Application of Optical Systems to Detect Flow Pattern in Two-Phase Flow

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Abstract

The objective measurement and detection of flow patterns in two-phase flow is not only one of the most significant problems in research today, but it is also absolutely necessary in the aerospace, automobile, petroleum, and chemical industries. The development of methods and systems for objective measurement and detection requires the identification of the dependent physical parameters, which are impacted by flow patterns. Any attempt to find such parameters and describe their relationships contributes to the process of finding such a system to detect flow patterns. This paper presents the results of an exploratory experimental research project on two variations of optical system response to changes of three arbitrarily chosen flow patterns and changes of mixture viscosity. The analysis of the results should provide guidance for the next steps in the development of flow pattern detections and the applicability of optical systems to this purpose. The evaluation of the application of optical systems to detect flow patterns is based on experimental research for two-phase flow. This work was conducted in a vertical pipe using two sets of optical systems to measure the variations of interfacial phenomena caused by different flow patterns. A detailed analysis of the output signals in time, amplitude and frequency domains using NI ELVIS (Educational Laboratory Virtual Instrumentation Suite), MatLab and LabView software will revise the impact of flow patterns on the resistance change of opto-detectors used in both optical systems.

Introduction

The process of flow pattern recognition in two-phase flow is currently and widely considered as a random, unpredictable process, and it has continuously challenged the academic community since the 1940s[8, 9]. Considering the widespread application of two-phase flow in industrial processes, any solution to this problem is very important. In the literature, historically, one can distinguish two main periods in the response to this problem. First, the period lasting until the late 1980s, when the use of superficial parameters led to the development of flow pattern maps. Secondly, the period starting at the beginning of the 1990s, when in-situ parameters were used. Because each experimental system's unique properties impact the reported results using superficial parameters, however, the reported results are unique and cannot be compared with the results generated by other experimental systems.

One of the most current applications of two-phase flow is the management of intense heat in large surfaces like Space Shuttles or very small surfaces such as the micro devices used in the cooling of electronics for CPUs. These electronic systems require high-standard heat and thermal protection characterized by intense heat removal, which requires heat exchangers with phase transitions, and thus two-phase flow. Newly proposed the use of Advanced Micro Cooling Modules (AMCMs), which are compact, two-phase heat exchangers that remove large amounts of heat by incorporating phase transition. These AMCMs require fundamental advancements in many areas, including two-phase flow pattern control and measurements.

Because flow patterns could influence the parameters of the flow such as the pressure drop and the velocity of the system, it is necessary to find objective methods to detect and measure them instead of allowing them to be detected visually by an observer. A possible first step in this process involves finding measurable, in-situ two-phase flow parameters, which are somehow sensitive to changing flow patterns. One of these parameters is interfacial phenomenon, which could be detected with the use of optical systems.

This paper reports the preliminary results of experimental research involving two-phase flow in a vertical pipe, using two variations of optical systems to detect its sensitivity to interfacial phenomena. Included are the description of the applied systems and procedures, the experimental data, and the analysis of the results. In the reported experiment, three arbitrarily chosen flow patterns for water or glycerin as the mixture component with air were distinguished visually (bubble, froth and disperse) and generated by variable airflow rate. In the developed experiment, two different measurement systems of optical resistors were applied, and the change of an opto-resitor’s resistance were transferred into a proportional voltage signal and interfaced into an ELVIS (Educational Laboratory Virtual Instrumentation Suite) for analysis using LabView and MatLab software.

Literature Search

There are many different combinations of two-phase flows. In this paper, however, it is understood that two-phase flow is a heterogeneous mixture of gas (air) and liquid (either water or glycerin). For such mixture flow, the process of flow pattern determination and recognition in two-phase flow is currently and widely considered to be a random (unpredictable) process, and it has posed a continual challenge to the professional community since the 1940s[1, 8, and 9]. There have been some attempts to solve this problem. One of the proposed solutions comes from Keska and Simon[1, 6] and Keska[4], which--based on their experimental research on flow patterns in two-phase flow with the use of computer-aided measurement systems utilizing LabView and Matlab software--presents a developed mathematical model of two-phase flow for a gas/vapor-liquid mixture that incorporates flow pattern phenomena.

Wongwises[2] performed an experiment using a mixture of lubricant oil and HFC-134a in order to study the two-phase flow. The results indicate that the observed flow patterns changed due to the presence of lubricant oil. Wongwises also encountered a “tear-like,” oil-rich layer running down the upper side of the tube. The phenomenon may be attributable to the wetability (or the contact angle) of the fluids.

