Main Menu

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Technical Paper

Insights into Multiphase Flow Through Ultrasound Doppler

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1 INTRODUCTION

Multiphase flow can be fully characterized and measured if the velocities and phase fractions of all the components in the flow were available through sensor measurements. For a three phase (oil, water and gas) flow, this involves the measurement of 6 parameters i.e oil, water and gas phase fractions and oil, water and gas velocities. Of these, only 5 are independent parameters (if any two phase fractions are known, the third can be calculated). While most meters have access to at least two fraction measurements (gas phase fraction and water in liquid ratio), not all 3 velocity components can be measured. The burden then falls on the flow meter algorithm to fill in the missing pieces with an appropriate model. The most commonly used velocity measurement techniques are venturi based mixture velocity and cross correlation based velocity. For the venturi measurement, a slip model and a phase fraction estimate are required to estimate the gas and liquid velocities. For the cross correlation based measurement, an accurate flow model is required to translate it to a gas velocity and an additional slip model to translate the gas velocity to liquid velocity. The objective for most of these flow models/correlations is to capture the physics of the flow in the hopes of capturing the information that could not be directly measured. The flow physics can be considerably complex for certain flow regimes and hence velocity correlations or models can be unreliable for specific flow conditions or regimes. Moreover, flow models tend to be empirically tuned to achieve the desired accuracy. So they typically perform well as long as the flow conditions are within the ranges for which they have been built, but their extrapolative capabilities are questionable making their performance and accuracy unreliable and unpredictable in the field. The achieved field accuracy is often unknown as providing a reference system (eg test trailer for land wells) is difficult and expensive.

2 INTRODUCTION TO DOPPLER VELOCIMETRY

2.1 Doppler Fundamentals

When an ultrasonic wave propagates through a fluid media cross-section, depending on the presence of inhomogeneous constituents, the media may reflect, refract or scatter the ultrasonic waves. In multiphase flow, the inhomogenities can be liquid droplets (of secondary phase, water in oil phase or oil in water phase), gas bubbles or sand particles present in the liquid phase. The size of the inhomogeneities in the media crosss-section, angle of incidence and the frequency of ultrasonic wave (wavelength) dictates the amount of reflection, scatter or refraction that happens. For measuring in multiphase flow, we have chosen to employ the pulsed Doppler technique as opposed to continuous wave Doppler. In pulsed Doppler, instead of emitting continuous ultrasonic waves, a transducer emits periodically short ultrasonic bursts but receives the signals/waves continuously with time as they reach the receiver. Scattered signals from stationary gas bubbles or water/oil droplets remain constant from pulse to pulse but moving bubbles or particles exhibit differences in the time of flight. The movement in time domain causes a phase shift in the frequency domain which is called the Doppler shift [1]. The main advantage of the pulsed Doppler is its ability to construct a velocity profile by localizing (in depth terms) the scatterrers or the inhomogenity once the speed of sound in the fluid media is known. However the pulsed Doppler technique has a few limitations that need to be considered when using it for multiphase flow measurement. Firstly, there is an upper limit on the velocity that can be measured that depends on the pulse repetition frequency, the signal frequency, the angle and the speed of sound. Secondly, it can underestimate the true velocity of the scatterers if the angle between the beam and the scatterer is higher (~15deg), although higher angles would increase the sensivity of the method to velocity.

Doppler based velocity measurement is very common in varied applications ranging from radar to blood flow measurement [1].

2.2 Doppler measurement for multiphase flow

A typical pulse Doppler received signal image for bubbly flow is shown in figure 1. Instances of high amplitude denoted in red represent scatterers or bubbles. The striations sloping towards the right represent the movement of the bubble in time. The direction of the striation represents the direction of movement of the bubble. This phase shift in the signal can be related to the Doppler frequency shift

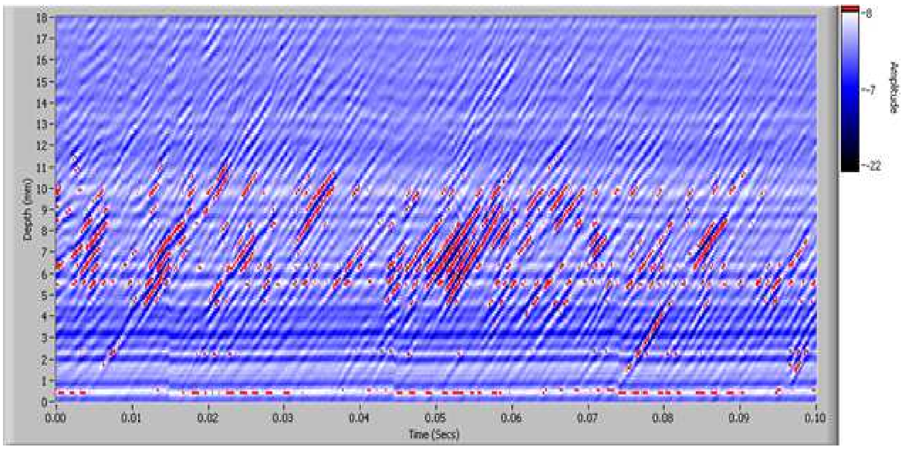


Figure 1: Ultrasound Doppler received signal for bubbly flow

and to velocity through the Doppler equation (equation 1).

Ultrasonic Doppler method is also a commonly used technique in flow measurements. However, extending the application of the Doppler technique for metering multiphase flow poses several challenges:

- While there are several obvious advantages to having a clamp-on ultrasoud system on the outside steel pipe-wall, ultrasonic energy transmission across steel & liquid media interface is very poor due to the high accoustic impedance contrast. Scattering, which is the basis for ultrasound Doppler measurement, is a weaker phenomenon compared to transmission or reflection. Hence, any loss in energy transmission can affect the SNR of the measurements. The electronics have to be carefully designed to be able to pick up on the weak phenomenon of scattering in the presence of large fixed-time echoes.

