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Measurement of Gas and Liquid Velocities in an Air-Water Two-Phase Flow using Cross-Correlation of Signals from a Double Sensor Hot-Film Probe

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NOTICE

Measurement of Gas and Liquid Velocities in an Air-Water Two-Phase Flow using Cross-Correlation of Signals from a Double Sensor Hot-Film Probe

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1. Summary

Local gas and liquid velocities are measured by cross-correlating signals from a double sensor hot-film anemometer probe in pure water flow and air-water two-phase flow. The gas phase velocity measured in two-phase flow agrees with velocity data obtained using high-speed video to within ±5%. A turbulent structure, present in the liquid phase, allows a correlation to be taken, which is consistent with the expected velocity profiles in pure liquid flow. This turbulent structure is also present in the liquid phase of a two-phase flow system. Therefore, a similar technique can be applied to measure the local liquid velocity in a two-phase system, when conditions permit.

2. Introduction

Local measurements of gas and liquid velocities in a two-phase system are of great interest to researchers trying to predict the behavior of such flows. These flows are often encountered in boiling water reactors, chemical reactors, oil reprocessing plants and electronic and refrigeration devices. The relative velocity between the gas and liquid phases is an essential parameter in determining pressure drop and void fraction, which are often needed for design guidance.

Several classical measurement techniques have been applied to measure the phasic velocities. Laser Doppler Velocimetry (LDV), a well established means of obtaining velocity in pure liquid flow, has been extended to two-phase velocity measurements (e.g., [1] and [2]) with varying degrees of success. The LDV technique is usually limited to highly dispersed two-phase flow and it is often difficult to discriminate between the Doppler signals from the gas and liquid phases. Particle Image Velocimetry (PIV) has been used to measure velocity distributions in pure liquid flow; however, it is difficult to measure the liquid velocity in two-phase flow because the voids interfere with the light sheet illumination, and it is difficult to separate the continuous and dispersed phases. Hot-film anemometry (HFA) has been used to measure the liquid velocity in two-phase flow [3] by removing the bubble signals in the HFA voltage trace and employing a liquid velocity calibration on the remainder of the trace. The difficulties here are in accurate exclusion of all the non-liquid contribution in the voltage trace as well as calibration voltage drift.

A double sensor HFA probe has also been used in the past to obtain the average velocity of voids passing through the probe by employing a cross-correlation method [4]. Recent measurements have shown that it is also possible to obtain the liquid velocity using the cross-correlation method, which, to our knowledge, is a new extension of HFA technology. Essentially, turbulent structures, or eddies, in the fluid are convected by the

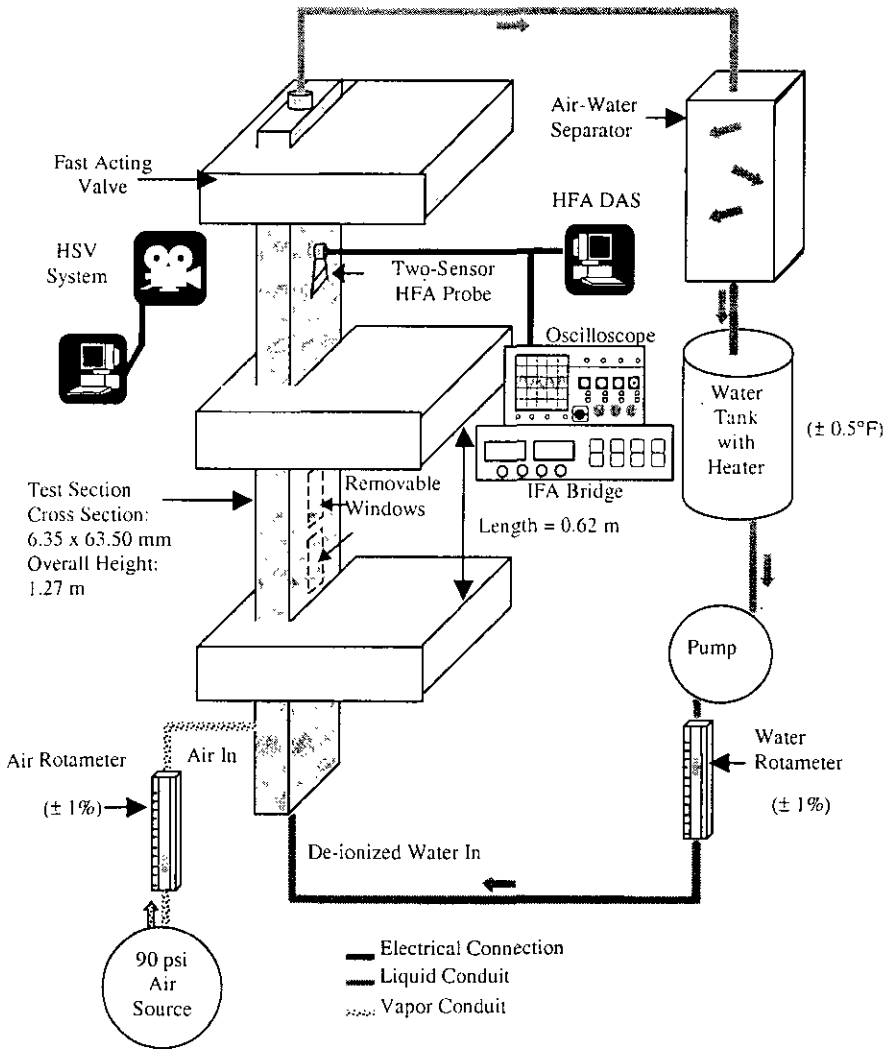
mean flow, and tracked between the two sensors to provide a time-of-flight measurement of liquid velocity. This is similar to tracking the time lag for a natural temperature variation in the flow between two fast response temperature detectors [5]. In this paper, details are provided on the measurement of gas and liquid velocity using cross-correlation of signals from a double sensor HFA probe in air-water two-phase flow. The focus will be on the technique itself, both in the correlation of the gas and liquid part of the signal, and on factors which affect the accuracy of the measurements.

3. Discussion

3.1. Setup

The air-water loop, used for these experiments, consists of a 1.27 m vertical transparent test section, an air-water separator, a 10 gallon water tank with heater, and a magnetic drive water pump (see Fig. 1 for a schematic). The loop was built by Mohr and Associates to facilitate instrumentation development in multi-phase flow. The test section has eight removable windows along its length; the window closest to the exit houses the two-wire hot film anemometry (HFA) probe. Three fast acting valves (not used for these experiments) connect the four sections of the overall test section together. The rectangular geometry of the test section allows undistorted high speed video recordings compared with other geometries and, via the removable windows, allows easy installation of instrumentation.

Figure 1. Air-Water Loop Configuration
(not drawn to scale)



±1% of full range, were used to establish the desired flow conditions. The temperature of the water was maintained at 90°F ± 0.5°F to ensure a stable water temperature throughout the experiments.

