Acoustics for the monitoring and the characterization of suspended solids

L'acoustique pour le suivi et la caractérisation de Matière En Suspension

A. Pallarès*, X. France** , M.N. Pons***, and P. Schmitt*

*Institut de Mécanique des Fluides et des Solides, Université de Strasbourg, 2, rue Boussingault, 67000 Strasbourg, France
Email : anne.pallares@unistra.fr, pschmitt@unistra.fr
** GEMCEA, 149, rue Gabriel Péri, 54500, Vandoeuvre-les-Nancy
E-mail: xavier.france@gemcea.u-nancy.fr
*** Laboratoire Réactions et Génie des Procédés - CNRS, UP 3349, Université de Lorraine , INPL, 1, rue Grandville, BP 20451, F-54001 Nancy cedex, France
Email : marie-noelle.pons@univ-lorraine.fr

RÉSUMÉ

Les potentialités de la mesure acoustique ne sont actuellement pas suffisamment exploitées dans le cadre de la surveillance des rejets urbains. La décomposition du signal acoustique montre que la turbidité acoustique est sensible à la nature des particules en suspension et à leurs concentrations.

Ainsi des caractéristiques acoustiques (fonction de forme et section efficace totale de diffusion) relatives à chaque type de particule peuvent être mesurées et permettre l'estimation de concentrations.

Le suivi temporel de l'évolution de la turbidité acoustique offre également une alternative aux méthodes conventionnelles de mesure de vitesse de chute.

Des résultats expérimentaux sur des matériaux témoins et des effluents réels confirment ces possibilités.

ABSTRACT

The potential of the acoustic measurement is currently not sufficiently exploited in the context of the monitoring of urban wastewater. The decomposition of the acoustic signal indicates that the acoustic turbidity is sensitive to the nature of the suspended particles and their concentrations.

So the acoustic characteristics (form function and total cross section of scattering) can be measured for each type of particle and allow the estimation of concentrations.

The time tracking of changes in the acoustic turbidity also offers an alternative to conventional methods for measuring settling velocity.

Experimental results on reference materials and real effluents confirm these possibilities.

MOTS CLES

Acoustic, Backscattering, Settling velocity, Suspended solids, Particle, Ultrasound

1 INTRODUCTION

Stormwater runoff has a major role in the pollution of receiving waters. Unfortunately, only few supervision techniques (Vanrolleghem et al. 2003) provide real time data. This paper focuses on the opppotunities offered by acoustic monitoring in terms of qualitative and quantitative characterization of stormwater discharges in urban drainage. As will be shown, the information provided by an acoustic flowmeter, a gauging device commonly used in urban hydrology (Joannis, 2001) can be used to evaluate the proportion of suspended particles in the flow and some of their characteristics. The analysis of the backscattered signal leads to the particle acoustical characteristics which can be used to approach the particle concentration. It is also shown that the time evolution of the backscattered signal in a settling column gives easy and quick access to settling velocities. The settling velocity is also an indirect reflection of the Total Suspended Solids (TSS) composition and concentration.

However, urban wastewater is a highly complex medium containing mineral and organic elements in various proportions and with variable characteristics. Within the common particles found in wastewater, only the sands have been exhaustively studied by acoustics (Thorne et al., 2002). According to a recent study (Sophonsiri et al., 2004), the percentage of organic matter varies with the type of wastewater and can routinely reach 50%. Thus, more investigation on the organic fraction of urban drainage water is needed.

A stable surrogate of the organic fraction in wastewater was found to be potato starch (Pallarès et al. 2011). Laboratory quality potato starch is used as a model for the tuning of our measurements. Some experimentation on real wastewater is also proposed.

2 ULTRASOUND BACKSCATTERING THEORY

Acoustic flowmeters work on the Doppler principle. In the beginning of a measurement cycle, an ultrasonic burst of given frequency and duration is emitted into the medium. At the end of the emission, the instrument switches in reception mode. The emitted signal travels along the emission axe and each encountered particle partly backscatters the acoustic wave. If the particle is moving in the medium, a frequency shift is observed in the backscattered wave (so-called Doppler shift). This assumes that the velocity of the suspended particles is equal to the flow velocity.