Ibrahim[3] conducted an experiment on the use of optical sensors for velocity measurement. The optical sensors were installed upstream and downstream on a hydraulic flow rig to detect the flow of bubbles and to monitor the dynamics within the process equipment. The experiment also presented results of the successful development of a cross-correlation technique for velocity measurements.

Ravellin[5], based on experimental research on flow patterns in two-phase flow, proposed a modified, adiabatic flow pattern map of boiling heat transfer in microchannels. The new adiabatic map classifies flow into three types rather than segregating the observations into the traditional flow regimes. For the detection of flow patterns, an optical measurement technique incorporating two laser beams, was used.

Ulbrich[7] conducted experiments using flow visualization techniques for the recognition of two-phase flow patterns using image analysis. In order to enhance the contrast required for optical methods, an alcohol-air mixture was used in the two-phase flow. Combining the digital image processing carried out by the author's own software with the analysis method is a great research tool that can be modified for particular applications. Gas-solid flow is also described.

The limited survey conducted on works related to flow patterns in two-phase flow relating to optical systems found many objective methods for determining or measuring flow patterns and the significant limitations in the estimation of a mixture's physical parameter sensitivity to flow patterns. In the literature, historically, two main periods can be distinguished. The first period runs to the end of the 1980s, when the use of superficial parameters led to the development of flow pattern maps. The second period began in the early 1990s, when in-situ parameters were used. Because of the impact of unique properties of an experimental system using superficial parameters on the reported results, the reported results are always unique and cannot be compared with the results generated by other experimental systems. Consequently, there is a need to conduct research on the properties and sensitivity of optical systems as well as their applicability for the detection of flow patterns.

Experimental System

A measurement system was developed and built for the measuring of flow patterns using optical systems (both hydraulic and electronic). The hydraulic system—shown in Figure 1—consists of a vertical test tube, two optical measurement systems (reflective and passing), air pressure and flow meters, and an air compressor. The electronic system consists of a computer-aided data acquisition system (CADAS) and a prototyping board with a Wheatstone bridge, which is interfaced to NI ELVIS using a digital oscilloscope. Experimental research was conducted using two different optical measurement systems (translucent and reflective). For both systems, an optical resistor was installed on the tube with the light source. The optical sensor is part of the Wheatstone bridge (details are shown in Figure 2). The system is operated by ELVIS in order to observe the signals generated by the changing flow patterns in the vertical tube, which is controlled by the air compressor's air flow intensity. The translucent system consists of a light source and a photodetector installed on the opposite side of a transparent pipe and interfaced into a computer-aided data acquisition via a Wheatstone bridge. For the reflective system, the light source and the photodetector are installed on the same side of the tube.

