Measurement of Void Fraction

Laboratory Manual

Department of Mechanical Engineering,
Indian Institute of Technology – Bombay.

Measurement of Void Fraction

Objectives

1. Determination of static calibration curve of void fraction vs. measured voltage from the area and volume void fraction sensors for various void fractions simulated using an acrylic stepped rod.

2. Determination of the dynamic calibration curve of void fraction vs. measured voltage from the area and volume void fraction sensors for various inlet gas mass flow rates.

Theory

In this section the definitions to void fraction are provided. The local-instantaneous void fraction $\alpha_P(x,y,z,t)$, at the point (x,y,z) in the flow at an instant t is defined as:

$$\alpha_P(x,y,z,t) = \begin{cases} 1, \text{if point (x, y, z) is in gas phase at time t} \\ 0, \text{if point (x, y, z) is in liquid phase at time t} \end{cases}$$

The time-averaged local void fraction $\overline{\alpha}_P(x,y,z)$ at the point (x,y,z) in a time interval T is defined as follows.

$$\overline{\alpha}_P(x,y,z) = \frac{1}{T}\int_t^{t+T} \alpha_P(x,y,z,t)dt$$

The time-averages are represented with an over-bar $(\bar{\cdot})$

Void Fraction can also defined by spatial averages. One of the measures is the area-averaged void fraction. It can be considered as the area-average of the local instantaneous void fraction $\alpha_P(x,y,z,t)$, at an instant t over the reference area.

Representing the spatial-average across an area as $\left(\langle\cdot\rangle_A\right)$, the area-averaged void fraction can be written as :

$$\langle\alpha\rangle_A(z,t) = \frac{1}{A}\iint_A \alpha_P(x,y,z,t)dA$$

This can be interpreted as the fraction of area of the reference area occupied by the gas phase at a given z and an instant t. The time and area-averaged void fraction $\langle\overline{\alpha}\rangle_A(z)$ at the section distanced z along the flow direction, in a time interval T is defined as follows:

$$\langle\overline{\alpha}\rangle_A(z)=\frac{1}{T}\int_t^{t+T}\langle\alpha\rangle_A(z,t)dt$$

Another measure is the volume-averaged void fraction. It can be considered as the volume average of the local instantaneous void fraction $\alpha_P(x,y,z,t)$, at an instant t over a volume V.

$$\langle\alpha\rangle_V(t)=\frac{1}{V}\iiint_V\alpha_P(x,y,z,t)dV$$

This can be interpreted as the fraction of volume of the reference volume occupied by the gas phase at an instant t. The time and volume-averaged void fraction $\langle\overline{\alpha}\rangle_V$ in a volume V in the flow, in a time interval T is defined as

$$\langle\overline{\alpha}\rangle_V=\frac{1}{T}\int_t^{t+T}\langle\alpha\rangle_V(t)dt$$

The Measurement Principle

Void fraction can be measured by measuring the changes of material properties owing to the presence or absence of the gas. Some of the properties that can be used for checking the presence of gas and the corresponding sensors are as follows:

1. Electrical Impedance - Impedance Probe
2. Refractive Index - Optical Probes
3. Density(absorption coefficient) X-rays or Gamma Ray Densitometers

In this experiment, the amount of gas present in a gas-liquid mixture can be estimated by measuring the amount of electrical impedance of the fluid. Gases (Steam and air) usually have poor electrical conductivity in comparison with Water. The probes used are of two types – Volume Averaging Ring Probes and Area Averaging Arc Probes as shown in Figures 1 and 2 respectively.

