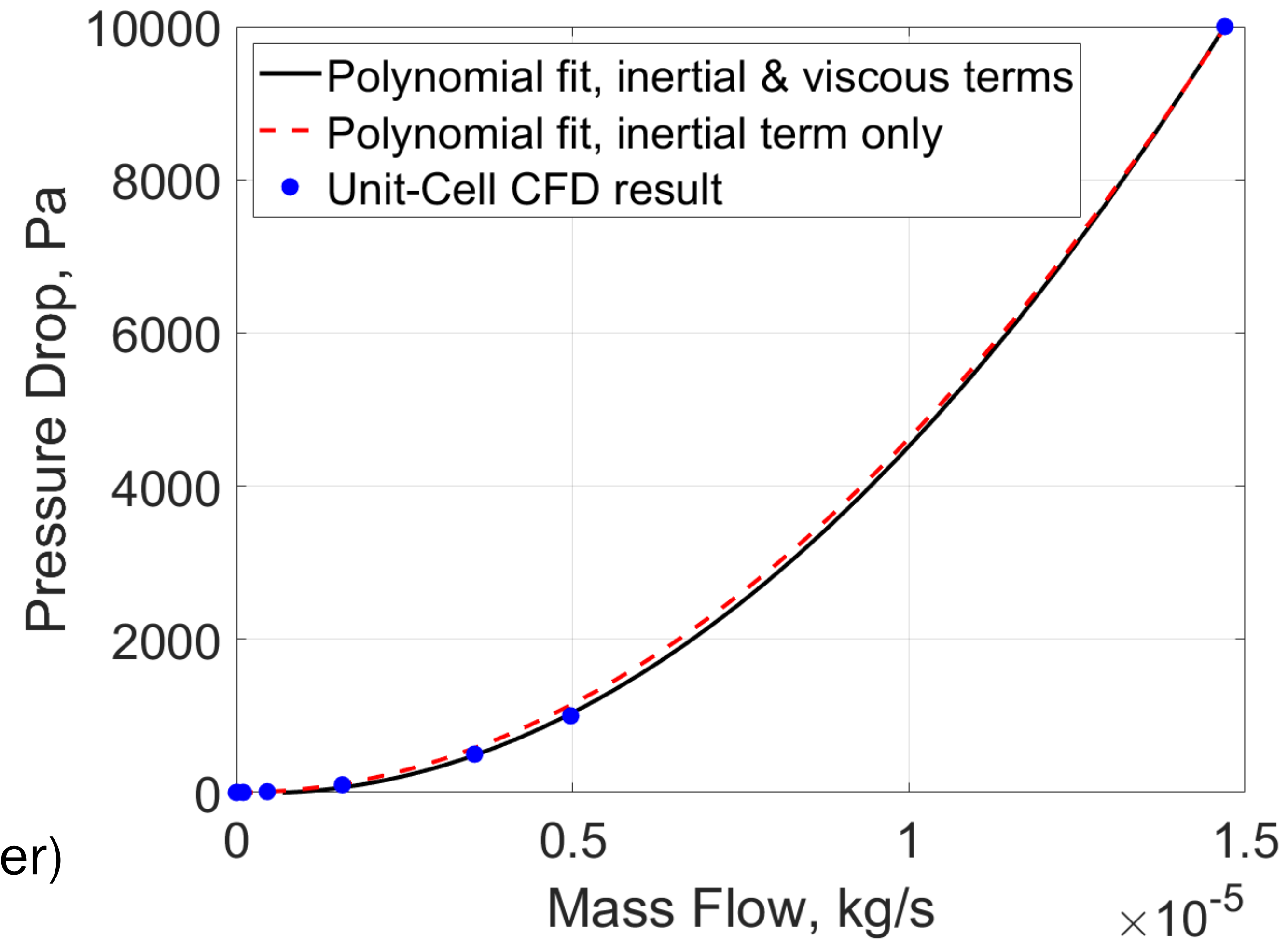
- Viscous term neglectable <u>for this panel</u>
- Inertial coefficients:

$$P_{i\xi} = \left(\frac{\rho}{\rho_{ref}}\right) 9.662 \times 10^6 \; \frac{kg}{m^4}$$

$$P_{i\eta} = \left(\frac{\rho}{\rho_{ref}}\right) 4.956 \times 10^7 \; \frac{kg}{m^4}$$

