STUDY OF ULTRASONIC SIGNALS IN LIQUID-GAS-SOLID MIXTURES AND INFLUENCE OF PARTICLE SIZE DISTRIBUTION ON THE ACOUSTIC DISSIPATION

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Abstract.
In many industrial applications, especially in the oil industry, the requirements for measuring multiphase flow impose numerous technological challenges. Overcoming these challenges requires an understanding of basic phenomena of multiphase flow and the development of specific techniques to be easily applied in the industry. From an experimental apparatus, experimental data were obtained with variations from 0 to 3% concentration by weight of glass beads in water, in steps of 0.25% in upflow only, with void fraction around 8.00%. The desired concentrations were prepared in a suspension reservoir, where the accounts were weighed and mixed glass on the total volume of water in the tank. The conclusion is that the main structures present in the information flow, better results are presented with the sensor 180 ° followed by the 0 ° sensor. And with respect to sensors 135 and 45 ° provide additional information that can be used as fine tuning. This paper intends to performing a systematic investigation of the influence of the beads size on the transit time and signal attenuation, in addition an analysis of the influence of the parameter "ka" (product of the wave number "k" and the radius of the particle "a") in acoustic scattering will also be presented in the final version of this document.

Keywords*: ultrasonic technique; air-solid-water flow; Fast Fourier Transform.*

1. INTRODUCTION

The term multiphase flow is used to refer to any fluid flow consisting of more than one phase or component. One could classify them according to the state of the different phases or components and therefore refer to gas/solids flows or liquid/solids flows or bubbly flows and so on. Many texts exist that limit their attention in this way, and to avoid errors of classification and definition of multiphase flows, it is necessary to keep in mind that focus or theme will be treated to prevent digressions with innumerous observations on the subject.

Two general topologies of multiphase flow can be usefully identified at the outset, namely disperse flows and separated flows. By disperse flows we mean those consisting of finite particles, drops or bubbles (the disperse phase) distributed in a connected volume of the continuous phase. On the other hand separated flows consist of two or more continuous streams of different fluids separated by interfaces.

In many industrial applications, especially in the oil industry, the requirements of multiphase flow measurement impose numerous technological challenges, and overcoming these challenges requires understanding the basic multiphase flow phenomena and the development of specific techniques that can be readily applied in the oil or any other industry. For this reason the need for Multiphase Flow Metering (MFM) arises when it is necessary or desirable to meter multiphase flow of the separators.

MFM enables measurement of unprocessed multiphase streams very close to the well, thereby providing continuous monitoring of well performance and better reservoir exploitation/drainage. Therefore, there is an immense interest in the use of the noninvasive and real time techniques for the disperse phase monitoring in the multiphase flow. Moreover, information about the flow pattern can benefit the fluid classification and improve the transportation processes. Following the developments in this research area, this paper analyses a potential technique for monitoring these types of flow: the ultrasonic one.

The ultrasonic technique has been studied for these applications by many authors in the literature like (Chang 1981, Carvalho 2009, Lampreia 2005, Zheng and Zhang 2004). This technique is already well established in other fields of application, such as medicine and flaw detection in solid materials. The transducers are readily available commercially at relatively low cost, and these techniques are also compact and robust.

So, this paper shows an experimental apparatus projected for the measurement of the void and particle suspension fractions by utilizing the ultrasonic technique, where the direction of the flow is upwards and the particle concentrations vary from 0 to 3% wt. The main goal of this work is to investigate the transit time, energy ratio, and acoustic attenuation measured by the transducers coupled in a solid-water and solid-water-gas flow.

2. APLLICATION OF THE ULTRASONIC TECHNIQUE TO MULTIPHASE FLOW METERING

2.1. Preliminary Discussion

The multiphase flow metering and the accurate monitoring of oil production impose numerous technological challenges. In the oil industry, the multiphase flow may be found in hostile environments, with aggressive fluids, sometimes carrying suspended particles, and multiphase flows are very common in the petroleum, chemical, and nuclear industries, oftentimes involving harsh media, strict safety regulations, access difficulties, long distances, and aggressive surroundings; accordingly, there is a need to determine the dispersed phase holdup/particle suspensions using noninvasive fast responding techniques. Therefore, there is an immense interest in the use of the noninvasive and real time techniques for the disperse phase monitoring in the multiphase flow. Moreover, information about the flow pattern can benefit the fluid classification and improve the transportation processes. The ultrasonic technique fulfills these requirements and could have the capability to provide the information required.

Ultrasonic transducers are readily available commercially at relatively low cost, and this technique is already well established in other fields of application, such as medicine and flaw detection in solid materials, the transducers are readily available commercially at relatively low cost, and these techniques are also compact and robust.