High Speed Video (HSV)

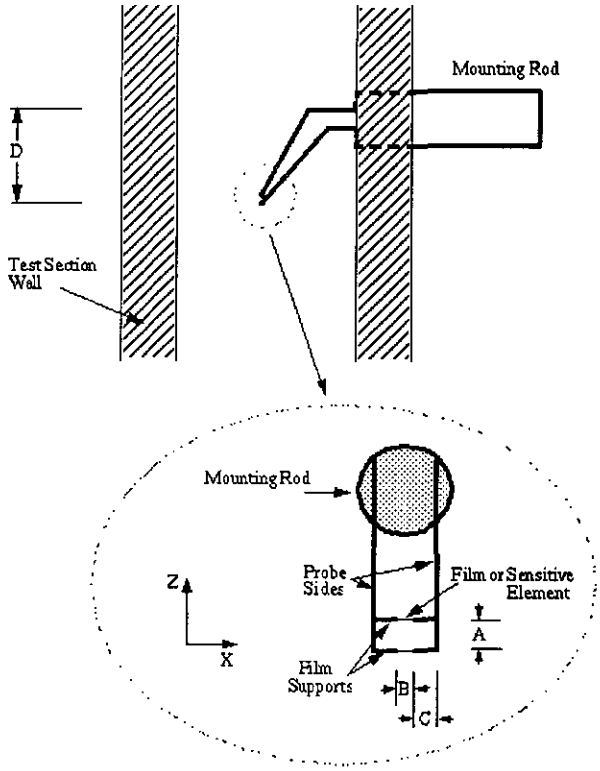
A Kodak HSV system was used to visualize the flow and independently determine gas phase velocity. The HSV can capture up to 5 seconds of data, at a rate of 1,000 frames per second. A calibrated grid within the HSV software was used to determine bubble velocity by tracking the distance the interface travels in a known time interval. Approximately 20 samples were acquired at random times over several minutes to obtain an average velocity. The uncertainty of this measurement (taken at a screen magnification of 8.75) is estimated to be ±5%.

Hot Film Anemometry (HFA)

The HFA probe (TSI Model 1244-10AW) consists of two quartz coated platinum film sensors (each on fused-quartz substrates) separated by a vertical distance of 75 mils (1.91 mm) with an uncertainty of ±2.5 mils (±0.064 mm). The active wire diameter is 1.5 mils (0.038 mm) with a sensing length of 8 mils (0.20 mm). The probe was located in the center of the test section in both the transverse and thickness dimensions, at an axial distance of about 120 hydraulic diameters from the test section inlet. Fig. 2 shows a sketch of the HFA probe in the test section, with pertinent dimensions included.

Figure 2. Sketch of HFA Probe in Test Section

A = 1.91 mm, B = 0.20 mm, C = 0.72 mm, D = 10 mm
Film: 0.038 mm diam. Film Supports: 0.15 mm diam.

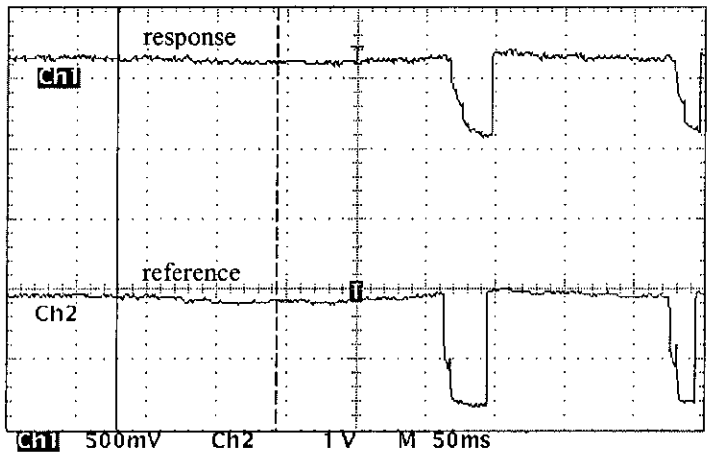


The HFA probe was connected to a TSI IFA-100 anemometer. A circuit within the anemometer regulates the current through the HFA sensors to maintain a constant temperature. As the fluid flows over the sensors, they are cooled by convection. Since air and water have dissimilar cooling properties, the current needed to maintain the temperature in air is less than in water. Hence, the bridge voltage dips when an air bubble traverses the probe. Fig. 3 shows an example of a voltage trace in bubbly flow for

each of the two HFA sensors. The time difference (Δt) between the signals represents the lag time. The interfacial velocity is equal to the distance between the sensors divided by this lag time. The lag time demonstrated in Fig. 3 is specific to this particular bubble and varies from bubble to bubble. Therefore, the Data Acquisition System (DAS) is used to obtain an average of the local interfacial velocity (velocity at the probe).

The HFA DAS is composed of a Hewlett-Packard (HP) VXI mainframe with a HP 6233 embedded Pentium controller and 96 Megabytes of RAM that runs Windows NT (version 4.0). The signals are acquired using a HP E1433A 8 Channel Digitizer Card. The software used to analyze the incoming signal was written in HP-VEE; the algorithm performs a fast Fourier transform to obtain the cross-correlation function. The HFA DAS acquires blocks of data at a frequency equal to the sampling rate (for the following measurements 128 kHz with a bandwidth of 50 kHz) over a given block size. Each block contributes one correlation function to the overall average. The output of the algorithm is a cross-correlation curve. The location of the peak yields the most probable average lag time between the two voltage signals.

Figure 3. Voltage Trace in Bubbly Flow



A Tektronix TDS 320 oscilloscope, connected in parallel to the HFA probe and IFA bridge circuit, was used to view and compare the upstream and downstream signals produced by the probes. The lag between the two signals can also be estimated directly using the oscilloscope.

3.2. Correlation Algorithm – General Overview

The cross-correlation function, R, is the average (during a period of time, T) of the product of two data sets, one at time t and the other at time $t+\tau$:

$$R(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T x(t)y(t+\tau)dt$$

There are two generally accepted methods to calculate the cross-correlation: direct and indirect [6]. The direct method computes the average product using sampled data values. The indirect method uses Fourier transforms of the data to obtain the cross-correlation. Since the direct method is computationally expensive, the indirect method is preferred.

The indirect method can be executed in a variety of manners: uncorrected, corrected using a global mean, or corrected using a local mean. The uncorrected approach simply

calculates the cross-correlation without concern for wrap-around pollution. The corrected approach accounts for the pollution by adding zeros to the data sets and applies a weighting factor to the result. Additionally, it is preferred that the data sets have a mean of or close to zero prior to calculation. To condition the data such that the mean is zero, either a local mean or a global mean can be subtracted to translate the data sets. The local mean is the average of the points for each individual block of data, whereas the global mean is the average of the entire data record, which includes all blocks. The type of mean used may affect the cross-correlation results; this is discussed further in Section 3.3.

