Improvement of the acoustical characterization of suspended particles in wastewater

Philippe SCHMITT[1], Anne PALLARES[1], Marie-Noëlle PONS[2]
[1]Institut de Mécanique des Fluides et des Solides, Université de Strasbourg,

2, rue Boussingault, F-67000 Strasbourg, France

[2] Laboratoire Réactions et Génie des Procédés - CNRS, UP3349, Université de Lorraine, INPL

1, rue Grandville, BP 20451, F-54001 Nancy cedex, France

The interpretation of acoustic measurements in wastewater has to come up against the huge variety of encountered particles. Previous work showed that a good representative of the organic fraction is potato starch. Thus, this work focuses on the acoustical characterization of potato starch in order to evaluate acoustically its concentration and particle size distribution. The theoretical aspects and a methodology for the determination of the averaged form function <*f*> and the normalized total scattering cross section χ_m are given for potato starch suspension. The final aim of this work is an identification method of the particle size distribution in wastewater.

Keywords: Acoustic, suspended particles, scattering

1 INTRODUCTION

Over the past two decades the understanding of small scale sediment transport processes has strongly increased with the use of acoustic instrumentation. This technology was first used by the sedimentological community because of its potential to measure non-intrusively, with high temporal and spatial resolution, the velocity, size and concentration profiles of sediments over the seabed [1]. It also allows the mapping of the bedform morphology. Indeed, the use of multi-frequency Acoustic Backscattering Systems (ABS) allows the measurement of particle size and concentration over sandy beds. These systems typically operate at frequencies in the range 0.5 – 5MHz, which fits with the sand particles diameter, and in transceiver mode, which permits the measurement of the backscattering and attenuation characteristics of the suspended sediments.

Our application, urban wastewater, is a complex medium mixing mineral and organic elements with variable characteristics. Within the common particles found in wastewater, only the sands have been exhaustively studied by acoustics. A recent study [2] showed that the percentage of organic matter varies with the type of wastewater and can reach routinely 50%. Preliminary work on various materials like paper pulp, loess, garden earth, soups and excrements was already carried out. It showed that none of these materials has an identical behavior to sand.

Some aspects of our previous work [3] focused on the suspended solids standard characterization. After the evaluation of the composition of standard wastewaters in terms of total suspended solids (TSS), amount and nature, we tried to define stable representative compounds of wastewater. Different kind of starches were studied (corn, wheat, rice, potato), to represent the organic fraction in wastewater. Potato starch was found to be a good candidate.

The aim of the present work focuses on the acoustical characterization of potato starch in order to evaluate its concentration and particle size distribution. The general principle of the method will be presented, as well as some measurement results. The goal of this approach is to develop an identification methodology in order to establish a suspended particle size distribution in an unknown fluid mixture.

2 BACKGROUND SCATTERING THEORY

2.1 Incoherent backscattering

In a medium insonified by a piston transceiver, if we assume that the attenuation over a bin range is not substantial [4] and that the phase of the backscattered signal from the suspended particles is randomly distributed between 0 and 2π, then the recorded root-mean-square backscattered voltage can be written [1] at a range r as follows:

$$V_{rms} = \frac{k_s k_t}{r\psi} M^{1/2} e^{-2\alpha r} \quad (1)$$

with

$$k_t = R T_v P_0 r_0 \left\{\frac{3\pi c}{16}\right\}^{1/2} \frac{0{,}96}{k a_t} \quad (2)$$

$$k_s = \frac{\langle f \rangle}{\left(\rho_s \langle a_s \rangle\right)^{1/2}} \quad (3)$$

$$\alpha = \alpha_w + \alpha_s = \alpha_w + \frac{3}{4\rho_s r}\int_0^r \frac{\chi_m}{\langle a_s \rangle} M(r')dr' \quad (4)$$

V_{rms} is an average over a number of backscattered returns. An individual backscattered signal is Rayleigh distributed.

k_t is an acquisition system constant for a given setting. P_0 is the reference pressure, normally defined at $r_0=1m$, R is the receiver sensitivity, T_v is the voltage transfer function of the system, τ is the pulse duration, c is the velocity of sound in water, k is the wavenumber for sound in water ($k=2\pi/\lambda$, λ is the wavelength of sound in water), and a_t is the radius of the transducer.

k_s represents the sediment backscattered properties, with $<f>$ the averaged form function which describes the backscattering characteristics of the particles, ρ_s the sediment density, $<a_s>$ the mean particle radius.

