REDUCTION OF FREQUENCY FLUCTUATION DEVIATION OF VOID FRACTION IN WATER-AIR HETEROGENEOUS MIXTURE FLOW

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Abstract

In the steady-state flow of a heterogeneous mixture such as an air-water mixture, velocity and void fraction are space- and time-dependent parameters. These parameters are the most fundamental in the analysis and description of multiphase flow. For a steady-state gas-liquid flow, the energy used for transfer is proportional to pressure losses and influenced by concentration, velocity, and flow patterns. Determination of flow patterns is extremely critical, since this is directly related to sudden changes in spatial and temporal changes of the concentration having a random characteristic, which could be described by concentration signals in time, amplitude and frequency domains. Despite its vital importance and countless attempts to solve or incorporate the flow pattern phenomena into models, still it has been a very challenging topic in the scientific community since the 1940's and has not yet reached any close satisfactory solution.

This paper reports results of an experimental study of air-water heterogeneous mixture in a computer-aided laboratory system with a vertical channel on in-situ spatial concentration characteristics for steady-state flow. The characteristics manifested random characters and generated flow instabilities and changes in both flow patterns and flow rates. The data are analyzed in time and frequency domains. Due to the random character, the void fraction vs. time data indicated unique characteristics generating wide differences between two consecutive signals shown in the frequency domain as the power spectral density (PSD) and cumulative power spectral density (CPSD) characteristics. In addition, the effective way to reduce those differences is shown and addressed in this paper.

1. Introduction

Nowadays, intensive applications of multiphase flow in space transportation systems, nuclear reactors, microsystems such as the microheat exchanger, oil and gas piping, as well as the petroleum, aerospace, transport, bioengineering, medicine, and power engineering technologies create the necessity of a better control of the parameters associated with multiphase flow. Two-phase flow is significantly problematic due to the presence of many parameters such as velocity of the mixture and its components, spatial concentration, film thickness, and the spatial and temporal distributions of these parameters. The effect of these variables creates challenges in describing the flow phenomena since these variables greatly influence the nature of the two-phase flow, resulting in significant differences in reported results, compounded by difficulty in defining the experimental conditions, in verification and validation of measured and calculated data, and in comparing the results of different experimenters. Since the 1940's, researchers have been exercising extensive work to develop a more reliable method for the analysis and application of two-phase flow parameters. 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. The flow pattern phenomenon is the most challenging, yet not well-defined problem[1-3].

In the steady-state flow of a heterogeneous mixture such as an air-water mixture, velocity and void fraction are space- and time-dependent parameters. These parameters are the most fundamental in the analysis and description of multiphase flow. Researchers have used several techniques to measure void fraction. Local void fraction measurements can be made using resistive or capacitive probes. A similar method utilizes the change in refractive index, which occurs when a fiber optical probe tip is immersed in a gas or a liquid. Other methods such as radiation attenuation, pressure transducers, x-ray, nuclear magnetic resonance, and multi-beam gamma densitometers have also been developed for void fraction measurements. For a steady-state gas-liquid flow, the energy transfer is proportional to pressure losses, concentration, and flow patterns. Determination of flow patterns is extremely critical, since this is directly related to sudden changes in space and temporal fluctuations of the void fraction[2,4].

In this paper emphasis is given to the analysis of the random fluctuations using experimental results from steady-state, heterogeneous, air-water mixture flow in a vertical pipe. Specially, how they could be documented, analyzed, and finally applied in the process and how such fluctuations are related to flow patterns. Due to the random character of the signal, the void fraction vs. time data generates wide differences between two consecutive signals in the frequency domain as the power spectral density (PSD) and cumulative power spectral density (CPSD).

According to Dunn, signal's PSD represents the signal's amplitude components versus their corresponding frequency components. This spectrum can be determined from the Fourier series of the signal. Consider the time average of the square of y(t),

$$\langle [y(t)]^2 \rangle \equiv \frac{1}{T}\int_0^T [y(t)]^2 dt. \tag{1}$$

The square of y(t) in terms of the Fourier complex exponential sum is

$$[y(t)]^2 = \left(\sum_{m=-\infty}^{\infty} C_m e^{im\omega_0 t}\right)\left(\sum_{n=-\infty}^{\infty} C_n e^{in\omega_0 t}\right) = \sum_{m=-\infty}^{\infty}\sum_{n=-\infty}^{\infty} C_m C_n e^{i(m+n)\omega_0 t}. \tag{2}$$

If Equation 1 is substituted into Equation 2 and the integral on the integral on the right-hand side is performed, the integral will equal zero unless $m = -n$, where, in that case, it will equal T. This leads to

$$\langle [y(t)]^2 \rangle = \sum_{n=-\infty}^{\infty} |C_n|^2, \tag{3}$$

where $y(t)$ is assumed to be real and $\langle [y(t)]^2 \rangle$ is termed the mean-squared amplitude or average power. Hence, the total average power in a signal equals the sum of the average powers of all its harmonic components. So, the integral of the power density spectrum over a particular frequency range yields the power contained in the signal in that range[5].

To properly measure the differences between the PSD and CPSD of consecutive signals, different averaging techniques and statistical methods are used in the frequency domain in order to minimize the error so that it falls within an acceptable margin.

2. Background

Until recently, common practice was to categorize flow patterns based on visual identification of the phase distribution. However, visual flow pattern identification is observer related and subjective. As a result, several other methods have been studied to generate a more objective approach, such as spatial concentration/time signals, RMS of concentration/time signals, the PSD, and the PDF. Although these methods contribute to the better understanding of flow patterns in two-phase flow, these attempts are in an investigative stage[6].

