

# Computational and Experimental Study of Gas-Liquid Fluid Flows through Flow Cells

**G. Ahmadi,<sup>1,2</sup> W. Zhang,<sup>1</sup> A. Abdollahi Mofakham,<sup>2</sup> K. Jarvis,<sup>1</sup>  
D. Crandall,<sup>1</sup> G. Bromhal<sup>1</sup>**

**<sup>1</sup> National Energy Technology Laboratory,  
U.S. Department of Energy, Morgantown, WV 26507-0880**

**<sup>2</sup> Department of Mechanical and Aeronautical Engineering, Clarkson University,  
Potsdam NY, 13699, USA**

# Outline

- **Applications**
- **Flow through Porous Media**
  - **Coarse Flow Cell**
  - **Viscous and Capillary Fingerings**
  - **Multiphase Flows**
  - **Micro-Flow Cell**
  - **Experimental Measurement**
  - **Numerical Modeling**
- **Conclusions**

# Applications

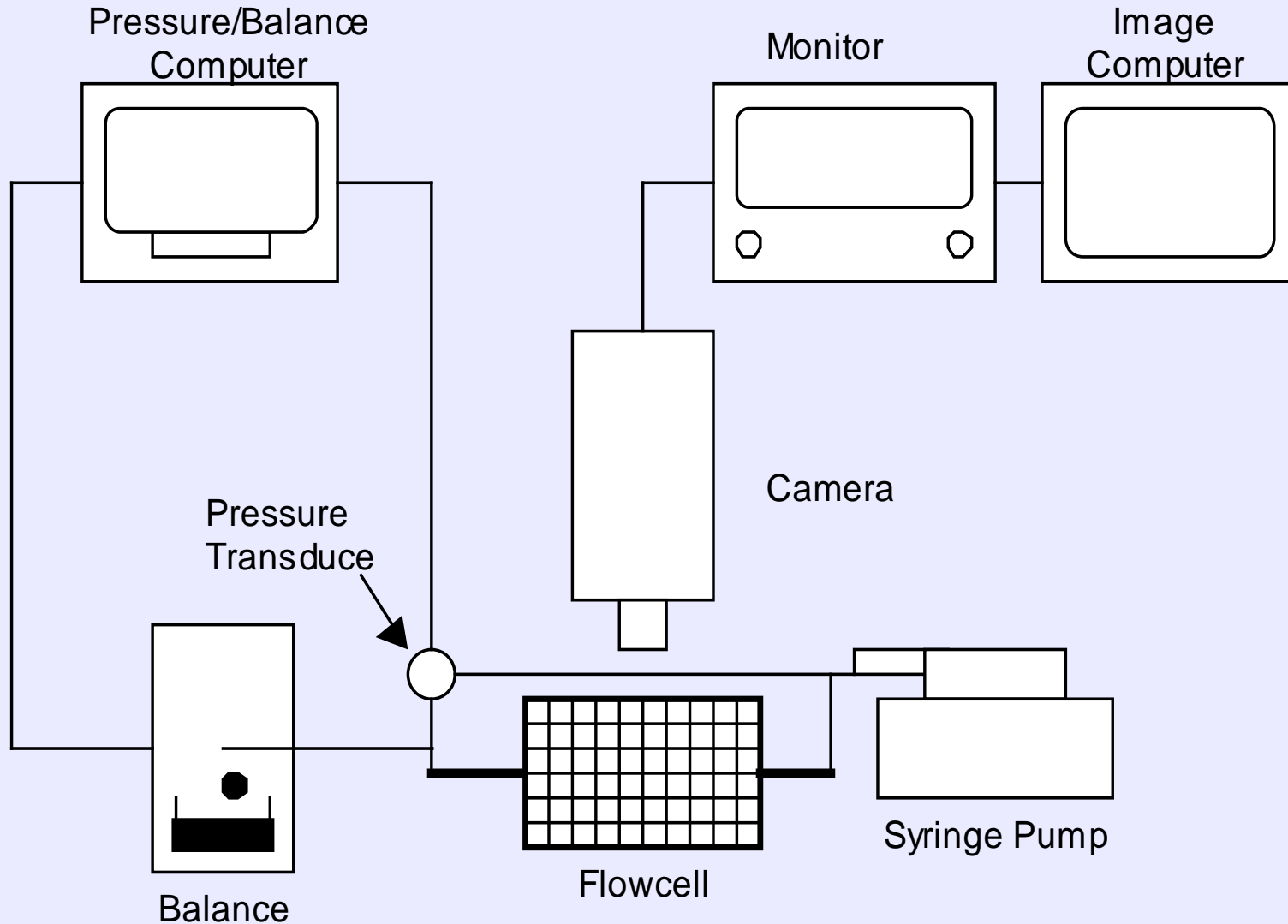
- **Enhanced Oil Recovery**
- **Reservoir Engineering**
- **Carbon Sequestration**
- **Fracking**
- **Subsurface Flows**

# Objectives

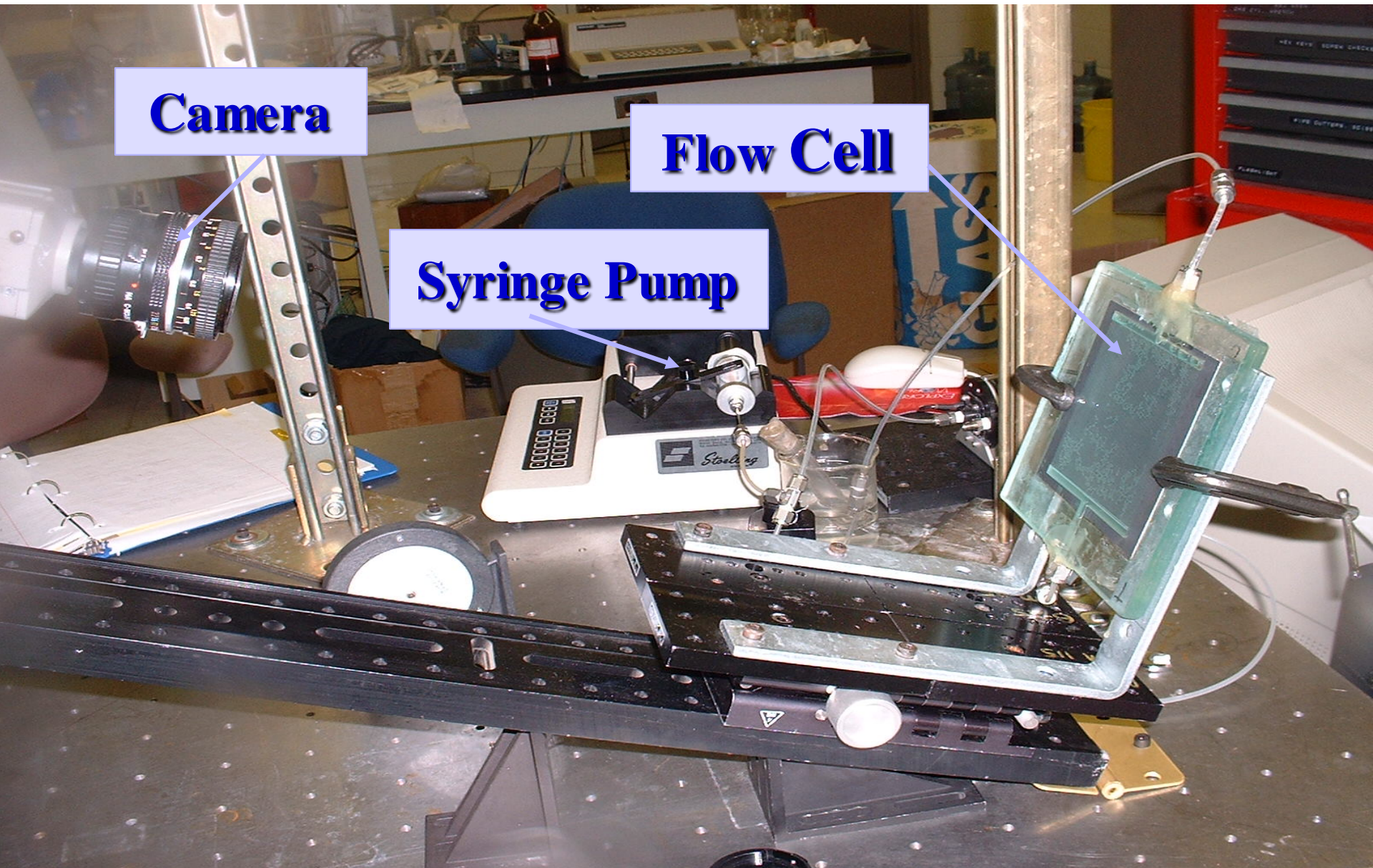
- **Develop a better understanding of subsurface single and multiphase flows**
- **Provide data in flow-cell**
- **Develop a computational model for simulations of flow in the cell**
- **Verify the computational model**
- **Provide guidelines for carbon sequestration**

- **Flow Cell Experiments**
  - **Experimental setup**
  - **Fractal Dimension**
  - **Residual Saturation**
  
