# High Power Density Thermal Management of Proton Exchange Membrane Fuel Cells

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**Planned Completion: 8/2007**

# Research Goals and Objectives

- Improve overall power density of Proton Exchange Membrane (PEM) Fuel Cells by significantly increasing heat removal capacity
- Implement two-phase passive cooling system to eliminate power consuming pump.
- Minimize unwanted temperature gradients utilizing the isothermal evaporation process.
- Utilize high heat transfer rates through evaporation in microchannels.
  - Identify mechanisms controlling heat transfer in microchannels and successfully model thermal fluid transport.
  - Identify and predict the onset of performance limiting operating conditions, such as instabilities and critical heat flux.

# Relevance to Current State-of-the-Art

- Combining phase-change heat transfer with microchannels can significantly increases the heat removal capacity per unit volume beyond the state-of-the-art.
- Passive cooling technologies also improve overall power density and fuel cell efficiency

# Relevance to NASA

- One limiting factor in increasing the overall power density of PEM fuel cells is the inability to to remove the heat load with high power loads.
- NASA power density target for PEM fuel cells is currently 5000 W/kg, which is an order of magnitude larger than the state of the art.

# Budget, Schedule and Deliverables

- Budget
  - $80,000
- Quarterly tasks and milestones accomplished during year 1
  1) Designed and fabricated microchannel cooling plate for PEMFC's.
  2) Instrumented cooling plate for heat transfer, pressure drop, and flow visualization measurements.
  3) Made extensive measurements of heat transfer coefficient, pressure drop, and characterized flow regimes.
  4) Developed predictive heat transfer, pressure drop, and flow regime models for microchannel evaporative flow.
  5) Designed condenser and fabricated condenser.
  6) Assembled thermal management system through microchannel plate.
  7) Characterized thermal and flow performance of thermal management system with simulated heat load.
- Quarterly tasks and milestones planned for year 2
  1) Design radiator and fabricate radiator.
  2) Collect experimental data on performance of integrated thermal management system
  3) Calibrate system performance models
  4) Test thermal performance in forced flow model
  5) Develop design methodology
  6) Build and test prototype in test bed fuel cell

# Deliverables

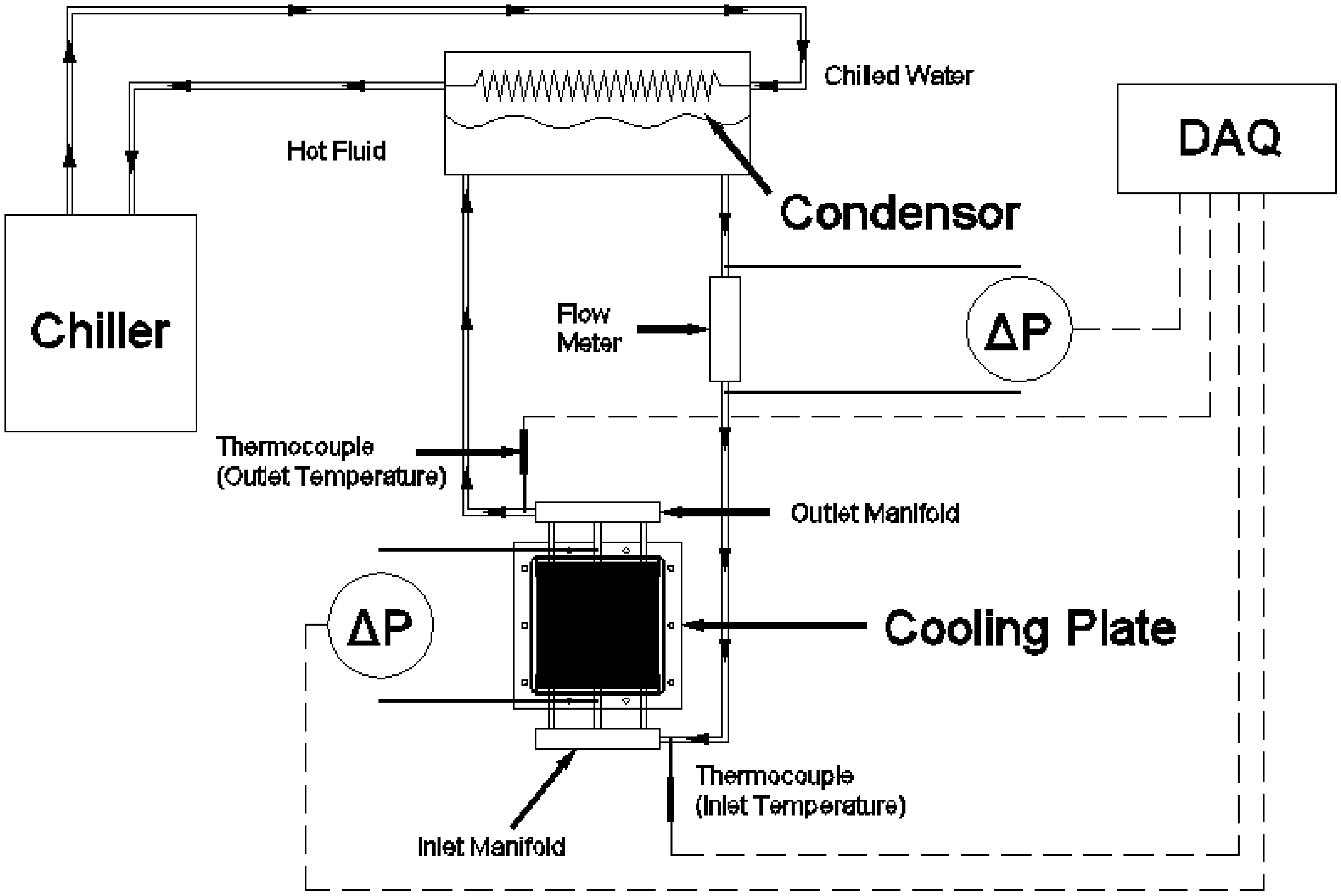
- Prototype passive & forced flow high power density thermal management system
- Experimental data base on thermal flow performance of thermal management system
- Design methodology for fuel cell system and different applications
- Computational analysis tool to predict thermal management system performance