- The Doppler measurement does not measure liquid or gas velocity but the scatterer velocity. Hence, extracting either the liquid or gas velocity from the Doppler shift velocity is not a trivial problem. The fact that this relationship may be flow regime dependent tends to complicate the problem further. Several research publications [2][3][4] on the topic of Doppler for multiphase flow tend to focus on bubbly flow regime since this regime is conducive for deriving a transfer function for the Doppler velocity. Some others[4][5] have considered liquid-solid two phase flows with solids as the discontinuities for the Doppler measurement.

2.3 Doppler measurement system

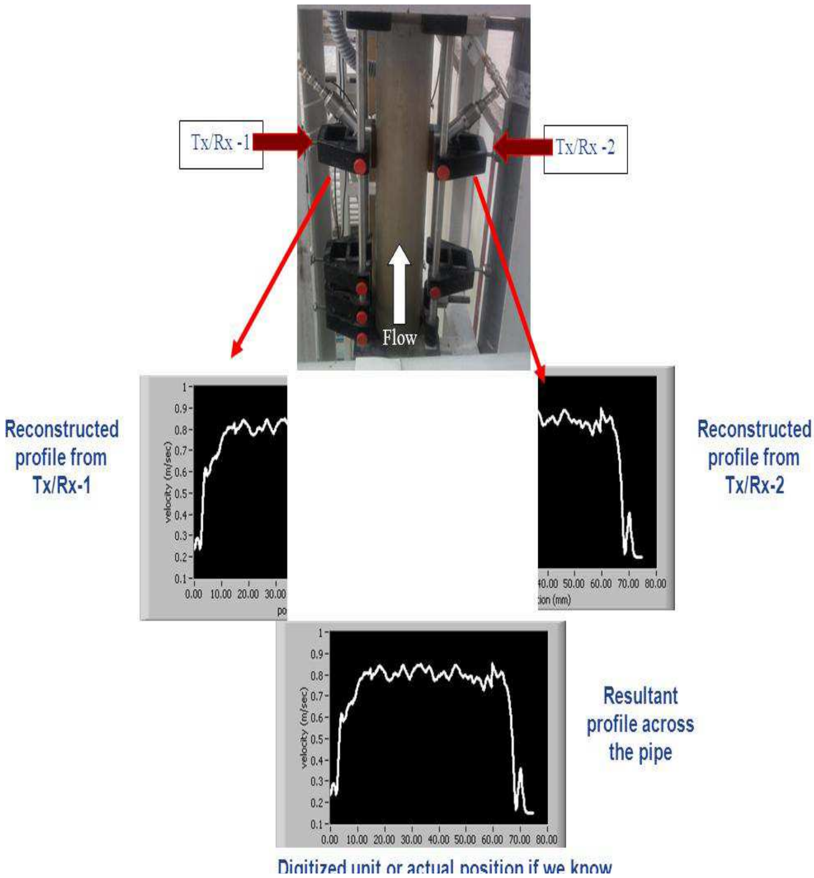


Figure 2: Ultrasound Doppler measurement system

The Doppler system developed for the purpose of this analysis consisted of transducers on either side of the pipe placed diametrically opposite, a customized electronic board that can transmit and receive ultrasonic waves at a central frequency between 100KHz and 2 MHz. The DAQ system was designed to sample the received signal at 4MHz with a 12 bit ADC resolution. An FFT was applied to the received signal to obtain the Doppler shifted frequency which was then converted to velocity using the standard relationship:

$$V = \frac{cf_D}{2f_e cos\theta} \quad \text{--1}$$

Where c is the speed of sound, f_D is the Doppler shift, f_e is the frequency of the transmitted signal and θ is the angle of the beam.

Spatial location of the velocity can be determined using the time of flight of the received signal and the speed of sound to determine the distance between the receiver and scatterer. Having two transducers diametrically opposite to each other provides a complete profile in the pipe cross section as shown in figure 2. Thus, a 2 dimensional map of the velocity can be obtained with this configuration. Moreover, for every velocity data point, a corresponding scattered amplitude can also be measured and recorded. This is required to validate that the velocity reading came from a significant scatter feature.

This measurement system was tested at that National Engineering Labs (NEL), Southwest Research Institute (SwRI) as well as GE's in-house multiphase test facility to understand and analyse the Doppler data. The configuration and test setup for the three test locations is listed in table 1 and the results of the analysis are presented in sections 3 and 4.

Test conditions	NEL	SWRi
Measurement distance from blind tee	35D	5D
Horizontal run to blind tee	35m	1m
GVF range	0-95%	0-95%
WLR range	0-100%	0-100%
Liquid flow rate	15000bbpd	26000bbpd
Gas flow rate	1.3acfs	1.7acfs
Pressure	5 bar	10-100 bar

Table 1: Test conditions

3 QUALITATIVE ANALYSIS OF DOPPLER DATA

As explained in the section 2, the data from the Doppler technique spans both space and time, thus providing rich information about the flow. Analysis of the amplitude as well as the velocity information captured by Doppler can provide invaluable insights into the dynamics of the flow. Figure below shows 2D images acquired by the Doppler system during extensive tests conducted at NEL. The

