Task 1B: Experimental and Numerical Investigations of Cryogenic Multiphase Flow

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Start Date = 6/2002
Planned Completion = 12/2006

Research Goals and Objectives

1. Develop the capability to perform multi-phase flow experiments with cryogenic fluids of interest to NASA propulsion systems
   - Dynamics of solid H_2 in liquid helium (Ting Xu, ME-PhD graduate student)
   - Cryogenic two phase flow sensor (H. Ashmore, ME-MS graduate student)

2. Develop optical sensors for multi-phase flow quantification and test at FSU
   (w/ J. F. Justak – Advanced Technology Group)

3. Perform numerical simulations of multi-phase flow systems to compare with experimental results
   (Prof. Y. M. Hussaini & Dr. B. Unlusu (Postdoc)

Relevance to Current State-of-the-Art

- Understanding of multi-phase flow phenomena is qualitative at best requiring experimental confirmation
- Numerical simulations are increasingly able to model complex phenomena; however, experimental data are required to benchmark codes
- Flow metering of multi-phase cryogenic flows is still unachievable with existing technologies

Relevance to NASA

- Advanced propulsion systems for NASA may utilize a variety of hydrogen fluid systems: two phase flow, densified or hydrogen slush or solid H_2 in liquid helium.
- Critical interest to NASA for fluid management systems on earth and in microgravity conditions.
- Optical flow monitoring methods offer significant advantage to conventional fluid monitoring techniques, particularly for micro-gravity conditions.

Budget, Schedule and Deliverables

Schedule

• **Solid hydrogen particle generation analysis complete**	**3/31/05**
• **Two phase flow experimental apparatus complete**	**4/15/05**
• **Optical mass flow sensor test w/ two phase N_2**	**5/1/05**
• **Attend NASA review**	**5/10/05**
• **Present paper at AIAA Joint propulsion conference**	**7/10/05**
• **Optical flow sensor upgrade**	**8/1/05**
• **Present papers at Cryogenic Engineering Conference**	**8/29/05**
• Attend NASA Review	11/1-4/05
• Complete testing of optical flow sensor w/ two phase N_2	12/15/05
• Complete experiments on sH_2/LHe flow	6/1/06
• Final report	12/31/06

Deliverables

- Report on performance of optical flow quality sensor
- Report on two phase flow experiments and analysis
- Copies of publications

Budget: $270,000 for 1/1/05 to 12/31/05. These funds are primarily to support staff salaries, materials including cryogens, travel and subcontract to ATG ($75,000).

Accomplishments and Results (2005)

Experimental Multi-Phase Flows

- Developed experimental flow loop for sH_2/LHe and liquid/vapor N_2 testing
- Developed and tested a sH_2 particle injector for producing two-phase sH_2/LHe
- Developed concept for cryogenic two phase (liquid – vapor) flow meter

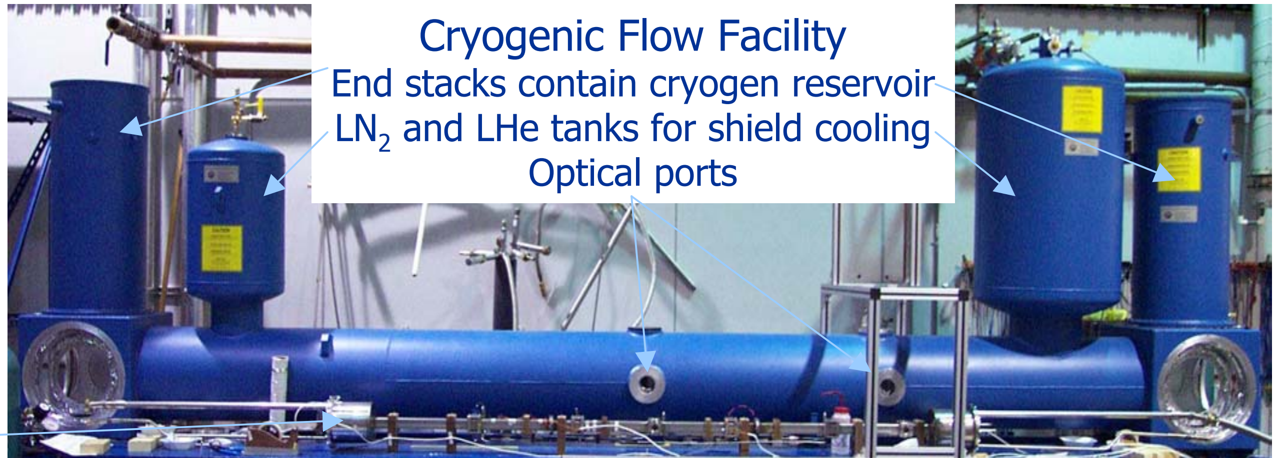
Cryogenic Flow Sensor Development

- Developed a bench-top optical flow meter for test on FSU two phase flow apparatus
- Performed preliminary test with nitrogen liquid/vapor two phase flow

Numerical Simulations and Modeling

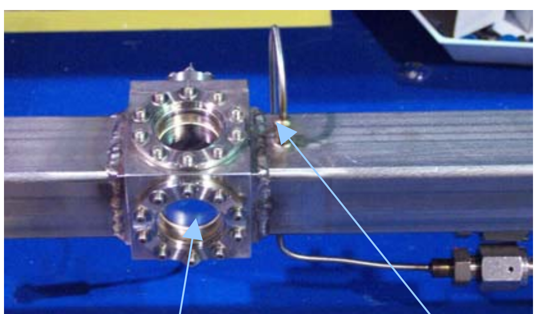
- Developed an algorithm that models the complex processes in the solidification of H_2 particles in LHe.
- Compared a model for small LH_2 droplet generation and compared to experiment
- Performed preliminary work on hydrogen fuel cell (to be discussed later)

1. Multiphase Flow Experimental Apparatus



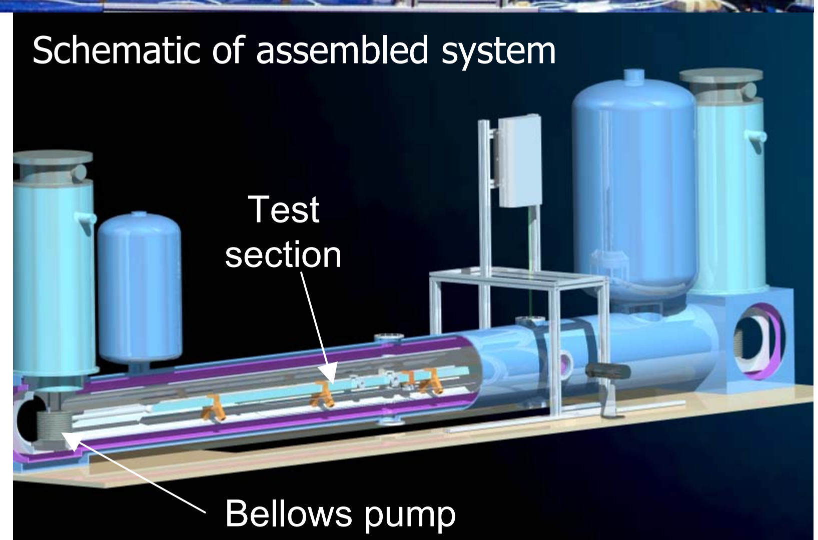
Cryogenic Flow Facility
End stacks contain cryogen reservoir
LN_2 and LHe tanks for shield cooling
Optical ports