Chengyi Ma and Jerry K. Keska suggest that finding a characteristic of RMS values for an in-situ parameter such as concentration or pressure can increase the understanding of two-phase flow of a heterogeneous mixture. Based on an experimental research on RMS characteristics of in-situ parameters for an air-water heterogeneous mixture steady-state flow in a horizontal minichannel, the authors conclude that the phenomenological correlations of RMS values for two-phase flow averaged in-situ parameters demonstrated significant sensitivity to the flow pattern phenomena[3,7]. Similarly, both authors also used two different optical measurement systems (translucent and reflective) with an air-water water heterogeneous mixture steady-state flow in a vertical pipe to characterize two-phase flow patterns by analyzing the signal in the time, amplitude, and frequency domain. The results show that both systems have different responses to flow patterns which could easily be observed on PDFs and PSDs[8].

Omebere-Iyari and B. J. Azzopardi obtained void fraction measurements for a two-phase air/water mixture in a small diameter vertical pipe using conductance probes. Their analysis proposes that the PDF technique is inadequate for accurately defining the transition between slug and churn flows but performs better for the churn to annular flow transition[9].

H. Cheng, J.H. Hills, and B. J. Azzorpardi conducted an experiment in a vertical pipe to test the transitions of two-phase flows using resistive and conductive sensors. The instantaneous signals from two successive measuring stations are simultaneously measured and then statistically processed, to determine the PDF, the PSD, cross-spectral density function (CSDF), coherence function, system gain factor, system phase factor, signal-to-noise ratio (SNR) and cross-correlation function. All the analyses were performed by a data acquisition system by applying a Fourier Transform to the digitized signal. The authors found that the PDF and the PSD give direct useful information on the flow structure[10].

W. Jaewoo Shim and Chul Hue Jo used three differential pressure transducers to measure the pressure fluctuations for a water and air vertical flow in an annulus at different lengths and flow rates. Then the collected data was used to find the PSD and PDF for bubbly, slug, and churn flows. The author concluded that the PDF for short lengths could describe the flow because the plots exhibited similar trends. However, at long and high flow rates, only bubbly flow was distinguished while the others became harder to classify. The PSD analysis, on the other hand, provided information that was too complex to be practical in all cases[2].

3. Experimental System

In the research, the experimental system used, 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. The channel has two pairs of copper probes that allow the measurement of impedance of the mixture flow by means of a capacitive measurement system. Such system consists of an AC Wheatstone Bridge interfaced with a signal conditioner and a data acquisition system made up by NI-ELVIS and a PC as shown in Fig. 2. The signal conditioner used is a Microchip Active Filter Demo Board Kit as shown in Fig. 3.