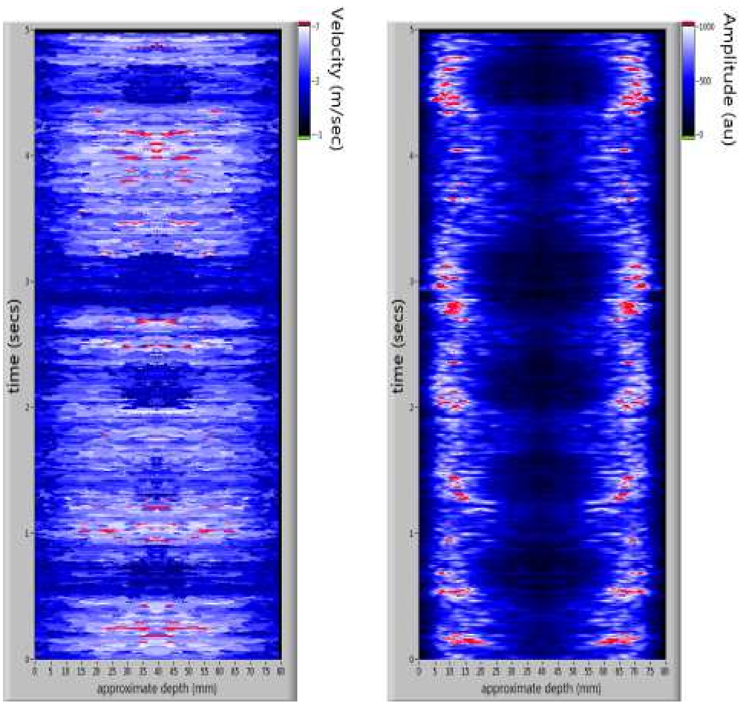


Figure 3: Ultrasound Doppler amplitude and velocity images

data consists of two pieces of information:

1. Velocity map – Velocity is localized in space in the pipe cross section by translating the time of the received signal to a depth location in the pipe using the travel speed of sound. It is also measured over time by exciting the pipe cross section using consecutive pulses. Thus the velocity map can be reconstructed in a two dimensional space as shown below.
2. Amplitude map – For every location in space and time that a velocity value is obtained, a corresponding value of scattered amplitude can be calculated. The amplitude data is harder to interpret than the velocity since it is affected by multiple factors such as transducer-receiver gain, bubble distribution, bubble size and orientation and fluid properties. But it can provide a powerful means for understanding the dynamics of the flow.

One of the characteristics of the Doppler technique is that it is insensitive to bubbles that are larger than a certain diameter. In other words, when encountering for example, large Taylor bubbles in slug flow, the data appears to have a "blank" space where the ultrasound signals are reflected off the large bubble and there is very little propagation of the signal past the bubble (figure 3). While, at first glance, this may seem like a loss of data, it can actually provide insights into the flow regime and in turn the complex dynamics inherent to each flow regime. Figures 4a through 4c depict the Doppler data under varying flow conditions. There are several interesting observations to be made from these figures.

3.1 Flow Regime

By capturing information about the small scatterers in the flow, the Doppler amplitude map provides a startlingly clear representation of the flow regime. As the flow transitions from low to high GVF, the Doppler amplitude shows the transition from slug to churn to annular flow regimes.

- Slug flow (Figure 4a):

  In slug flow, the Taylor bubbles appear as blanks in both the velocity map as well as the amplitude map. The Taylor bubble is typically surrounded by smaller bubbles traveling with different velocities. This information is captured fairly accurately by the Doppler technique as shown in the velocity map.

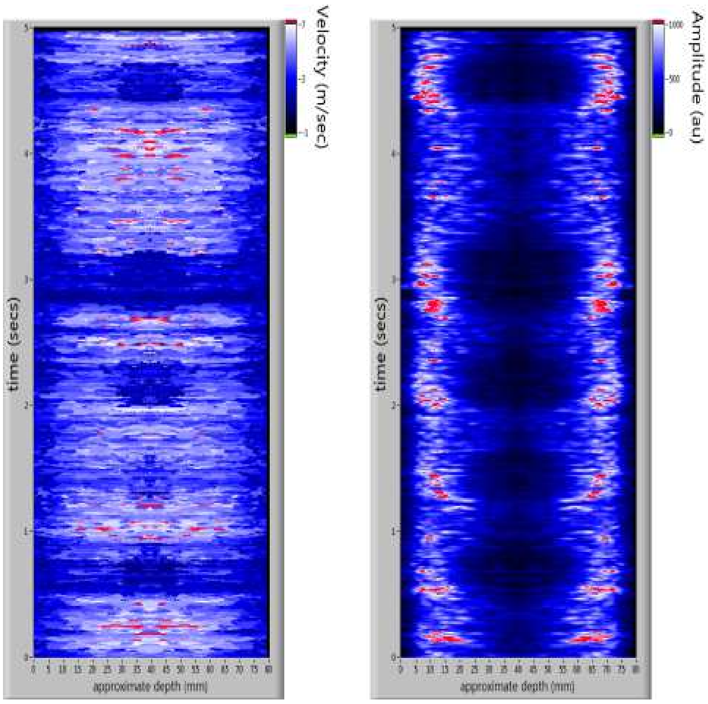


Figure 4a: Ultrasound Doppler amplitude and velocity images for slug flow

- Churn flow (Figure 4b):

  As the flow transitions from slug to churn regime, the number, size and frequency of the Taylor bubbles increase, a fact that is evident from the Doppler amplitude map. During the instance that a liquid slug goes by, the Doppler signal picks up the small scatterers present resulting in a non-zero amplitude and velocity representative of the liquid slug.