Ultrasonic signals are rich information and can penetrate pipe to successfully interrogate optically opaque fluids and dense suspensions. In addition, the signals are not significantly degraded by a wide range of process. The drawback of current ultrasonic techniques is the need for prior signal attenuation calibration; however, other MFM techniques also have the same limitation and this should not be a reason for neglecting the great potential exhibited by the ultrasonic technique. The technique has been tested for flow pattern detection and phase concentration measurements in a variety of multiphase mixtures.

Accordingly, one of the goals this work is to investigate and to compare the acoustic attenuation caused by different structure in suspensions. The purpose of this paper is bringing the ultrasonic technique closer to real application in the oil industry.

A correlation between the acoustic attenuation (energy ratio) with the increase glass beads in suspension is closely de acoustic data on the paper from (Gonçalves et al, 2011), where the authors also found a correlation between the acoustic attenuation and the solids concentration in the oil. Finally, inferences were made regarding the acoustic attenuation mechanisms of both sand particles and gas bubbles in water, which contributed to the development of the ultrasonic technique for monitoring and measurement of the sand concentration and gas fraction in real applications of the oil industry.

2.2. Experimental Apparatus and Procedure

The experimental apparatus were assembly at the Federal University of Itajubá (LRF-UNIFEI), which allowed the measurement of multiphase flow (glass beads-water-air) in both ascendant and descendant directions.

In the present investigation, the goal at this point was to make sure that reliable, repeatable ultrasonic signal could be obtained from which the information about the flow pattern and/or the phase fractions could be derived.

The flow was investigated using an ultrasonic apparatus consisting of one emitter transducer and three receivers at different positions along the pipe circumference, as it is shown in Figure 1. The direct transmission receiver ($\theta = 180^o$) measures the energy transmitted through the flow. The side sensors ($\theta = 45^o$ and 135^o) measure most of the energy coming from the scattering off the acoustic beam.

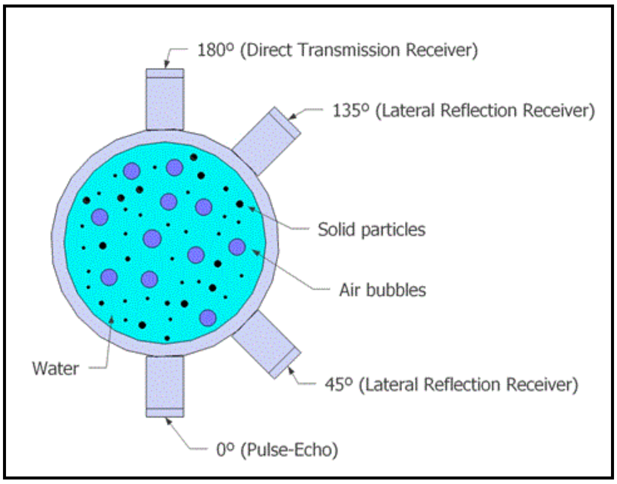

Figure 1: Ultrasonic Instrumentation.

The ultrasonic sensors used were “Panametrics videoscan type”, 2.25 MHz, 13 mm diameter, and longitudinal waves. The data acquisition used was the PXIe-1062Q (National Instruments). The emitter transducer was excited at 2 kHz; the sampling period was set to 5.0 sec and the sample frequency 20 MHz.

The adapters found in the assembly had the task of allowing only the "field of ultrasonic much" to interact with the mixture, the acrylic was constructed from different sizes, locating the "near field" inside. Using the dates from the Panametrics Notes' of 2010, the near field was calculated, and the size of adapters has been designed according to the type of material.

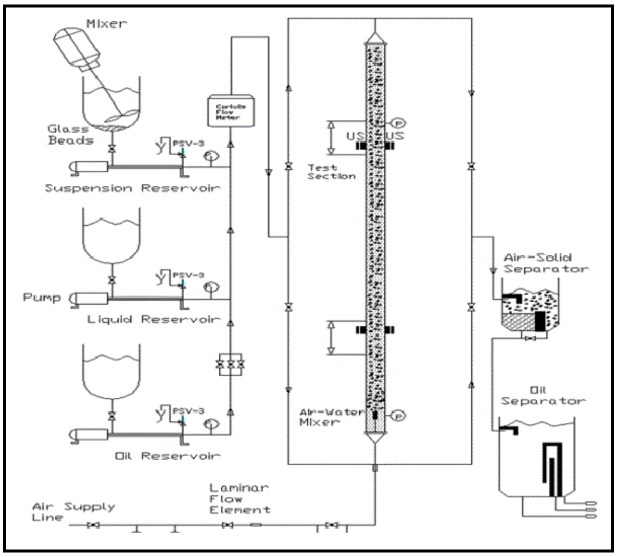

Figure 2: Schematic view of water-sand-air flow test rig

3. The Procedure

The multiphase flow mixtures (air, glass beads and water) produced in a reservoir is conducted through a Plexiglas pipe where the ultrasonic test section is mounted as it is shown in Figure 2.

