Root-Mean-Square (RMS) Values of In-Situ Parameters in Air-Water Heterogeneous Mixture Flow in a Horizontal Minichannel

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Abstract

The number of existing, diversified applications of heterogeneous mixture flow has made the generation of an adequate mathematical model, which incorporates flow pattern phenomena, an urgent task. In order to successfully design, analyze, and control such a process, it is necessary to first obtain a fundamental understanding of two-phase flow in mini- and microchannels for steady-state conditions, where the mean values of the in-situ concentrations/void fractions, velocities, and pressure gradients are constant (though they have smaller, time-scale fluctuating randomly components). Any random fluctuating component (in general), and any fluctuation intensity of two-phase in-situ parameters (in particular) can be characterized by its RMS value. Finding a characteristic of RMS values for an in-situ parameter such as concentration or pressure will give us a better understanding of two-phase flow of a heterogeneous mixture. This paper will present the results of experimental research on RMS characteristics of in-situ parameters for an air-water heterogeneous mixture steady-state flow in a horizontal minichannel. Knowledge of such a characteristic will allow us to better predict and study both the dynamicity and flow pattern and how they are influenced by in-situ parameters like pressure and concentration. This paper will also discuss some comparisons of RMS values for in-situ parameters and how are they influenced by flow patterns.

Introduction

Many electronic and mechanical systems have very precise temperature requirements which necessitate the presence of cooling or heating systems as high-standard thermal protection. Though many advances have been made in the development of such systems, new and effective systems, which can provide high heat intensity and geometrical size limitation, are still needed. One such system can be accomplished by using compact, two-phase heat exchangers which remove large amounts of heat by incorporating phase transition. The development of compact heat exchangers requires fundamental advancements in many areas, including fluid dynamics of two-phase flow. The broad number of existing, diversified applications of heterogeneous mixture flow has made the generation of an adequate mathematical model an urgent task. Consequently, without the formulation of an adequate model for flow patterns, two-phase flow is still scientifically recognized today as one of the most challenging fluid dynamic problems to be explored since the 1940s. This process is still considered to be random and in many cases, it is treated using a statistical approach. In order to successfully design, analyze, and control such a process, it is necessary to first obtain a fundamental understanding of two-phase flow in mini- and microchannels for steady-state conditions, where the mean values of the in-situ concentrations/void fractions, velocities, and pressure gradients are constant (though they have smaller, time-scale fluctuating randomly components). Any random fluctuating component (in general), and any fluctuation intensity of two-phase in-situ parameters (in particular) can be characterized by its RMS value. Finding a characteristic of RMS values for an in-situ parameter such as concentration or pressure will give us a better understanding of two-phase flow of a heterogeneous mixture.

There are significant differences in the flow phenomena between single-phase flow and two-phase flow. These differences are the result of the presence of different velocities for different phases. They are also the effect of other parameters (such as spatial concentration) that impact both energy consumption models and flow patterns in two-phase flow.

This paper will present the results of experimental research on RMS characteristics of in-situ parameters for an air-water heterogeneous mixture steady-state flow in a horizontal square channel (6.35 mm in size). The obtained knowledge of such a characteristic will allow us to better describe and predict both the dynamicity and flow patterns, and how they are influenced by in-situ parameters like pressure and concentration.

Background

The in-situ parameter measurements are one of the significant issues in two-phase flow including concentration, and definition of flow patterns. These parameters (flow pattern, concentration and pressure drop) will significantly influence the fluctuations and RMS values. One of the methods to detect concentration is to measure the void fraction in two-phase flow.

Kawahara et al.[1] proposed that the void fraction in the channel can be estimated by analyzing the images of the air-liquid mixture. By counting the number of images for each flow pattern, the void fraction can then be determined by the number of gas core images divided by the total number of images that were counted. At high flow rates, due to the thick liquid film around the gas core, the numerator must be changed into the number of images of gas core flows with a thin film plus the number of images of gas core flows with thick liquid films.

A lot of the researchers use Lockhart-Martnelli[2] equations to predict the void fraction like Zhao and Bi[3]. When using this method, however, it is impossible to detect the homogeneous void fraction in the three dimensional section of the channel with any reasonable precision. This is due to the fact that the camera installed on both sides of the channel cannot take pictures of the mixture flowing through the three dimensional sections of the channels. Consequently, this three dimensional approximation is calculated assuming full homogeneity.

