Session U-03

AN EXPERIMENTAL APPROACH TOWARDS THE MEASUREMENT OF THE TWO-PHASE FLOW PATTERN PHENOMENON

Patrick L. Adams and Jerry K. Keska

Department of Mechanical Engineering
University of Louisiana at Lafayette
Lafayette, LA 70506
jkk9202@louisiana.edu

Abstract

Under the term two-phase flow of a heterogeneous mixture, it is understood a mixture which consists of a mixture of gas-liquid, gas-solid, liquid-solid or two immiscible fluids components. Due to flow pattern phenomena, which are causing its random behavior, two-phase flow is one of the most challenging topics of fluid mechanics. As the flow rate of the mixture in a vertical column is increasing, the visually observed flow pattern changes, starting from single bubbles travelling upward, then through dispersed bubble, bubbly, slug, churn, annular, and finalizes with the mist flow pattern. However, the visual flow pattern observation is very subjective. Since the flow current methods for flow pattern identification are not objective, it is necessary to develop a method to objectively measure the flow patterns.

In this paper, results of an experimental research are presented on the impact of the variation of two-phase flow patterns on the in-situ parameters of a water-air mixture in a vertical column with an ID of 50.0 mm using different configurations of concomitant measurement systems. The concomitant computer-aided measurement systems consist of capacitive and resistive sensors with different system configurations, which measure in-situ dynamic mixture concentrations. The capacitive and resistive sensors built into the vertical column have the same active space and the data is collected during the same time interval. The proportional voltage signals to spatial concentrations from both resistive and capacitive sensors are calibrated and transferred to spatial concentration signals and analyzed in both the amplitude and frequency domains.

Introduction

Two-phase flow of a heterogeneous mixture is considered to be one of the most challenging fluid dynamic problems to be explored since the 1940s [1]. Two-phase flow of a heterogeneous mixture it is understood to consist of a mixture of gas-liquid, gas-solid, liquid-solid or two immiscible fluids components, e.g. oil/gas, air/water. As the flow rate is increased, the flow gradually transitions from one flow pattern to the other. The flow pattern initializes with the dispersed bubble pattern and as the air flow rate increases, the mixture transitions through bubbly, slug, churn, annular, and then finalizes with the mist flow pattern. As the flow

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transitions from one flow pattern to another, the use of energy, as well as the equations which are used to predict the flow's behavior, changes.

Due to the random nature of the flow, the development of the equations to be used in predicting its behavior is a challenging topic. Therefore, it is best to measure the flow under steady-state conditions and study the mean values of in-situ parameters such as velocity, concentration, and pressure gradient. Any fluctuation intensity of two-phase in-situ parameters (in particular) can be characterized by its mean value. By studying the mean values of the measured flow fluctuating component (in general) and finding a characteristic of mean values for an in-situ parameter, such as concentration or pressure, will give a better understanding of two-phase flow of a heterogeneous mixture [1, 8]. Although the topic is challenging, the benefits of studying and developing methods of quantifying the phenomenon of two-phase flow are extremely beneficial.

This experiment is designed to observe the various flow patterns and obtain characteristics which pertain to each particular flow. The focus of this experiment is on the two-phase flow of air and water in a vertical column for the bubbly, slug, and churn flow patterns. The experiment is designed to evaluate the mean in-situ concentration values obtained for a wide range of air flow rates supplied by both capacitive and resistive measurement systems in an attempt to quantify the flow patterns observed.

Literature Search

The greater part of research conducted on two-phase flow is experimental. Thus measurement systems and data validation of in-situ concentration are very significant issues. For data validation the application of concomitant measurement systems is very appealing. The concept of a concomitant measurement system is to obtain at least two independent measurements of a variable in the same time and space using two independent measurement systems which work based on different physical concepts. If the deviation between these measurements falls into an acceptable deviation, the probability that the measured parameter is correct is significantly higher than in the case of a single measurement [1, 13]. What makes the development of concomitant two-phase measurement systems so distinctively important is that it represents more than a simple linear extension of existing computer technology for dynamic signal measurements. Concomitant measurement systems offer the potential to create systematic methods that allow for the precise control of complex dynamic measurements to be obtained. The implementation of such techniques allows for precision and accuracy beyond what is currently available with traditional methods.

Previous measurement methods for two-phase flow include both invasive and noninvasive techniques. Common methods include utilizing electrical impedance, optical transmission radiography and radiometric sensing techniques [8, 10, 13]. Below are examples of previous measurement techniques employed in the past to quantify two-phase flow.

In their experiment, Chen et al. observed the variation in the flow pattern visually through the use of a high speed camera. The supplied flow rate was recorded and used to develop flow regime maps [4].

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Keska and Ma developed an optical system by making use of an optical resistor interfaced into a CADAS through the use of a Wheatstone bridge. The experiment measured the flow using both the reflective and translucent modes of the optical system. The reflective mode set the light source and optical resistor on the same side of the flow while the translucent mode mounted the light source and optical resistor on opposite sides. The signals obtained showed that the translucent and reflective modes provide different results [3].

In the past several methods different configurations of capacitive sensors have been used [6, 8, 13]. Such types include flat plate, concave, ring, helical and multiple helical wound in contact or isolated from the mixture. Elkow and Rezkallah compared the performance of concave and helical type sensors and determined that the problems associated with helical type sensors, including the nonlinear response, poor sensitivity and poor shielding, can be eliminated by using the concave type sensors. The accuracy of the concave parallel sensors can be improved by having both electrodes of equal length to decrease the non-uniformity of the electric field between the two electrodes and eliminate the non-linear response [14]. Elkow and Rezkallah recommended that the distance between the electrodes and the shield should be large relative to the separation distance between the two electrodes in order to improve the immunity to stray capacitance [10].

This experiment is designed to utilize both capacitive and resistive sensors simultaneously in order to measure the two-phase flow. The capacitive measurements are based upon the gas and liquid having a different dielectric constant. The capacitive sensor follows Equation 1. Since the physical parameters of the system are held constant over time, the only variable which changes is the concentration of the mixture (c_v).

$$C_i = \frac{1.01\varepsilon_0 L(\varepsilon_1 c_v + (1-c_v)\varepsilon_2)}{\ln(1+(\pi D/b_c)\tanh^2(0.7(D/b_c)))} \qquad (1)$$

The resistivity of the resistive sensor is dependent upon Equation 2. Similar to the capacitive sensor, the resistive sensor is a function of mixture concentration only and functions by utilizing the variation in resistance of the two-phase flow. By utilizing Equations 1 and 2 along with a transducer, it is possible to measure dynamic signals for the flow pattern.