A schematic view of the experimental apparatus used in the current investigation, the circuit was designed to operate in batches, and after running through the Plexiglas pipe the flow is directed to separation tanks. There also exists an air injector in the entrance of the Plexiglas pipes to generate the flow. Data were obtained from 0 to 3% of mass concentration of glass beads in water, in 0.25% steps and upward flows only and the void fraction tested was 5.00%.

The desired concentrations were prepared in the suspension reservoir by weighing the glass beads (±0.001 kg) and previously measuring the water mass and temperature in the tank with a Coriolis flow meter (±0.15%); the resulting uncertainty in the concentration values was estimated to be about ±0.2%, and temperature readings were used to monitor the temperature effect on the ultrasonic parameters.

The main goal in the present investigation was to check the consistency and study the ultrasonic signals in water-continuous mixtures. The direct transmission receiver ($\theta = 180^o$) was expected to get most of the energy transmitted through the multiphase flow while the dual element emitter/receiver transducer ($\theta = 0^o$) was intended to provide the main complementary information about reflections of the gas structures and solid particles the ultrasonic path. The side sensors ($\theta = 45^o$ and 135^o) were expected to receive at least part of the energy scattered off the acoustic beam and thus provide additional information about the interaction between the ultrasonic wave and the multiphase flow.

The reported energy ratios are the averages of these samples and the associated uncertainty interval was calculated at the 90% confidence level.

By calculating the acoustic energy ratios, the reference signals for the 0º and 180º sensors were those obtained for single-phase water, which corresponds to the maximum energy condition for these transducers. For the 45° e 135° sensors, the reference used was the signal single-phase water from 180°, the 45° and 135° sensors receive no acoustic energy as there are no particles to scatter the energy off the acoustic beam to the sides.

Temperatures measurements were made at the beginning and end of each series of tests in order to obtain the fluid properties. Data were acquired by means of a National Instruments PXIe-1062Q acquisition board using the resident LabView® software. The data was stored in Microsoft Excel spreadsheets and filtered later on using MatLab® software to reduce the noise in the signals.

4. RESULTS AND DISCUSSION

For this work, the review concerning the ka and Re parameters found are described as follows. The main goal of this work is to investigate the transit time, energy ratio, and acoustic attenuation measured by the transducers coupled in a solid-water flow.

Kytömaa (1995) presented a discussion about the mechanisms of acoustic attenuation in solid and liquid suspensions, where he indentified three different regimes of compression wave propagation as a function of the length scales of process.

Two principal parameters are used to determine which regime a particular situation fits in. The multi-scattering regime (regime of short wavelength) for ka>>1, where

$$ka = k \cdot a$$

Equation 1

Where the value of (a) the in Equation 1, is the radius of micro glass beads given in μm and the term k called wave number is given the form:

$$k = \frac{2\pi}{\lambda} = \frac{2\pi f}{c}$$

Equation 2

In Equation 2, λ is the wave length, f the wave frequency, c the wave velocity in the continuous phase at 20° (C). In this situation (ka>>1), the particle diameters are much bigger than the wavelength, and the acoustic wave scatters uniformly in all directions, resulting in a poor penetration. For the other regimes, ka<<1, the acoustic wave scattering and attenuation depend on the Reynolds number and the relevant length, then, is the boundary layer thickness, δ, which involves the particles, often called the Stokes layer thickness. The Reynolds number is then defined as

$$\mathrm{Re} = \frac{a}{\delta} = a\sqrt{\frac{\rho_l \omega}{2\mu}} = a\sqrt{\frac{\rho_l 2\pi f}{2\mu}}$$

Equation 3

In Equation 3, ρl is the continuous phase density and μ the dynamic viscosity of water at 20°, ω the angular frequency. When Re <<1, the boundary layer is thick compared to the radius of the particle and the viscous relaxation time is shorter than the period of excitation.

In his work, Urick (1947) showed that the particles were infinitely small compared to the wavelength of the sound (long wavelength limit), and neglected the effects of scattering. In the suspension, the ratio of sound velocity as a function of solid volume behaves as a parabolic function, and consequently has a maximum or a minimum at some particular concentration. Data obtained from suspensions of kaolin (chemical composition $Al_2Si_2O_5(OH)_4$) in distilled water showed a minimum in the sound velocity (increase in transit time) for 20% v/v of kaolin. In all these experiments conducted by Urick (1947), particle size was much smaller than the wavelength, thus corroborating the assumption of long wavelength limit.