# Anticipated Technology End Use

- Integrate microchannel cooling plates internally within fuel cell stack to allow for significantly enhanced thermal power density.
- Other applications requiring high power density thermal management
  - High Power density batteries
  - Automotive fuel cell applications
  - Spacecraft Avionics

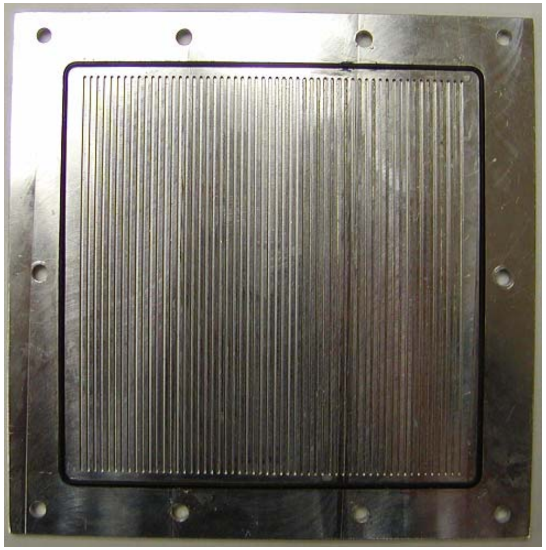
# Accomplishments and Results

## Experimental Facility

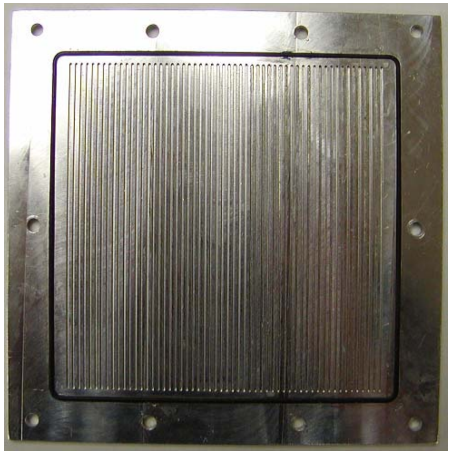


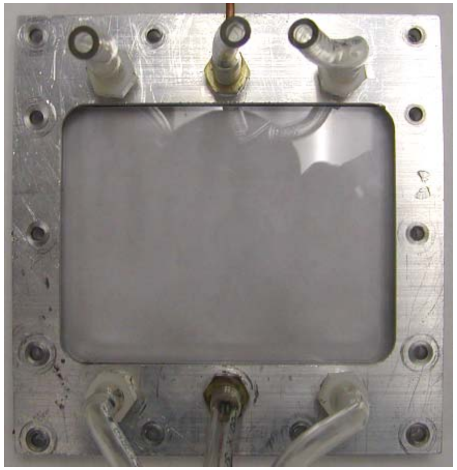
# Cooling Plate & Working Fluid

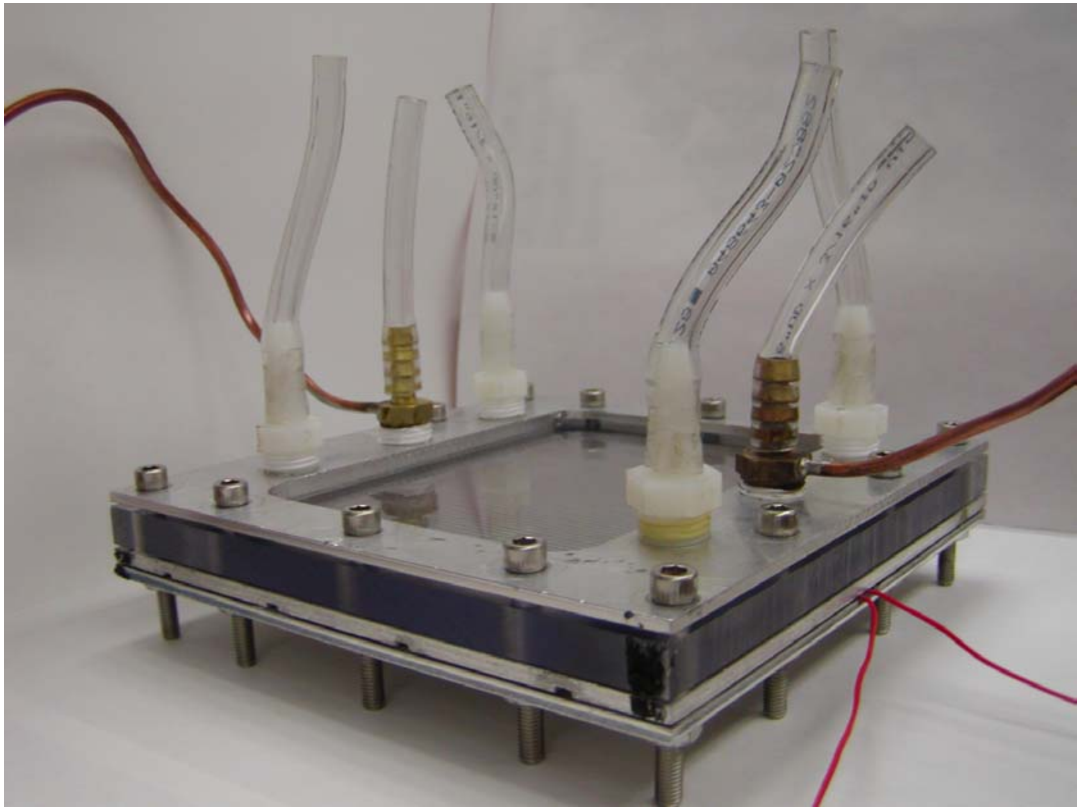
- Microchannel Cooling plate