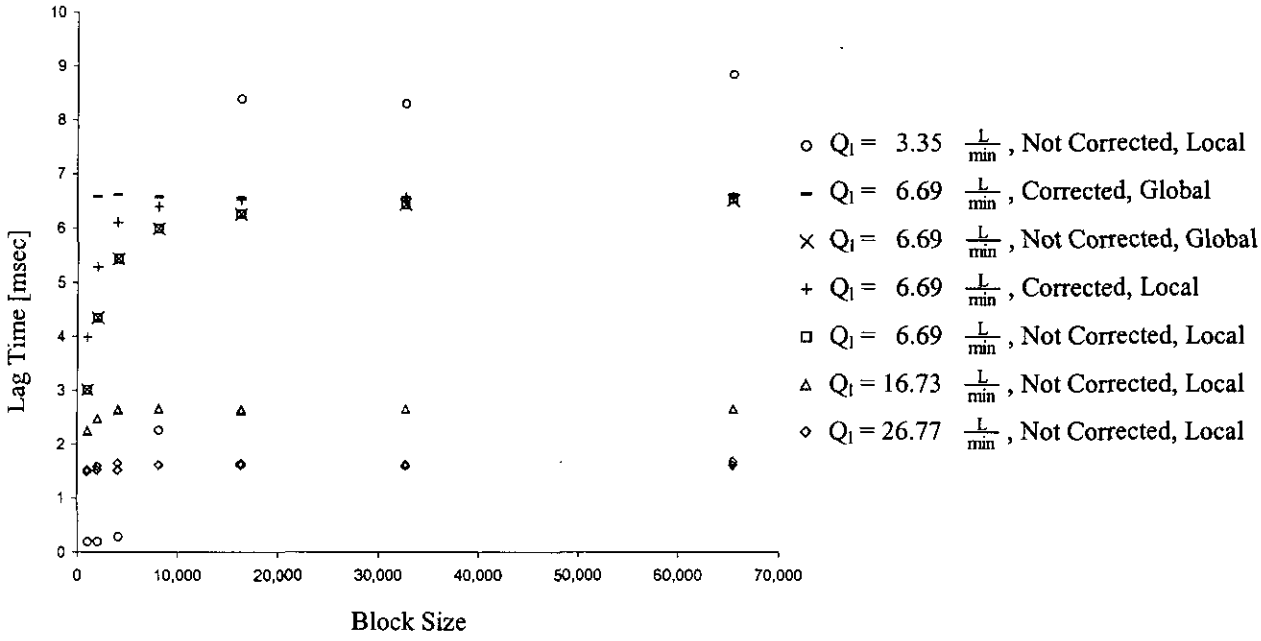
3.3. Parameter Effects On Correlation

The resulting cross-correlation can be affected by a number of factors associated with the handling of the data. The accuracy of the correlation is a function of, among other parameters, bandwidth and block size. When the sampling rate is less than the signal's frequency, the data collected is not representative of the actual signal. In this condition, referred to as aliasing, the measured signal would not have the same period or phase as the actual signal, and would lead to a bias in the calculated lag time. Therefore, a sufficiently large sampling rate should be chosen to avoid aliasing the signal. For the measurements performed here, a sampling rate of 128 kHz with a corresponding bandwidth of 50 kHz was found to yield accurate results.

The block size parameter controls the amount of data that is used in each cross-correlation, which are averaged to yield the overall cross-correlation function. Along with the sampling time, the block size also controls the length of time over which each average is acquired. The block size must be large enough to adequately resolve repeatable signals in the HFA trace between the two HFA sensors. At the very least, the block size must be large enough to track several strong events passing between sensors.

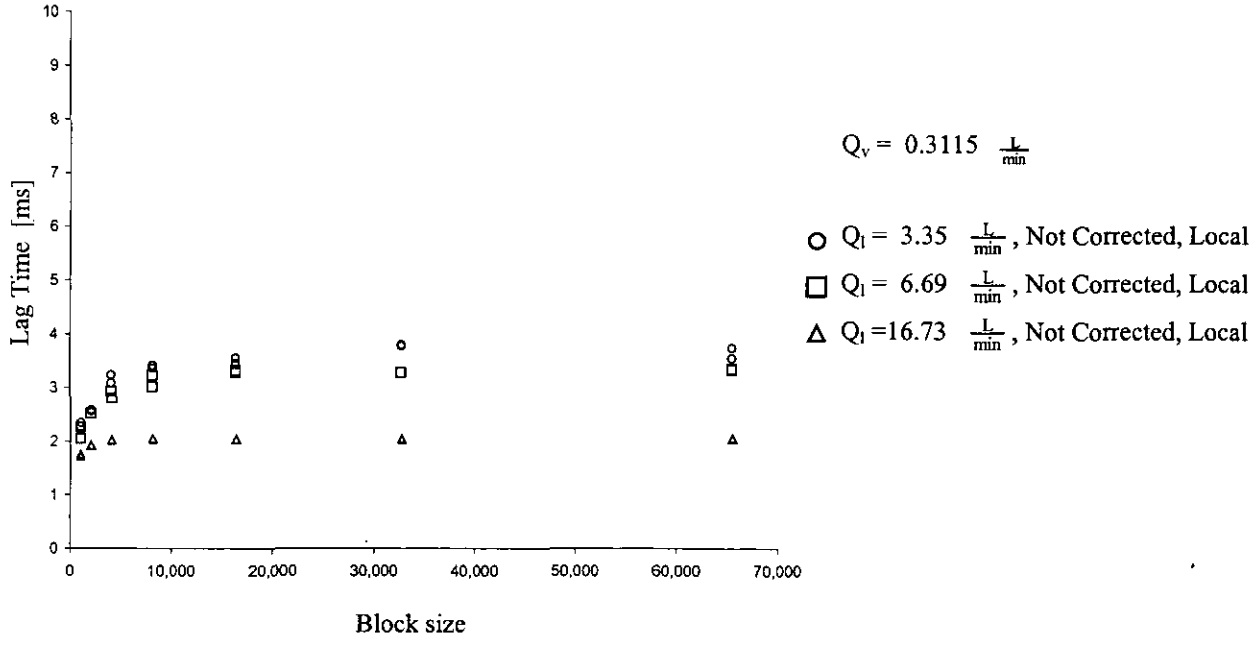
The determination of the block size parameter can also be dependent upon the algorithm used to analyze the data. The block size denotes the number of data points per block. Therefore, a block size of 8,192 indicates that 8,192 data points are sampled at 128,000 points per second for data that spans 0.064 seconds. Fig. 4a demonstrates the sensitivity of the cross-correlation algorithm to block size for various liquid flow conditions. The data using block sizes greater than 8,192 demonstrate little or no bias for most flow conditions and algorithms. As the block size is decreased, a bias in the data is observed when the cross-correlation is performed without using additional zeros or when using a local mean. This effect is attributed to the wrap-around pollution inherent in the Fourier transform and the use of a local average, compared to a global average. This bias is most prominent at the lower flow rates, where the transit time between HFA sensors becomes a larger percentage of the overall block acquisition time and the local average is more scattered from the global mean. Therefore, if the algorithm does not append zeros to the data set prior to the calculation (as described in Section 3.2), then a larger block size should be used to minimize this effect.

Figure 4a. Block Size Effect on Cross-Correlation of Liquid Data



The two-phase data, shown in Fig. 4b, shows similar, but less pronounced trends to that in the single phase liquid data, especially at the lower flow rates. The larger amplitude of the bubble signal causes the contributing noise to be less effective at skewing the results of the cross-correlation.