Keska et al. [4,5,6,7] developed a measurement system based on a Computer-Aided-Data-Acquisition-System (CADAS) that measured the in-situ parameters of two-phase flow by using both capacitive and resistive 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:

$$C_i = \frac{1.01\varepsilon_0 L_c(\varepsilon_1 c_v + (1-c_v)\varepsilon_2)}{In(1+(\pi D/b_c)\tanh^2(0.7(D/b_c)))}. \tag{1}$$

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:

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

Therefore, a calibration method for detecting the void fraction by incorporating the resistive and capacitive sensors was developed by Keska et al.[4,5,6,7]. This method can precisely measure the three dimensional void fraction or concentration in the three-dimensional section of a channel. The calibration process of the concentration measurement system involves two different sensors (conductive and capacitive) that have been used in previously discussed models. Once the concentration values have been attained, we can also calculate the void fraction.

The method developed by Keska et al.[4,5,6,7] solves the problem of measuring the concentration of a dynamic homogeneous mixture flow. Applying this method, however, requires sophisticated procedures and equipment as well as significant amount of time. This is probably why most researchers are still not using such a method. Rather than focus on the measurement of void fractions or concentrations, many researchers are instead focused on predicting the void fraction in two-phase flow, most likely as a way to avoid the inconveniences that are usually associated with those measurements.

From the literature survey and summary, the concentration and flow pattern are the key issues which cause different flow patterns and other dynamic fluctuations. A research focused on the RMS values of concentration, pressure drop will be beneficial to the dynamic nature of two-phase flow.

Experimental Research

The system for a horizontal, two-phase flow experiment is composed of a flow channel section as well as capacitive and resistive concentration sensor systems for computer-aided experimentation. The flow channel section consists of a transparent minichannel with a cross-section of 6.35mm X 6.35mm. The pressure, flow rate, capacitive, resistive, and film thickness sensors are installed separately in the minichannel. After the completion of preliminary tests and calibrations on the hydraulic and electronic parts, the system is ready for the experiment. The pressure sensors are included and connected on the prototype boards. An automatic calibration procedure is used to calibrate both the capacitive and the resistive systems so they can measure in-situ concentration. All of the data are collected by the DAQ system. After the initial data are taken from LabVIEW[12] for calibration, the main data are then collected and saved into a text file. This is then transferred into a spreadsheet for further analysis. Each run of the experiment is saved in one worksheet of the spreadsheet. The calibration curve is then applied in order to analyze and receive appropriate parameters. A stroboscope is used in the system in order to "freeze" the mixture flow image and observe the flow pattern in the minichannel. The flow patterns observed in the experiment are bubble, slug, annular/slug, and annular flow.

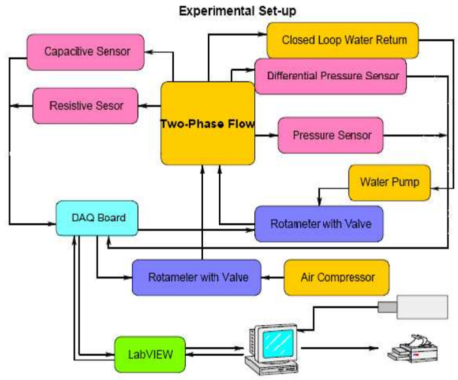


Figure 1. Set-up of the Experimental Two-Phase Flow System

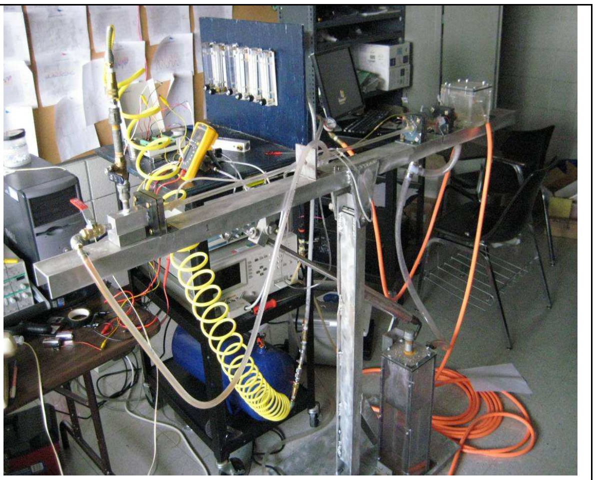


Figure 2. View of the Computer-aided Experimentation System for Two-Phase Mixture Flow in Horizontal Square Channel