  where ρ_{ref} = density of unit-cell simulations

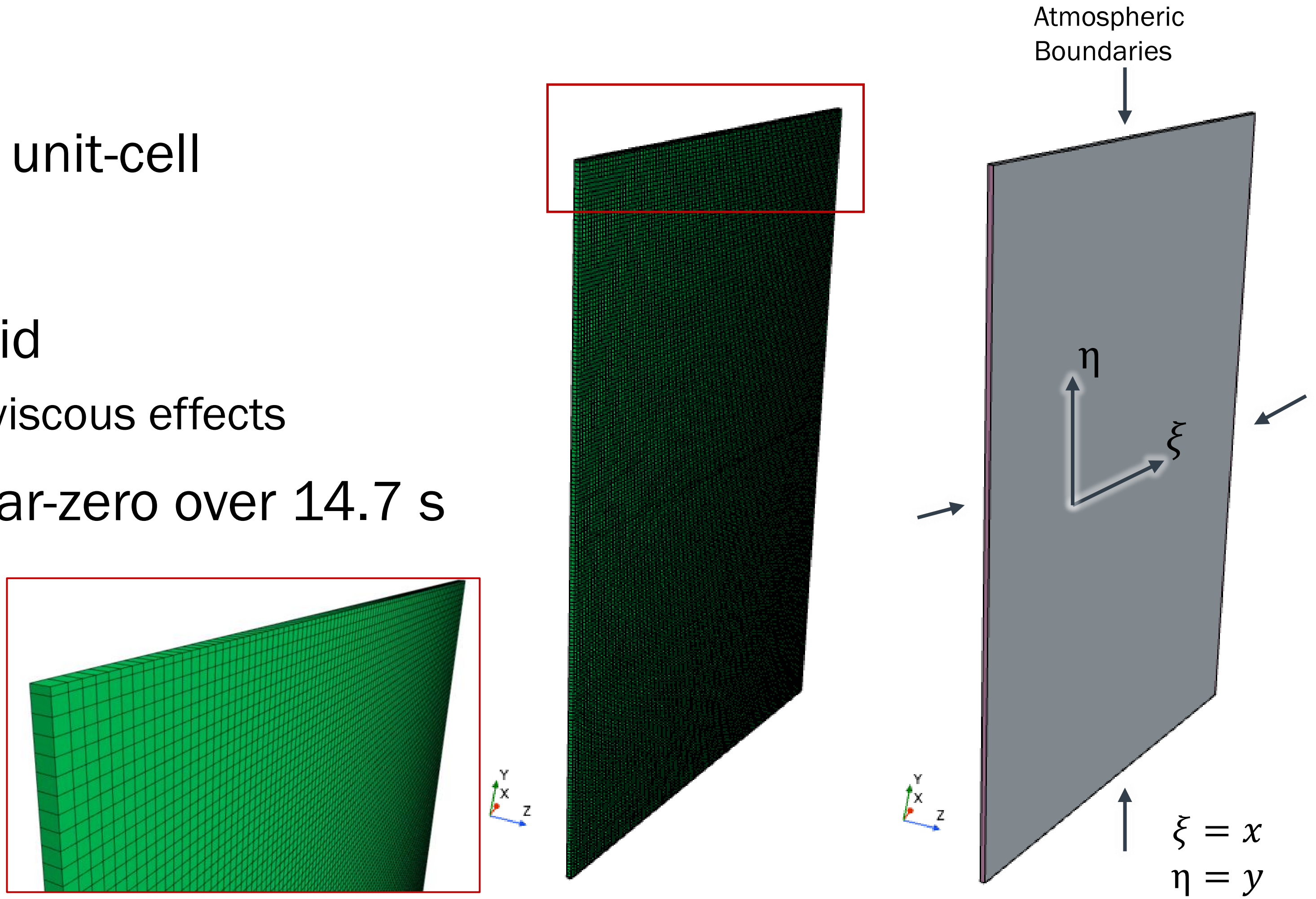
- Values within 12.5% of 1D theory (see paper)



Transient Porous CFD Model

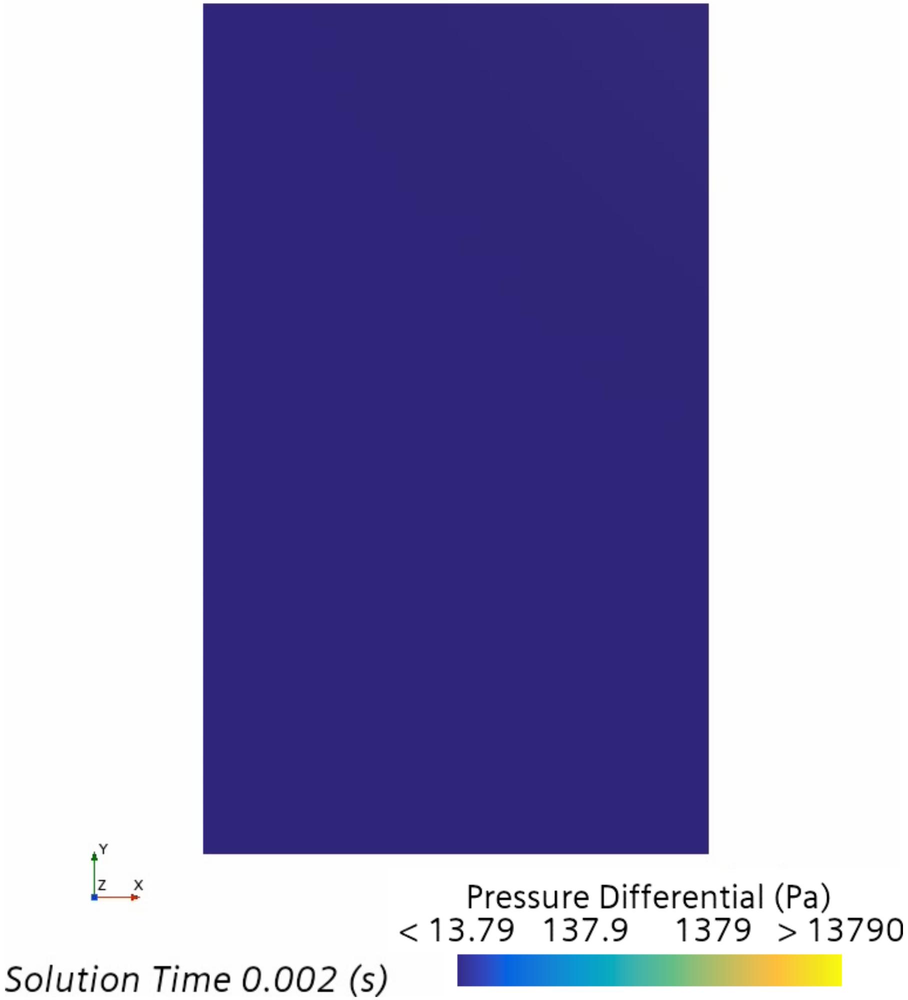
Simple porous cuboid replaces complex honeycomb