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

Although the use of capacitive and resistive measurement techniques has been employed in the past, this project is unique in many ways:
(1) Robust techniques have been designed for measuring two-phase flow parameters by implementing a concomitant measurement system.
(2) Algorithms have been implemented which allow researchers to anticipate incorrect data by comparing the data obtained by both the capacitive and resistive sensors.

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(3) A calibration technique has been utilized which uses the mean in-situ concentration values obtained.
(4)Modifications from previous experiments have been established which make it easier to build the sensors.
(5)From experience gained in the experiment, strategies have been designed that will allow future researchers to determine characteristics pertaining to the flow patterns observed.

Experimental System

For the experimental research reported in this paper, a vertical column was used which consists of a vertical translucent pipe ID = 50.0 mm. The vertical column features an air valve, which is located at the bottom of the column and provides compressed air supplied by an air compressor. The air valve at the bottom of the column is connected to an air flow meter so that the air flow rate which is supplied to the column, as well as the flow pattern within the column, may be controlled. There is a return water system which returns water back to the column in the case of splashing. Located in Fig. 1 is an image of the vertical statistical column used in the experiment.

Figure 1: Vertical Column

The test apparatus for two-phase flow experiments in vertical column consists of an air compressor which is used to supply the air for the two-phase mixture. In order to control the flow pattern within the statistical column, the air flow rate supplied to the column was controlled by an air flow meter. As the air enters through the air valve and travels upward through the column, the capacitive and resistive sensors measure the variations in the dielectric constant within the column as they vary with time. The resistive and capacitive sensors consist of metal plates mounted on opposite sides of the vertical column, shown in Fig. 2, and interfaced into CADAS via the transducers. The sensors measure data during the same time interval and at the same location within the vertical column.

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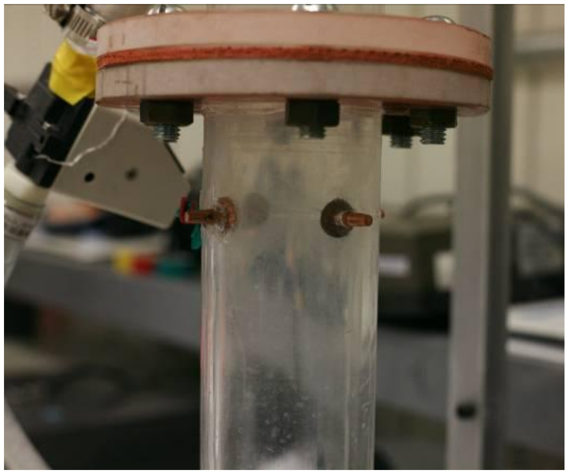

Figure 2: Capacitive and Resistive Sensors

In order to interface the resistive and capacitive sensors into the computer, AC (for capacitive) and DC (for resistive) Wheatstone bridges are used. Figure 3 displays the schematic of a Wheatstone bridge. The bridge functions as a transducer by interfacing the sensor through one of the resistor locations; either R1, R2, R3, or R4. The DC Wheatstone bridge supplies a constant DC voltage across the bridge while the AC Wheatstone bridge utilizes a function generator. By measuring the voltage across locations 1 and 2, a dynamic voltage signal may be obtained from the sensors.

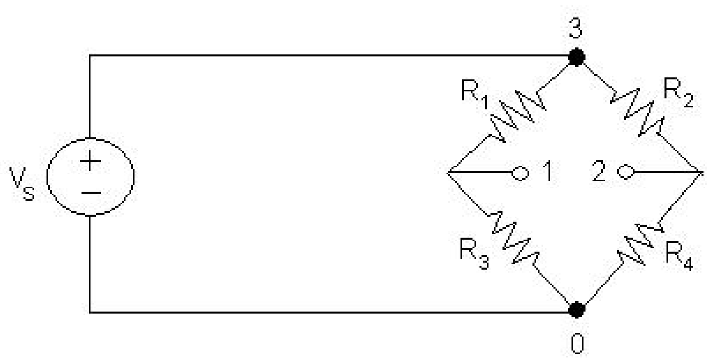

Figure 3: DC Wheatstone Bridge Schematic

Due to the high frequency noise introduced into the signal by the function generator located in the AC Wheatstone Bridge, a low-pass filter is employed. This experiment used both a physical low-pass filter and a digital low-pass filter. Fig. 4 displays the physical low-pass filter which was built for this experiment. A Chebyshev digital low-pass filter was used as the digital low-pass filter and was used along with MatLab. In order to produce accurate results, the function generator must be set to a frequency that is higher than the cut-off frequency of the low-pass filter. After passing through the low-pass filter, a signal is produced which is similar to the signal generated by the resistive sensor. The results of both filtering methods will be compared in order to determine if they are compatible

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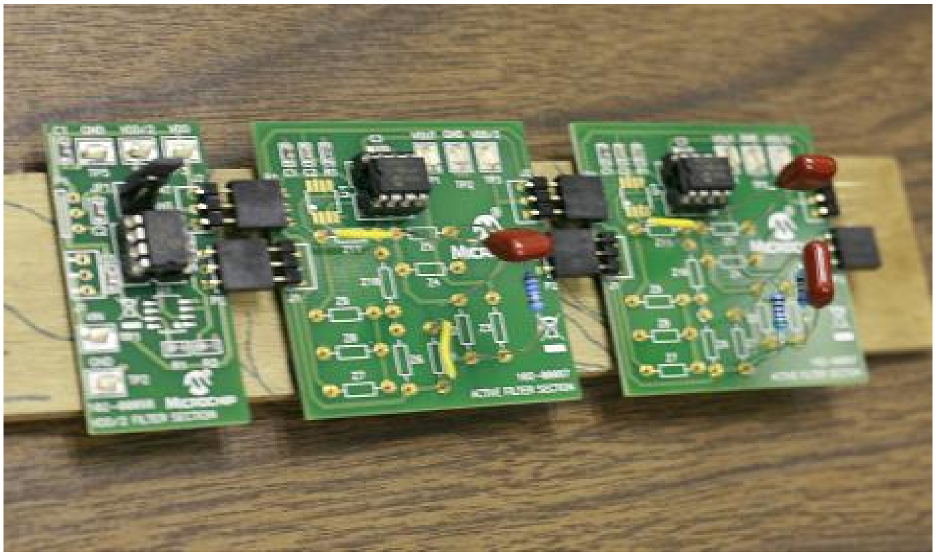