- **Computer Simulations**
  - **VOF Model**

# Experimental Setup



# Experimental Setup

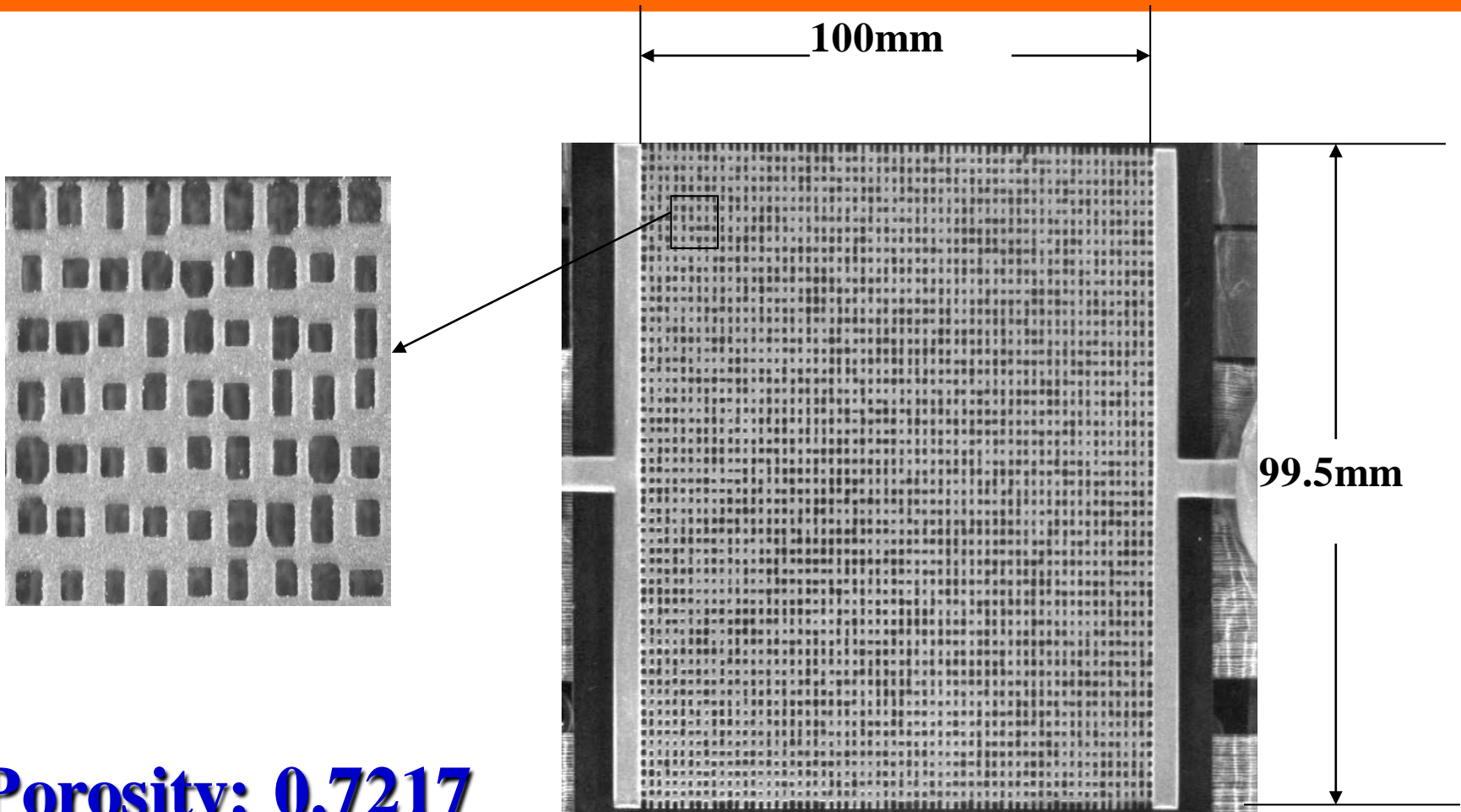


Camera

Flow Cell

Syringe Pump

# Glass Flow Cell

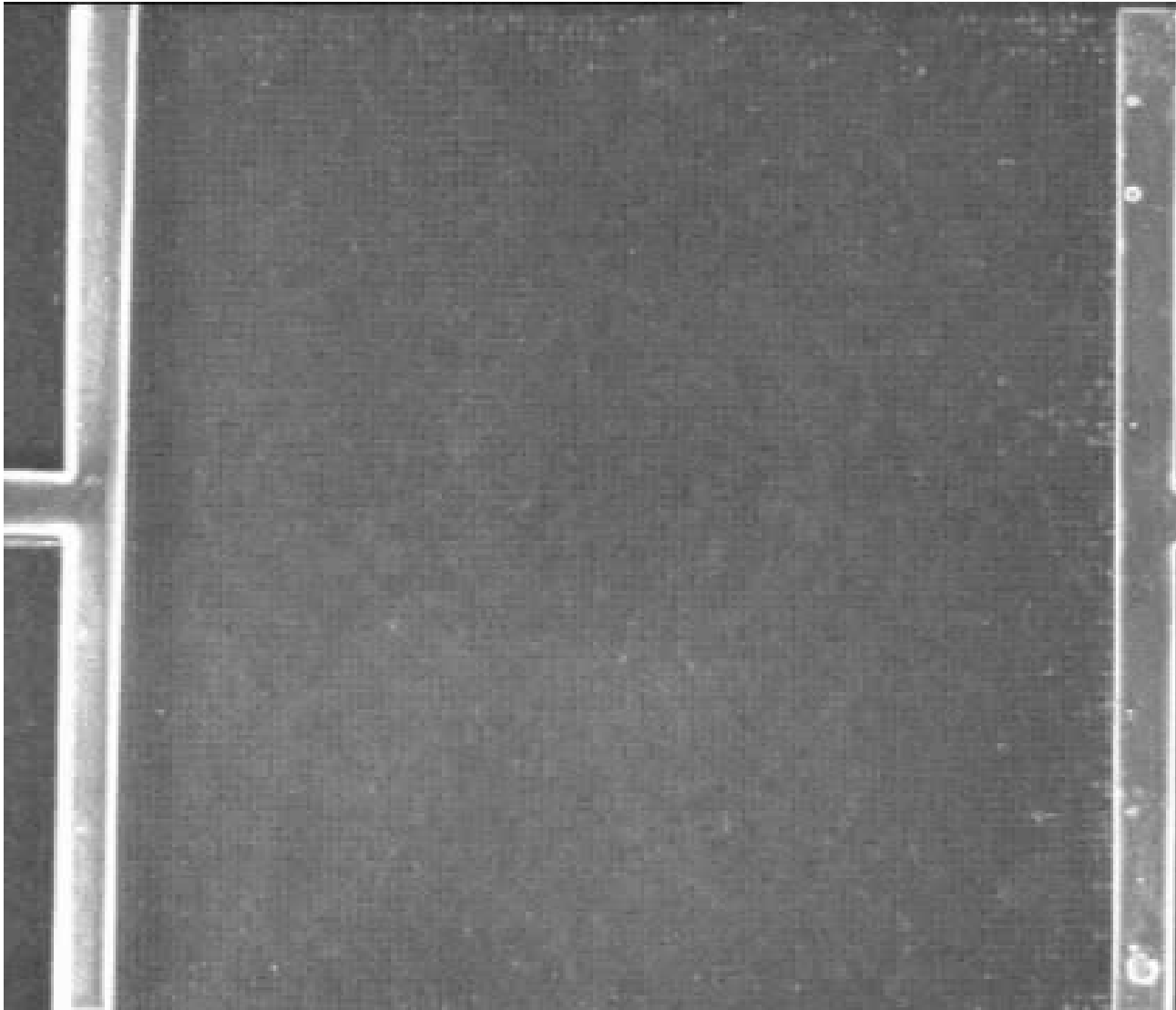


**Porosity: 0.7217**

**Average Channel Width: 0.41mm**

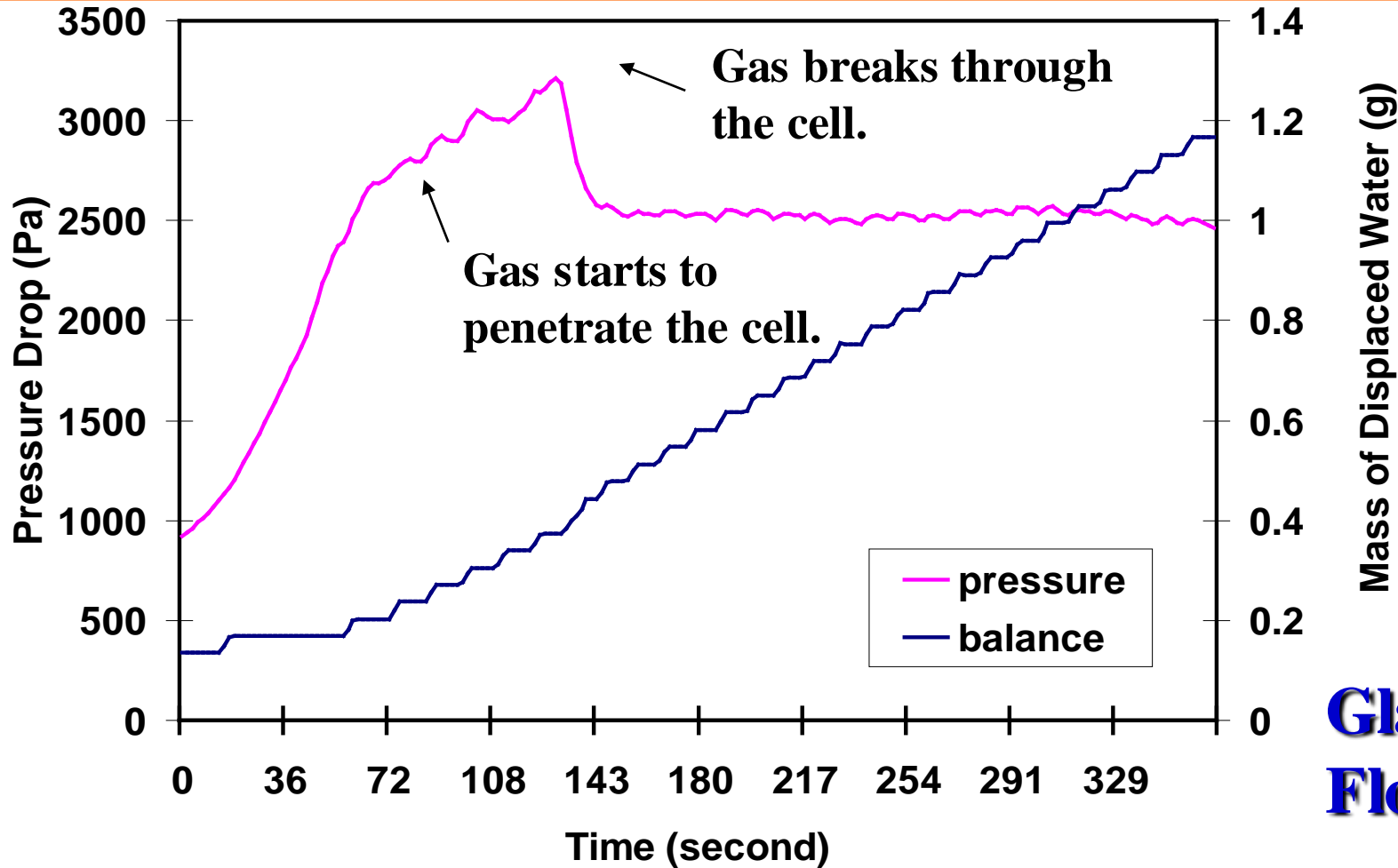
**Average Channel Depth: 0.12mm**

# Flow Pattern





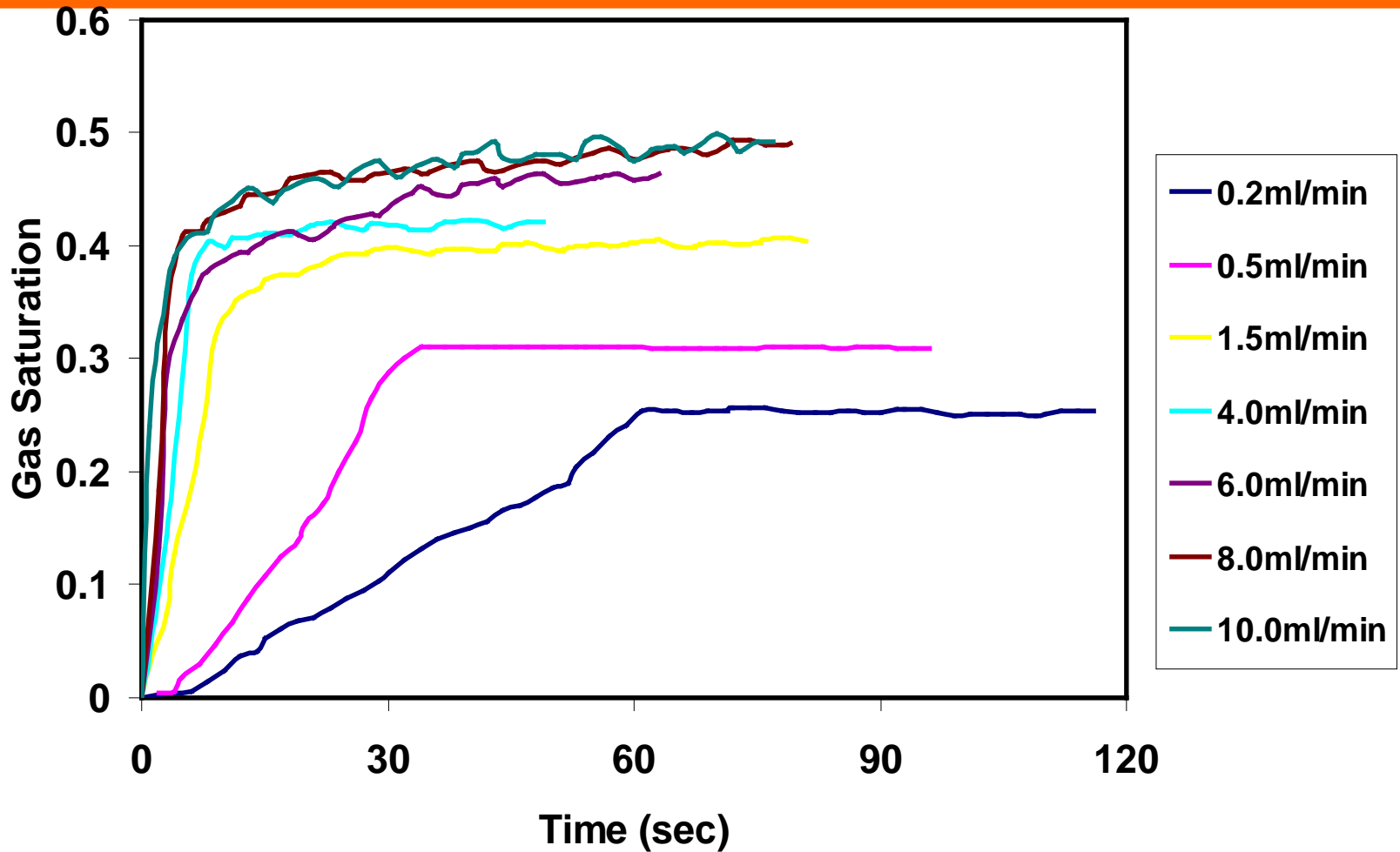
# Pressure Drop, Flow Rate



**Glass  
Flow Cell**

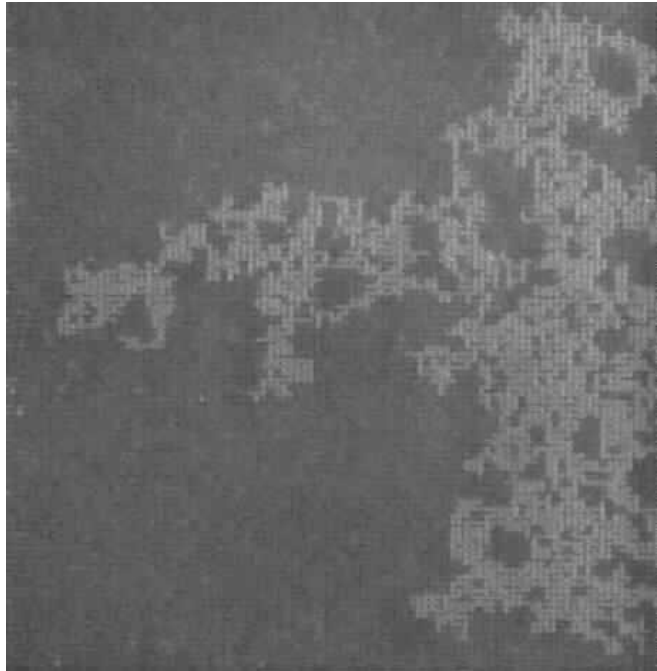
**Time variations of pressure drop along the flow cell and mass of displaced water for gas inject rate of 0.2ml/min.**

# Gas Saturation

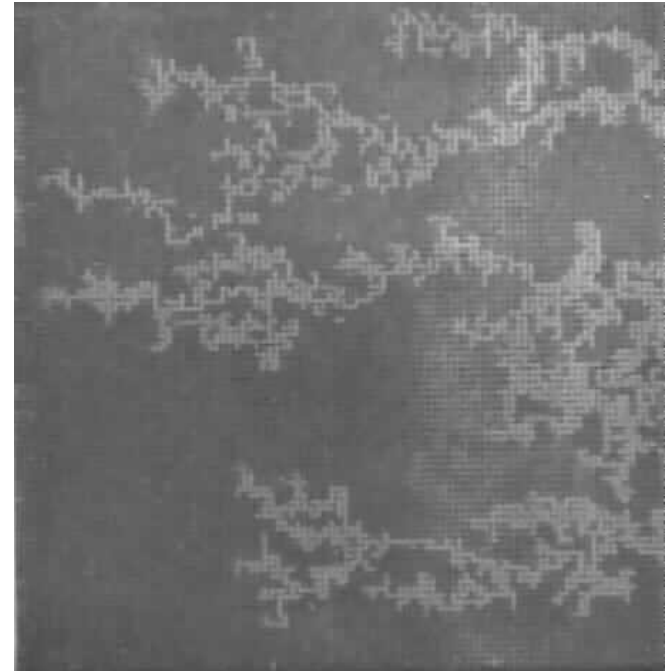


**Time variations of gas saturation when gas  
Displaces water at different flow rates.**

# Fractal Analysis



**Resemble IP  
(Inversion Percolation)**



**Resemble DLA  
(Diffusion-Limited Aggregation)**

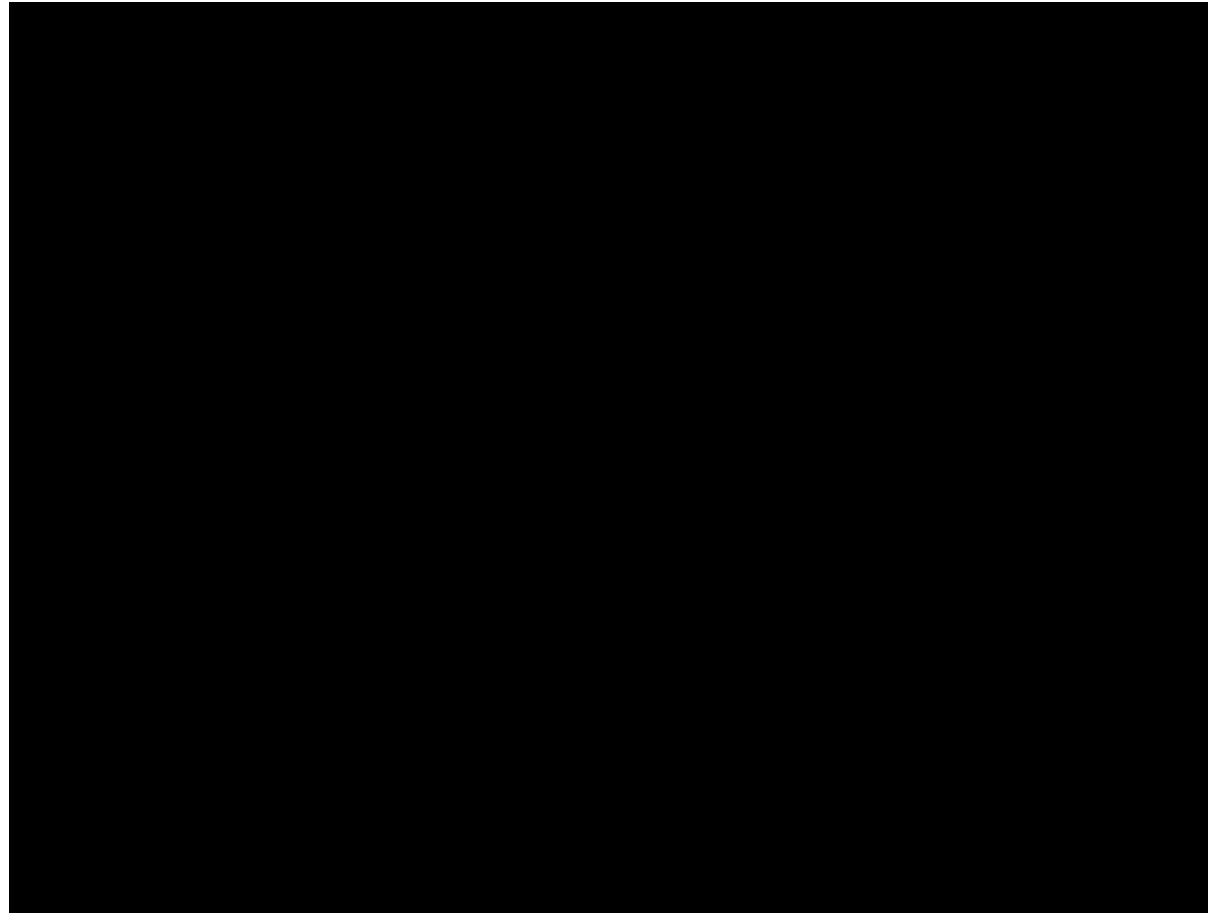
**Flow pattern observed in the experiment.**

