ULTRASOUND MEASUREMENT OF THE CONTENT OF SOLID PARTICLES IN LIQUID MEDIA APPLIED TO OIL INDUSTRY

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Abstract. *In oil industry, sand content in crude oils is commonly used as a parameter to determine the well deterioration level and to assess horizontal wells collapse risk. The sand content measurement is usually performed by a sand content meter device, which is based on a sieves system. This device requires a human operator to collect and analyze the crude oil samples. In order to allow a real time sand content monitoring in crude oil, this work presents a new ultrasonic technique to determine solid particle concentration in liquids. This technique consists in emitting an ultrasonic wave by an ultrasonic transducer and measuring the backscattered ultrasonic signals produced by sand particles. Therefore, the objective of this work is to develop a measurement cell based on the ultrasonic waves scattering to estimate the sand particles concentration in crude oil. The experimental observations were made with a measuring cell built for laboratory batch testing and continuous solid particles flow. Ultrasound transducers with central frequencies ranging from 5 and 10* MHz *in pulse-echo mode were used. Laboratory batch tests using sand particles ranging in size from 100 to 500* μm *in diameter shown that there is a linear relationship between the volumetric fraction of particle and ultrasonic backscattered energy. The backscattered energy is proportional to the squared voltage measured from the receiving transducer. The echo signal mean energy at a given time window corresponds to the instantaneous flowing sand content through the cell. A micro-controlled feeder device was developed to perform tests on continuous solid particles flow. An analytical balance was used to calibrate the feeder to operate in the range from 2 to 20* mg/s*, producing a water mixture ranging from 200 to 2000* ppm*. Tests with continuous flow are in agreement with the expected results from the adopted methodology. A backscattered energy computational model based on a transducer impulse response and a plane piston model was developed to understand the experimental results. This model predicts the linear relationship between the backscattered energy and the particle concentration observed experimentally. The results demonstrate the technical feasibility of continuous flow measurements of sand in oil.*

Keywords: *Ultrasound, Sand content in oil , Backscattering*

1. INTRODUCTION

Solid particle content measurement in liquid media has practical application in a variety of situations, including chemical, petrochemical and food processing. There can be several techniques to achieve such a industrial demand. Conventional measurement techniques for solid suspension involves physical screening techniques, gravity-driven methods that use the density difference for separation and a simple balance for weighing the solid content. Most recent methods involves nondestructive techniques such as laser diffraction, gamma-ray attenuation, near infrared spectroscopy and ultrasonic waves.

Oil production in unconsolidated or poorly consolidated sandstones typically generates sand production. A high sand production may limit the petroleum production, damage the equipments, generate total production cessation, loss of well control, cause fire and environmental damage. Therefore, sand content monitoring within oil production is used as parameter to determine the well deterioration level, to assess horizontal wells collapse risk and oil-drilling platform productivity. Currently there is an extensive literature of ultrasonic non-destructive techniques for liquid testing (J C Adamowski, 1995), as well as solid particle concentration in liquid media measuring methods (He and Hay, 1993).

The studied technique is the ultrasonic backscattering, which is based on the principle of acoustic wave scattering (Kinsler, 1982). Therefore, this paper has the purpose to understand the main mechanisms of acoustic scattering by checking their dependencies in terms of concentration, particle size, media properties involved, seeking their application in the measurement of sand content in crude oil production. This paper is organized in five section. Following this introduction, the next section describes a ultrasonic measurement principle to provide a numerical model to study the involved acoustic phenomena that occur in acoustic waves propagation in liquid media containing solid particles such as sand particles suspended in oil and glass spheres suspended in water. The third section explains the experimental apparatus used to perform ultrasound tests to determine the suspended solid content (SSC) in liquid media. In section five we present the experimental results that correlates acoustic parameters with the SSC. The fifth section presents our conclusions.

2. ULTRASONIC MEASUREMENT PRINCIPLE

2.1 Concept

The SSC measurement principle by capturing the backscatter wave lays on the well-known pulse-echo technique. A short acoustic wave pulse is emitted by a ultrasonic transducer and as the sound pulse spreads away from the transducer it insonifies any suspended particle within its range. This scatters the sound energy, reflecting some of it backwards to the transducer, which also acts as a receiver. Figure 1 illustrate the measurement principle using a transducer in transmission/receive mode. With the sound speed in liquid media, the solid particle scattering strength and the propagation characteristics, a relationship between the received echoes intensity and the suspended solid concentration may be developed.