Other authors (Soong et al. 1995) proposed other acoustic attenuation measurement in a three-phase reactor consisting of water, glass beads, and nitrogen bubbles. They used glass beads with 80 ± 5 μm, ultrasonic pulses frequency of 2.5 MHz and the concentration was varied from 1% to 35% for a given void fraction of nitrogen. With these data the authors were able to observe a decrease in the wave transit time with an increase of the glass beads concentration. The transit time was defined as the time interval corresponding to the first distinct zero crossing of the acoustic wave at the receiver transducer. The nitrogen flow rate did not cause any effect on the transit time so defined. It was argued that the portion of the acoustic beam that is transmitted through the solid particles is speeded up by the higher sound velocity in the new medium, which explains the decrease in the transit time.

Similar to this present work, Stolojanu and Prakash (1997) performed acoustic measurements in two-phase and three-phase systems. In their work, transducers with 4 MHz nominal frequency were used. The solid loadings were up to 90% wt and the gas holdup up around 40% vol. Glass beads of 35 μm in diameter were used as the solid phase while tap water and compressed air constituted the liquid and gas phases, respectively. In two-phase systems, the transit time was observed to decrease monotonically with increasing solids concentration, the corresponding plot exhibiting a linear relationship throughout the entire concentration range tested. The measured transit times, however, were quite different from the values predicted by the phenomenological approach proposed by Urick (1947). Regarding the amplitude ratio, an exponential decay was observed with increasing solids concentration.

Zheng (2003) also presented ultrasonic data for two-phase and three-phase systems. The liquid, gas, and solid phases consisted respectively of water, air, and 500 μm glass beads; acoustic parameters were normalized with reference to single-phase liquid water. In liquid-particles flows, the standard deviations of the transit time were observed to increase with increasing solids concentration at the same time the standard deviations of the normalized amplitude were observed to decrease. Moreover, the standard deviations in liquid-solid flows were substantially smaller than those in liquid-gas flows, especially for the normalized amplitude.

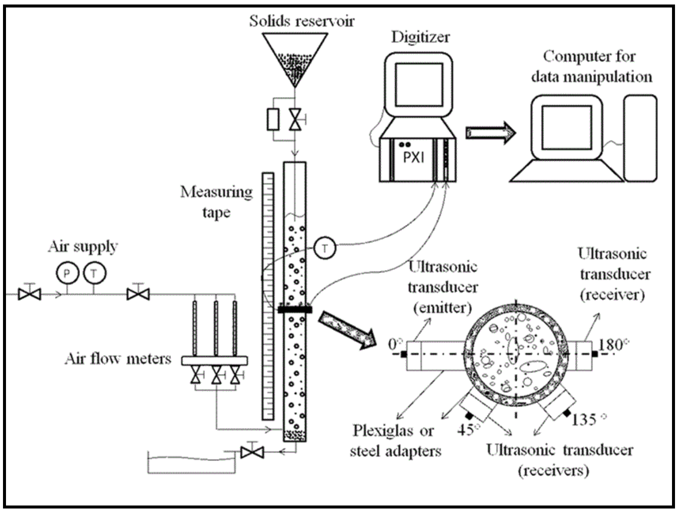

Figure 3: Schematic view of the experimental apparatus [(Gonçalves et al, 2011)]

The same way in the present paper, in (Gonçalves et al, 2011), ultrasonic data was obtained for suspension of sand in oil up to 4% v/v in one Plexiglas pipe using too 2.25 MHz transducers

The arrangement in Figure 3 was that there should be one ultrasonic transducer in each quadrant of the pipe circumference; however, assuming the solids/oil suspension being axially symmetrical from a statistical point of view, only half circumference was instrumented, the same way in this present paper.

As already mentioned earlier, the direct transmission receiver (180°) was expected to get most of the energy transmitted through the mixture and the suspension, while the dual element, emitter/receiver transducer (0°) was intended to provide the main complementary information about refraction and reflections off the same gas structures in the ultrasonic path.

In (Gonçalves et al, 2011), the ultrasonic transducers was the 2.25 MHz, Panametrics Videoscan, 13 mm diameter, which were mounted on the adapters. The data was acquired by PXI – 6250 – Labview software – from National Instruments, like this present work. In Figure 4 can see the acoustic attenuation with the increase glass beads in continuous phase oil, and can observe the rapid decrease of amplitude with increase the solid particles (glass beads).