# Experimental Study

**$Q = 10 \text{ ml/min}$**

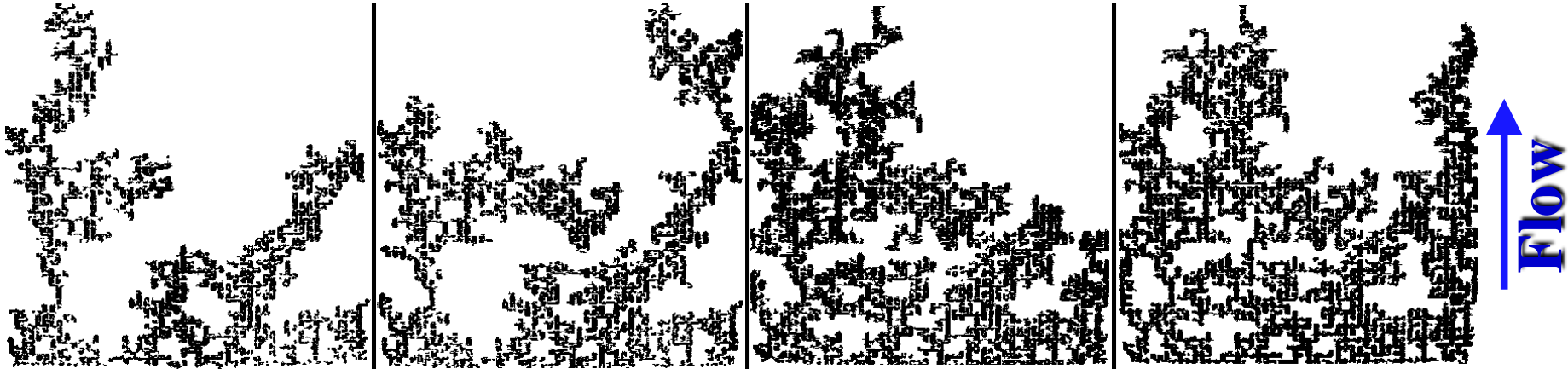
**Air - Water**

**SL Plastic  
Flow Cell**



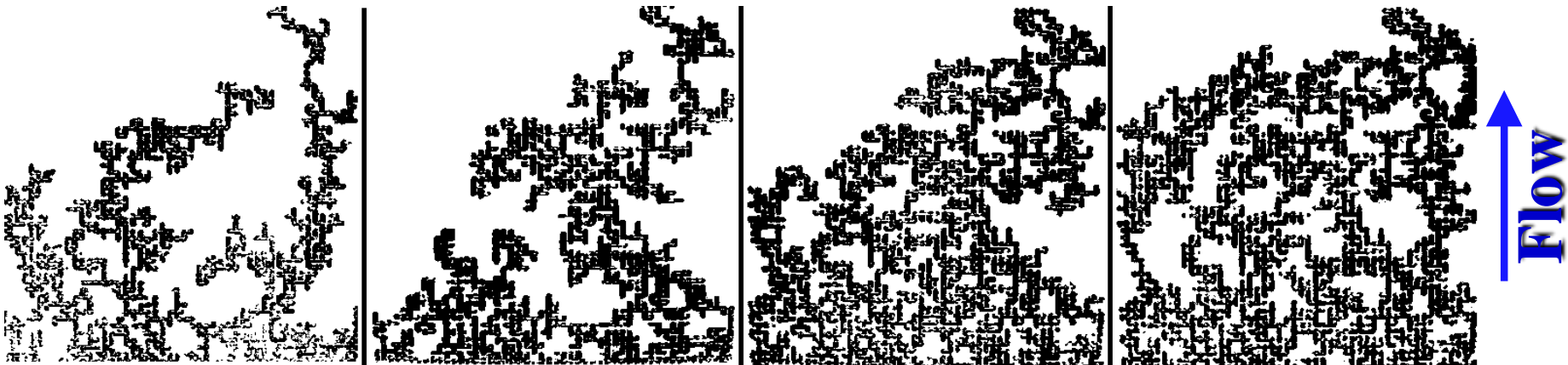
# Experimental Study

## ❖ Inlet Side 1

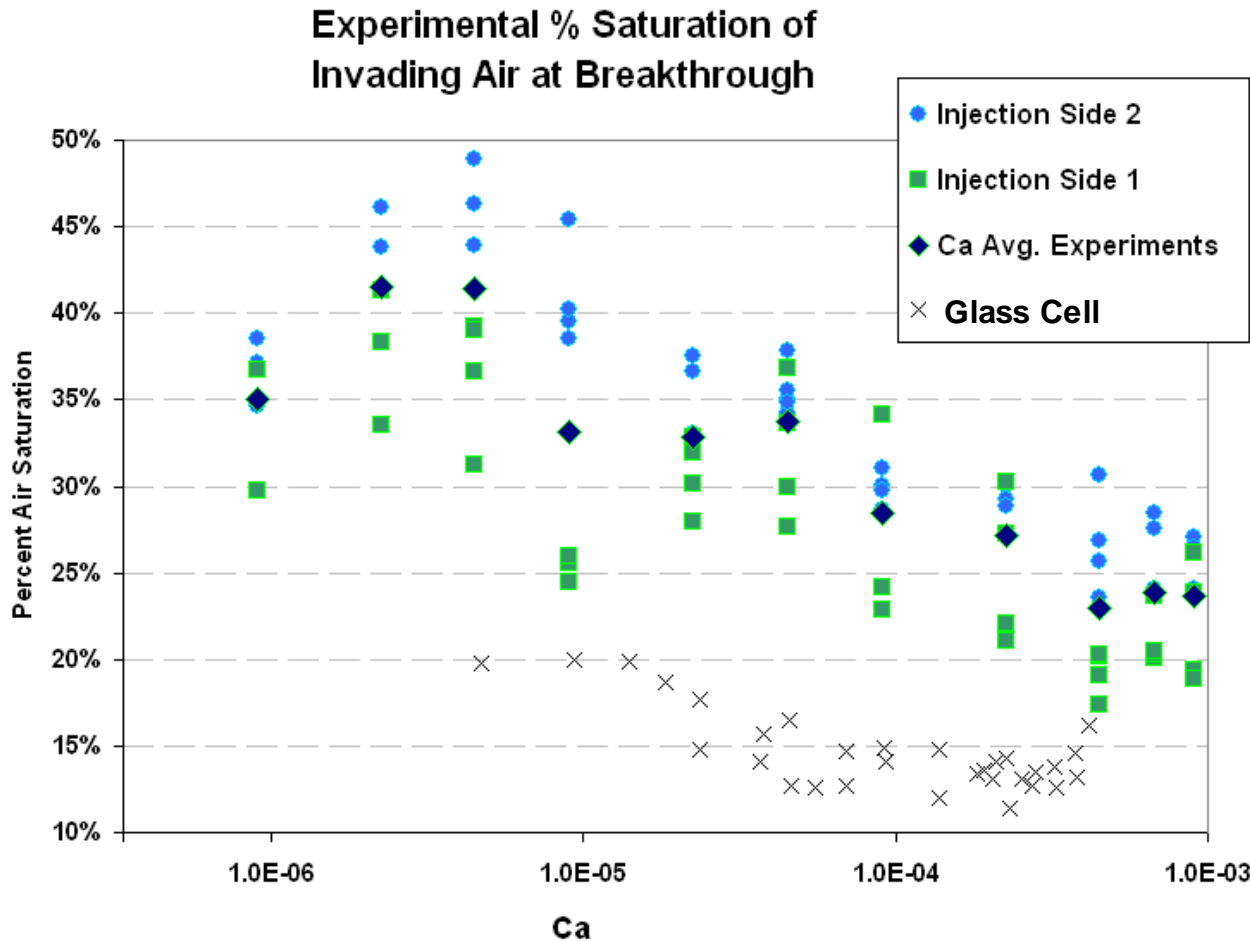


Decreasing Ca →

## ❖ Inlet Side 2

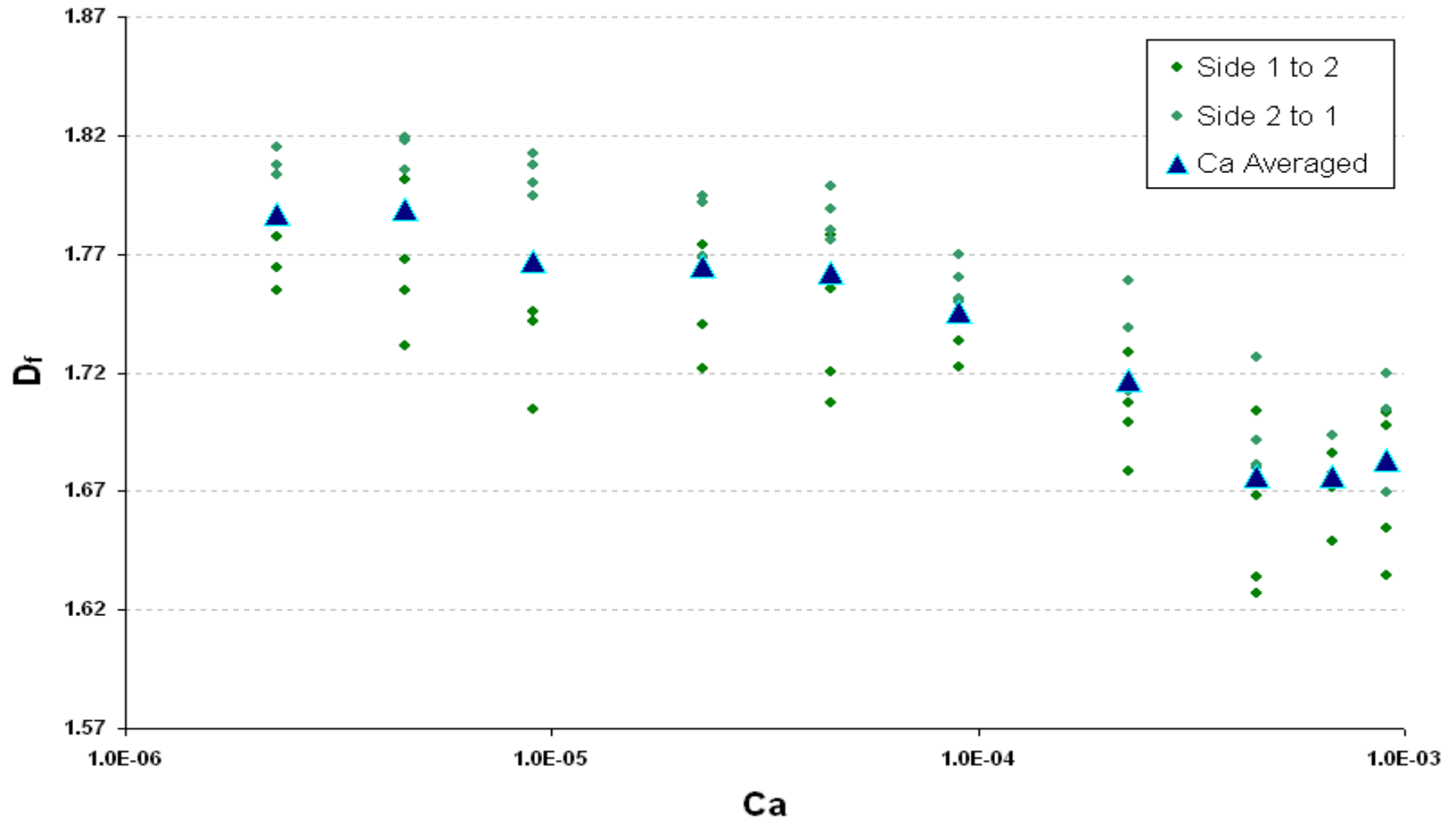


# Experimental Results



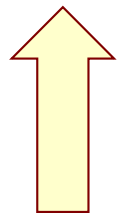
- **% Saturation of invading air increased with decreasing Ca**
- **% Saturation of invading air in new SL cell greater than corresponding % saturation in glass cell (glass-air-water has a  $\theta \sim 0^\circ$ )**