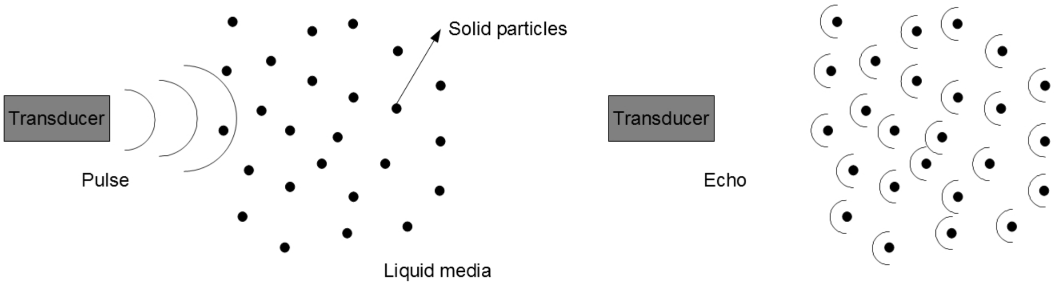

Figure 1. Pulse-echo technique principle and acoustic backscattering phenomena illustration

The acoustic wave scattering by obstacles was first investigated mathematically by Lord Rayleigh (1945). Faran (1951) studied the theory and experimental measurements of sound scattering by simple geometry and solid material. Most of the analytical results could be simplified to the case where the wavelength is much larger or much smaller than the characteristic dimension of obstacle. The problem becomes much more difficult when the wavelength is in the order of their dimension.

Considering the single scatter phenomenon the scattered acoustic field can be determined by Huygens principle. The resulting wave is a secondary sources waves summation on the surface obstacle, taking into account their amplitudes and relative phases. This problem is generally intractable for an arbitrary body size and shape, but can be studied in terms of the cross sectional area and the form factor. As in Cheeke (2002), two parameters is used to represent the scattering by a simple object, the polar diagram and the total scattered intensity as a function of frequency. The polar diagram is highly useful because it gives a immediate visual clue of the sound scattered intensity for all direction direction. The total scattered intensity is calculated as a function of ka, where k is the wavenumber and a is the central scattering characteristic size, expressed for a given direction.

2.2 Numerical modeling of the ultrasonic measurement cell

The measurement of solid particles concentration in liquids is done by using an ultrasonic measurement cell. In this cell, a broadband ultrasonic transducer is used to emit a sound wave and receive the backscattered signals produced by the solid particles. In this section, a numerical model is presented to predict the measurement cell behavior. The numerical model assumes that the particles sizes are much smaller than the wavelength, such that each particle can be considered as a point reflector. The numerical model also assumes that the particle concentration is small. In this case, the multiple scattering between the particles can be neglected. The numerical model is used to determine the pressure field generated by the ultrasonic transducer and to determine the backscattered signals produced by a collection of random point reflectors. Figure 2 shows the ultrasonic transducer geometry and the random point reflectors positions.

The first step in modeling the ultrasonic measurement cell is to determine the acoustic field generated by a circular plane transducer of radius a. Considering that the transducer face vibrates in x direction with arbitrary velocity $v(t)$, the pressure waveform $p(r,t)$ at a position $\mathbf{r} = (x, y, z)$ is given by Weight (1984):

$$p(\mathbf{r}, t) = v(t) * p_i(\mathbf{r}, t) \tag{1}$$

where $*$ represents a convolution and p_i is the pressure impulse response at r.

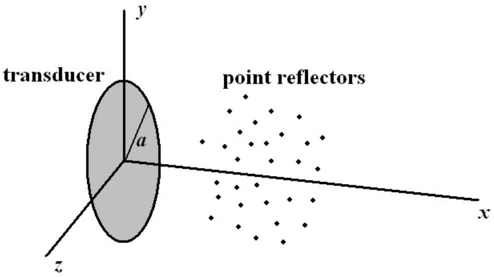

Figure 2. Ultrasonic transducer geometry and the random point reflectors modeling

The pressure impulse response is given by:

$$p_i(\mathbf{r},t) = \rho\left(\frac{\partial\phi_i}{\partial t}\right) \tag{2}$$

where ρ is the density of the fluid and ϕ_i is the velocity potential impulse response, which is given by:

$$\phi_i = \frac{c\Omega(ct)}{2\pi} \tag{3}$$

where c is the sound velocity in the fluid and $\Omega(ct)$ is the angle of an equidistant arc on the transducer face.