Test section



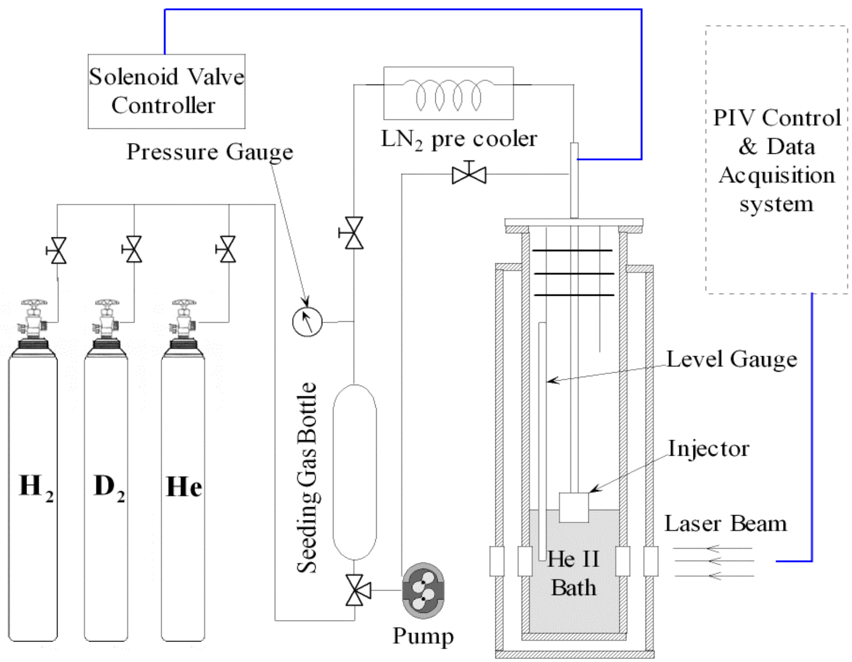
Optical port 1” diameter

Pressure tap

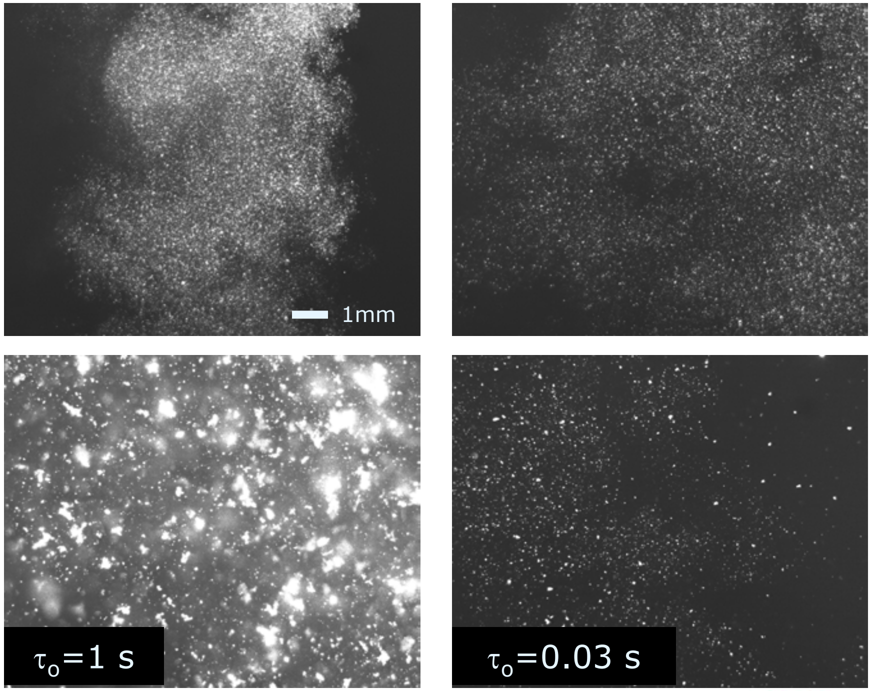


Development of sH_2 particle injection

- Technique to generate sH_2 particles in liquid helium
  - Spray jet from LH_2 reservoir (reported at previous program reviews)
  - Condensation directly from vapor phase



