Electrical Capacitance Volume Sensor for Microgravity Mass Gauging:

Advancements in Sensor Calibration for Microgravity Fluid Configurations and Propellant Management Devices

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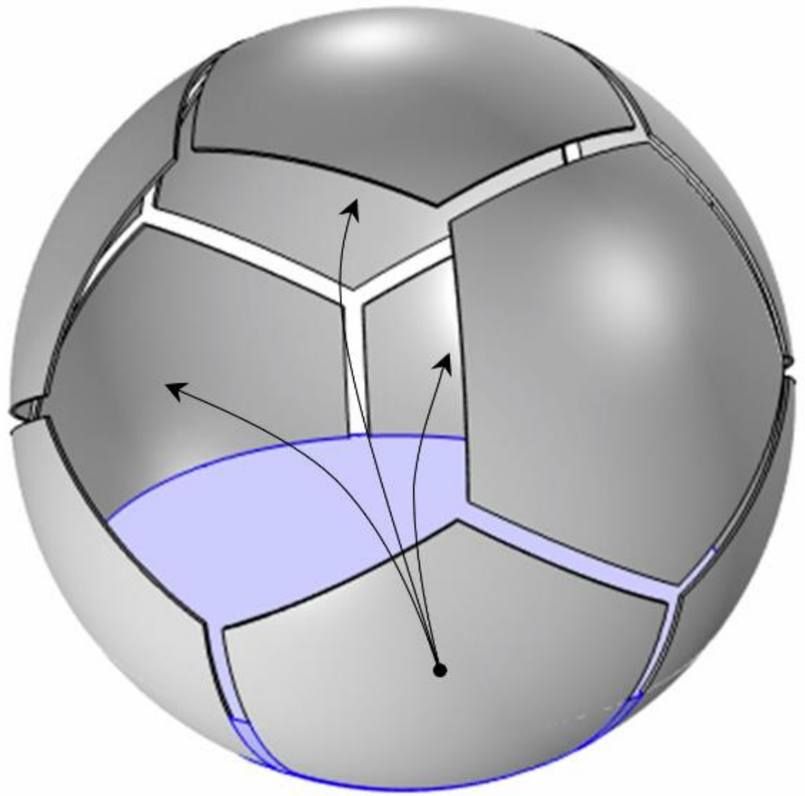
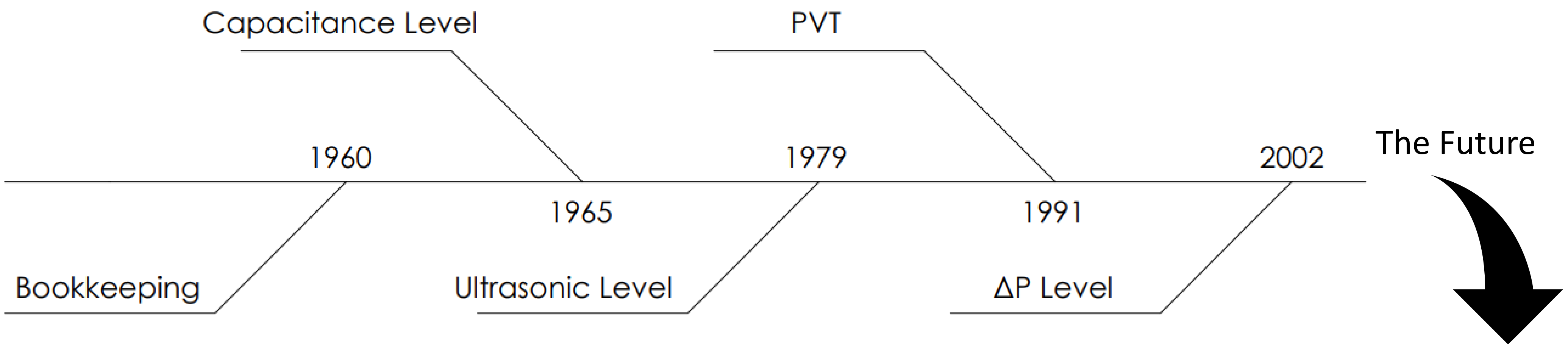
Electrical Capacitance Volume Sensing

- 3D, Non-Invasive Measurement Technology
- Array of electrodes arranged around a volume
- Electrodes are excited one at a time and the inter-electrode capacitances are measured
    - 12 electrodes – 66 measurements
- The volume fraction is then reconstructed from the measurements
- Used for Cryogenic LH_2, LOX or Monopropellants



Brief History of Propellant Mass Gauging



Whole Tank Mass Gauge Techniques

- Radio Frequency
- X-Ray
- Acoustic Modal
- Optical
- ECVS

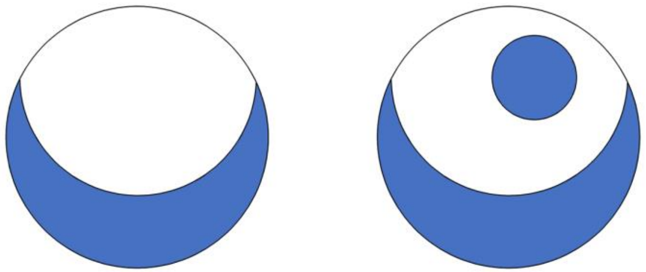
- Bookkeeping and level sensing techniques can only be used during engine burns and require settled conditions.
- PVT can be used in low-gravity but is slow and has complex calibrations.

Why ECVS is needed…

- ECVS is a whole-volume sensor
- Mass gauging of arbitrary spatial distributions
  - Sloshing fluid
  - Settled fluid
  - Microgravity surface tension dominated fluid configurations
- Leak detection
- Real-time measurement
  - Maneuver calculations
  - Fuel mass flow rate & custody transfer

Information of Fluid Position and Mass

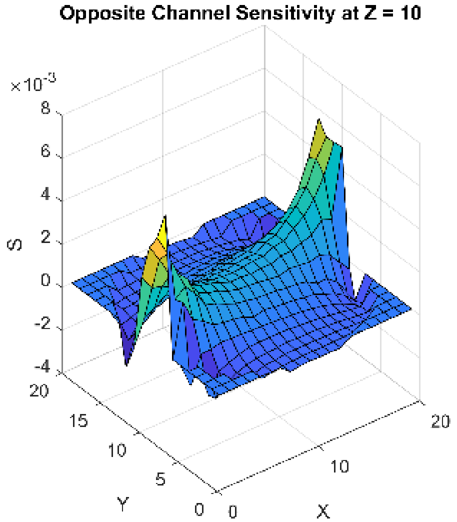
- Current methods:
  - model based - assume a settled fluid distribution
  - Lose accuracy in dynamic situations
  - Cannot handle metastable situations
- ECVS
  - 66 Independent Measurements
  - Fluid Position Agnostic
  - Real time data collection
  - Dynamic, Settled – Gravity, and Settled – Microgravity fluid distributions
    - All stages of a space mission