  - 56 channels 1 mm X 1mm square cross section, 155 mm long
  - Made from aluminum
- Working Fluid
  - HFE-7100 by 3M
  - Saturation Temperature: 61 C
  - Specific Heat: 1250 J/kg*K
  - Heat of vaporization: 111.6 J/kg
  - Compatible with most materials



# Cooling Plate Assembly





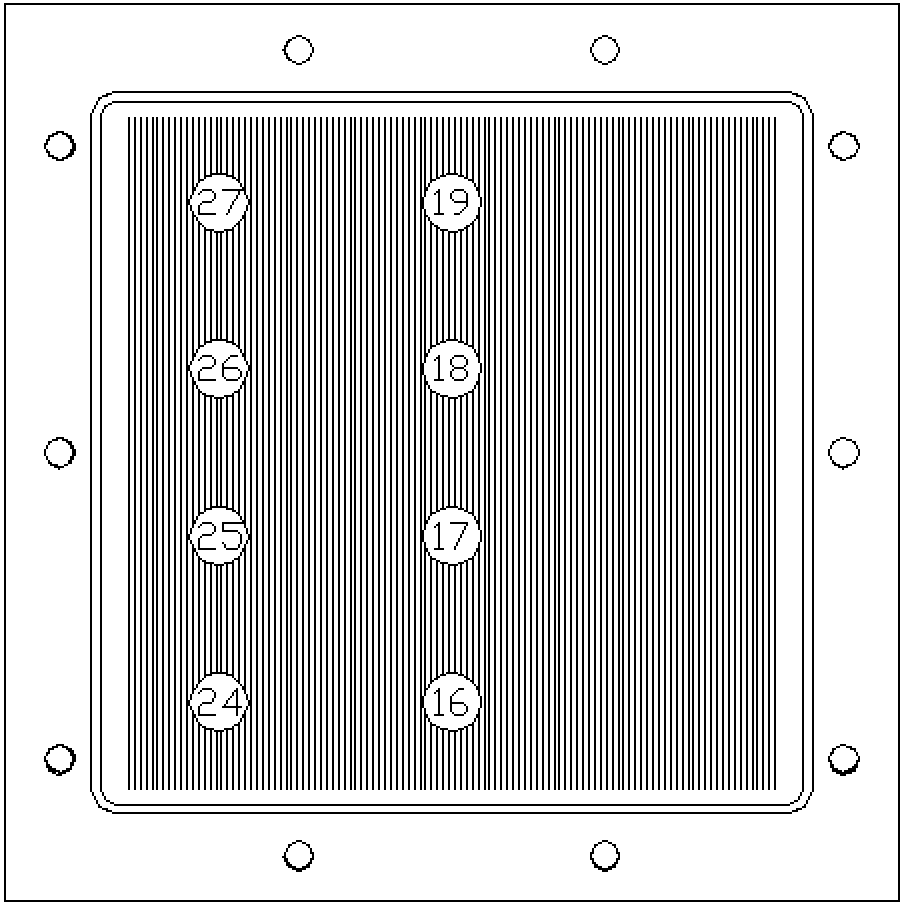


# Experimental Objectives

- Evaluate flow rate and pressure gradient with different heat loads
- Evaluate flow boiling heat transfer coefficients
- Evaluate maximum heat load
- Compare predicted flow rate and pressure gradient with predictions from computational model