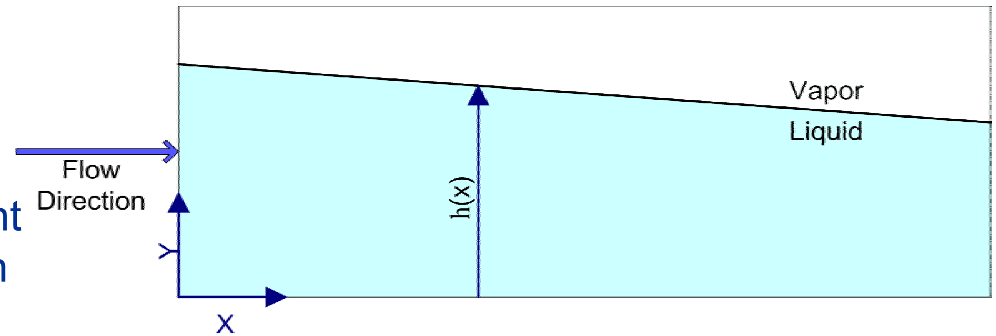
Vapor condensation experiment



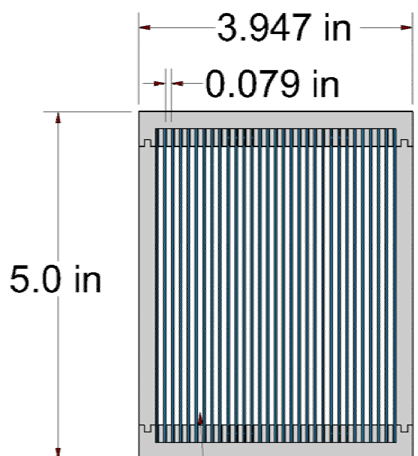
Varying the injection time

Cryogenic Two Phase Flow Meter

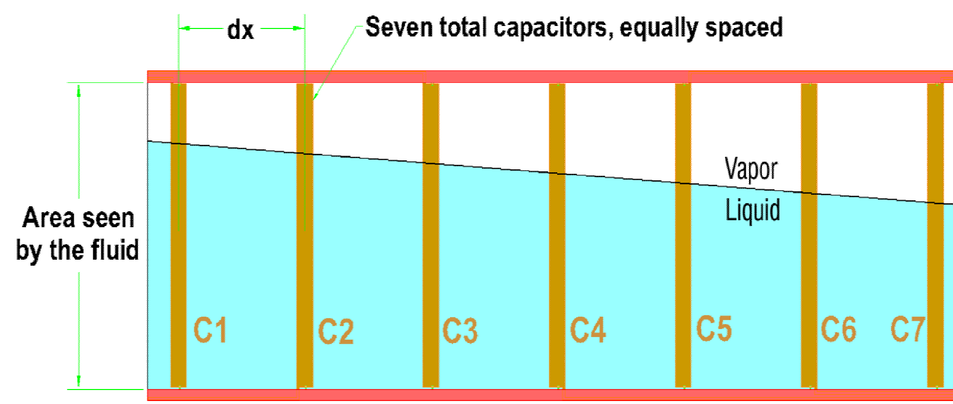
- The cryogenic flow passes through parallel, narrow rectangular channels
- Liquid and vapor phases have different dielectric coefficients, so the local fluid height is determined from the capacitance between the narrow rectangular channels.



- Channels made from G -10 Printed Circuit Boards
- Housing has a entrance and exit region for insertion in cryogenic line

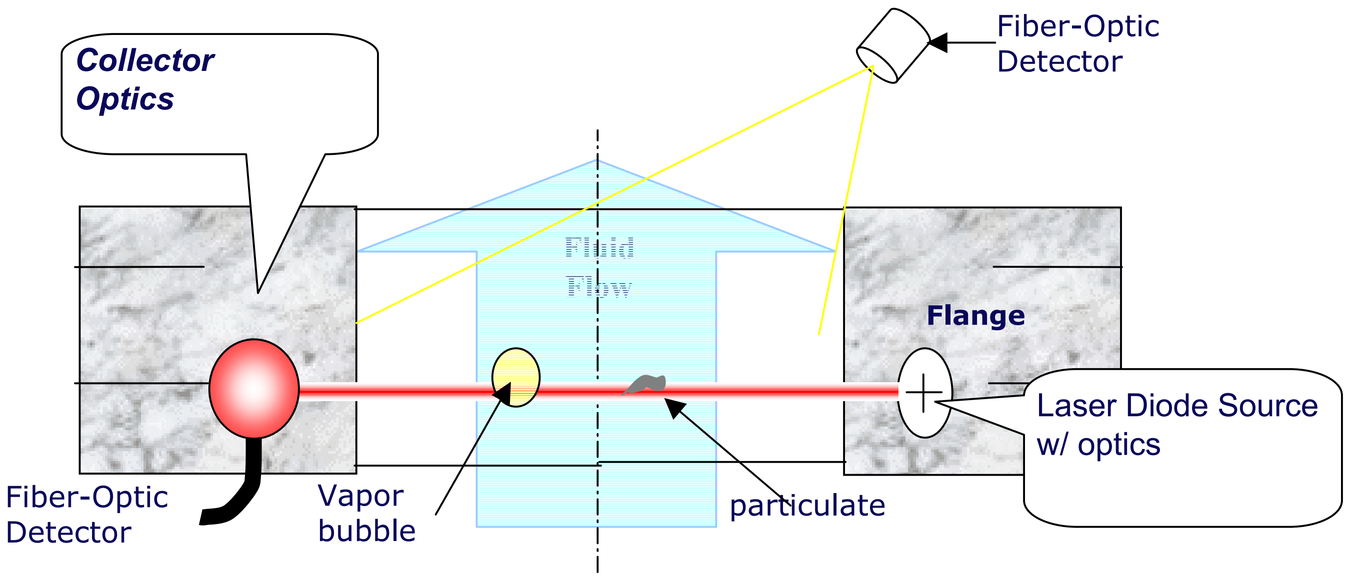


30 narrow channels separated by thin Custom PCBs



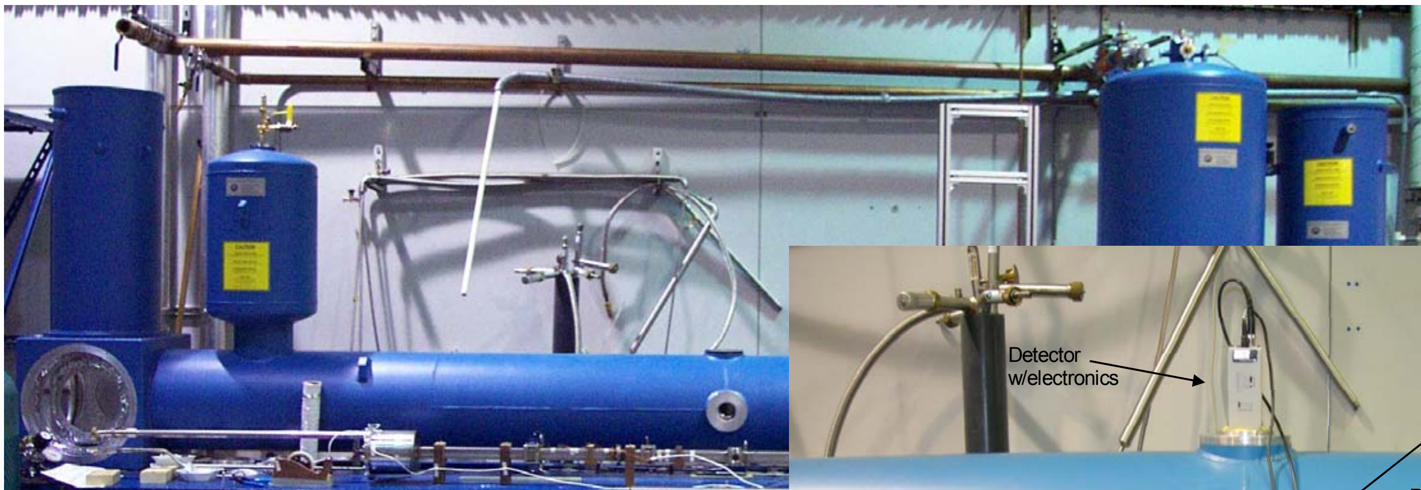
2. Cryogenic Flow Sensor (CFS) Development

