VALIDATION OF EXPERIMENTAL DATA USING CONCOMITANT MEASUREMENT SYSTEMS

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Abstract

This paper presents and discusses results of experimental research on validation of measured physical and dynamic parameters using concomitant measurement systems. The measured parameter is spatial concentrations of two-phase flow of air-water mixture in a vertical column using both capacitive and resistive computer-aided measurement systems. This information is important in applications of pipe and reactor flow optimization since concentration is directly related to frictional losses. Two-phase flow is also important in optimizing and controlling other applications such as lubrication, heat exchangers, evaporators, condensers, and boilers.

In the case of this study, two phase flow medium will be air-water heterogeneous mixture. This mixture is easily simulated in a laboratory using a vertical column of water with an air source attached to the base. Concentration is changed by regulating the amount of air flow into the column. In this experiment, a resistive and capacitive sensor is used to collect data. The data collected will be analyzed using root mean square (RMS), probability distribution function (PDF) and power density spectrum (PSD). In aerospace, mechanical, chemical, and civil engineering, the phenomena of two-phase flow is often encountered, including air-water mixture. One of the most important parameters in controlling two phase flow is void fraction or its complementary parameter, spatial concentration. Started in 40's and as of today, two-phase flow is still a challenging phenomenon to predict and control because of its random nature. A concern with a random natured signal is noise. This paper attempts to eliminate interference noise by incorporating different types of low-pass filters. One is a simple low-pass filter built with a 741 op-amp, the other is a low-pass filter kit supplied by Microchip, and the last is a digital Cheby filter. The comparison and calibration of dynamic signals will show the importance of the experimental approach. This discussion will encourage undergraduate and graduate students to be precise in their studies and experimentation.

1. Introduction

Currently, two-phase flow has emerged as a promising research area in the petroleum, aerospace, bioengineering, medicine, and power engineering technologies. Continuing advances in space transportation systems, nuclear reactors, microsystems such as the microheat exchanger, oil and gas piping technology along with concomitant system cost reductions have supported the development of more usable, useful, and accessible two-phase flow systems that can uniquely attempt to incorporate two-phase flow into a mathematical model.

Over the last 50 years, researchers have produced intensive work towards a better understanding of two-phase flow. However, there are many discrepancies between the different studies due to employing different sizes, shapes, and lengths of flow channels along with different methods for introducing each phase and flow pattern. These differences are the result of the presence of different velocities for different phases as well as other parameters such as the void fraction. Researchers have used several techniques and systems to measure void fraction such as optical, resistive, and capacitive sensors as well as x-rays, gamma-rays, pressure transducers, radiation dyes, etc. Yet, the determination of flow pattern phenomena is extremely subjective and ambiguous[1,2].

This paper introduces an experimental research on the validation of void fraction measurements for an air-water mixture in a vertical pipe using resistive and capacitive computer-aided measurement systems. Keska[4] developed a computer aided measurement system that measured the in-situ parameters of two-phase flow by using resistive and capacitive sensors. The capacitance of a capacitive sensor is a function of the geometric parameters of the sensor and the resulting dielectric constant of the mixture, which is a function of concentration:

$$C_i = \frac{1.01\varepsilon_o l_c \left(\varepsilon_1 c_v + (1 - c_v)\varepsilon_2\right)}{\ln\left(1 + \frac{\pi D}{b_c} tanh^2\left(0.7\frac{D}{b_c}\right)\right)} \tag{1}$$

The resistance of a resistive sensor is a function of the geometric parameters of the sensor and the resulting specific resistivity of the mixture, which is a function of concentration:

$$R = [\rho_w c_v + \rho_a(1 - c_v)]\frac{L}{A} \tag{2}$$

The objective of this paper is to report the results of experimental investigations (with validation of results) on two-phase flow parameters for various two-phase flow patterns/regimes in air-water heterogeneous mixture flows in a 50.8 mm diameter vertical pipe using two concomitant (capacitive and resistive) void fraction measurement methods. Concomitancy between the capacitive and conductive method is documented by analysis of the data in the time, amplitude, and frequency domains using AC and DC signals, PDF, CPDF, PSD, CPSD, and error analysis.

2. Related Work

In recent years, researchers are carrying out extensive work to satisfy the need for more reliable analysis and application of two-phase flow systems. Two-phase flow has been studied using different measuring devices and analysis techniques. Generally, methods such as void fraction/time signals, RMS of void fraction/time signals, the PSD, and the PDF are used to accurately identify and interpret two-phase flow. Visual identification methods using high speed cameras and/or stroboscopes have also been used to identify flow patterns but as the applications of two-phase flow system increases, the visual flow pattern identification becomes inappropriate. Although all these methods contribute to the better understanding of flow patterns in two-phase flow, there is no accepted method that precisely describes flow patterns[7].

N. K. Omebere-Iyari and B. J. Azzopardi obtained void fractions data and flow pattern information for two-phase air/water flows in a small diameter (5 mm) vertical pipe using conductance probes. In their studies, a novel approach has been developed for determining slug-to-churn and churn-to-annular flow transitions in vertical two phase flow based on changes in the structure velocity. According to their results, the PDF method fails to delineate the exact location of the slug/churn transition accurately but performs better for the churn to annular flow transition[6].

Renqiang Xiong and J. N. Chung experimentally investigated adiabatic gas-liquid flow patterns and void fractions in microchannels using nitrogen and water flow in rectangular microchannels with varying hydraulic diameters and gas and liquid superficial velocities. The main objective of the authors was focused on the effects of microscale channel sizes on the flow regime map and the void fraction. The instability of flow patterns was observed. The authors concluded that with the decreasing of the hydraulic diameter, the time-averaged void fraction showed a nonlinear relationship with the homogeneous void fraction. And a new empirical correlation was proposed to predict such nonlinear relationship[8].

Keska was the first to introduce concomitant measurement systems to determine a more objective mathematical method to identify and analyze two-phase flow in-situ parameters. Such method solves the problem of measuring the concentration of a dynamic homogeneous mixture flow.

Keska and Simon used a 0.996 mm x 0.996 mm horizontal microchannel to investigate air-water flow with measurement systems for concentration using both capacitive and conductive sensors, an optical system, and pressure measurement devices. Within the channel, two independent and concomitant measurement systems were used to measure the in-situ spatial concentration of the air-water mixture flowing through the capacitive and conductive sensors. Their work concluded that a there is a high level of concomitancy between the conductive and capacitive systems of concentration measurement, and each method has a high sensitivity to flow patterns having a deterministic character[3].

Ma and Keska used a horizontal, 6.35mm x 6.35 mm minichannel with a capacitive and resistive computer-aided measuring system to find a RMS values for in-situ parameters such as concentration, velocity, and pressure for an air-water flow. The experimental results show that both capacitive and conductive systems are fully concomitant with respect to spatial concentration[4].

3. Experimental System

The experimental system shown in Fig. 1 consists of a vertical transparent channel measuring 50.8 mm (2 inches) in diameter and 0.61 meters (2 feet) in length. At the bottom of the channel is an inlet line, which allows air to enter into the channel and mix with the water generating two-phase flow. Air was provided by the laboratory compressed-air supply, metered through valves, and the flow rate was measured with a rotameters.