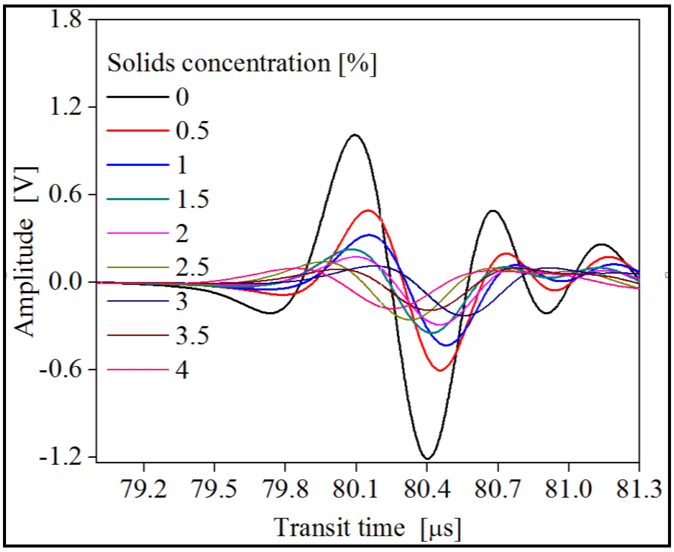

Figure 4: Acoustic Attenuation [adapted (Gonçalves et al, 2011)].

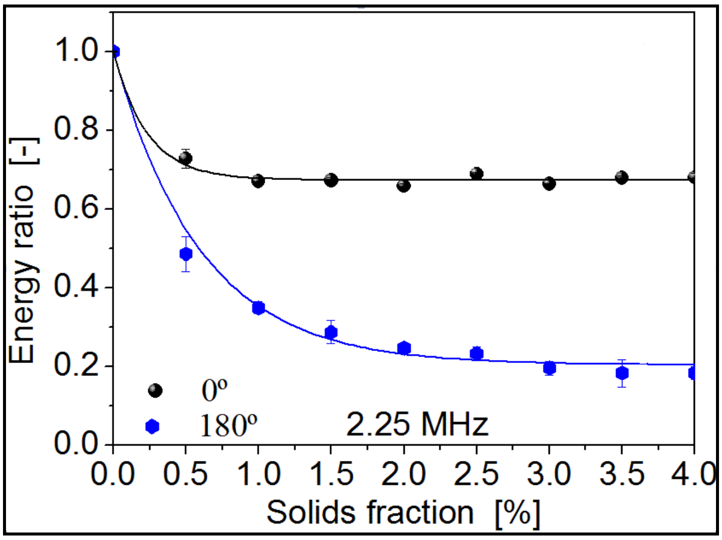

Figure 5: Energy ratio [adapted (Gonçalves et al 2011)].

Figure 5 shows the energy ratios sensors shown as a function of the solids concentration in oil. Despite of the authors using oil instead of water, the behavior of the ratio of energy had the same trend with this work. In (Gonçalves et al 2001), shown that the particle Reynolds number, $\mathrm{Re} = \frac{a}{\delta}$ ranged from about 80 to 120, to δ (thickness of the boundary layer surrounding the particles).

A rapid decrease in the energy ratios was observed for the 0º and 180º sensors for concentrations as small as 1% v/v; which agrees with the trends in for suspensions of sand in water. However, in this case the data leveled off at much higher values of the energy ratios; the small differences in the ka parameter between the two studies are not expected to account for this discrepancy. On the other hand, the particle Reynolds numbers extended to about 800, which could have caused the increased attenuation in that case due to inertial effects.

In relation to transit time in sand-oil, in the Figure 6 was shown that transit time decreases with increasing fraction glass beads. Considering that the wave can pass through a portion of the microspheres, this wave is then accelerated, which can be intensified with increasing fraction solid.

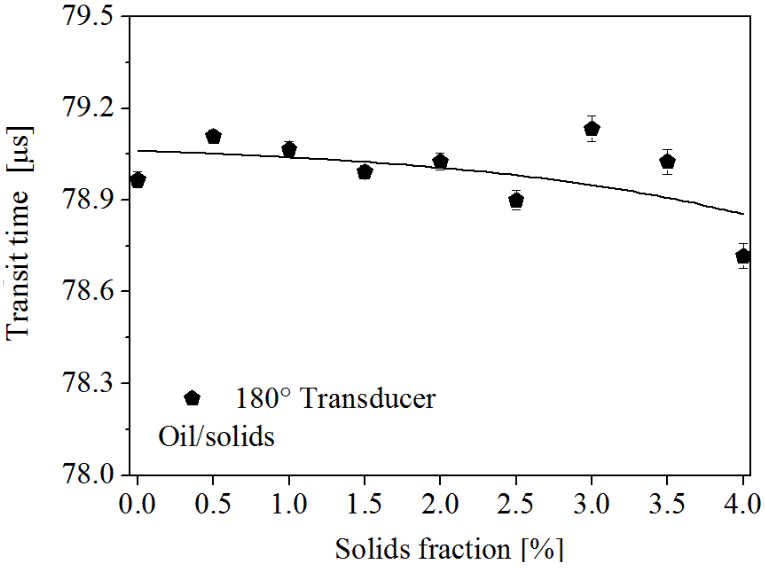

Figure 6: Acoustic Attenuation [adapted (Gonçalves et al, 2011)].