Flow Visualization

# Locations of Temperature Measurements

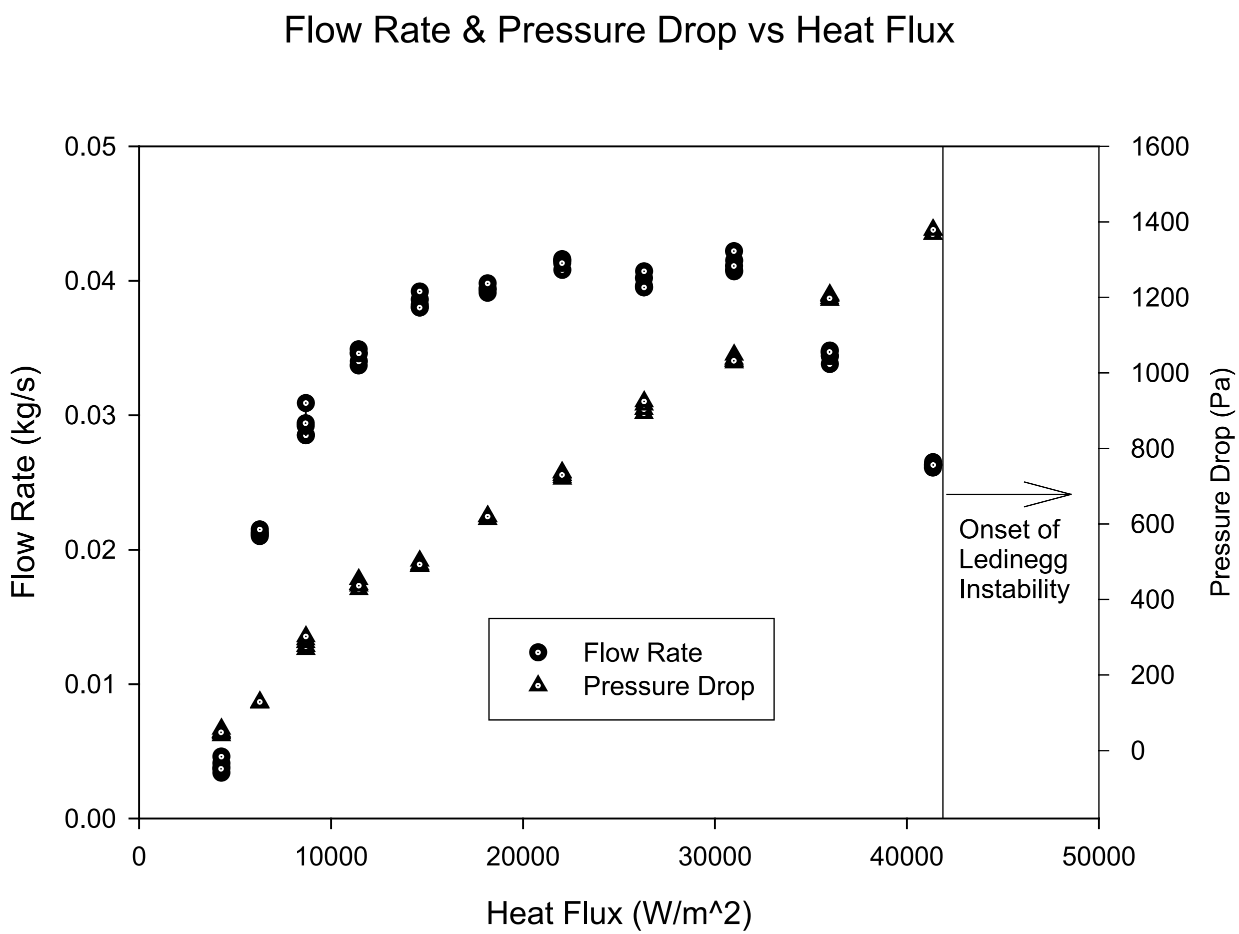



**Optimal Operating Temperature For PEM fuel cell is 70-80 degrees C**

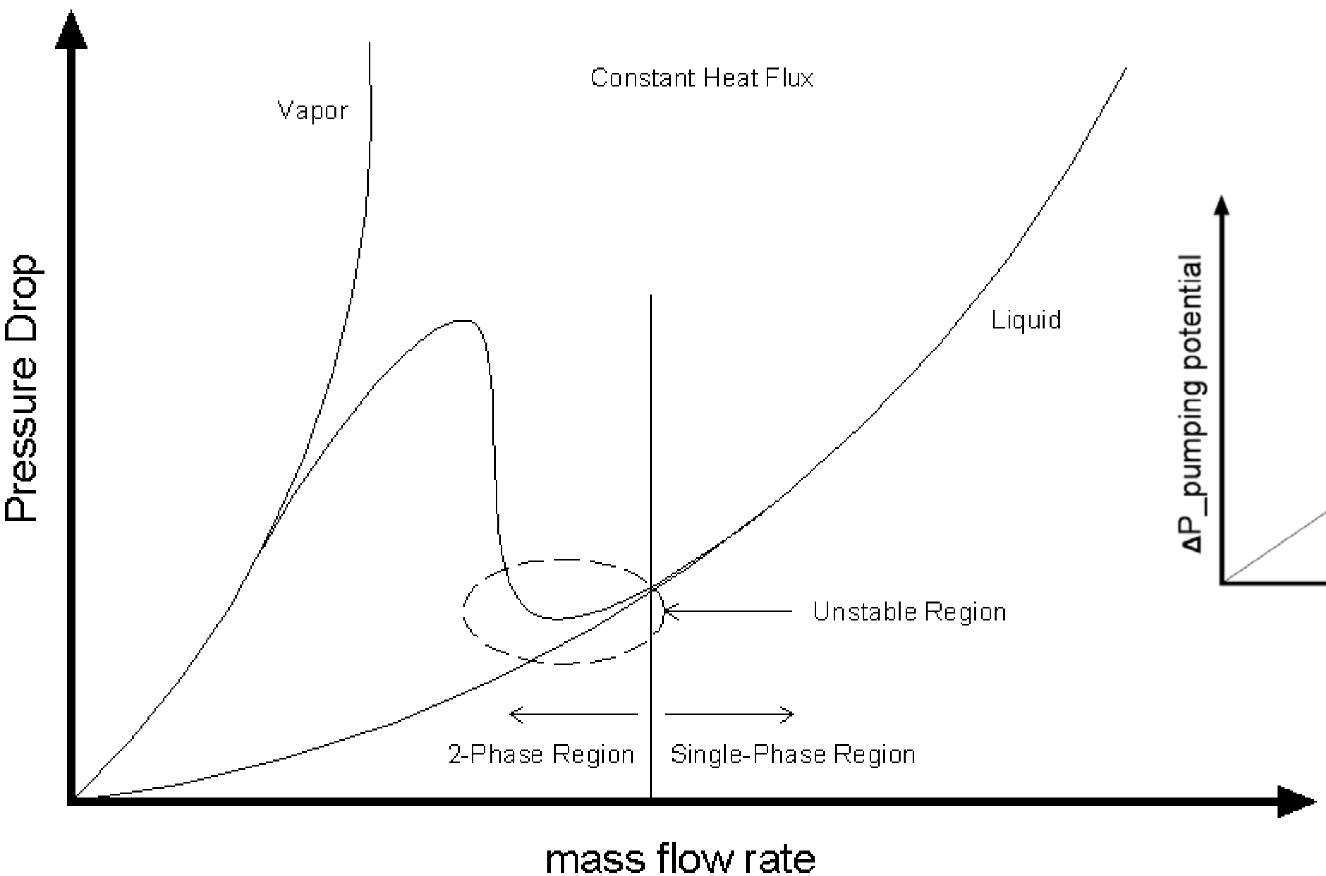