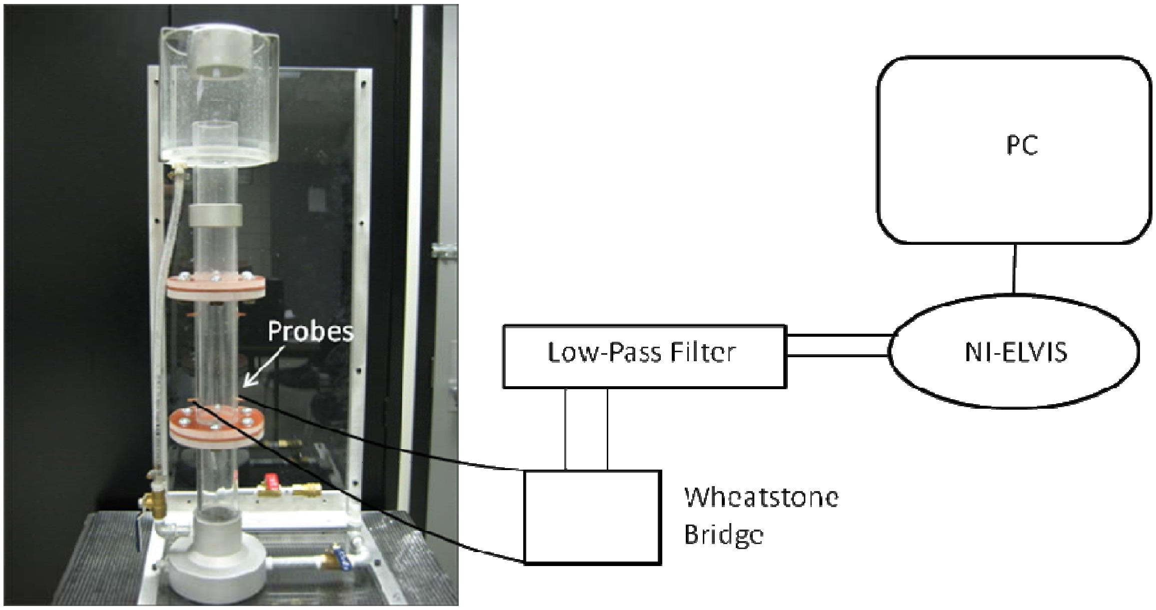

Figure 1. Experimental Vertical Column

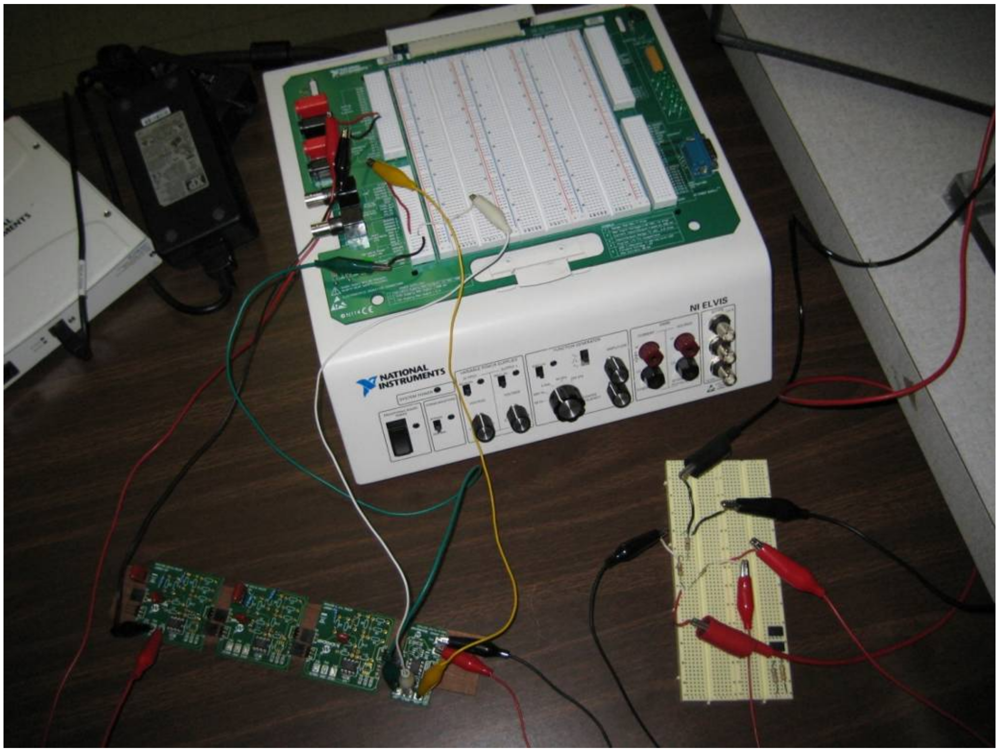

Figure 2. Electronic Measurement System Circuitry

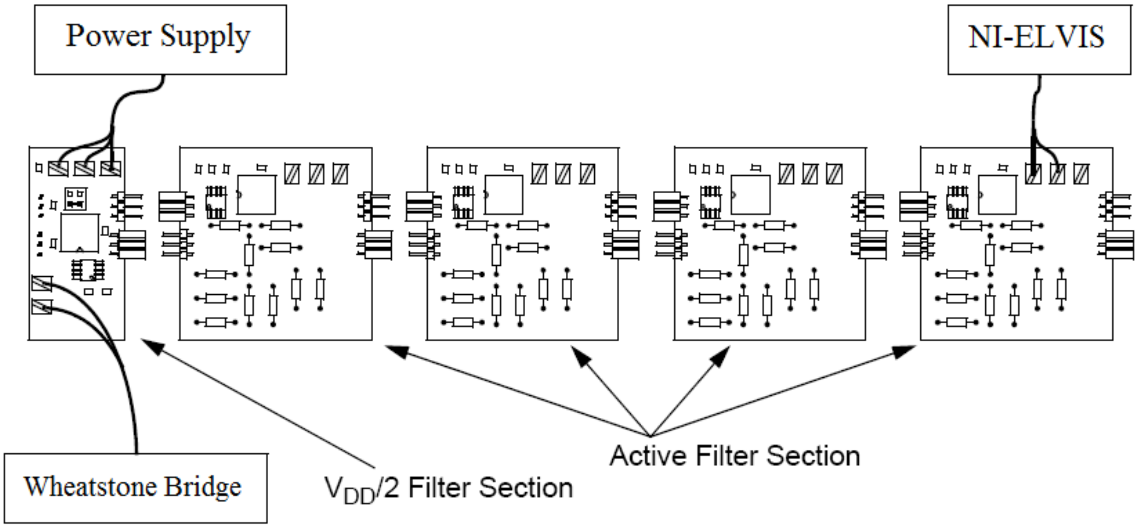

Figure 3. Microchip Low-Pass Filter Diagram

The measurement of two-phase flow parameters is performed using a capacitive sensor. The capacitive sensor measures 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 an AC Wheatstone Bridge and a low-pass filter, as shown in Fig. 4, generating signals proportional to the void fraction[9,11].

Figure 4. Experimental System Consisting of 1) Computer-Aided Data Acquisition System, 2) Compressed Air Lline, 3) Vertical Column, 4) Rotameters, 5) Function Generator, 6) NI ELVIS with Prototype Board, 7) Wheatstone Bridge, and 8) Professional Low-Pass Filter

The noise due to the electromagnetic field around the sensor and connecting wires can significantly affect the signal[12]. Consequently, the object of this experiment is to measure the random fluctuations in void fraction for the two-phase flow air-water mixture by logging 15 random signals that are taken during the same conditions and analyze them in the frequency domain by generating PSD and CPSD.

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 different flow conditions were taken and analyzed in the time domain using a resistive and capacitive sensor as shown in Fig. 5.