Figure 4b. Block Size Effect on Cross-Correlation of Gas in Two-Phase

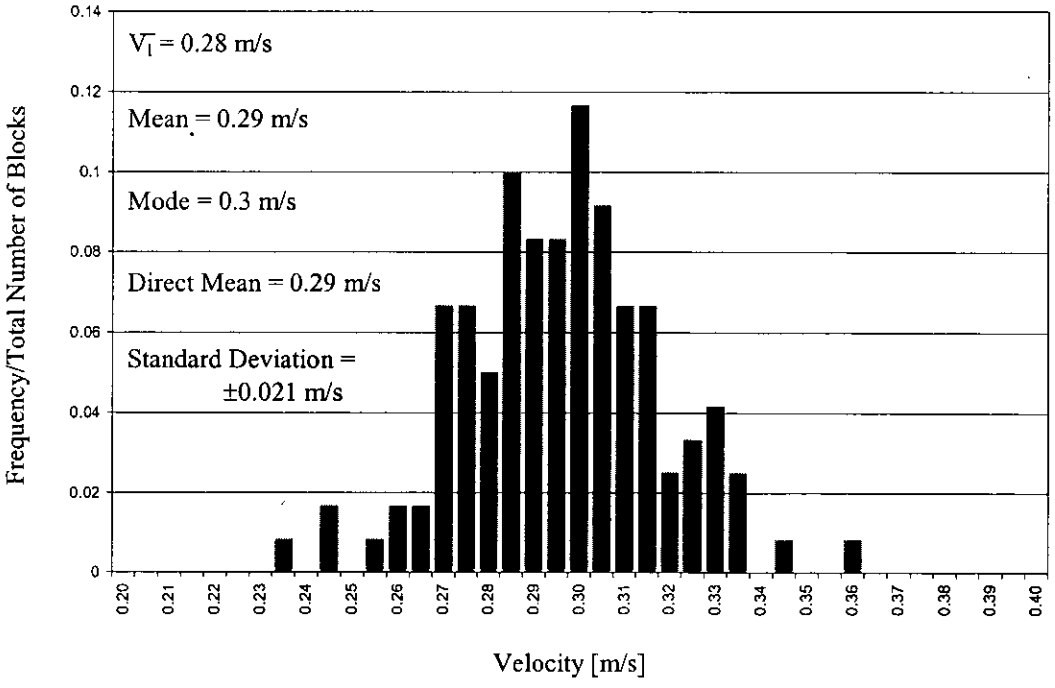


To summarize, an algorithm that accounts for the wrap-around pollution of the data and uses a global mean has the ability to take measurements at smaller block sizes, as long as the weighting factor, as described in Section 3.2, is applied. This is the recommended approach. When using an algorithm that does not add zeros, it is difficult to accurately determine the minimum acceptable block size for a given set of experimental parameters. Generally, a block size of 5-10 times the lag time being measured is a good choice. The best way to confirm that the block size is adequate is to perform a series of measurements as shown in Figs. 4a and 4b, and make sure the algorithm does not contribute a bias to the data at the desired block size.

3.4. Cross-Correlation Application for Velocity Distribution

The cross-correlation method may be applied block by block to obtain a distribution of velocities in the flow. This may be useful when measuring flow transients and oscillations or if some relative measure of the turbulence level is desired. To do this, either a local or global mean can be used for each individual block and an average lag time is obtained from the cross-correlation of each block. These lag times can be converted to velocity and graphed to show the measured velocity distribution. Note: although the collective results of the individual blocks are useful to indicate the distributions of flow within the test section, the overall mean velocity of the flow is best determined from the corrected cross-correlation function from the overall data set. Therefore, the average or mode of the individual lag times should not necessarily be substituted for the result of the cross-correlation algorithm described in Section 3.2.

Figure 5. Local Velocity Distribution (65,536 Block Size)



The data shown in Figure 5 illustrates a reasonable estimate of the local velocity distribution in the centerline of the test section (120 individual blocks of 65,536 points). The mean and mode of the data are consistent with the mean obtained using direct correlation. Note that the distribution can be acquired using smaller blocks, but the deviation will be increased. This is generally because at smaller block sizes the noise component in the HFA signal may overwhelm the correlation and contribute erroneous lag times to the overall average. The measured lag time will most likely be lower than the actual time associated with the velocity because the noise will generally contribute lower lag times to the average.

3.5. Simulated Application in V_g and V_l Measurements

A mock-up of the signals acquired by the HFA probe in two-phase flow was used to validate the cross-correlation algorithm. The two signals were identical, but offset in voltage and time. Matlab and Simulink were used to create the signals, which consisted of square waves with random noise added to them. The square wave, with a period of 0.018 s, represented the vapor signal, while the noise represented the liquid portion of the signal. Magnitudes of these two signals were consistent with actual HFA voltage traces observed on the oscilloscope. The constant lag time values for the liquid and gas phase were 6.9 msec and 6 msec, respectively.

Figure 6a. Matlab Two-Phase Output

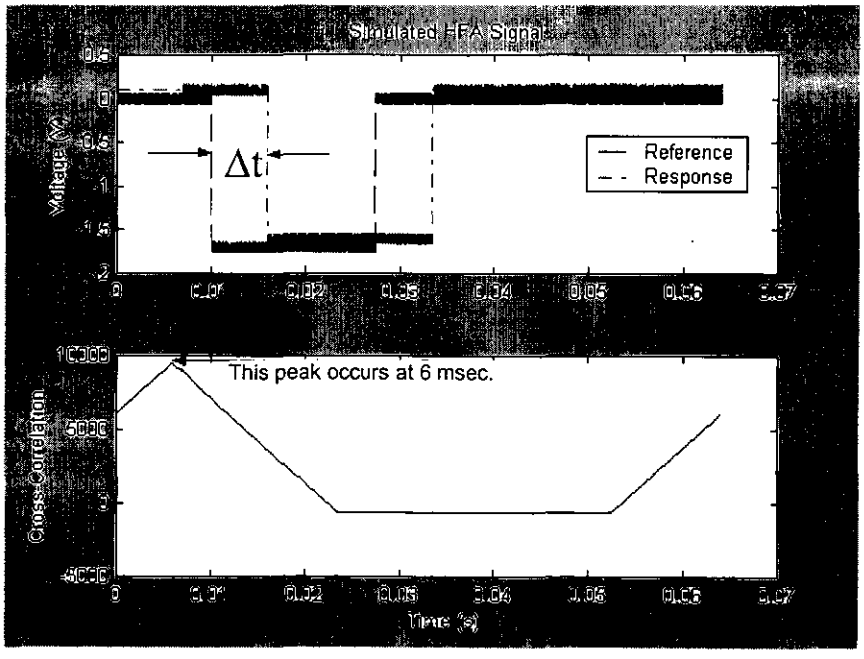
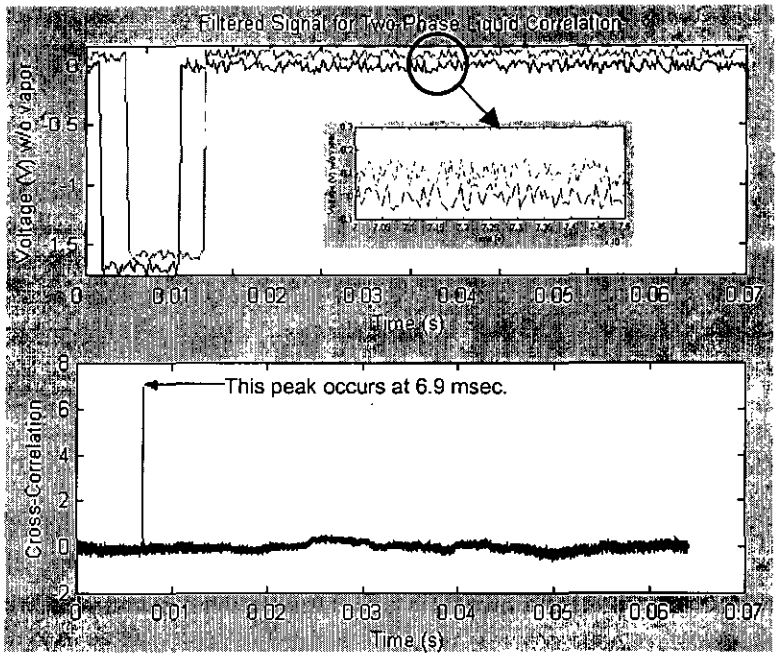


Fig. 6a illustrates the simulated two-phase signals, as well as the cross-correlation for those signals. The peak yields the bubble lag time because in a two-phase flow situation, the void dominates the correlation. That is, even though there are many more liquid samples in the block, the voltage magnitude of the gas phase is significantly higher than the liquid, and the correlation of these large amplitudes leads to a dominant peak in the cross-correlation.