2.1 Pulsed ultrasound principle

All instruments working on the pulsed principle can potentially provide measurement profiles. Their working principle allows the precise knowledge of the position in the flow of a given data at a given time stamp. Periodically, an ultrasonic pulse is emitted in the medium. This signal is backscattered by the particles suspended in the flow.

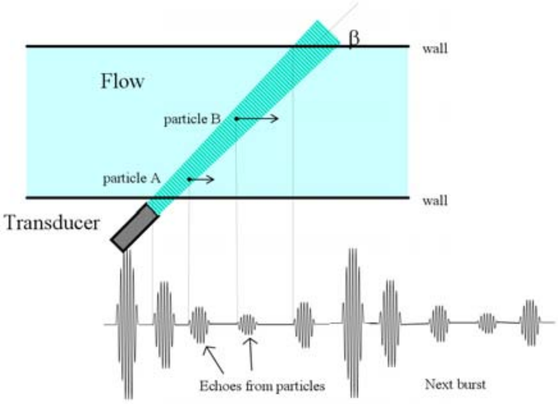

Figure 1 : Pulsed ultrasound principle.

In the same time, due to thermal conduction and viscosity effects, the intensity of the ultrasonic wave propagating in a homogeneous medium decreases. In particle laden flows, an additional attenuation due to scattering and absorption by the particles themselves contribute to the intensity decay. Received by the transducer, the backscattered signal is finally conditioned, amplified and sampled in order to extract the information.

2.2 Incoherent backscattering

On the theoretical point of view, for an acoustic flowmeter, the recorded root-mean-square of the backscattered voltage can be written (Thorne et al., 2002) at range *r* as follows:

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

where

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

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

V_{rms} is an average value over a large number of backscattered receptions. k_t is a acquisition system constant for a given instrument working at a given frequency. ψ stands for the near field correction, M is the particle concentration, α_w is attenuation due to the water absorption and α_s is the particle attenuation mainly due to scattering for non cohesive particles insonified at megahertz frequencies ultrasound. As shown, α_s is related to the normalized total scattering cross-section χ_m of the particle.

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

Thus, the backscattered signal directly includes information about the particle encountered in the explored medium. With adequate analysis, different elements concerning the nature and the concentration of the particles can be extrapolated. If the particles in the medium are well known, in terms of shape, size and density, their acoustic characteristics can be determined. If the content of the flow is unknown, only a qualitative interpretation can be made as the relative behaviour of the total suspended solids (TSS) concentration for example.

2.3 Acoustic characteristics of particles

The averaged form function <*f*> and the normalized total scattering cross-section χ_m are the acoustic signature of a particle in a fluid. The form function is used to describe the intrinsic scattering properties of an element. The normalized total scattering cross-section refers to the sound attenuating properties of particles in a suspension (Thorne et al., 2008).

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

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

For a homogeneous suspension, this becomes a linear equation in ln($Vr\psi$) and *r*, and one can write:

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

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

where η and κ are respectively the intercept and the slope obtained from the measurements as expressed in Eq.(2).

This allows the characterization of the behaviour of an insonified particle by specifying its form function <*f*> and its normalized total scattering cross-section χ_m. Knowing these parameters, the particle concentration can easily be deduced from the backscattered signal. Even if the accurate composition of the medium is not known, the backscattered signal is proportional to the particle concentration.

Thus, if the composition of the medium remains constant, the relative evolution of the backscattered signal is directly the same as observed for the TSS concentration. This concept is used for the settling velocity measurements.

2.4 Settling behaviour of particles

A well known standard for the measurements of the distributions of suspended solid settling velocities within urban drainage wastewater is the VICAS protocol (VItesse de Chute en ASsainissement) developed and validated by the CEREVE (Chebbo et al. 2009). This procedure is rather simple but requires however more than 12 hours of measurement and additional time for the sample analysis.

As mentioned above, the same principle of concentration variation as a function of time (Chebbo et al. 2003) can be observed through the time evolution of the backscattered voltage. After defining an observation window along the beam axe and knowing the time stamp of each measurement, a direct estimation of the fraction of particles with a settling velocity smaller as a given value is possible.