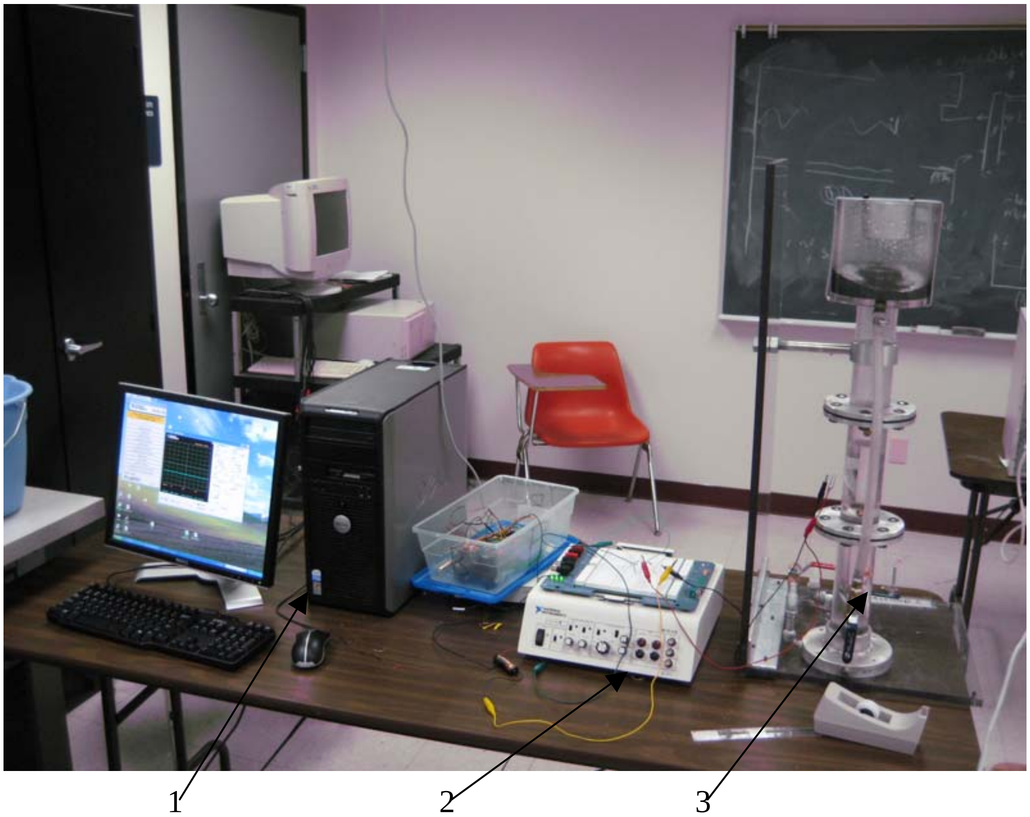
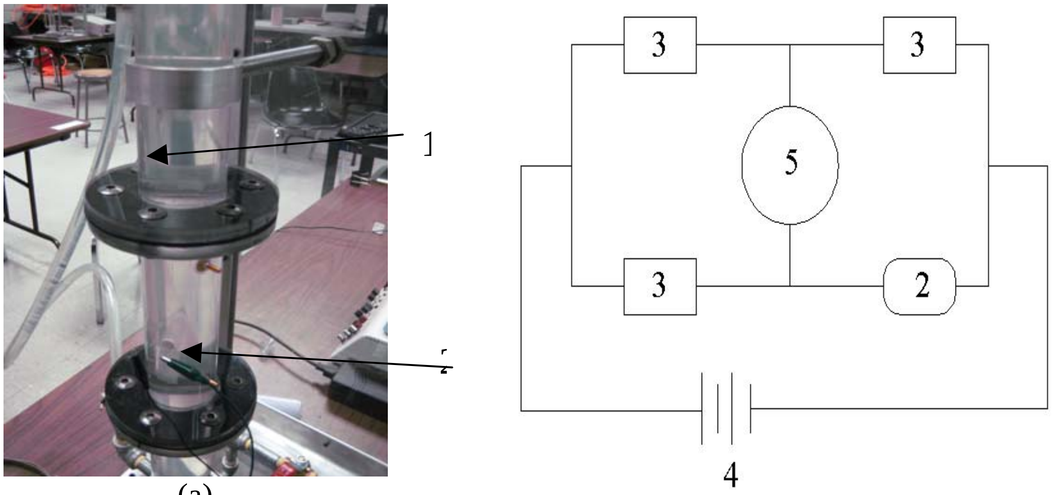


Figure 1. Experimental Apparatus for Two-Phase Flow in a Vertical Column.
1. Computer aided data acquisition system (CADAS), 2. NI ELVIS with prototype board and Wheatstone bridge, 3.Two-phase flow in a vertical column.