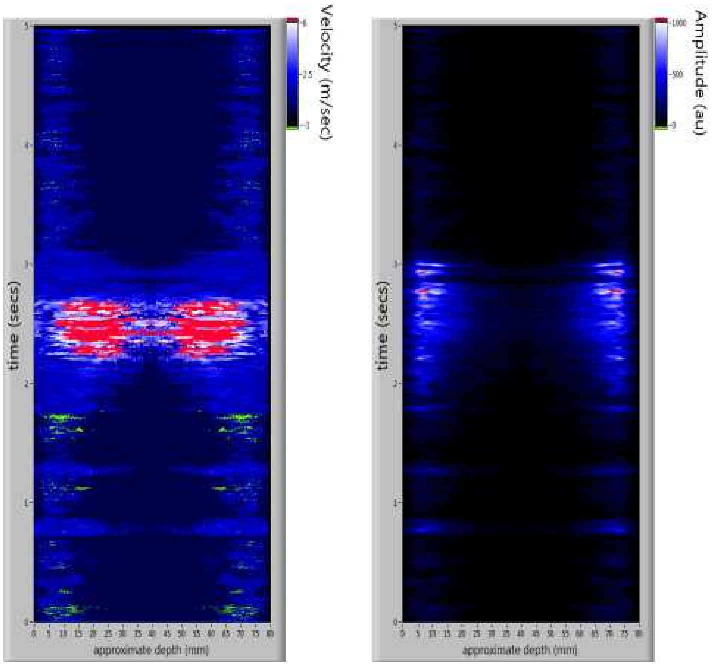


Figure 4b: Ultrasound Doppler amplitude and velocity images for churn flow

- Churn-annular flow (Figure 4c):

  As the flow starts to transition from churn to annular regime, there are fewer and fewer instances of a liquid slug where the transducers are able to pick up

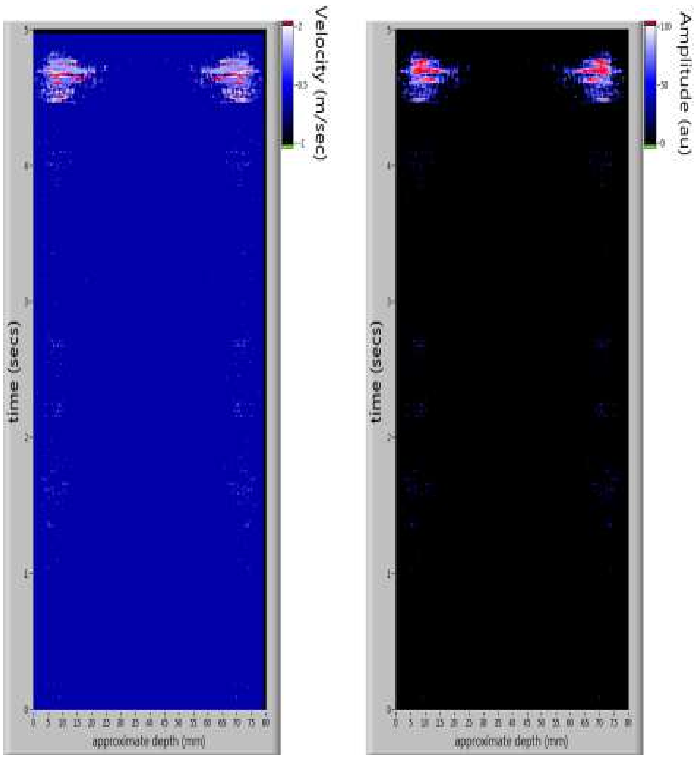


Figure 4c: Ultrasound Doppler amplitude and velocity images for churn-annular flow

the scattered signal. This is expected for flow conditions where the GVF is fairly high, a higher proportion of the pipe cross section is filled with large gas bubbles.

3.2 Flow Dynamics

Most methods of velocity measurement are averages over time or space or both, thus capturing only sparse details of the fairly complex dynamics of multiphase flow. This implies that models that use this information for calculating other flow parameters are required to make approximations in order to account for the averaging. The ultrasound Doppler technique on the other hand is able to localise the information that it measures in both time and space. The Doppler images shown below have a time resolution of about 1 millisecond and a spatial resolution in the pipe cross section of about 0.2mm. With this high resolution data, several interesting observations about the flow dynamics become evident on analysis.

- *Negative velocities:*
  One of the most advantageous characteristics of the Doppler technique is that it is able to measure and quantify velocities in both directions (in the direction of bulk flow as well as against it). This is in sharp contrast to other velocity techniques which only measure bulk flow over a large volume as in the case of a venturi based measurement or over a long period of time as in the case of cross correlation velocity. Of particular

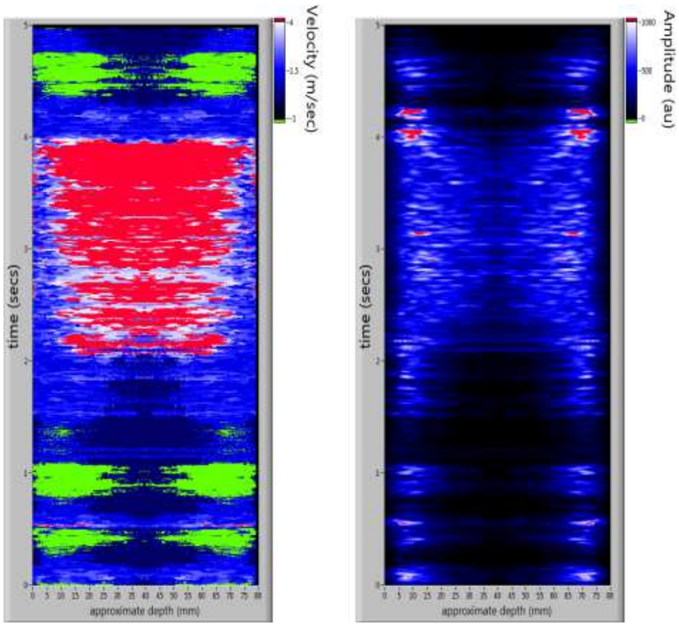


Figure 5: Ultrasound Doppler amplitude and velocity images for slug-churn transition regime

interest is the data acquired for the slug-churn transition regime that is shown in figure 5. As the large bubbles passes through the pipe, the liquid and smaller gas bubbles around it momentarily fall downwards due to the force of the large bubble pushing through as well as due to gravity. This is clearly seen from the negative velocity (green) measured in the Doppler signal in the wake of the Taylor bubble. Once the Taylor bubble passes by, the smaller bubbles and liquid reverse direction and move upwards following the Taylor bubble. When not accounted for, such complex phenomena can produce errors with flow methods that provide only space and time averaged estimates.