Assuming that $z = 0$, the angle $\Omega(ct)$ was presented by Weight (1984) and it can be determined according to Table 1. In Table 1, the times $t0$, $t1$, $t2$ are given by Weight (1984):

$$t_0 = \frac{x}{c} \tag{4}$$

$$t_1 = \frac{1}{c}\sqrt{(a-y)^2 + x^2} \tag{5}$$

$$t_2 = \frac{1}{c}\sqrt{(a+y)^2 + x^2} \tag{6}$$

Table 1. Angle $\Omega(ct)$ as a function of t, x, y, a and c, assuming that $z = 0$.

Region	Time	$\Omega(c,t)$
$y < a$	$t_0 \le t \le t_1$	π
$y < a$	$t_1 \le t \le t_2$	$2\cos^{-1}\left(\frac{c^2t^2 - x^2 + y^2 - a^2}{2y(c^2t^2 - x^2)^{1/2}}\right)$
$y = a$	$t = t_0 = t_1$	π
$y = a$	$t_0 < t \le t_1$	$2\cos^{-1}\left(\frac{(c^2t^2 - x^2)^{1/2}}{2a}\right)$
$y > a$	$t_0 < t \le t_1$	0
$y > a$	$t_1 \le t \le t_2$	$2\cos^{-1}\left(\frac{c^2t^2 - x^2 + y^2 - a^2}{2y(c^2t^2 - x^2)^{1/2}}\right)$

When the ultrasonic transducer is operating in the pulse-echo mode, the sound wave emitted by the transducer, reflected by a point reflector and received by the transducer is given by Weight (1984):

$$E(t) = -\left(\frac{ka}{2\rho c}\right)\nu(t) * P_i(\mathbf{r},t) * P_i(\mathbf{r},t) \tag{7}$$

where k is the wavenumber. Assuming that N point reflectors are random positioned in front of the ultrasonic transducer, the backscattered signal received $E(t)$ by the transducer is given by:

$$E(t) = \sum_{m=1}^{N} -\left(\frac{ka}{2\rho c}\right)\nu(t) * P_i(\mathbf{r}_m,t) * P_i(\mathbf{r}_m,t) \tag{8}$$

where $\mathbf{r}_m$ is the position of each point reflector.

The developed computational routine main approach uses algorithms for generating random parameters that simulate the particles positioning and analyze the resulting acoustic parameters. Some assumptions were made in order to establish a simplified model and obtain a correlation between the acoustic and the particles concentration, similarly to the experimental data. The computational model assumptions are:

- The circular plane transducer radiation has axial symmetry and therefore the results obtained in a given diametral plane that intersects the acoustic transducer central axis can be extrapolated to the infinite planes considered in the simulated region;
- The normally distributed particle size is limited by the ratio between present dispersed particles and the liquid media volume on the region considered. This ratio is configured at the beginning of each iteration;
- The backscattering phenomena contribution is simplified by multiplying the signal received $E(t)$ by the cross section area A_m of each particle considered in the simulated region;
- The media properties ρ and c, the wavenumber k, the transducer radius a and the velocity $v(t)$ is fixed. This assumption simplifies even more the model considering just the particle size and their position influence;

The signal $E_c(t)$ in the numerical model considering the assumptions above is given by:

$$E_c(t) = \sum_{m=1}^{N} -(A_m)\,\nu(t) * P_i(\mathbf{r}_m, t) * P_i(\mathbf{r}_m, t) \tag{9}$$

2.3 Numerical results and discussion

The `MATLAB` software environment was used to obtain the numerical results. The simulations were conducted by using Eq. 9 to obtain signal $E_c(t)$. All the results presented here were obtained using a 5-cycle 5 MHz sinusoidal signal with applied hanning window representing the transducer face velocity $v(t)$. The fixed parameters are also, transducer radius $a = 9.5mm$, media properties $\rho = 1000\ kg/m^3$ and $c = 1500\ m/s$. The analyzed region in front the transducer is limited by a parallelogram region, called V_p, ranging from -40 mm to 40 mm off the acoustic axis, $20mm$ to $80mm$ of range from the transducer and -25 mm to 25 mm of height.