Fig. 6b presents the Matlab output for the liquid velocity measurement in a two-phase flow. A trigger level (in this case 0.3 V) allows the algorithm to distinguish between the vapor and liquid signal when calculation of the liquid velocity is desired. The simulation rejects all blocks that contain points that are less than the negative trigger and greater than the positive trigger for both the reference and response. The cross-correlation peak occurs at the time difference between the liquid signals. When the lag time of the signals is altered, the Matlab output changes accordingly. Therefore, the indirect method of calculating the lag time between the two voltage signals is shown to be accurate.

Figure 6b. Liquid Component in Two-Phase Flow

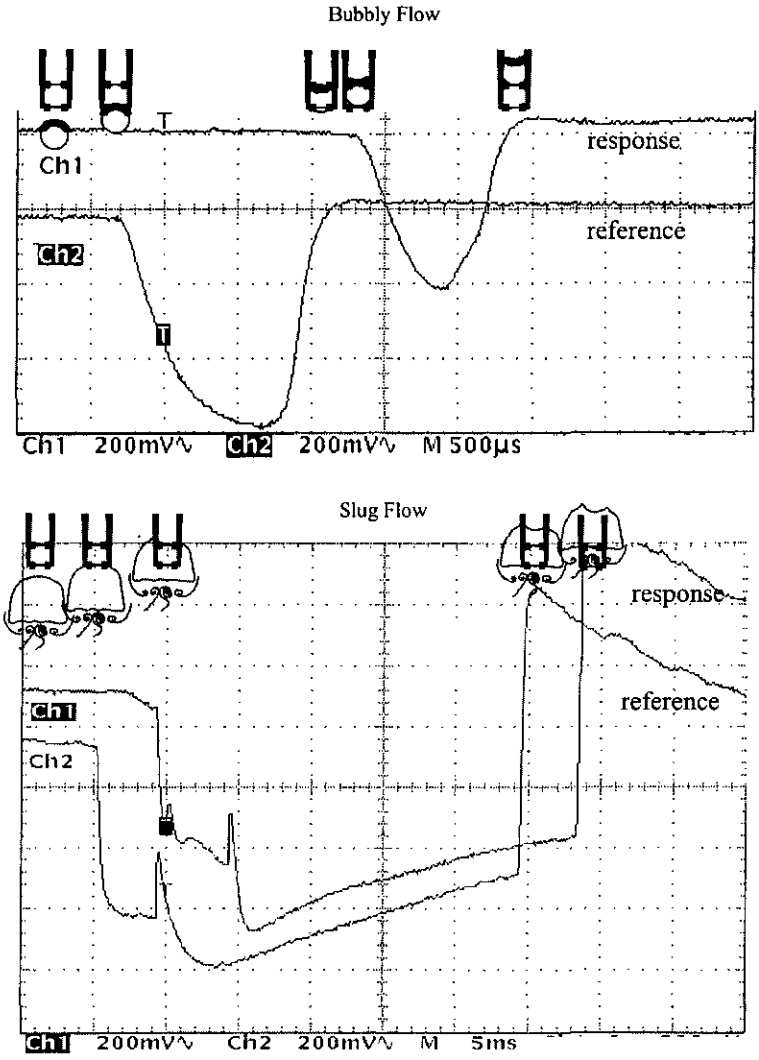


3.6. Gas Phase Velocity Measurements in Two-Phase Flow

Ideally, the lag time between signals at the trailing and leading edges of a passing void would be identical, but in reality, this is often untrue. As seen in Fig. 7, when a bubble contacts the HFA probe, it deforms due to surface tension and frictional interaction with the HFA probe supports. The top of the bubble collapses while the bubble centroid is still moving at the original bubble velocity. Since the "puncture resistance" at the leading edge of a bubble is greater than that of the trailing edge, due to the interface curvature and the fact that the pressure inside the bubble is greater than the liquid surrounding it, the probe passes easily through the trailing edge with less deformation. This explains why it takes longer for the leading edge to pass by both sensors compared to the trailing edge.

The leading edge of a slug exhibits similar qualities to a bubble, but the trailing edge is quite different. Because the trailing edge of a slug is flat and followed by a liquid stream containing turbulent eddies, very little force is required to puncture the rear interface of the slug. This explains why the signal shape at the leading edge of the slug is much less defined than the trailing edge. In general, the voltage signals produced by the trailing edge of either a bubble or slug are sharper and more linear than the leading edge. Consequently, the signal produced by the trailing edge of the bubble or slug is the dominant contributor to the cross-correlation, producing a more accurate measurement of the interfacial velocity.

Figure 7. Bubbly and Slug Flow Past Sensors

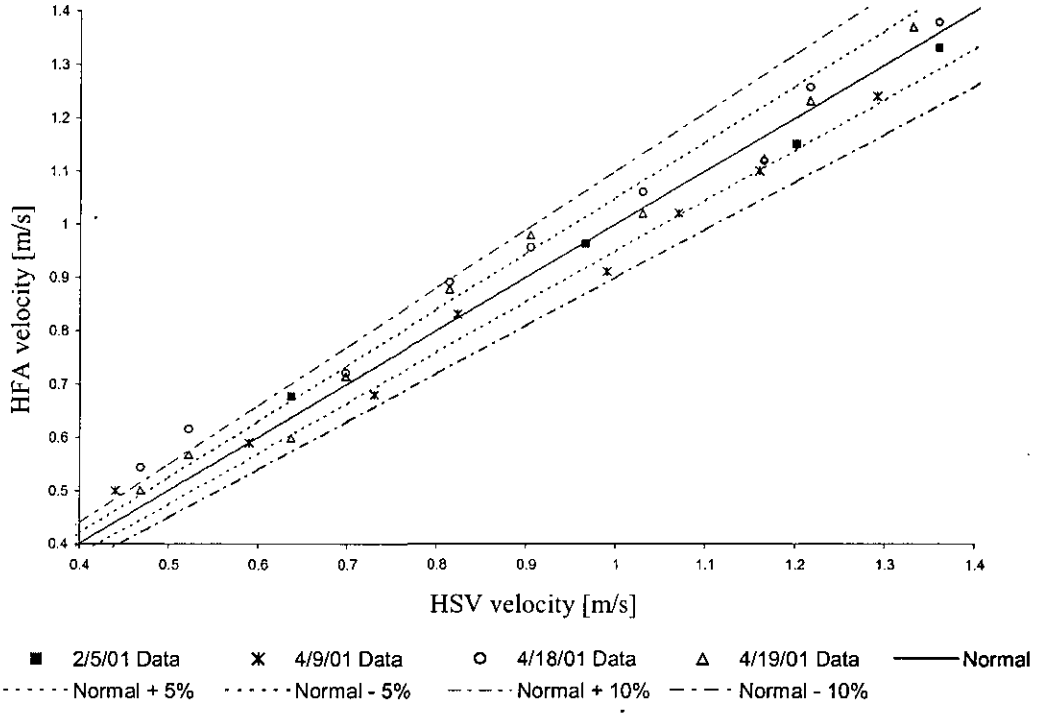


Because the gas phase dominates the cross-correlation, virtually any trigger level within the extent of the HFA voltage trace would lead to an accurate measure of gas phase velocity. However, to ensure that only those blocks containing voids are actually considered in the cross-correlation calculation, a high level trigger is used. If any voltage sample in the block falls below the trigger level (which is negative), a cross-correlation is performed and the resulting function is included in the running average to produce the average cross-correlation function. For these experiments, the trigger was usually set at – 0.5 V. The cross-correlation was performed using an uncorrected local mean with the Hanning window.