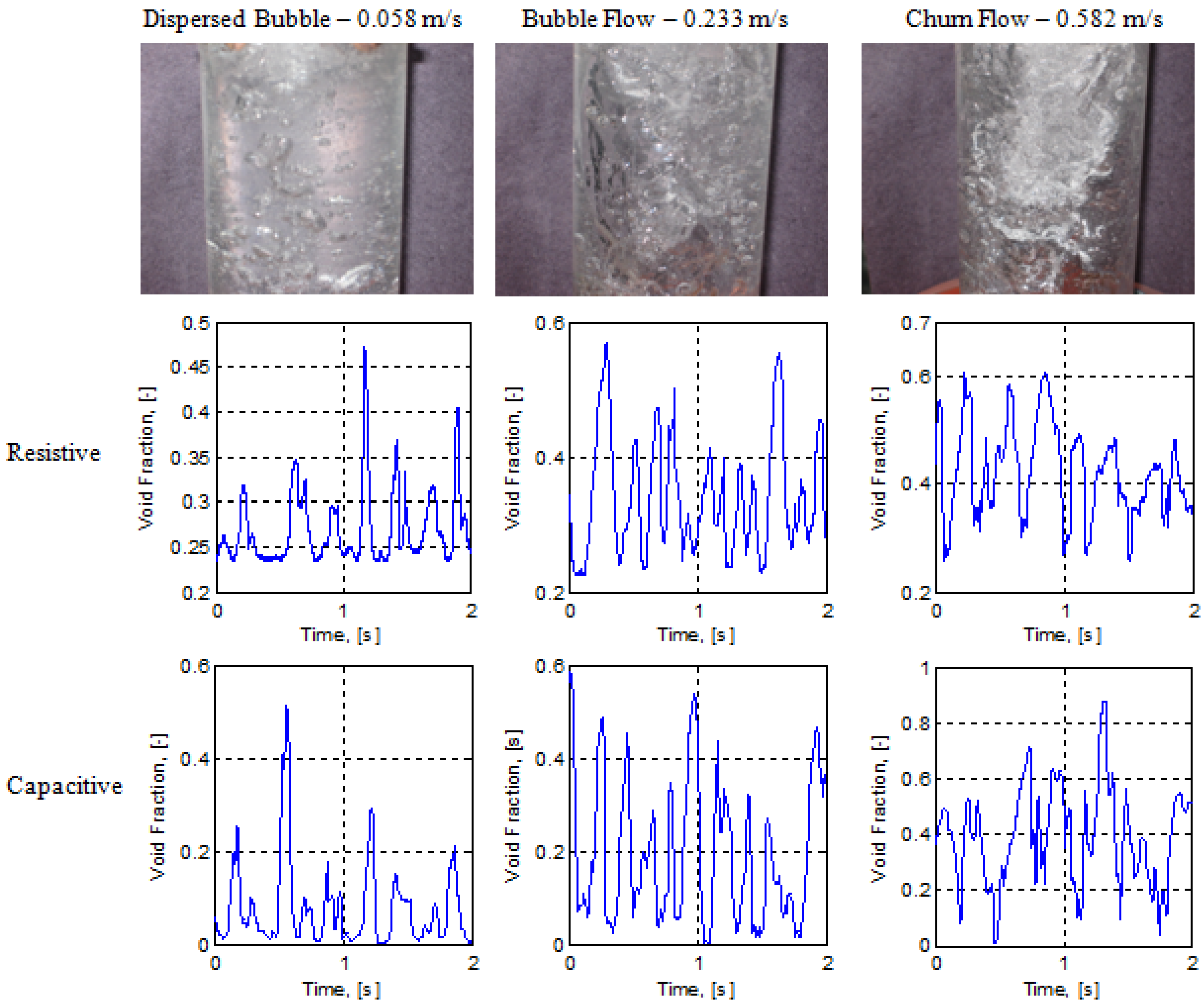

Figure 5. Comparison of Two-Phase Flow Signals in Time Domain for Resistive and Capacitive Sensors for Three Different Flow Patterns.

The first row of Fig. 5 shows a picture of the flow patterns created by air flow velocities of 0.058, 0.233, and 0.582 m/s. According to visual observation, the flow patterns have been classified as dispersed bubble, bubble, and churn. The second row represents dynamic signals of void fraction vs. time taken by the resistive sensor for each flow pattern respectively. Finally, the third row illustrates dynamic signals of void fraction vs. time taken by the resistive sensor 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.

The approach of the experiment is to test how the air-water mixture's void fraction varies for the same flow conditions when recording multiple continuous signals of the flow. For this experiment, 15 signals are recorded and analyzed in the time and frequency domain to see the effects of random fluctuations in the phenomena of flow patterns and to develop a method to analyze two-phase flow parameters and their effect on the flow conditions. Since insufficient space is available to present all the 15 signals obtained during the experiment, only limited amounts of test data are presented herein. However, the data presented describes the flow characteristics along with the random fluctuations of the signals covering the entire range for the flow pattern investigated.

Fig. 6 illustrates the flow pattern caused by an air velocity of 0.233 m/s in the time and frequency domains. In order to get a better image of the two-phase flow, a stroboscope was used to enhance the picture. As can be seen, the flow is characterized by many small bubbles and sporadic big bubbles traveling through the column, which can be categorized as churn flow.

