Thermal-Fluid Transport Issues for High Power Density and Gravity Independent Aviation and Space Applications of PEM Fuel Cells

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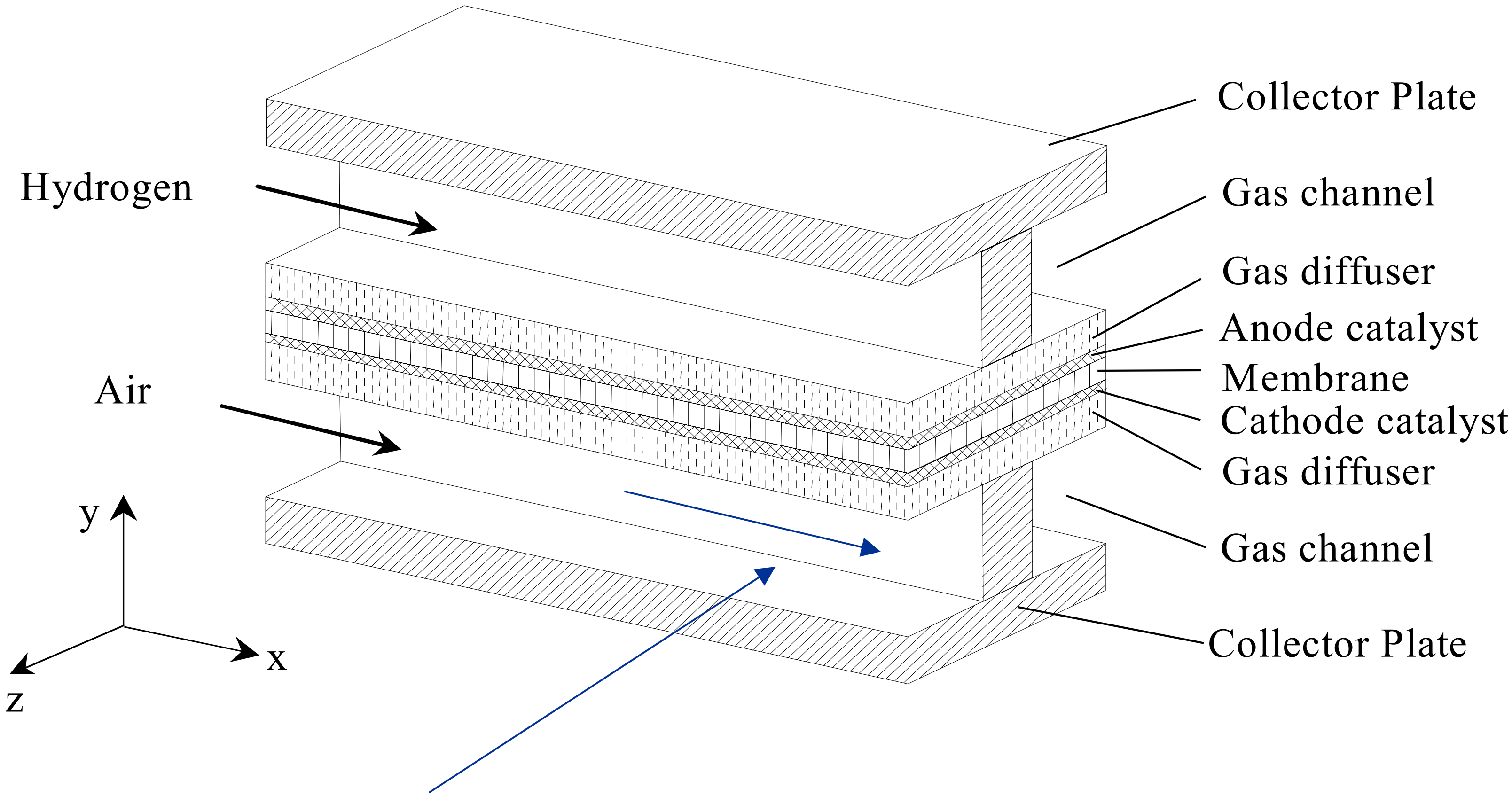


Exhaust : liquid water + nitrogen gas two-phase flow

PEM Fuel Cell System

Relevance to Current State-of-the-Art

Issues and Challenges

- **I. Two-Phase Flow Management**

  Water + gases (nitrogen and oxygen)
  - Gravity independence
  - Flooding
  - Hold-up
- **II. Non-uniform distribution of reactants to each cell and in each cell**
  - Affects current density and stability

Relevance to Current State-of-the-Art

Issues and Challenges

- **III. Separation of the two phases**
  - H_2 and O_2 reuse
  - Removal of water
- **IV. Non-uniform temperature distribution in cells**
  - Affects catalytic reaction
  - Cause excessive wear
  - Too dry or too much water

Relevance to NASA

I. Weight and Power Density

0.375 KW/kg - current standard for automobile applications.

10 KW/kg – required for aviation use.

- Surface to volume ratio required for 10KW/kg power density (aviation)
- 0.375 KW/kg in parentheses (automobile)

For Surface/Volume ratio = 200 cm^{-1} The diameter of the cylindrical channel = 200 microns

Current Density (mA/cm^2)	Surface to volume Ratio (1/cm)	Channel Size (microns)
200	450 (180)	100 (220)
400	256 (95)	180 (420)
600	193 (70)	230 (560)
800	165 (60)	270 (660)

Relevance to NASA

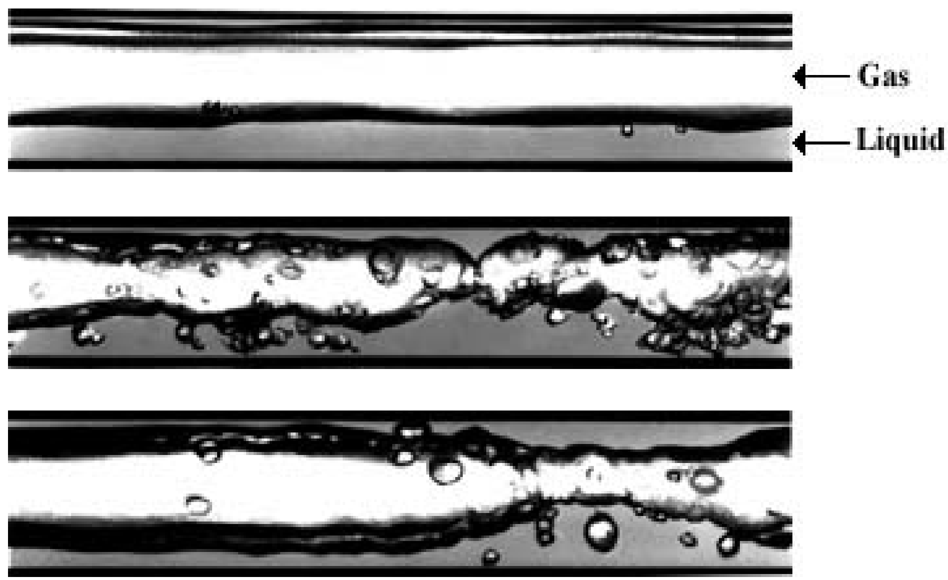
Gravity Independence : the gravity plays an important role in two-phase flow, Especially in a horizontal channel.