- *Acceleration and Deceleration:*
  Another important aspect of the Doppler technique is its ability to measure near instantaneous velocities unlike other velocity measurement techniques which measure averages over time. The high temporal resolution of the Doppler data captures the acceleration and deceleration in the flow. This is apparent from the figure below which shows the behavior of the bubbles accelerating and decelerating in the wake of the Taylor bubbles in slug-churn transition flow. The acceleration and deceleration phenomenon is at a sub-second level and cannot be captured by techniques with low sampling rates or slow response time.

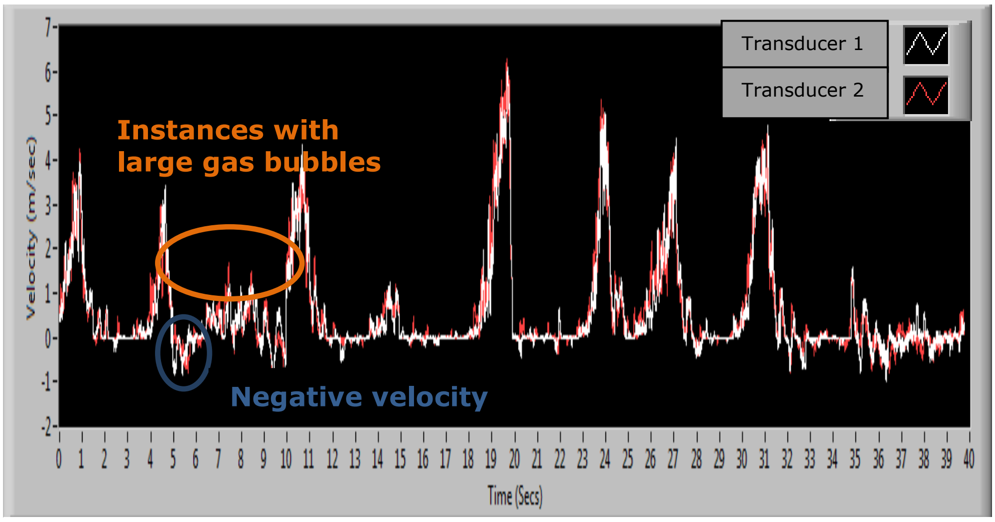


Figure 6: Ultrasound Doppler velocity time series (averaged over the pipe cross section)

- *Flow profiles:*
  Another big unknown for most multiphase models is the distribution of flow parameters across the cross section. Most models make assumptions for the velocity and phase fraction profiles that may not be valid over a wide range of flow conditions. The Doppler data is inherently able to capture not just the profile of the velocity and the distribution of the scatterers or bubbles, but also the variation of the flow profile over time.

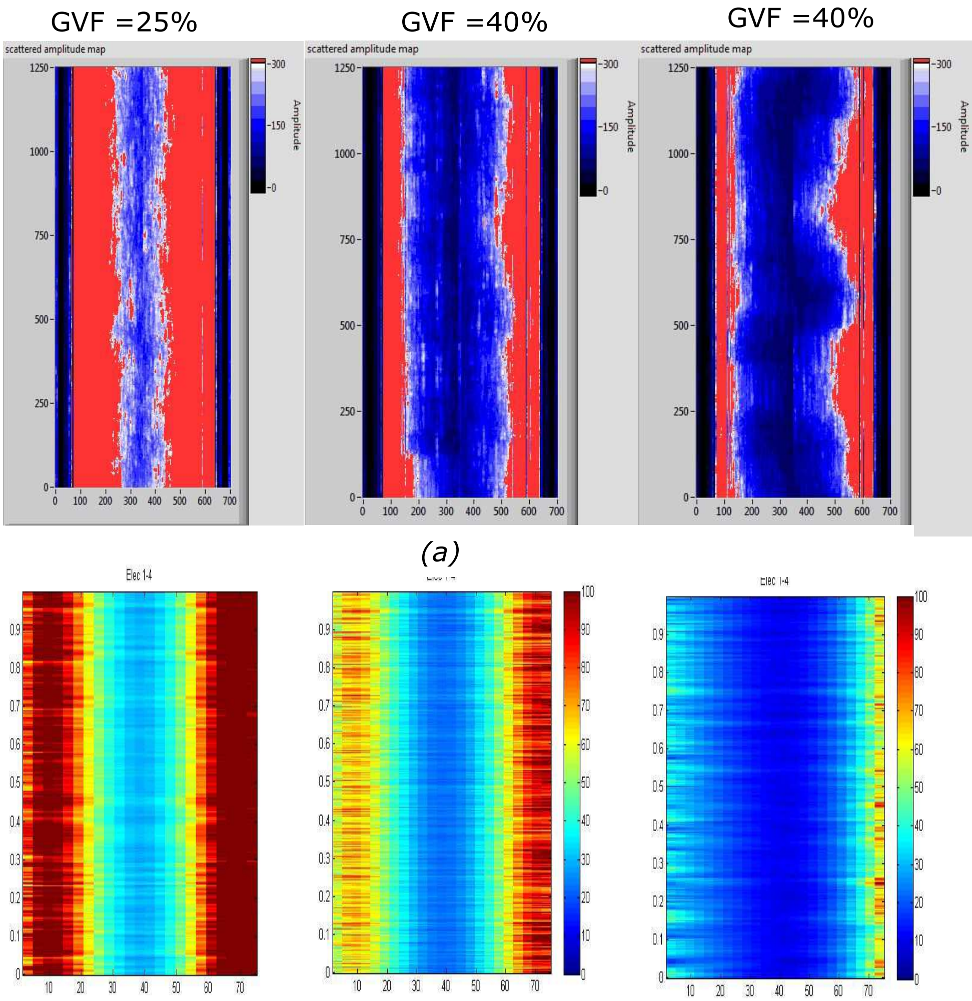


Figure 7 Experimental data from SwRI @ WLR=80% a) Ultrasound Doppler amplitude profiles b) Electrical impedance liquid phase fraction profiles