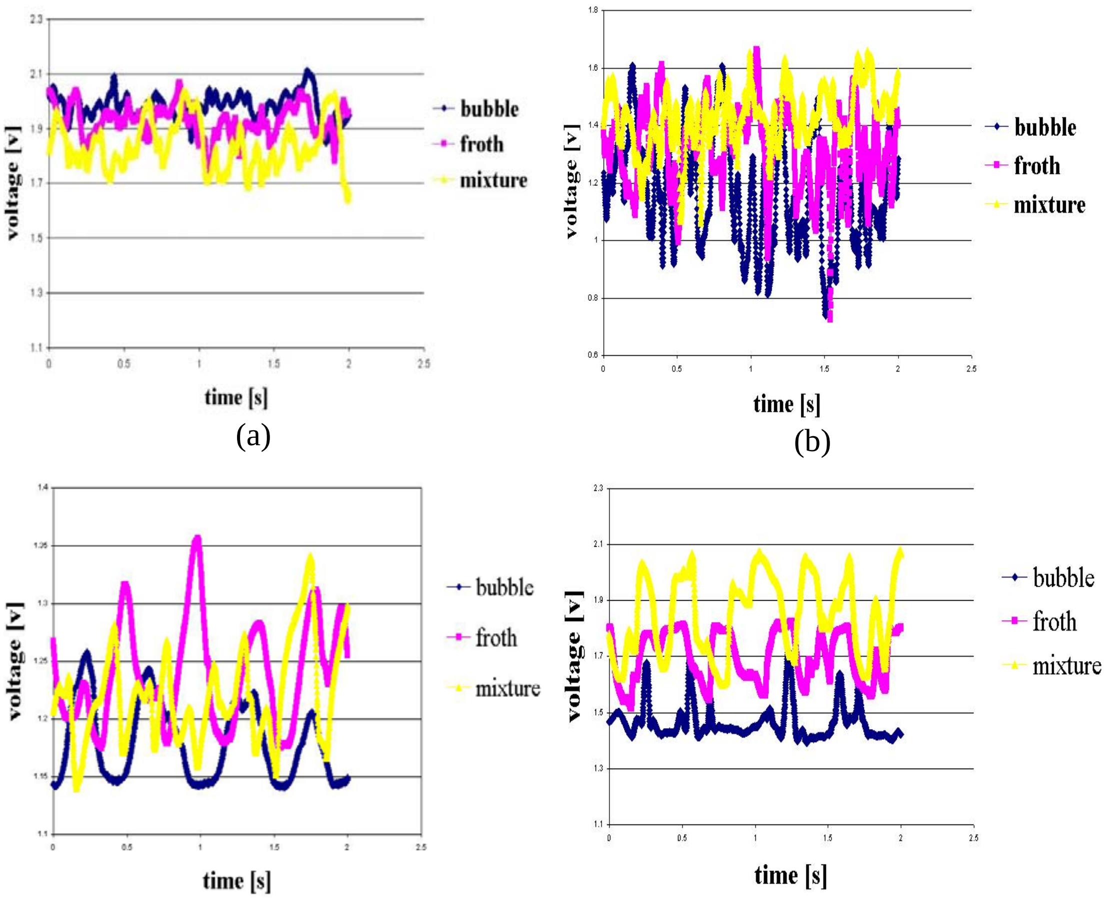
(a)

(b)

Figure 2. Scheme of the Experimental Apparatus for Two-Phase Flow in a Vertical Flow and Electrical Scheme and Sensing Details
(a) Scheme of the experimental apparatus for two-phase flow in a vertical column, (b) Electrical scheme and sensing details.
1. Two-phase flow vertical column, 2. Opto-sensor, 3.Resistors, 4.Battery, 5.NI ELVIS

Data Analysis of Experimental Results

The primary data of the dynamic voltage signal from the Wheatstone Bridge, which is proportional to the interfacial phenomena in the passage of the opto-resistor–light source influenced by flow patterns, is interfaced by NI ELVIS into CADAS and stored as an electronic file. It is then observed on-line using the digital oscilloscope. Examples of such signal traces in time-domain are shown in Fig. 3. These signals underwent analysis off-line using Matlab and LabView software to transfer the signals into both amplitude and frequency domains. The results are shows in Figs. 4 and 5.



(a) (b)

(c) (d)

Figure 3. Time-Domain from the Primary Data
(a) Time-domain for reflective system (water), (b) Time-domain for passing system (water), (c) Time-domain for reflective system (glycerin), (d) Time-domain for passing system (glycerin)

The results in the time-domain, as shown in Figure 3 (charts 3a through 3d), demonstrate that there are significant differences in the signals caused by the changes in flow patterns and mixture viscosity for both optical systems (passing and reflective). To better understand these differences, further analysis of the primary signals in amplitude and frequency domains is conducted. The histograms, which are characteristic in amplitude domain, represent the frequency of occurrences (vertical axis) vs. voltage (horizontal axis). These are proportional to the resistance changes of the opto-resistor, and are presented on Fig. 4 (charts 4a through 4l). By performing a histogram comparison on charts 4a through 4c (reflective system for water) with charts 4g through 4i (reflective system for glycerin), significant differences for the same flow pattern in the histogram's shape caused solely by viscosity change can be observed. Similar significant differences were observed in the passing system. Additionally, a slight difference was observed in the shape of histograms for both systems, which is especially clear in the mixture with high viscosity (glycerin). We can see that the shape of the histogram remains almost constant for water, but with a viscosity increase with a substance like glycerin, the shape of the histogram is different. This means that the change of flow pattern from bubble to the froth and dispersed flow patterns did not only cause the change of voltage amplitude vs. time results, but also demonstrated a significant measurement system response to interfacial phenomena, which are probably caused by the change of both flow patterns and the mixture's viscosity.