Figure 4: Physical Low-Pass Filter

The purpose of the experiment is to design a concomitant measurement system by comparing the spatial concentration data obtained from measurements. The experiment also aims to obtain deterministic information on the various types of two-phase flow for liquid-gas mixtures by comparing amplitude (PDF) and frequency (PSD) domain graphs of the same flows for the various sensors. Also, the experiment strives to produce a digital low-pass filter which may be substituted. The experiment's goal is to describe the transition of flow in terms of graphs of amplitude and frequency. The system is designed to measure the dispersed bubble, bubbly, slug, and churn flow patterns. Fig. 5 displays the concomitant measurement system employed in the experiment.

Data Analysis and Experimental Results

In the conducted experimental research the in-situ dynamic parameter of concentration, flow patterns and terminal flow parameters of air flow rate were measured. Fig. 6 displays images of the flow patterns observed in the column, as well as the associated air flow rate, the mean resistive concentration, and the mean capacitive concentration measured.

The primary data obtained from the experiment is the voltage signals obtained via the Wheatstone bridge interfaced into the CADAS. Located in Fig. 7 are some example voltage signals obtained by the capacitive and resistive sensors. The signals observed are clearly different. This emphasizes the importance of using in-situ parameters, such as concentration, for the comparison of concomitant measurement systems. Fig. 8 displays a voltage signal measured by the capacitive sensor before low-pass filtering. This signal contains the high frequency component introduced by the signal generator in the AC Wheatstone bridge. Observation of this signal emphasizes the importance of low-pass filtering in order to produce clear signals.

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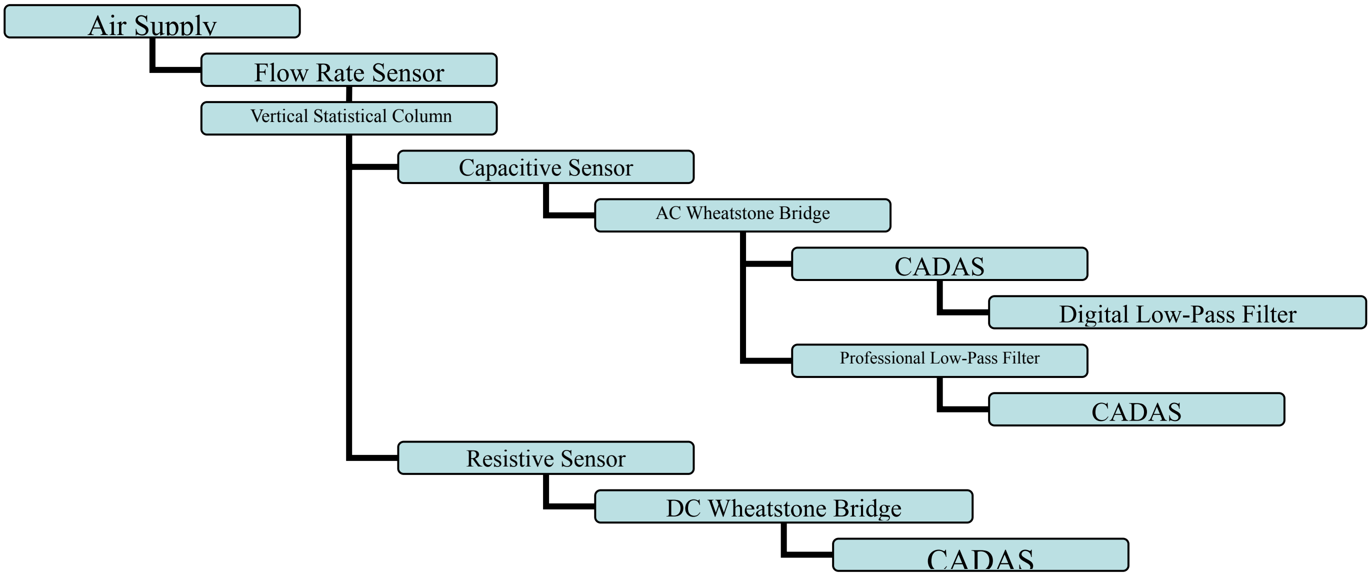
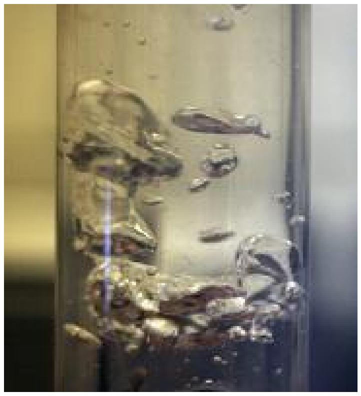


Figure 5: Measurement System Design

a.) Dispersed Bubble
Q_a= 0.0850 m^3/hr
$c_{v,capacitive=}$ 0.8093



b.) Bubbly
Q_a= 0.1416 m^3/hr
$c_{v,capacitive=}$ 0.8105

c.) Slug
Q_a= 0.5097 m^3/hr
$c_{v,capacitive=}$ 0.7695

d.) Churn
Q_a= 2.039 m^3/hr
$c_{v,capacitive=}$ 0.6930

Figure 6: Flow Patterns

Primary Data:

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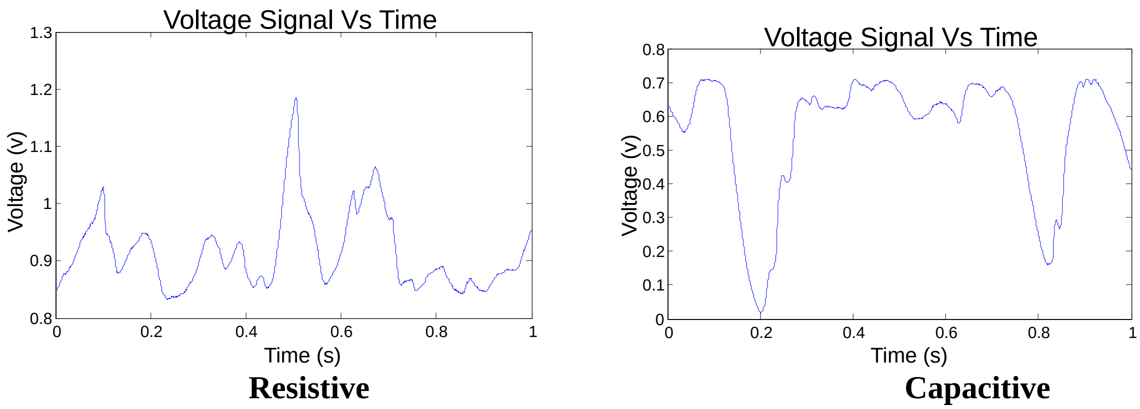

Figure 7: Voltage Signal Comparisons of Resistive and Capacitive

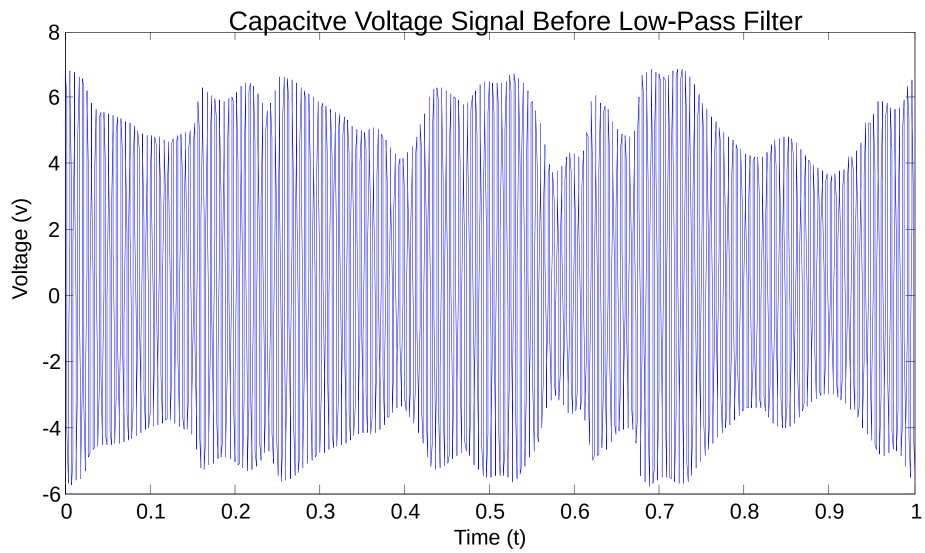

Figure 8: An Example of a Voltage Signal Obtained by Capacitive Sensor before Filtering

Secondary Data:

Once the voltage signals for both capacitive and resistive signals have been recorded, the results were then converted into their in-situ concentration signals for further analysis. By converting the voltage signals into concentration signals, the results from the capacitive and resistive sensors may then be compared. In order to produce the in-situ water concentration signals, the system must be calibrated. The calibration process consists of measuring the voltage signal of both the capacitive and resistive sensors, for the air only and water only conditions. The concentration within the column obeys Equation 3.

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$$c_v = \frac{\text{Volume Water}}{\text{Volume of Mixture}} \quad (3)$$

However, since the dimensions of the column remain constant, Equation 3 reduces to the following equation:

$$c_v = \frac{\text{Water Height}}{\text{Mixture Height}} \quad (4)$$

Therefore, by measuring the change in height of the mixture in the column as it varies with the air flow rate supplied, the concentration of the flow may be obtained. Similarly, by measuring the DC voltage signal within the column and utilizing the calibration measurements, voltage of air and water only, the concentration signal may be obtained. The following equation, when compared with the results from the height measurements, produced the concentration signals for this experimental setup. Located in Fig. 9 is the concentration signals obtained, using the calibration process mentioned above, for the resistive and capacitive sensors.

$$c_v = \frac{\text{Vin (DC) - Vwater (DC)}}{\text{Vair (DC) - Vwater (DC)}} \quad (5)$$

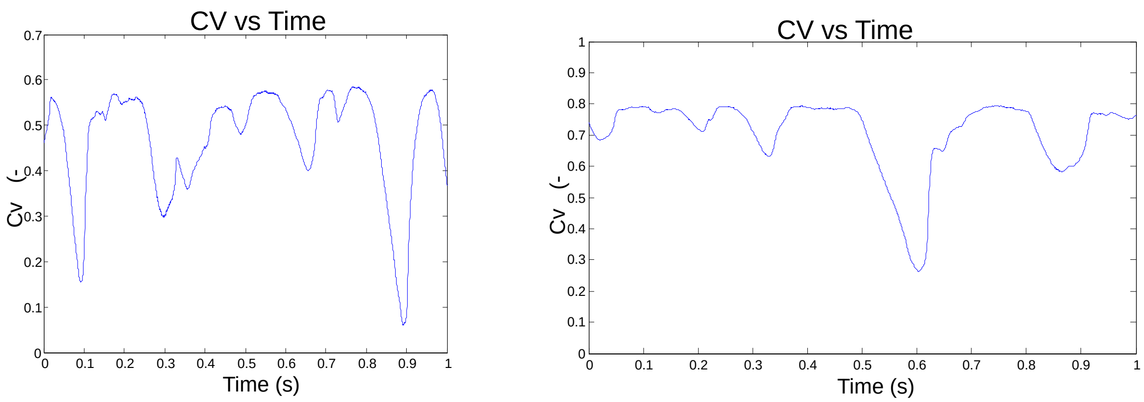

Figure 9: Concentration Signal Comparisons of Resistive and Capacitive Sensor

To determine the concomitancy of the system, the average values of the concentration signals for both sensors were compared over a wide range of air flow rates.