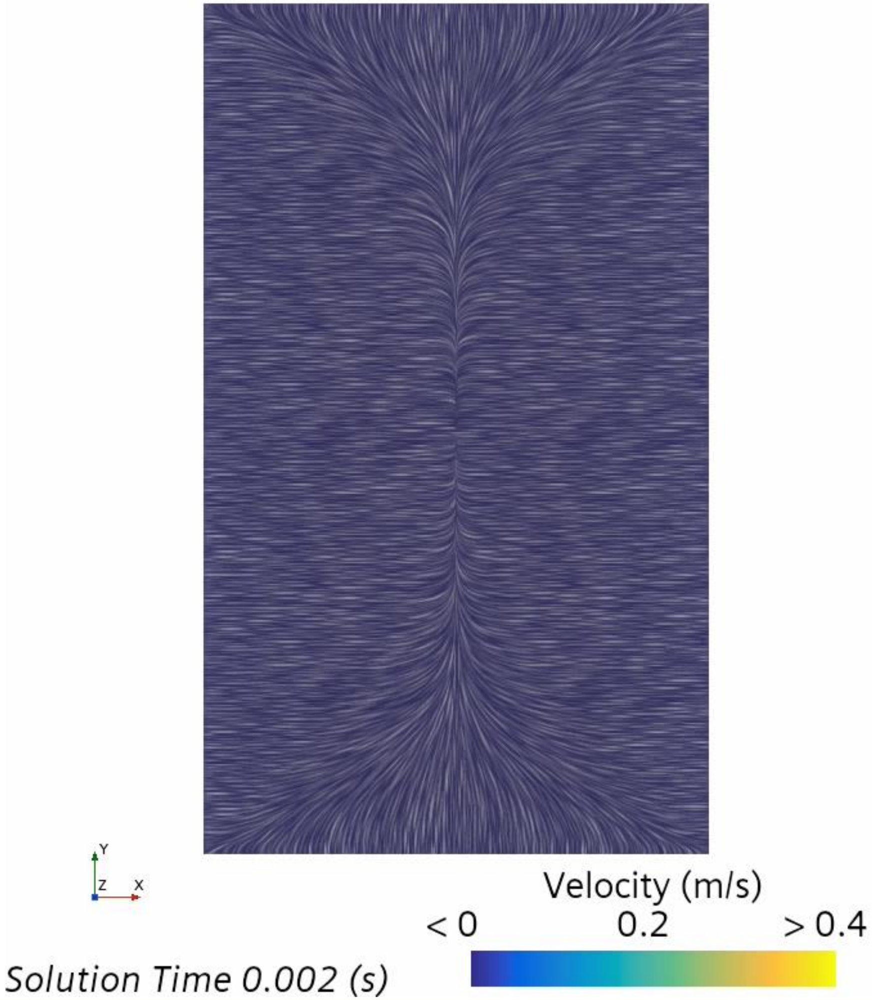
- Apply resistance coefficients from unit-cell
- Trimmed cell mesh, one cell thick
- Quasi-2D URANS, ideal gas, inviscid
  - Resistance coefficients account for viscous effects
- Atmospheric pressure drops to near-zero over 14.7 s
- 8.2hr run time for 20s flow time