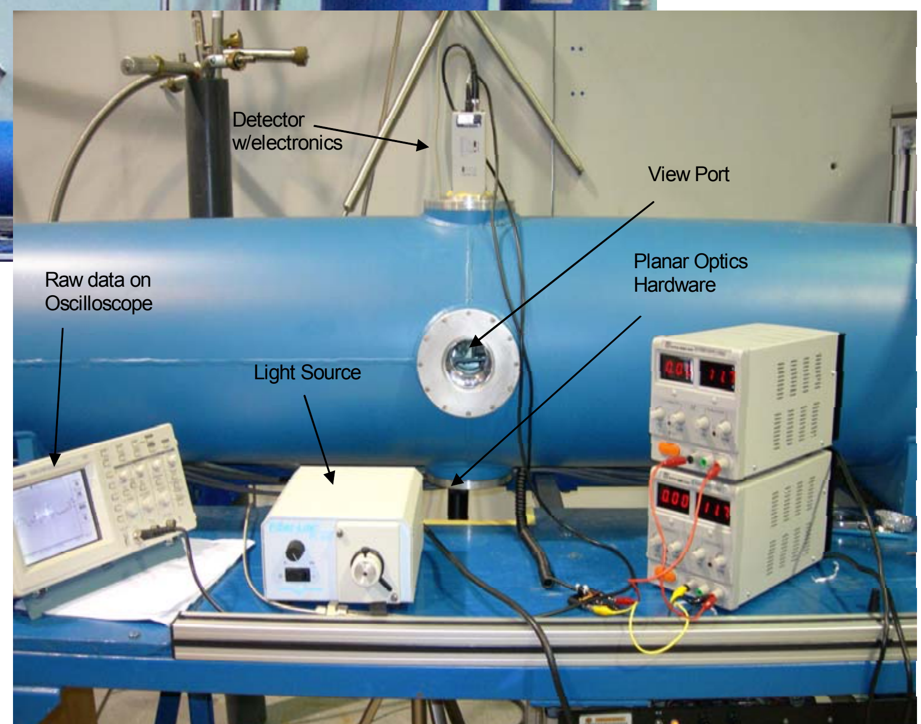
Optical absorption/scatter:



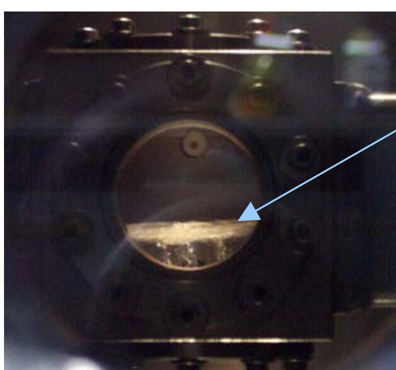
- Determine light attenuation due to change in refractance and absorption coefficient using a plane-of-light
- Yields two-phase flow and multiple-fluid detection

Quality Flow Experiments at FSU





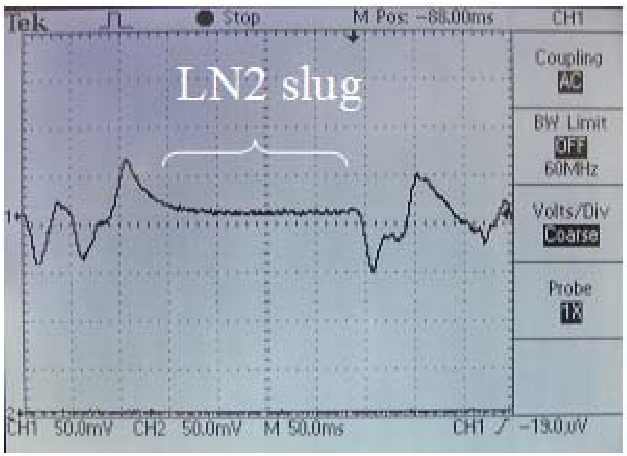
Liquid nitrogen test fluid



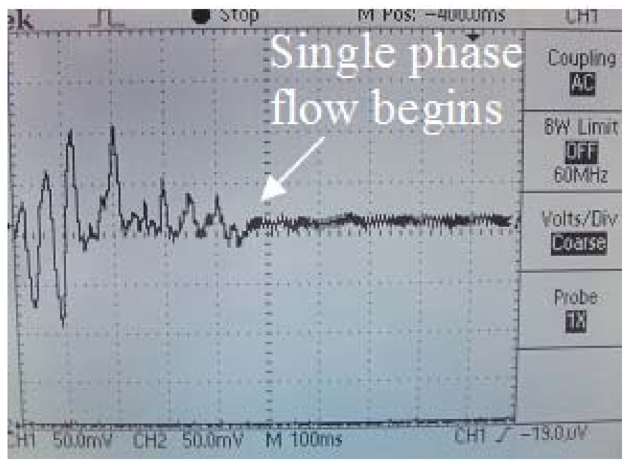
Stratified two phase LN_2 flow

Flow Sensor Quality Data

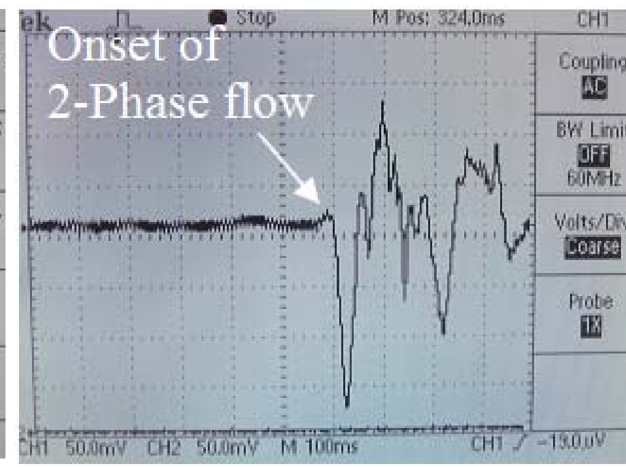
Single channel oscilloscope traces showing:



Slug of
liquid nitrogen



Single phase
liquid nitrogen



Two-phase flow
of liquid and gas
nitrogen

Continuing Development

- The ATG-CFS requires two primary determinations
  1. Determination of density in the sensing plane
  2. Measurement of flow velocity

- Utilize wavelength that is absorbed in nitrogen (2100nm)
  1. Direct measurement of flow density
  2. Utilize differential absorption to remove throughput error (ratio of two wavelengths, one absorbing, one non-absorbing)
  3. Time sync digital camera with sensor data for visual analysis (confirmation of two phase flow v/s single phase flow)

3. Numerical simulation: Solid Hydrogen Solidification

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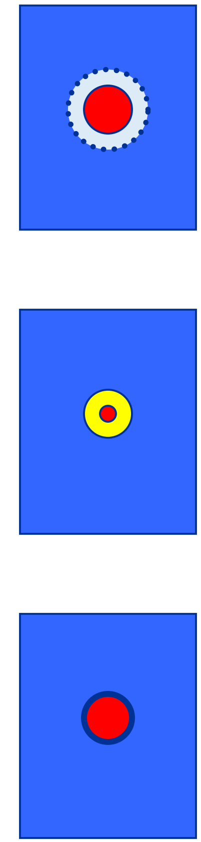
- Incompressible Navier-Stokes Equations for Multi-Phase Flow
- Volume of Fluid Method to track the moving interface between Liquid and Vapor Helium
- Enthalpy-Porosity Technique to track the moving interface between Liquid and Solid Hydrogen
- Thermal Coupling of Hydrogen Droplet with Helium Tank