**At maximum heat flux- 43 kW/m^2 Before onset of instability**

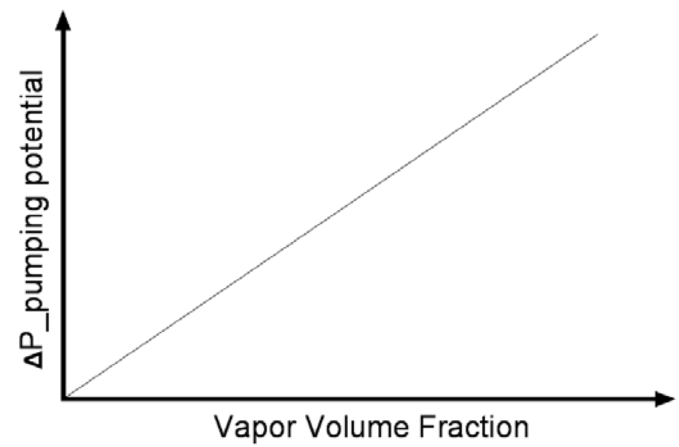
**T(16)=76.7 C**
**T(17)=79.8 C**
**T(18)=78.4 C**
**T(19)=78.3 C**
**T(24)=76.0 C**
**T(25)=79.1 C**
**T(26)=81.9 C**
**T(27)=82.9 C**