From its initial value I_0, the signal decreases gradually as the particles leave the exploration area. The particles leaving this area have a settling velocity V_s which is greater than H/t where H is the vertical path they travel. After some time, all particles will have settled and the signal will returns to noise value in the measuring window. The cumulative fraction of particles $F(V_s)$ having a settling velocity less than or equal to V_s is therefore given by:

$$F(V_s) = 100\frac{I_i}{I_0}$$

where I_0 is the backscattered signal at $t = 0$ and I_i the signal at time $t = i$. Knowing the cell length, H will be obtained by multiplying the inter-cell distance by the numbers of cells in the measurement window.

3 MATERIAL AND METHODS

3.1 Instrumentation

The UB-Lab profiler (Ubertone , Strasbourg, France) has three functionalities: it allows the recording of a flow velocity profile, the measurement of the acoustic turbidity (also known as backscattered signal amplitude) and the determination of a flow water height. It consists of a small case containing the electronics and the calculation platform. Up to two transducers on a large frequency range (from 700 kHz to 7.5 MHz) can be plugged on the instrument and used simultaneously.

The device is configured through a dynamic web interface. Multiple settings are possible. The emission frequency and the pulse repetition frequency can be manually adjusted. The cell depth, the number of cells and the inter-cell distance are adjusted by the user. Also the number of samples used in a cell to evaluate the velocity and the amplitude value is fixed by the user. Gain is manually fixed or automatically adjusted.

3.2 Acoustical characteristics of particles

All measurements on potato starch (sigma Aldrich, St-Quentin-Fallavier, France) are performed at room temperature in a 50 L steel tank (figure 2). The suspension of the starch was obtained by continuous stirring with a propeller whose frequency was adjusted to insure homogeneous slurry. For all the measurements, a common procedure is applied. The tank is filled with water from the main supply, and the propeller is activated during a period of several hours in order to allow the water to degas. This procedure is monitored and continued until the signals recorded by the instrument reduced to background levels. The compounds to analyze are added after the water degassing.

Figure 2 : Water tank and instrumentation.

3.3 Settling behaviour of particles

We use various graduated cylinders made out PMMA as settling columns (from 2 to 10 L). The suspension to be analysed was simply poured in the column after having been homogenized. In regard to the configuration of the instrument for settling studies, experience shows that a minimal length of 0.1m should be covered by adjacent cells in order to get significant and reproductible data. The acoustical data recording begins before the transducer is immerged in the liquid. The backscattered signal in air is close to the noise of the system. When the transducer is immobilized just below the water surface, immediately after the suspension has been poured in the settling column, the signal increases and thus signs the measurement beginning time. The data is then recorded until reaching the expected noise value which takes one to two hours depending on the explored medium and the used frequency.

Figure 3 : Settling column filled with wastewater and the ultrasonic transducer on top.

4 EXPERIMENTAL RESULTS

4.1 Potato starch

4.1.1 Acoustical characteristics of potato starch

The suspension of potato starch is added to the water in the tank at known concentrations and the backscattered signal is collected for different ultrasound frequencies. An example of the raw data collected by the instrument is given figure 4 a).