Results of further analysis in frequency domain are shown in the charts on Figure 5 as pairs (5a through 5d). The left chart in each pair represents PSD characteristics vs. frequencies while the right chart represents CPSD vs. frequencies for three different flow patterns. The left charts in pairs 5e and 5f show PSD characteristics vs. frequencies while the right charts show CPSD vs. frequencies for different mixture viscosity. PSD values show that flow patterns and viscosity have a significant variation in response to different systems. For the reflective system, the maximum frequency of PSD fluctuation for the air-water mixture is 15 Hz, 7HZ for the air-glycerin mixture, and the ratio of the maximal PSD values is approximately 1 to 4. For the passing system, the maximum frequency for the air-water mixture is 20 Hz, 10 Hz for the air-glycerin mixture, and the maximal PSD values for both mixtures are equal.

Both systems (passing and reflective) have different responses to flow patterns and the viscosity of the mixture, which could easily be observed on histograms, PSDs and CPSDs. Histograms show similar sensitivities to flow patterns for both systems, when the impact of change in the mixture viscosity is very limited. Values of PSDs demonstrated that flow patterns and viscosity cause significant variations in responses to the different system. For the reflective system, the maximum frequency of PSD fluctuation for the air-water mixture is 15 Hz, 7 Hz for the air-glycerin mixture, and the ratio of the maximal PSD values is approximately 1 to 4. For the passing system, the maximum frequency for the air-water mixture is 20 Hz, 10 Hz for the air-glycerin mixture, and the maximal PSD values for both mixtures are equal.

Conclusions

The conducted preliminary experimental research for the visually distinguished and arbitrarily chosen three flow patterns was performed in such way that the flow patterns could generate sufficient differences in interfacial phenomena (bubble, froth, or disperse) for two kinds of heterogeneous and optically transparent mixtures (air with water or glycerin). Observing the flow in a vertical tube using two variations of optical systems (reflective and passing) with a newly developed computer-aided experimentation system generated the following conclusions:

1. The voltage output data from a DC Wheatstone Bridge were taken in time domain using two optical systems (passing and reflective), both of which were responsive to the interfacial phenomenon. For a passing (translucent) system, a light source and photodetector were installed on the opposite side of a pipe. For the reflective system, the light source and photodetector were

installed on the same side of the tube. The signals from both systems were interfaced to CADAS via a Wheatstone bridge and analyzed in time, amplitude, and frequency domains.