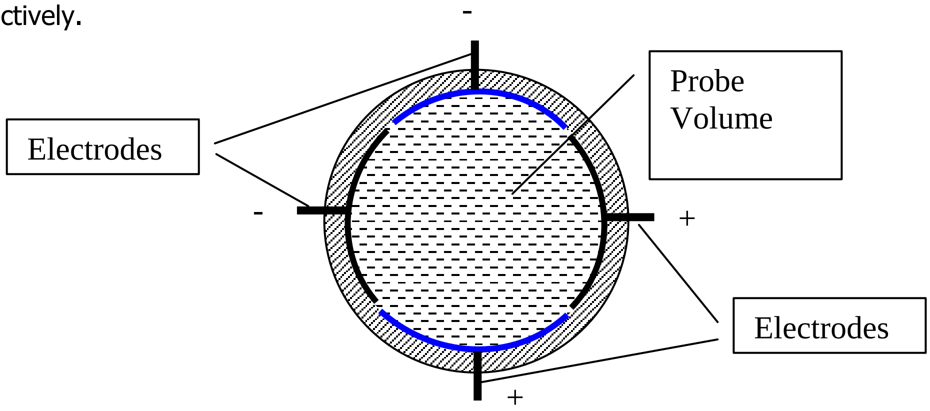


Figure 1 : Area Averaging Arc Probe

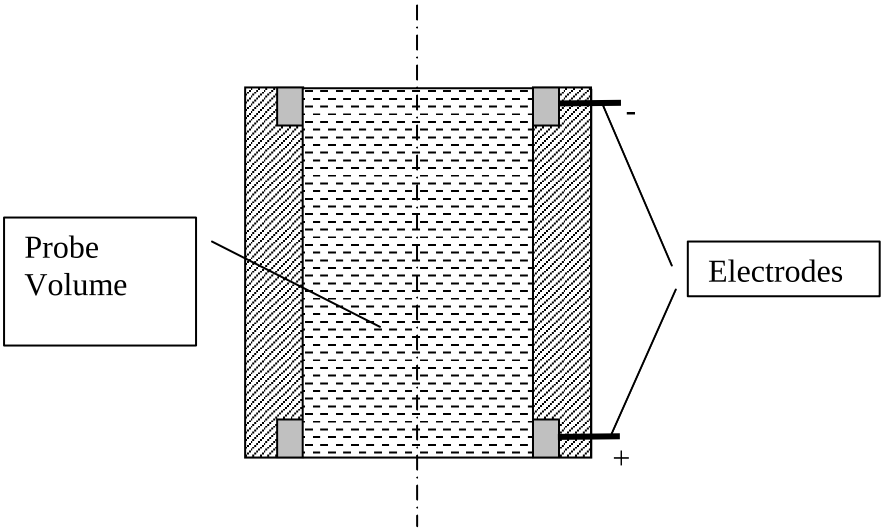


Figure 2 : Volume Averaging Ring Probe

The Electrical Potential between the probe pairs are held constant and thus by Ohm's Law, the current through the probe would be proportional to the resistance of the probe i.e. proportional to the amount of gas present in the mixture. The block diagram of the measurement circuit is provided in the Figure 3.

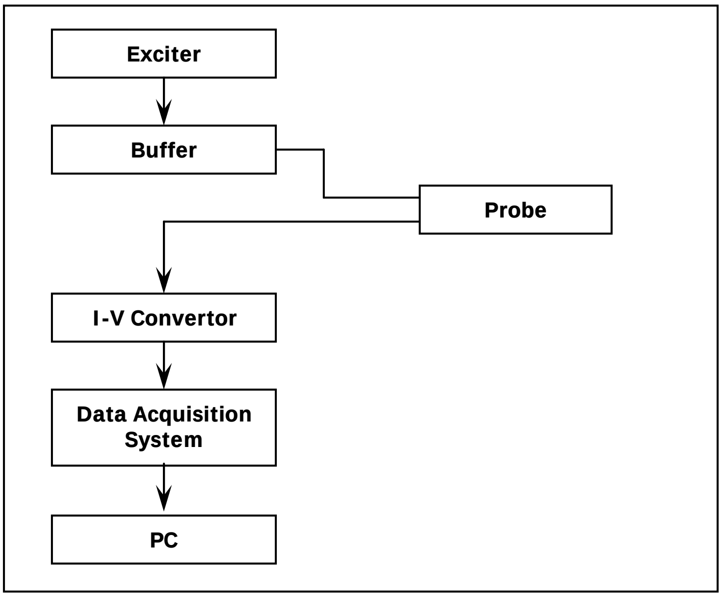


Figure 3 : The Block Diagram of the Probe Measurement Circuit

The exciter generates an alternating sinusoidal voltage of 1V at near 50kHz. Alternating signal patterns are necessary to prevent electrode corrosion and to prevent other electrochemical processes happening at the electrodes. The signal enters a buffer amplifier stage, which maintains a constant potential at the injection point of the probe. The electrical resistance variation of the probe modulates the current and hence produces a time-varying current signal whose envelope carries the resistance information of the probe. The current signal from the probe is converted into a voltage signal by the I-V Converter stage. The Voltage Signal is provided to the Data Acquisition System which measures the voltage and displays the output.