Fig. 8 displays the HFA gas velocity data compared to the data taken with the HSV. The data, taken over time to demonstrate repeatability, is generally within ± 5% of the normal curve (y = x), which is within the uncertainty of the HSV. There does appear to be a slight bias (+10%) in the HFA data at the low velocity range. The measurements here were taken in slug conditions in low liquid flow where the voids travel in a serpentine manner up the test section; these type of conditions are inherently more difficult to

measure accurately. Overall, the HFA technique does a good job in measuring interfacial gas velocity over a wide range of flow conditions.

Figure 8. Gas Velocity in Two-Phase Flow



3.7. Single Phase Liquid Measurements

Examination of HFA signals acquired in single phase liquid flow often shows a structure or pattern that is repeatable from probe to probe. Some examples of these structures are shown in Fig. 9. These structures are believed to be related to the turbulent eddies or turbulent bursts present in the fluid, which are carried by the mean flow from sensor to sensor on the HFA probe. The structure contains distinct peaks that can be correlated with the same algorithm used to obtain gas phase velocities in two-phase flow. Therefore, as long as the structure maintains itself for the distance between the probes, the cross-correlation technique can yield an accurate measurement of the local average liquid velocity.

To demonstrate the application of the technique, measurements of velocity were obtained in the test section centerline for a range of liquid flow rates. The HFA data was acquired with a block size between 16,384 and 32,768 in AC coupled mode; 200 correlation averages were used to compute the overall average. The ratio of the local liquid velocity, measured with the HFA probe, to the average velocity, determined using the water flow meter, is plotted versus Reynolds number[1] in Fig. 10. For fully developed profiles, the

[1] Reynolds number is defined as $\mathrm{Re} = \frac{\rho \bar{V} D_H}{\mu}$ with D_H being the hydraulic diameter of the duct.

expected values for the velocity ratio is 1.67 in laminar flow and roughly 1.15 in turbulent flow using the power law profile. The actual data follows the expected trend, although most of the data in the turbulent regime is about 10% less than a fully developed profile would suggest. It is unclear why this discrepancy exists. If measurement accuracy less than 10% is desired, this discrepancy would have to be addressed further and quantified more precisely.

Figure 9. Voltage Trace in Single Phase Liquid

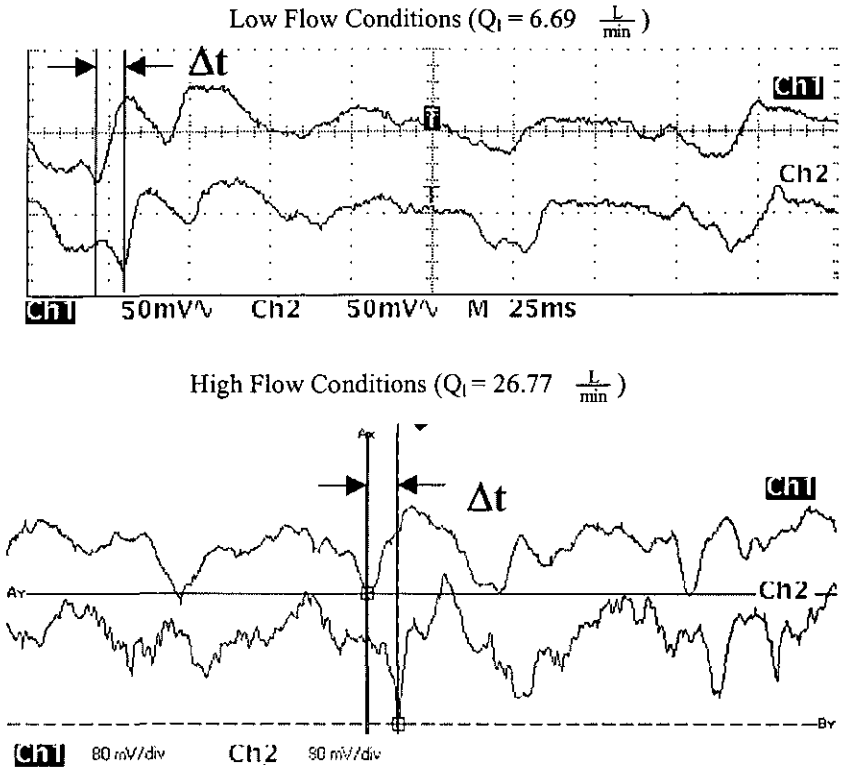
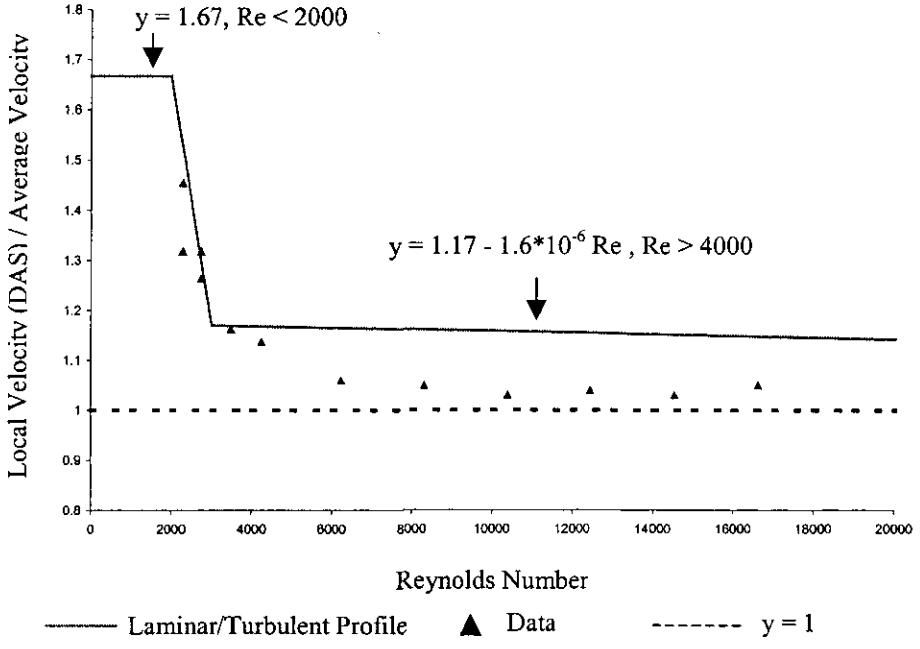


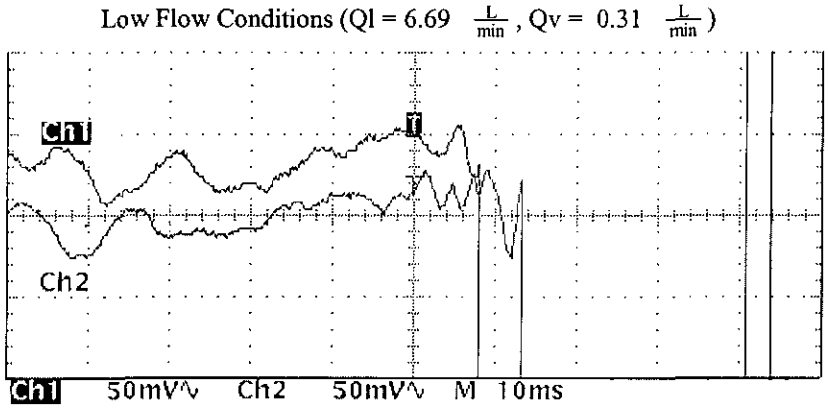
Figure 10. Comparison of Data to Laminar/Turbulent Profile