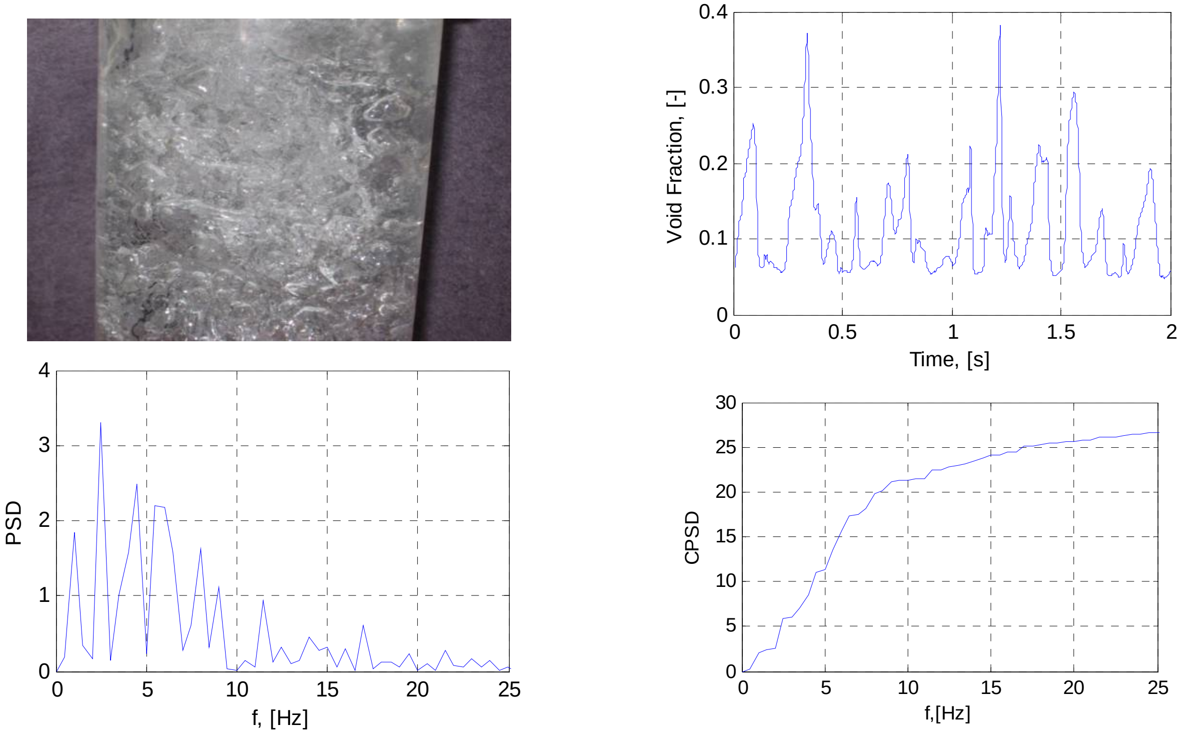

Figure 6. Representation of In-Situ Void Fraction by Means of a) Flow Pattern Picture, b) Void Fraction vs. Time, c) Power Spectral Ddensity, and d) Cumulative Power Spectral Density

However, we need to investigate the repeatability and differences between the continuous signals for the same conditions. In order to analyze the 15 different signals taken, it is necessary to see how they fluctuate from each other for illustrative purposes. Fig. 7 shows the void fraction vs. time data for only 6 representative continuous signals of the 15 signals taken.

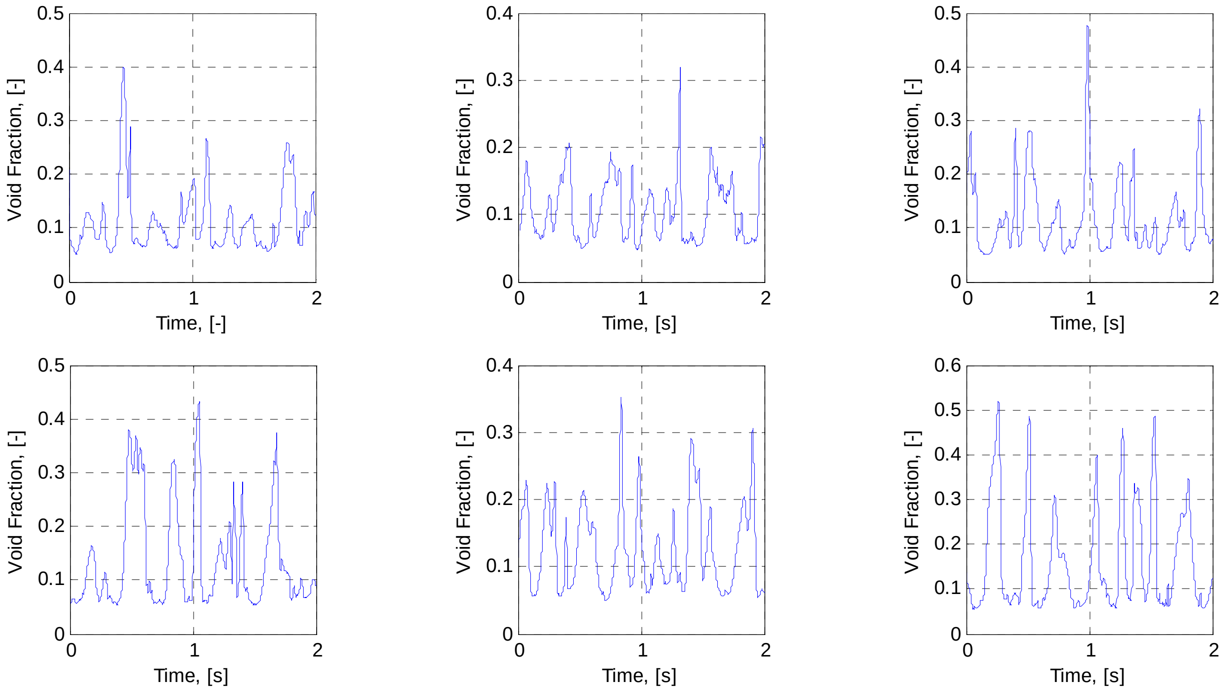

Figure 7. Void Fraction vs. Time for Two-Phase Flow. Repeated Signals.

In an ideal flow, all the signals should be identical; however, Fig. 7 shows how the signals differ from each other although they are all run under the same conditions. Overall, the average void fraction varies significantly with respect to each other as shown in Fig. 8.