Apparatus

A schematic of the experimental setup is presented in Figure 4. Air from the compressed air supply enters the bubble column through a regulating valve and a rotameter which measures the mass flow rate of the inlet gas. The bubble column comprises of a vertically held, 2 meter long acrylic tube mounted with a sintered glass porous plug (in a buchner funnel) at the bottom and a void fraction sensor housing comprising of a single pair of volume averaged void fraction sensors and two pairs of area averaged void fraction sensors. There are pressure ports to measure the differential pressure of the fluid at points above and below the void fraction sensor housing. The pressure ports are connected to a U-tube differential manometer. The volume and area averaged void fraction sensors are connected to a measurement circuit and a data acquisition system.

The bubble column is filled with water which has sufficient ions to carry out the conduction. If the water is having poor conductivity, salts like Potassium Chloride can be added to the solution to enhance the ionic conductivity of the liquid.

On opening the regulating valve, the air supply enters the bubble column through the rotameter into the buchner funnel fitted with the sintered glass porous plug. The air passes through the pores of the sintered porous plug and enters the bubble column and form a homogenous bubbly mixture inside the tube. The measurements proportional to area and volume averaged sensors are picked up be the area and volume averaged void fraction sensors. The volume averaged sensor comprises of a pair of rings mounted inside the sensor housing co-axial to the pipe. The area averaged sensors comprises of two pairs of split ring sensors of included angle 80°, each spaced at 10°, mounted inside the sensor housing co-axial to the pipe. Both the volume averaged sensors and the area averaged sensors have the same internal diameter as that of the acrylic pipe. Electrical contacts from the sensors and attached to a measurement circuit and the data acquisition system through a selector switch panel. Only one probe should inject the current at a time and hence the probe to be measured should be selected using the selector switch.