The first approach considers a constant particle flux settling in front of the transducer. These particles positioning are restricted to a small subregion that vary along the V_p region. As times goes by, some new particles are considered and others are unconsidered. The constant ratio in volume is always respected inside this subregion. Some ensemble of scatterers are accounted and its corresponding signal calculated. It was considered a cylinder subregion, called V_c, with diameter $D = 28mm$ and height $H = 50mm$. Figure 3 and Fig. 4 shows simulated signal samples and its respectively subregion. The temporal axis is in microsecond (μs) scale and the amplitude axis is in an arbitrary unit (AU) scale. It should be noticed that the signal pattern varies along the range distance and has a direct relationship with its time of flight (TOF). One should also notice that the distance off axis can be predicted according to the calculated mean energy of each signal. The signal energy was calculated for each ensemble sample using a 50 μs temporal window.

A histogram was calculated to illustrate the subregion center influence, V_c, with the signal energy. This histogram considers a broad scan within a 1 mm grid along spacial axis of the region V_p. A temporal series of ensemble of scatterers

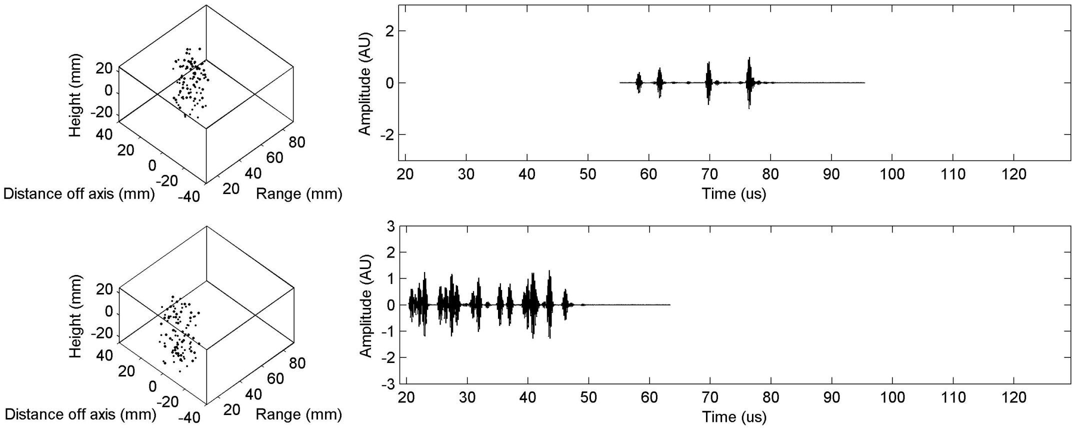

Figure 3. Simulated signal samples corresponding to a distance off axis equal to 20 mm and range from source equal to 50 mm (upper image); and a distance off axis equal to 0 mm and range from source equal to 25 mm (lower image).