Figure 1. Experimental column

The measurement of two-phase flow parameters is performed using a capacitive and a resistive sensor. The capacitive and resistive sensors measure void fraction because water is an electrical conductor, although a poor one, while air is essentially resistive. In this technique, the relationship between electrical impedance and phase distribution is measured by the probes, which give a voltage output which is proportional to the resistance of the two-phase mixture. The measurements from the probes are acquired using a PC installed with a National Instrument (NI) ELVIS System that is interfaced to the probes using DC and AC Wheatstone Bridges respectively as shown in Fig. 2, generating signals proportional to the void fraction[5,6].

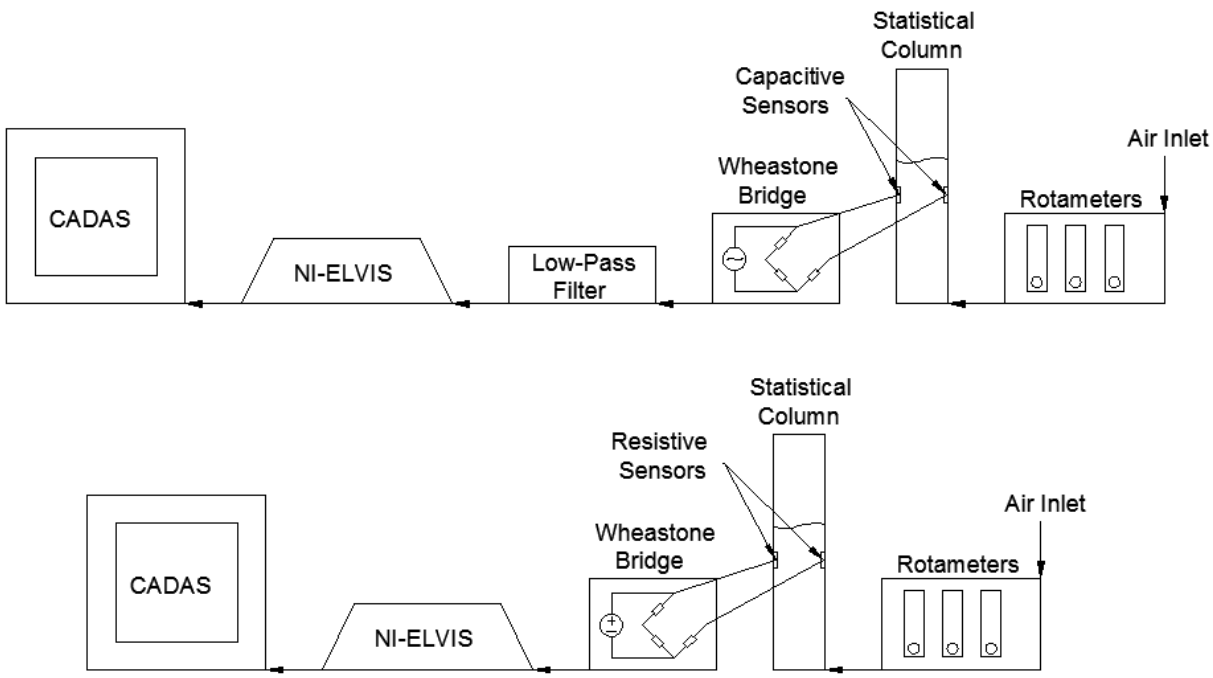

Figure 2. Experimental setup of the computer-aided a) capacitive system, and b) resistive system

For the capacitive system, three different filters are used to condition the signal. The first is a simple RC filter (741) build according to Fig. 3, the second is a professional filter supplied by Microchip (professional) as shown by Fig. 4, and the third is a digital Chebyshev filter (Cheby) programmed via MatLab. The approach of the paper is to analyze the signal generated by each of the experimental systems and check the concomitancy of each capacitive signal with each other as well as with the resistive signal.