# Fractal Dimensions

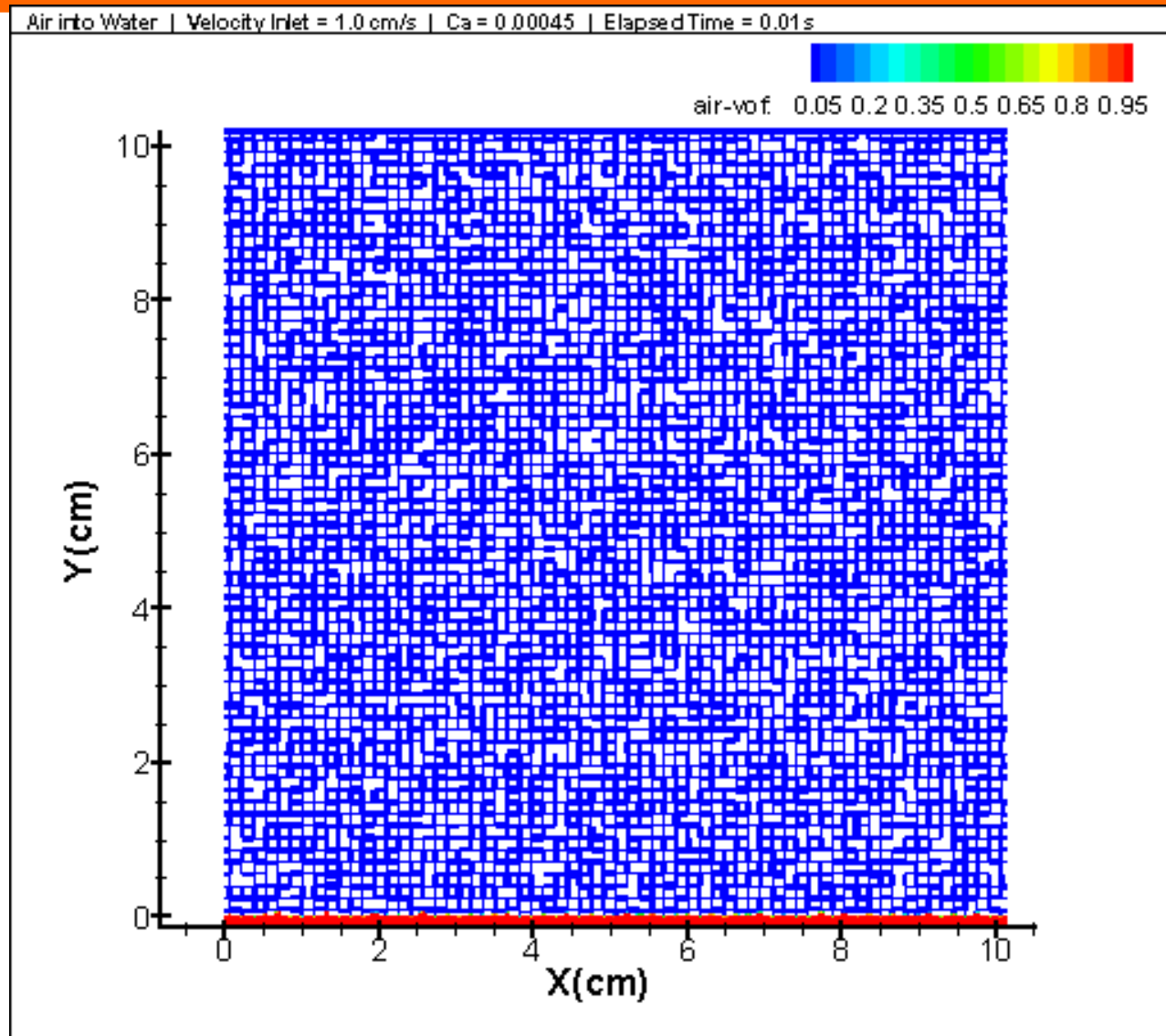


# Drainage: Air into Water

Water



Air



# Drainage: Air into Water

- Air invasion into water saturated flow cell

$$M = \mu_{\text{inv}} / \mu_{\text{def}} = 0.018$$

$$\sigma = 72 \text{ dyns/cm}$$

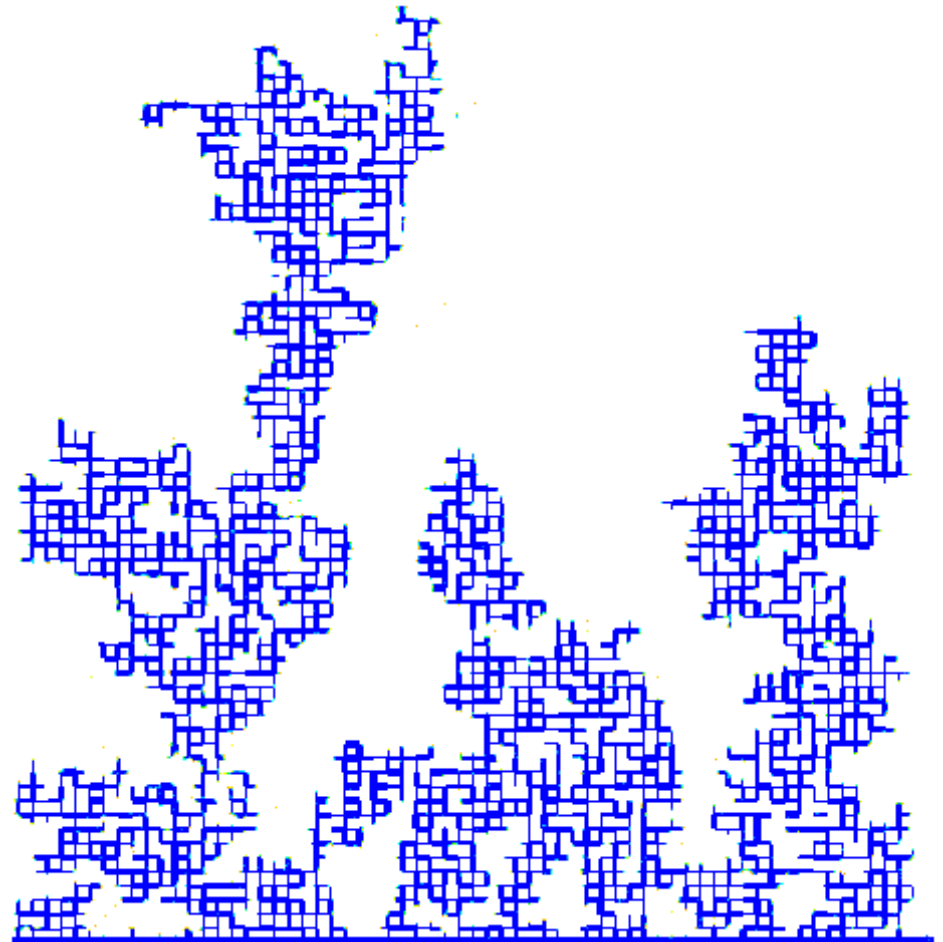
$$\theta = 72^\circ$$

(Stereolithography)