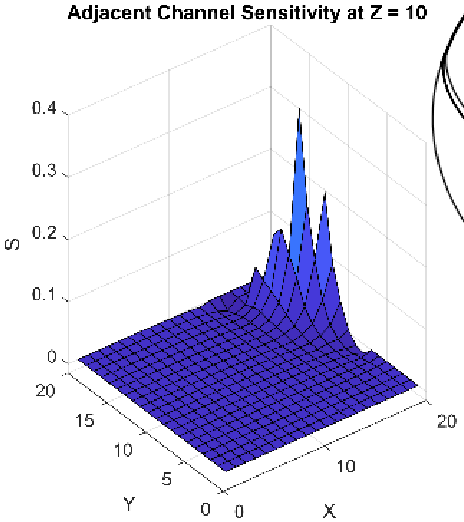


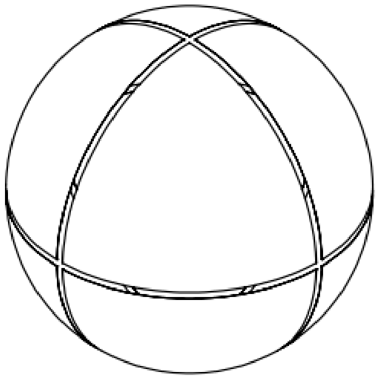
Metastable Distributions

Sensor Design

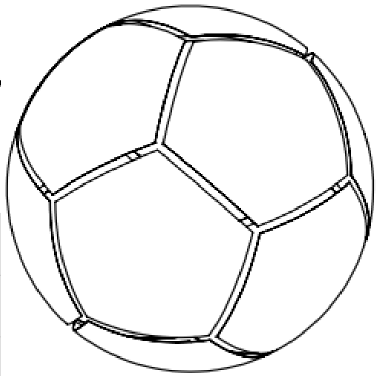
- Previously tested two designs and determined that Dodecahedron design performs well
- High symmetry = low signal change when constant mass of fluid moves around
- Adjacent Plates have localized sensitive regions
- Many non-adjacent channels are needed for accurate and stable gauging







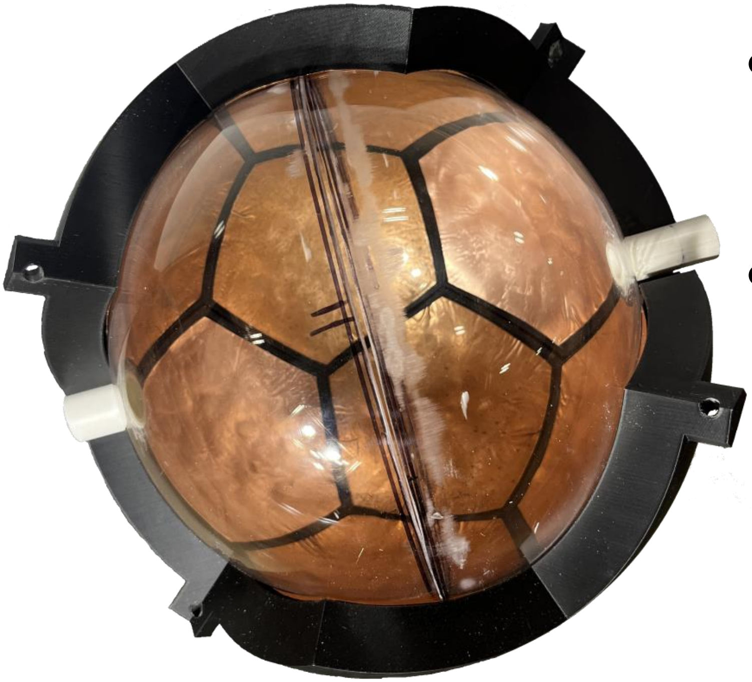
Design 1: Octahedron



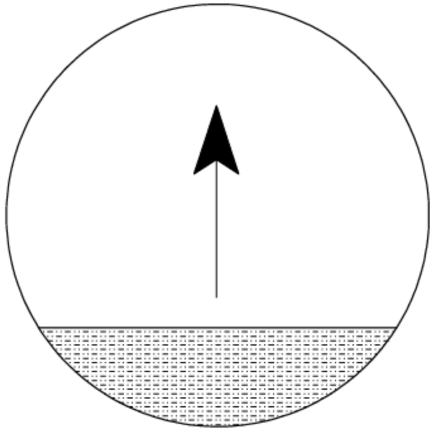
Design 2: Dodecahedron

Sensor Construction

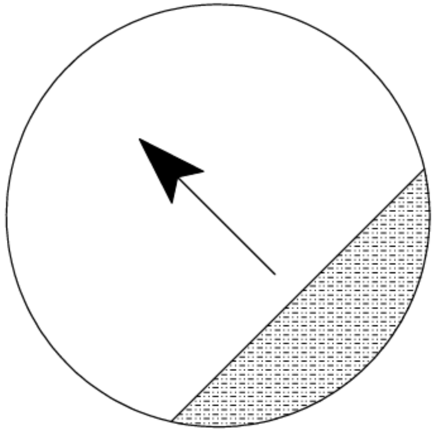
- Formed copper plates
- 3-Segment clamp-on design with 3D printed Shells
- Easy Disassembly for Troubleshooting
- Mineral Oil Fluid
  - Ɛ = 2.16
  - Similar to cryogens