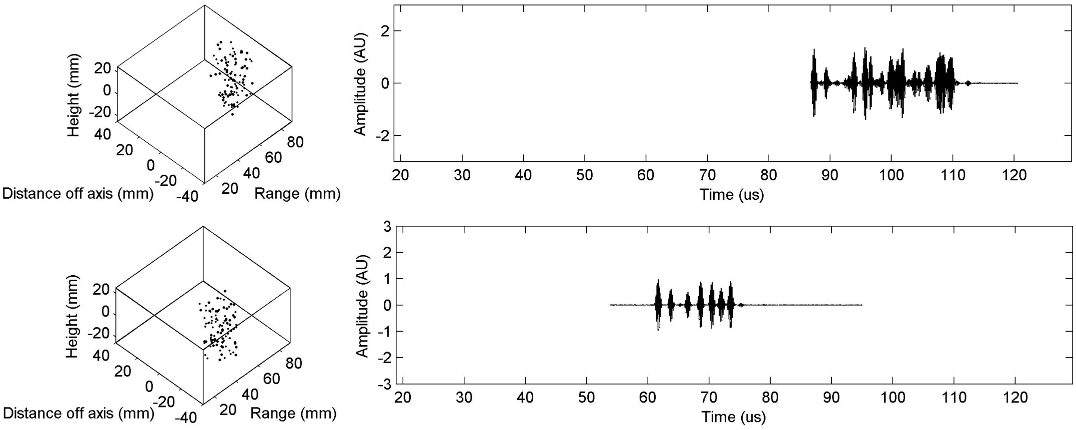

Figure 4. Simulated signal samples corresponding to a distance off axis equal to 0 mm and range from source equal to 75 mm (upper image); and a distance off axis equal to -20 mm and range from source equal to 50 mm (lower image).

was simulated for each position in the grid. The corresponding temporal mean energy average is calculated and plotted in a dB color scale. This histogram is presented in Figure 5, showing that is reasonable to consider a straight zone centered with the transducer axis. This zone correspond to a equally distributed backscatter energy response and should be considered in the experimental test.

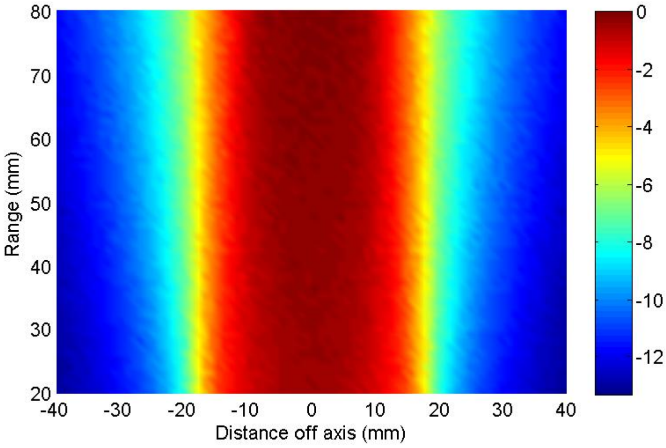

Figure 5. Entire region V_c simulated histogram scanned in a 1 mm grid.

Another analysis was conducted to establish the relationship among the temporal averaged mean energy and the volume ratio between the solid particle and liquid media. This analysis considered a variable particle flux for a single subregion location center. The subregion used was the same cylinder V_c. The region V_p center was chosen corresponding to a distance off axis equal to 0 mm and range from the source equal to 50 mm. The simulations were carried out considering a volume ratio linear variation ranging from 200 ppm to 1000 ppm in steps of 200 ppm.

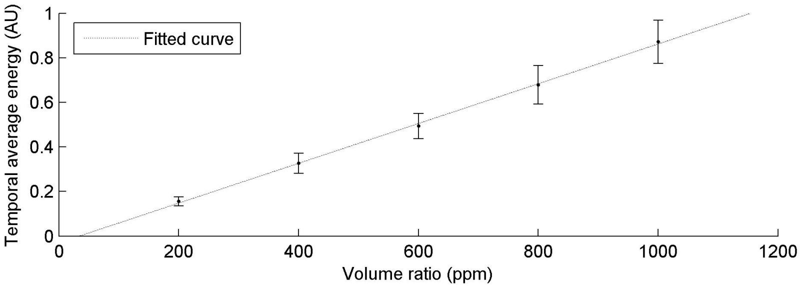

Figure 6. Simulated correlation.

Figure 6 shows that the averaged mean energy vary linearly with the volume ratio. This result also provide a relationship between the particle mass flux since the solid density is considered constant. One should notice that the energy is also accounted in arbitrary unit. So, it is not convenient to compare quantitatively this result with any experimental data. The error bars represent the standard deviation of a 200 ensemble of scatterers time series. From the Fig. 6 we can consider reasonable to find a relationship in experimental data like:

$$E_{rms}^2 = KM + R \tag{10}$$

where E_{rms}^2 represents the backscatter signal mean energy, K an empirical coefficient for a given experimental set up, M the suspended solid particles fraction in liquid media and R could be considered the signal noise.

Therefore, in this paper it is chosen an empirical approach to the solid particle content measuring problem in liquid media.