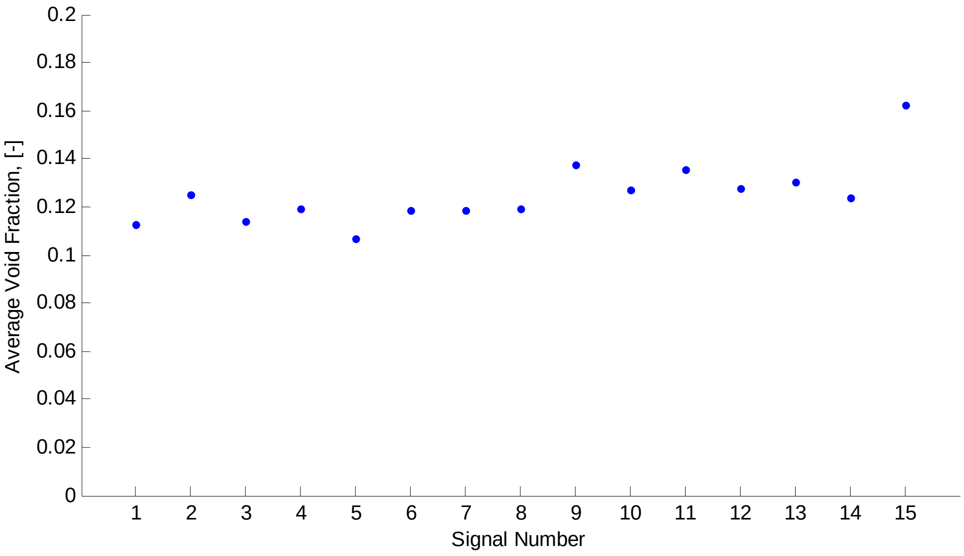

Figure 8. Average Void Fraction for 15 Signals for the same Conditions

The average void fraction fluctuates from 0.107 to 0.162. Although this only represents a standard deviation of 0.0133, such fluctuations in the signals indicates the need for further investigation of the flow differences including frequency fluctuation of the signals using PSD and CPSD. Fig. 9 depicts the PSD analysis for the same signals illustrated in Fig. 7.

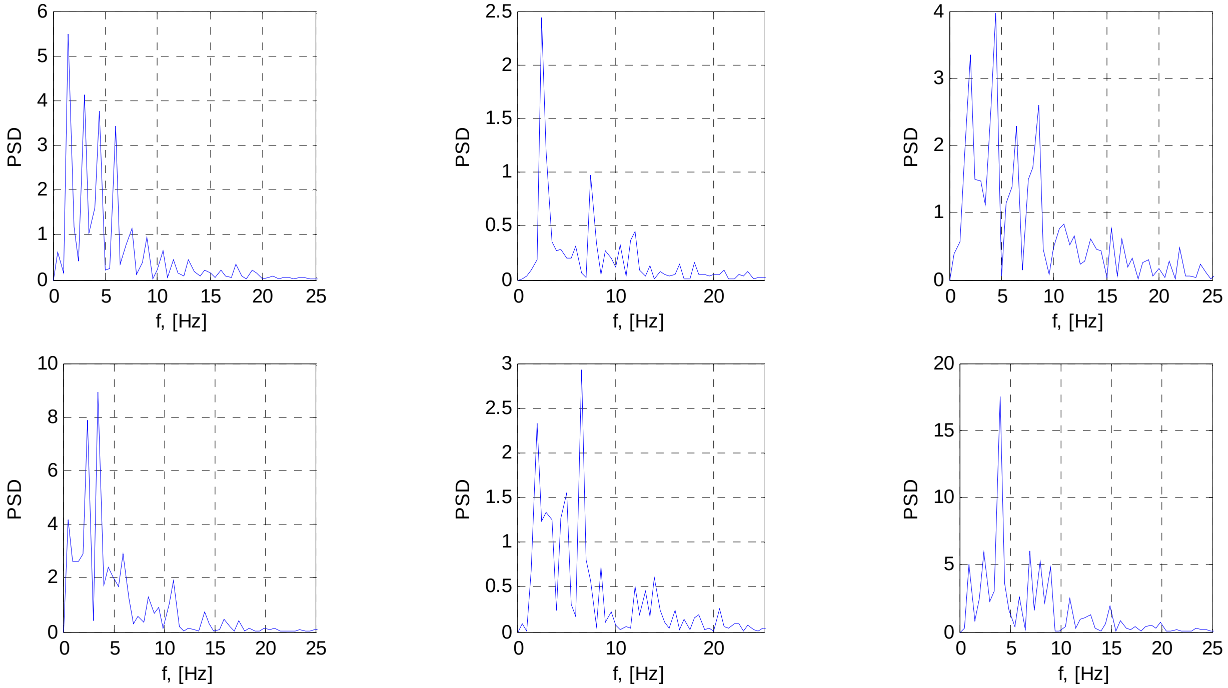

Figure 9. PSD for Repeated Signals

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, the random fluctuations can cause a flow pattern to exhibit totally different PSD's. For instance, the first, third, fourth, and fifth signals in Fig. 7 show that the energy is distributed between at least four different frequencies. However, the frequencies at which they occur are significantly different. On the other hand, the second and sixth signals show only one main frequency at which the energy is dispersed. Yet they occur at different values. Now the question is how significant such variations are and how can they be reduced. As a result, it becomes of critical importance to develop a method to precisely compare each signal taken under the same conditions in order to understand the random fluctuations of two-phase flow. The CPSD may pose a solution to this problem. Fig. 10 shows the CPSD for all 15 signals.