3.8. Two-Phase Liquid Measurements

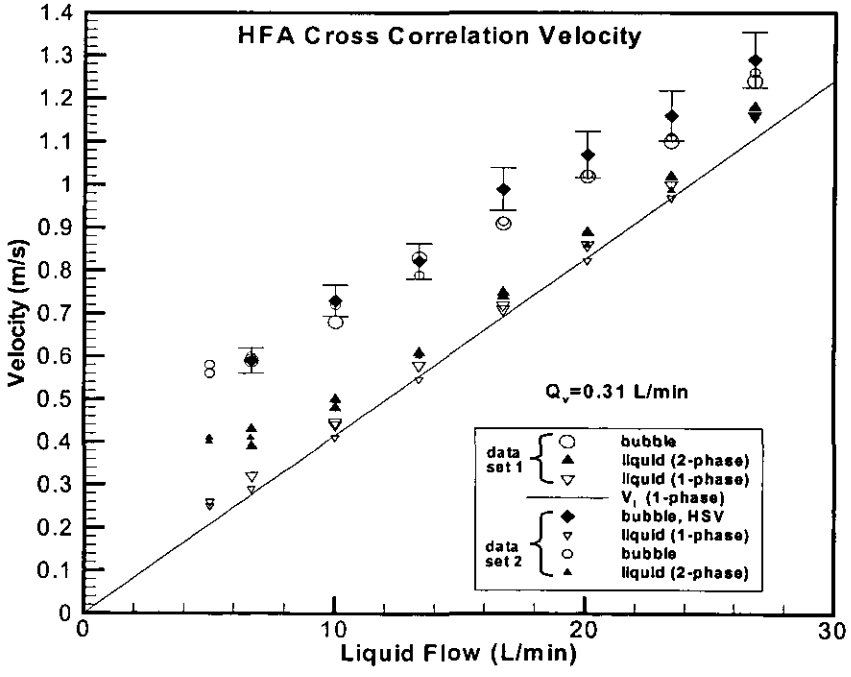
The repeatable structure in the liquid phase is also present in the liquid component of a two-phase system. Fig. 11 shows an example using a HFA trace in a bubbly flow. With proper filtration of the voltage signal, it is possible to obtain the local velocity of the liquid phase in a two-phase system. To do this, a low-level threshold is used in the cross-correlation algorithm to discriminate against blocks with void. If any part of the signal in a given block exceeds the threshold level, that block is not considered in the analysis. Therefore, as long as blocks exist without void in a two-phase condition (a function of the overall void fraction and time scale of the block), a measure of the liquid velocity can be obtained.

Figure 11. Voltage Trace in Bubbly Flow



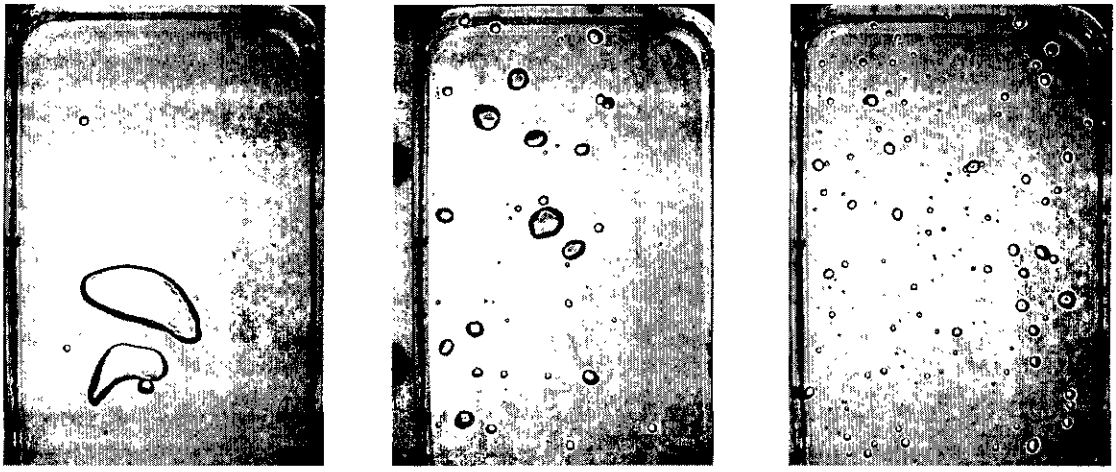
To demonstrate the application of the technique in a two-phase environment, measurements of gas and liquid velocity were taken in the air-water loop for a variety of flow conditions. In the first set of measurements, shown in Fig. 12, the liquid flow (Q_l) was varied while the gas flow (Q_v) was held constant. In the second set of measurements (Fig. 15), the gas flow was varied while the liquid flow was held constant. Some examples of the flow topologies are included in Figs. 13 and

Figure 12. Two-Phase Liquid Measurements
liquid flow varied, gas flow constant



14. The data was taken in the center of the test section at an axial location of about 120 hydraulic diameters from the air injection. For $Q_v = 0.31 \frac{L}{min}$, at lower liquid flow rates (< 16 $\frac{L}{min}$), the voids were large, about 25 mm across, while at the higher liquid flow rates, smaller bubbles (about 2-5 mm in diameter) were observed.