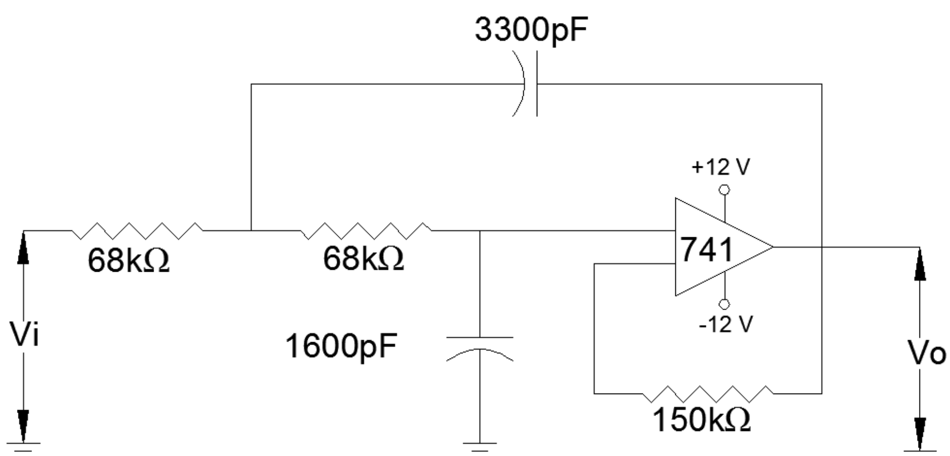

Figure 3. 741 low-pass filter

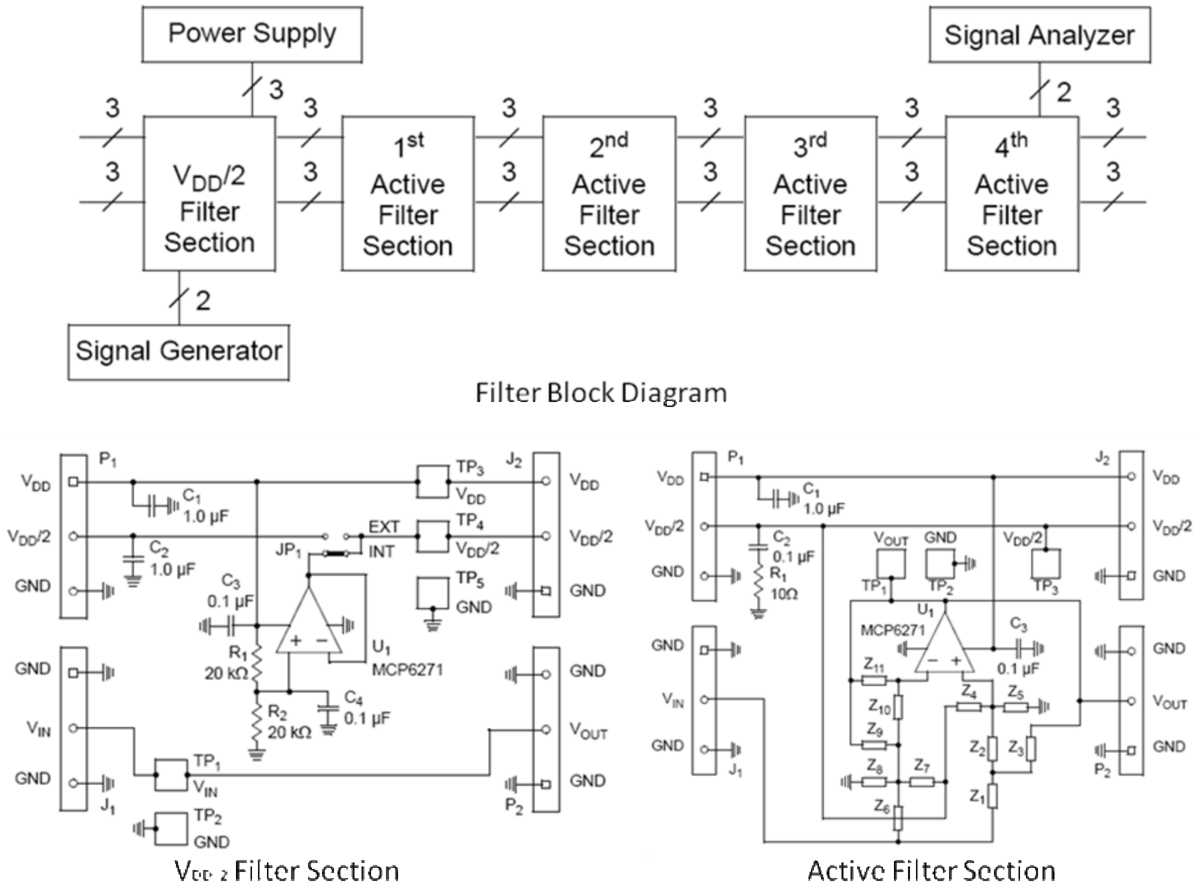

Figure 4. Microchip low-pass filter schematics

4. Experimental Data Gathering and Analysis

The need to face the challenges associated with two-phase flow generated our approach to investigate the phenomenon of flow patterns in two-phase flow. Using the experimental system, signals for four different flow conditions, as shown in Table 1, were taken and analyzed in the time domain using a resistive sensor and capacitive sensors with different signal conditioners as illustrated in Fig. 5.

	Air Flow Rate, [m^3/s]	Superficial Air Velocity, [m/s]
Flow 1	0.000039	0.0194
Flow 2	0.000118	0.0582
Flow 3	0.000472	0.2329
Flow 4	0.001180	0.5821

Table 1. Specification of flow conditions

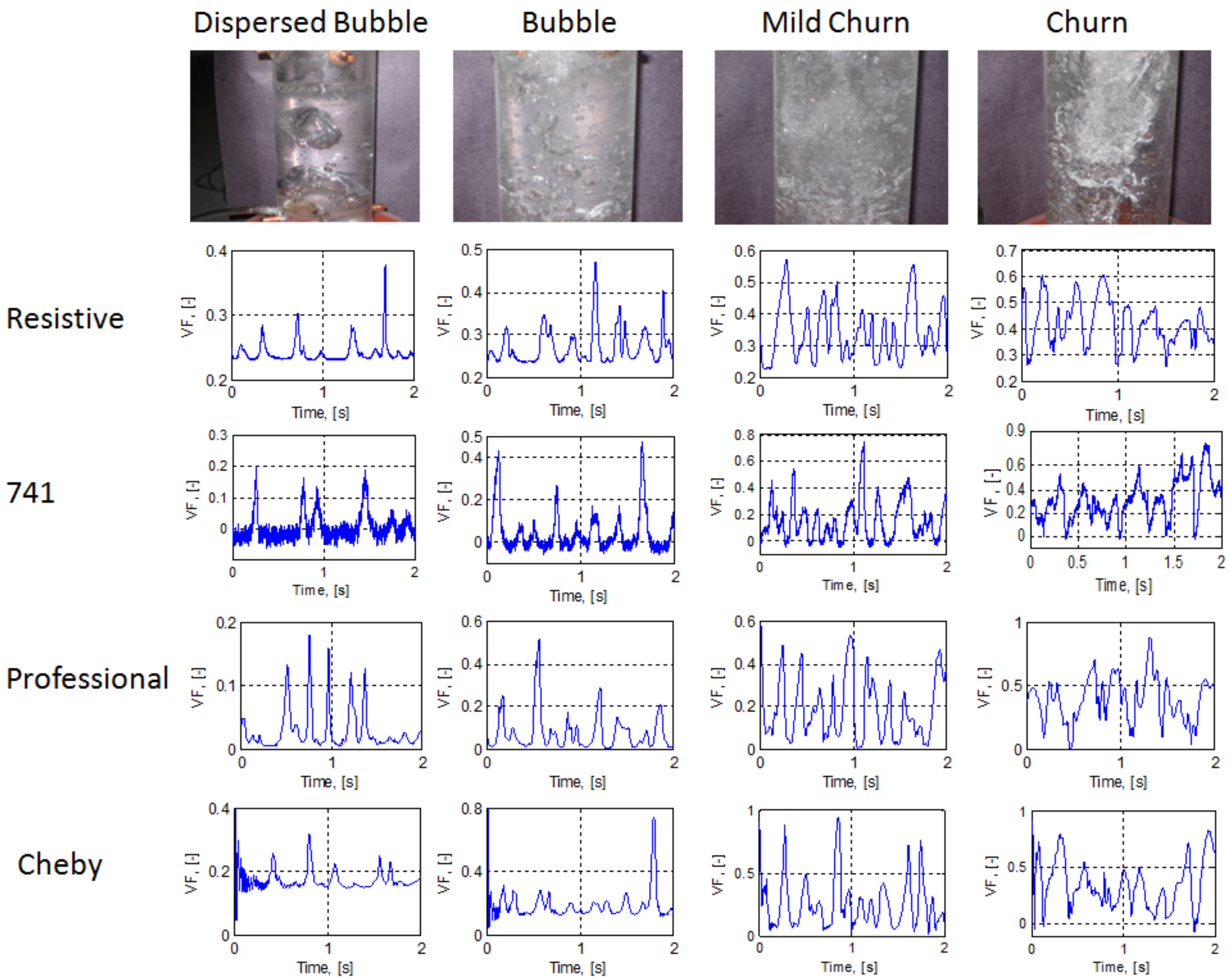

Figure 5. Comparison of two-phase flow signals in time domain for resistive and capacitive sensors for four different flow conditions

The first row of Fig. 5 shows a picture of the flow patterns created by air flow velocities of 0.019, 0.058, 0.233, and 0.582 m/s respectively. According to visual observation, the flow patterns have been classified as dispersed bubble, bubble, mild churn, and churn. The second row represents dynamic signals of void fraction vs. time taken by the resistive sensor for each flow pattern respectively. The third row illustrates dynamic signals of void fraction vs. time taken by a capacitive sensor using a simple low-pass filter as shown in Fig. 3 for each flow pattern respectively. The fourth row illustrates dynamic signals of void fraction vs. time taken by the a capacitive sensor using a Microchip filter as shown in Fig. 4 for each flow pattern respectively. Finally, the fifth row illustrates dynamic signals of void fraction vs. time taken by a capacitive sensor using a digital Cheby filter for each flow pattern respectively.

Fig. 5 depicts that there is a similitude between both methods and the same flow pattern; additionally, there are differences between the flows for different flow patterns. However, a better analysis is needed to expose the differences. In the past decades, researchers have been utilizing PDF and CPDF plots to analyze and categorize two-phase flow. The distribution of the void fraction measurements for the resistive signal as well as the capacitive signal of Fig. 5 are shown in Fig. 6.