$$Ca = 4.5 \times 10^{-4}$$

- Sat = 23.2 %

- Good agreement with experiment

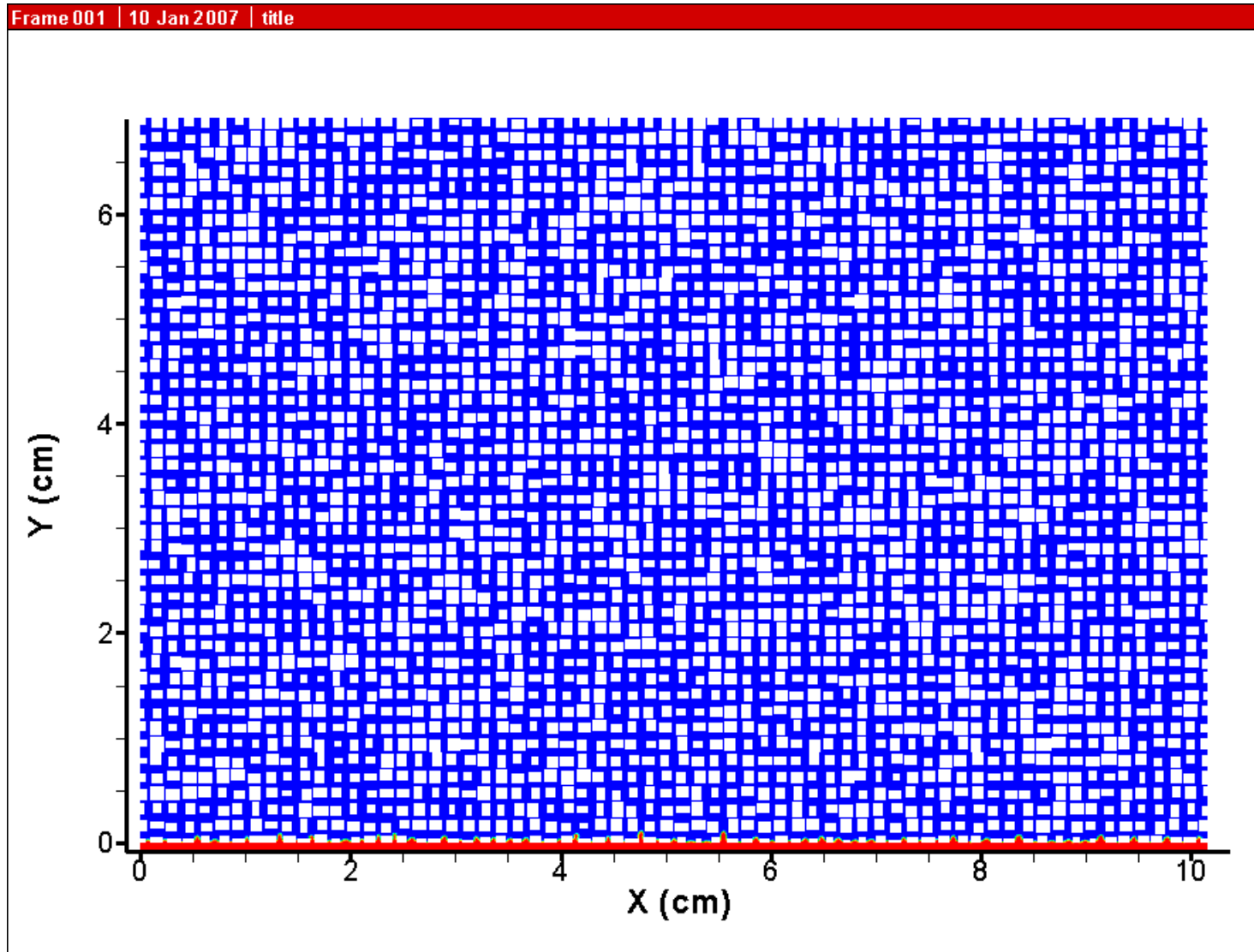


# Drainage

Water



Air



# Drainage: Air into Oil

- Air invasion into the oil saturated flow cell

$$M = \mu_{inv} / \mu_{def} = 1.7 \times 10^{-5}$$

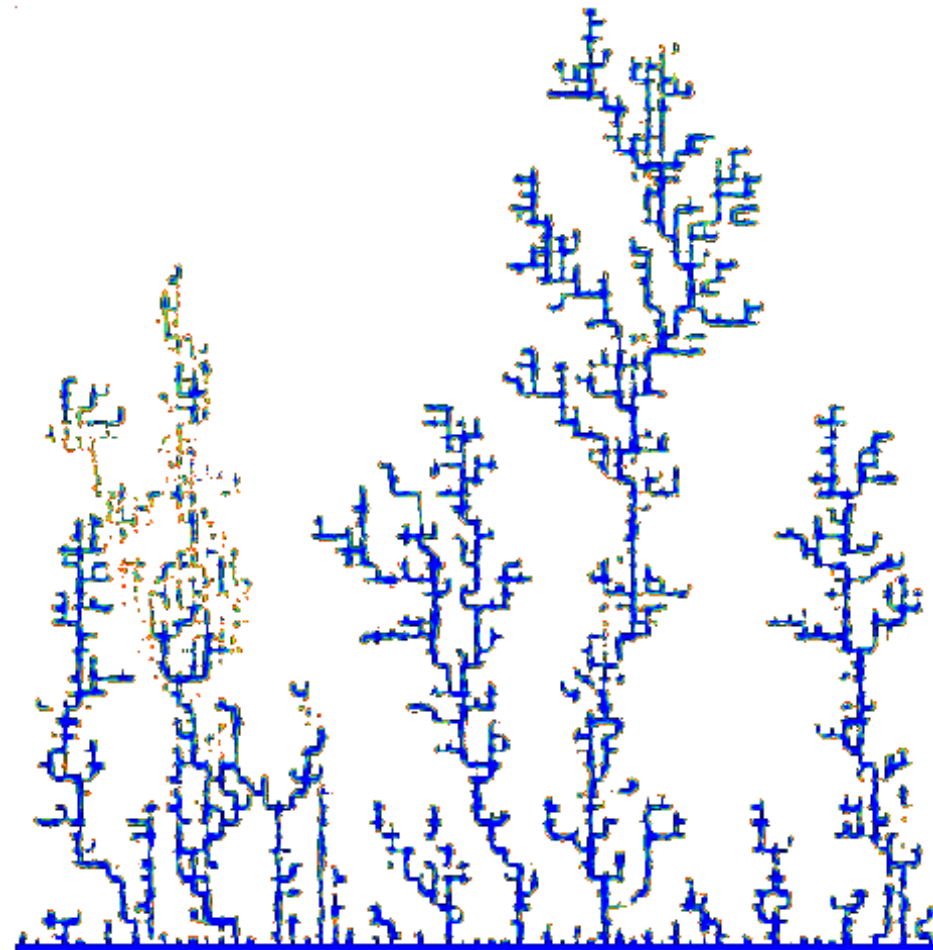
$$\sigma = 35 \text{ dyns/cm}$$

$$\theta = 72^\circ$$

$$Ca = 0.98$$

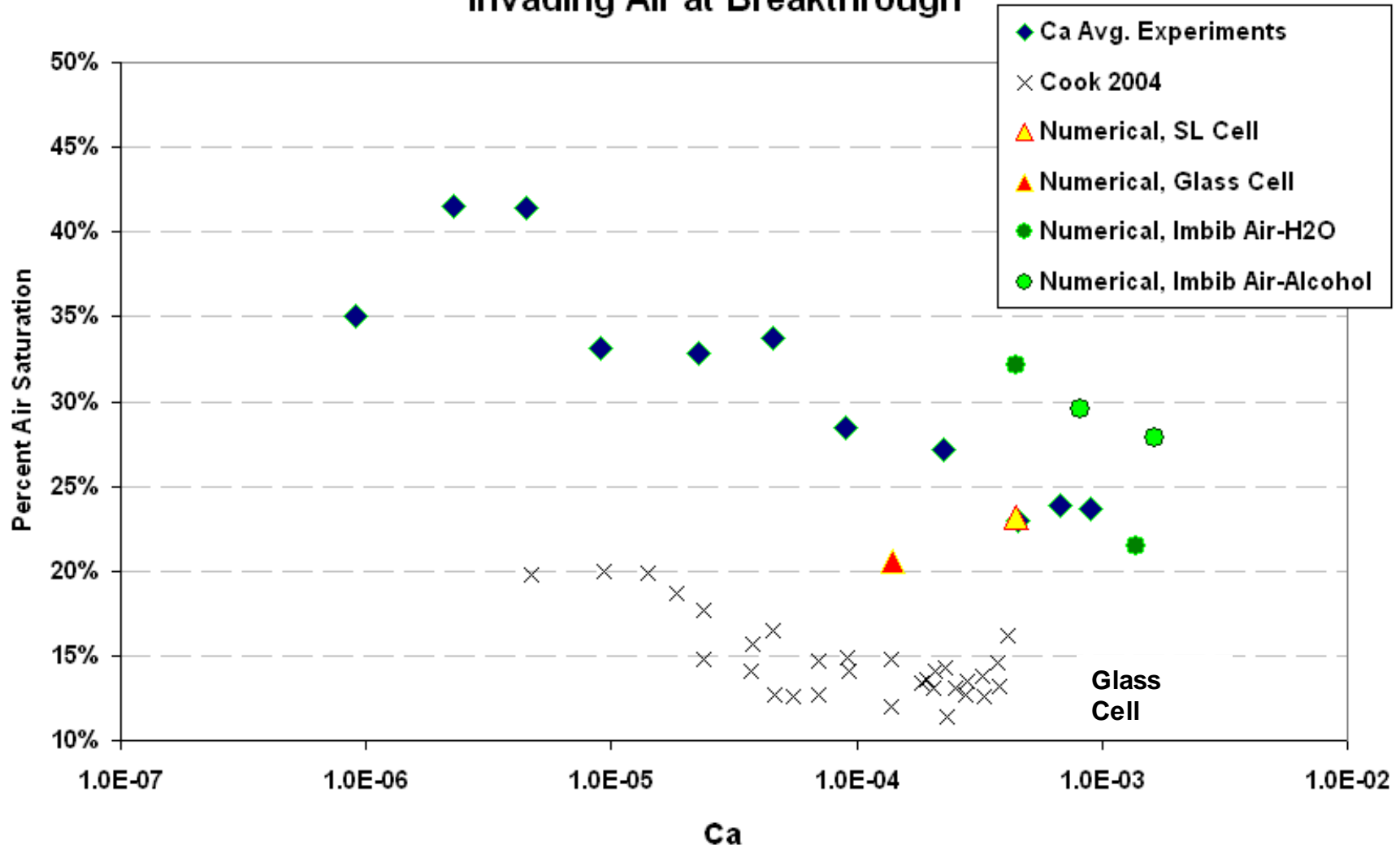
- Sat = 10.1 %

- Similar to enhanced oil recovery

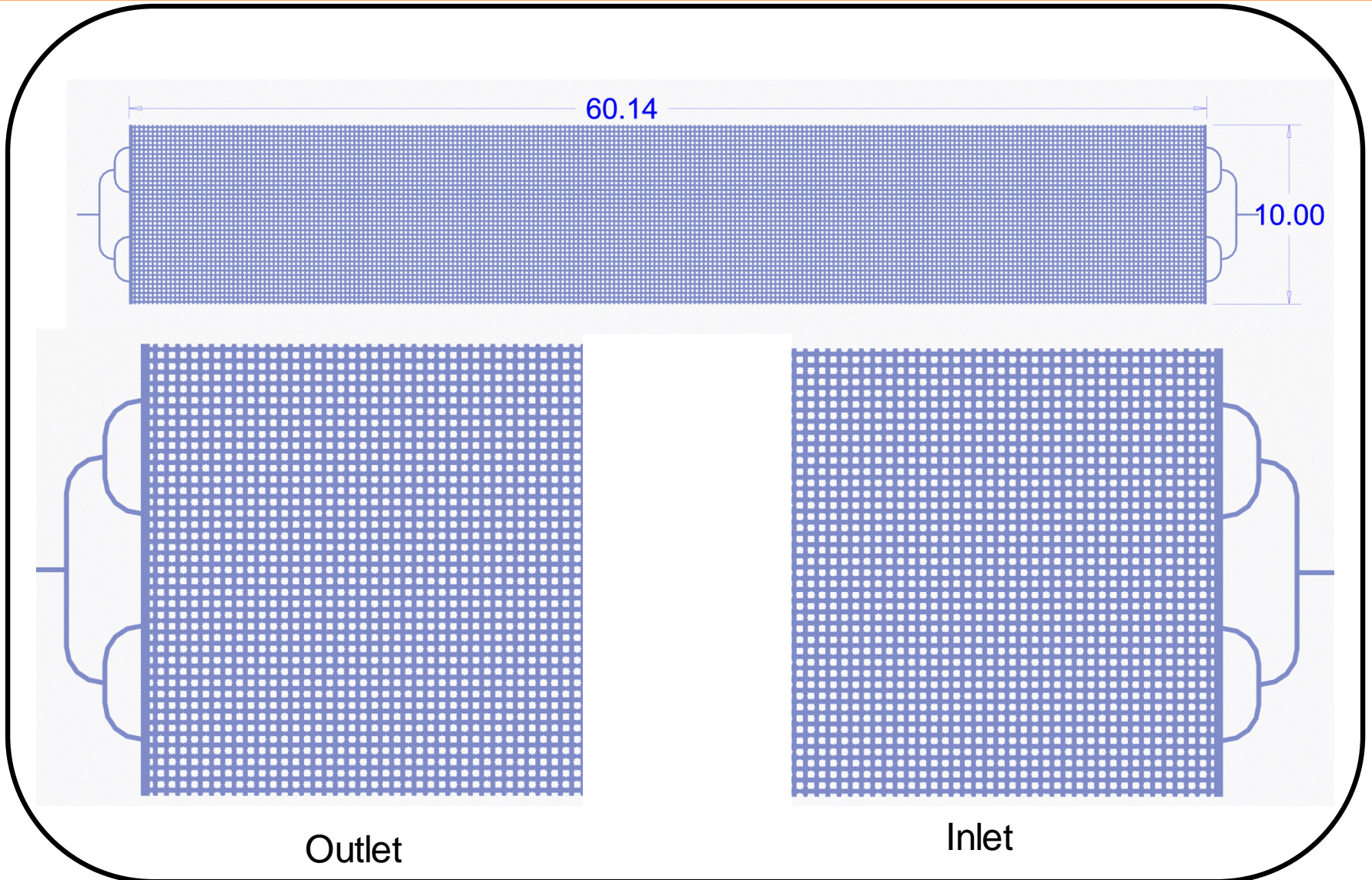


# Saturation

Experimental % Saturation of  
Invading Air at Breakthrough