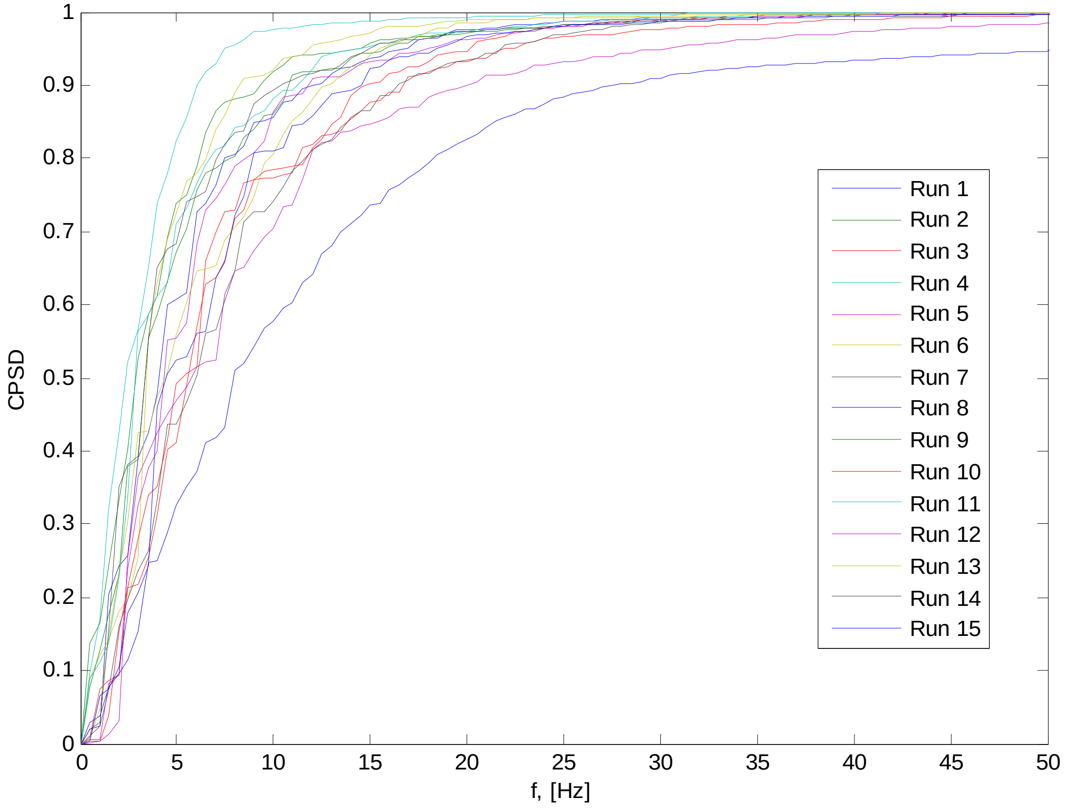

Figure 10. Non-Dimensional CPSD for 15 Repeated Signals

Fig. 10 depicts how the CPSD changes for all 15 continuous signals. The spread of the signals generates problems when analyzing flow patterns. For a representative frequency of 10Hz, the cumulative power spectrum varies from 0.578 to 0.976. Such difference suggests that one signal has only about 57% of its energy in the 0-10Hz range while the other has dispersed almost all of its energy in the same range. Hence, further investigation is required to see how acceptable is the deviation presented by Fig. 10. The approach is to calculate the standard deviation of each signal as a function of the number of averaged signals as shown in Fig. 12.

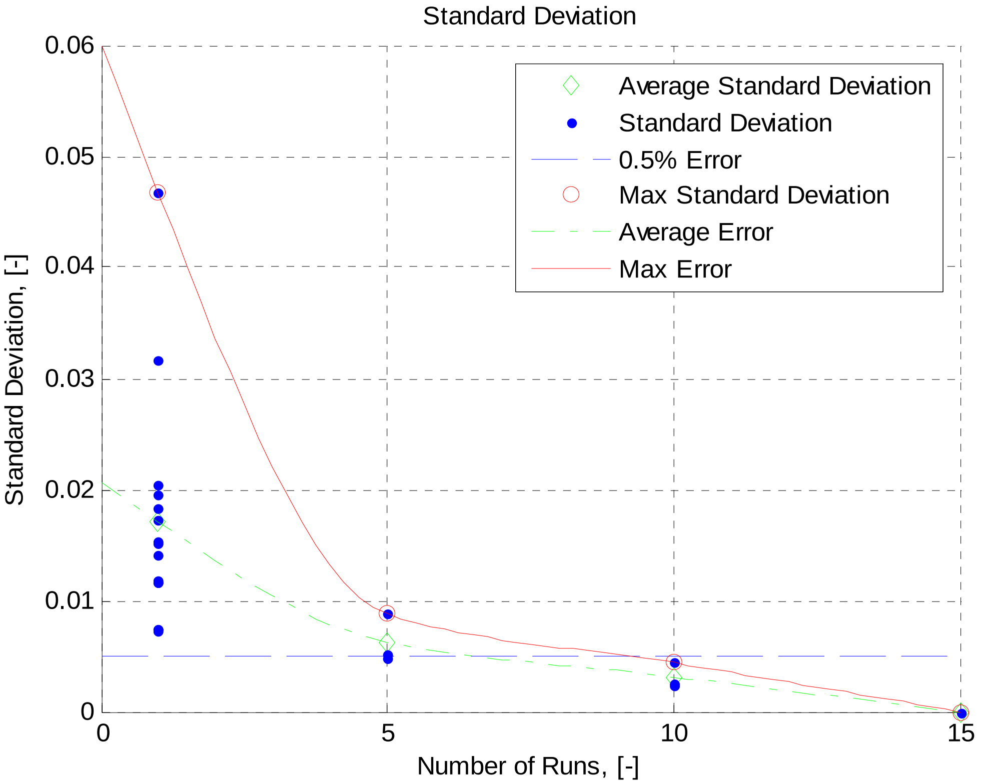

Figure 11. Standard Deviation of Averaged Signals vs. Numbers of Averaging

Fig. 11 illustrates how the standard deviation is reduced as the averaging process increases. This analysis suggests that the fluctuation of two-phase flow signals can be reduced by averaging out several signals. The statistical calculations were performed by taking the curve represented by the average of all 15 signals as the mean. Then, the standard deviation of each individual curve for independent as well as averaged signals is calculated as follows:

$$SD = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \mu_i)^2}{N}} \tag{4}$$

where x_i is the signal CPSD data and μ_i is the CPSD data from all 15 signals.