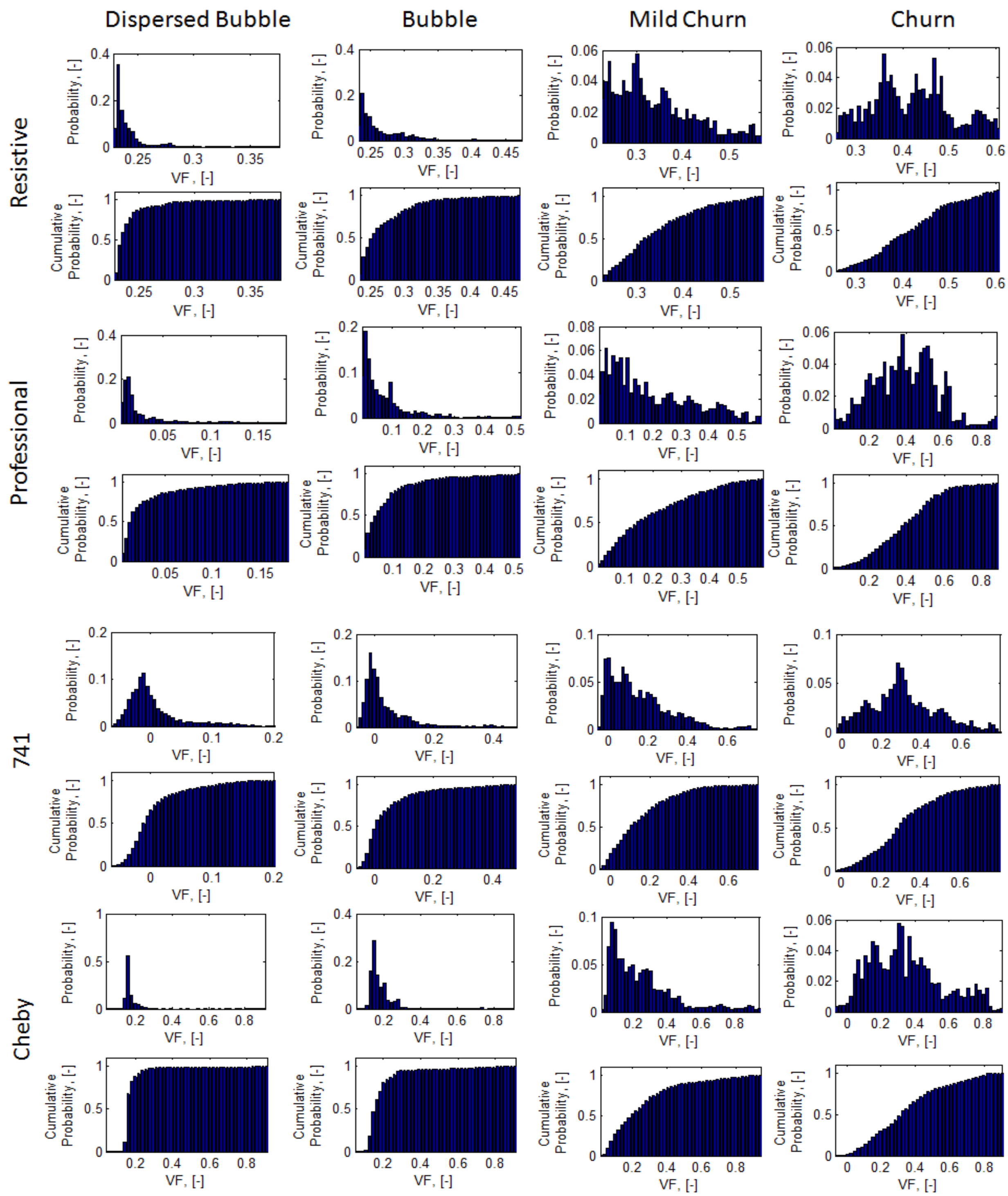

Figure 6. Comparison of two-phase flow signals in amplitude domain for resistive and capacitive sensors for four different flow conditions

The first and second rows of Fig. 6 show the PDF and CPDF respectively for the four flow patterns created by the conditions of Fig. 5 for the resistive sensor. The third and fourth rows show the PDF and CPDF respectively for the four flow patterns created by the conditions of Fig. 5 for the capacitive sensor using the professional filter. The fifth and sixth rows show the PDF and CPDF respectively for the four flow patterns created by the conditions of Fig. 5 for the capacitive sensor using the 741 filter. The seventh and eighth rows show the PDF and CPDF respectively for the four flow patterns created by the conditions of Fig. 5 for the capacitive sensor using the Cheby filter.

Fig. 6 depicts that there is a similitude between both methods and the same flow pattern; in addition, there are differences between the flows for different flow patterns. The flow pattern for the dispersed bubbly flow is characterized by one significant peak at a void fraction value between 0-0.2. This suggests that the mixture is mostly water; the other small peaks show higher void fraction values due to the presence of air from the bubbles. Similarly, bubbly flow is characterized by one representative peak at a low void fraction value; however, there is more air in the mixture. On the other hand, the churn flows show a highly fluctuating PDF with several peaks that represent the void fraction in liquid and gas bubbles.

As a result, a better analysis is needed to expose the differences in the churn flow and to better define the dispersed bubble and bubbly flows. This creates the need for further investigation of the flow differences including frequency fluctuation of the signals using PSD. Fig. 7 depicts the PSD analysis for the same signals illustrated in Fig. 6.