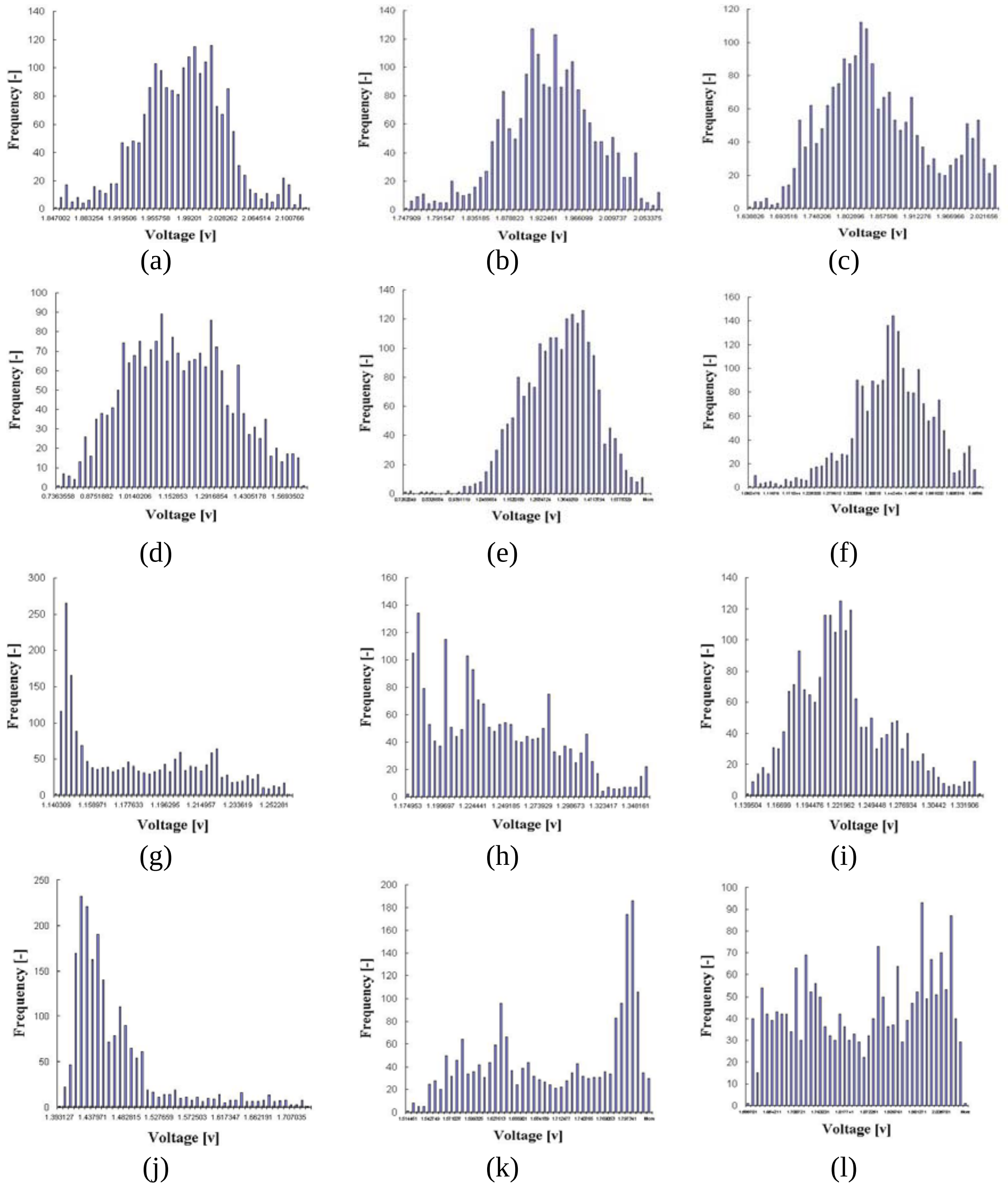
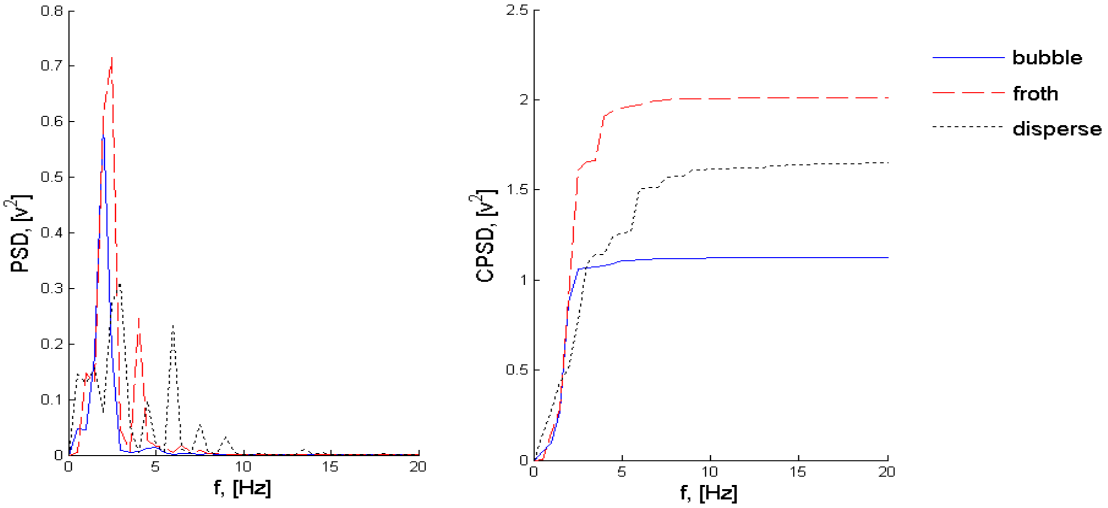
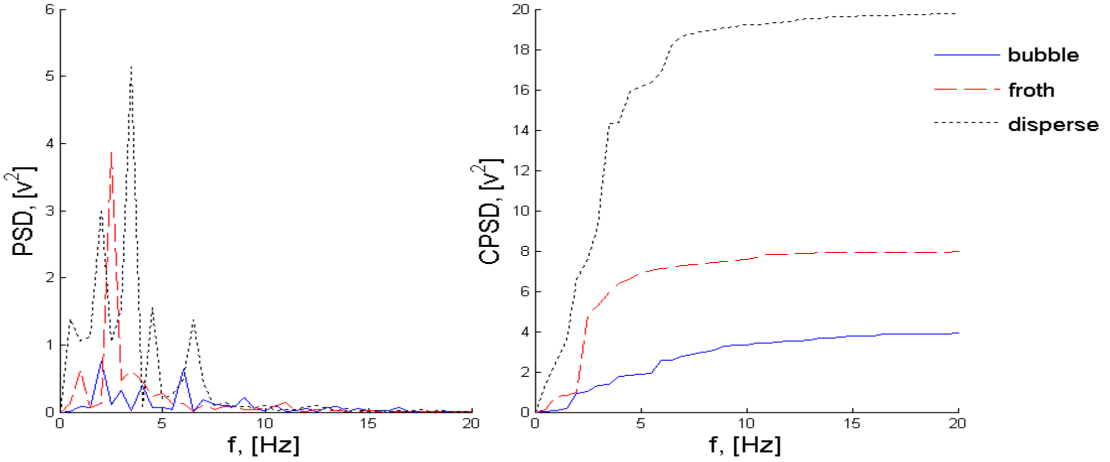