3. EXPERIMENTAL PROCEDURES

A recent procedure (Moate and Thorne, 2009) for measuring the acoustic scattering in suspensions was used as the basis in the experimental procedures developed. The experimental apparatus tests was described including acoustic chamber, ultrasound transducers, acquisition equipment and experimental procedures. The acoustic parameters were used in terms of the mean square of the voltage produced by an ultrasound transducer, E_{rms}, acquired through single scattering with arbitrary distribution of spherical particle size.

3.1 Apparatus

The apparatus used in experimental test is shown schematically in Fig. 7. The experiments were carried out in a rectangular acoustic chamber. The chamber consisted of a (100x100x500mm) plexiglas structure with a superior vault and a centralized lateral hole. The ultrasonic transducer (Panametrics UT, Model V315-SU and V308-SU) with central frequencies ranging from 5 and 10 MHz, respectively, was placed to the chamber within the lateral hole with an o'ring sealed nylon glove. The measuring cell was filled with water at rest and a internal ϕ 28 mm stainless steel tube was placed vertically through the superior vault. The transducer axial symmetry axis was mounted perpendicular to the tube axis. The solid particles were released from the top inside the tube, falling into the water, passing through the transducer axis and settling down at the chamber bottom.

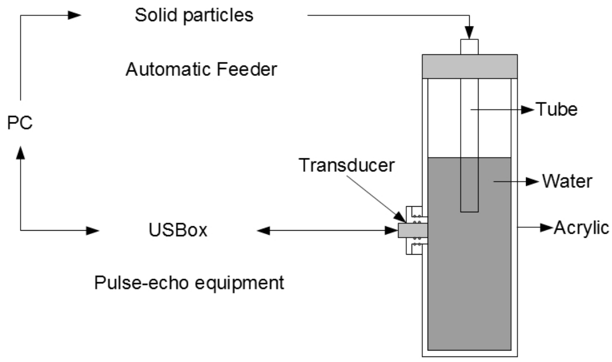

Figure 7. Measurement system of suspended solid content.

We developed an automatic feeder to dispense low concentration of particles at steady state. The feeder mechanism consist of a stepper motor assembly which is micro-controlled by a set of drivers. The automatic feeder was calibrated with an analytical balance. The solid particles fall into the acoustic chamber intersecting the transducer axial symmetry axis perpendicular to a vertical pipe.

The ultrasonic transducer was excited with a short pulse by a narrow pulse-echo equipment (Lecoeur Electronique model UT-SA-100). Upon excitation, a ultrasound wave was generated and propagated in the water containing sand particles falling by the effect of gravity. The backscattered wave returned to ultrasonic transducer and the received signal was amplified between 40 and 60 dB. The signal was stored in A-scan mode for further digital processing. These echo signals were post-processed and the backscattered acoustic energy were calculated and displayed on the PC screen.

4. MEASURED RESULTS AND DISCUSSION

The experiments were conducted using the apparatus illustrated in Fig. 7. All the results presented were obtained with solid sphere particles with diameters ranging from 100 to 200 μm. It was possible to control these particles flow rate from 2 to 10 mg/s during the test period with the automatic feeder device. The first set of experiments reproduce the early simulated results. A constant particle flow rate of 6 mg/s was fixed with the automatic feeder and the vertical tube

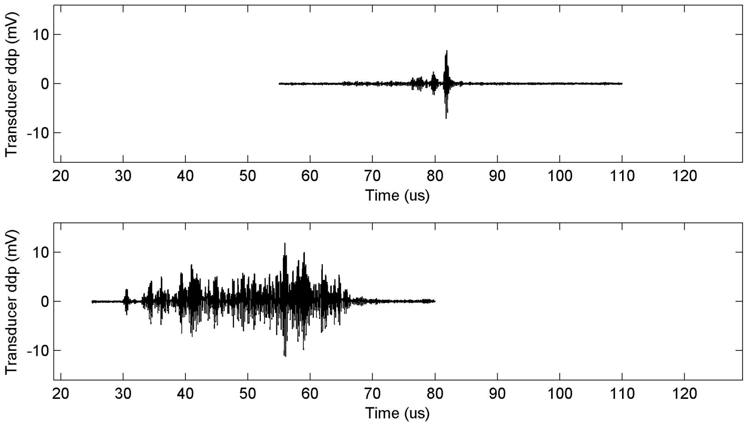

Figure 8. Samples of experimental signal corresponding to the same position as Fig. 3.