ψ stands for the near field correction, M is the sediment concentration, α_w is attenuation due to the water absorption and α_s is the sediment attenuation mainly due to scattering for noncohesive particles insonified at megahertz frequencies ultrasound.

As shown, α_s is related to the normalized total scattering cross-section χ_m.

2.2 Form function and scattering cross-section

The averaged form function $<f>$ and the normalized total scattering cross-section χ_m characterize the behavior of an insonified particle in a fluid. The form function is used to describe the intrinsic scattering properties of an element. The normalized scattering cross-section is related to the sound attenuating properties of particles in a suspension [5].

The behavior of this two functions are well-describe by the variable $x = k<a_s>$, which is the ratio between the particle circumference and the wavelength of the sound in water. There are no general solutions for the scattering behavior of irregular shaped particles, but some estimates can be made for the asymptotes.

For $x \ll 1$, the so-called Rayleigh regime, the wavelength of sound is much greater than the particle circumference and thus the scattering is considered to be independent of the particle shape. Thereby, the Rayleigh scattering for a sphere can be kept and this implies that $<f> \propto x^2$ and $\chi_m \propto x^4$. For $x \gg 1$, the geometric regime, the wavelength of sound is smaller than the particle circumference, and the scattering cross-section is directly related to the particle's geometry. In this case, for a rigid sphere, $<f>$ and χ_m tend to a constant value of unity. For irregularly shaped particles $<f>$ and χ_m will tend to a constant value slightly greater than unity.

2.3 Analysis in homogenous solutions

Eq.(1) can be rewritten under its logarithmic form:

$$\ln(V_{rms} r \psi) = \ln\left(k_t \langle f \rangle \sqrt{\frac{M}{\rho_s \langle a_s \rangle}} \right) - 2r\left(\alpha_w + \frac{3\chi_m M}{4\rho_s \langle a_s \rangle} \right) \tag{5}$$

For a homogeneous suspension (for which the concentration won't vary with the range), this becomes a linear equation in $\ln(Vr\psi)$ and r, and we obtain:

$$\eta = \ln\left(k_t \langle f \rangle \sqrt{\frac{M}{\rho_s \langle a_s \rangle}} \right) \tag{6a}$$

$$\kappa = 2(\alpha_w + \alpha_s) = 2\left(\alpha_w + \frac{3\chi_m M}{4\rho_s \langle a_s \rangle} \right) \tag{6b}$$

where η and κ are respectively the intercept and the slope obtained from the measurements as expressed in Eq.(5). This allows the characterization of the behavior of an insonified particle by specifying its form function $<f>$ and its normalized total scattering cross-section χ_m.

3 PARTICLE CHARACTERISTICS

The present study focuses on the acoustical characterization of potato starch in order to evaluate its concentration and particle size distribution. Concerning its density, the literature on the subject seems quite concordant and gives a density of potato starch ranging from 1.53 to 1.552.

A density measurement of the used potato starch (S4251, Sigma-Aldrich) was also performed and gave a coherent result:

$$\rho = \frac{m}{V} = 1{,}470 \pm 0{,}087 g/ml = 1470 kg/m^3$$

The dimension and the shape of the potato starch has been studied optically (figure 1). Its size distribution was also determined using a Malvern Mastersizer 2000 (figure 2).

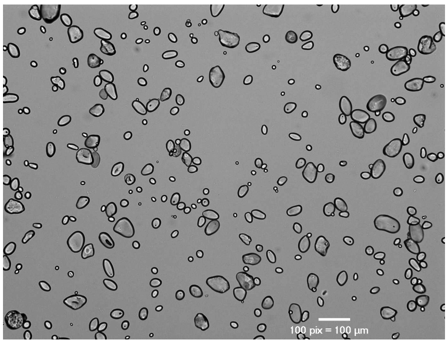

Figure 1: Optical microscopy view of potato starch

One can see that potato starch has wide spread shapes and sizes. However the mean observed size is around 50 µm with particle size ranging from 24 to 80 µm. Knowing that the particle sizes of less than a few microns are invisible at the used ultrasonic frequencies, we can assimilate these samples of potato starch to an unimodal distribution with a mean value of $<a_s>\sim 24\mu m$.