Experimental Data and Analysis

Due to the calculation of velocities, the two different mixture velocities are the result of two sets of assumptions. The first velocity, $v_{m1,}$ is calculated under the assumption that the mass flow of the mixture is equal to the sum of masses of air and water. Another velocity, v_{m2}, is calculated under the assumption that the mixture volume flowrate is equal to the sum of the air and the water volume flowrates. Both of the mixture velocities are important. They are incorporated with the data in order to analyze, compare, and determine which one can more accurately describe the flow conditions of the two-phase flow in the minichannel.

The conducted experiments—for steady-state conditions in the full range of concentrations (0-1) and mixture velocities (0-56m/s), using in-situ sensors, and taking data simultaneously for air- water heterogeneous mixture flow in the horizontal minichannel—indicate that using two concentration measurement systems is concomitant (Figure 3). The characteristics of water and air velocities, as a function of concentration, are shown in Figure 4. The air velocity is always higher than the water velocity and it increases as the concentration decreases.

For steady-state conditions of a heterogeneous mixture flow, all of the instantaneous parameters (concentration, velocity, pressure, etc.) are a superposition of a static component (DC) and a fluctuating component (AC). The intensity of fluctuation is measured using a Root Mean Square (RMS) Value, which indicates the intensity of turbulence. The experimental values of the RMS fluctuating component of the concentration versus the concentration with algorithm are shown in Figure 5(a). Also RMS concentration will be influenced by the mixture velocity and that three-dimensional view, as a function of concentration and velocity is shown in Figure 6.

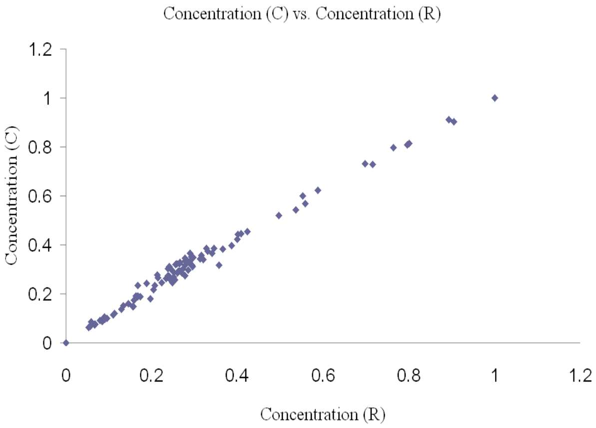


Figure 3. Concentration from Capacitive Sensor vs. Concentration from Resistive Sensor