Considering all this information, like installation, acoustic attenuation, energy ratio and transit time, for a comparison between the data, the testing procedure was followed.

Ultrasonic data were then obtained for suspensions of sand in water and sand-air in water flow. The 2.25 MHz transducers were used for this experimentation for the four sensors as a function of the solids concentration in the Plexiglas pipe; the average particle size was show at Table 1.

For ka > 1 and Re >> 1, and the attenuation mechanism looks like a combination of multiple scattering and inertial losses (in-phase component of the Basset force). Since the value of ka is not larger than the unit, the multiple scattering processes are not expected to be very intense. However, the other values, the acoustic attenuation is expected to be more related to inertial effects, and it does not cause too much scattering.

Table 1: Test condition for the ultrasonic data acquired in solid-liquid-gas flow.

***ka* [-]**	**k [m^{-1}]**	**f [MHz]**	**c [m/s]**	**λ [m]**	**d [µm]**
Acoustic Parameter	**Wave number**	**Pulse Frequency Ultrasonic**	**velocity of water at 20°C**	**Wavelength**	**Particle diameter**
0,71	9,55E+03	2,25	1480,00	6,58E-04	149,00
2,84	9,55E+03	2,25	1480,00	6,58E-04	595,00
a [µm]	***Re* [-]**	**δ [µm]**	**ρ [Kg/m^3]**	**ω [rad/s]**	**µ [N.s/m^2]**
Particle radius	**Reynolds number**	**The boundary layer thickness**	**Specifies mass**	**Angular Frequency**	**Viscosity for water at 20 ° C**
74,50	202,06	3,69E-07	998,00	1,41E+07	9,59E-04
297,50	806,88	3,69E-07	998,00	1,41E+07	9,59E-04

Related to the acoustic energy measured by the 180° transducer, very small quantity of solids already can reduce the energy which reaches to this sensor, as we can see at the Figure 7 and Figure 8, where is showed a representation of the average response signals for the 180° receiver, for some solids concentration in two and three-phase flow. One can see that signals amplitudes are attenuated even for very small concentration. However, the signals duration practically maintained the same.

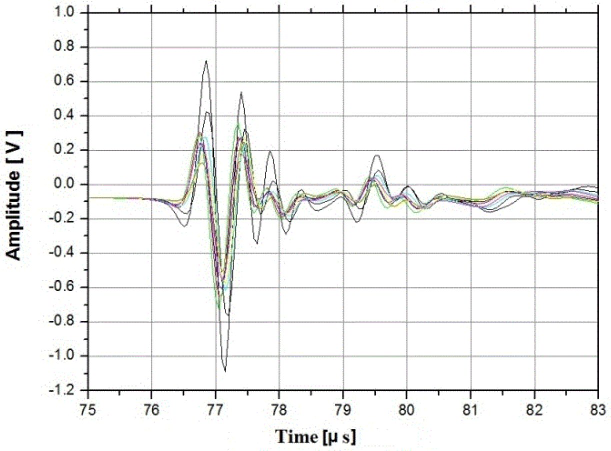

Figure 7: Mean pulse sensor to 180 ° (Two-phase).

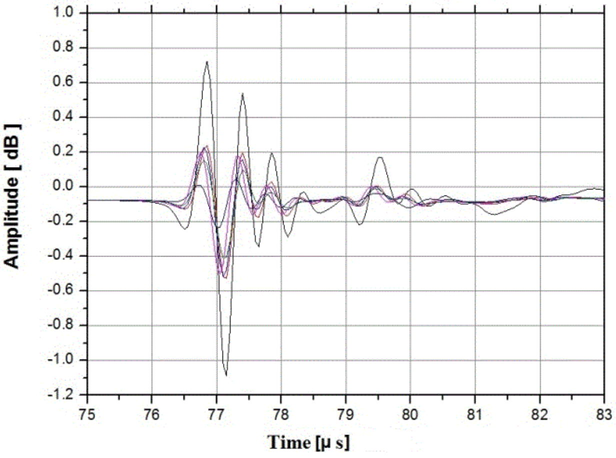

Figure 8: Mean pulse sensor to 180 ° (Three-phase)

Comparing the attenuation found in this work with the attenuation by (Gonçalves et al 2001), is possible to verify the behavior of decrease in the two phase and three phase flow. In both of the flows there was one decrease, and this behavior confirms what has been present from the author, who used oil instead of water, the performance was given the same proportions.