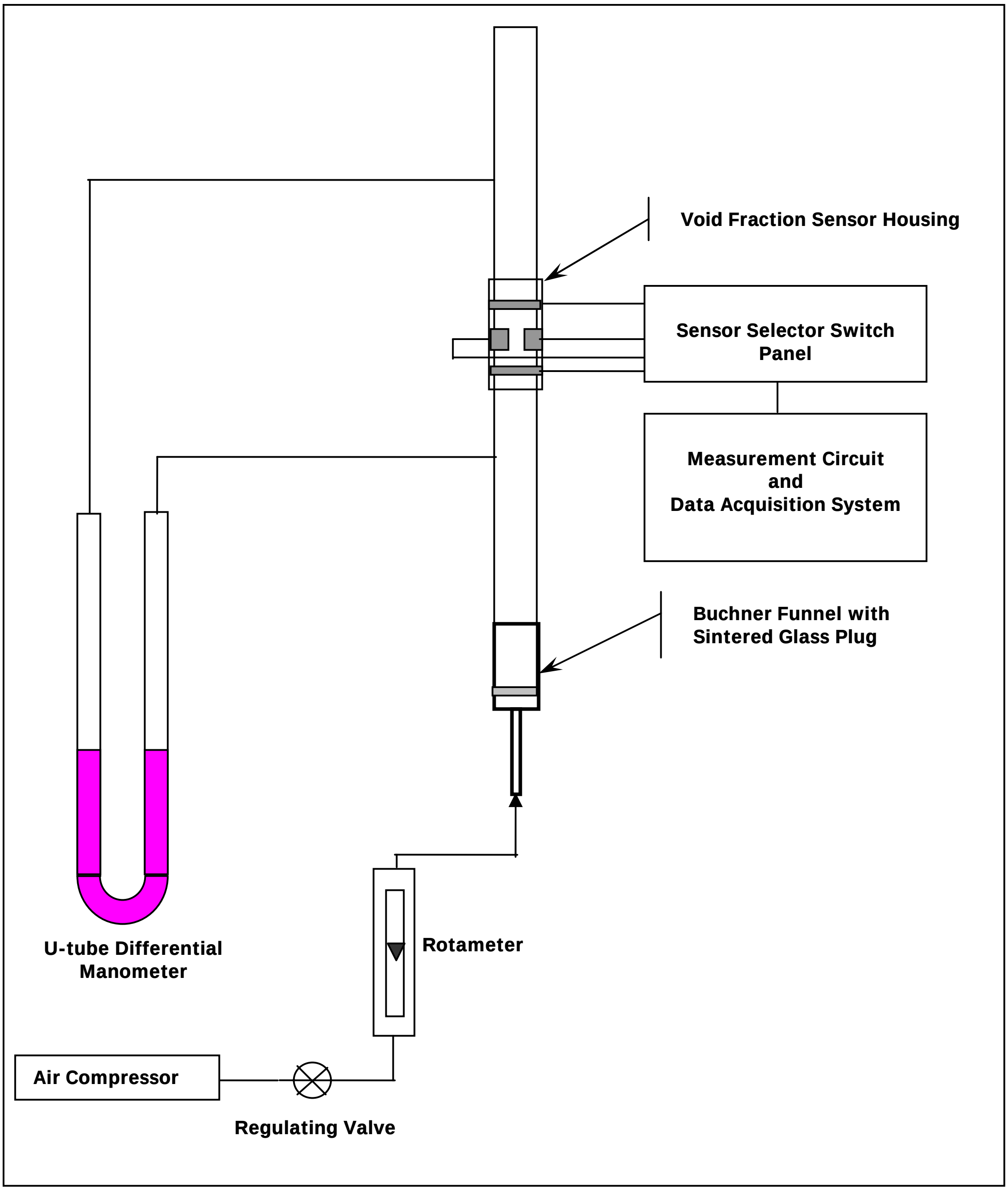


Figure 4 : Bubble Column Experimental Setup Schematic

The measurement circuit injects a constant voltage into the sensor and measures the current flowing through the probe. The current signal is converted into a proportional voltage signal by the circuit. This voltage signal is picked up by the data acquisition system.

Calibration of Sensors

Static Calibration using Acrylic Rods

Static calibration involves the introduction of a void of a known geometry into the bubble column, in the absence of injected gas so to measure an estimate of the volume and area averaged void fraction.

The electrical properties of air are much closer to that of a perfect electrical insulator. As the sensor sees only the electrical conductivity of the fluid, any object that is a good electrical insulator can be machined to a known geometry and introduced in between the sensor, so as to simulate the presence of void.

The cross sectional area of the bubble column is known and the cross sectional area of the introduced insulator section is also known. As the rest of the cross section of the bubble column is filled with liquid, the area averaged void fraction can be taken as the ratio:

$$\text{Area Averaged Void Fraction} = \frac{\text{Cross section area of the insulator}}{\text{Cross section area of the bubble column}}$$

In the experiment, cylindrical acrylic rods are used to simulate four void fractions by lowering the rod into the bubble column and by placing it in the measurement area / volume of the sensors. A calibration curve can then be plotted as the Simulated Void Fraction Vs. the Measured Voltage.

Dynamic Calibration using Pressure Drops

Dynamic calibration involves injecting air into the bubble column and calibrating the void fraction measurement from the sensor to the estimate of void fraction obtained from the pressure drops across the sensor housing, measured using the U-tube differential manometer in the experimental setup.

In a steady, one dimensional vertical two-phase flow, from the homogenous equilibrium model for two-phase flow (the flow considered is a bubbly flow, which can be treated as a homogenous mixture of air in water) :

$$\underset{\textbf{Pressure Gradient}}{-\frac{\partial p}{\partial z}} = \underset{\textbf{Acceleration}}{\frac{1}{A}\frac{\partial}{\partial z}\left(\rho_H A u^2\right)} + \underset{\textbf{Friction}}{\frac{\tau_w P}{A}} + \underset{\textbf{Gravitation}}{\rho_H g}$$

Where

p - Pressure
z - Distance in the flow direction
A - Cross Sectional Area of Flow
ρ_H - Homogenous Density given as $\rho_H = \rho_g \alpha + \rho_l (1-\alpha)$,

Where

  ρ_g - Density of gas
  ρ_l - Density of liquid
  α - Void Fraction

u - Flow Velocity
τ_W - Wall Shear Stress
P - Wall Perimeter
g - Acceleration due to gravity

At void fractions below 50%, the effect of frictional pressure drop is less and can be neglected. As the flow is adiabatic and is of constant cross sectional area, the acceleration contribution to pressure drops can also be neglected (small effects on account of bubble expansion due to local change in pressure is ignored). Thus

$$-\frac{\partial p}{\partial z} \approx \rho_H g$$

By integrating the above expression between the two pressure ports

$$\Delta p = \rho_H g H$$

Where

Δp - Pressure drop measured between the pressure ports
H - Distance between the pressure ports in the direction of flow

Thus

$$\Delta p = \left(\rho_g \alpha + \rho_l (1-\alpha)\right) g H$$

Or

$$\alpha = \frac{\Delta p - \rho_l g H}{\left(\rho_g - \rho_l\right) g H}$$

In this experiment, a manometer is used to measure the pressure drop. A detailed derivation of the void fraction estimation from the manometric deflection is presented in the Appendix. The final equation for estimation of void fraction is,

$$\alpha = \frac{(\rho_m - \rho_f)h}{(\rho_f - \rho_g)H}$$

Where, H is the vertical distance between the manometric taps, h is the manometric deflection, ρ_m, ρ_f and ρ_g are the densities of the manometric fluid, the liquid phase and the gas phase respectively.