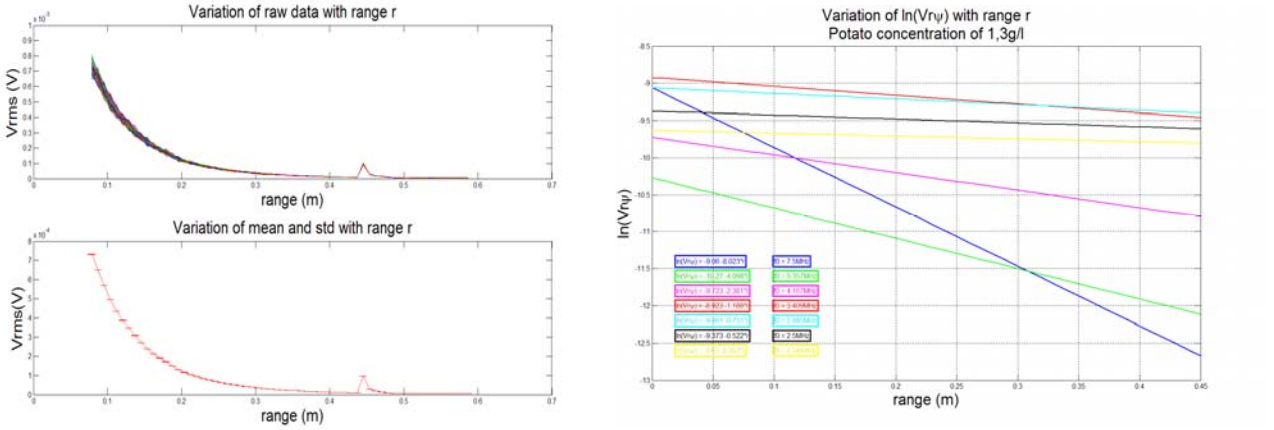

Figure 4 : a) Raw data, mean and standard deviation on measurements on potato starch, b) Graphical display of Eq. (2) for several frequencies.

One can see in Eq.(2) that the attenuation is directly and exclusively related on the suspension characteristics. The water attenuation reliance on the temperature and ultrasound frequency is well-known (Admiraal and al., 2000). Figure 4 b) shows the linear range dependence of equation (2) and the increase of the attenuation with frequency.

Considering that the potato starch density, its mean size and its concentration are well-known, it is possible to evaluate the normalized total scattering cross-section χ_m at different ultrasound frequencies. Figure 5 shows the normalized total scattering cross-section χ_m obtained from the measurements as a function of the variable $x = k\langle a_s \rangle$ where $k=2\pi/\lambda$, λ is the wavelength of sound in water. The data show a constant increase in magnitude of χ_m with x, as expected by theory. The fit allows the extraction of the dependence of χ_m with x and gives:

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

This result shows that for $x \ll 1$, the Rayleigh regime, the measurements are in close agreement with the theoretical description, which predict a reliance in x^4.

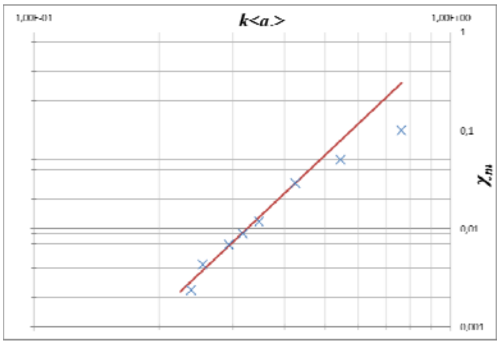

Figure 5 : Evolution of X_m as a function of x.

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 underway.

In order to evaluate the possibility of measuring particle concentrations with the UB-Lab instrument in this configuration, several experiences were carried out. By inversion of the backscattering data, the potato starch concentration was extrapolated: a difference of less than 2% was observed between the measured and expected values.

Considering the results obtained for a well known particle type, it is quite impossible to have an identical approach for stormwater runoff. However, the acoustic characteristics of rainwater particles, mostly mineral, differ from the dry weather ones. Thus, the monitoring of the backscattered signal could be used as a rain event indicator. Also, after a site calibration, the backscattered acoustic signal could provide the total suspended solids concentration as currently done with turbidity meters (Langeveld et al. 2012).

4.1.2 Settling behaviour of potato starch

The settling velocity of potato starch has been measured by the VICAS protocol and also acoustically. The global trend of the settling velocity of potato starch is quite identical by the two methods. As shown on figure 6, a very good quantitative agreement is observed between the acoustical and the VICAS determined settling velocities, with differences less than 10%, are observed for velocities above 0.3 mm/s. Below, values can differ up to 50%.

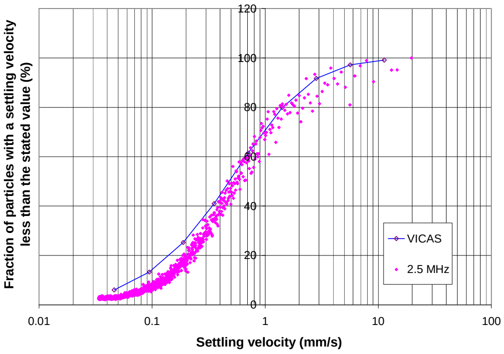

Figure 6 : Fraction of potato starch particles with settling velocity less than the stated value as a function of settling velocity.