# Flow Rate & Pressure Drop Variation with Heat Flux



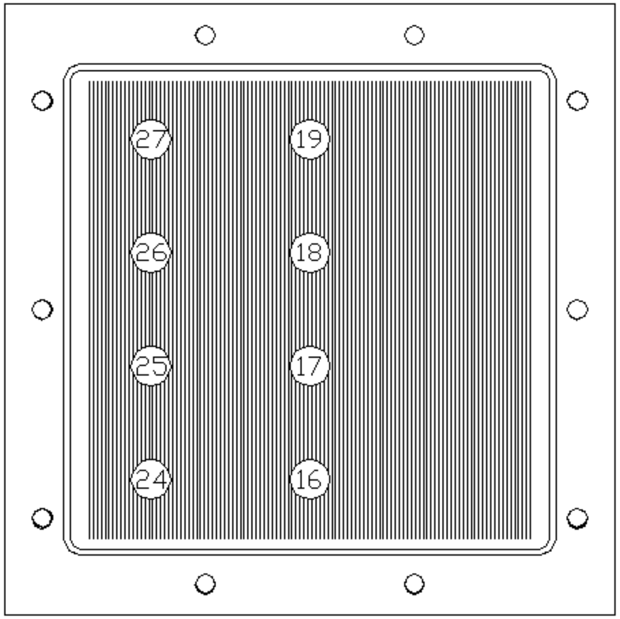
# Ledinegg Instability

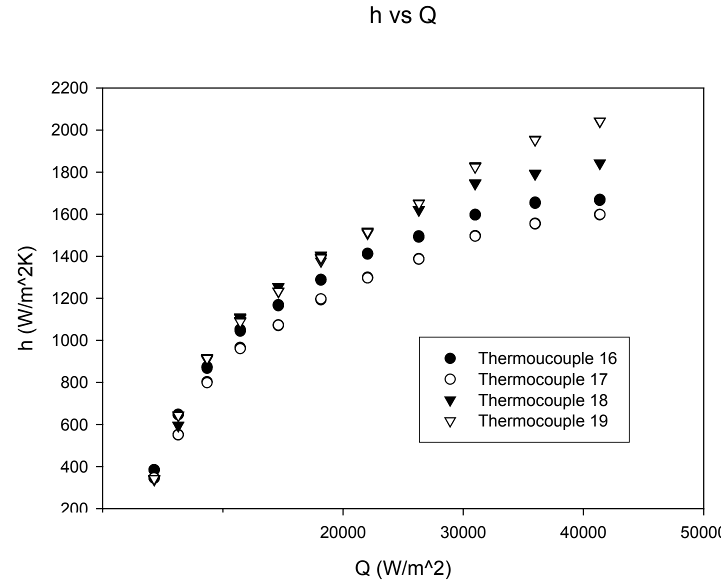


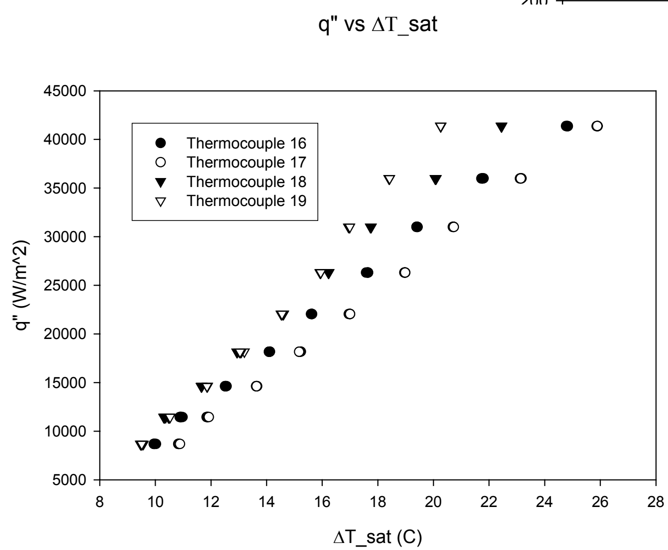




Flow Visualization

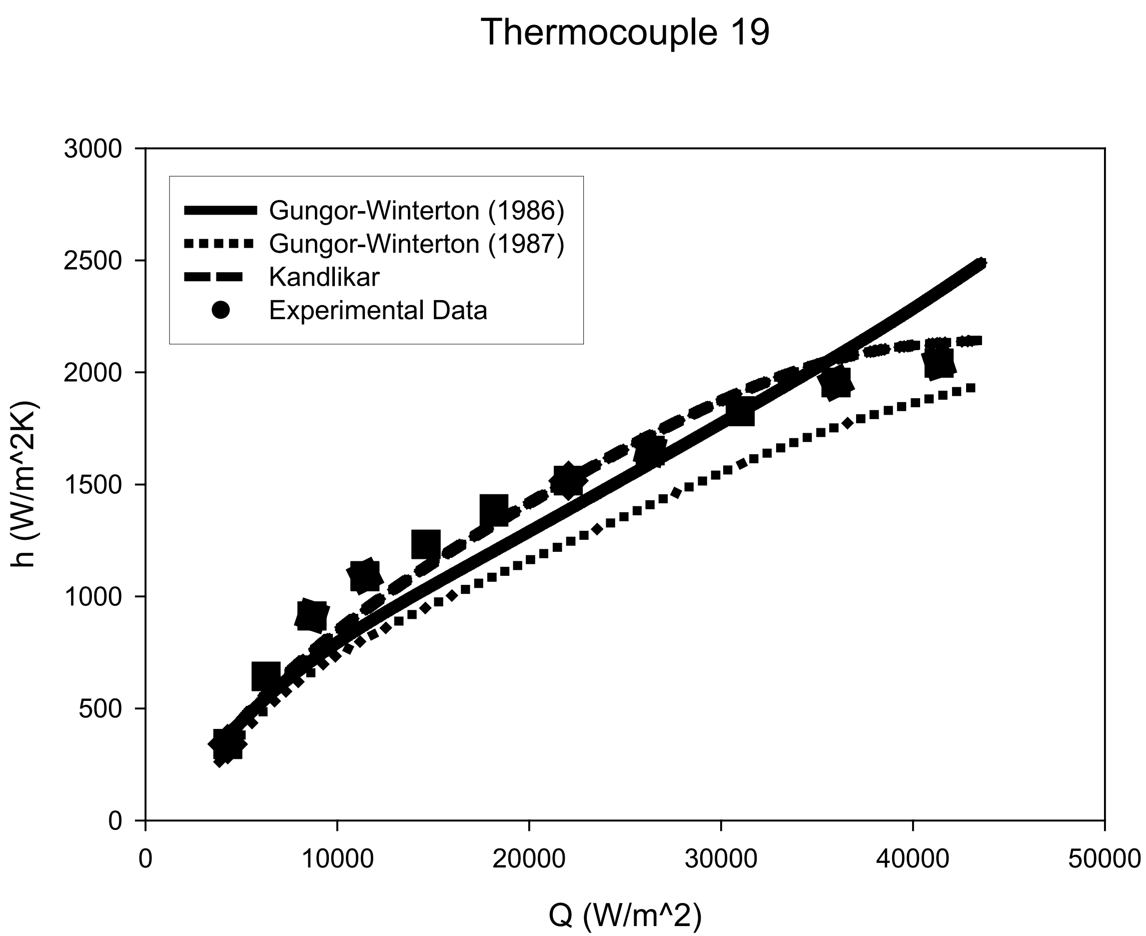
# Measurement of Heat Transfer Coefficient



# Comparison Between Measured and Predicted Heat Transfer Coefficient



# Flow Rate Governing Equations

$$\left(\frac{dP}{dz}\right)_{2\phi} = \left(\frac{dP}{dz}\right)_g + \left(\frac{dP}{dz}\right)_f + \left(\frac{dP}{dz}\right)_a$$

$$\left(\frac{dP}{dz}\right)_g = \rho_m g \sin\theta$$

$$\rho_m = \alpha\rho_v + (1-\alpha)\rho_l$$

$$\alpha = \left( C_0 \left( 1 + \left(\frac{1-x}{x}\right)\frac{\rho_v}{\rho_l} \right) + \frac{\rho_v}{Gx} V_{vj} \right)^{-1}$$

$$V_{vj} = \left( 1.53 g\sigma \frac{(\rho_l - \rho_v)}{\rho_l^2} \right)^{1/4}$$

$$C_0 = 1.2$$

$$x = \frac{Q - \dot{m} C_p \Delta T}{\dot{m} h_{fg}}$$

$$\frac{\left(\frac{dP}{dz}\right)_f}{\left(\frac{dP}{dz}\right)_{f,l,1\Phi}} = \Phi_l$$