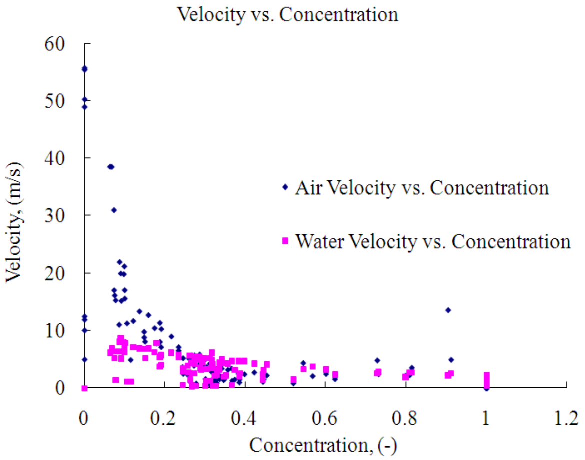


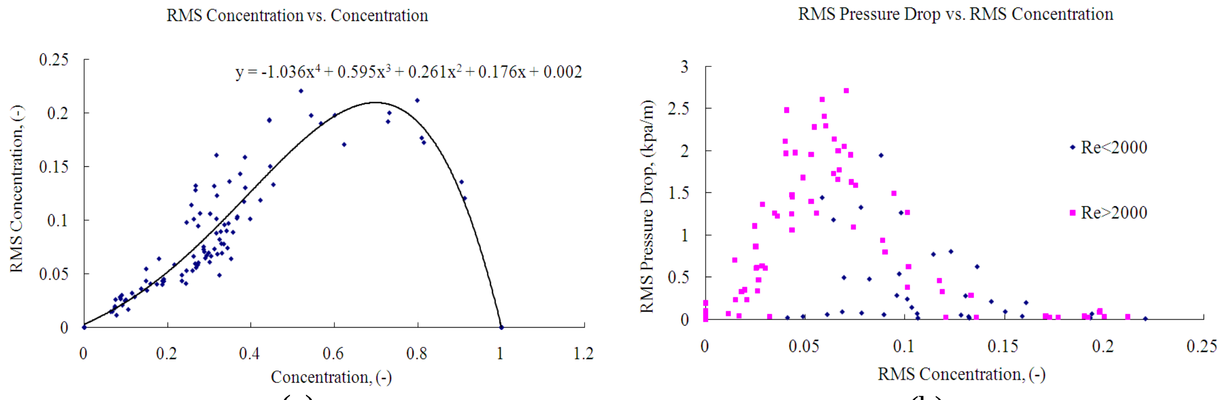
Figure 4. Water and Air Velocities vs. Concentration

Figure 5(b) shows the RMS values of pressure drop versus the RMS values of concentration. This type of correlation and the lack of a definite pattern indicate that the two RMS parameters have a different physical character.

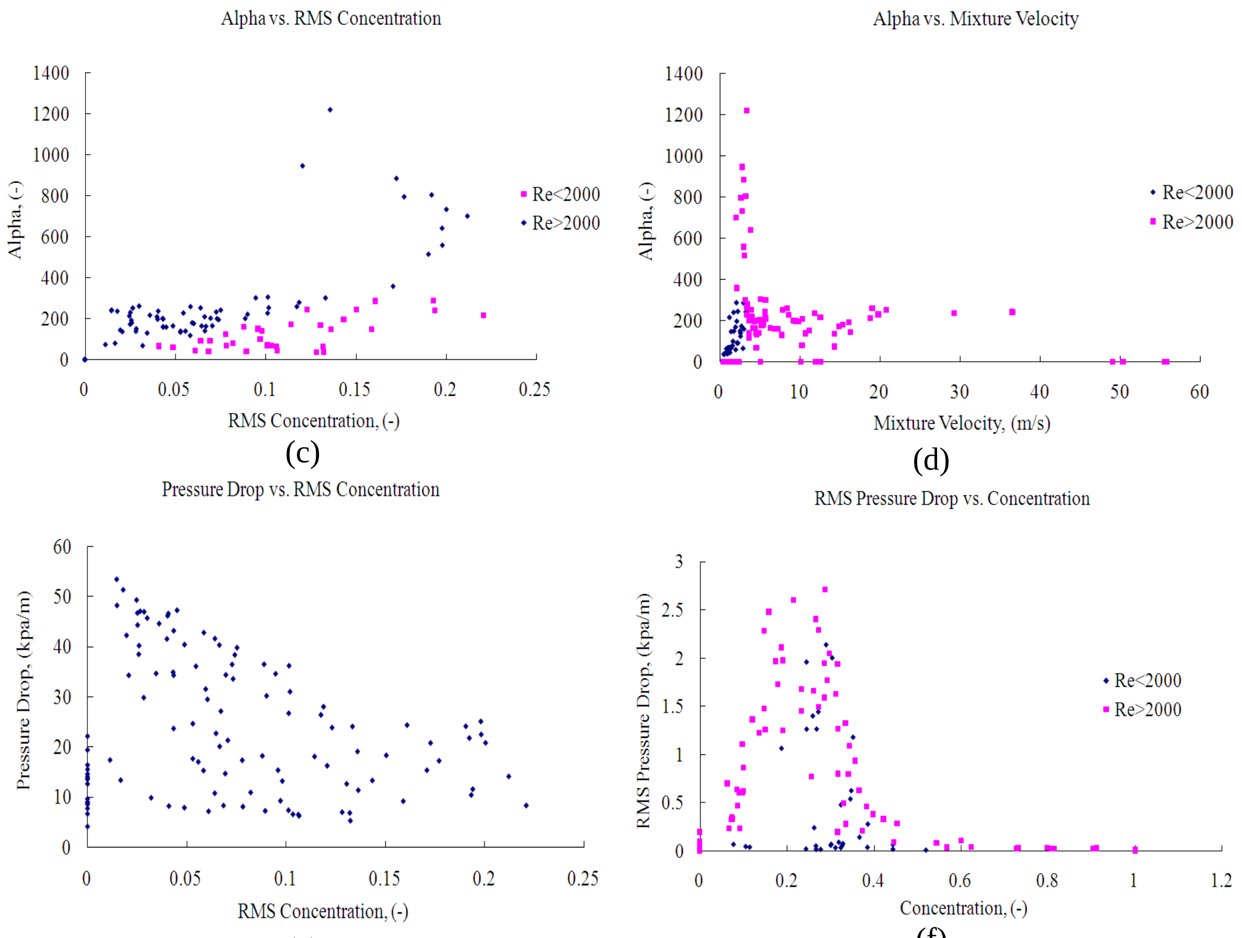
In two-phase flow, turbulence phenomena significantly affect flow patterns and other characteristic parameters. Therefore, it is necessary to incorporate it into the description of two-phase flow. One possible way to do this is through the use of an alpha coefficient. Figure 5(c) shows the correlation between the Alpha number and the RMS values of a concentration.