This then provides a real time estimate of the profile related terms in a flow model, thus obviating the need for unreliable assumptions and corrections in flow rate estimation. With access to a map of the flow profiles under different flow conditions, the data can also be analyzed for potential irregularities and asymmetries under non-steady state flow conditions. This is typically the case for undeveloped flow, where the flow profiles haven't reached steady state conditions and may still continue to evolve over space and time. Figures 7a and 7b show the phase fraction profiles from an electrical impedance system with synchronous measurements from the Doppler technique. This data was acquired at SwRI in a setup where the two sensor systems were co-located making such a comparison possible. The results from the electrical impedance measurement and the evidence of asymmetry were discussed in detail in [6]. The Doppler measurement shows the exact same asymmetry as measured by the impedance measurement in the scattered amplitude data as show in figure 7a and 7b. Under such flow conditions, ignoring or approximating the asymmetry in the flow rate calculations can result in significant bias in the result as described in [6].

Technical Paper

While the qualitative analysis sheds light on the complexity of the flow dynamics, it also explains the reason why popular flow models are unable to describe multiphase flow physics accurately and end up being unreliable under certain flow conditions. It is clear from this analysis that approximating the dynamics of the velocity as shown in figures 4-7 through a single average number may turn out to be rather inadequate in explaining particularly difficult regimes such as slug-churn, churn and churn-turbulent regimes. This may be one of the reasons why flow models have had to be tweaked empirically to achieve the desired accuracy, while the same empirical corrections leave the models wanting for reliability and robustness. The power of the Doppler measurement comes from its ability to capture elements of the flow that other measurement techniques are liable to miss.

4 QUANTITATIVE ANALYSIS OF DOPPLER DATA

While the previous section elaborated on the many insights provided by Doppler into the complexities of multiphase flow physics, the real value add of the technique comes from being able to translate this learning to improving the accuracy of flow rate estimation. The very same characteristics of the Doppler measurement that allow for such intricate understanding of the flow also pose unique challenges for quantitative analysis. While the Doppler technique is not a new phenomenon as far as multiphase measurement is concerned, there has been very little success in proving its measurement capability across a wide range of flow conditions and flow regimes. As explained in section 2, the Doppler received signal carries with it information about the small scatterers in the flow. To be able to use this signal for quantitative analysis, a relationship needs to be derived between the scatterer velocity and a flow parameter and therein lies the challenge of this technique.

The key towards deriving this relationship is in understanding what the Doppler velocity is related to. To this end, an experiment was conducted at GE's in-house flow loop with the Doppler measurement system placed on a transparent section of the pipe as shown in figure 8a. Several different flow conditions were generated with air and water flows while Doppler measurements were obtained. Simultaneously, a high speed video camera captured the dynamics of the flow through the transparent section. An image cross correlation technique was used to track the movement of the bubbles through the flow. Subsequent images of the video were cross correlated to track and measure the velocity of the bubbles