$$\left(\frac{dP}{dz}\right)_{f,l,1\Phi} = \frac{2 f G^2 (1-x)^2}{\rho_l}$$

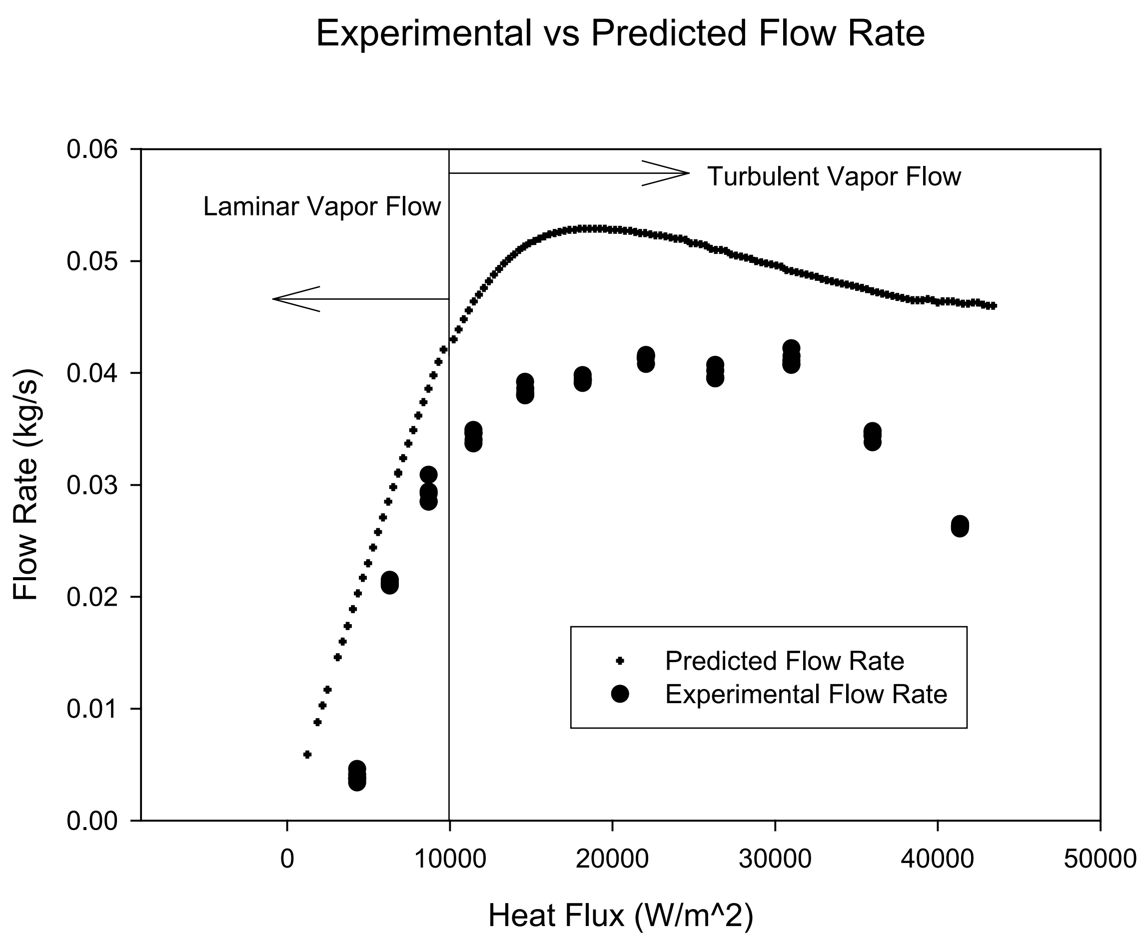
$$\Phi_l = \left( 1 + \frac{C}{X} + \frac{1}{X^2} \right)^{1/2}$$

$$X = \left( \frac{\left(\frac{dP}{dz}\right)_{f,l,1\Phi}}{\left(\frac{dP}{dz}\right)_{f,v,1\Phi}} \right)^{1/2}$$

$$\left(\frac{dP}{dz}\right)_a = \frac{G^2 (\beta_e - \beta_i)}{\Delta L}$$

$$\beta = \left( \frac{(1-x)^2}{\rho_l (1-\alpha)} + \frac{x^2}{\rho_v \alpha} \right)$$

# Comparison Between Measured & Predicted Flow Rate



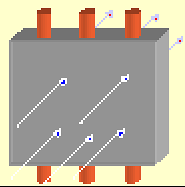
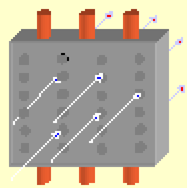
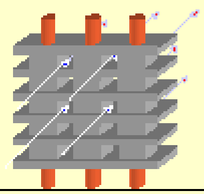
# Summary of Experimental Results

- Wall Temperature within desired range for optimal fuel cell performance
- Cooling Plate capable of removing 43 kW/m^2 of heat prior to instability
- Onset of Ledinegg Instability limits maximum heat flux
- Kandlikar and Gungor-Winterton models are satisfactory for micro-channel heat transfer
- Flow rate and heat transfer coefficient are strongly dependent on heat flux
- Forced flow will inhibit Ledinegg instability and significantly increase maximum heat flux

# Future Plans

- Design and fabricate compact carbon foam radiator.
- Design and fabricate similar microchannel cooling plates with various geometries to increase heat transfer coefficient.
- Develop more rigorous heat transfer and flow models.
- Conduct experiments in forced flow mode
- Integrate thermal management system with test bed fuel cell and characterize thermal flow performance.
- Use improved heat transfer and flow models to design optimal thermal management systems for PEM fuel cells.

# Carbon Foam Radiator Design Concept

| | Heat Transfer Coefficient h, (W/m²·K) | ΔP/L (psi/in) |
|---|---|---|
| Solid Foam  | 10,000* | 2 |
| Through-holes  | 1,000* | 0.1 |
| Finned  | 1,000* | 0.05 |
| Current Radiator | 30-200 | <0.05 |

- Utilize high heat transfer coefficients from carbon foam