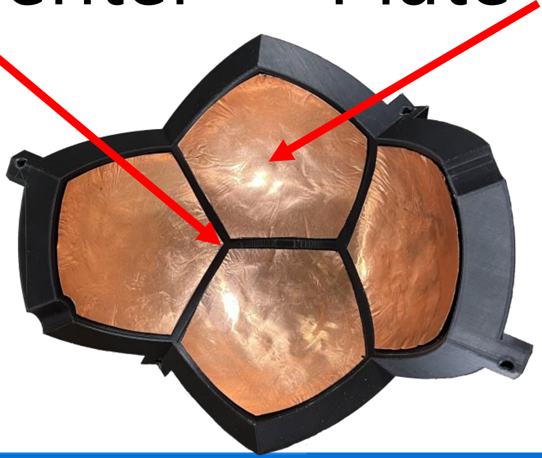
Experimental Test Cases

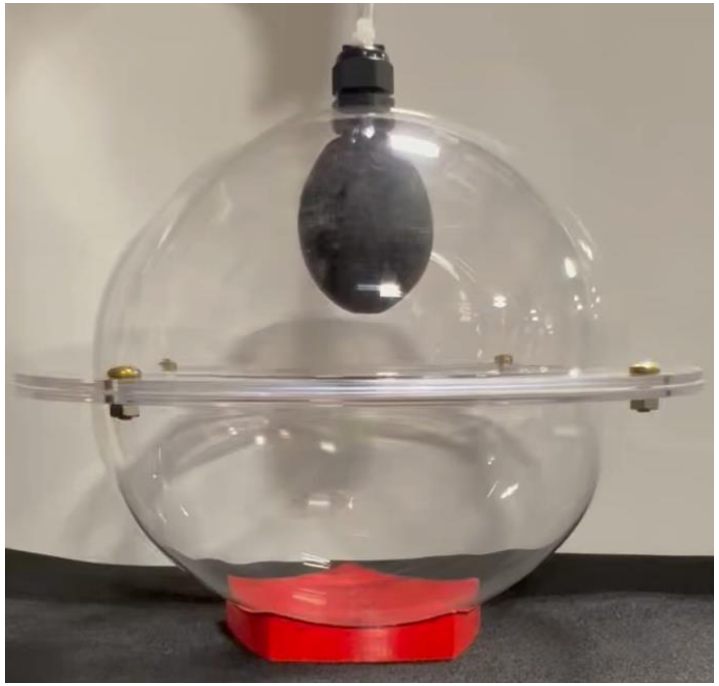


- Stratified Gap-Center



- Stratified Plate-Center

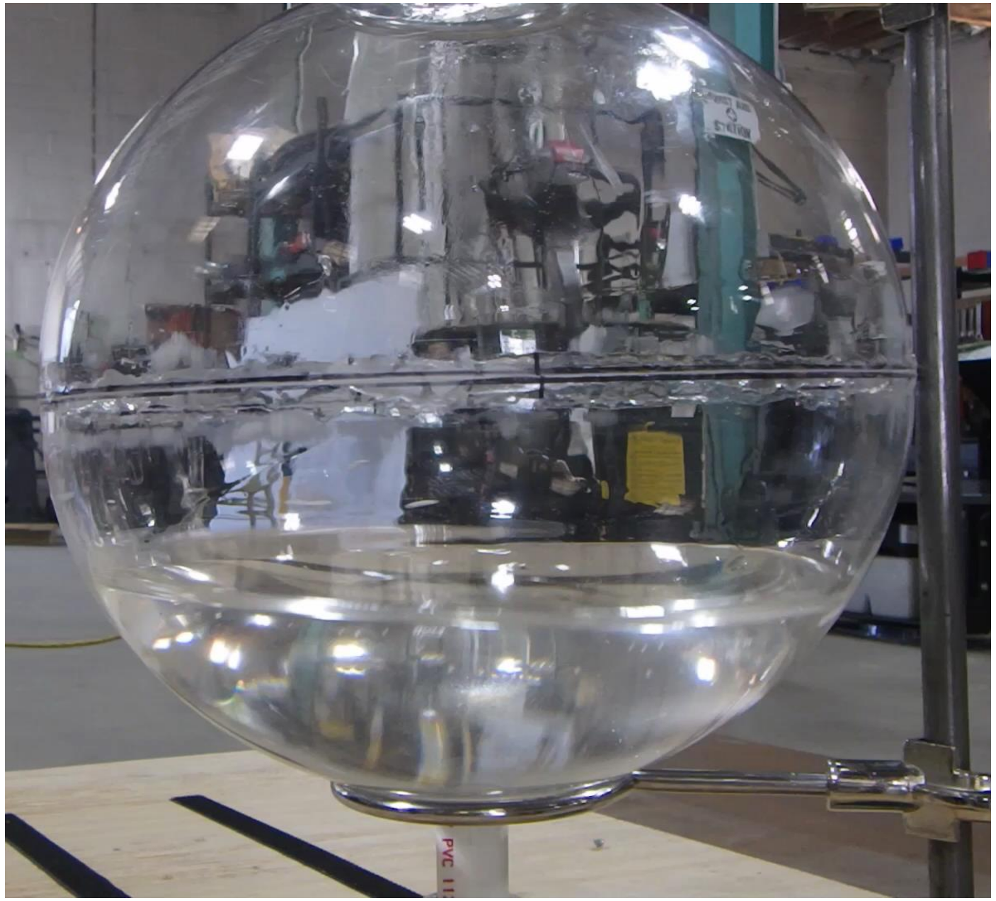




- Balloon

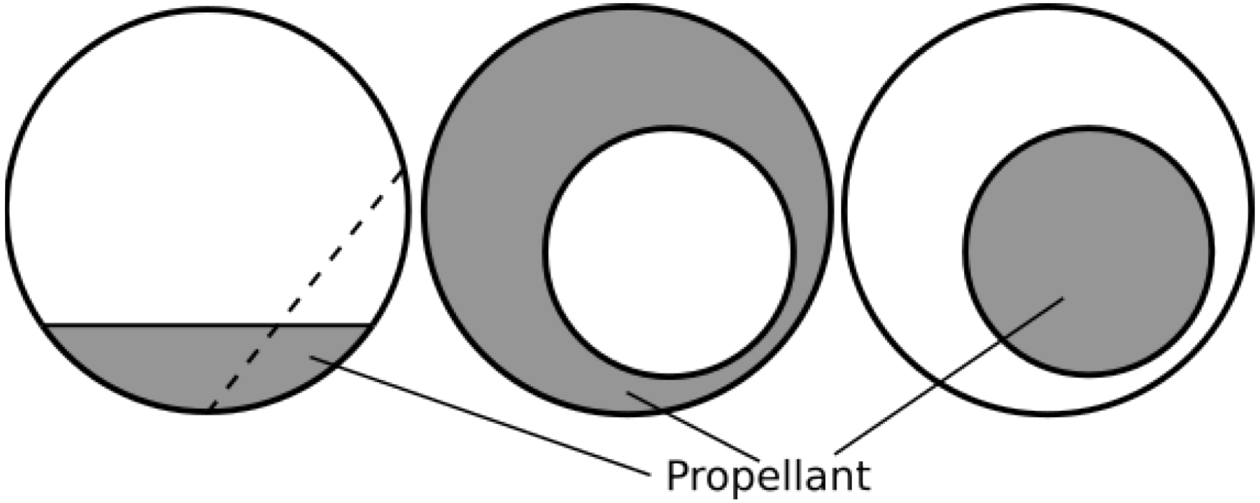
Experimental Test Cases

- Gentle Slosh



- Vigorous Slosh

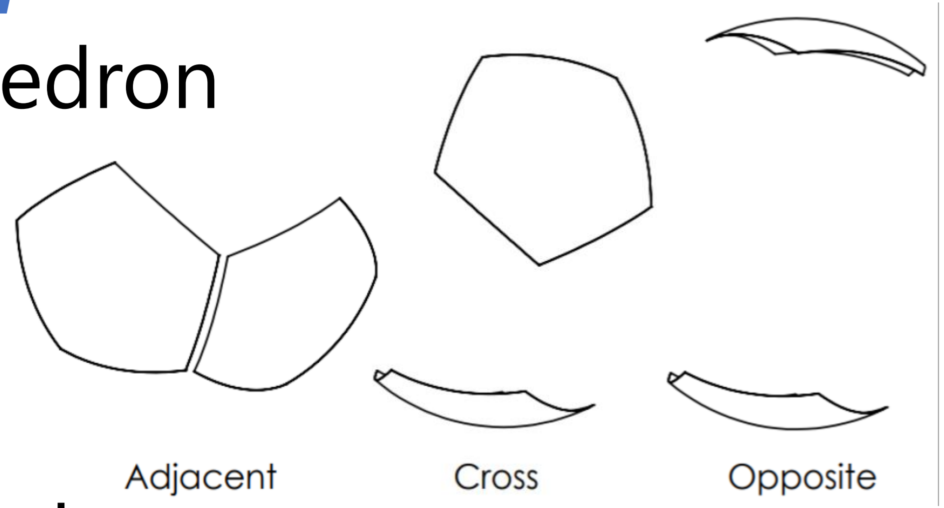
Simulation Test Cases



- Stratified Gap-Center
- Stratified Plate-Center
- Annular & offset
- Core Annular & offset
- Rotations of each of the above so that different plates are on the bottom
- Total: 11,280 data points

Machine Learning Algorithm – Channel Types –

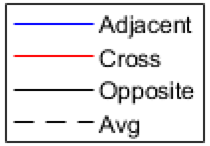
- 3 Symmetry groups in the Dodecahedron
  - Adjacent Channels
  - Cross Channels
  - Opposite Channels
- Due to rotational symmetry, channel types can be averaged together
- Reduces 66 measurements into 3
  - Easier to train!