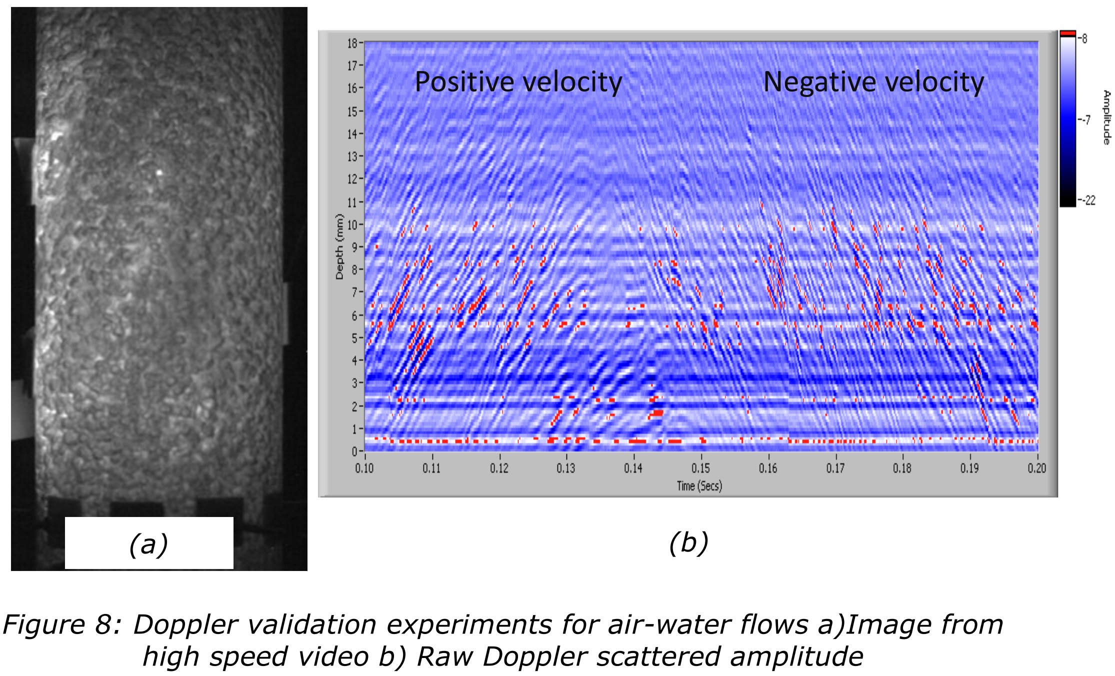
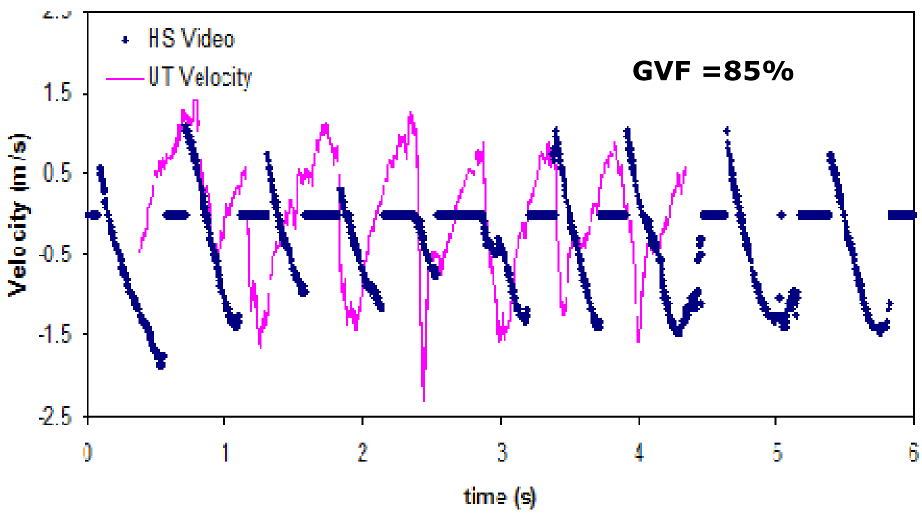
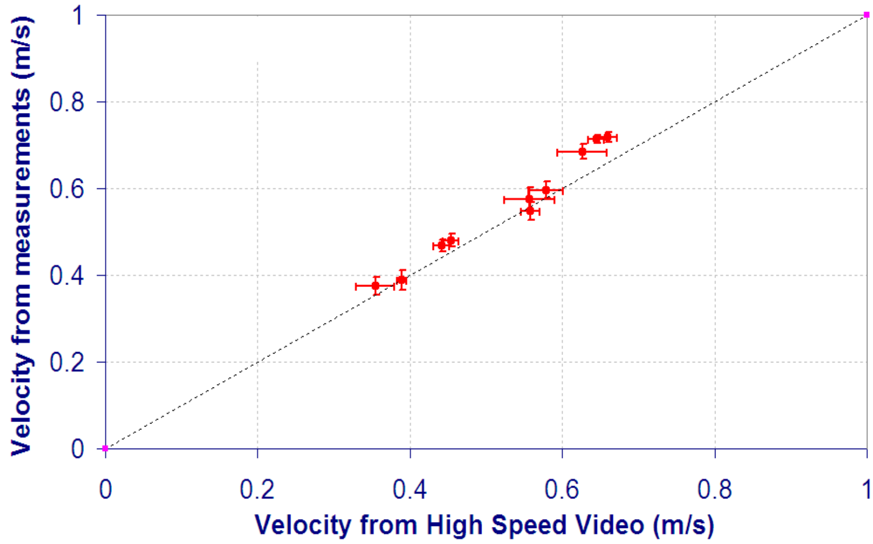


Figure 8: Doppler validation experiments for air-water flows a)Image from high speed video b) Raw Doppler scattered amplitude

in the section of interest. This was then compared with the velocity measured by the Doppler system both instantaneously as well as on an average. Figures 8 and 9 depict the results of this experiment. Figure 8a is a still image from the high speed video clearly showing the bubbles in the flow. Figure 8b shows the raw Doppler amplitude data that depicts the movements of the bubbles. The reversal of direction is clearly seen in the image as striations in opposite directions as indicated. The average velocities measured by both techniques show a high degree of correlation with each other as shown in figure 8d. While this confirms that the Doppler measured velocity is indeed sensitive to the small bubbles in the flow, it needs to be borne in mind that the image cross correlation technique only measures the velocities closer to the wall and is immune to bubbles traveling closer to the centre of the pipe. This fact becomes more evident from the comparison at the instantaneous level in figure 8c where certain instants of the flow are missed by the image cross correlation but are captured by the Doppler measurements which can measure through the cross section.



(a)



(b)

Figure 9: Doppler validation experiments for air-water flows a)Instantaneous comparison between image cross correlation and Doppler velocities b) Average Doppler velocity vs average velocity from image cross correlation

In order to extract liquid velocity information from the Doppler data, the information content needs to be analyzed carefully to extract velocities components that are least affected by the presence of bigger gas bubbles. The justification for this is that the smaller bubbles or scatterers travel with a velocity closer in magnitude to the liquid velocity with minimal slip. With this as a basis and using the results from above and the insights derived from the qualitative analysis, a robust algorithm was built to derive the liquid velocity from the Doppler data. This is a GE proprietary algorithm that addresses the challenges described so far by selectively extracting key pieces of information from the Doppler data.

During extensive testing conducted at the Southwest Research Institute (SwRI) in San Antonio, Texas, data was acquired with the Doppler measurement system described in section 2 along with gamma densitometer measurements for varying flow conditions. The flow conditions for data presented in this section are as given in table 1. Figure 10 shows the estimated liquid flow rate using the Doppler and