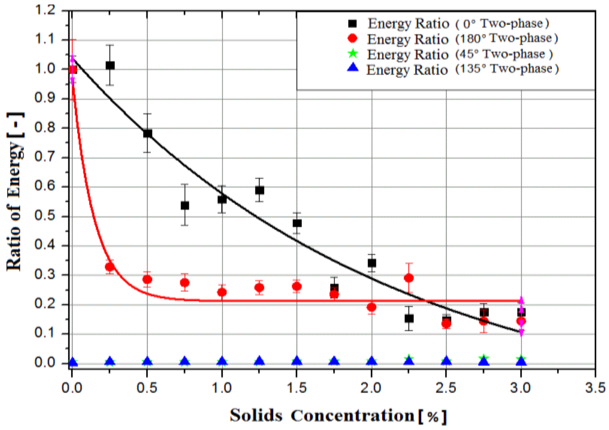

Figure 9: Ratio of Energy Biphasic.

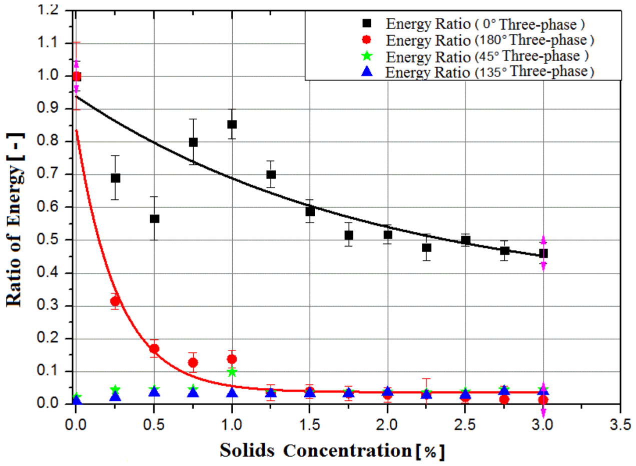

Figure 10: Ratio of Energy Three-phase

Still related to the acoustic energy, Figure 9 e Figure 10 exhibit the average energy ratio as a function of solids concentration for all receivers in two and three phase flows. A rapid decrease was observed for the 0º and 180º sensors for concentrations as small as 1% both the flows, two-phase and three-phase flow; Related to the acoustic energy measured by the transducers, very small quantity of solids already can reduce the energy which reaches to this sensor.

The energy ratio measured by the 0° and 180° sensors decreased exponentially with the increase of solid concentration. It is noteworthy that even for concentrations as low as 0.25% the energy ratio was already less than 0.5 and decreased to much lower values within the narrow concentration range tested.

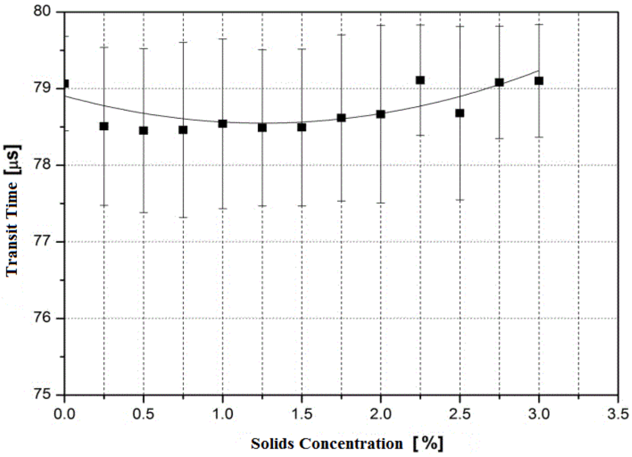

Figure 11: Transit time as a function of the particles concentration for the 180° transducer (two-phase flow).

Again, it is necessary make a comparison with (Gonçalves et al 2001), where the authors do the same energy ratio, using the one phase energy from transducer to calculate the ratio energy (0° and 180°) the same way that the present work, but it was not done for 45° and 135° sensors, where the author using the energy from transducer with the upper range concentration. But, both the works shown the behavior expected of all resources sensors. As expected, the energy plots show that very little energy gets through to the 180º sensor and very little energy is scattered sideways. Once again, the data showed an interrelated behavior among the sensors.