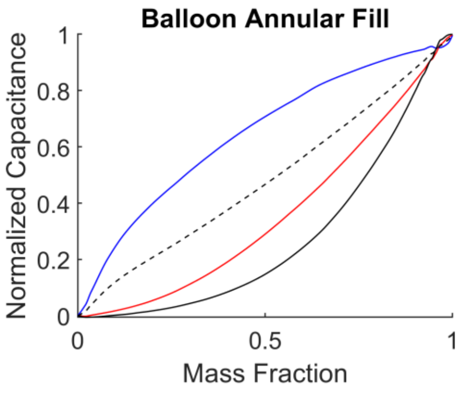


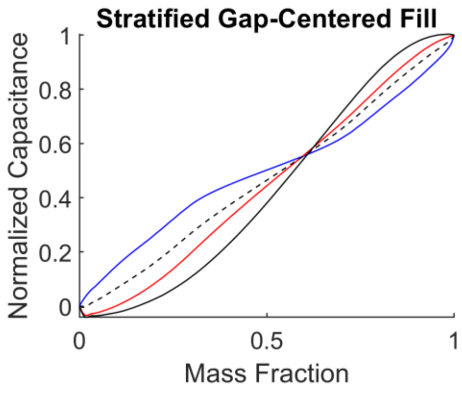
66 Measurements → 3 Measurements → Machine Learning Model → Mass Fraction