Effect of G-Level on Multiphase Flow

Stratified Flow
Normal Gravity
~1.0 G's

Stratified Wavy Flow
Lunar Gravity
~0.17 G's

Slug-Annular Flow
Zero Gravity
<0.01 G's



Flow ⟶

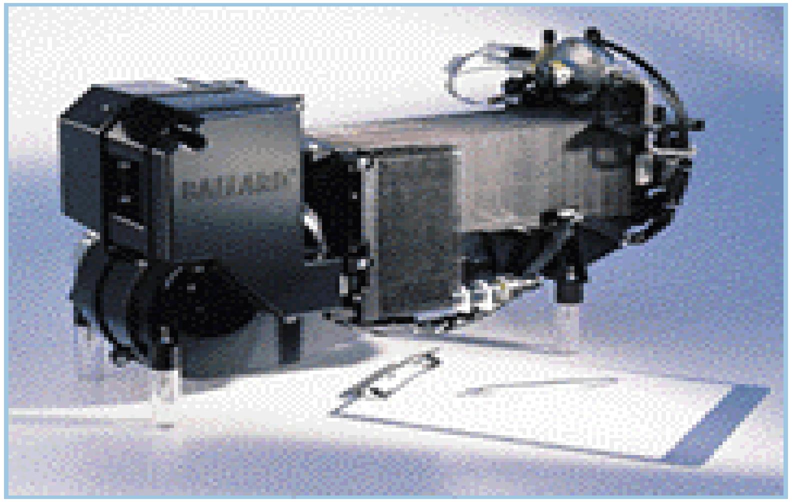
Air-Water in 1.27 CM ID Tube
Superficial Gas Velocity ~ 2.1 M/S
Superficial Liquid Velocity ~ 0.01 M/S

Research Goals and Objectives

- To achieve the highest power density (> 10 kW/kg) for aviation applications.
- To design a gravity independent system for space applications.
- To develop an efficient water management scheme, to find out how to maintain uniform distribution of reactants to each cell and in each cell, efficient separation of liquid from gases, and uniform temperature distribution in cells.

Approach

- Experimentation :
  - An apparatus has been built together with the required diagnostic systems, which has been used to perform quantitative measurements and flow visualization on the flow and transport in microchannels and effects of gravity.
  - A Ballard Nexa 1.2 KW PEM fuel cell module and associated thermal and fluid management component will be used to evaluate system characteristics for different designs.



Approach

- Optimization :
    - A data base developed from combined analysis/experiment results will be used for construction of a surrogate model and for device optimization with an evaluation of the sensitivity/impact of design variables.

Budget : 70K
Schedule

- 1st Quarter: Design and build the twelve-channel flow apparatus. Perform the multi-channel apparatus calibration and perform measurement of the 1-g flow distribution in each channel.
- 2nd Quarter: Perform microgravity drop tower experiment on the flow distribution study for the same cases as in 1-g. Perform image and data analysis for both terrestrial and micro-g cases.
- 3rd Quarter: Perform 1-g and micro-g water-gas separation experiment. Then perform the image and data analysis.
- 4th Quarter: Perform 1-g and micro-g temperature profile experiment, and data and image analysis.
- 5th Quarter: Design and build the 1200-Watt fuel cell system apparatus based on the results form the above experiments. Perform a complete calibration of the fuel cell apparatus and collect its steady operation data.
- 6thQuarter: Perform optimization on the integration of thermal-fluid transport with the MEA stack.

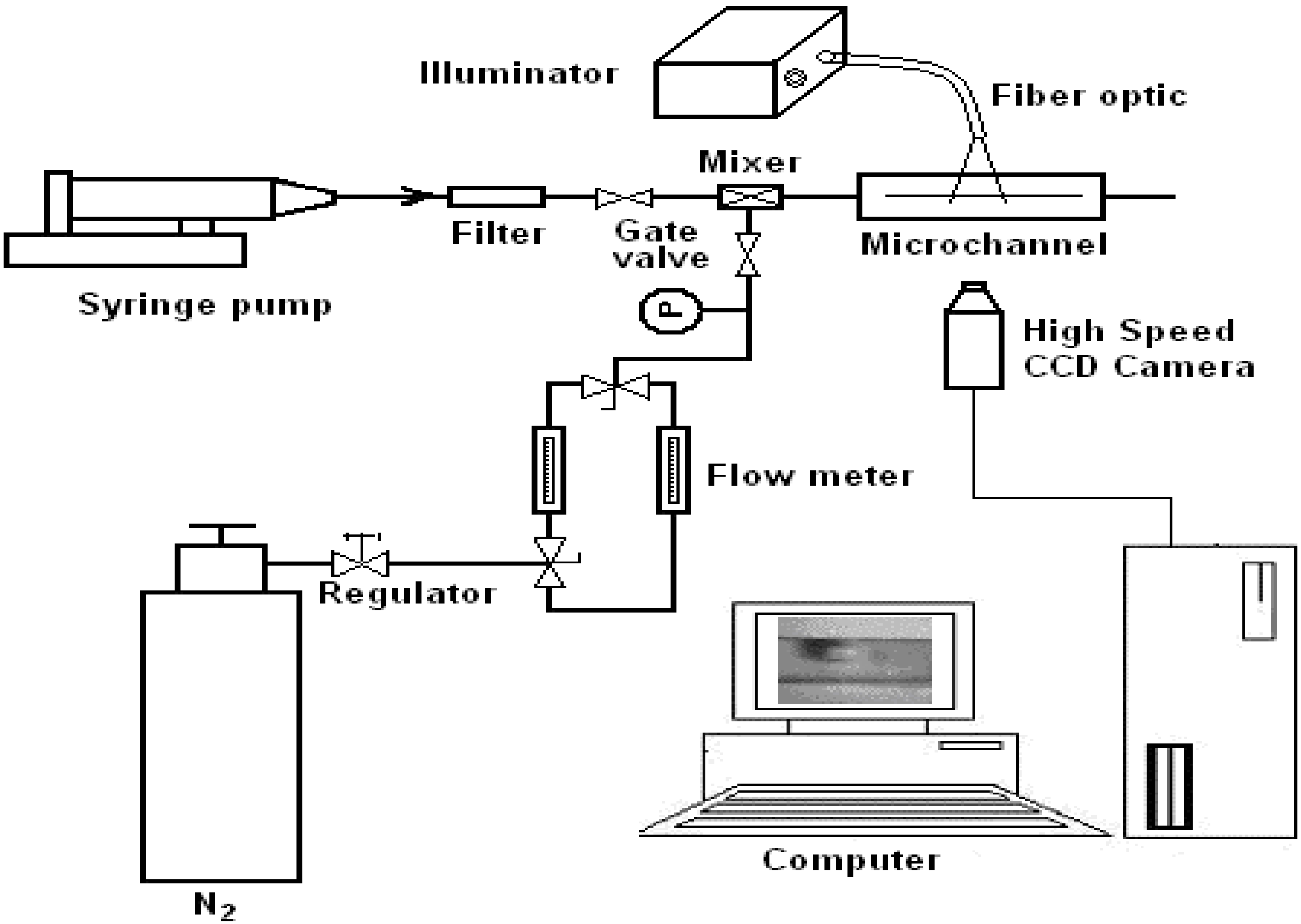
Deliverables

- 1st Quarter: 1-g flow distribution data, flow visualization images, and analyzed result.
- 2nd Quarter: Micro-g flow distribution data, flow visualization images, and analyzed results.
- 3rd Quarter: 1-g and micro-g water-gas separation data,flow visualization images, and analyzed results.
- 4th Quarter: 1-g and micro-g temperature profile data and flow visualization images. Analyzed results for temperature profile study.
- 5th Quarter: Calibrated 1200-Watt fuel cell system and its steady operation data.
- 6th Quarter: An optimized system of integrated thermal-fluid component with the MEA stack.