Procedure

Measurement Circuit Setup

1. Switch on the experimental setup and keep it on for 10 minutes and allow the system to stabilize.
2. Load the LabView Data Acquisition Program and Start Execution.
3. Press Start button on the Display Panel to begin acquisition and averaging. The Start Button acquires signals for a time interval (can be specified on the user interface of the LabView Data Acquisition program) and averages them and provides with an estimate of the minimum, maximum and the mean values of the measured voltages in the time interval.

Static Calibration

1. Insert the Acrylic Rod into the bubble column after measuring its diameter.
2. Lower the rod into the liquid until it comes along the sensor axis.
3. Select the Volume Averaging Probe using the Sensor Selector Switch Panel.
4. Press the Start Button on the Display Panel to perform acquisition of signal and once the voltage readings are displayed, note them down.
5. Select the Area Averaging Probe 1 using the Sensor Selector Switch Panel.
6. Repeat the Voltage Measurement.
7. Select the Area Averaging Probe 2 using the Sensor Selector Switch Panel.
8. Repeat the Voltage Measurement.
9. Repeat the measurement for all the steps by repeating steps 4 – 9 for each rod.
10. For the various simulated void fractions, draw the calibration curve for simulated void fraction vs. measured voltage for the three probes.

Dynamic Calibration

1. Ensure that there are no air bubbles in the tubes connecting the pressure ports to the U-tube differential manometer.
2. Take the zero reading of the U-tube Differential Manometer.
3. Permit air-flow into the bubble column using the regulating valve.

4. Wait for about a minute and once the manometer reading has settled down and the rotameter reading is steady, make a note of the differential pressure reading from the U-tube Differential Manometer.
5. Press the Start Button on the Display Panel and after the averaging is complete, note down the minimum and maximum readings of the measured voltage.
6. Repeat the steps 3 to 5 for various air flow rates.
7. Compute the Void Fraction from the Differential Pressure Measurement and Plot the Calibration Curve for Void Fraction Vs. Measured Voltage.

Observations

Enter in the attached observation sheets and plot graphs.

Results and Discussions

Appendix - Estimation of Void Fraction from Pressure Drops

Consider the Bubble Column depicted in Figure 1. The bubble column has two pressure ports 1 and 2 at static pressures P_1 nd P_2 respectively. The pressure ports are connected to a U-tube Differential manometer which has a fluid of density ρ_m. The Manometric fluid column height difference would be denoted by h. Let a be the elevation of the left limb manometric fluid level from the first pressure port as shown in Figure 1.