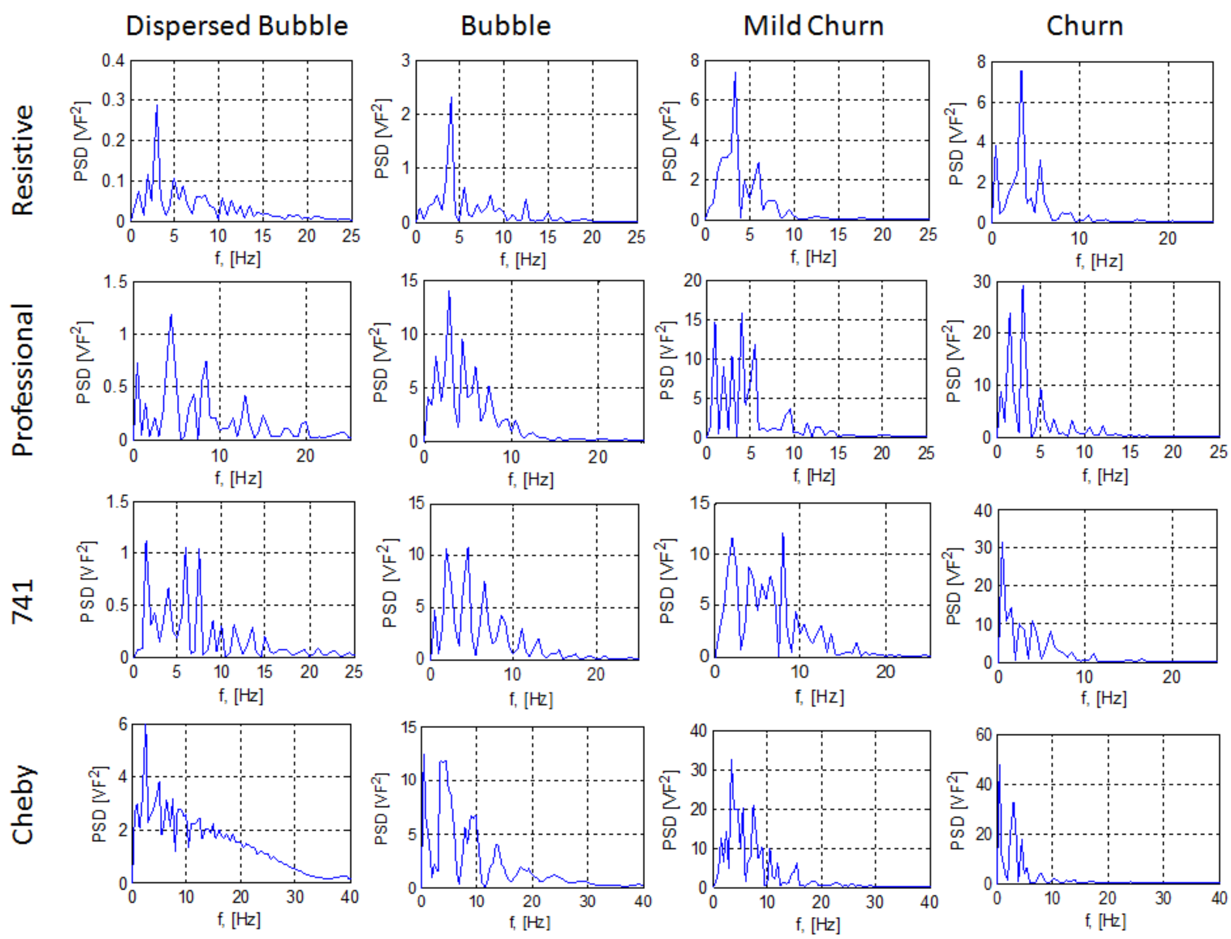

Figure 7. Comparison of two-phase flow signals in frequency domain for resistive and capacitive sensors for four different flow conditions

The PSD plots are a very powerful method to study flow patterns because they detect signal changes in the frequency domain which can be associated to different flow patterns and flow regimes. Generally, each flow pattern has a typical characteristic PSD. However, Fig. 7 shows differences between all four methods and the same flow patterns; additionally, there are differences between the flows for different flow patterns.

For instance, for dispersed bubble flow, Fig. 7 shows highly fluctuating power spectrum between methods. The resistive sensor registers a maximum PSD of about 0.3 while the capacitive sensors register maximums 1.2, 1.1, and 6.0 between the professional, 741, and Cheby filters respectively. Additionally, the resistive PSD exhibits one distinctive peak at a frequency of 3 Hz while the capacitive PSDs have several peaks at different frequencies. For the other flow patters the same phenomena occurs.

As a result, it becomes of critical importance to develop a method to precisely compare each signal taken under the same flow patter in order to understand the concomitancy of the measurement systems. Fig. 8 shows the non-dimensional PSD for all flow patterns for the capacitive sensor using the professional filter.

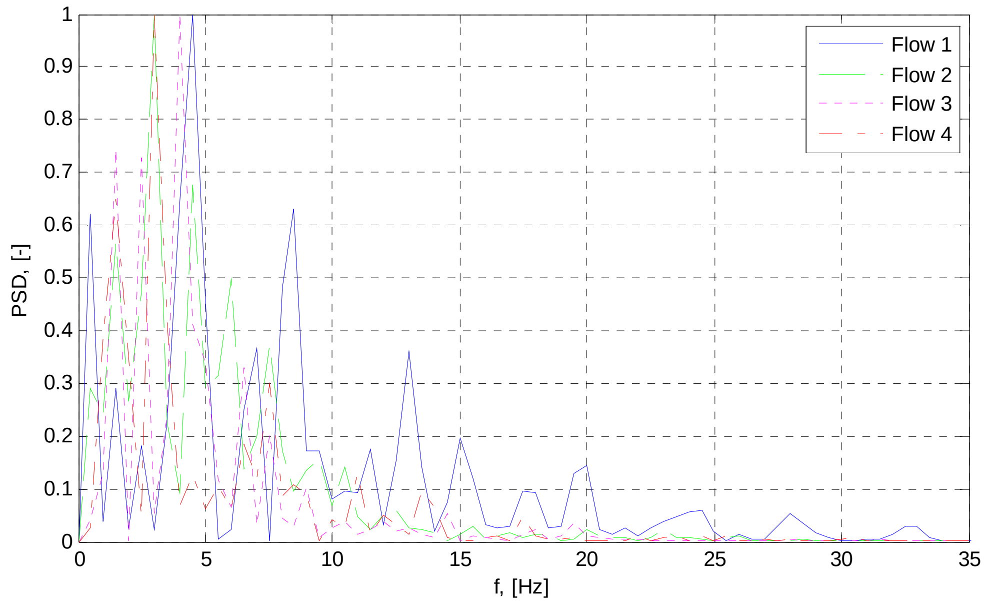

Figure 8. Comparison of two-phase flow signals in non-dimensional frequency domain for capacitive sensor using professional filter for four different flow conditions

Similarly, Fig. 9 illustrates the non-dimensional CPSD for all four flow pattern shown in Fig. 8.

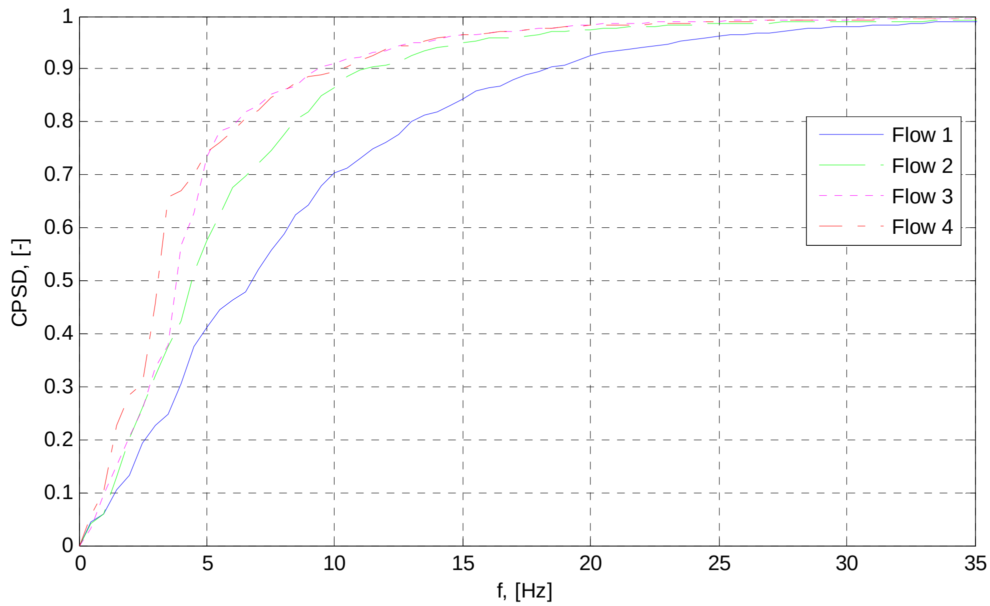

Figure 9. Comparison of two-phase flow signals in non-dimensional cumulative frequency domain for capacitive sensor using professional filter for four different flow conditions

By observing Fig. 9 a value taken at 0.5 (50%) of the non-dimensional CPSD will produce several different frequencies for each flow pattern. The frequency decreases as the flow rate increases. Fig. 9 information leads to further analysis of non-dimensional CPSD. The 50%

NCPSD value for each flow is interpolated from MatLab arrays. Below in Fig. 10 is a comparison of 50% NCPSD value of a chosen sensor vs. the total average of 50% values for each flow pattern.