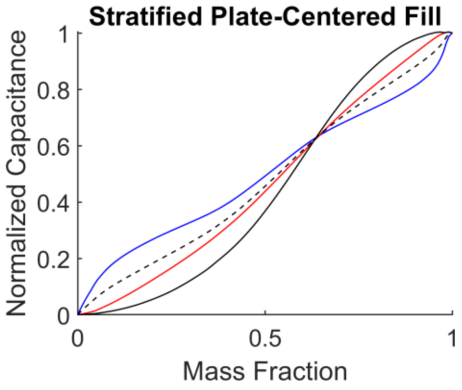
Averages of Data by Channel Type

Experimental Data

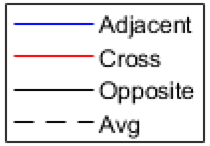


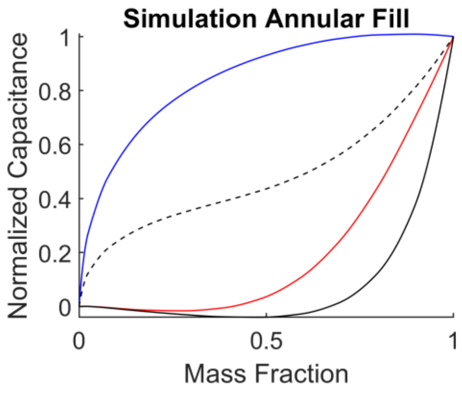


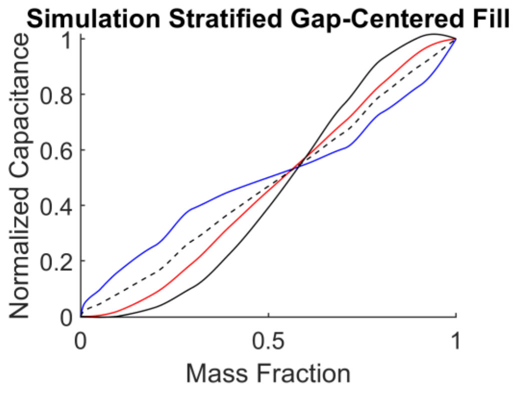


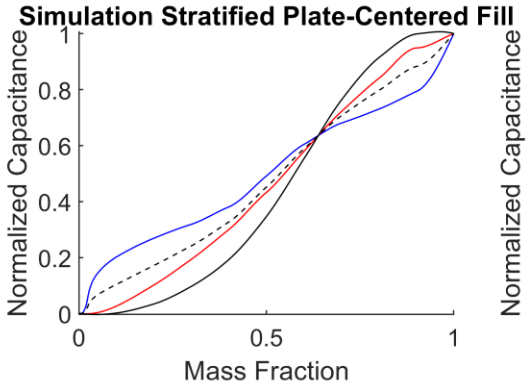


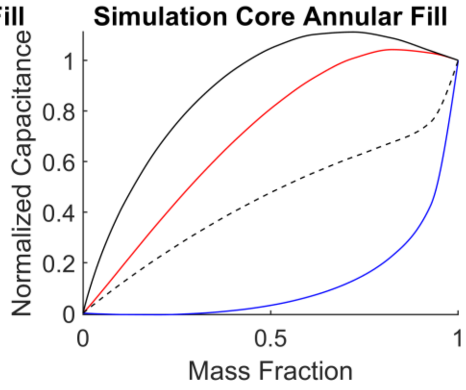
Simulation Data





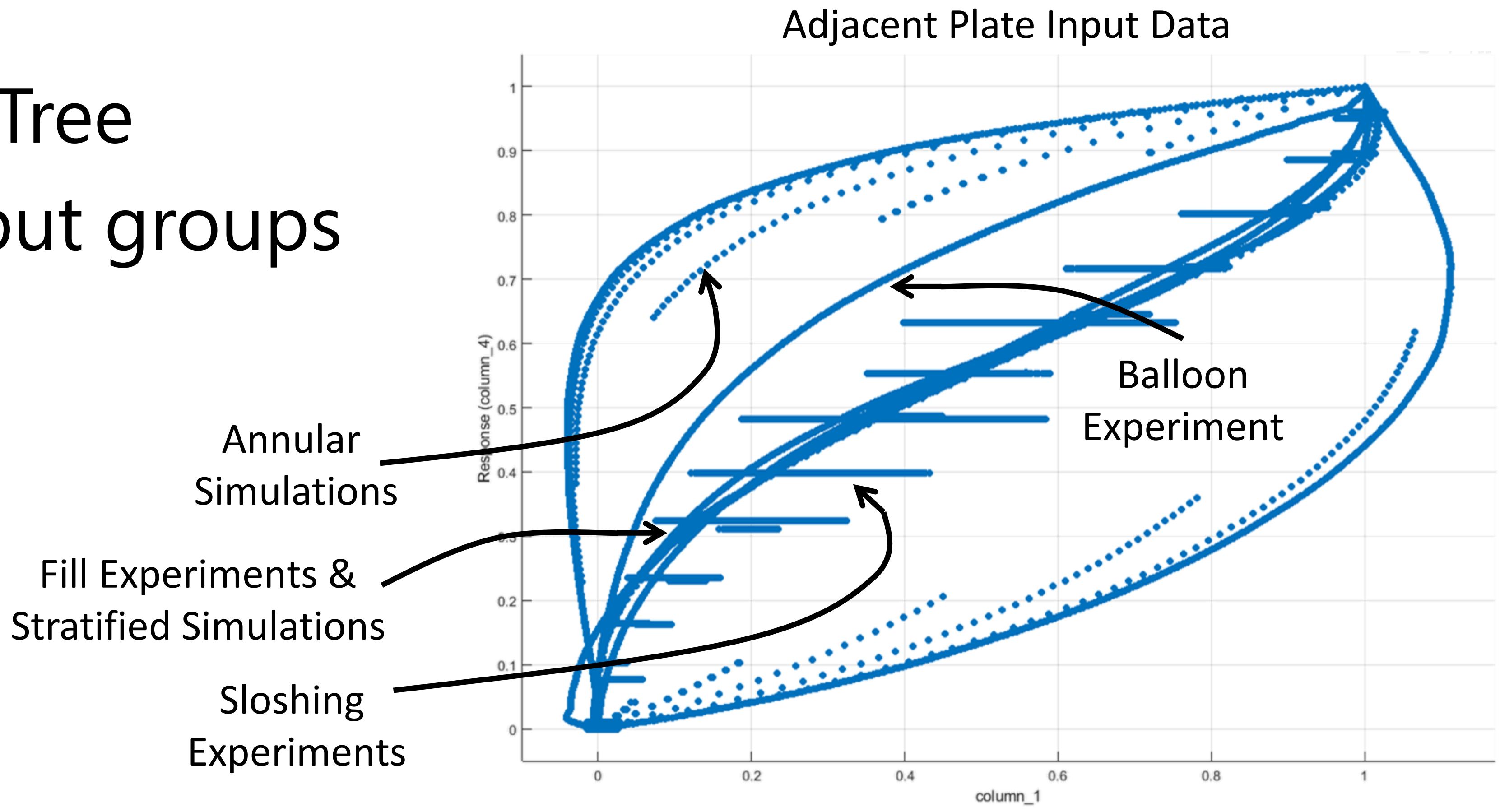




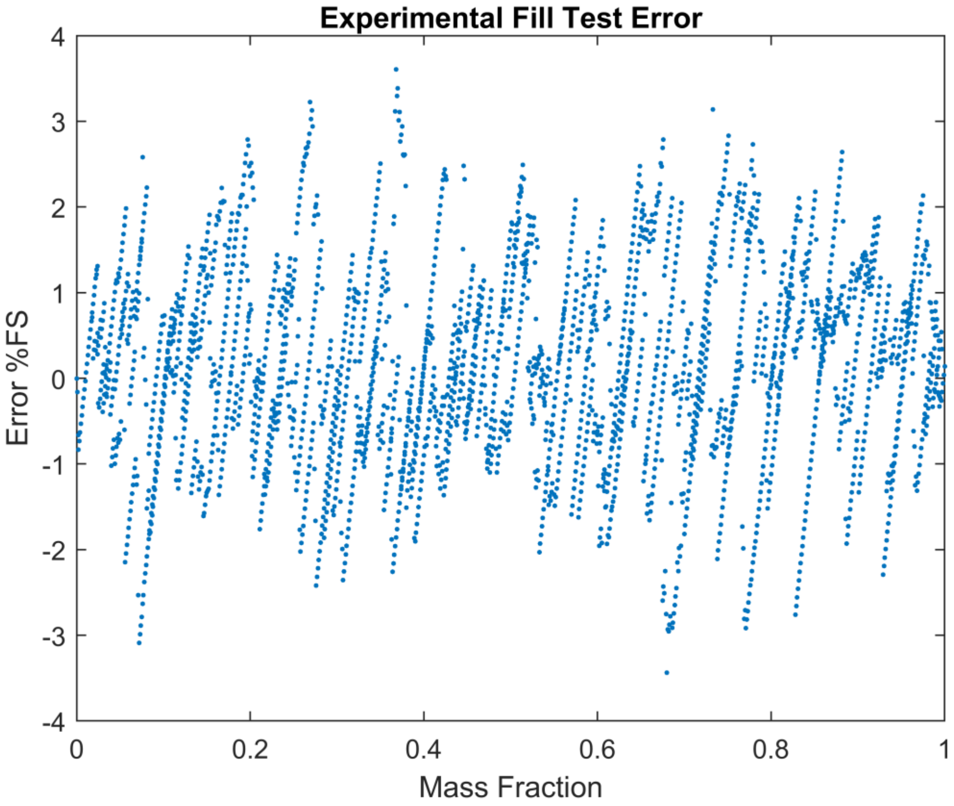


Machine Learning

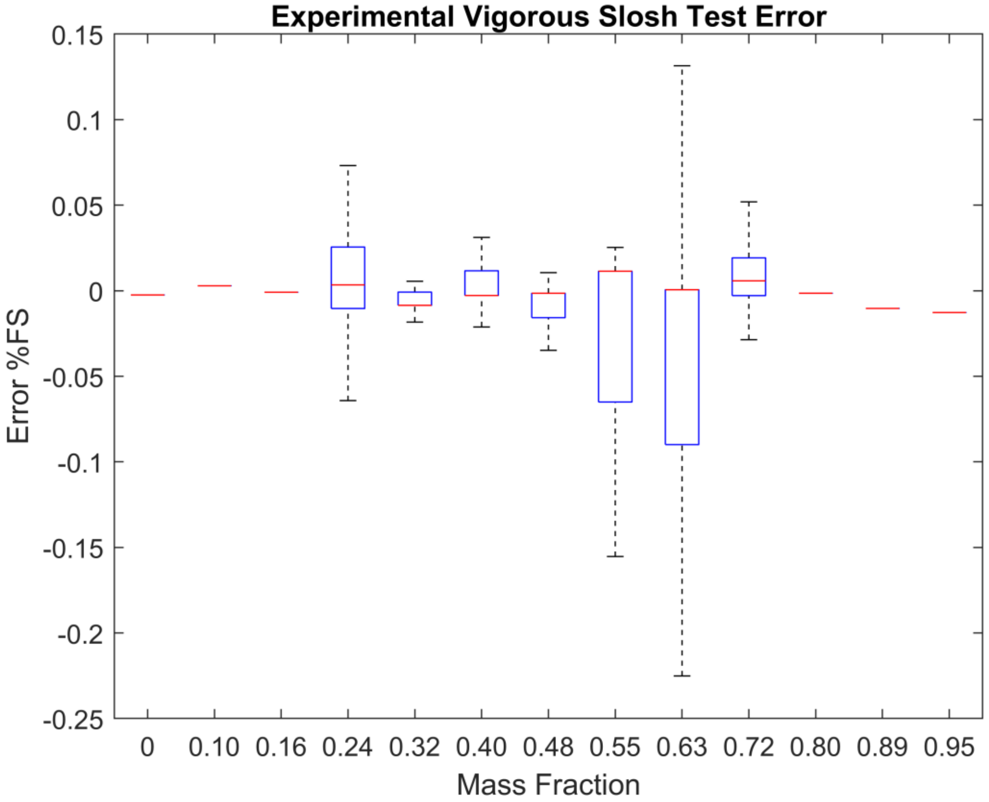
- Bagged Decision Tree
- Using 223,649 Input groups
- RMSE 0.0029