Figure 4. Data in Amplitude-Domain

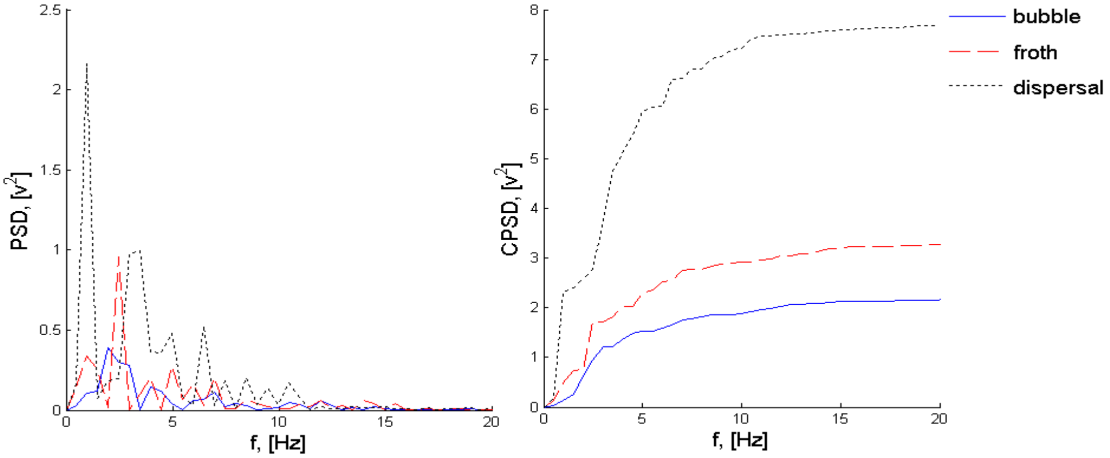
(a) Bubble histogram for reflective system (water), (b) Froth histogram for reflective system (water), (c) Disperse histogram for reflective system (water), (d) Bubble histogram for passing system (water), (e) Froth histogram for passing system (water), (f) Disperse histogram for passing system (water), (g) Bubble histogram for reflective system (glycerin), (h) Froth histogram for reflective system (glycerin), (i) Disperse histogram for reflective system (glycerin), (j) Bubble histogram for passing system (glycerin), (k) Froth histogram for passing system (glycerin), (l) Disperse histogram for passing system (glycerin)


PSD, [v^2]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
f, [Hz]
CPSD, [v^2]
2.5
2
1.5
1
0.5
0
0
5
10
15
20
f, [Hz]
bubble
froth
disperse

(a)


PSD, [v^2]
6
5
4
3
2
1
0
0
5
10
15
20
f, [Hz]
CPSD, [v^2]
20
18
16
14
12
10
8
6
4
2
0
0
5
10
15
20
f, [Hz]
bubble
froth
disperse

(b)