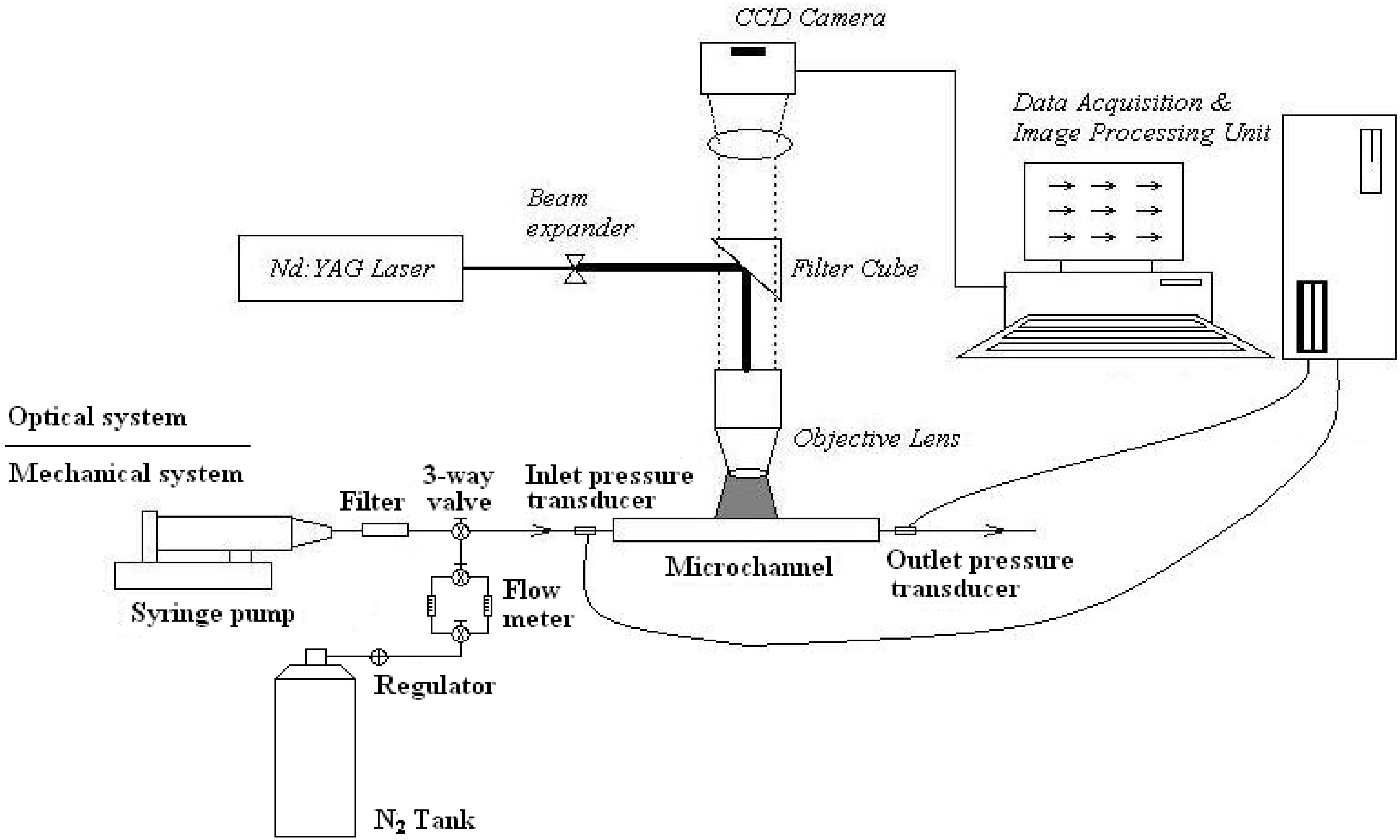
Anticipated Technology End Use

- **PEM fuel cells can be used as an Auxiliary Power unit (APU) for aviation applications**
- **Because the hydrogen and oxygen can be shared with propulsion systems and the water can be shared with crew life-support systems, PEM fuel cells are an attractive primary power source for human space missions.**
- **When fuel cells are coupled with an electrolyzer to form a regenerative fuel cell system (RFC), the technology becomes an attractive energy storage alternative to battery systems, especially for lunar missions where the day-night cycles are much longer than those in low Earth orbit.**