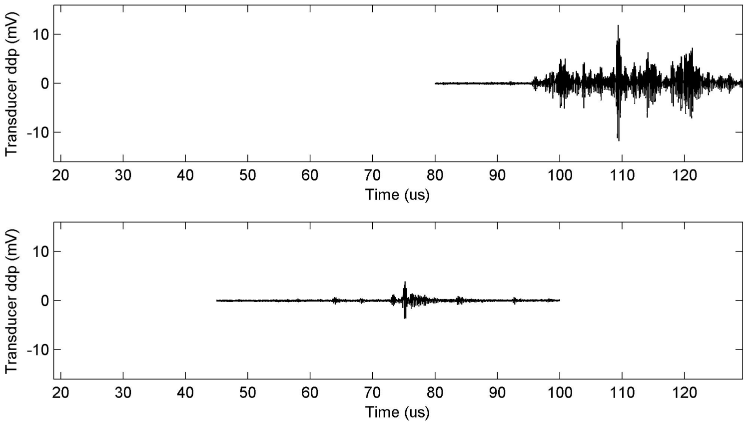

Figure 9. Experimental signal samples of corresponding to the same position as Fig. 4.

was placed in 9 different subregions inside the acoustic chamber. Figure 8 and Fig. 9 illustrate 4 received signal samples from the transducer. These results indicate that the experimental signals are in good agreement with the simulated ones. The different time of flight matched quiet well with the expected results. One should notice that the mean energy also represents the distance off axis if the particle flow rate is kept constant.

The same procedure explained previously were performed to generate a histogram. A mean energy temporal average were taken for each of the 9 cases and the corresponding results are illustrated in Fig. 10. The colored circles shown represents the approximately vertical tube center position. Colors indicates the averaged mean energy for each of these position. These results were also predicted from the numerical model as the superposed histogram indicates.

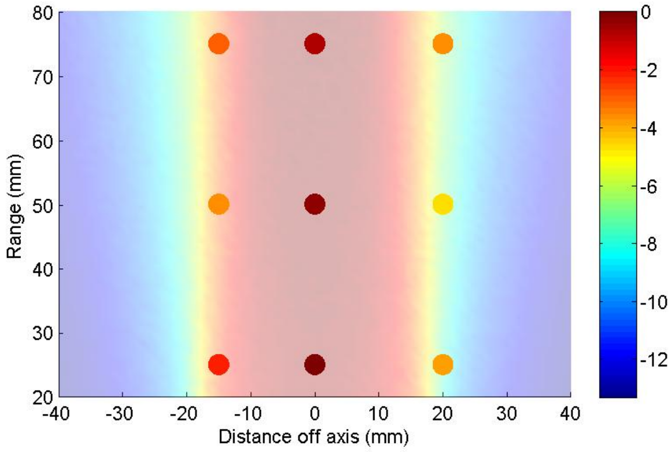

Figure 10. Experimental histogram.

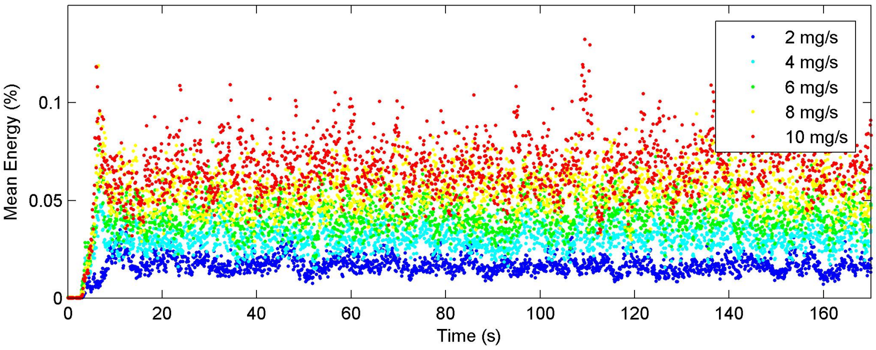

Figure 11. Backscattered energy temporal series (%) obtained from different flow rate ranging from 2 to 10 mg/s using a 10 MHz central frequency transducer