PSD, [v^2]
2.5
2
1.5
1
0.5
0
0
5
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15
20
f, [Hz]
CPSD, [v^2]
8
7
6
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3
2
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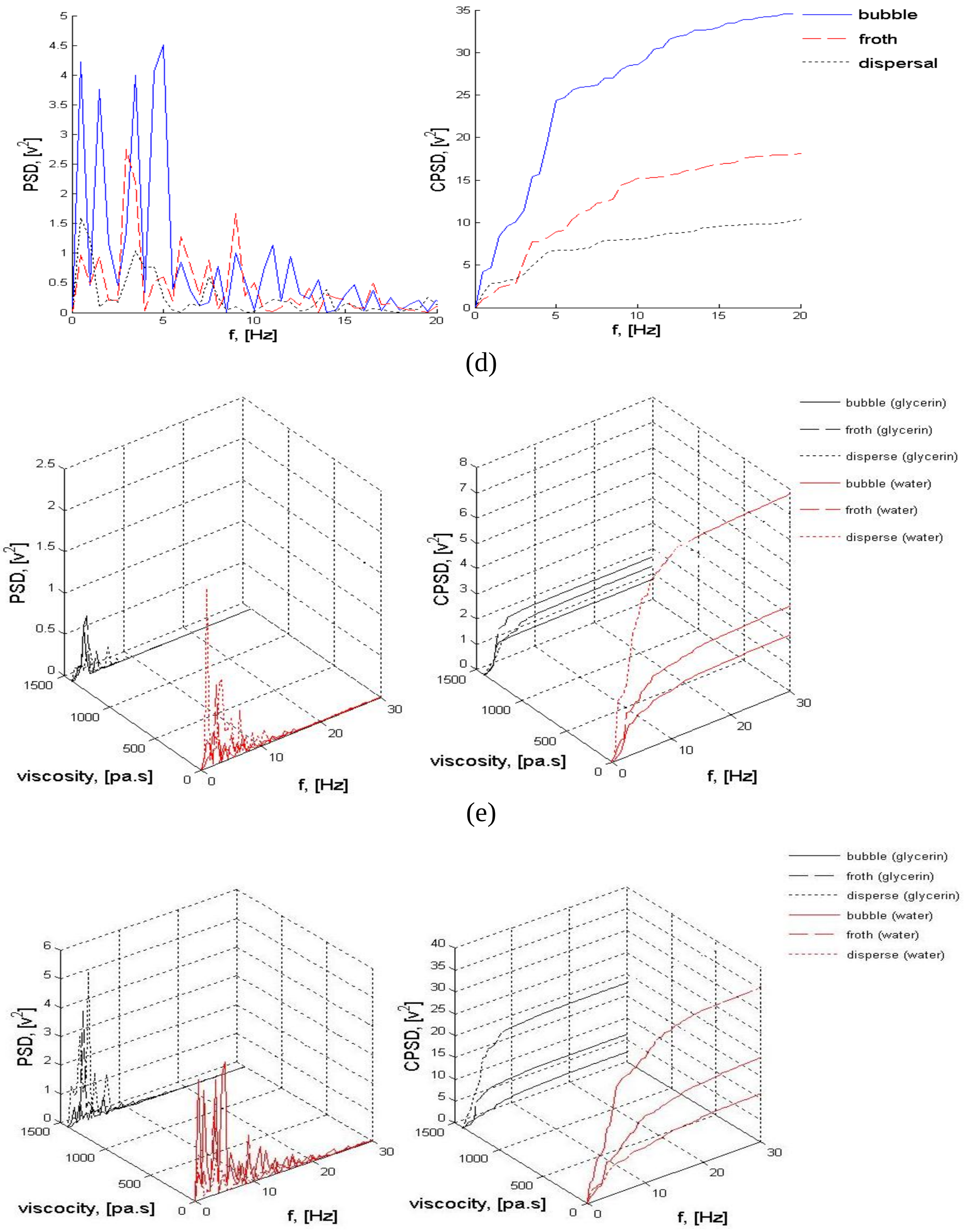
f, [Hz]
bubble
froth
dispersal

(c)



(d)

(e)

(f)

Figure 5. Data in Frequency Domain
(a) Reflective system for air-glycerin mixture, (b) Passing system for air-glycerin mixture, (c) Reflective system for air-water mixture, (d) Passing system for air-water mixture, (e) Reflective system comparison for both air-water and air-glycerin mixture, (f) Passing system comparison for both air-water and air-glycerin mixture

2. In the experiments, bubble, froth and disperse flow patterns were generated by changes of airflow rates and determined visually. Not only did the voltage amplitude vs. time results demonstrate a significant measurement system response to interfacial phenomena (probably caused by the change of flow patterns and the mixture viscosity), but the histograms, power spectral densities, and cumulative power spectral densities also demonstrated the impact of flow patterns and the viscosity of the mixture.

3. Both systems (passing and reflective) have different responses to flow patterns and the viscosity of the mixture, which could easily be observed on histograms, PSDs and CPSDs. Histograms show similar sensitivities to flow patterns for both systems, when the impact of change of the mixture viscosity is very limited. Values of PSDs showed that flow patterns and viscosity cause significant variations in responses to different system.

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