4.2 Urban drainage

Only settling velocity measurements have been made on wastewater. As it can be seen on figure 7, again a good correlation of the evolution of the settling velocity behaviour between the VICAS measurement and the acoustic measurement at 2.5 MHz is obtained. As shown by theory, at this frequency the major contribution in the backscattering signal is due to particles with a diameter close to 190 µm. Anyhow, for a given settling velocity, the value of the fraction of particles having a settling velocity less than this value is systematically smaller when observed through ultrasound with respect to the one given by the VICAS protocol.

The settling velocity extrapolated from the 7.5 MHz observation shows a quite different trend which should mainly concern particles with a diameter around 60 µm. It shows that 50% of the particle population has a settling velocity below 1 mm/s. Also a large fraction, 30%, has a settling velocity below 0.01 mm/s which is coherent with the small particle size.

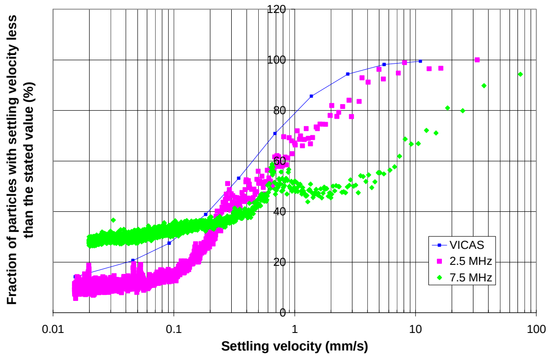

Figure 7 : Fraction of wastewater particles with settling velocity less than the stated value as a function of settling velocity.

An insonation at higher frequencies, 7.5 MHz, seems to reflect the behaviour of smaller particles. Its major advantage is the execution speed, as the settling velocity values will be available immediately after the measurement which itself lasts only one to two hours.

5 CONCLUSIONS

The aim of this paper was to demonstrate the possible use of acoustics for stormwater studies. The experimental results show promising monitoring and discriminating facilities through the use of the backscattered signal amplitude provided by an acoustic flowmeter.

The TSS concentration could easily be monitored through acoustic turbidity. As sensitive to the nature of the particle, the acoustic turbidity could also be a storm event indicator on a given site.

It has also been shown that settling velocities could be easily obtained through the time evolution of the acoustic turbidity.

Complementary studies are under progress, both on characterization and settling aspects, to refine the influence of the particle size in the acoustic turbidity of a given frequency.

Ultrasound measurements might become a simple, quite real time, tool in urban drainage.

ACKNOWLEDGEMENT

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

LIST OF REFERENCES

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

Chebbo G., Gromaire M.-C., Lucas E. (2003). *Protocole VICAS : mesure de la vitesse de chute de MES dans les effluents urbains*. TSM, 12, 39-49.

Chebbo G. and Gromaire M-C. (2009). *VICAS—An Operating Protocol to Measure the Distributions of Suspended Solid Settling Velocities within Urban Drainage Samples*, J. Envir. Eng. 135, pp. 768-775.

De Clercq B., Kinnear D.J. and Vanrolleghem P.A. (2002). *On-line dynamic fluid velocity profiling in secondary clarifiers*. Proceedings of AutMoNet2002, 281.

Joannis C., (2001). *La mesure de débits en assainissement*, La Houille Blanche, 2001-5, pp. 58-62.

Langeveld, J.G., Liefting H.J., Boogaard F.C. (2012). *Uncertainties of stormwater characteristics and removal rates of stormwater treatment facilities: Implications for stormwater handling*, Water Research, in press.

Pallarès A., François P., Pons M-N. and Schmitt P. (2011) *Suspended particles in wastewater: their optical, sedimentation and acoustical characterization and modelling*, Wat. Sci. & Technol., 63, pp 240–247.

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

Thorne P.D., Hanes D.M., (2002). *A review of acoustic measurement of small-scale sediment processes*. Continental Shelf Research, 22, 603-632.

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

Vanrolleghem P. A. and Lee D. S., (2003). *On-line monitoring equipment for wastewater treatment processes: state of the art*, Water Science and Technology 47-2, 1.