The concentration signals obtained were then compared in both the amplitude and the frequency domains. The probability distribution function (PDF) and cumulative probability distribution function (CPDF) were used for the amplitude analysis. Fig. 10 and 11 compare the amplitude distributions for both sensors with an air flow rate of 2.04 m^3/hr. This air input was observed to produce a churn flow. The results show that the values produced by the capacitive sensor are more distributed while the concentration signal obtained from the resistive sensor produces a signal with a large number of values located in the 0.8 range. By comparing the CPDF graphs of generated for both sensors, it is observed that both graphs are concave up.

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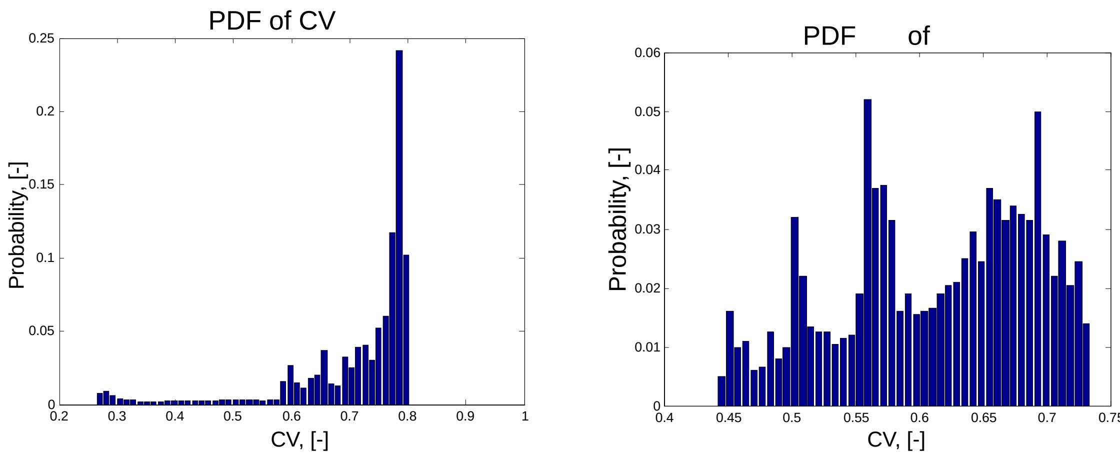

Figure 10: PDF Comparison of Resistive vs. Capacitive Sensor for Churn Flow

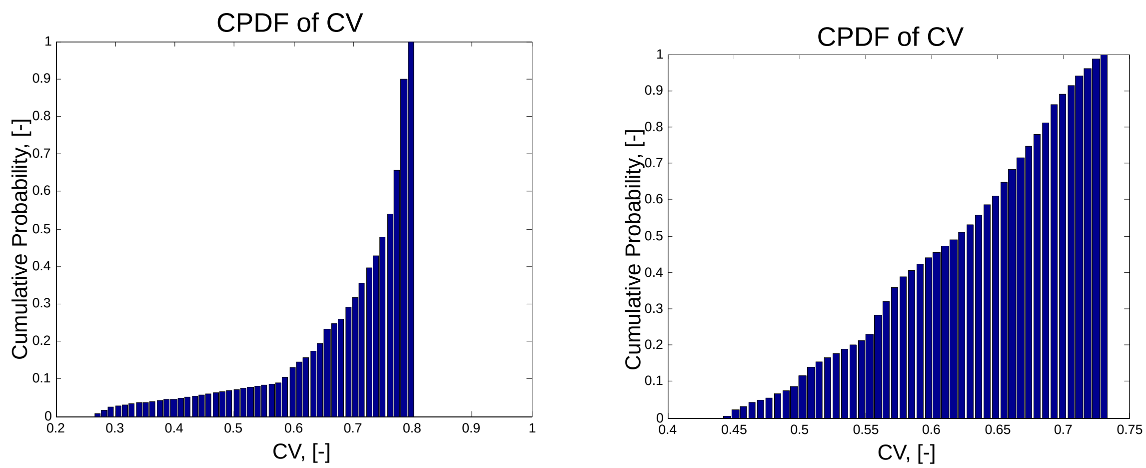

Figure 11: CPDF Comparison of Resistive vs. Capacitive Sensor for Churn Flow

The power spectral density (PSD) and cumulative power spectral density (CPSD) functions were used for the frequency analysis of the in-situ concentration signals. Fig. 12 and 13 analyze the frequencies of the signals produced as the air flow rate supplied to the column is increased for the resistive and capacitive sensors, respectively. The results from Fig. 12 and 13 show that for both resistive and capacitive sensors, the power of the signal increases as the air flow rate supplied is increased. This can be clearly seen in the CPSD charts since the graphs maximize at higher values as the air flow rate increases.

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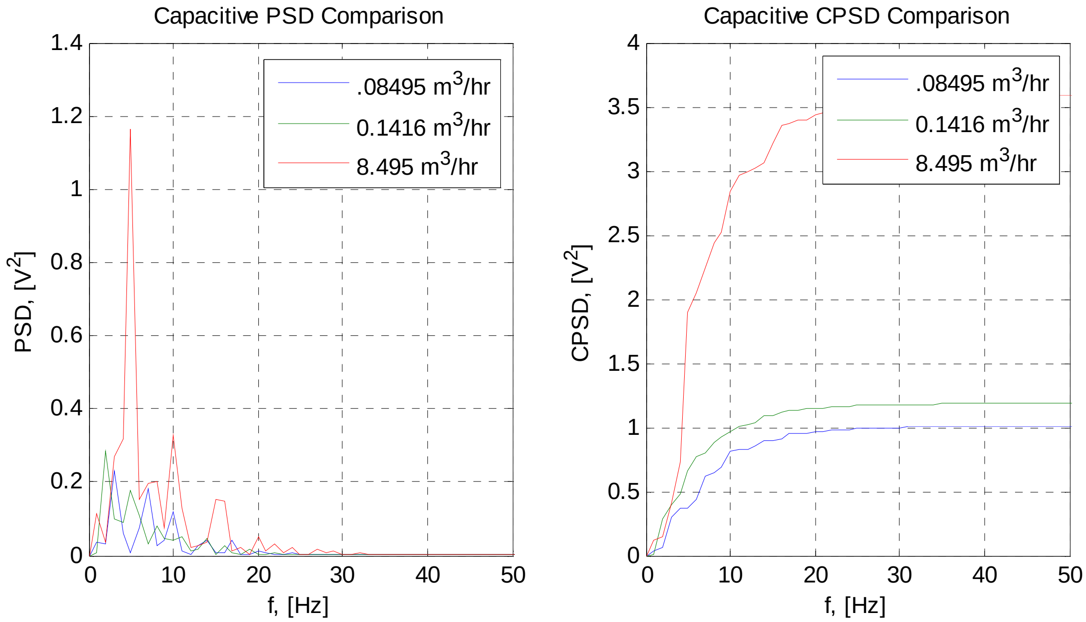