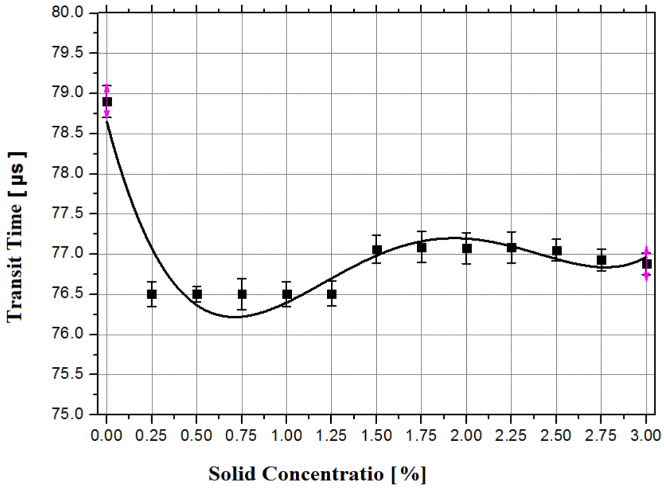

Figure 12: Transit time as a function of the particles concentration for the 180° transducer (three-phase flow).

On the other hand the 45° and 135° sensors did not measure any significant energy throughout the entire solid concentration. This behavior confirms the expectations that multiple scattering should not be very intense for the particle sizes in this experiment, ever for the void fraction of 5% was maintained approximately fixing, and its deviations as expected not very evident and therefore scattering essentially uniform acoustic beam to throughout the perimeter of the pipe, and them receive practically the same amount of acoustic energy or almost none, showing essentially uniform scattering of the acoustic beam along the all perimeter of the pipe. Once again, the data showed an interrelated behavior among the sensors. Moreover, in the oil industry the sand concentrations are very small, typically less than 1% v/v, so that the ultrasonic technique seems to have enough sensitivity in the concentration range of interest.

To relation an initial transit time, in the Figure 11 and

Figure 12 is shown an example as a function of solid concentration. In Figure 11, a minimum point is observed at approximately 1.5% wt, but the same behavior isn't seen in the

Figure 12, where the behavior is in the beginning continuous and after 1.50% of solid concentration, the transit time increase to after that start to decrease. The uncertainties in the averages were calculated from the standard deviation in 10,000 pulses of each sample, and six samples for each concentration.

But when we compare the behavior of the transit time of the present work with the (Gonçalves et al 2001), is possible to observe that the parabolic behavior is practically the same until the concentration of 3%, and from this point on the transit time started decrease. Clearly there is a correlation between the concentrations glass beads in the suspension with the acoustic attenuation and transit time.

Nevertheless, in view of the apparent strong dependence of the transit time variation on the particle size distribution relative to the wavelength, the use of the initial transit time to measure solids concentration would be very much dependent upon calibration for the particle sizes expected in the real application. In case this distribution could not be known beforehand, the transit time would not yield reliable information. Values below that for single-phase water would mean the entrance of energy is being speeded up by the dispersed phase. It should be kept in mind that the chronological duration of the acoustic pulse remained essentially unchanged despite the severe attenuation by the dispersed phase.

5. CONCLUSION

As a conclusion from the discussion above, it can be seen that the ultrasonic technique has the potential to detect the flow pattern and, from the cross-correlation of the acoustic signals, to measure the flow velocity, the selection of a good ultrasonic instrumentation (transducers frequency) for measurement of solids concentration depends on the particle size distribution, the continuous phase, the concentration range desired, and the resolution required.

However, methods for velocity measurements based on cross-correlation of acoustic signals still need to be further established and the particular procedure to be used in a given application will probably be flow-pattern dependent. On the other hand, if the flow pattern can be reliably detected, data reduction procedures could be developed that would not require the flow to be homogenized. The flow pattern can be reliably detected from the ultrasonic signals, the same ultrasonic apparatus could be used for flow pattern detection and velocity measurements.

Upon calibration, the ultrasonic technique can provide the phase fractions in two-phase solid-liquid and three-phase solid-liquid-gas flows. Therefore, the possibility exists that the same ultrasonic apparatus can be used for flow pattern detection, velocity measurements, and determination of the phase fractions. In addition, provided the methods for determination of the phase concentrations from acoustic signals obtained in three-phase mixtures can be fully developed, the ultrasonic technique could also be used with multiphase mixtures without the need for phase separation.

The initial transit time variation with solid concentration shows to be very much dependent on the particle size relative to the wavelength and, thus, prior knowledge of size distribution is a requirement for reliable measurements. Finally, poor ultrasonic penetration due to intense multiple scattering would cause the sound beam as received by the opposite sensor to be fast attenuated. In these cases, the side sensors could provide useful information that, together with the 0° and 180° sensors, would make the measurement, as a whole, more robust. Specific combinations of the ultrasonic technique with other instruments in Multiphase Flow Measurements systems will depend on the extent to which the ultrasonic technique can be developed. Currently, these issues are being tackled as a project by Petrobras to field test the ultrasonic technique is scheduled to begin this year

6. ACKNOWLEDGEMENTS

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