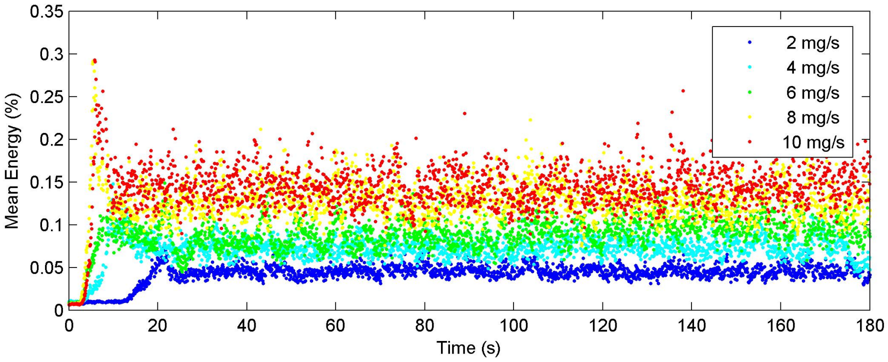

Figure 12. Backscattered energy temporal series (%) obtained from different flow rate ranging from 2 to 10 mg/s using a 5 MHz central frequency transducer

Experiments were conducted in order to analyze the backscattered signal mean energy for different particle flow rate. In this case, the energy was calculated by means of a certain quantity energy percentage. The reflected wave signal inside the acoustic chamber was used to calculate this percentage. A backscattered energy temporal series were monitored in 5 different set of test. Each one were performed with a flow rate ranging from 2 to 10 mg/s in steps of 2 mg/s. Figure 11 and Fig. 12 illustrates these different sets in the same plot using a 10 and 5 MHz transducer, respectively. The colored dots indicates the instant mean energy during the test period. The particle initial flow dynamics inside the acoustic chamber is indicated at beginning of the graphic. The initial low energy was accounted as background noise and the constant energy level (after the first 20 s) was accounted for the temporal averaged energy calculation. The energy dispersion during the test period is shown in these figures. Nevertheless, the average energy should predict the mass flow as illustrated in Fig. 13. This figure shows the results obtained experimentally and reproduce well the correlation simulated results.

Equation 10 could be used to calibrate this measuring cell. Thus, it is demonstrated that there are theoretical and experimental basis for the development of a in liquid meda solid particle content meter of from the backscattered acoustic energy (Silva, 2010).

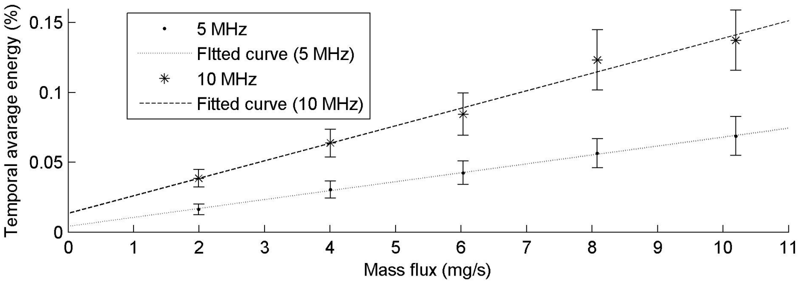

Figure 13. Experimental correlation

5. CONCLUSIONS

Laboratory tests with the measuring cell shown that there is a good correlation between the sand amount and backscattered acoustic energy. We developed a micro-controlled automatic feeder that is calibrated with an analytical balance to operate in the range 2 to 10 mg/s producing a mixture in water from 200 to 1000 ppm. Tests using the automatic feeder with solid particle continuous flow reproduced well the results expected from the methodology adopted. We developed a model of backscattering theory based on the piston plane impulse response. The results from this simplified model showed the same correlation between the sand amount and backscattered acoustic energy. For future work, it is suggested a study to obtain the backscattered signal sensitivity with the solid particle size. The cell application for sand content in oil field measurement, replacing the system of sieves. The improvement of backscattering model based on the piston plane impulse response theory.

6. ACKNOWLEDGEMENTS

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