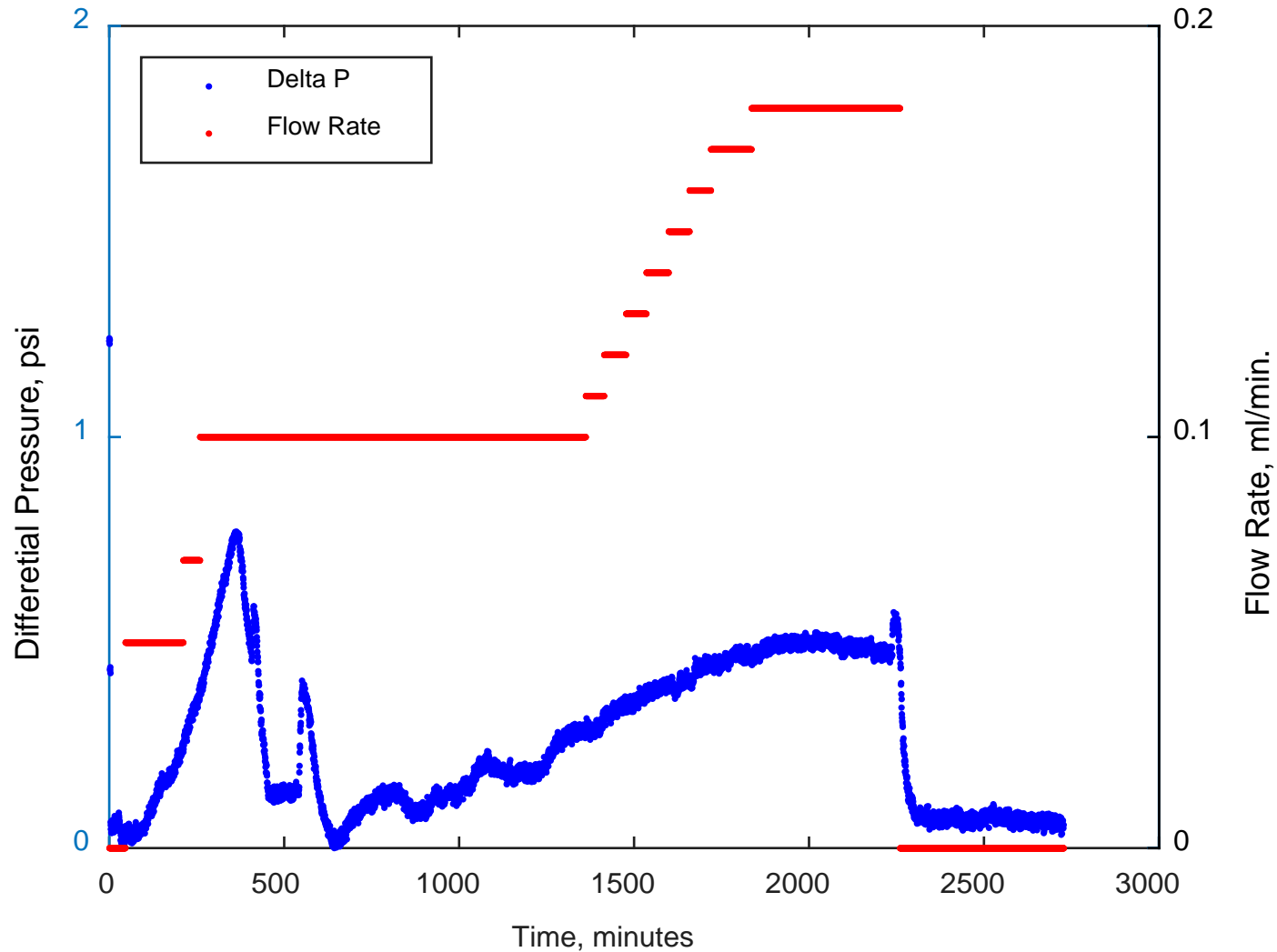


# Micro-Cell Geometry





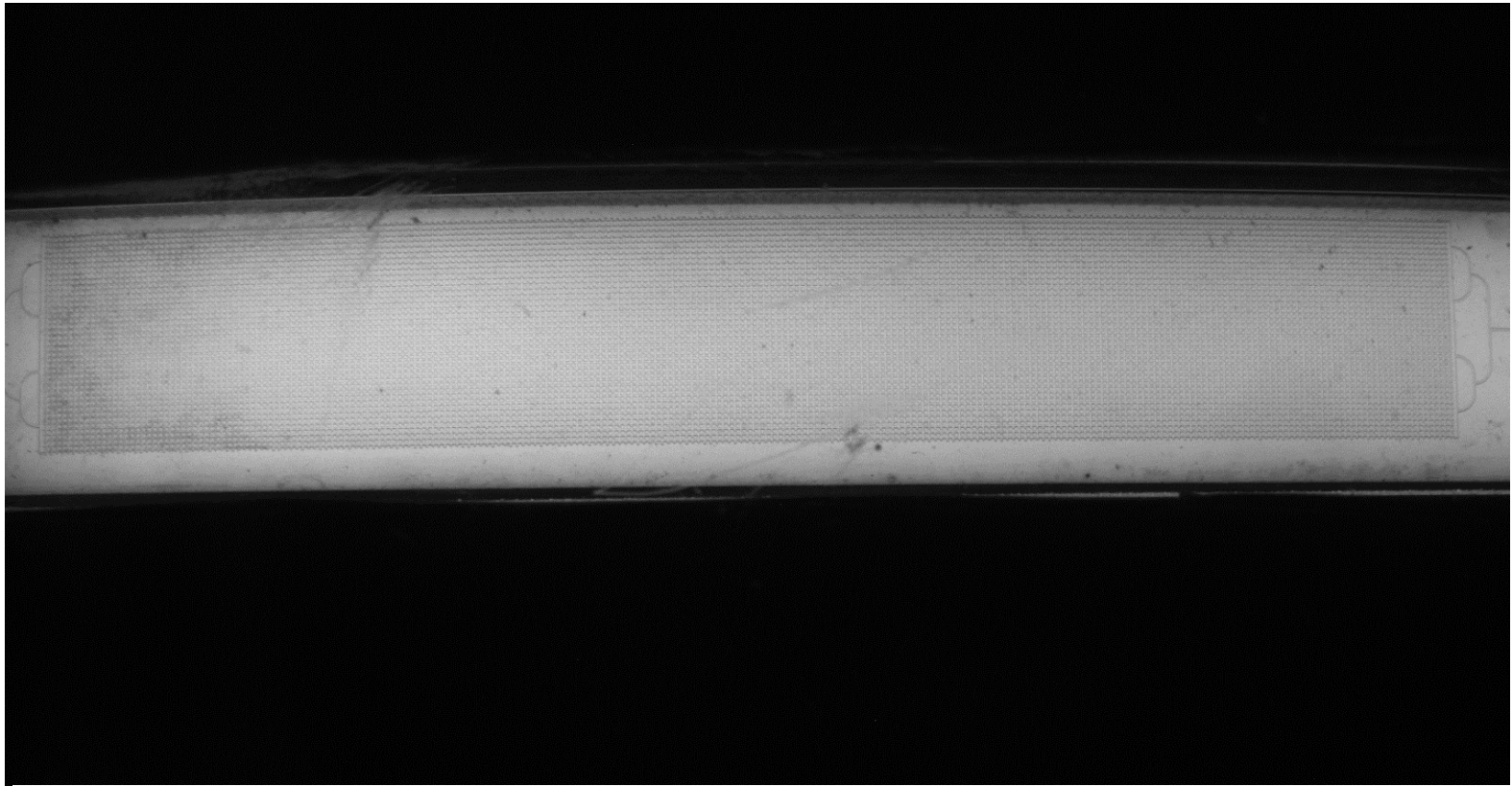
# Experimental Study



# Experimental Study

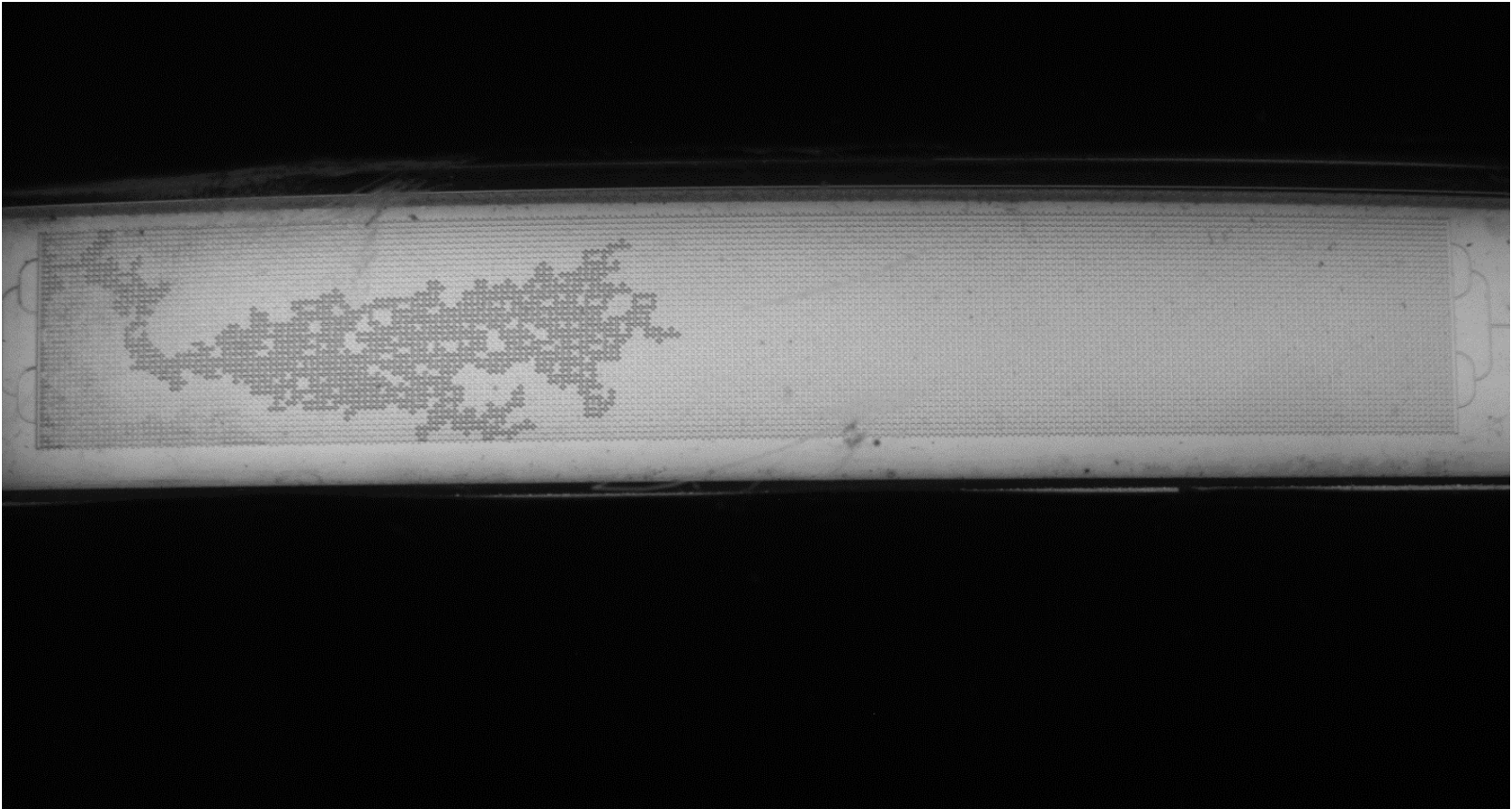
---

# Experimental Study



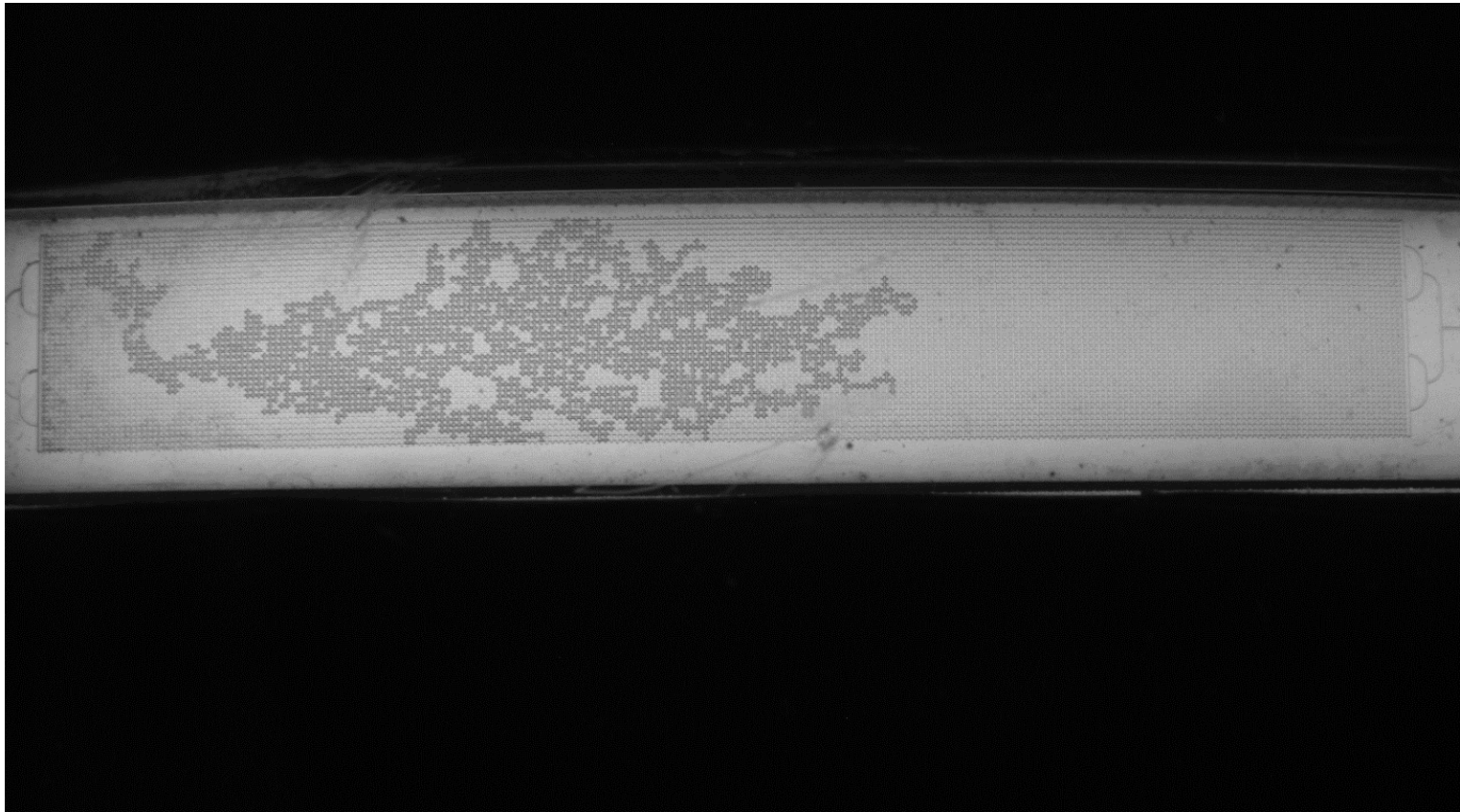
**CO<sub>2</sub> Injection, 0.1 ml/min, DP=0.7523 psi, t=351.6 min.**

# Phase 2, invasion-1



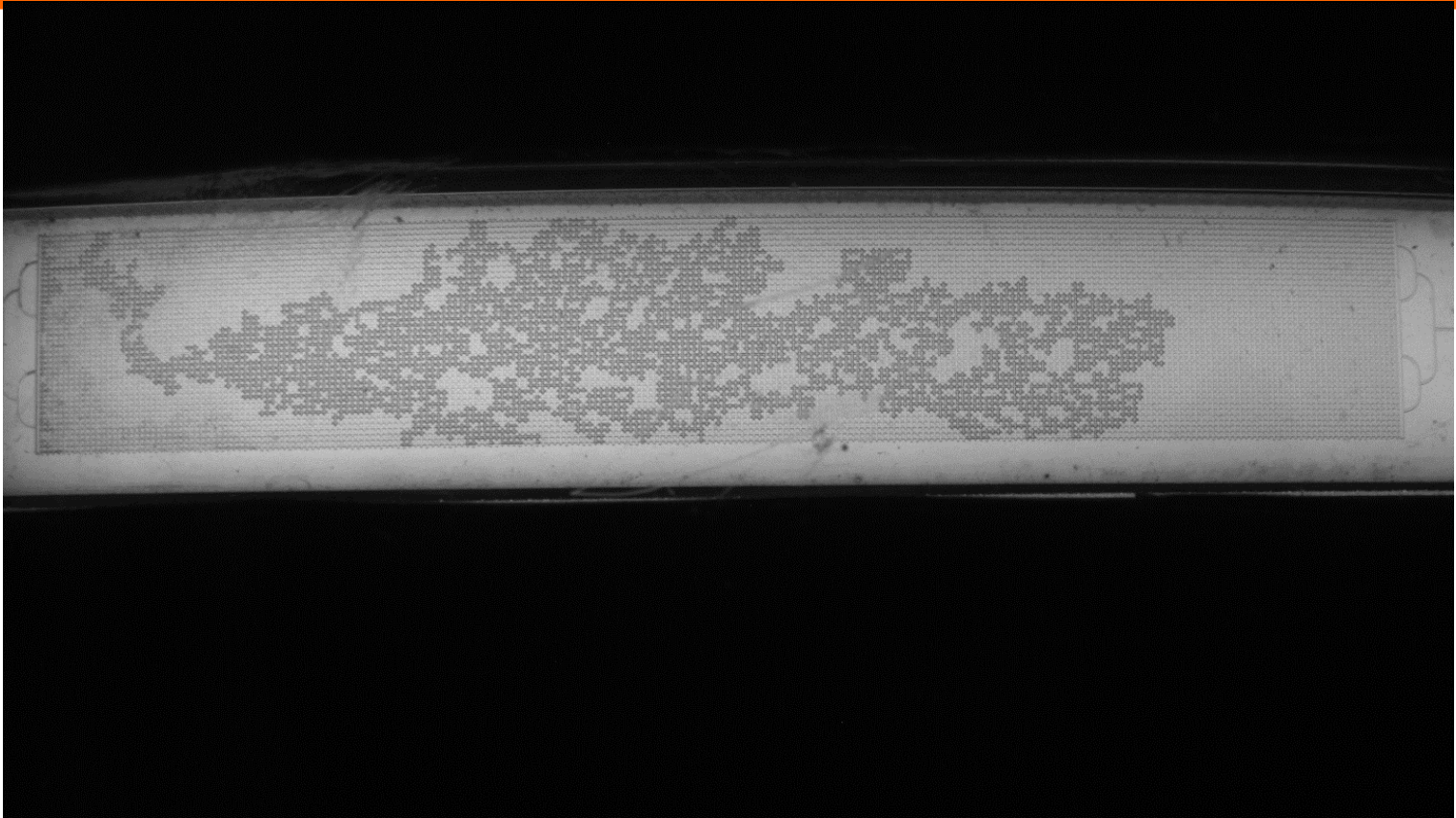
**CO2 Injection, 0.1ml/min, DP=0.757psi, t=356.1min.**

# Phase 2, invasion-2



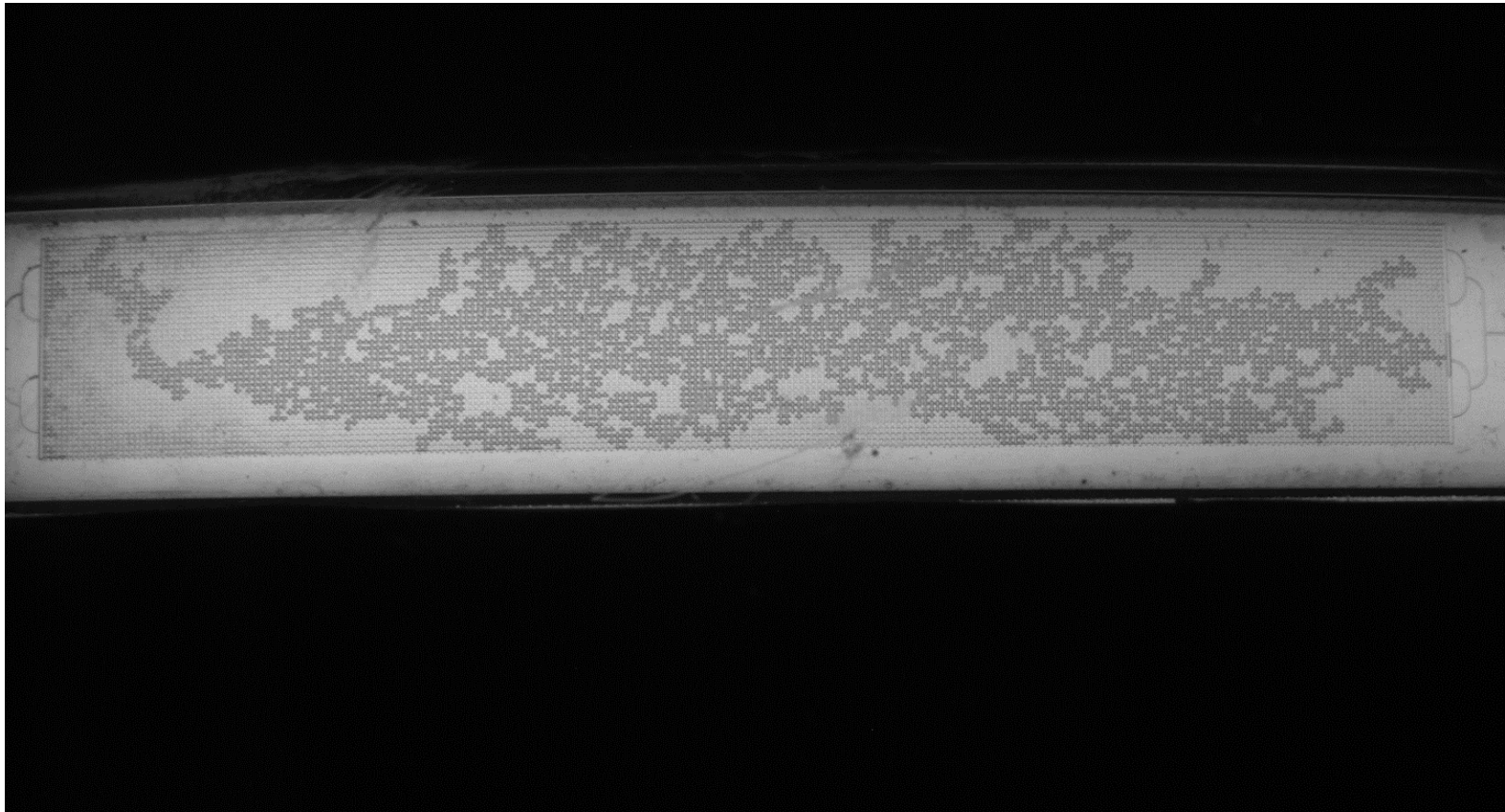
**CO2 Injection, 0.1 ml/min, DP=0.76 psi, t=356.3 min.**