Figure 13. Two-Phase Flow Topologies
liquid flow varied, gas flow constant

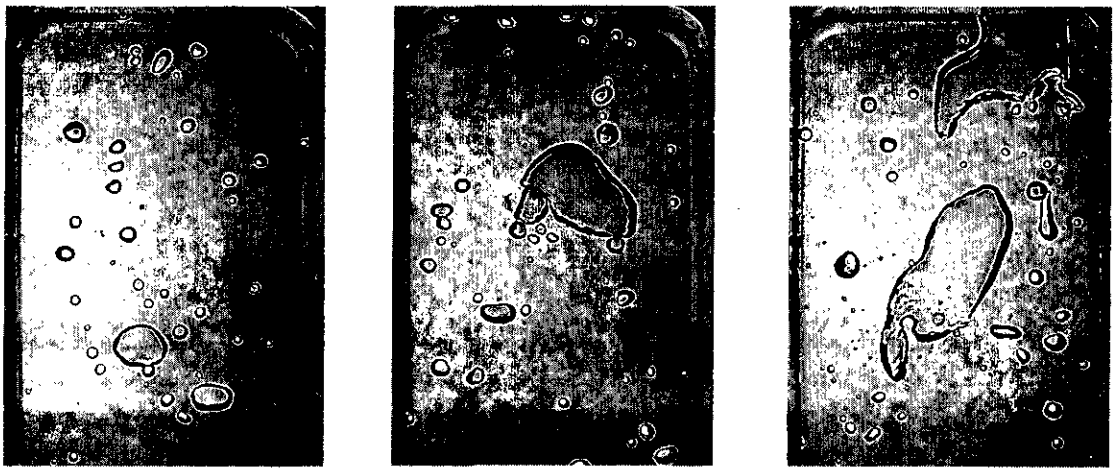


(a) $Q_l = 6.69 \frac{L}{min}$, $Q_v = 0.31 \frac{L}{min}$

(b) $Q_l = 16.73 \frac{L}{min}$, $Q_v = 0.31 \frac{L}{min}$

(c) $Q_l = 26.77 \frac{L}{min}$, $Q_v = 0.31 \frac{L}{min}$

Figure 14. Two-Phase Topologies
gas flow varied, liquid flow constant



(a) $Q_l = 16.73 \frac{L}{min}$, $Q_v = 0.62 \frac{L}{min}$

(b) $Q_l = 16.73 \frac{L}{min}$, $Q_v = 1.25 \frac{L}{min}$

(c) $Q_l = 16.73 \frac{L}{min}$, $Q_v = 2.49 \frac{L}{min}$

Some parameters used in the HFA measurements are given next. The HFA overheat ratio (ratio of operating resistance to resistance at ambient) was set at 1.07 for each of the two sensors. The block size for the gas velocity measurements was 8,192 with a voltage threshold of –0.5 V (at a sampling rate of 128 kHz). Two hundred correlations were acquired to obtain an average gas velocity over a period of about 3-4 minutes. The block size for the liquid velocity measurements was chosen to be as large as possible for a given flow condition with a voltage threshold of ± 0.075 V. As the void fraction and flow velocity increased, the maximum acceptable block size decreased because voids appeared in the block and were rejected from the liquid phase correlation. Depending on the acquisition rate, 50, 100, or 200 correlations were acquired to obtain an average liquid velocity.

Table 1. Typical Acquisition Rates for Cross-Correlation Method

Liquid Flow, Q_l $\left(\frac{L}{min}\right)$	**Gas Flow, Q_v** $\left(\frac{L}{min}\right)$	**Block Size**	**Threshold**	**Data Rate (Hz)**	**Void Fraction**
6.69	0.31	32,768	0.075	0.3	
6.69	0.31	16,384	0.075	0.66	
16.73	0.31	4,096	0.075	1.5	
16.73	0.31	16,384	0.075	0.38	
16.73	1.95	8,192	0.075	0.18	
16.73	3.26	2,048	0.075	0.028	
16.73	3.26	8,192	0.075	0.008	
6.69	0.31	16,384	0.05	0.56	
16.73	0.31	16,384	0.05	0.32	
6.69	0.31	8,192	-0.5	0.58	8.8 %
16.73	0.31	8,192	-0.5	0.85	6.6 %
16.73	1.95	8,192	-0.5	1.04	21 %
16.73	3.26	8,192	-0.5	1.09	27 %

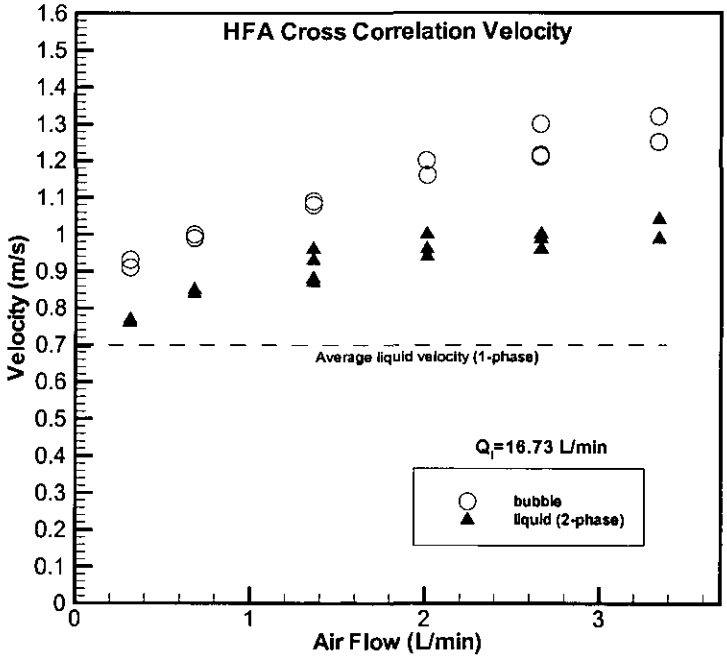
Table 1 presents the acquisition rate for liquid and gas cross-correlation measurements for selected flow conditions. The void fraction data in Table 1 was determined from 100 blocks of HFA data taken over 6.4 seconds using a slope and level thresholding approach [7]. The level threshold was set at the midpoint between the gas and liquid parts of the output voltage signal, with slope thresholding additionally applied to account for the finite time for gas-liquid interfaces to pass the HFA sensors. The number of gas phase voltage samples were divided by the total number of samples to give a rough measure of the void fraction. The acquisition rates of the gas phase correlation were about 1 Hz for void fractions of 21-27% and slightly less for void fractions between 6 and 10%. The acquisition rates for the liquid phase correlation were lower than the gas phase and were strongly dependent on block size. The 32,768 block size was appropriate only for the flow condition with relatively low interarrival times between voids and the 8,192 block

size was necessary for the highest void levels. The 16,384 block size was used for most of the data taken in Fig. 12.

Turning to Fig. 12, the HFA gas velocity measurements are seen to agree reasonably well with independent measurements determined using the HSV. The estimated uncertainty of the HSV data is ±5% for an average of 20 images taken over several minutes. The HFA liquid velocity measurements in pure liquid are in good agreement with the average known liquid velocity, with most of the points being slightly above the curve for reasons given in Section 3.7. Also, as expected, the liquid measurements in the two-phase flow are between the pure liquid values and the gas velocity values. As shown in Fig. 13, for the higher liquid flow rates ($Q_l > 16 \frac{L}{min}$), the flow consists of increasingly dispersed low void fraction bubbly flow; because of this, the increase in liquid velocity between the pure liquid and two-phase condition is small. For the lower liquid flow rates, larger slugs and bubbles rise up the center of the test section and, because of drag and the center-peaked void distribution, the liquid velocity in the test section center is significantly higher in the two-phase mixture than for the pure liquid condition.

Fig. 15 shows data taken at constant liquid flow with increasing gas flow rate. Dispersed bubbles exist at the lowest gas flow while larger slugs are evident at the higher gas flows. Typical void fractions for some of these conditions are provided in Table 1. A total of 50 averages were taken for the liquid correlation using a block size of 8,192. The measurements were repeated over a period of several days to ensure adequate precision. The data shows that the relative velocity between the gas and liquid phases increases in a consistent manner as the flow topology transitions from bubbly to slug flow.

Figure 15. Two-Phase Liquid Measurements
(gas flow varied, liquid flow constant)



4. Conclusions

Hot film anemometry is currently an acceptable method of measuring the interfacial velocity in a two-phase flow system [4]. Using the same equipment and a similar technique, it is possible to measure the liquid velocity in both single and two-phase flow conditions. The liquid phase contains a turbulent structure that is carried with the mean

flow. The velocity is obtained by cross-correlating the voltage signals from a double sensor hot-film probe and applying a filter to remove the contributions from the gas phase. The current measurements have shown that accurate results are possible for bubbly and slug conditions up to a local void fraction of about 25%.

After several variations of the algorithm were investigated, it was determined that the corrected cross-correlation performed using a global mean is the best estimate of the direct cross-correlation for either single or two-phase flow. This method yielded accurate results of mean velocity over a wide range of block sizes. An uncorrected cross-correlation algorithm performed using a local mean can also yield accurate results provided the block length is sufficient. The cross-correlation algorithm may also be used on a block by block basis to obtain local velocity distributions, which may be useful when measuring flow transients or oscillations.

It is noted that the current data was taken in an air-water, non-boiling condition. It is unlikely that the technique will work in a boiling system since local boiling at the HFA sensors will mask the turbulent structure present in the liquid. It is possible that the technique will work in a sub-cooled boiling environment where local boiling at the sensors can be avoided.

5. References

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