Schematic of Experimental System

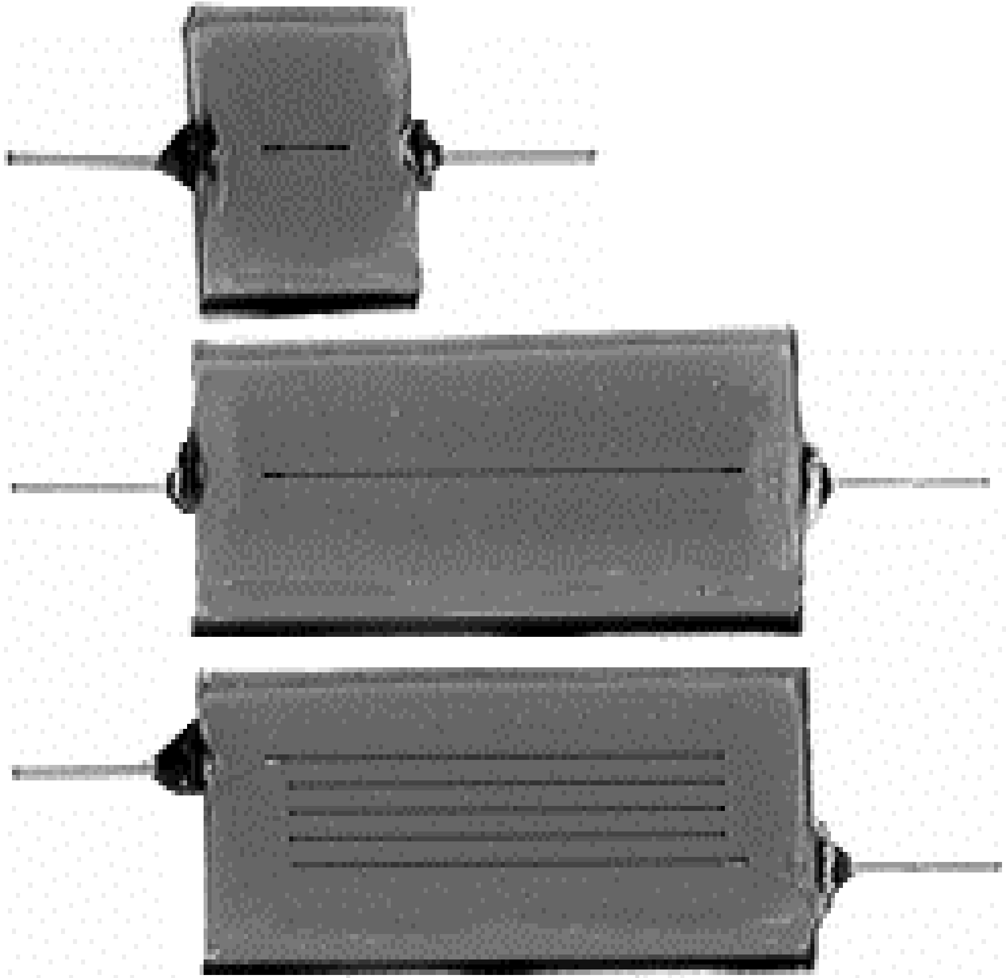


Micro-PIV Velocimetry System



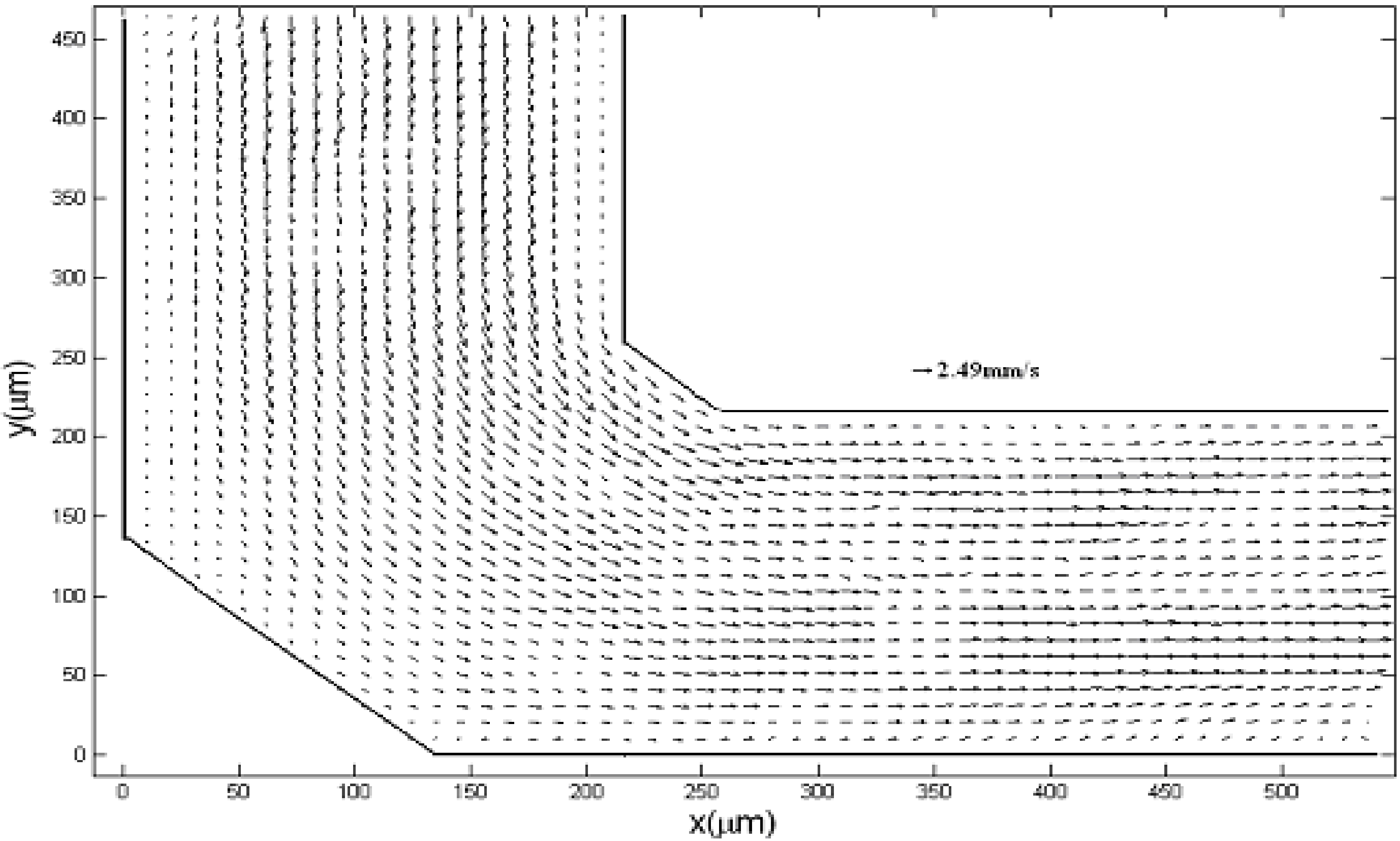
Microchannel Test Sections

- Channel sizes
  - 209 μm
  - 412 μm
  - 622 μm
- Geometries
  - straight
  - serpentine
- Other Information
  - square Cross section
  - made of silicon carbide

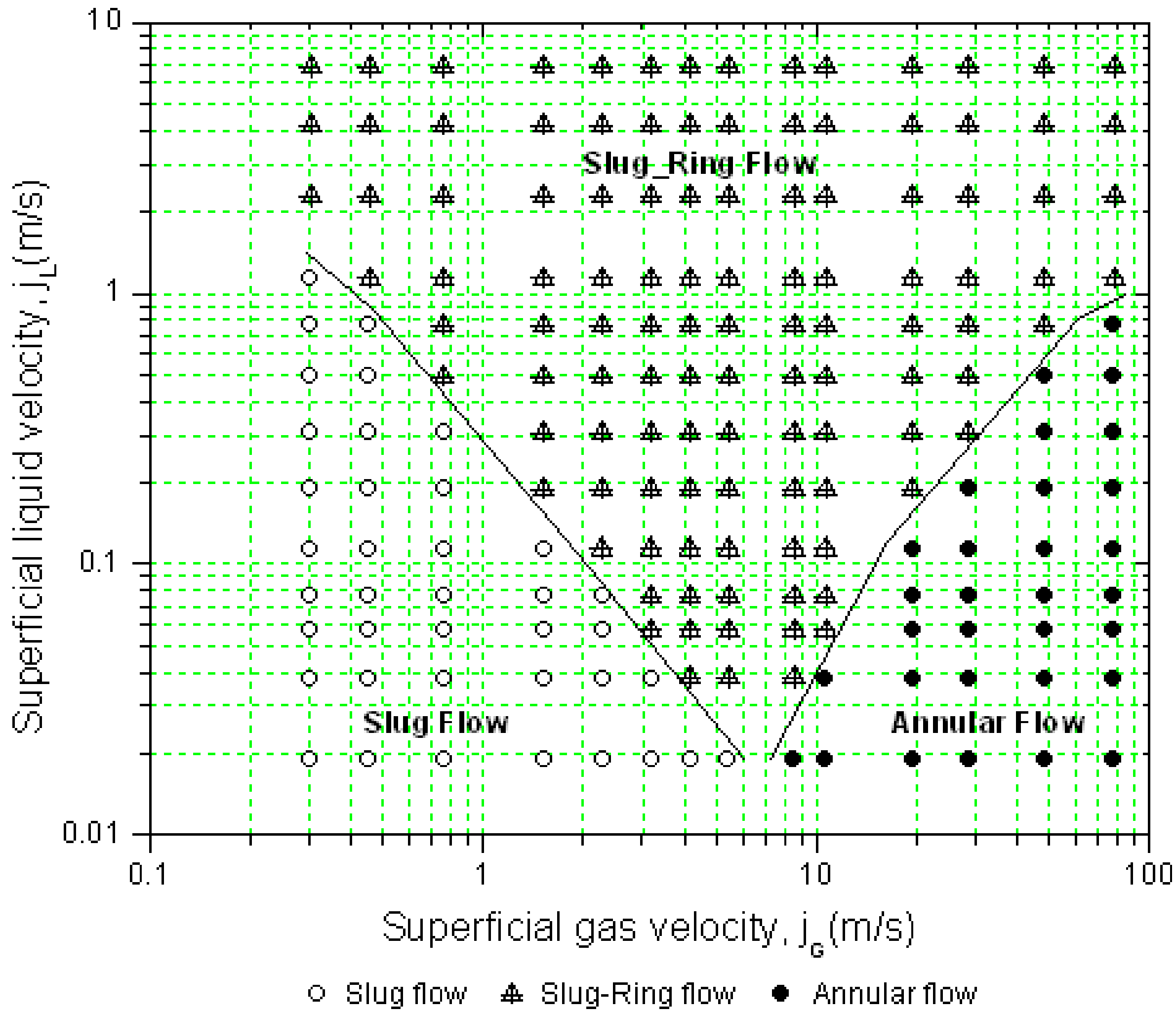


Representative Accomplishments and Results

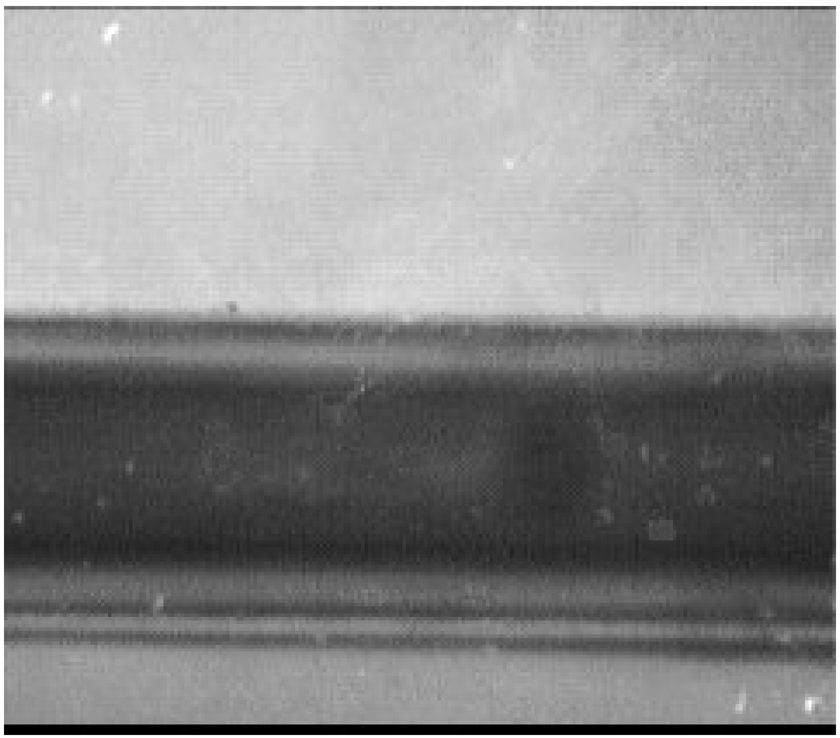
Micro-PIV Image
Velocity Profile Around an Elbow