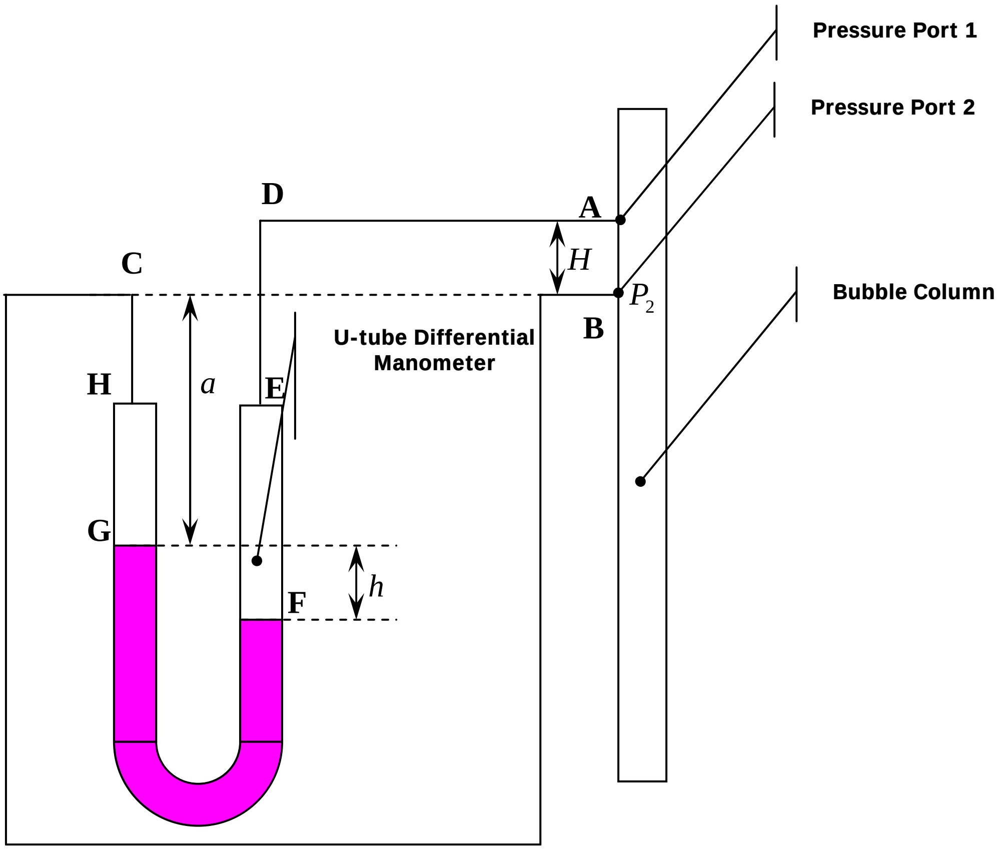


Figure 1 : Bubble Column Experimental Setup with U-Tube Differential Manometer

Following path **AB** in the test section

$$P_2 - P_1 = \rho_{eff} gH = \lfloor \rho_g \alpha + \rho_f (1-\alpha) \rfloor gH \tag{1}$$

Where α is the void fraction.

Following the path **BCHGFEDA**

$$P_2 + \rho_f ga + \rho_m gh - \rho_f gh - \rho_f ga - \rho_f gH = P_1$$

Or by rearrangement

$$P_2 - P_1 = -\rho_f ga - \rho_m gh + \rho_f gh + \rho_f ga + \rho_f gH$$

Canceling $\rho_f ga$

$$P_2 - P_1 = -\rho_m gh + \rho_f gh + \rho_f gH$$

Or by rearrangement

$$P_2 - P_1 = (\rho_f - \rho_m)gh + \rho_f gH \qquad (2)$$

From Equation (1) and (2) we can write

$$P_2 - P_1 = (\rho_g \alpha + \rho_f (1-\alpha))gH = (\rho_f - \rho_m)gh + \rho_f gH$$

Canceling g on both sides and re-arranging

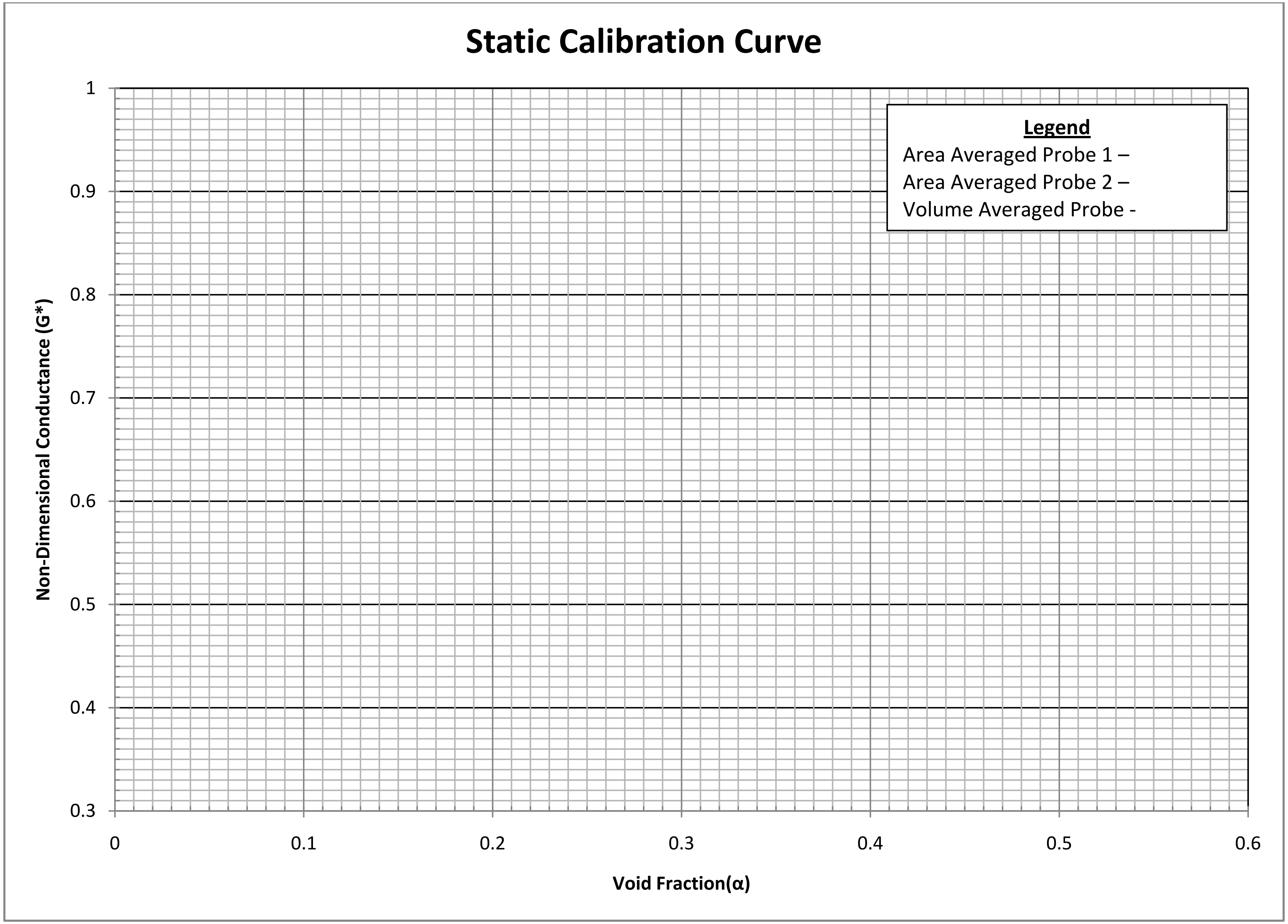
$$(\alpha\lfloor\rho_g - \rho_f\rfloor + \rho_f)H = (\rho_f - \rho_m)h + \rho_f H$$