Figure 12: PSD and CPSD Comparison for Capacitive Sensor

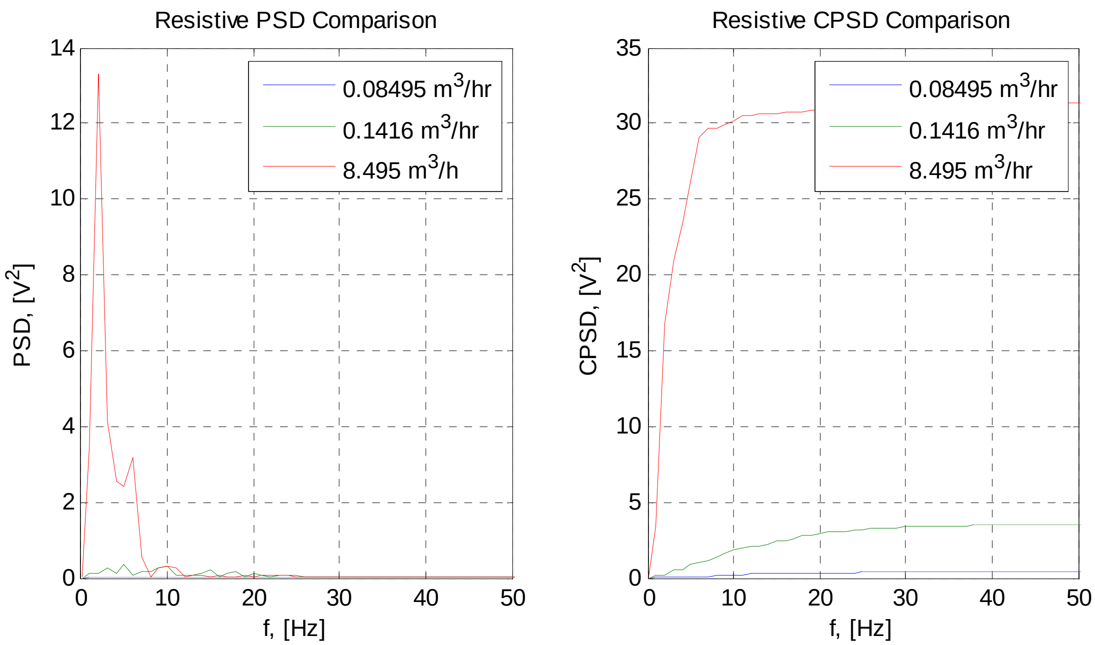

Figure 13: PSD and CPSD Comparison for Resistive Sensor

The results were also compared between the two sensors in the frequency domain through the use of PSD and CPSD graphs. Fig. 16 shows the frequency comparison of the two sensors for the same air flow rate.

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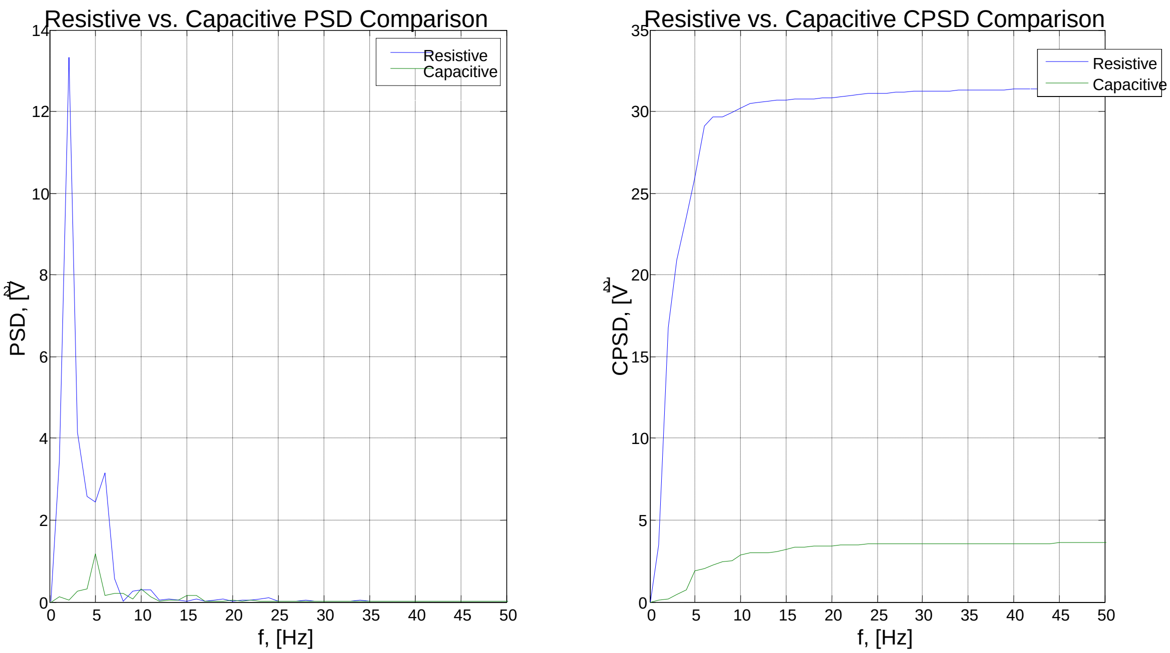

Figure 14: PSD and CPSD Comparison for Resistive and Capacitive Sensors

Fig. 15 displays a comparison of the capacitive sensor utilizing a physical low-pass filter as the air flow rate supplied to the column. By analyzing the in-situ concentration in both amplitude and frequency domain, it can be observed that the concavity of the CPDF increases with the flow rate as well as the strongest frequency found in the PSD. When an air flow rate of 0.850 m^3/hr was supplied to the column, the strongest frequency was around 3, while an air flow rate of 1.360 m^3/hr was supplied to the column, the strongest frequency was around 7.