Results on Trained Data

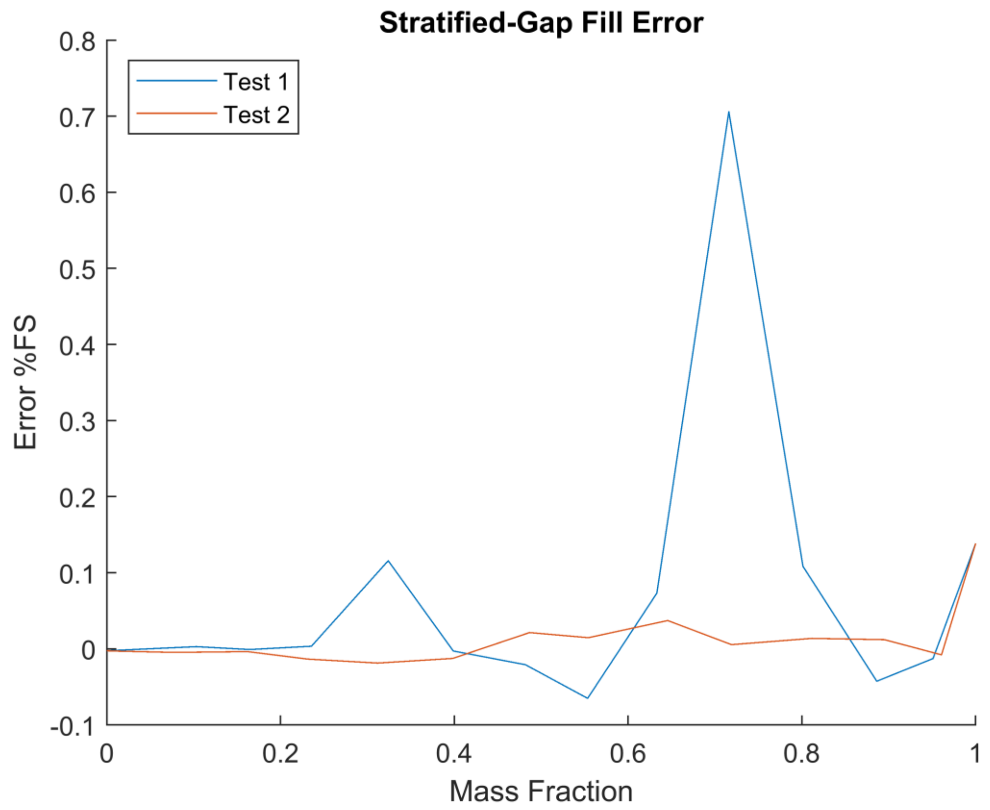


Error within: ±3.61%
3σ Error: ±3.29%

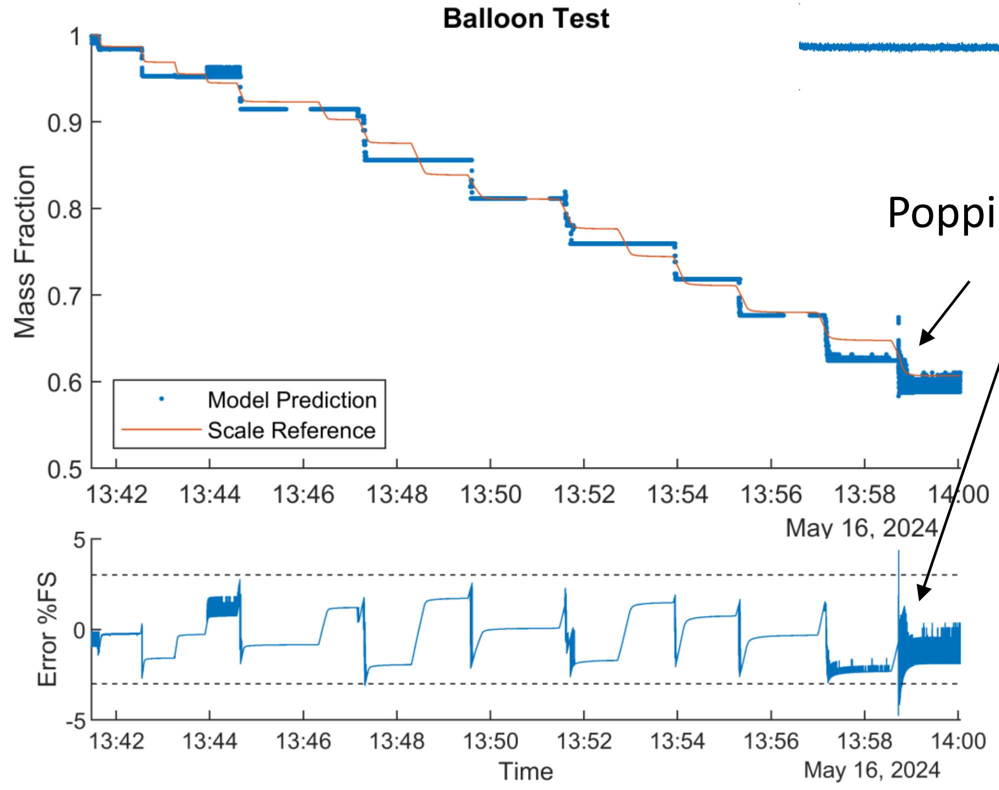


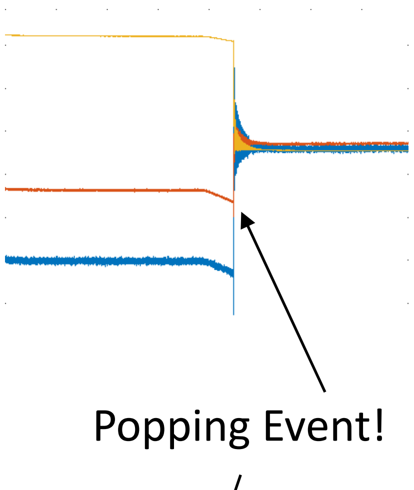
Error within: ±3.64%
3σ Error: ±0.47%

Results on Untrained Data



Error within: ±0.71%
3σ Error: ±0.41%





Error within: ±4.75%