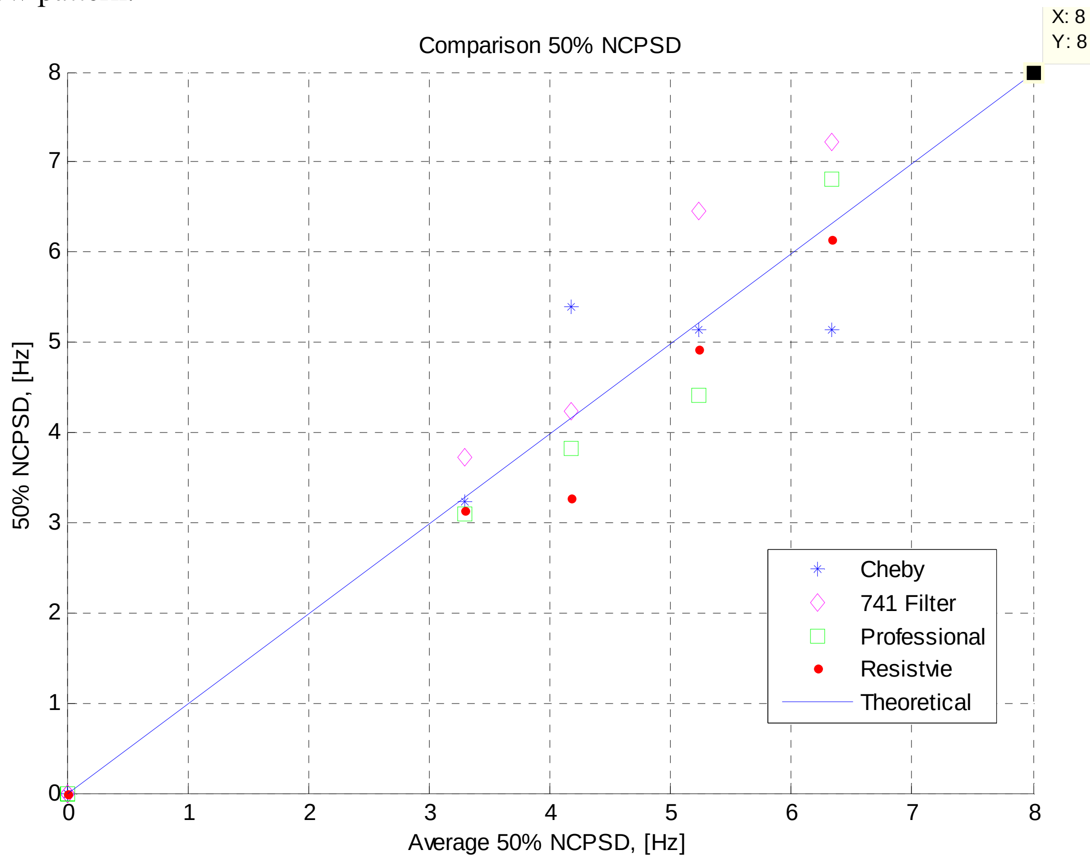

Figure 10. Comparison of 50% Non-Dimensional CPSD

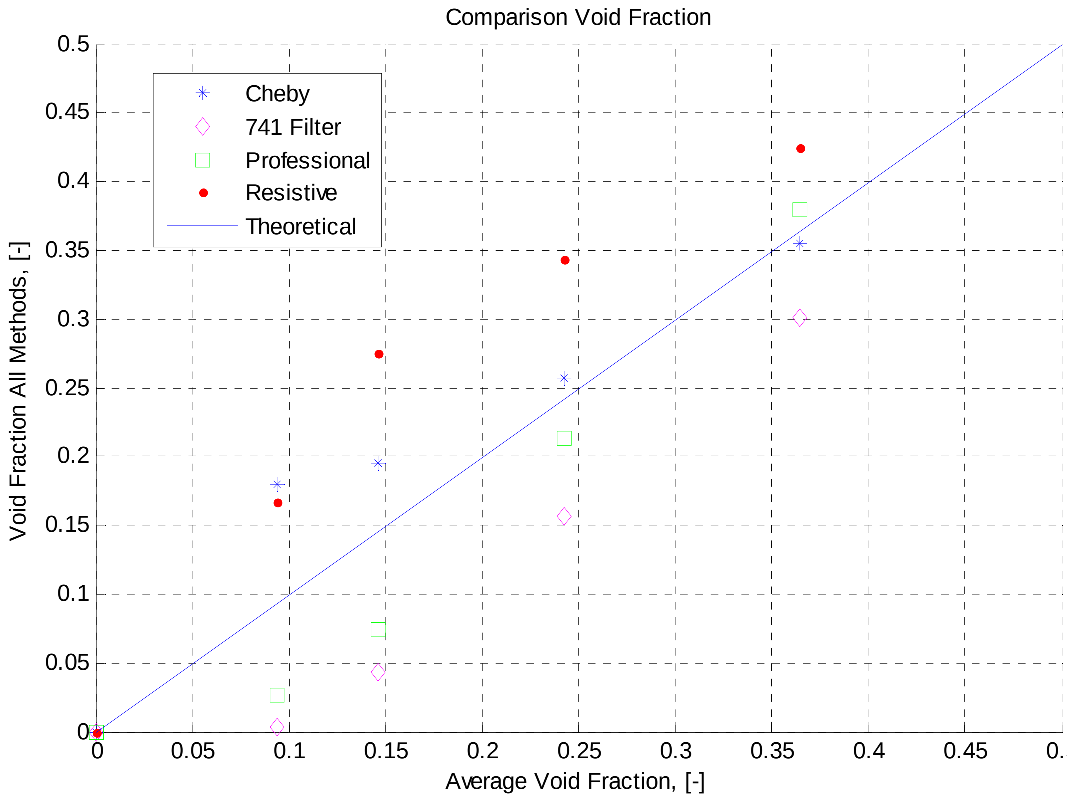

Figure 11. Comparison of Void Fraction

In Fig. 11 a plot of void fraction for a chosen sensor is compared to the total average value of the void fraction for each flow pattern.

For Fig. 10 and Fig. 11 an error was calculated using:

$$\delta = (\text{value} - \text{theoretical value}) / \text{theoretical value}$$

It shows that the Professional Filter produced the least error using 50% NCPSD value, but the Chebyshev digital filter produced the least error using the void fraction error. Overall the Professional Filter results had the least amount of error.

Below in Fig. 12 a plot of 50% NPSD value vs. Superficial Gas Velocity. It is shown here that frequency decreases as superficial gas velocity increases. This was also stated above concerning Fig. 9, but here it is shown for every sensor type used in this experiment.