To create the curve fit in Fig. 11, an envelope was created using the maximum standard deviation within the signals. This increases the confidence level on the number of averaging required to get results that have ±0.5% accuracy

Since the deviation is sensitive to the number of averaging, it is important to illustrate the differences. The approach is to average the CPSD in the following pattern as shown on Fig. 12:

- Signal I: Average signals 1-5

- Signal II: Average signals 6-10
- Signal III: Average signals 11-14

Then, each of these representative signals will be permutated to further average the signals in order to see the effects of averaging in the random fluctuations of two-phase flow as shown in Fig. 12.

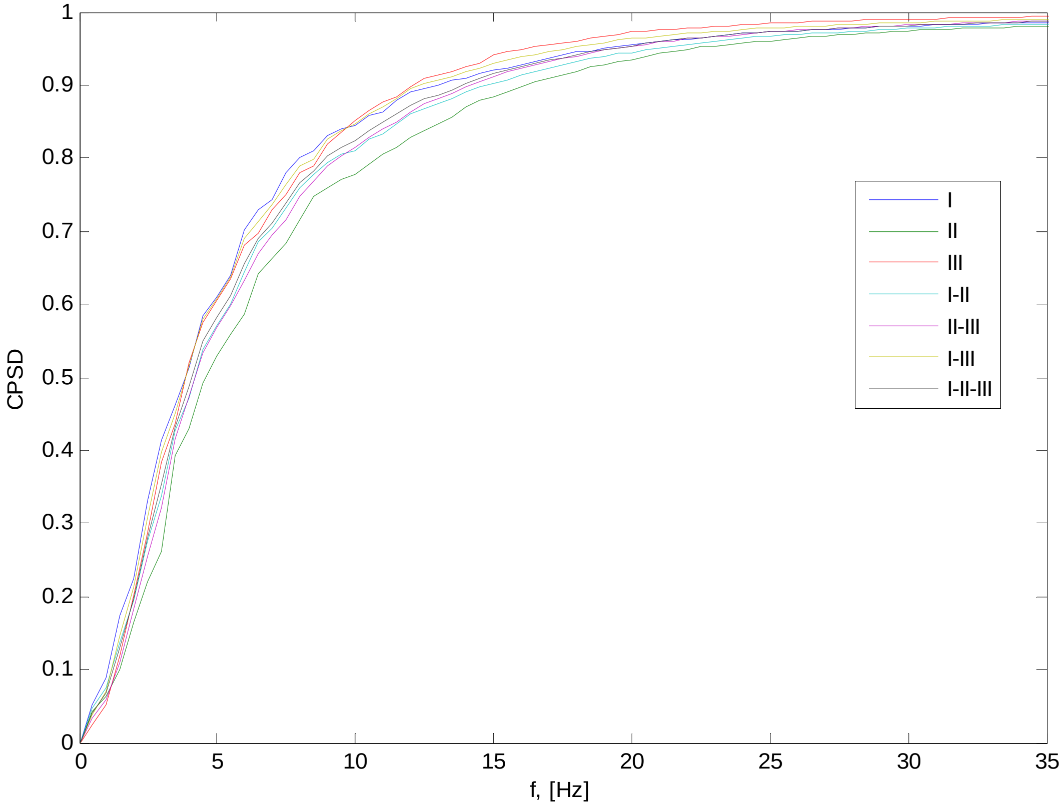

Figure 12. Non-Dimensional CPSD for Different Population of the Averaged Signals

Fig. 12 depicts how the spread of the signals has been significantly reduced by increasing the number of averaging. For a representative frequency of 10Hz, the cumulative power spectrum varies from 0.777 to 0.848. Hence, averaging the CPSD for multiple continuous signals has been proved to reduce the random fluctuations of the signal. Now it is necessary to see the effects of the averaging process in the standard deviation in order to produce a method that gives signals that are within an acceptable error margin.

5. Application of Results

The statistical method developed based on the results of the experiment suggests that a two-phase flow signal will have a more developed envelope if it is averaged with several signals. Fig. 11 shows that one can reach an accuracy of ±0.5% by averaging about 9 signals. For this approach the flow conditions was kept constant; however, now that the method has been proved to reduce the random fluctuation in two-phase, it is possible to analyze signals with different flow conditions. This will allow the application of the averaging process to signals of different flow patterns to see and analyze the flow in time, amplitude, and frequency domain.

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. In-situ spatial concentration characteristics for steady-state flow manifested random characters and are causing flow instabilities and changes in both flow patterns and flow rates. As a result, there is a strong correlation between flow patterns and PSD and CPSD functions.
2. The data analyzed in time, amplitude, and frequency domains indicated unique characteristics generating wide differences ranges in the standard deviation between two consecutive signals shown in the frequency domain as the PSD and CPSD characteristics.
3. Possible applications of the PSD and CPSD characteristics required reduction of the differences, which is achieved by increasing the numbers of runs and averaging of the concentration signals. When nine CPCD signals are averaged, a deviation of 0.5% is achieved.

7. Nomenclature

C	amplitude	[-]
C_m, Cn	Fourier coefficients	[-]
f	frequency	[Hz]
i	imaginary number = $\sqrt{-1}$	[-]
m, n	integer	[-]
t	time	[seconds]
ω_0	circular frequency	[Hz]

8. Acronyms

CPSD	cumulative power spectral density
PDF	probability density function
PSD	power spectral density
RMS	root-mean-square
SD	standard deviation

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