Evolution of the Liquid-Vapor Interface

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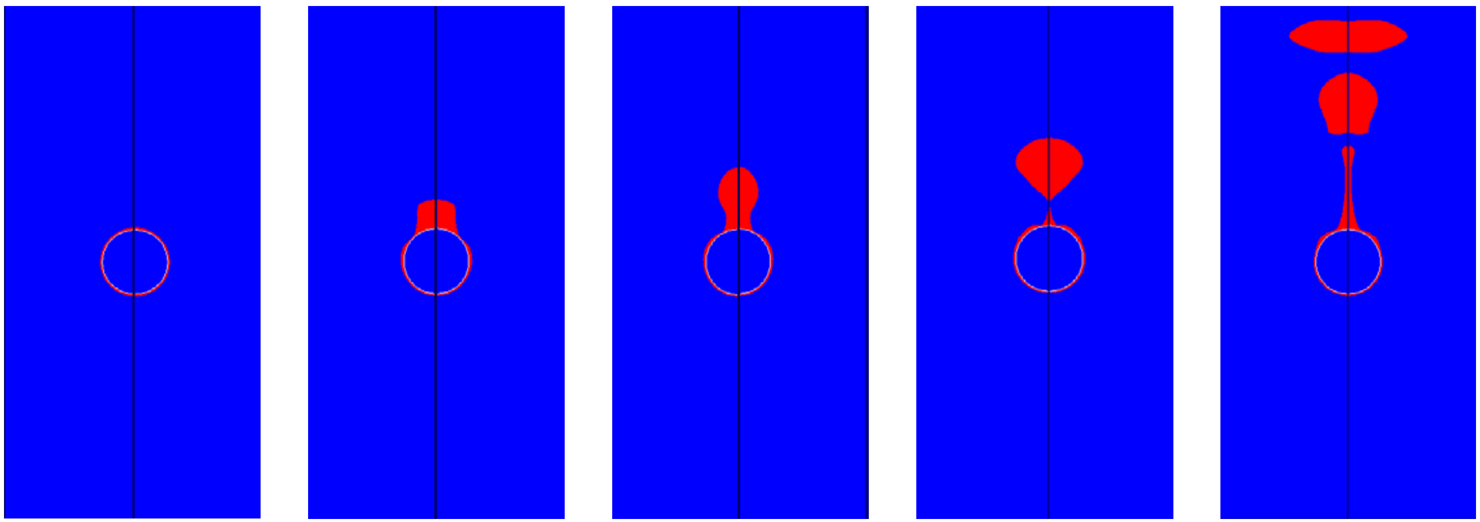

t=0.0 s t=0.01 s t=0.025 s t=0.035 s t=0.075 s

- Due to buoyancy forces, vapor moves toward the upper half of the droplet
- It takes t = 35 ms for the first bubble to depart
- Vapor bubble reaches the top of the bath in about t = 75 ms

Simulated Temperature Contours in the LHe Bath

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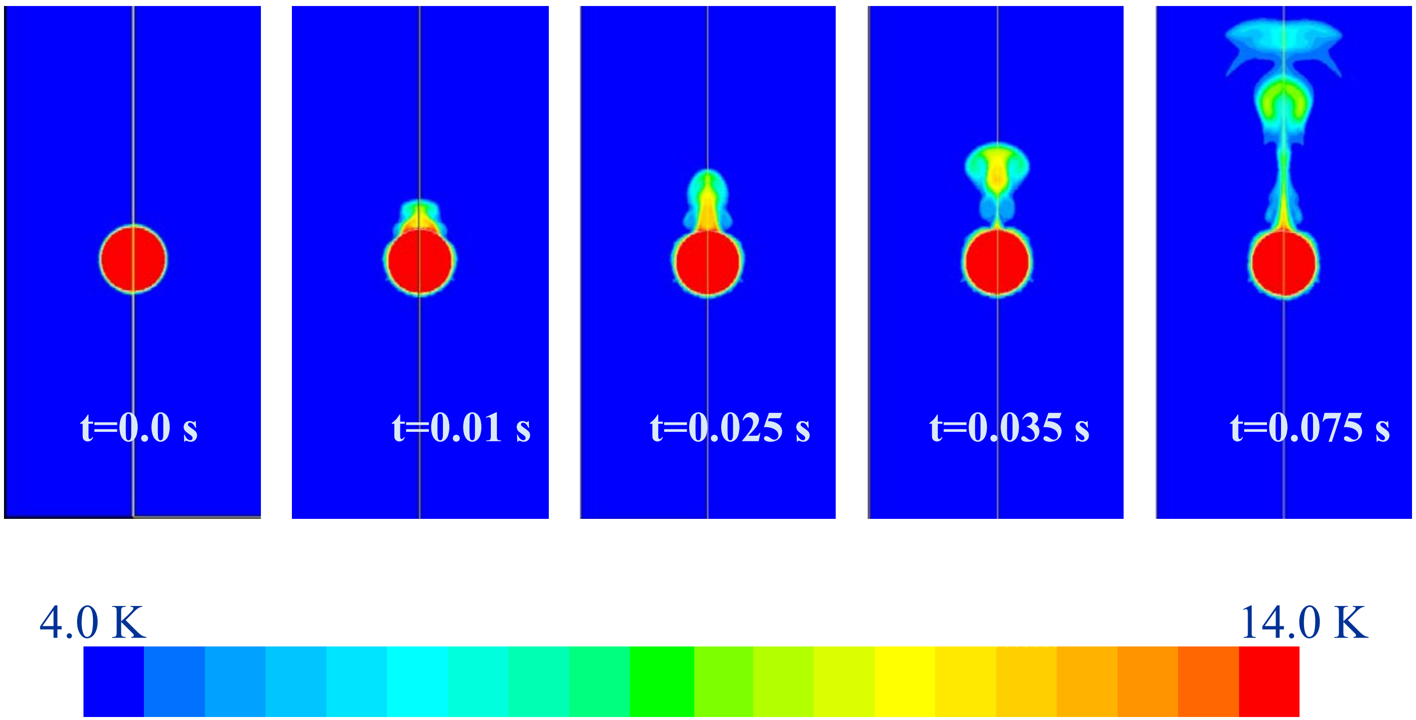

- Temperature of vapor bubble decreases as it moves away from the droplet
- Temperature of the droplet stays constant during solidification

Future Plans

1. **Multiphase Flow Experiments (Cryogenics Group)**
   - Complete the experimental studies of multi-phase flow including both sH_2/LHe flows and two phase LN_2 flows
   - Complete development of cryogenic two phase flow sensor
2. **Cryogenic Flow Sensor Development (ATG)**
   - Initiate optical velocity determination (acousto-optic)
   - FSU-NHMFL has a high velocity flow facility (CHEF) that could be utilized for future experiments
3. **Numerical Simulations and Modeling (SCS)**
   - Compare experimental results with numerical models for multi-phase flow
   - Initiate an effort in PEM fuel cells (proposed)