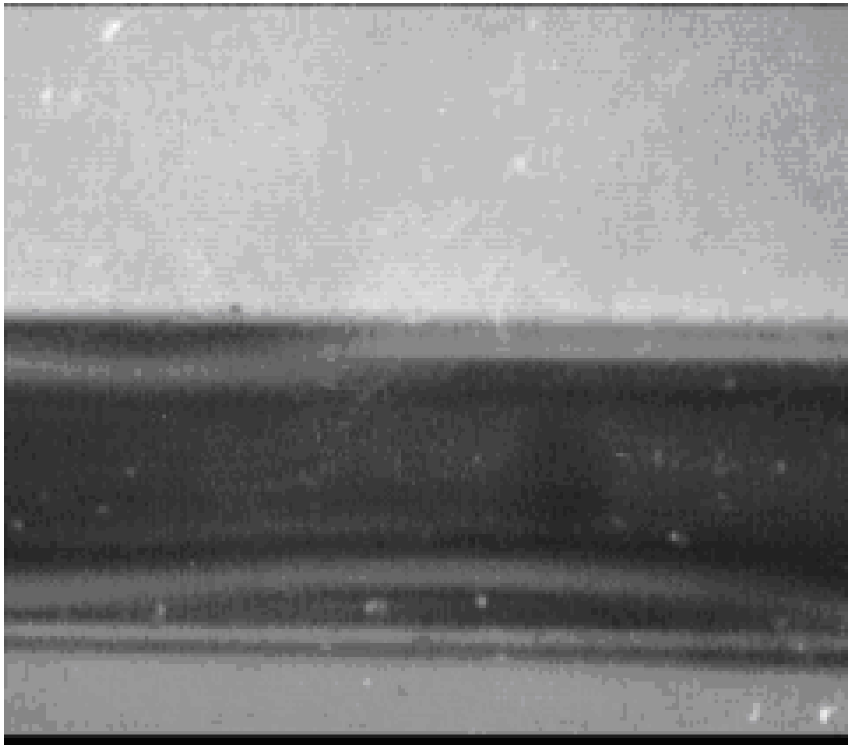


Liquid Water – Gaseous Nitrogen Two-Phase flow Regime Map (209 μm channel)