Transient Model Results

CFD provides spatial results, in addition to 1D metrics



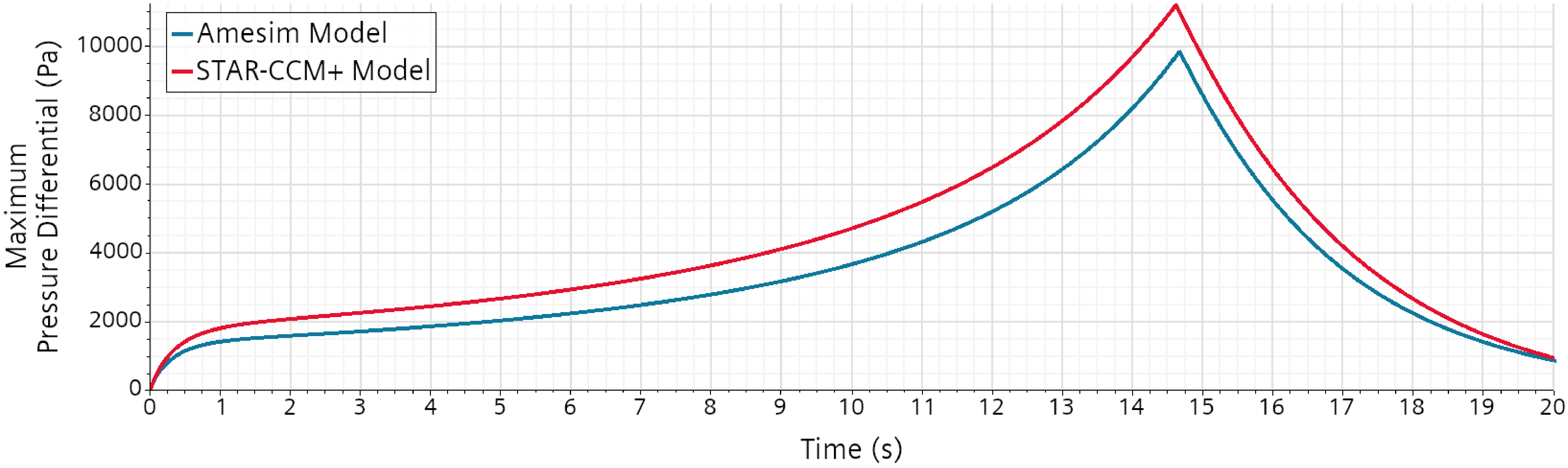


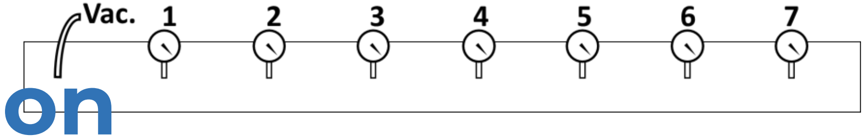
Note: Velocity scale clips towards end of simulation

CFD vs Flow Network Result Comparison

Maximum pressure differential agrees with flow network model within 12%

- Flow network model developed in *Siemens Simcenter Amesim* (see paper)

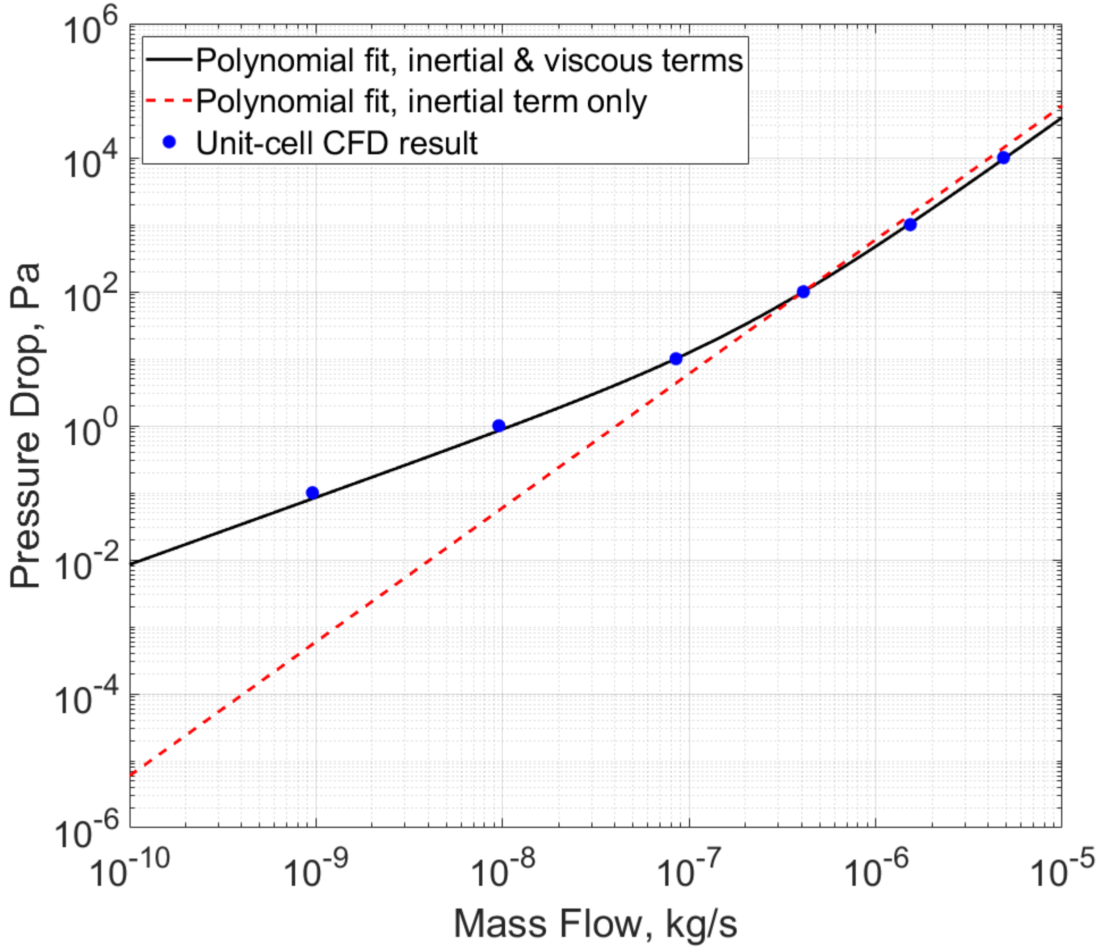




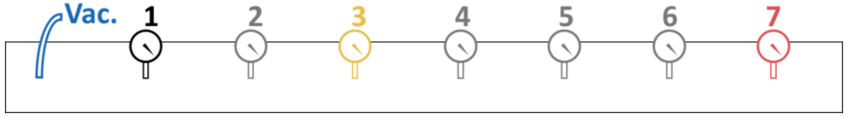
Experimental Validation

Literature case modeled using CFD methodology

- Schweickart and Devaud [1] ran experiment
- Sealed honeycomb, single evacuation point
- Uncertainty in perforation size, film gauge and vacuum radius (see paper)
- CFD approach identical to prior panel
- Non-zero viscous term (-74% perforation area)
- Inertial values 32× higher than prior panel