Figures 5(d) illustrates how the Alpha number is influenced by the velocity. The correlation for mixture velocity generated different characteristics and the characteristic Alpha number shows two different patterns. This generates a split phenomenon where two different paths are possible from the Alpha values starting at 250. The three-dimensional view of Alpha number, as a function of mixture velocity and concentration is listed in Figure 7.

Figures 5(e) presents the pressure drop in function of the RMS concentration, demonstrating that the RMS concentration has a significant and heterogeneous impact on the pressure drop.



(a) (b)



(c) (d)

(e) (f)

Figure 5. Experimental Result Analysis in Two-Dimensional View
(a) RMS Values of Concentration vs. Concentration (b) RMS Values of Pressure Drop vs. RMS Values of Concentration (c) Alpha Numbers vs. RMS Values of Concentration (d) Alpha Numbers vs. Mixture Flow Velocities (e) Pressure Drop vs. RMS Values of Concentration (f) RMS Values of Pressure Drop vs. Concentration

Figure 5(f) documents RMS pressure versus concentration values, where beginning from low concentration, the RMS values reach their maximum value for a concentration of 0.25 and then decrease significantly (almost to zero) for a concentration of 0.6. Figure 8 shows a three-dimensional view of RMS pressure as a function of concentration and mixture velocity.