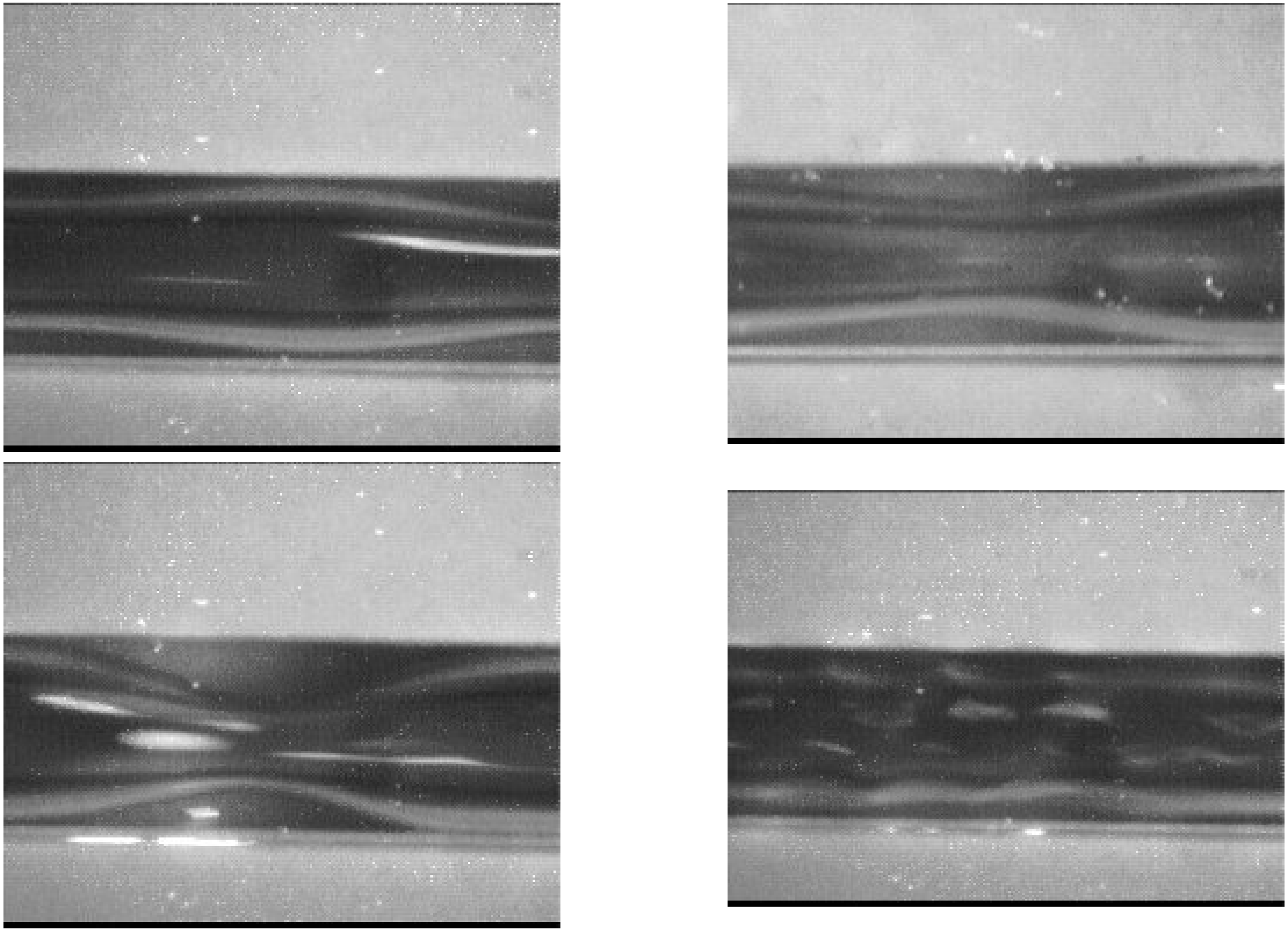


Typical Water-Nitrogen Annular Flow Pattern

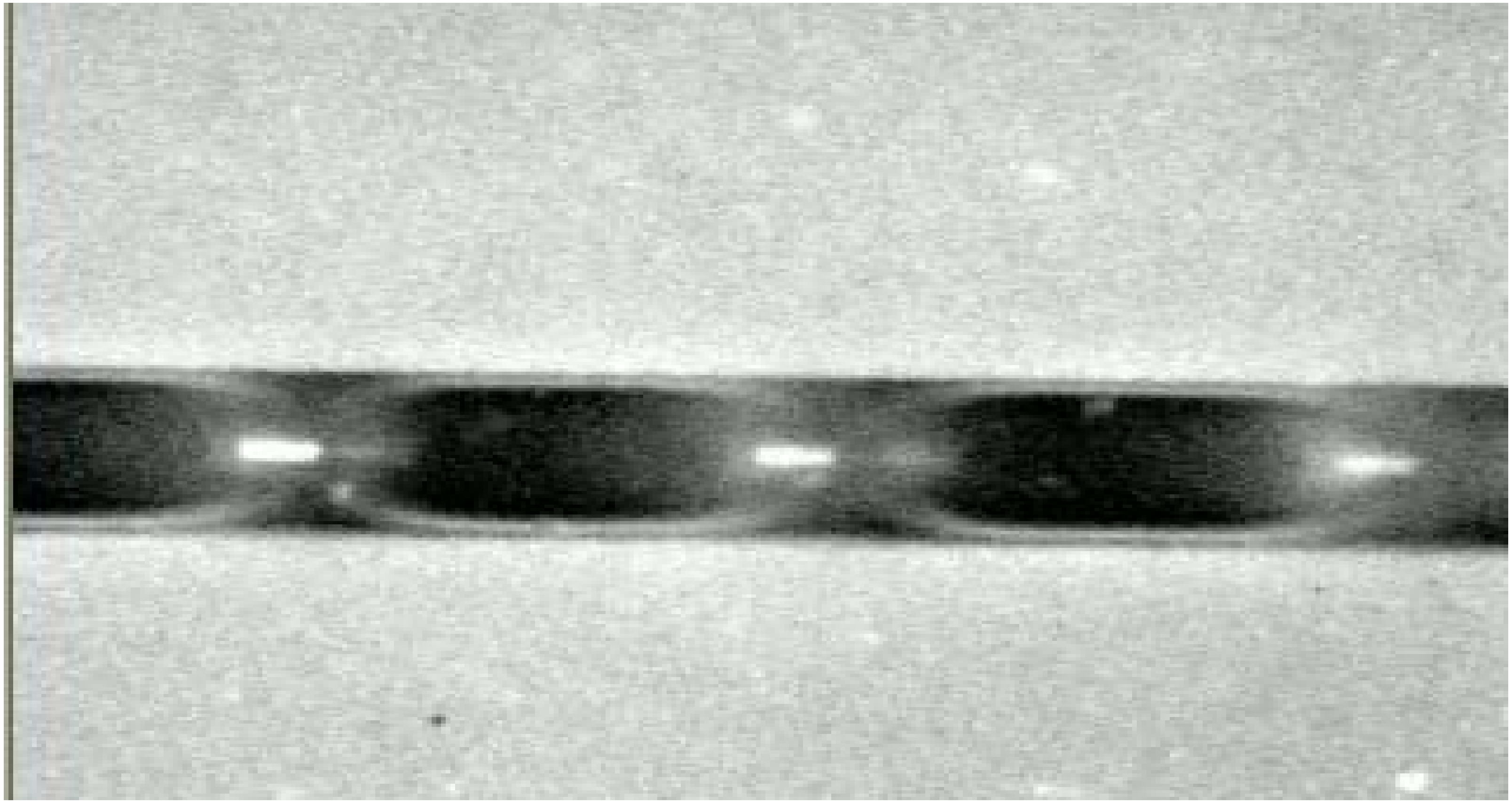




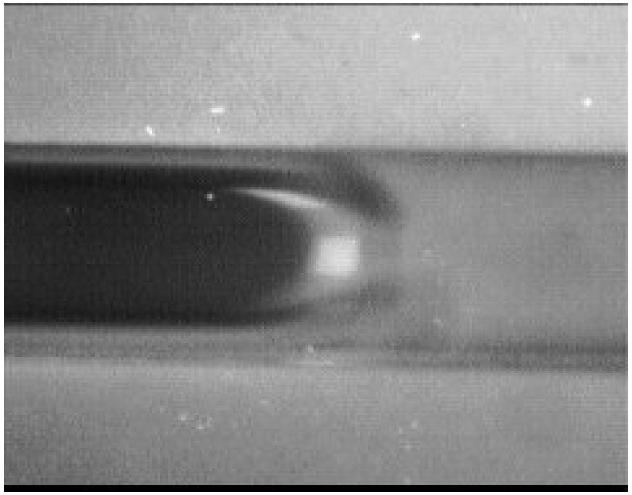
Typical Water-Nitrogen Slug-Ring Flow Pattern

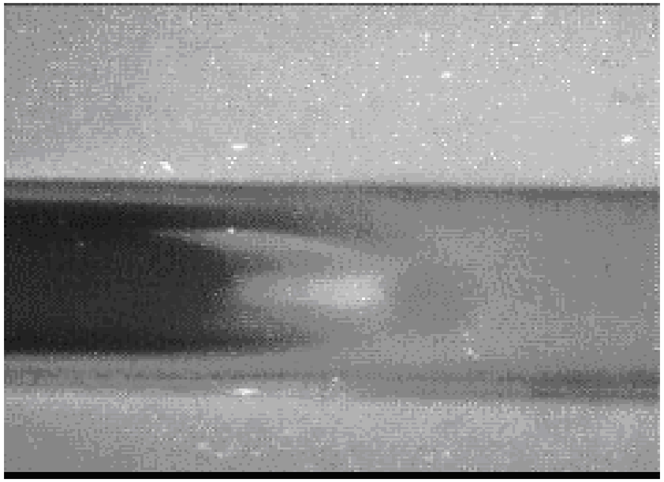


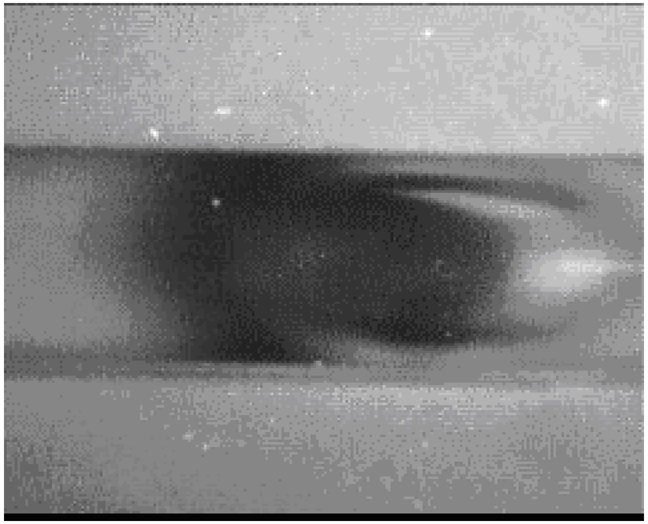
Typical Water-Nitrogen Sectional Annular Flow Pattern