Publications & Presentations

- “Optical Mass Gauging of Solid Hydrogen” S. Van Sciver, T. Adams, F. Caimi, D. Celik, J. Justak, and D. Kocak, **Cryogenics** Vol. 44, 501 (2004)
- “Two Phase Flow of Solid Hydrogen Particles and Liquid Helium”, J. Xu, a. Rouelle, K. Smith, D. Celik, M. Hussaini and S. W. Van Sciver, **Cryogenics** Vol. 44, 459 (2004)
- “Hydrogen Particles in Liquid Helium”, J. Xu, K. Smith, D. Celik, M. Hussaini and S. W. Van Sciver **Cryogenics** Vol. 44, 507, (2004)
- “Liquid Hydrogen Droplet Formation in a Vibrating Orifice” J. Xu, D. Celik, M. Y. Hussaini and S. W. Van Sciver, Proceedings ICEC-20, Bejing, PRC (2004)
- “H_2/D_2 Particle Seeding and Injection System for PIV Measurement of He II”, Ting Xu and S. W. Van Sciver, **Advances in Cryogenic Engineering**, Vol 51A (to be published)
- “Numerical Studies of Liquid Hydrogen Droplet Generation from a Vibrating Orifice” J. Xu, D. Celik, M.Y. Hussaini, and S.W. Van Sciver, **Physics of Fluids** Vol. 17, 082103 (2005)
- “Investigation of Hydrogen Droplet Solidification in Cryogenic Helium”, B. Unlusu, J. Xu, M. Hussaini, D. Celik and S. Van Sciver, Paper AIAA – 2005-4550, AIAA Joint Propulsion Conference, Tuscon, AZ July 2005
- “A Cryogenic Mass Flow Sensor”, D. M. Kocak, J. F. Justak, F. M. Caimi and S. W. Van Sciver, **Advances in Cryogenic Engineering**, Vol 51A (to be published)

Numerical Investigation of Water and Thermal Management in PEM Fuel Cells

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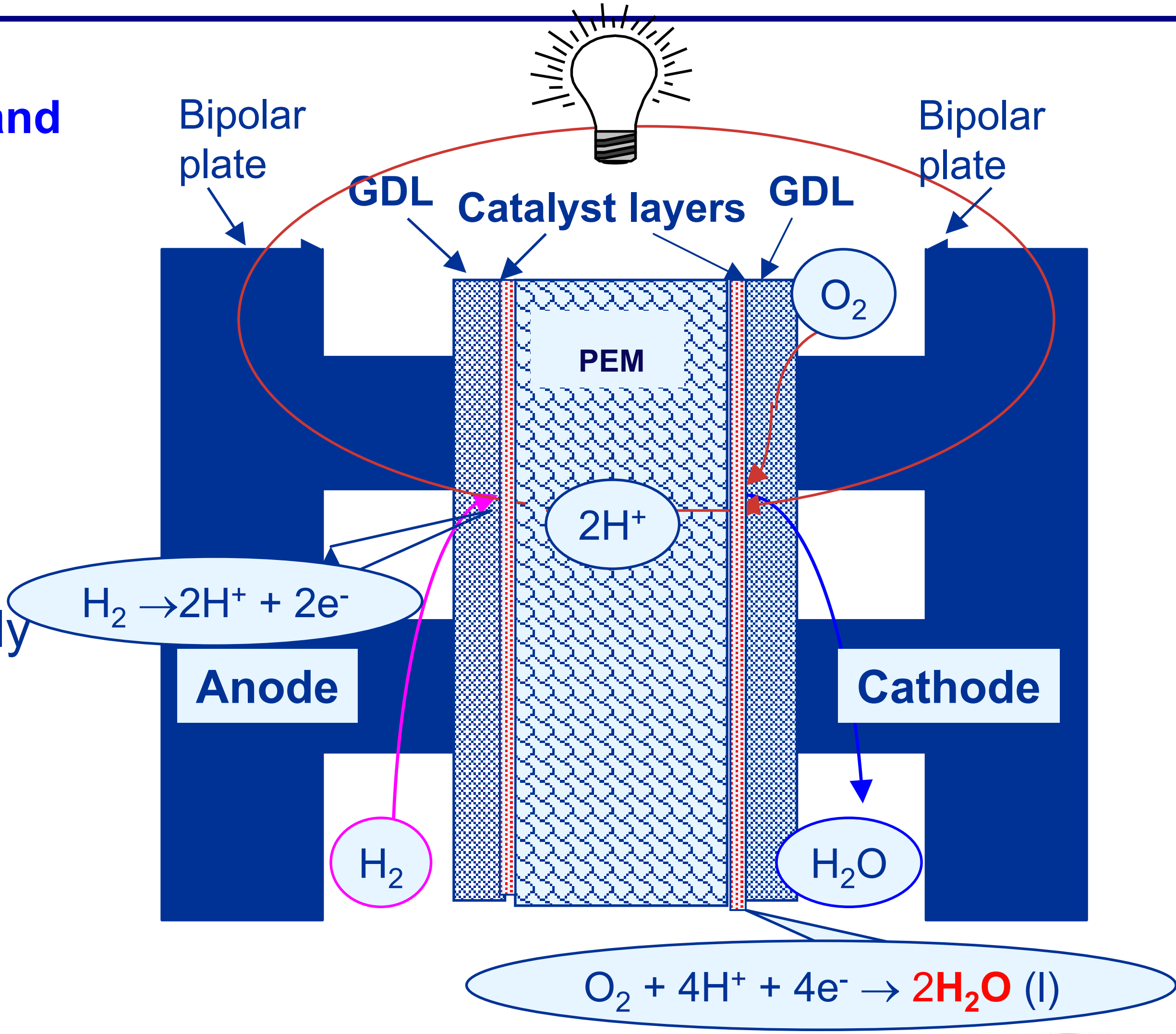
Collaborators: J. Xu, P. Ngnepieba, A-M Croicu and consultants