# Phase 2, invasion-3



**CO2 Injection, 0.1 ml/min, DP=0.76 psi, t=357.1 min.**

# Last shot before breakthrough



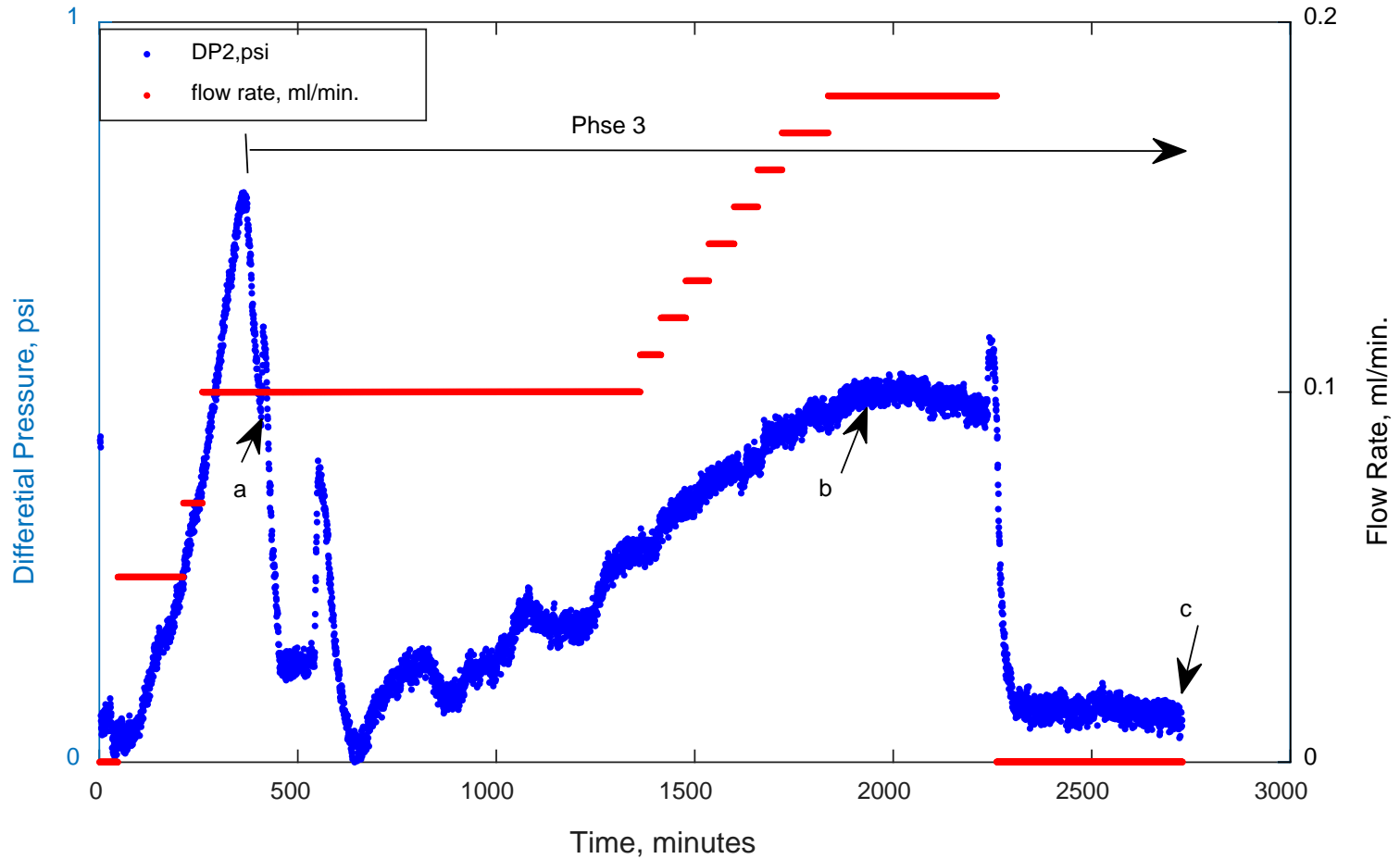
CO<sub>2</sub> Injection, 0.1 ml/min, DP=0.763 psi, t=357.85 min.

# breakthrough-end phase 2



CO2 Injection, 0.1 ml/min, DP=0.748psi, t=357.86min.

# Experimental Study



# Experimental Study

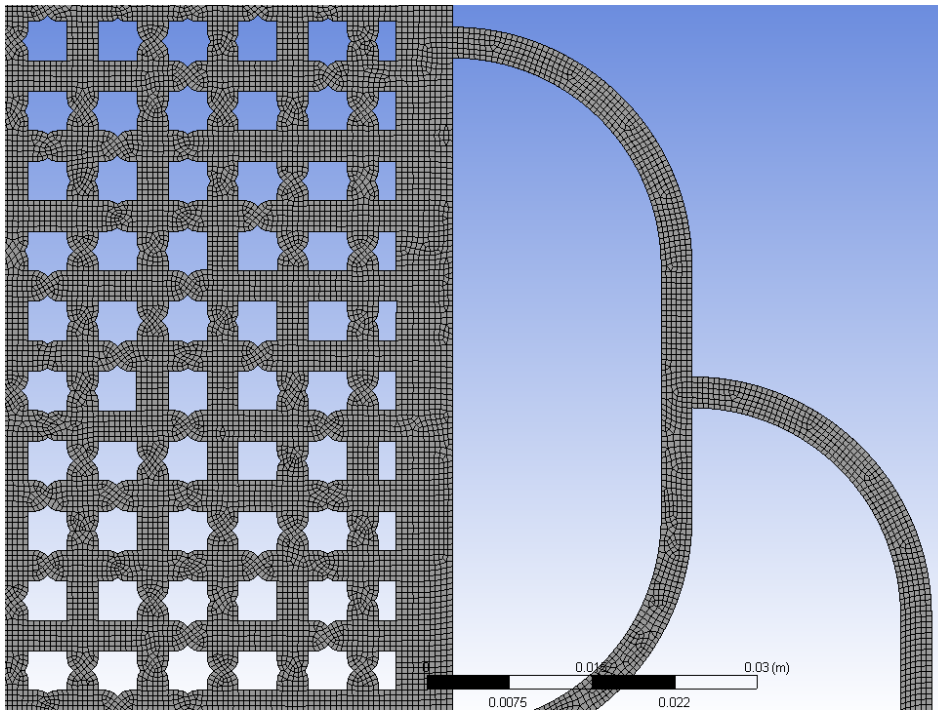
Dear Dr. Wu :

Please edit and revise the experimental part. I have used the report that you give me on the tests that was done in November 2015.