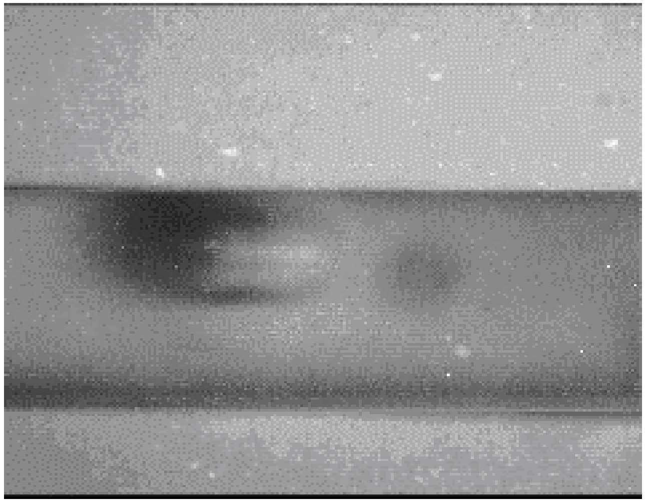


Typical Water-Nitrogen Bubbly-Slug Flow Pattern



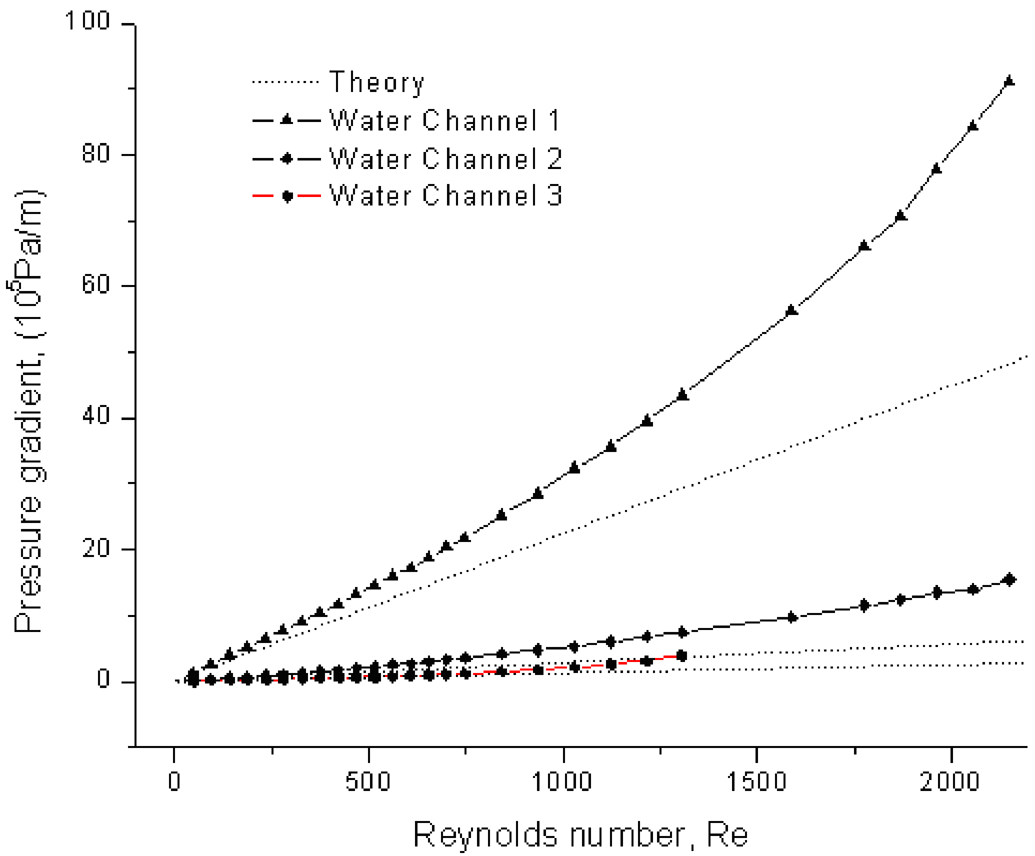




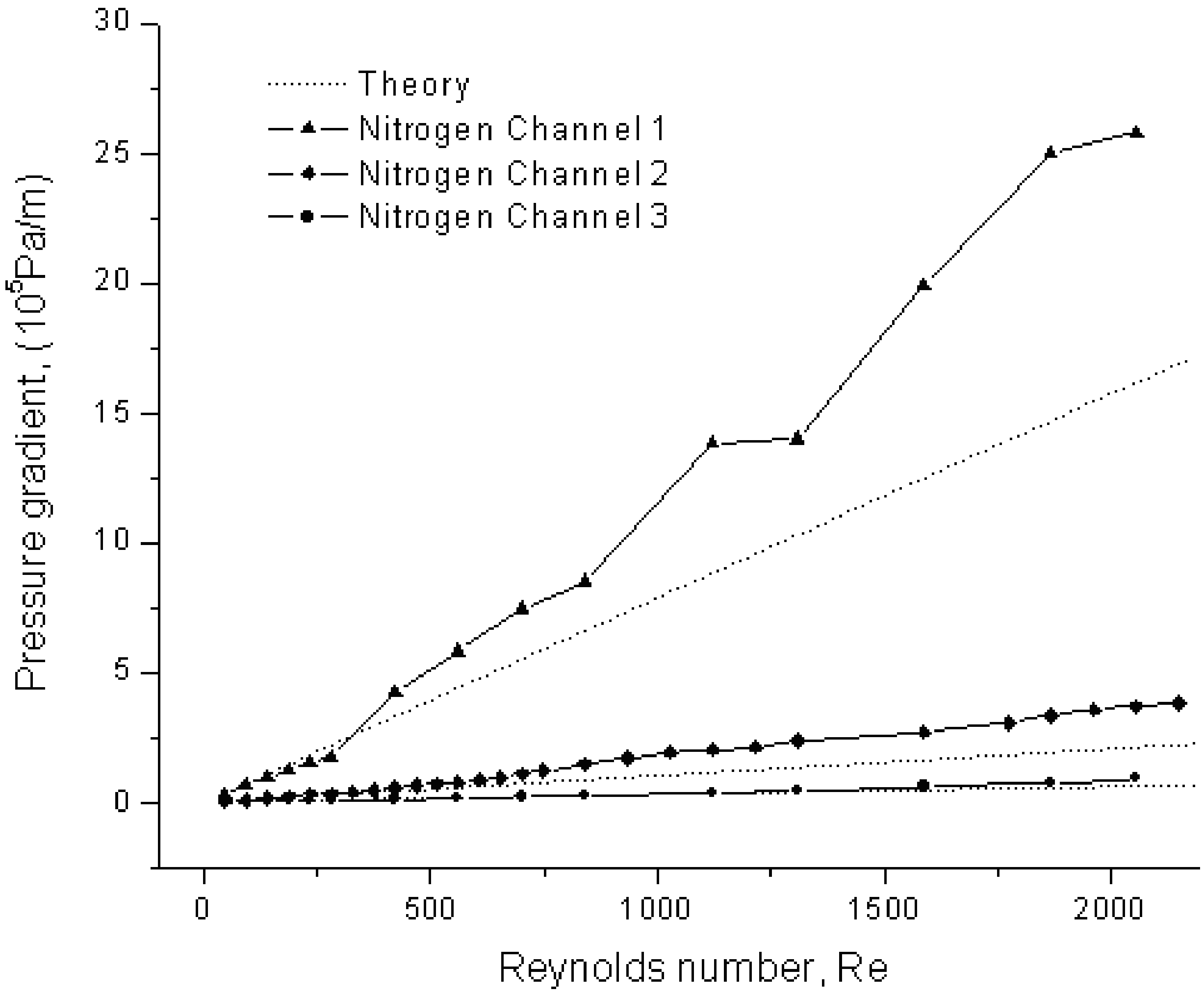


Accomplishments and Results

- Pressure gradient for single component (liquid water or nitrogen) flow in three different channels as a function of the flow rate (Re)
- Channel 1 – 209 µm
  Channel 2 – 412 µm
  Channel 3 – 622 µm

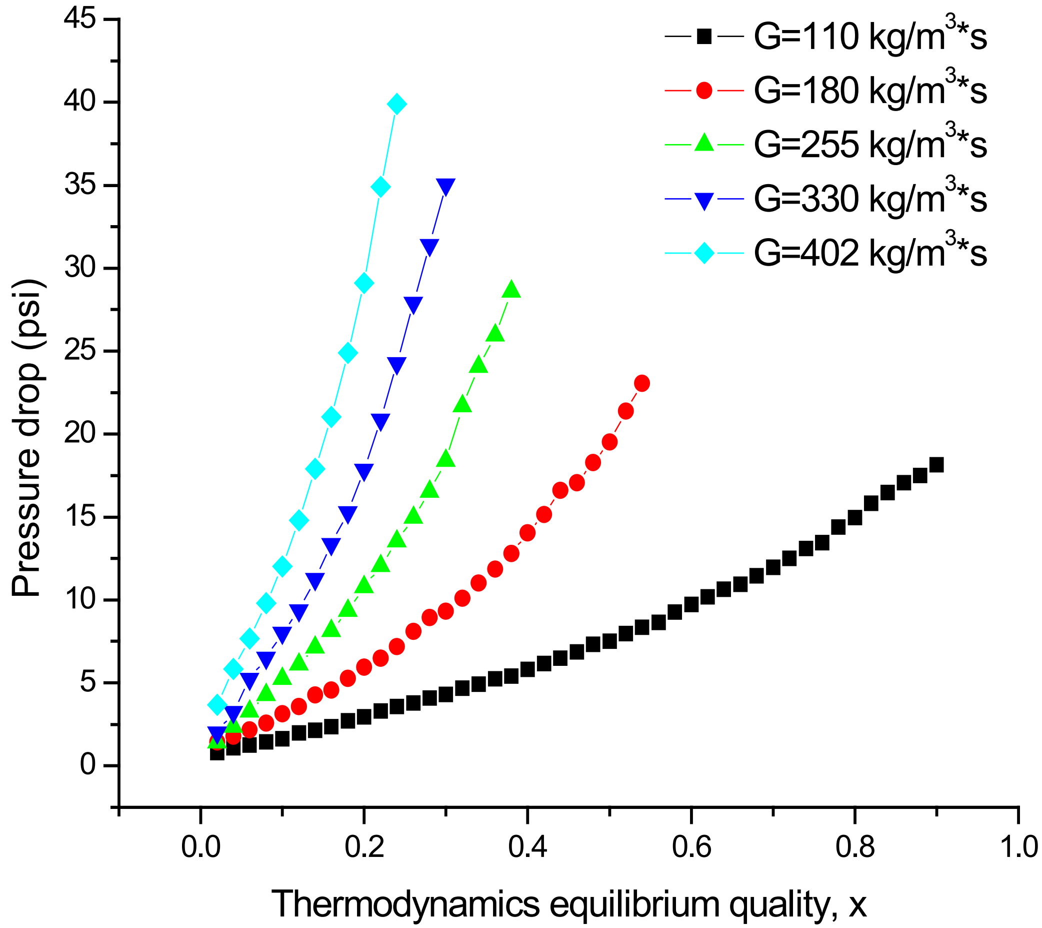


Single-Phase nitrogen



Two-Phase Flow Pressure Drop

- Pressure drop as a function of two-phase flow quality and volumetric flow rate for 412 μm straight channel