PEM Fuel Cell: **Water and Thermal Management**

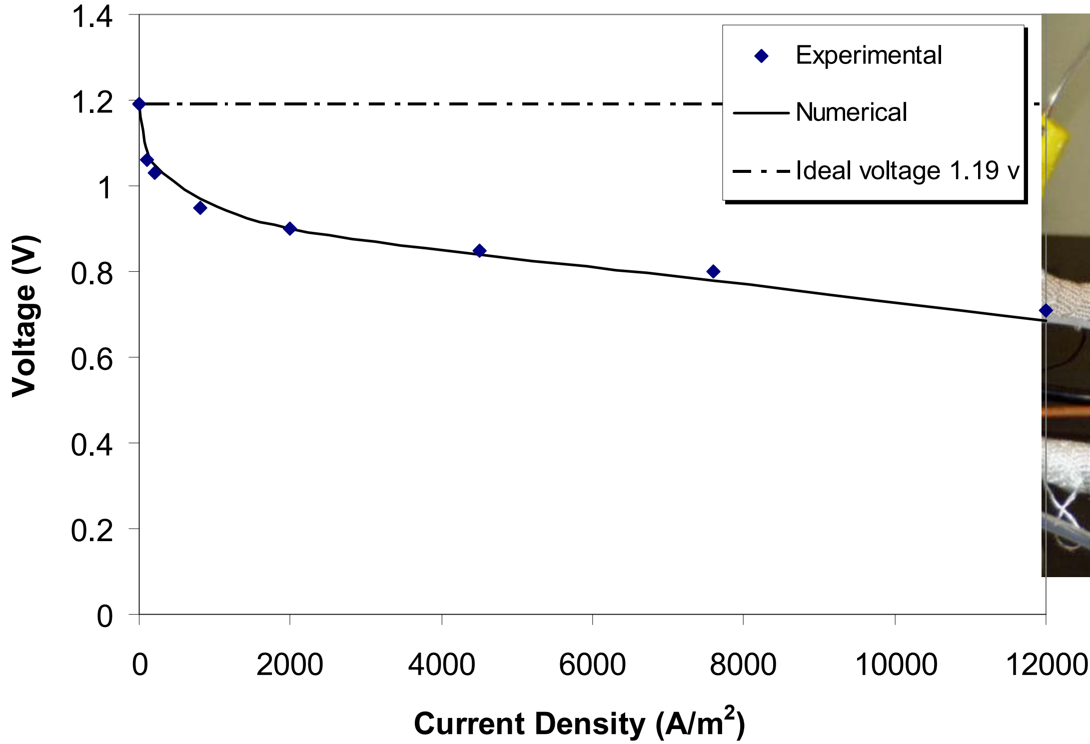
- Liquid water may flood GDL, CL
- Excessive heat may dehydrate or even rupture membrane
- Experimental investigations are extremely difficult if not impossible
- Calls for an integrated numerical model: **non-isothermal, two-phase, multi-species**

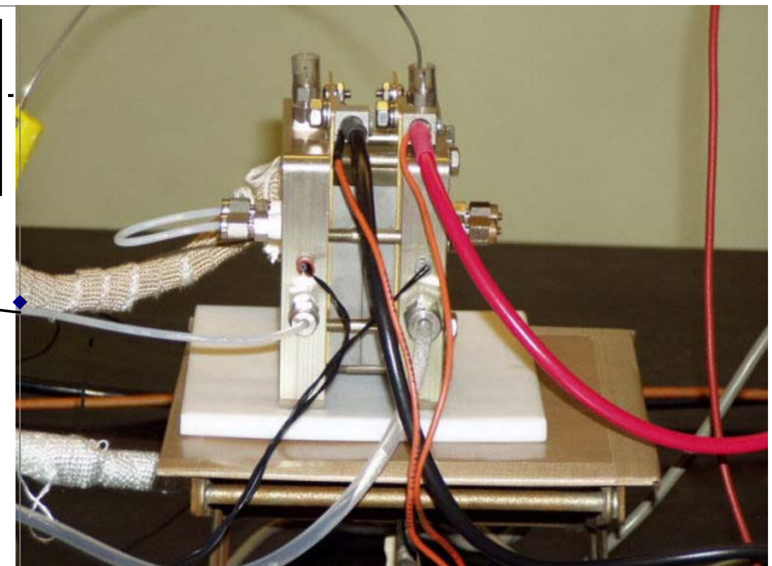


$$O_2 + 2H_2 \rightarrow 2H_2O \ \ (+\,\text{Heat} + \text{Electricity})$$

Model Validation

1. Performance: polarization curve





Validation facility

2. Theoretical prediction threshold current density

$I_{theoretical}$ = 4382 A/m^2 $I_{computational}$= 4600 A/m^2

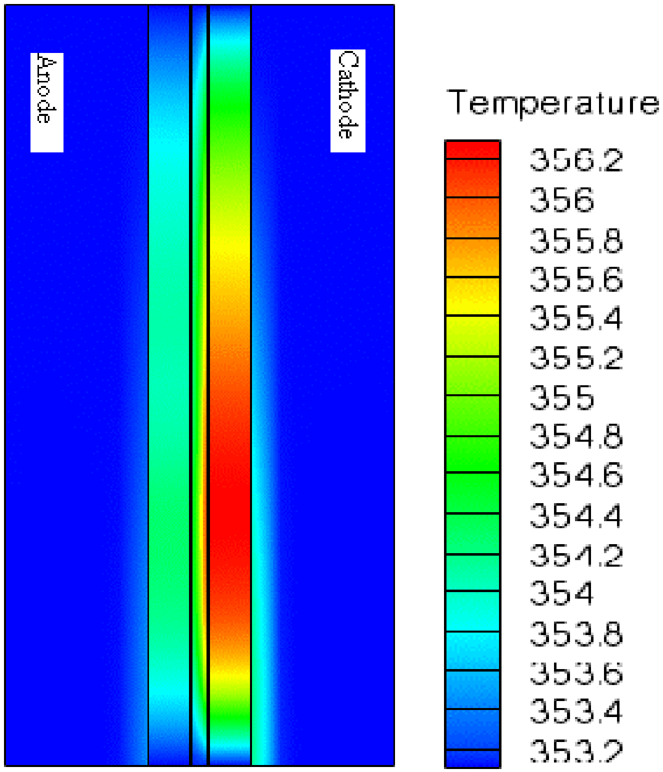
Case Studies

Fuel Cell Dimensions	Value
Length, m	7.0×10^{-2}
Channel width, m	1.0×10^{-3}
GDL width, m	3.0×10^{-4}
CL width, m	1.29×10^{-5}
Membrane width, m	1.08×10^{-4}
Porosity	0.30

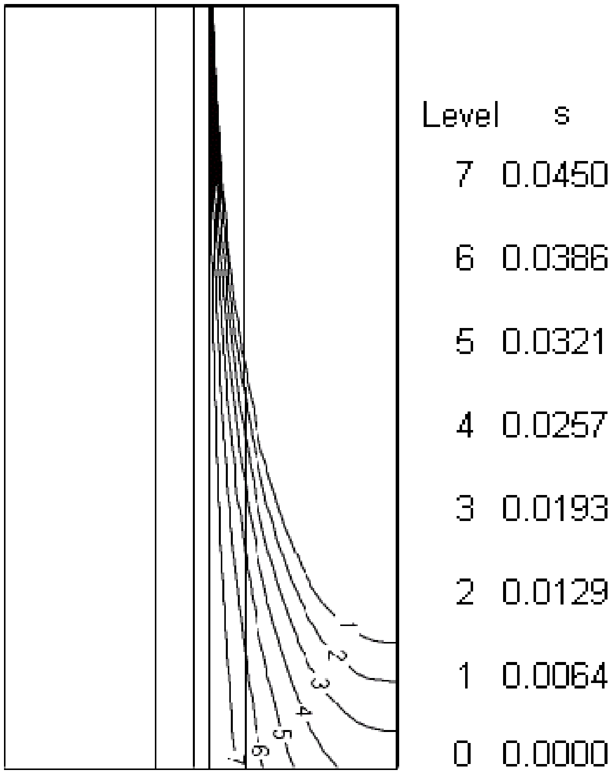
Operation Conditions	Case 1	Case 2
Initial operation temp., K	353.0	353.0
Air pressure at inlet, Pascal	303975	506625
Fuel pressure at inlet, Pascal	303975	303975
Flow temp. at inlet, K	353.0	353.0
Air velocity at inlet, m/s	0.35	0.35
Fuel velocity at inlet, m/s	0.35	0.60