The low-pass filter is necessary for the capacitive sensor since the voltage signal produced by the Wheatstone bridge has a high frequency component. Fig. 16 displays the voltage signals measured across the AC Wheatstone bridge before and after the physical low-pass filter. The high frequency component must be eliminated in order to produce a signal which may be compared to the signal produced by the resistive sensor. In order to reduce the complexity of future designs, the experiment utilized both a digital and a physical low-pass filter separately. In comparison, the physical low-pass filter is costly, difficult to construct, and introduces error. Therefore, if the digital filter produces a satisfactory substitute, then it would be beneficial to employ.

Fig. 16 displays the comparison of the mean concentration values obtained for the physical and digital low pass filter. The results indicate that the values obtained from the two methods produce similar results. Further, Fig. 17 displays the percent error produced by utilizing the digital filter for a wide range of supplied air flow rates. The results show that the error is constant and does not vary with the air flow rate. Therefore, the results produced by the digital low pass filter may be further refined by reducing this fixed error.

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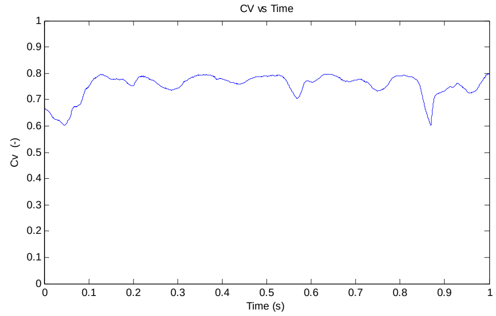
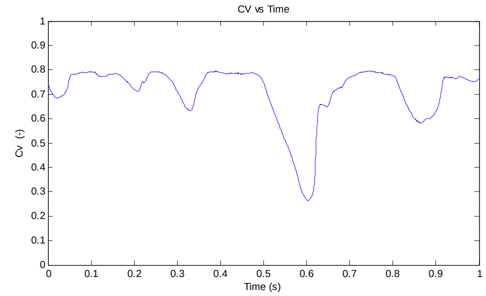
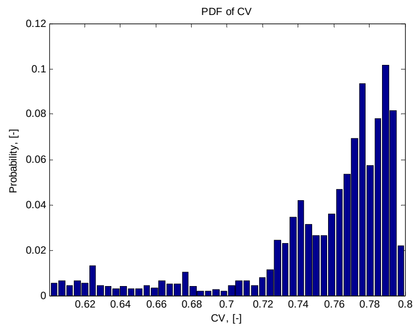
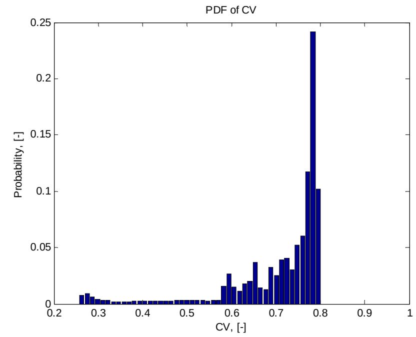
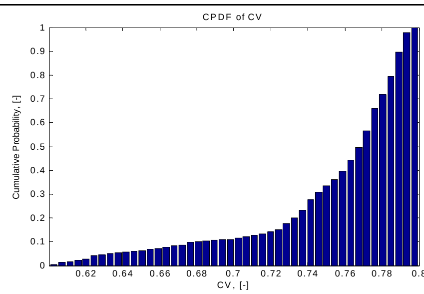
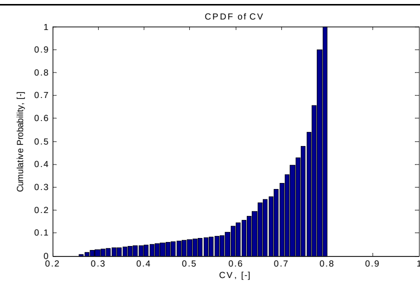
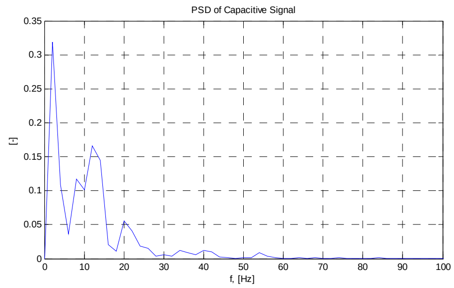
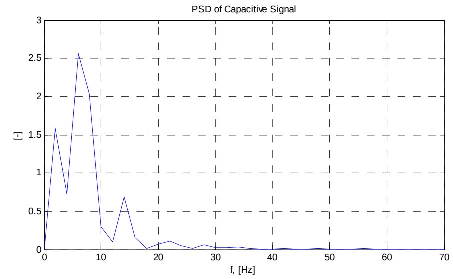
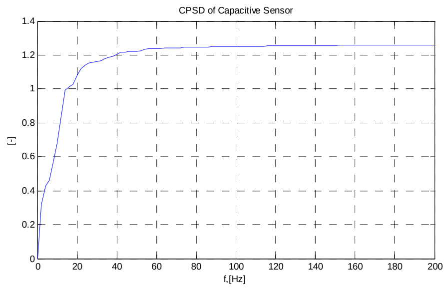
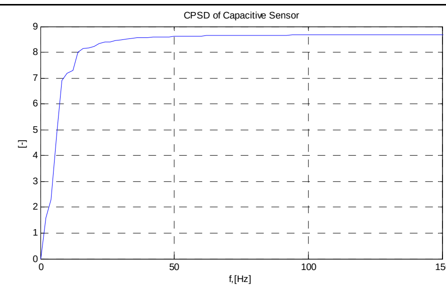
Flow Rate	0.850 m^3/hr	1.360 m^3/hr
C_v for Capacitive Sensor with Physical Low-Pass Filter		
PDF		
CPDF		
PSD		
CPSD		