3σ Error: ±3.79%

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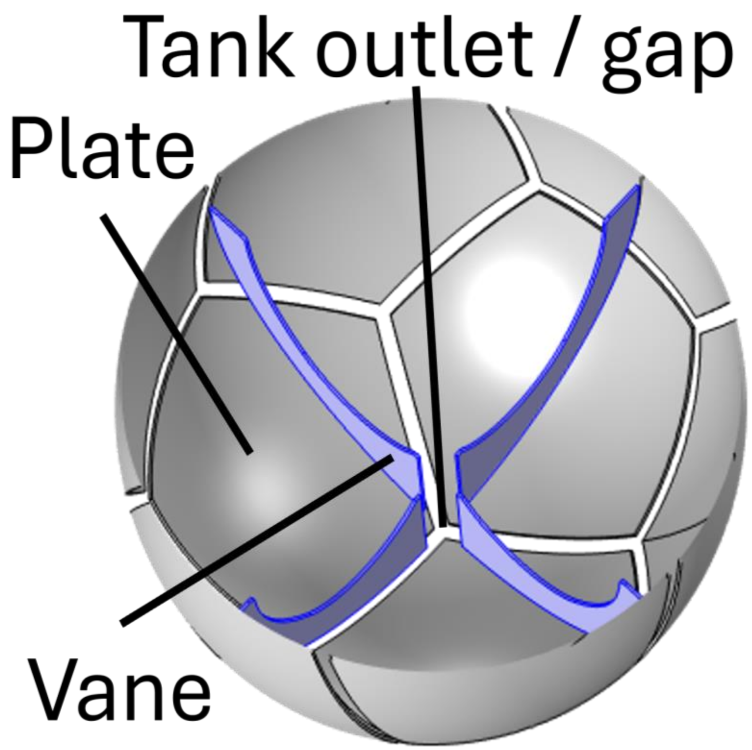
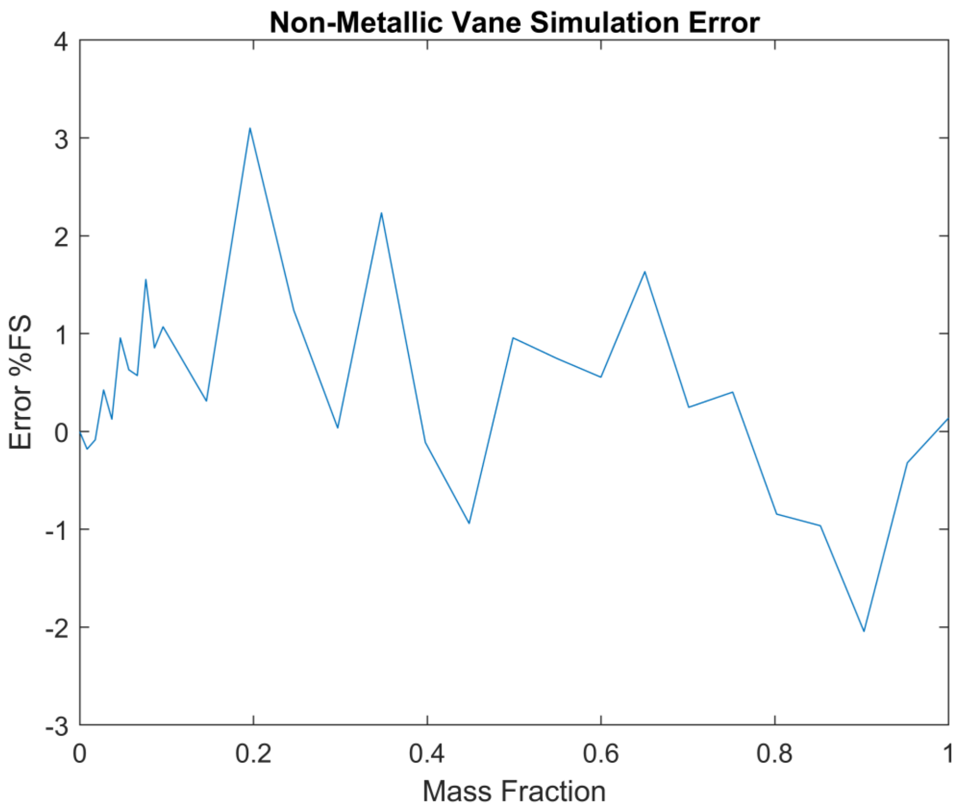
Non-Metallic Vane PMDs

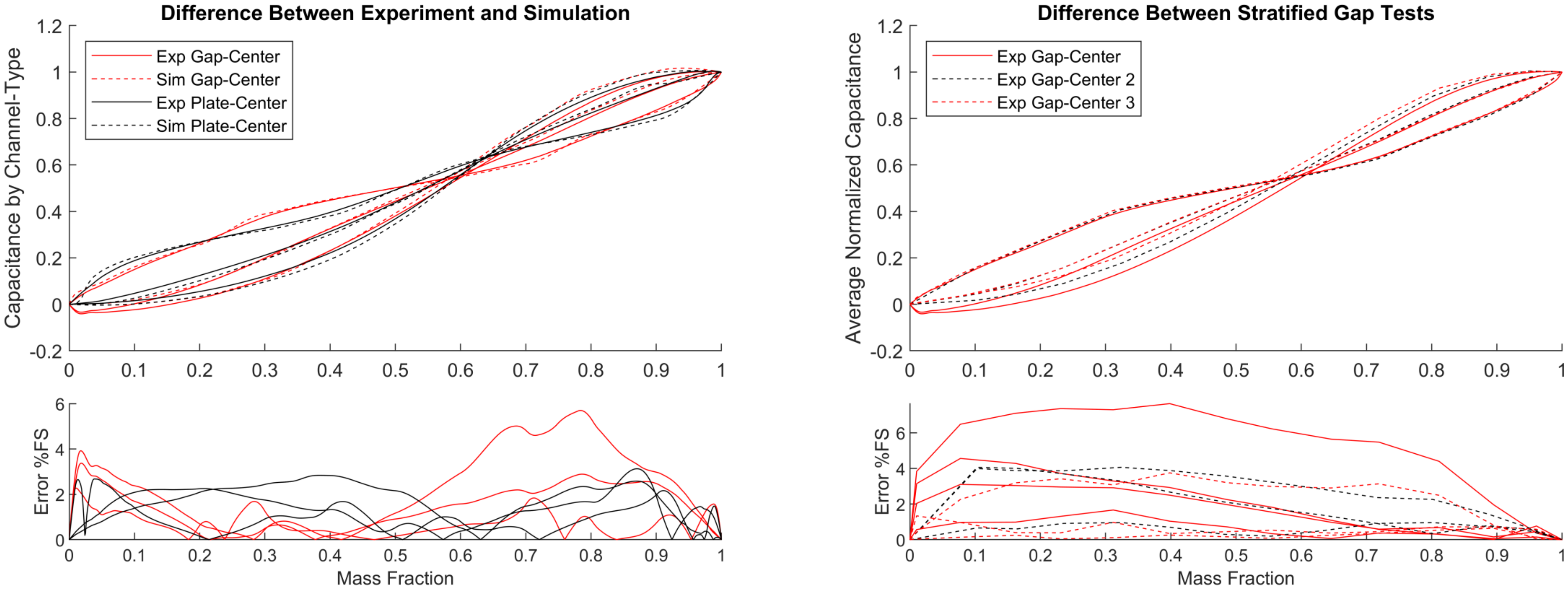




Non-Metallic Vanes like those used in NASA VTRE missions do not affect this method!