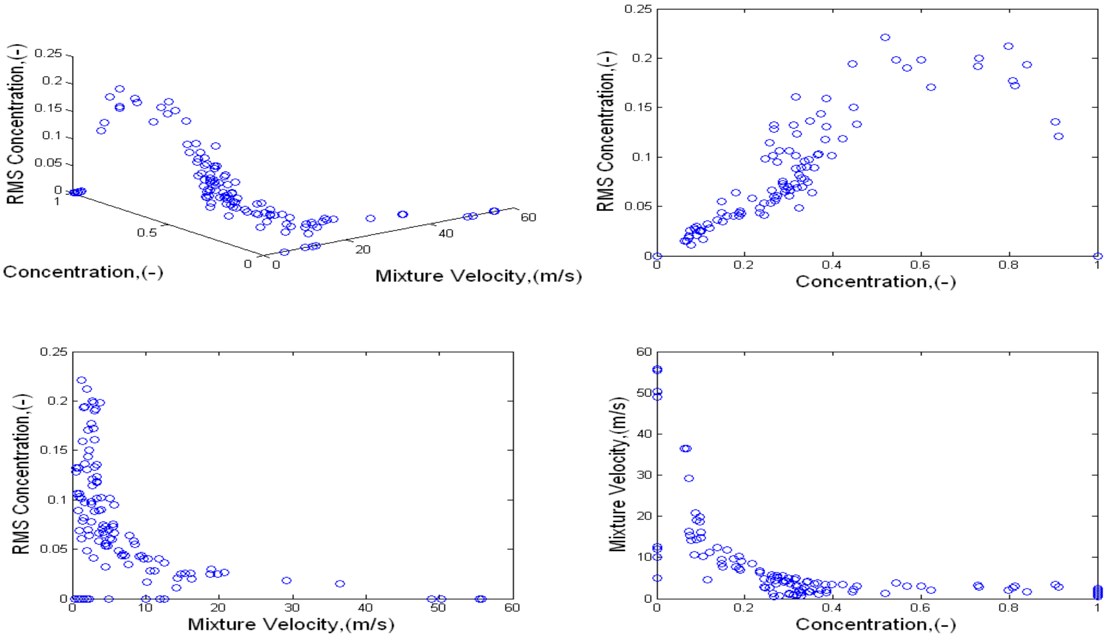


Figure 6. RMS Concentration vs. Mixture Velocity and Concentration

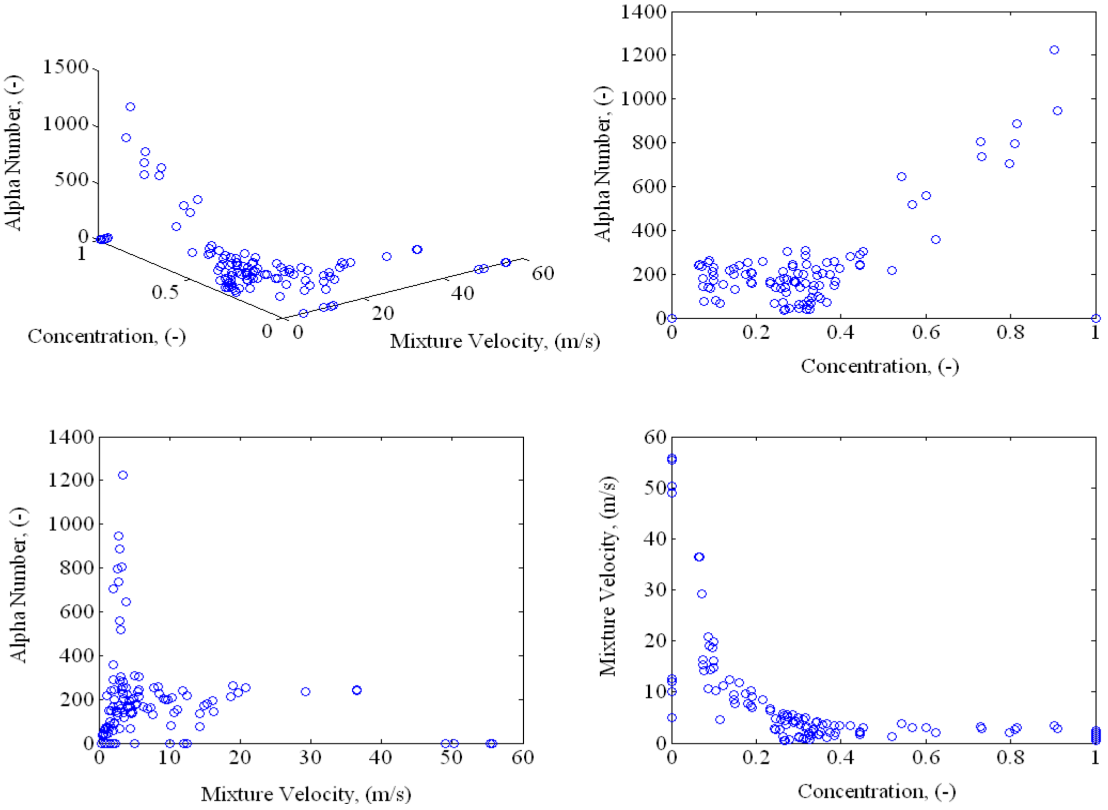


Figure 7. Alpha Number vs. Mixture Velocity and Concentration

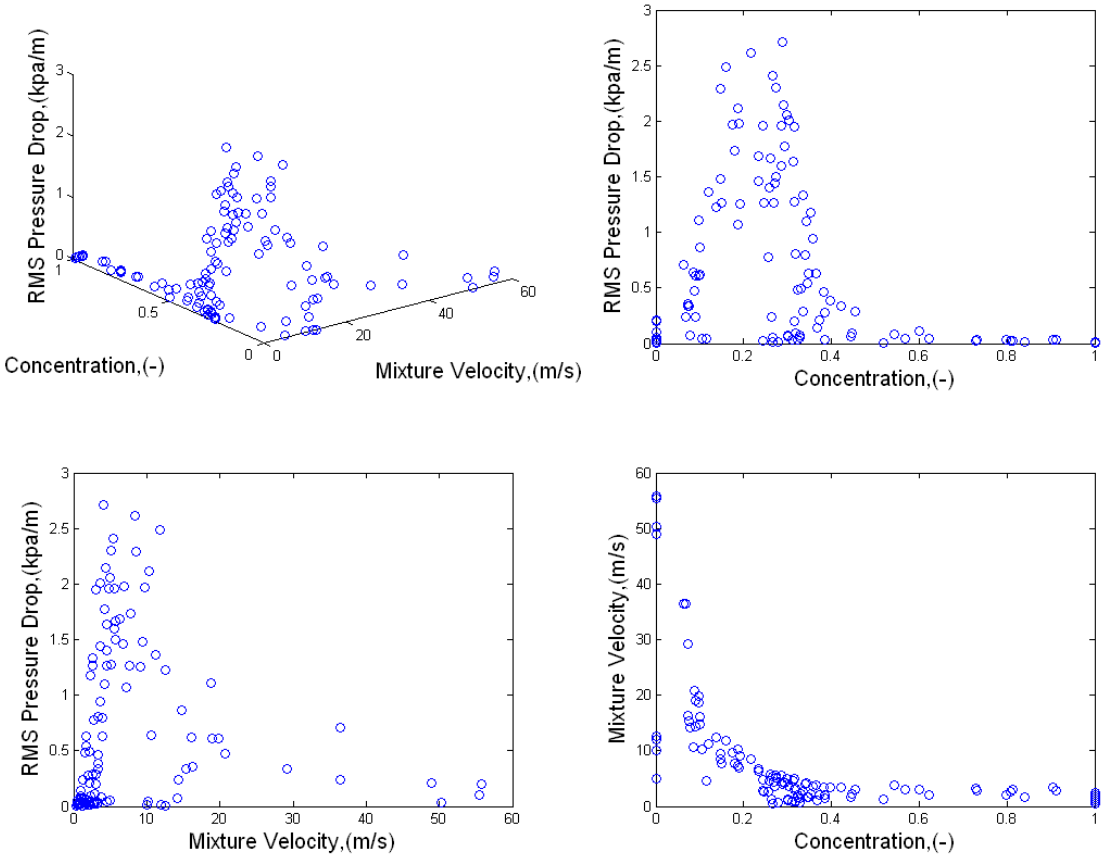


Figure 8. RMS Pressure Drop vs. Mixture Velocity and Concentration

Conclusions

Based on the experimental research conducted on the air-water mixture flow in the full range of spatial in-situ concentrations (0-1) and mixture velocities (0m/s to 60m/s) in a horizontal square minichannel, the following conclusions can be drawn:

(1) Experimental data for pressure, velocity, and concentration were collected in an experimental system. For data verification, several different concomitant measurement systems were used successfully, including the measurement of in-situ spatial concentration using both capacitive and conductive systems. The experimental results show that both capacitive and conductive systems are fully concomitant with respect to spatial concentration.

(2) Concentration plays a vital role in the determination of flow conditions and impact the mixture parameters such as velocity, viscosity, Reynolds Number, and Alpha Number. In the experiments, a very interesting "split" phenomenon was discovered and documented. The results indicate that the split phenomenon can be attributed to the in-situ concentration and its fluctuations.

(3) The phenomenological correlations of RMS values for two-phase flow averaged in-situ parameters demonstrated significant sensitivity to the flow pattern phenomena.

Nomenclature

C	capacitance (F)
D	channel diameter (m)
b_c	capacitor plate width (m)
c_v	concentration (-)
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)
A	cross-sectional area (m^2)

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