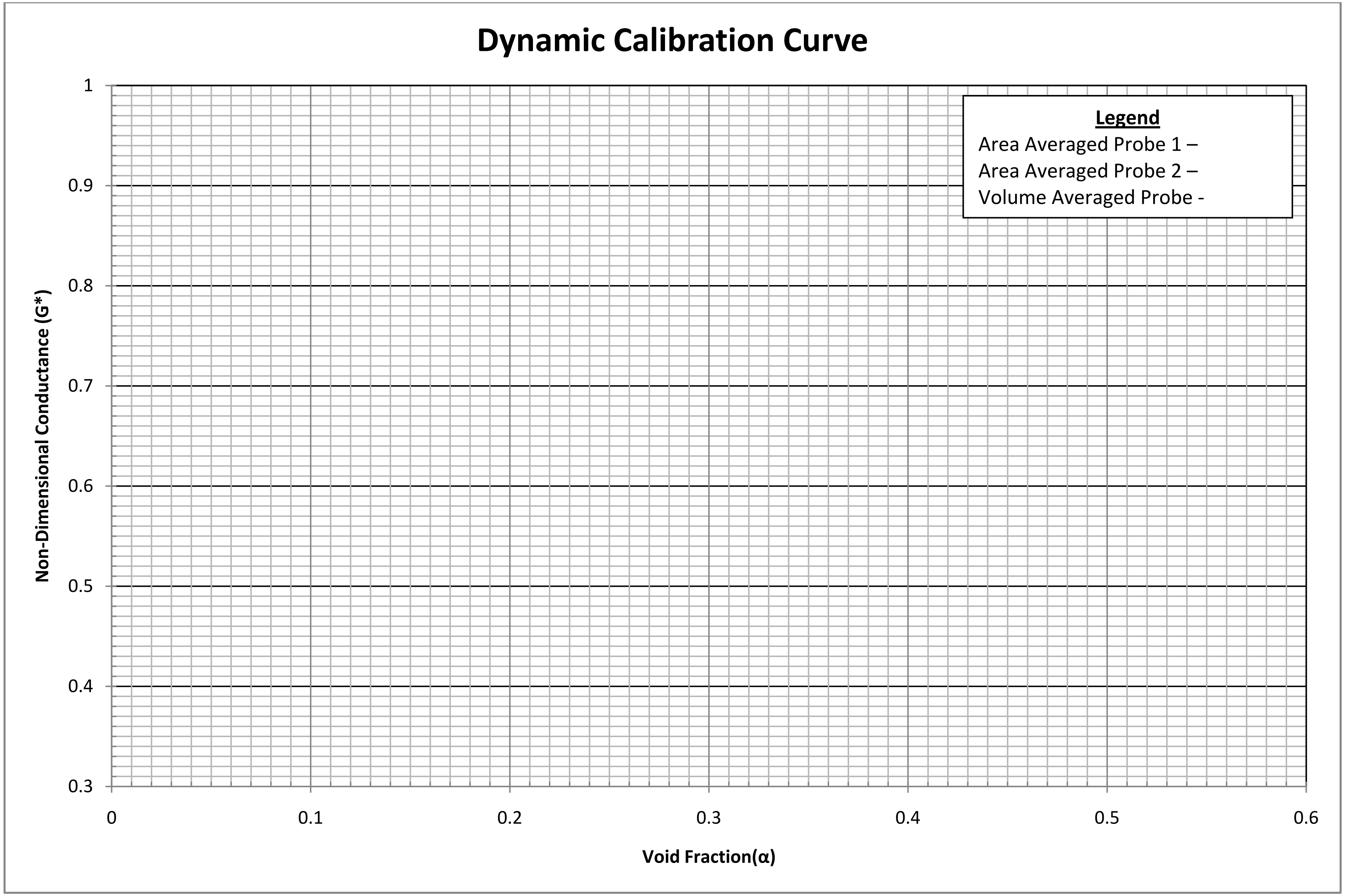
Canceling $\rho_f H$ on both sides and re-arranging