Case I

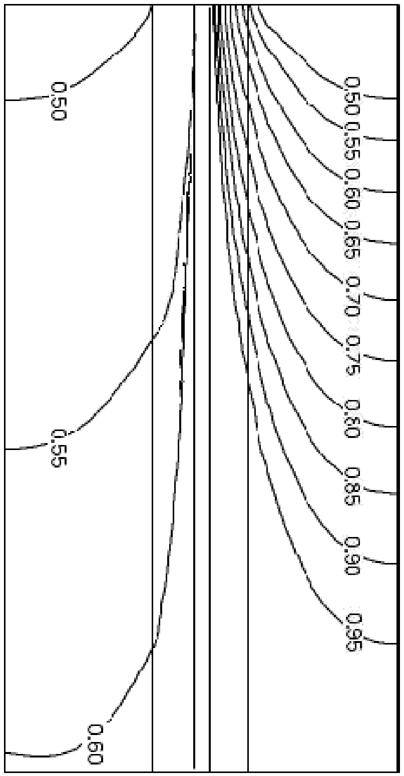
Thermal and Water "Collateralizing"



Temperature contours



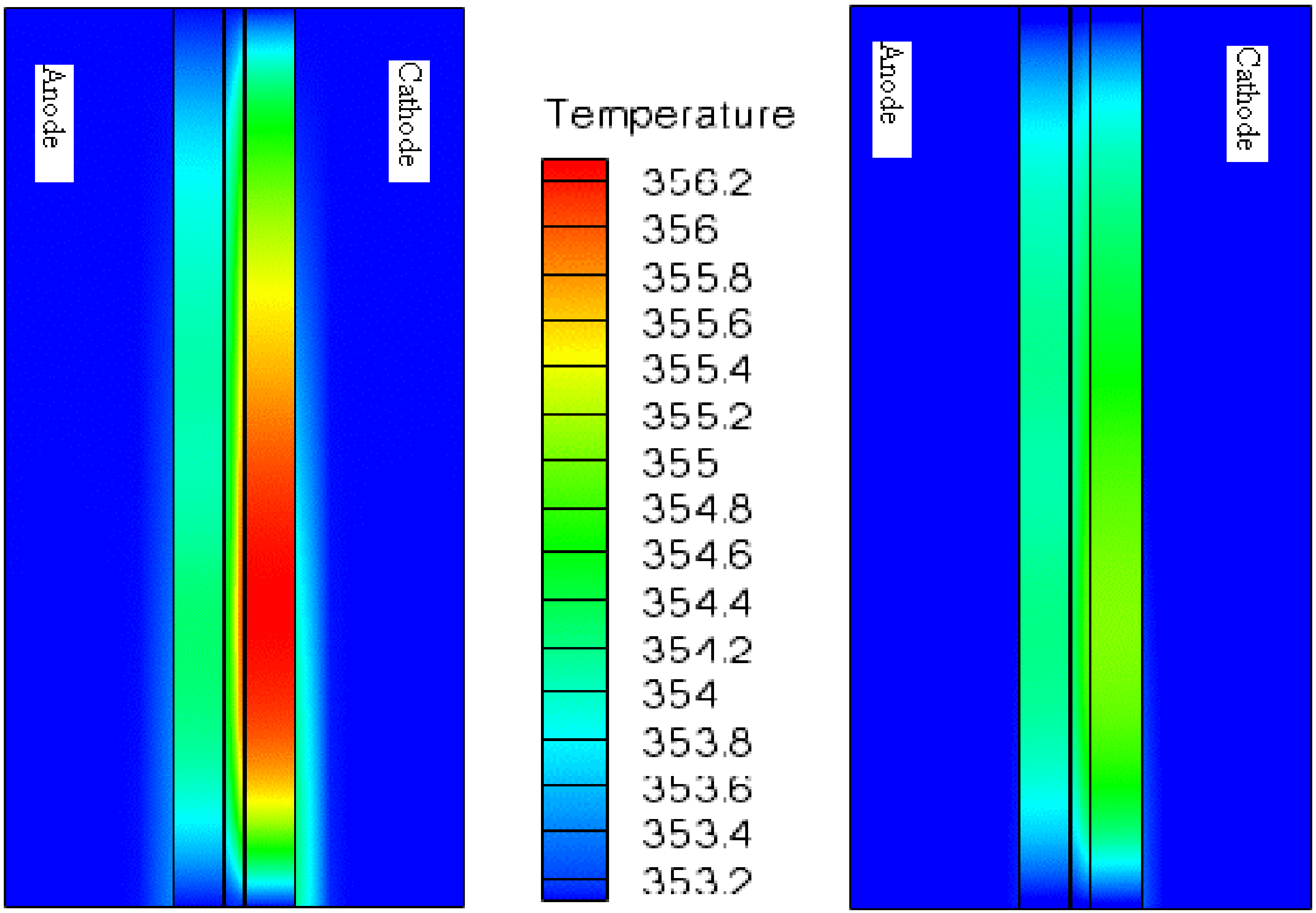
Liquid water saturation contours



Relative humidity contours

PEM Fuel Cell: Temperature Distribution

Case 1



Case 2

Conclusions

Accomplishment

- **Water and thermal “collateralization”**
- **Anode water removal strategy is feasible:**
  - It may prevent cathode side from flooding
  - Membrane is kept hydrated as the water diffuses across to the anode side
  - It may remove the need for humidifying the fuel

Future work

- **Multiobjective optimization**
  - Minimize liquid water accumulation
  - Min $\min[|(v_{\mathrm{w}} - N_{\mathrm{w}}^{(\mathrm{m})}) - N_{\mathrm{vap}}^{(\mathrm{c})}| + |N_{\mathrm{vap}}^{(\mathrm{a})} - N_{\mathrm{w}}^{(\mathrm{m})}|]$

$$\min |\dot{q}_{\mathrm{gen}} - (\dot{q}^{(\mathrm{a})} + \dot{q}^{(\mathrm{c})})|$$