Error within: ±3.10%
3σ Error: ±3.04%

Limits of the Current Investigation



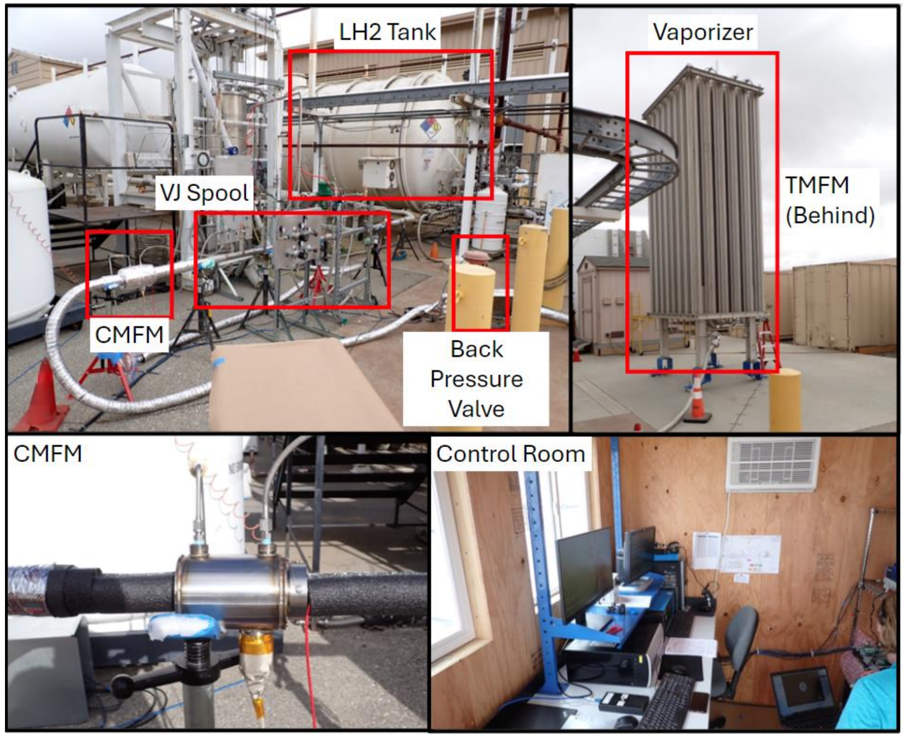
Differences between experiment and simulation and non-repeatability between experiments limits the maximum accuracy we can obtain to around 3%. This can be improved!

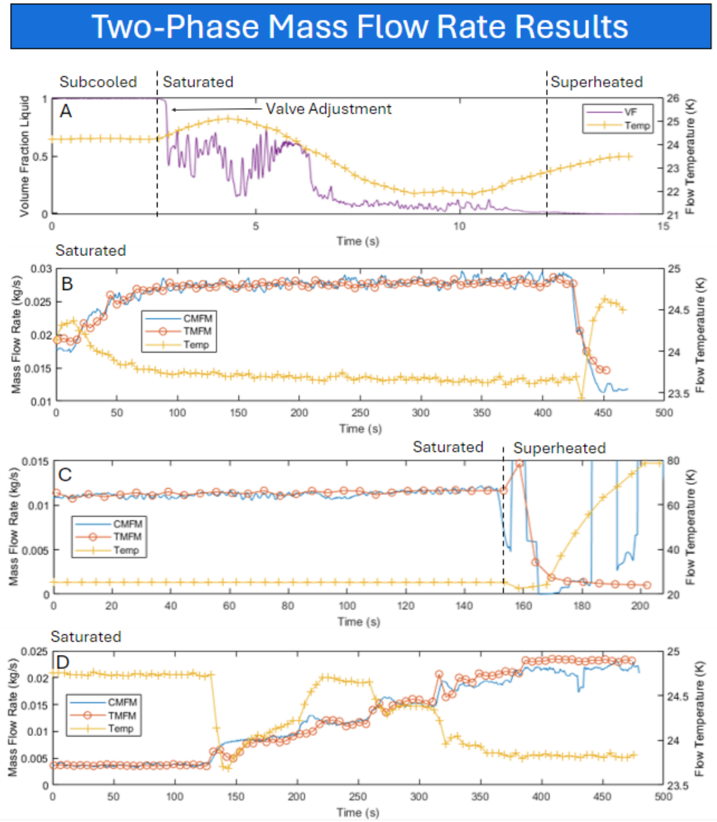
Next Steps

- Metallic Vane Investigation
  - Data is already collected
  - ML algorithm needs to be developed
  - Reduces symmetry and likely requires all 66 channels individually
- Improve repeatability of DAS and experiment
- Improve relation between experiment and simulation
- Test metallic tanks & cryogenic fluids
- Test microgravity fluid configurations in simulation
- Validate sensor in microgravity operation

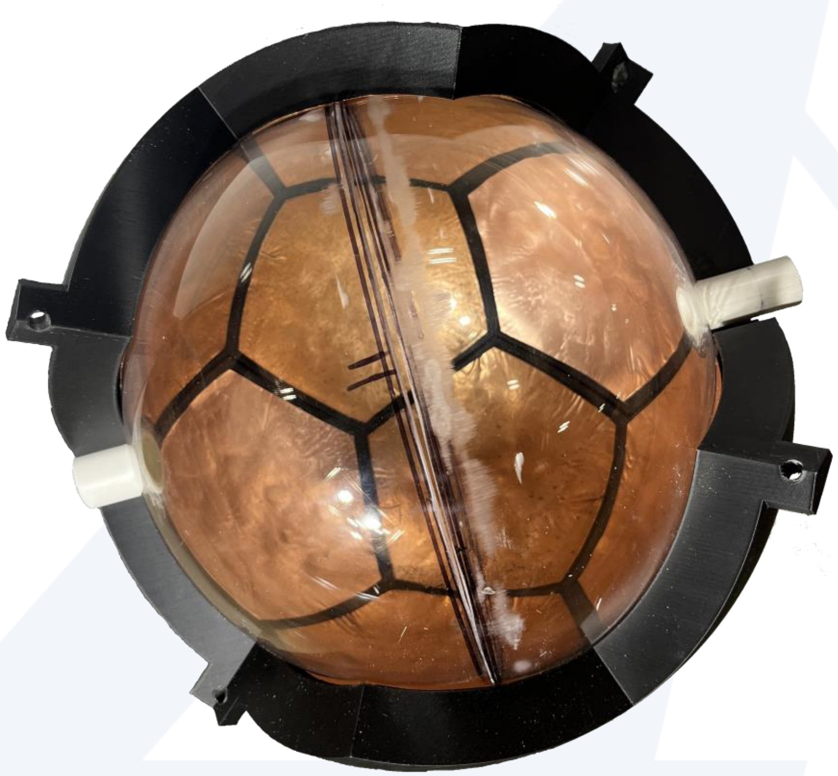
Cryogenic Feasibility

- Flowmeter with same measurement technology tested and working on LH_2!





Questions?



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