Figure 15: Comparison of Capacitive Signals Using Physical Low-Pass Filter

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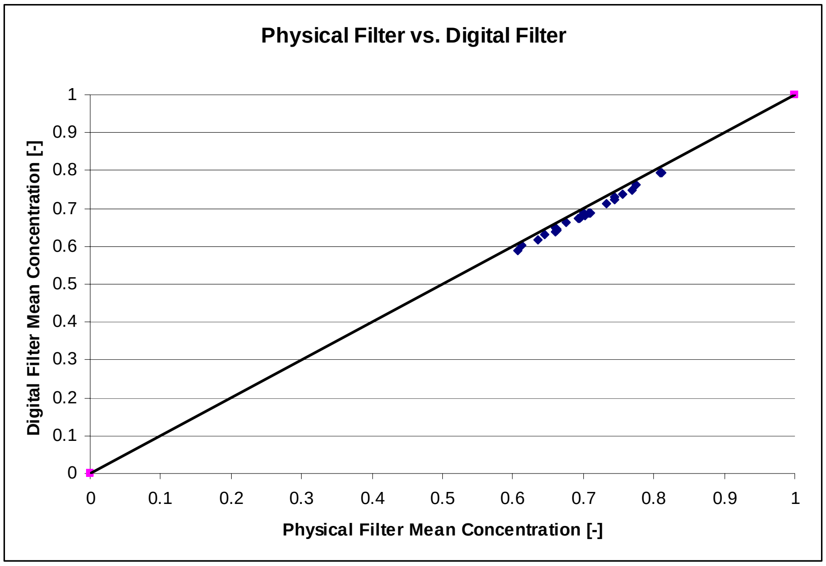

Figure 16: Comparison of Mean Concentration for Physical and Digital Low-Pass Filters

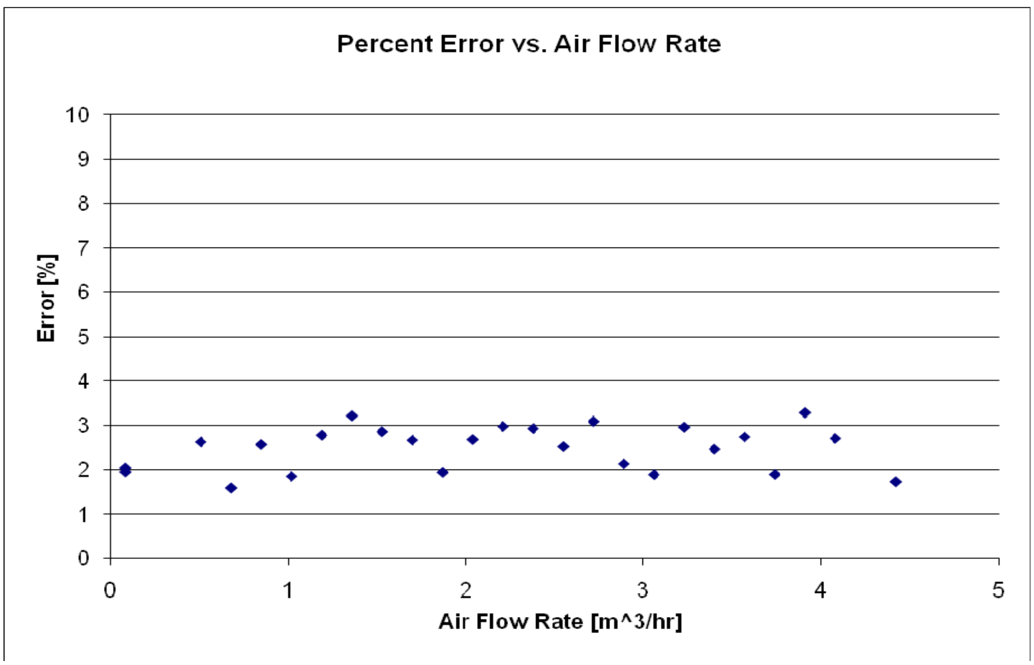

Figure 17: Error Obtained Using the Digital Low-Pass Filter

Conclusions

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Based on the experimental research conducted on air-water mixture flow in a vertical column the following conclusions can be draw:

1. The developed and built unique computer-aided capacitive and resistive concentration meters demonstrated a good frequency response for dynamic process with concomitant ability for concentration measurements.
2. The concentration signals analyzed in time, amplitude and frequency domains are very sensitive to flow patterns.
3. The three capacitive system options (no filter, physical low-pass filter, and digital low-pass filter) demonstrated different response and resulting accuracy to the in-situ concentration and flow patterns. The best results were obtained by applying the physical and digital low-pass filters.
4. The digital low-pass filter provides excellent results for in-situ concentration measurements when compared with the physical low-pass filter.

Nomenclature

C	Capacitance [F]
D	Channel diameter [m]
b_c	Capacitor plate width [m]
c_v	Spatial concentration [-]
ε_0	Dielectric constant [-]
ε_1	Dielectric constant of liquid [-]
ε_2	Dielectric constant of air [-]
f	Frequency [Hz]
L	Length [m]
R	Resistance [Ω]
t	Time [s]
V	Signal voltage [V]
ρ	Density [kg/m^3]
ρ_a	Resistivity of air [Ω*m]
ρ_w	Resistivity of water [Ω*m]
v_a	In-Situ air velocity [m/s]
Q_a	Flow rate of air [m^3/hr]

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PATRICK L. ADAMS

Patrick is currently an undergraduate student in the Mechanical Engineering Department at the University of Louisiana at Lafayette. He has spent the summer of 2008 in Germany at the Universität Duisburg-Essen where he researched motion visualization through the use of robots. He is currently researching the two-phase flow phenomenon and working on his undergraduate thesis.

JERRY K. KESKA, D. Sc. Eng.

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Dr. Keska is an Associate Professor and a member of the Graduate Faculty in the Department of Mechanical Engineering at The University of Louisiana-Lafayette. Although most of his experience is in academia, he has been employed in both the private sector (Copeland Corporation, Technicon Instruments) and in government laboratories (Pacific Northwest Laboratory, Argonne National Laboratory). His primary research interests are in the areas of Micro-Electro-Mechanical Systems (MEMS), fluid dynamics of complex heterogeneous mixtures (multiphase, slurries, etc.), tribology, micro heat exchangers with phase transition, computer-aided measurement systems and instrumentation, electromagnetic sensors, turbulence and flow pattern phenomena in mixtures, deterministic and random signal analysis, and data processing and validation. His work has been published in more than one hundred refereed technical journals, conference publications, books, and monographs, and he has been granted more than 20 patents.

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