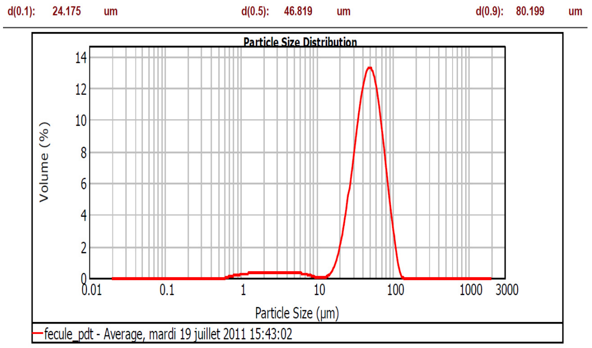

Figure 2: Laser diffraction potato starch size distribution

4 MEASUREMENTS AND ANALYSIS

4.1 Measurement bench

All measurements on potato starch were performed at room temperature in a *50 L* water tank (figure 3). The suspension of the starch was obtained by continuous stirring with a propeller whose frequency was adjusted to insure homogeneous slurry.

Figure 3: Water tank and instrumentation

The measurements were performed with an UB-Lab system and several stand-alone transducers allowing measurements at different frequencies growing from 600kHz up to 7,5MHz. Care was taken on the pulse repetition frequency adjustment in order to allow the sound from one emission/reception cycle to dissipate before the following cycle. A temperature sensor completes the test-bench in order to compensate temperature effects.

4.2 Potato behavior

For all the measurements, a common procedure was applied. The tank was filled with water from the main supply, and the propeller was activated during a period of several hours in order to allow the air bubbles to leave the water. This procedure was monitored and lasted until the signals recorded by the instrument reduced to background levels. Water-saturated potato starch was then added at a concentration of 1,3g/l and, after homogenization of the suspension, a run of five hundred profiles was realized, each one composed of two hundred samples. This procedure was applied for every used ultrasound frequency utilized. An example of the raw data collected by the instrument is presented in figure 4.

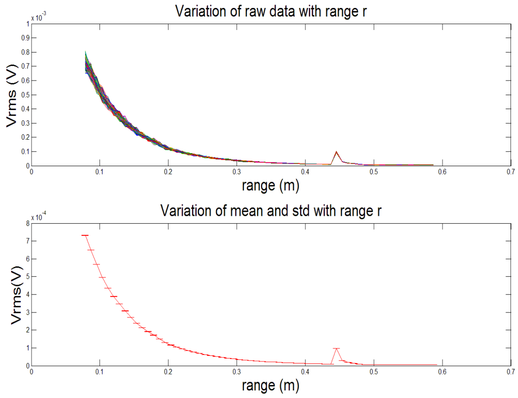

Figure 4: Raw data, mean and standard deviation on measurements on potato starch

The peak at ~45 cm corresponds to the inner wall of the tank.

4.3 Scattering cross-section extrapolation

The UB-Lab instrument was used to carry out the measurements at different frequencies. To obtain the information about the form function and the total scattering cross section, the expressions in Eqs. (6a&b) were used. Figure 5 show an example of analyzed data, it shows the variation of *ln(Vrψ)* as a function of the range *r* from the transducer. Note that the analyzed data correspond to a measurement zone situated between the end of near field and the echoes of the inner wall of the tank.

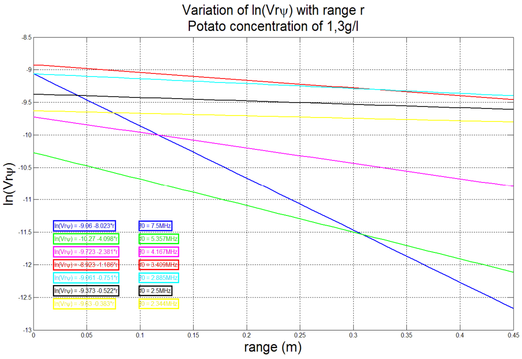

Figure 5: Graphical display of Eq. (5) for several frequencies generated by the UB-Lab

One can see in Eq.(6b) that the attenuation is directly and exclusively related on the suspension characteristics. The water attenuation reliance on temperature and ultrasound frequency is well-known [6]. Considering that the potato starch density, its mean size and its concentration are well-known in our tank, we can evaluate the normalized total scattering cross-section χ_m at different ultrasound frequencies. Tab. 1 shows the normalized total scattering cross-section χ_m obtained from the measurements as a function of the variable $x = k\langle a_s\rangle$. The frequencies available on the UB-Lab allow only measurements in the Rayleigh regime and in a part of the intermediate regime for the potato starch. It should be noted that for small values of x, nominally $x \ll 1$, the value for χ_m might have a high degree of uncertainty because in this case $\kappa \approx 2\alpha_w$. Nevertheless, several measurements were done on frequencies between *3,125MHz* and *7,5MHz* and show a small dispersion of *2* to *4 %*.

Table 1: Normalized total scattering cross-section χ_m and variable $x = k\langle a_s\rangle$ as a function of the UB-Lab ultrasound frequencies.