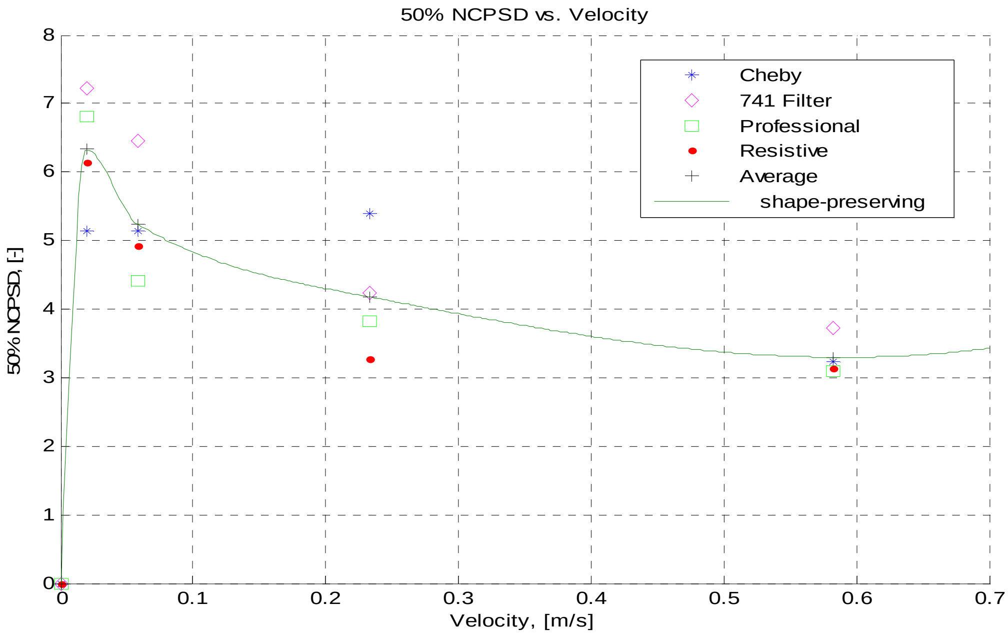

Figure 12. 50% Non-Dimensional CPSD vs. Superficial Gas Velocity

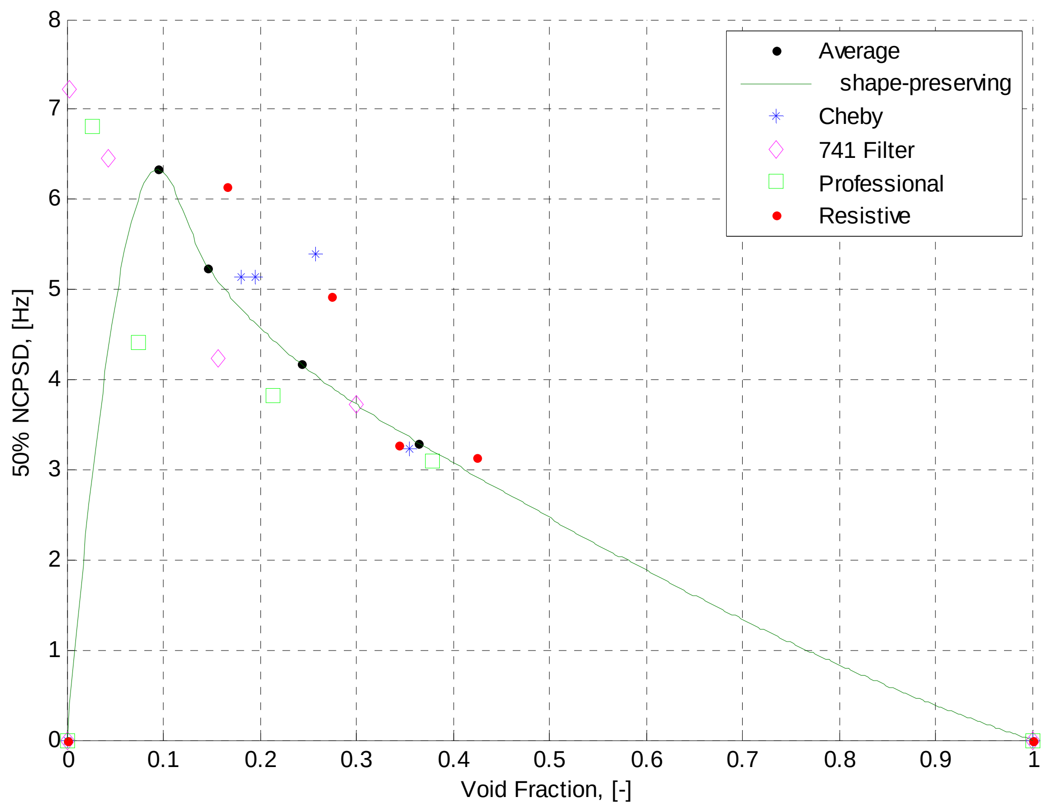

Figure 13. 50% Non-Dimensional CPSD vs. Void Fraction of All Sensor Methods

Figure 13 shows the frequency value decreases as void fraction increases.

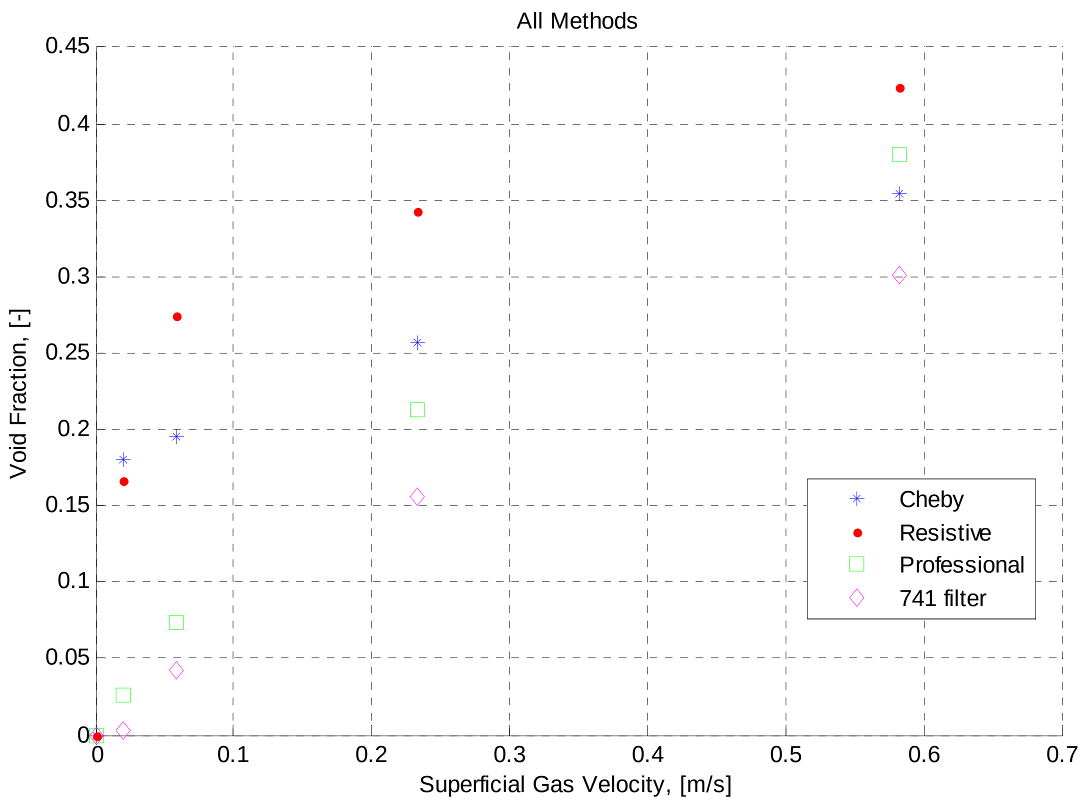

Figure 14. Void Fraction vs. Superficial Gas Velocity

In Fig. 14 it is observed that as the superficial gas velocity increases the void fraction measurement becomes more closely related for each measurement system. This is also shown below in Fig. 15 where the error decreases as the void fraction increases.