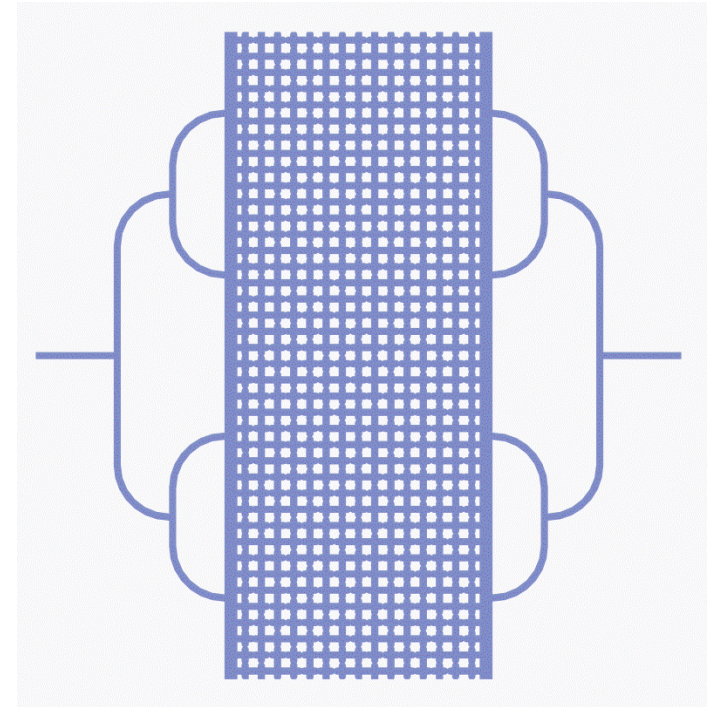
Thanks

Goodarz

# Small Scale Model

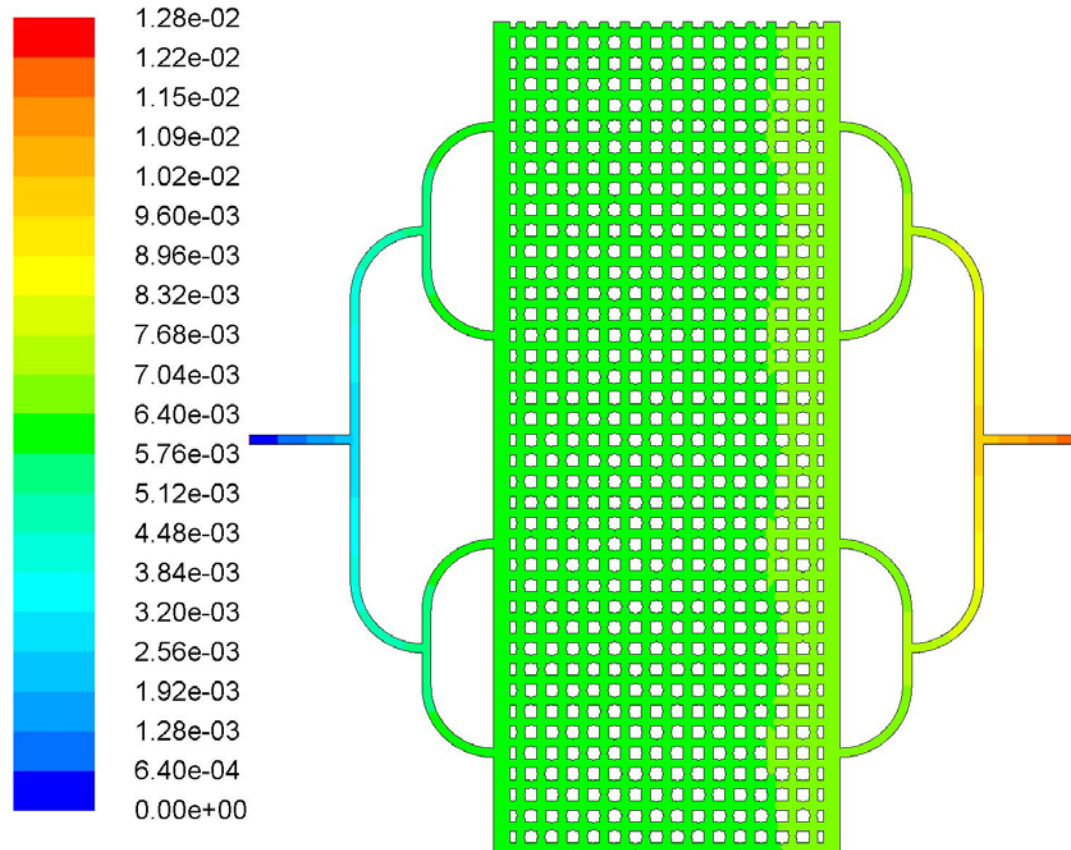


100,000 computational Cells

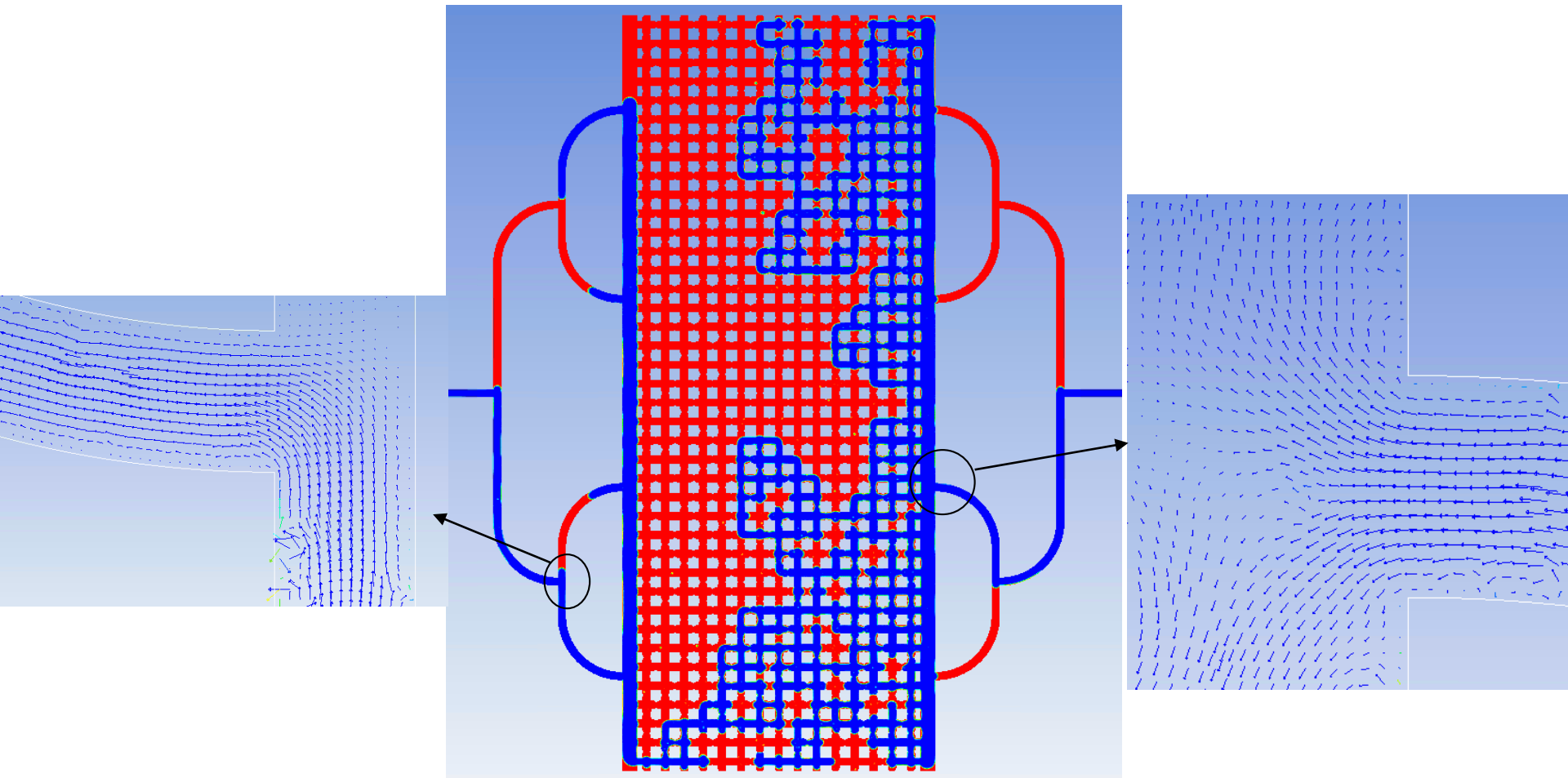


5 Units in Y-direction  
&  
2 Units in X-direction

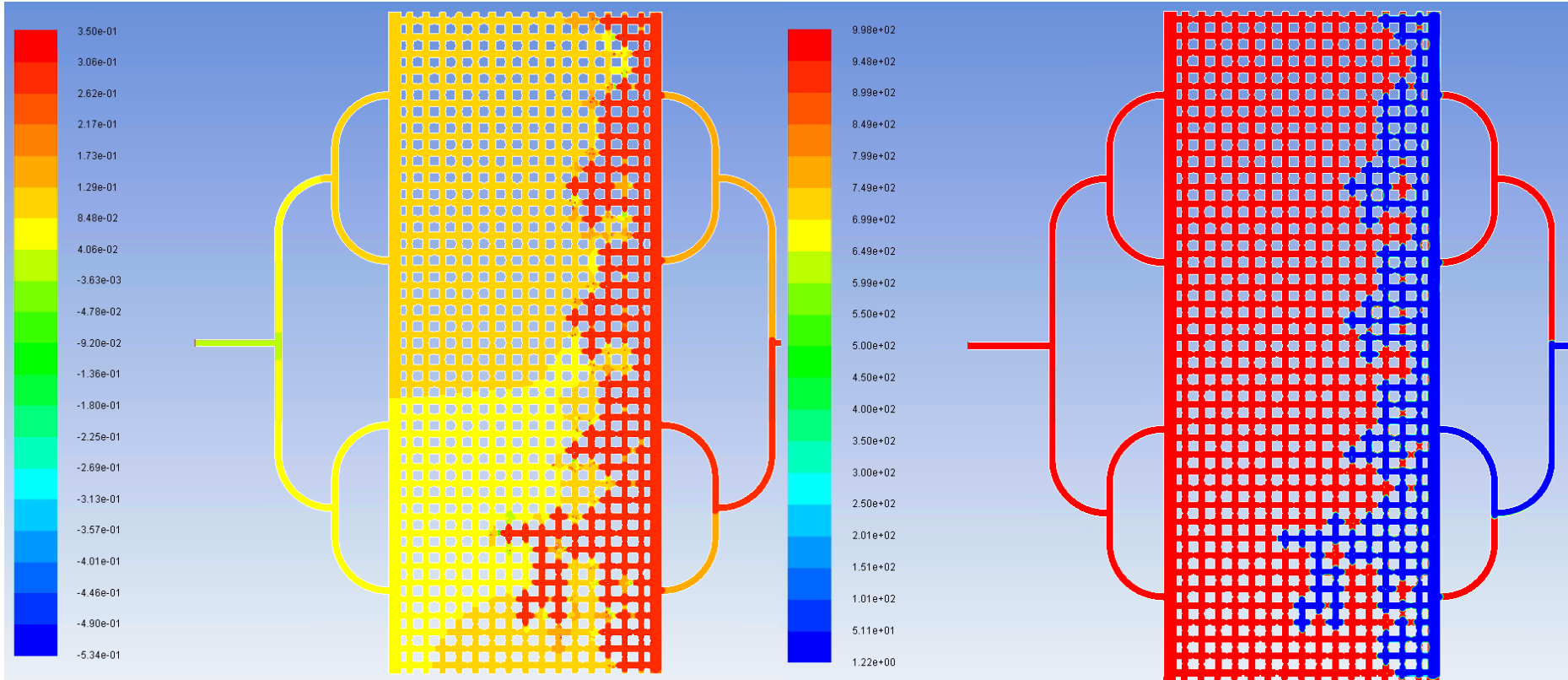
# Static Pressure



# Air Injection into Water Small Flow Cell Model



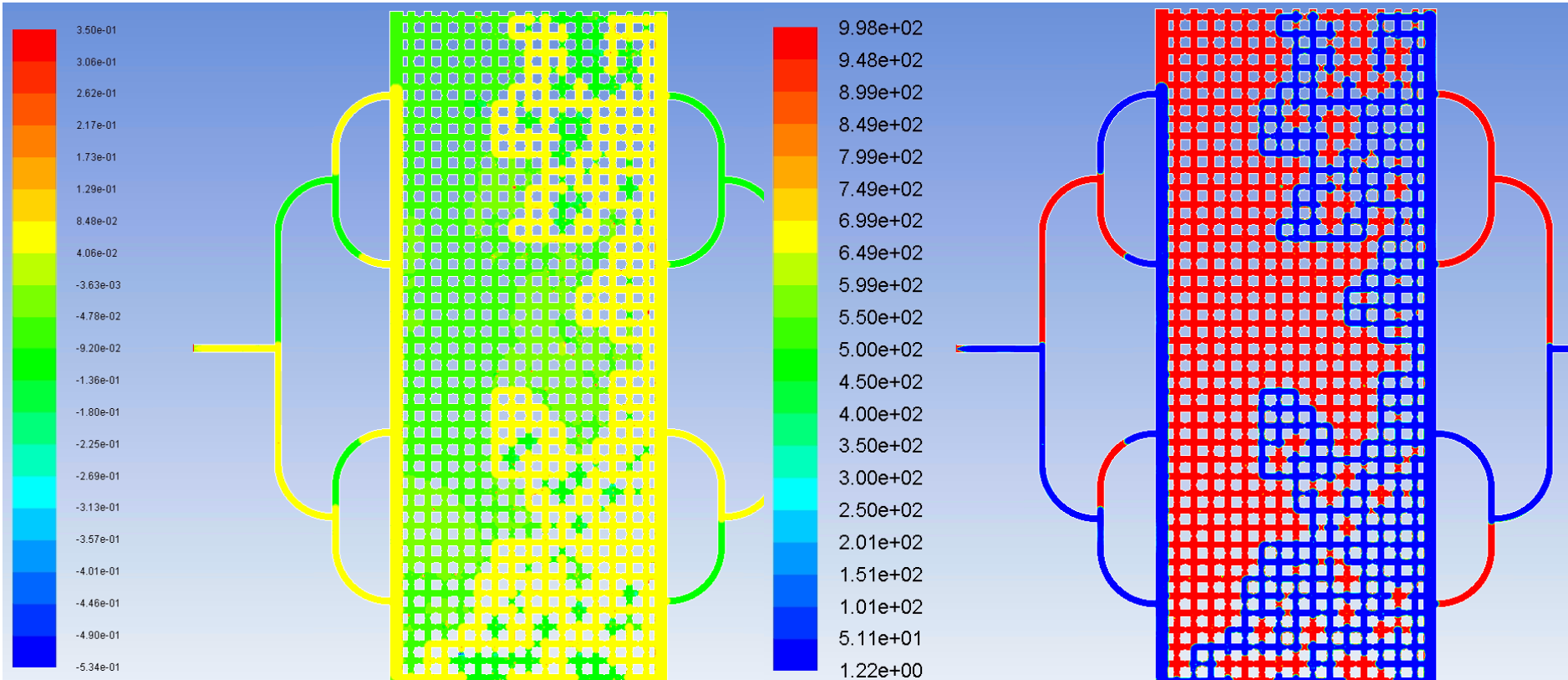
# Static Pressure and Density



Pressure Contour

Density Contour

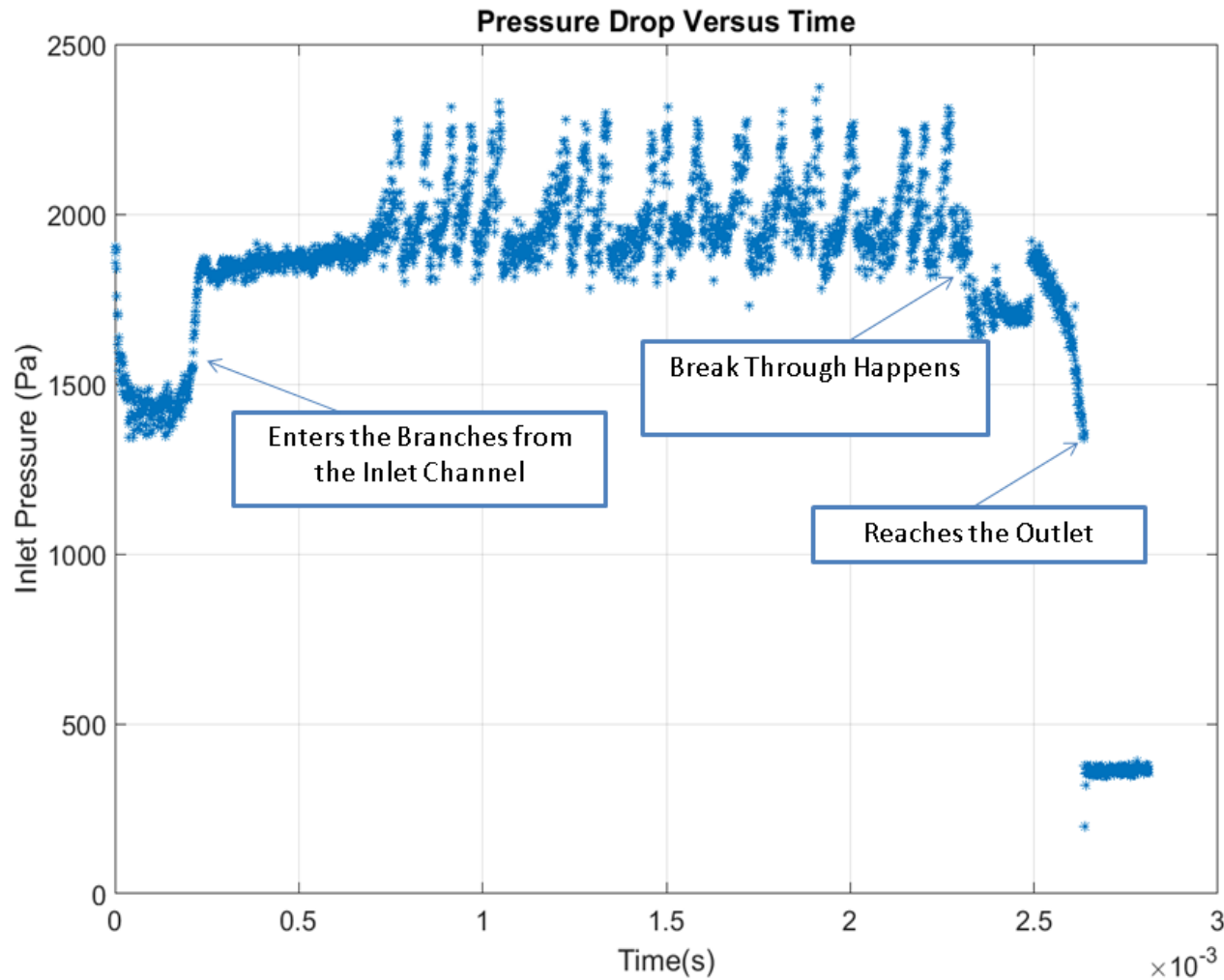
# Static Pressure and Density



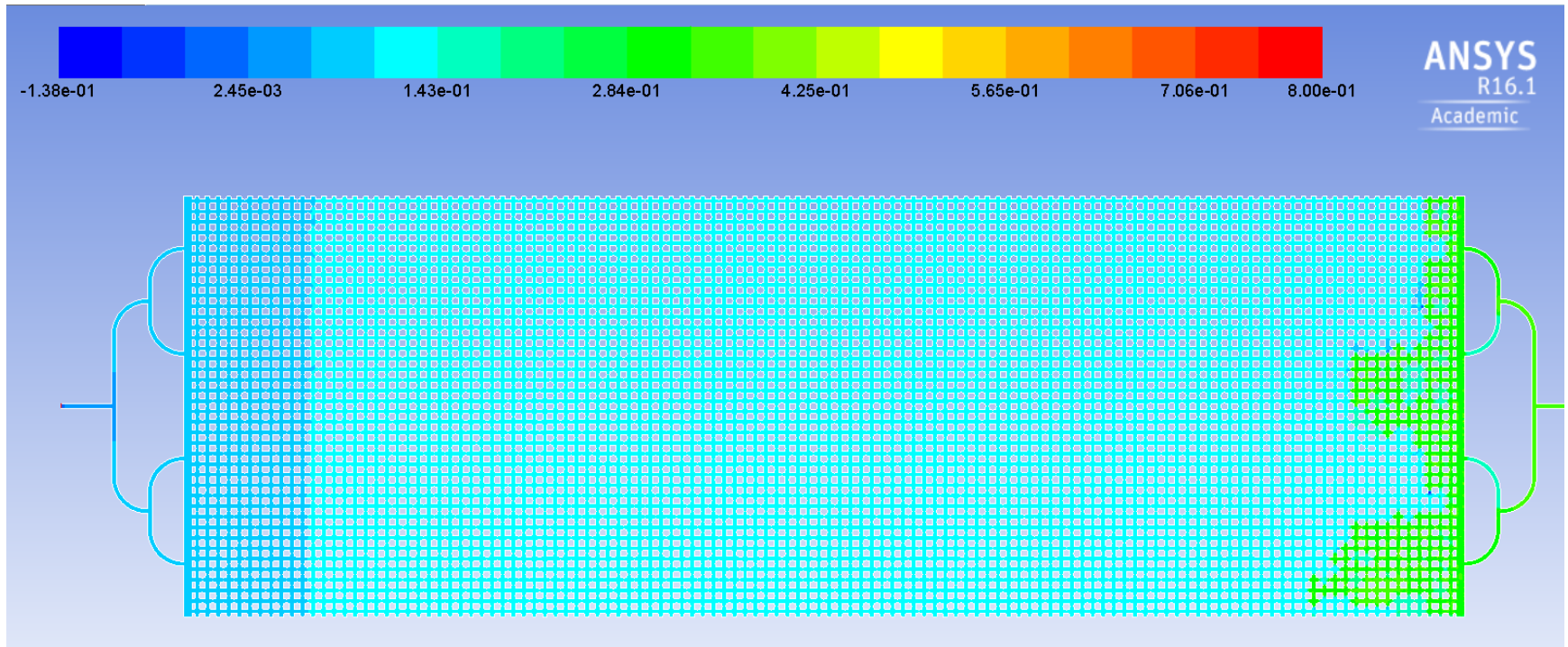
Pressure Contour

Density Contour

# Pressure Drop in Small Flow Cell



# Pressure Contours



# Conclusions

- **The gas-liquid flow in both coarse and micro-cells are fractal.**
- **Fractal dimensions varies with capillary number.**
- **VOF computational model could predict the behavior of the gas-liquids flow in the flow cell.**