Frequency (MHz)	$k\langle a_s\rangle$	χ_m
7,5	0,764	0,0993
5,357	0,545	0,0506
4,167	0,424	0,0291
3,409	0,347	0,01179
3,125	0,318	0,008795
2,885	0,294	0,006842
2,500	0,255	0,004321
2,344	0,239	0,002369

Figure 6 show a fit of the points of χ_m from Tab. 1.

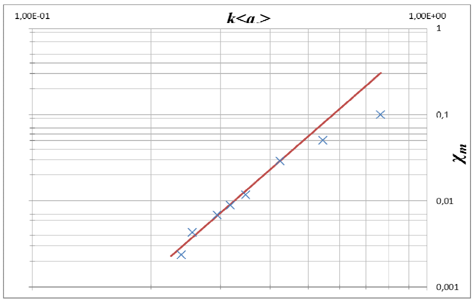

Figure 6: Graphical display of χ_m versus $k\langle a\rangle$ in the Rayleigh regime

The data show a constant increase in magnitude of χ_m with x, as expected. The fit allows the extraction of the dependence of χ_m with x and gives:

$$\chi_m = 0{,}85\left(k\langle a_s\rangle\right)^4 \tag{7}$$

This result shows that for $x \ll 1$, the Rayleigh regime, the measurements are in close agreement with the theoretical description, which predict reliance in $\left(k\langle a_s\rangle\right)^4$. The slope coefficient is higher than the one of the sand, which is close to 0,26. A reason can be that for a given concentration, the density and the radius of potato starch particles are smaller than for sand, and imply that there are much more particles. Currently, the evaluation of the form function is not possible because this needs a complete system calibration for every used frequency. However this work is on the run.

4.4 Concentration measurements

In order to evaluate the possibility of measuring particle concentrations with the UB-Lab instrument in this configuration, several experiences where carried out with various starch concentrations. Figure 7 shows the analyzed data which allows the estimation of χ_m for every concentration. A difference of less than *2%* was notice between the measured and expected values.

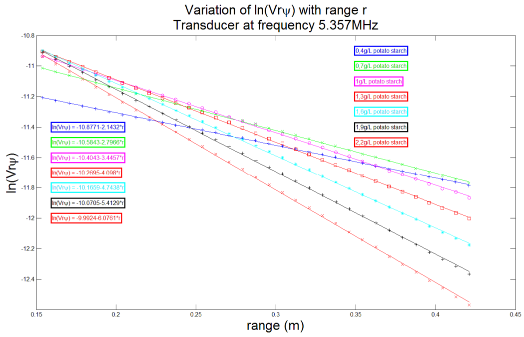

Figure 7: Analyzed data's of ultrasound measurements for different starch concentrations.

6 SUMMARY

The present study focused on the examination of the scattering properties of suspension of potato starch. It is a part of a larger work which includes the evaluation of $\langle f\rangle$ and χ_m in both Rayleigh and geometric regimes, and this for different test particles. This can then allow the possibility to classify suspensions in particle sizes by classes by the use of several different ultrasound frequencies.

Nevertheless, the current state of our work allows the measurement of the particle size or concentration. If one of these two parameters and density is known, this method can even bring knowledge on the concentration gradient in an unhomogeneous suspensions.

7 ACKNOWLEDGEMENT

This work was partly supported by GEMCEA, Groupement pour l'Evaluation des Mesures en Continu dans les Eaux et en Assainissement, France.

REFERENCES

[1] Thorne P.D., Hanes D.M.: A review of acoustic measurement of small-scale sediment processes, Cont. Shelf Res. 22 (2002), 603-632.

[2] Sophonsiri C., Morgenroth E.: Chemical composition associated with different particle size fractions in municipal, industrial, & agricultural wastewaters, Chemosphere 55 (2004), 691.

[3] Schmitt P. et al.: Suspended particles in wastewater: acoustical characterization and modeling, ISUD7 Proceedings (2010), 43-46.

[4] Hay A.E.: Sound scattering from a particle-laden, turbulent jet, J. Acoust. Soc. Am. 90 (1991), 2055-2074.

[5] Thorne P.D., Meral R.: Formulations for the scattering properties of suspended sandy sediments for use in the application of acoustics to sediment transport processes, Cont. Shelf Res. 28 (2008), 309-317.

[6] Admiraal D.M., Garcia M.H.: Laboratory measurement of suspended sediment concentration using an Acoustic Concentration Profiler (ACP), Experiments in Fluids 28 (2000), 116-127.