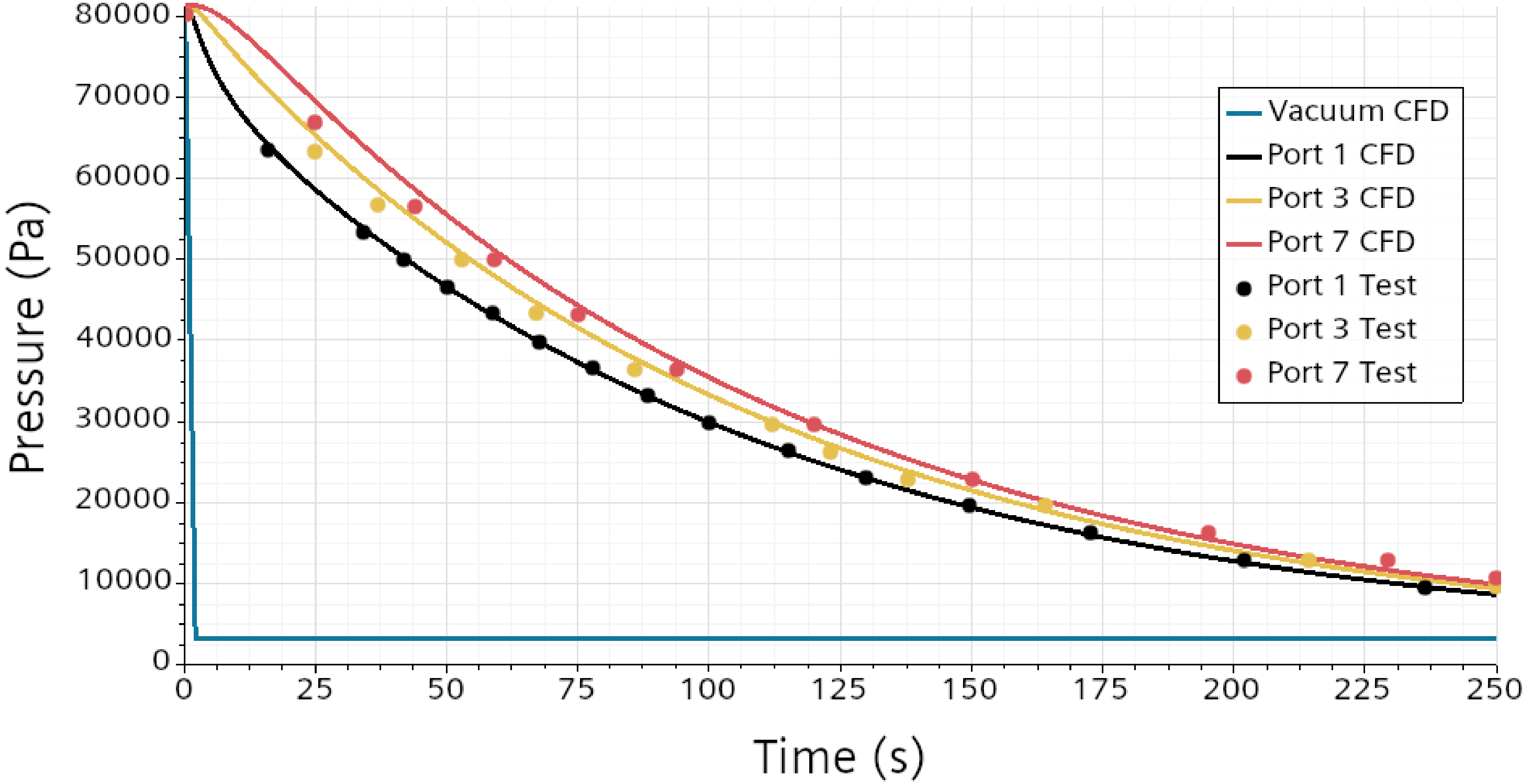


[1] Schweickart, R.B., and G. Devaud, "Predicting Spacecraft Component Differential Pressures during Launch," 50th International Conference on Environmental Systems, 12-15 July 2021.