$$\alpha = \frac{(\rho_f - \rho_m)h}{(\rho_g - \rho_f)H} = \frac{(\rho_m - \rho_f)h}{(\rho_f - \rho_g)H}$$

$$\boxed{\alpha = \frac{(\rho_m - \rho_f)h}{(\rho_f - \rho_g)H}}$$

***


Static Calibration Curve
Legend
Area Averaged Probe 1 –
Area Averaged Probe 2 –
Volume Averaged Probe -
Non-Dimensional Conductance (G*)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
0.1
0.2
0.3
0.4
0.5
0.6
Void Fraction(α)


Dynamic Calibration Curve
Legend
Area Averaged Probe 1 –
Area Averaged Probe 2 –
Volume Averaged Probe -
Non-Dimensional Conductance (G*)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
0.1
0.2
0.3
0.4
0.5
0.6
Void Fraction(α)

Observations - Static Calibration Experiment

Diameter of the pipe = 24mm Area of Cross Section of Pipe =

Area Averaged Probe 1

No	Rod Diameter ( )	Area of Rod ( )	Void Fraction	Measured Voltage (V)			Non Dimensional Conductance (G*)		
				Minimum	Mean	Maximum	Minimum	Mean	Maximum
1									
2									
3									
4									
5									

Area Averaged Probe 2

No	Rod Diameter ( )	Area of Rod ( )	Void Fraction	Measured Voltage (V)			Non Dimensional Conductance (G*)		
				Minimum	Mean	Maximum	Minimum	Mean	Maximum
1									
2									
3									
4									
5									

Volume Averaged Probe

No	Rod Diameter ( )	Area of Rod ( )	Void Fraction	Measured Voltage (V)			Non Dimensional Conductance (G*)		
				Minimum	Mean	Maximum	Minimum	Mean	Maximum
1									
2									
3									
4									
5									

Observations - Dynamic Calibration Experiment

Density of Manometric Fluid (ρ_m) = 1595.92 kg/m^3 Density of Liquid (ρ_l) = 1000 kg/m^3 Density of Gas (ρ_g) = 1.2 kg/m^3

Distance between Pressure Ports (H) = 600mm

Area Averaged Probe 1

No	Gas Flow Rate (LPH)	Height (h) of Manometric Fluid (mm)	Void Fraction	Measured Voltage (V)			Non Dimensional Conductance (G*)		
				Minimum	Mean	Maximum	Minimum	Mean	Maximum
1									
2									
3									
4									
5									

Area Averaged Probe 2

No	Gas Flow Rate (LPH)	Height (h) of Manometric Fluid (mm)	Void Fraction	Measured Voltage (V)			Non Dimensional Conductance (G*)		
				Minimum	Mean	Maximum	Minimum	Mean	Maximum
1									
2									
3									
4									
5									

Volume Averaged Probe

No	Gas Flow Rate (LPH)	Height (h) of Manometric Fluid (mm)	Void Fraction	Measured Voltage (V)			Non Dimensional Conductance (G*)		
				Minimum	Mean	Maximum	Minimum	Mean	Maximum
1									
2									
3									
4									
5									