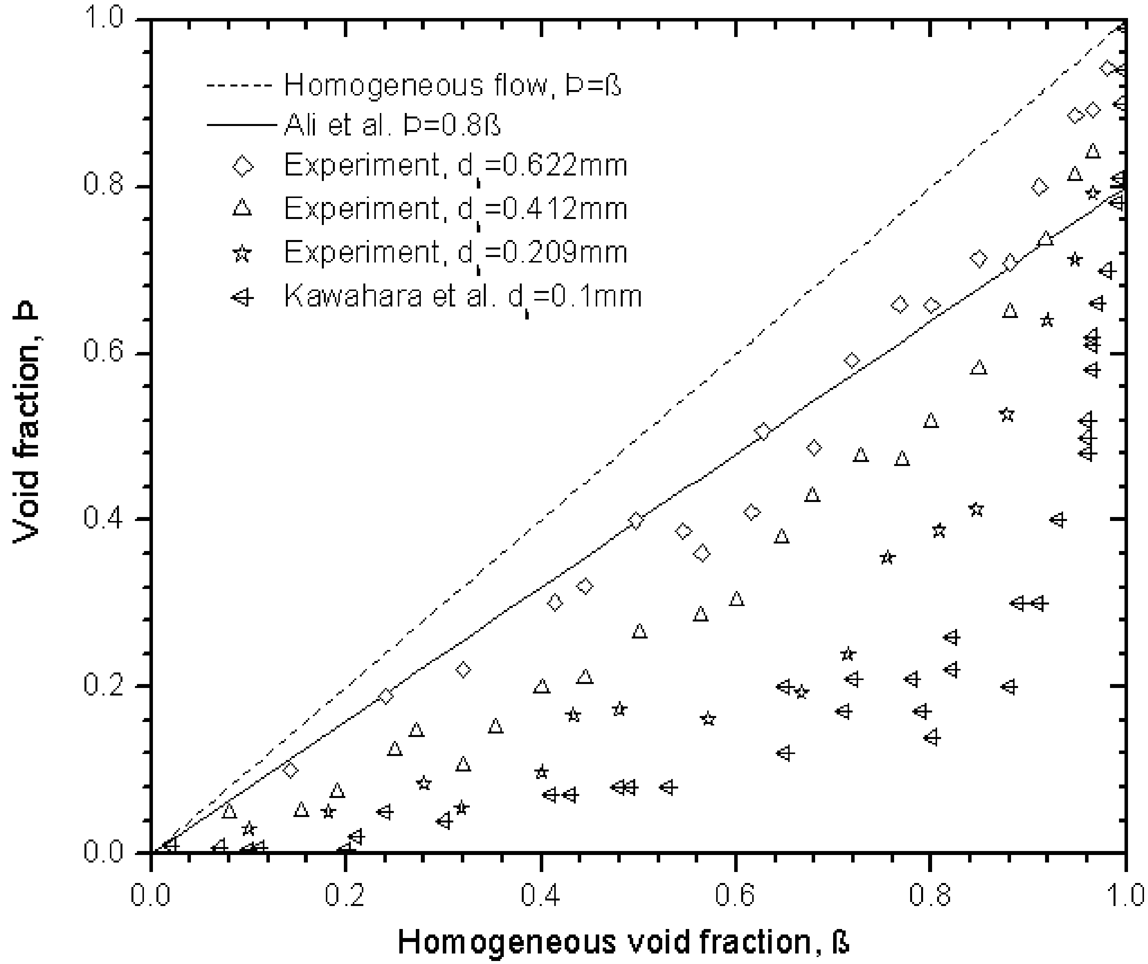


Experimental Result and Comparison

- The measured void fraction results and two previous correlations

  α = β
  Both phases move at equal velocity

  α = 0.8 β for 1 mm tube

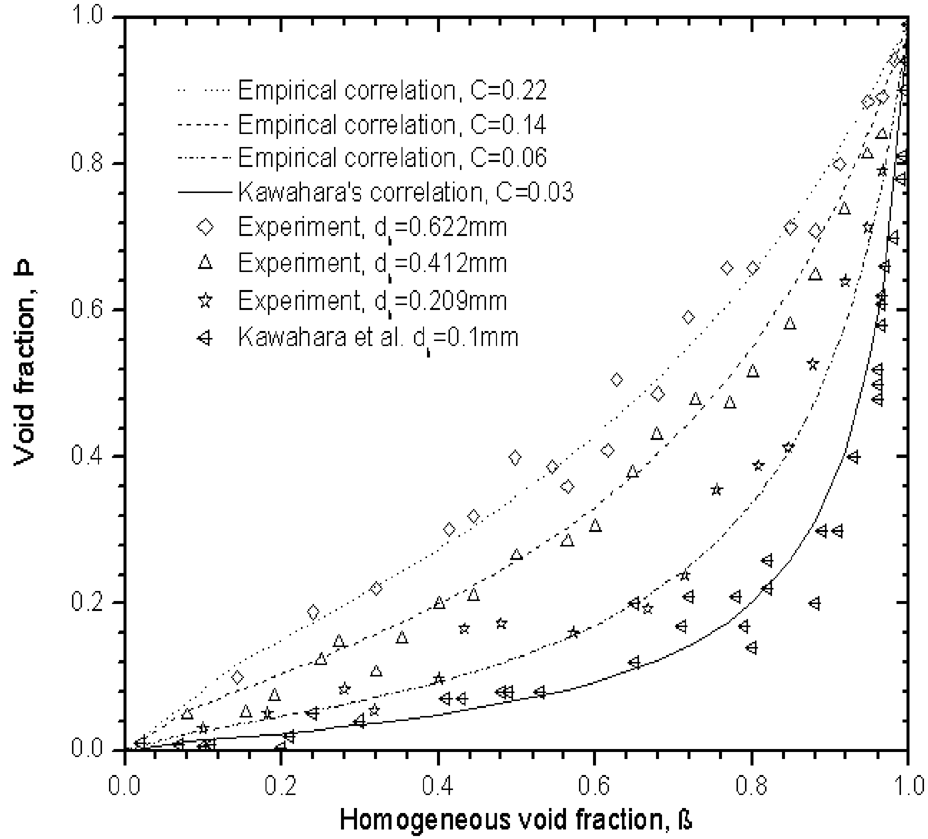


Experimental Result and New Correlation

- The measured void fraction results and the new correlations

$$\alpha = \frac{C\beta^{0.5}}{1-(1-C)\beta^{0.5}}$$

$$C = \frac{0.266}{1+13.8e^{-6.88d_h}}$$



Future Plans

- Establish collaboration with NASA Glenn Proton-Exchange-Membrane Fuel Cell (PEMFC) engineering model power plant where 1 kW to 125 kW PEM fuel cells have been tested and evaluated for space exploration missions.
- Seek collaboration and funding from other federal, state agencies and aviation and space industry for further research.