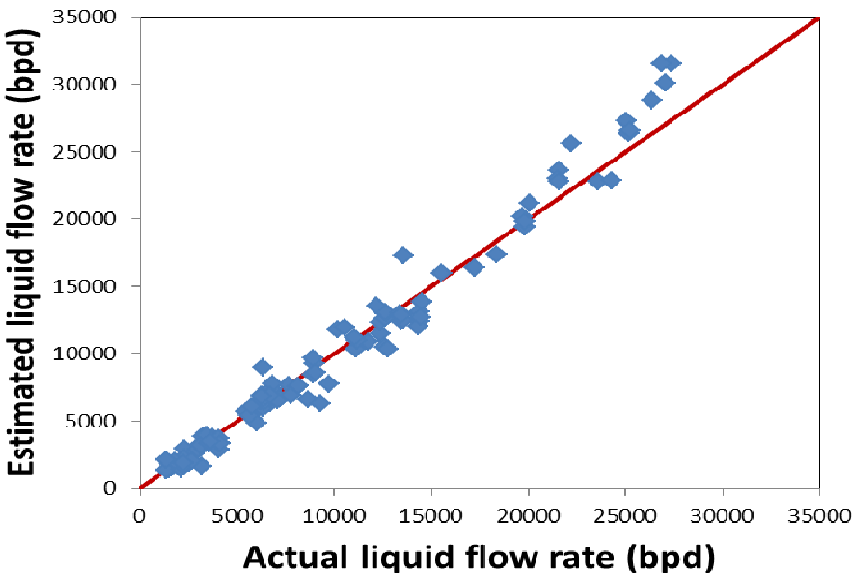


Figure 10: Doppler based liquid flow rate estimation at SwRI

Gamma densitometer measurements against the reference single phase measurements for the liquid flow rate. Clearly, the Doppler based liquid flow rate shows highly consistent performance for the wide range of operating conditions tested as shown in table 1. Combining a technique such as the ultrasound Doppler with traditional approaches such as the venturi or cross correlation based flow rate measurement has the following advantages:

- *Less sensitivity to fluid property error*: Models used for computing liquid or gas velocity from venturi or cross correlation require knowledge of fluid properties. Errors in fluid properties can significantly impact the accuracy of the velocities thus estimated. Doppler based velocity measurement is less sensitive to changes in fluid properties and is hence more robust to erroneous fluid densities or viscosities.
- *Estimation of model parameters*: As explained in section 3.2, the flow profiles obtained from the Doppler data can be used to update the profile related parameters in models thus improving their reliability
- *Addressing difficult to measure flow regimes:* Under certain flow conditions where the flow is transitioning between regimes or has not attained steady state, the correlations used with the venturi or cross correlation measurement may be inadequate in describing the flow physics

completely. In such flow conditions, having a technique such as the Doppler based flow rate estimation with its simpler assumptions would preempt this degradation in accuracy.

Augmenting the Doppler based velocity measurements with the venturi based flow rate can combine the advantages of both techniques to provide robust and accurate flow rate estimation. The results of such an approach are shown in figure 11 where the improvement in performance of the flow rate algorithm due to the addition of the Doppler technique is evident from the accuracy maps. From figure 9, it can be observed that the value of adding the Doppler based flow rate to the baseline measurement using only venturi for velocity is under certain flow regimes:

- Higher GVF cases where the complexity of the churn, churn-annular flow regimes limit the performance of the slip models used with the venturi dP measurement.
- Lower WLR where there are uncertainties around the estimation of fluid properties such as viscosity that affects the venturi discharge coefficient.

Thus, having the Doppler based velocity along with the venturi based measurement proved to be highly beneficial in improving the overall accuracy of liquid flow rate estimation.

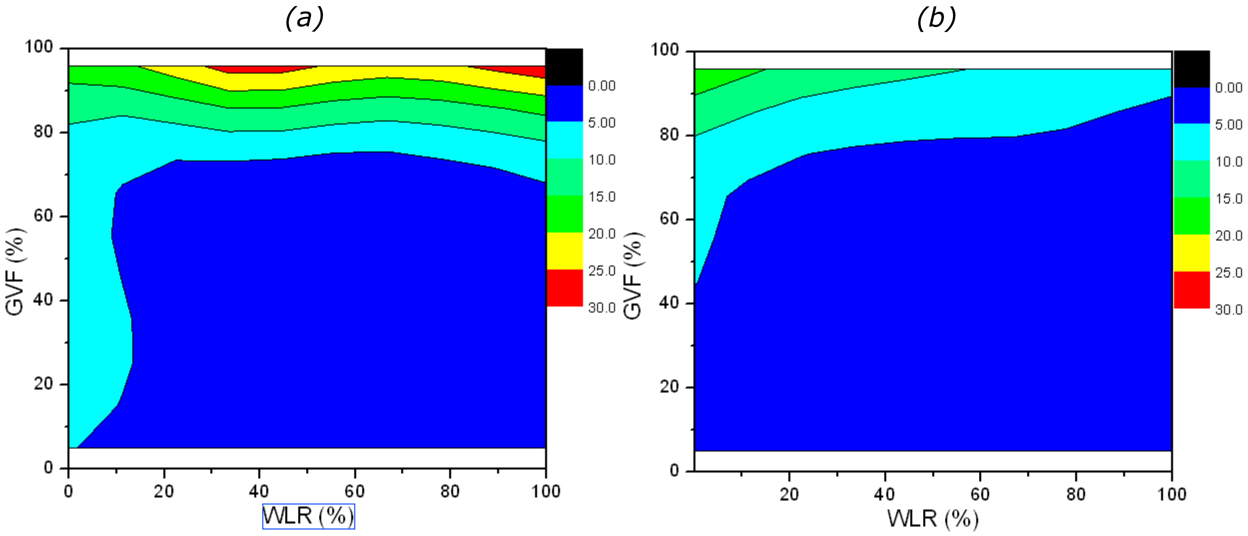


Figure 9: Accuracy map for SwRI data using a)Venturi based liquid flow rate estimation b) Combination of venturi and Doppler for liquid flow rate

5 CONCLUSIONS

The Ultrasound Doppler technique brings unique abilities and features to a multiphase measurement system by virtue of its ability to measure the smaller features in the flow. The qualitative value-add of the Doppler technique stems from the rich picture of the flow dynamics that is provided the Doppler amplitude and velocity. In conjunction with this qualitative information, the capability of the Doppler measurement to provide an accurate estimate of the liquid flow rate makes it an attractive choice for combining with the more traditional velocity measurement methods. Moreover, the Doppler flow rate measurements are less sensitive to fluid property variations and the flow rate estimation is riddled with fewer assumptions and approximations, thus making the computation fairly robust and reliable apart from improving the overall accuracy of the flow measurement.

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