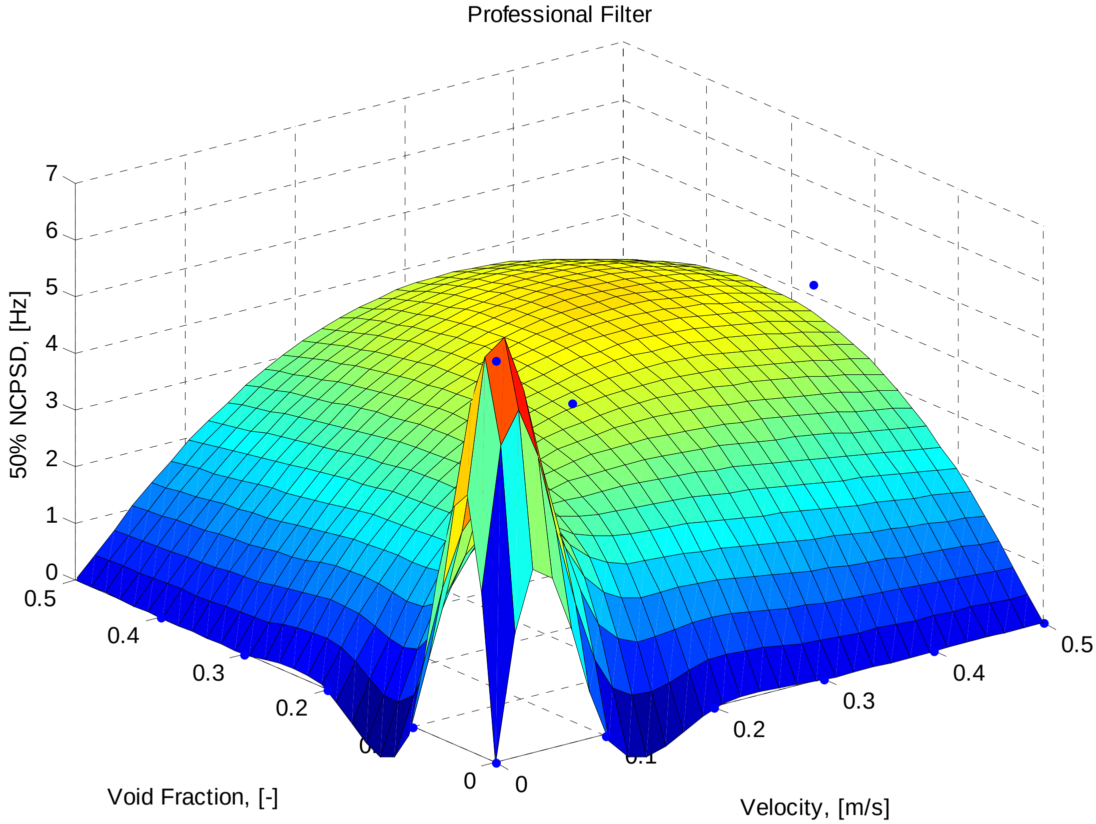

Figure 15. Professional Filter (Void Fraction vs. Velocity vs. 50% NCPSD)

Fig. 15 is a 3D plot of void fraction vs. superficial gas velocity vs. 50% NCPSD. An important note is the spike in frequency at low gas velocity. Beyond the max the plot is decreasing as velocity increases which is also noted in Fig. 12 and Fig. 13. For future investigation, it will be necessary to record more data points at smaller intervals of gas velocity especially from 0 to 0.1 [m/s].

6. Conclusions

This experimental study of air-water heterogeneous mixture in a computer-aided experimental system in a vertical channel on in-situ spatial concentration characteristics for steady-state flow concluded that:

1. The developed unique prototypes of computer-aided capacitive (AC bridge) and resistive (DC bridge) void fraction meters demonstrated a good frequency response to monitor this dynamic process with ability to serves as concomitant systems for void fraction measurements based on void fraction signal analysis in time, amplitude, and frequency domains.

2. The analyzed in-situ void fraction signals from both resistive and capacitive systems in time (void fraction vs. time), amplitude (PDF and CPDF) and frequency (PSD and CPSD) domains show changes with flow pattern changes indicates high sensitivity to flow patterns, as documented broadly in the frequency domain.

3. In order to find the best solution there were investigated three versions of capacitive void fraction meters differentiated by various low-pass filters specifically: (1) simply one stage low-pass filter based on op-amp 741, (2) professional Microchip low-pass filter, and (3) digital Chebyshev low-pass filter. The results shows that the Microchip low-pass filter application is generating the best results, however two other low-pass filters used are generating less accurate but still acceptable results.

4. Due to the limited variation of investigated flow patterns, the study is considered as a first step to further and broader research expanded of more and full spectrum of flow patterns and eventually column diameters and other mixtures.

7. Acronyms

741	low-pass filter build to Fig. 3 specification
CADAS	computer-aided data acquisition system
Cheby	Chebyshev digital filter
CPDF	cumulative probability density function
CPSD	cumulative power spectral density
NCPSD	non dimensional power spectral density
PDF	probability density function
Professional	Microchip low-pass filter
PSD	power spectral density
RMS	root mean square

8. Nomenclature

A	cross-sectional area (m^2)
b_c	capacitor plate width (m)
C	capacitance (F)
C_v	concentration (-)
D	channel diameter (m)
ε_0	dielectric constant (-)
ε_1	dielectric constant of liquid (-)
ε_2	dielectric constant of air (-)
L_c	length (m)
R	resistance (Ω)
ρ_w	resistivity of water (Ωm)
ρ_a	resistivity of air (Ωm)
VF	void fraction (-)

References

1. Shim, W. Jaewoo and Chul Hue Jo, "Analysis of Pressure Fluctuations in Two-Phase Vertical Flow in Annulus." Journal of Industrial and Engineering Chemistry, Volume 6, Issue 3, 2000, Pages 167-173.
2. Ma, Chengyi, "Flow Patterns in Air-Water Two-Phase Mixture Flow in a Small Horizontal Channel." 2008.
3. Keska, Jerry K., and William E. Simon, "Flow Pattern Phenomena in Two-Phase Flow in Microchannels." *AIP Conference Proceedings* 699.1 (2004): 3-11.
4. Ma, Chengyi and Jerry Keska, "Root-Mean-Square (RMS) Values of In-Situ Parameters in Air-Water Heterogeneous Mixture Flow in a Horizontal Minichannel." Proceedings of the 2009 ASEE Gulf-Southwest Annual Conference. Session FB1-3
5. Keska, Jerry K., and William E. Simon "Mathematical Model of Two-Phase Flow in Advanced Micro Cooling Modules Incorporating Flow Pattern Phenomena." AIP Conference Proceedings 880.1 (2007): 118-128.
6. N.K. Omebere-Iyari and B.J. Azzopardi, "A Study of Flow Patterns for Gas/Liquid Flow in Small Diameter Tubes." Chemical Engineering Research and Design, Volume 85, Issue 2, 2007, Pages 180-192.
7. Cai, Y., M. W. Wambsganss, and J. A. Jendrzejczyk, "Application of Chaos Theory in Identification of Two-Phase Flow Patterns and Transitions in a Small, Horizontal, Rectangular Channel." Energy Technology Division – Argonne National Laboratory, 1996.
8. Xiong, Renqiang, and J. N. Chung, "An Experimental Study of the Size Effect on Adiabatic Gas-Liquid Two-Phase Flow Patterns and Void Fraction in Microchannels." Physics of Fluids, 19, 2007.

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