Validation Results

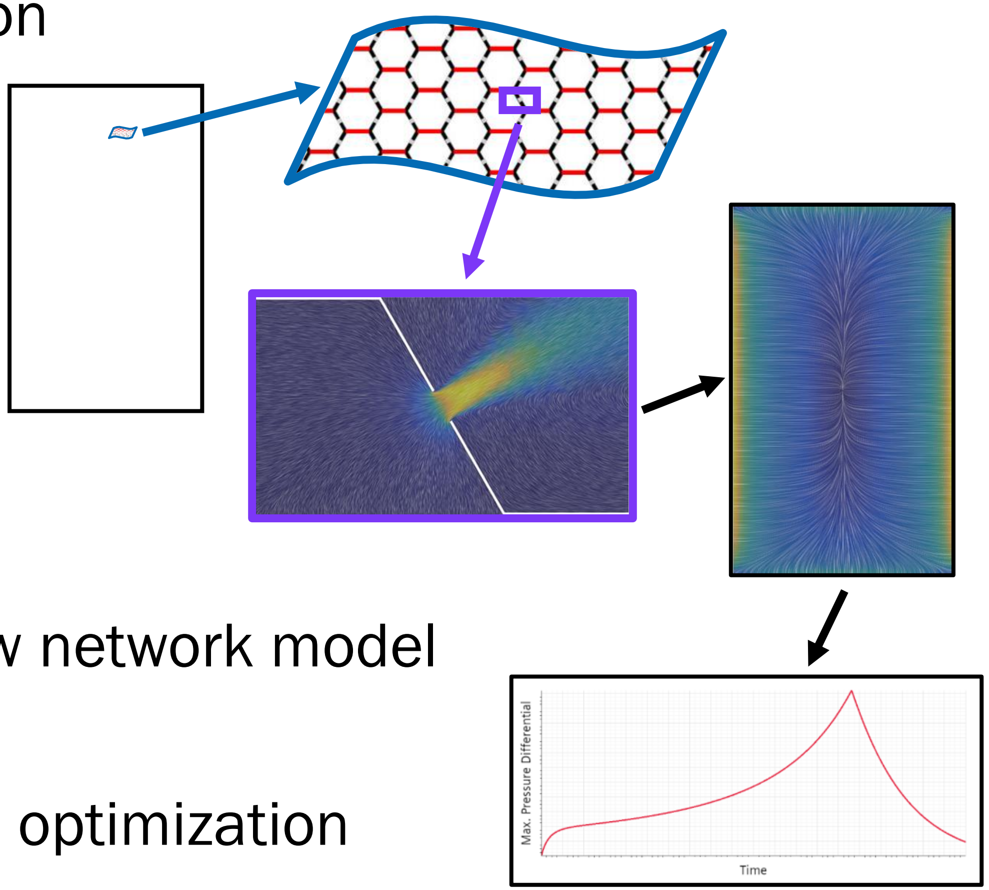
CFD results match test (within experimental error)



Conclusions

Workflow captures complex flow within depressurizing honeycomb panel.
Provides a fast tool in panel design

- Honeycomb panels experience rapid depressurization
- Perforated cell walls cause complex flow field
- *STAR-CCM*+ CFD methodology:
  - Unit-cell CFD
  - Characterize flow to provide porous coefficients
  - Transient porous CFD of whole panel
- Workflow can return results within 24 hours
- Methodology validated against test data and 1D flow network model
- Future potential:
  - Thermal effects, face venting, automated design optimization



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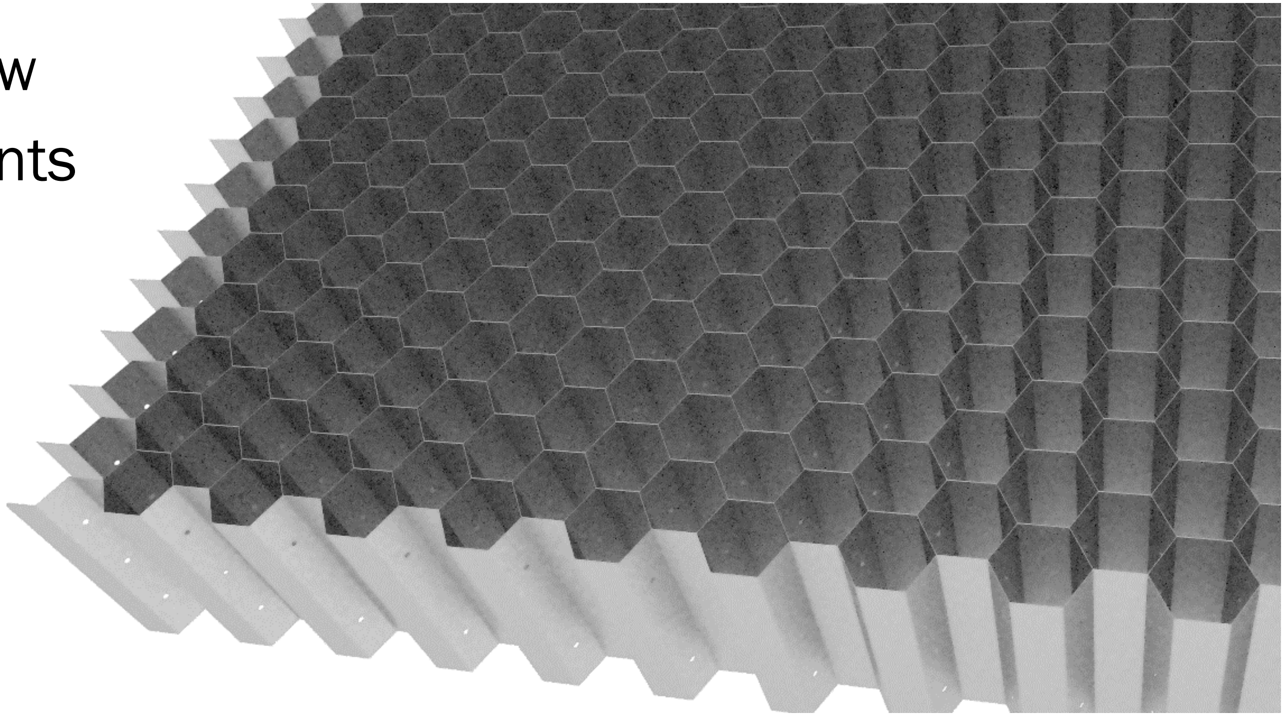
Analysis Approach

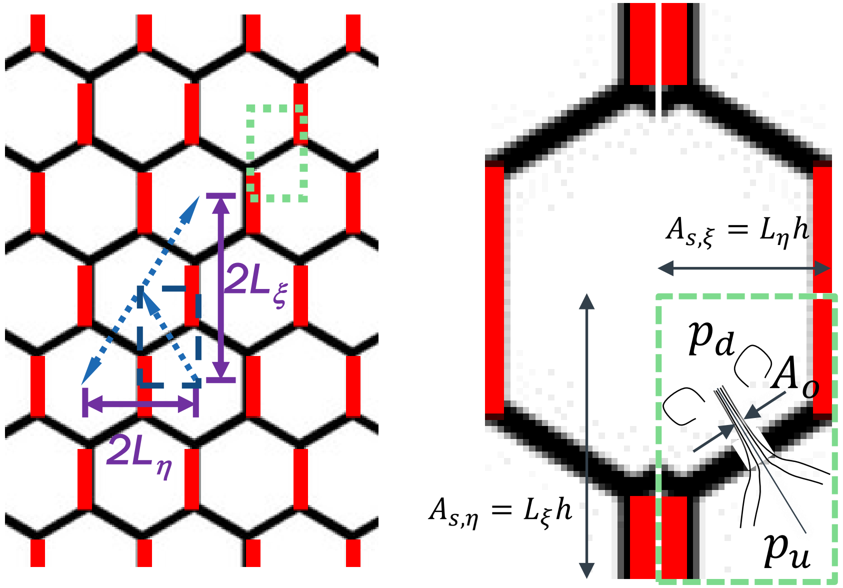
Unit-cell steady CFD & full-panel porous transient CFD

- Fully-resolved CFD of entire panel not feasible
- Problem simplified:
  - Unit-cell steady CFD characterizes flow
  - Calculate porous resistance coefficients
  - Transient porous CFD of whole panel
- Coefficients corroborated with 1D theory
- Validated with 1D flow network model (*Siemens Simcenter Amesim)*



Analytical Honeycomb Model

Estimate porous resistance coefficients using 1D theory



- Basic flow through orifice with sudden expansion
- Assume low-speed, *locally* incompressible, isothermal, negligible viscous resistance, negligible foil volume
- Fluid encounters N_O orifices of area A_O every L_ξ in ξ -direction, and L_η in η-direction
- Assume orifice discharge coefficient, C_D
- Full derivation (in paper) gives:

$$P_{i\xi} = \left(\frac{\rho}{2L_\xi}\right)\left[\frac{L_\eta h}{C_D N_o A_o}\right]^2 \qquad P_{i\eta} = \left(\frac{\rho}{2L_\eta}\right)\left[\frac{L_\xi h}{C_D N_o A_o}\right]^2$$

- Answer agrees with CFD within 12.5%

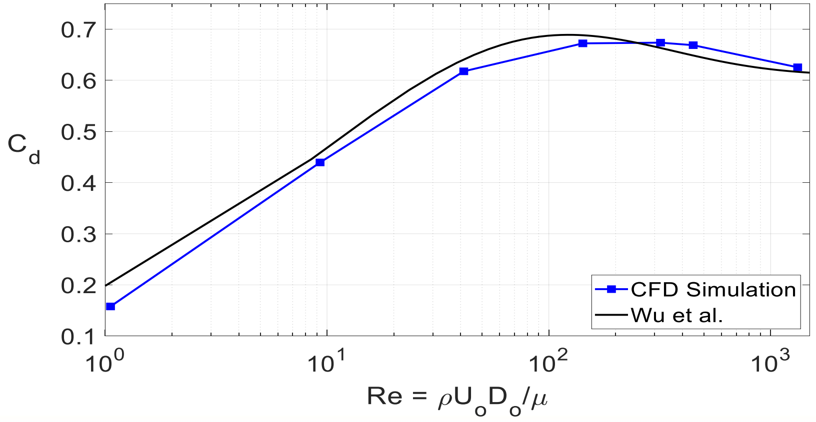
Unit-Cell Model Verifications and Sanity Checks

Density scaling, boundary conditions and discharge coefficients confirmed appropriate

- Confirm density scaling is appropriate
  - Unit-cell case with 10% original inlet density and 1000% delta pressure, i.e. Δp/ρ fixed
  - Resulting mass flow within 0.26%; confirms porous resistances scale with local density
- Check boundary conditions/flow direction doesn't affect mass flow:
  - Re-run with symmetry planes along constant X boundaries
  - Re-run with symmetry planes along constant Y boundaries
  - Resulting mass flows within 0.06%; resistance coefficients insensitive to flow direction
- Substantiate unit-cell model discharge coefficient values:
  - CFD results compared to empirical model of Wu et al. [5]

$$C_d = 0.61\left(1 + 1.07e^{-0.126\sqrt{Re_{D_o}}} - 2.07e^{-0.246\sqrt{Re_{D_o}}}\right)$$

  - CFD captures relationship well

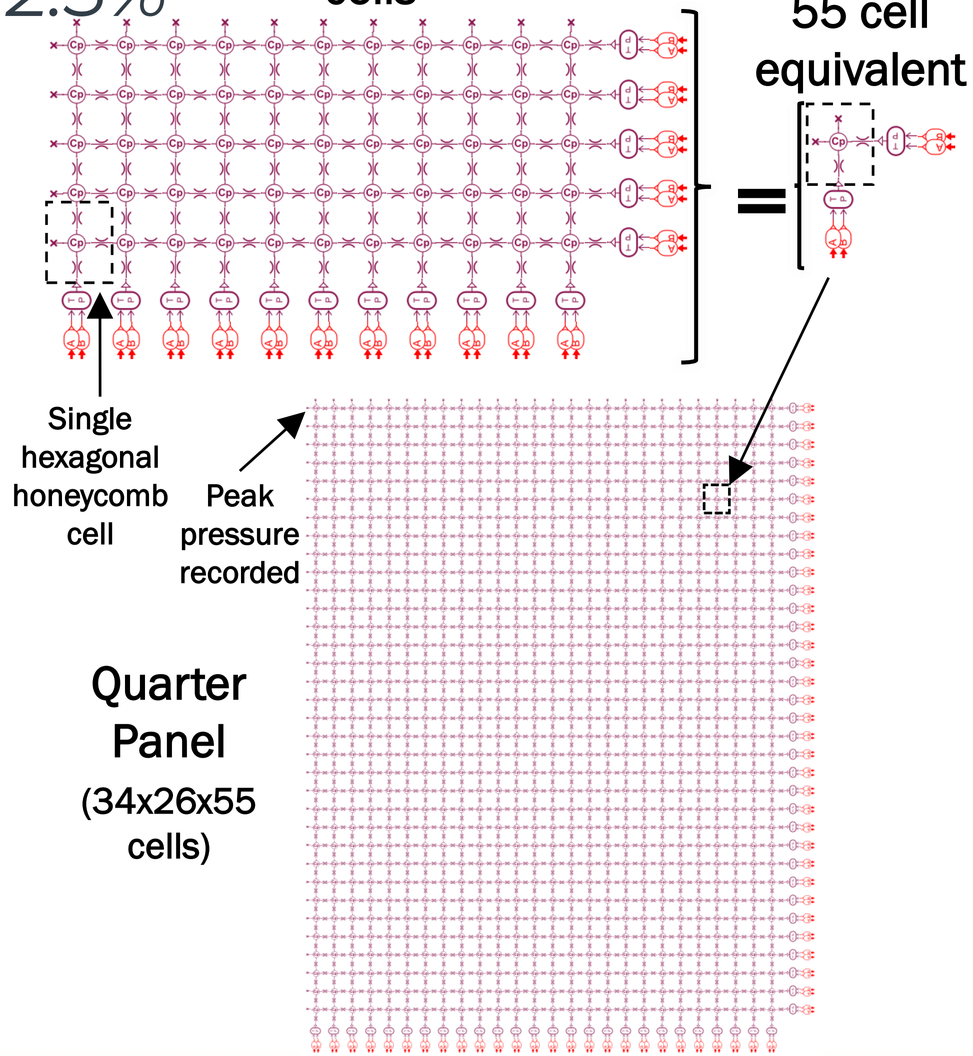


[5] Wu, D., et al., "An Empirical Discharge Coefficient Model for Orifice Flow," International Journal of Fluid Power (2002), Vol. 3, Iss. 3, pp. 13-18.

Flow Network Model

Matches CFD within 12.5%

- 1D flow network model of panel (*Siemens Simcenter Amesim)*
- Hexagonal cell modeled using simple pneumatic chamber with heat exchange and four ports
- Wall venting modeled with pneumatic orifices
- Flow discharge coefficient 0.67 (from unit-cell CFD)
- Computationally infeasible to model every cell
- Grid of 55 cells modeled using 55 pneumatic chambers and orifices
- These 55 chambers represented by one equivalent pneumatic chamber
- Orifice areas in equivalent chamber multiplied by model uncertainty factor, tuned through automated trade-study
- Groups of single equivalent chambers and orifices represent quarter panel
- Pressure logged and compared to transient CFD result



55 cells

55 cell equivalent

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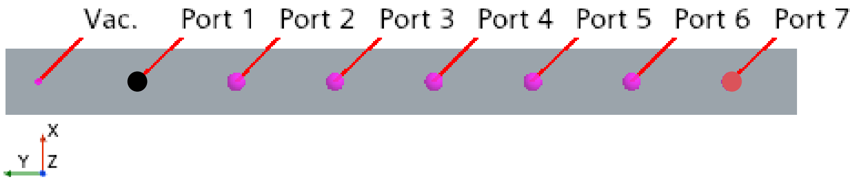
Single hexagonal honeycomb cell

Peak pressure recorded

Quarter Panel

(34x26x55 cells)

Geometric Sensitivity



Result sensitive to hole size and vacuum area. Original parameter values likely correct

- Film gauge reduced 25× to 2.54 um
  - 8% increase in inertial coefficients
  - 60% reduction in viscous coefficients
  - Limited effect on the result
  - Viscous effects not significant for this depressurization schedule
- Hole diameter increased from 0.13 mm to 0.14 mm
  - 32% reduction in inertial resistance coefficients
  - 30% reduction in viscous resistance coefficients
  - Significant venting increase, departure from test
  - Vent rate highly sensitivity to hole size
- Vacuum area doubled (with larger hole diameter)
  - Coefficients unaffected by vacuum change
  - Further increase in venting
  - Vent rate highly sensitive to vacuum area *(in this case)*