Experimental study of activated sludge batch settling velocity profile

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The last step of activated sludge wastewater treatment consists in separating the residual particulate matter from water. This separation process takes place in a clarifier: a large tank in which sludge particles settle while clear water overflows. In order to improve numerical models of clarifiers, a better understanding of activated sludge settling mechanism is required. Laboratory batch settling experiments involving acoustic Doppler velocity measurement methods have thus been developed. The raw Doppler signal was recorded over durations of up to 22 hours and then post treated. At the very beginning of the sedimentation process 3D turbulence produced by the initial stirring generates a high velocity standard deviation. 3D turbulence dissipates after a few minutes. Low amplitude fluctuations of the vertical velocity remain, whereas the average velocity decreases at any vertical location. Vertical velocity profiles exhibit two areas: an area of rising velocity in the lower part of the blanket and an area in which velocity fluctuates around a uniform settling velocity in the upper part. This last area decreases constantly and disappears completely after some minutes. A change in concavity of the rising velocity profiles after three hours rest indicates a change in the physical mechanism of consolidation.

Keywords: acoustic Doppler velocimetry, sedimentation, compression, velocity profile

1 INTRODUCTION

Activated sludge is a widespread wastewater treatment method: the influent is mixed with a bacterial suspension in a biological reactor. The bacteria consume and degrade the pollution, which results in the formation of particulate aggregates called flocs. They are made of bacteria, mineral and residual organic matter. The resulting suspension (mixed liquor) is sent to a secondary settling tank in which the flocs can settle in quiescent conditions while the supernatant overflows at the top. Activated sludge settling has been extensively studied [1, 2, 3,]. It is a complex process, influenced by many parameters, such as the size, fractal dimension and porosity of flocs, suspension concentration, carrier fluid viscosity, temperature, nutrient and oxygen concentrations, pH, conductivity and the hydrodynamics of the system. Several models have been developed in order to describe it [4, 5]. These models aim at evaluating the concentration and settling velocity of an activated sludge suspension dispersed in water on the basis of the aforementioned parameters. They require detailed experimental calibration and validation, particularly regarding the inner behaviour of the sludge blanket. However, most measurement systems allow only monitoring the position of the interface between the sludge and the supernatant, and are rarely usable in actual treatment plants. The present paper focuses on the development and testing of an experimental procedure aiming at measuring the height and settling velocity profile within the sludge blanket by the use of an ultrasonic Doppler profiler.

2 MATERIALS AND METHODS

2.1 Experimental settling column

The main body of the experimental setup is a settling column 0.4 m in diameter and 1.0 m high. The column is made of transparent Plexiglas® in order to allow visual observations. The suspension can be stirred by the mean of a pumping system in close loop. The liquid is pumped through four inlets located at the top of the column and injected back through four outlets at the bottom creating a high level of turbulence and an upward flow of about 1Cm/s sufficient to suspend the particles. A homogeneous concentration can thus be achieved.

2.2 Ultrasonic system and signal processing

The ultrasonic Doppler profiler used in the present study was developed in ICube laboratory [6]. The transducer is 1cm in diameter and has a central frequency of 1.9 MHz. 40 waves are emitted per pulse representing a length of the measurement volume of 1.5cm. The transducer was installed above the column in order to perform vertical measurements.

Velocity measurements:

One of the main problems in measuring velocity profiles lies in the huge range of velocities during the settling process. At the very beginning of the experiment stirring induced turbulence generates velocity fluctuation of about 1-3cm/s. This initial turbulence decays rapidly allowing the flocculation process to take place producing flocs about 5mm in size settling freely in the suspending liquid. During this phase average velocities are of the order of 1mm/s while velocity fluctuations still remain probably due to concentration heterogeneities. In the meantime, a layer of settled particles thickened progressively from the bottom of the tank. At the contrary to rigid bodies, flocs slide, compress and deform depending on the balance between weight, adverse pressure gradient due to water migration in the porous medium and solid stress. During this phase the largest velocity in the profile, at the top of the blanket, decreases constantly from 0.4mm/s to 1μm/s after 24 hours rest. A good understanding of this complex process requires velocity measurements down to 0.1μm/s. At this average velocity and for an ultrasonic frequency of 1.9 MHz floc displacement of half a wave length takes about one hour during which velocity change to a large extend. In consequence conventional FFT transform of the Doppler signal can not provide fine temporal resolution of velocity in reason of time averaging over the necessarily long time of signal required for FFT analysis [7,8].Therefore a direct phase measurement was tested allowing measuring the individual displacement of each floc or group of flocs as proved by the discontinuities in the velocity profiles. Velocity field is obtained by derivation of floc displacement. A better temporal resolution is obtained at the expense of profile smoothing. Velocity profiles presented in chapter 3.1 were obtained by FFT analysis for the sake of a better understanding of the graphs.

Concentration measurements:

Theoretically, concentration profiles can be obtained by an appropriate analyse of the backscattered intensity profiles. In the present case this method cannot be applied due to the very small particles displacement during the tests. In consequence, it is not possible to get sufficient independent intensity samples in order to obtain an accurate average. Therefore concentration was estimated by computing the trajectories of virtual tracers distributed uniformly over the column at the beginning of the test when concentration is known and uniform. The density of tracer at a given height and a given time during settlement is proportional to concentration.

Raw Doppler signal is recorded and post treated. As an experiment lasts 22 hours PRF is reduced incrementally from 25 to 0.05 Hz in order to save disk space and computation time during post treatment. In this way the minimum measurable velocity by FFT is 10^{-8} m/s and has no limit by phase measurement.

2.3 Experimental procedure

The sludge samples have been taken in the biological reactor of the wastewater treatment plant of the Rosenmeer syndicate (Rosheim, France, Bas-Rhin). Once sampled, the sludge was immediately transported to the laboratory and poured into the column. The ultrasonic transducer was then installed in such a way that its extremity was submerged in the suspension. Then, the sensor was activated and the suspension stirred for 5 to 10 min at a rate of 10^{-3} $m^3.s^{-1}$. The intensity of the backscattered signal was monitored during the stirring phase. The attenuation of the signal is dependent on particle concentration [6]. The suspension was therefore judged homogeneous when a constant attenuation profile was achieved. The pump was then shut down and the acquisition was launched.

2.4 Initial sludge concentration measurements

The suspended solids concentrations and volatile suspended solids fractions have been measured using standard protocols [26].

3 RESULTS AND DISCUSSION

3.1 Settling velocity profiles

Figure 1 shows in greyscale the evolution of the settling velocity as a function of depth and time during the settling of an activated sludge suspension. The envelope of the graph describes the curve of the position of the sludge blanket interface as a function of time, i.e. the settling curve, which clearly displays two different regimes:

• a settling phase, during which the particles' settling velocity is constant ; the settling curve is thus linear (Figure 1, (a)–(b)),

• a compression phase, during which the velocity of the interface steadily decreases; the concentration becomes high enough for the flocs to interact and form a compressible matrix [9] (Figure 1, after (b)).

At the beginning of the experiment, the settling velocity inside the suspension displays large fluctuations:. Those fluctuations are only visible in regions, the settling zone, where mean velocity is equal to the settling velocity (dotted line on Figure 3 (a)) . It can be seen that they dissipate almost immediately at the bottom of the suspension and are followed by the development of a stable velocity profile, which then spreads progressively upward. The disappearance of the fluctuations corresponds to the apparition of a permanent contact between particles: the compression zone. The settling phase ends when all particles are in contact up to the top of the sludge blanket, which corresponds to the moment when compression zone ascending from the bottom of the suspension reaches the interface (around 0.2 h on figure 1).

One unexpected characteristic of the velocity profiles during the settling phase is the absence of velocity jump between settling and compression zones. At the contrary to settling rigid bodies, the transition between the two zones is therefore characterized by a jump in velocity standard deviation rather than a jump in the mean velocity.

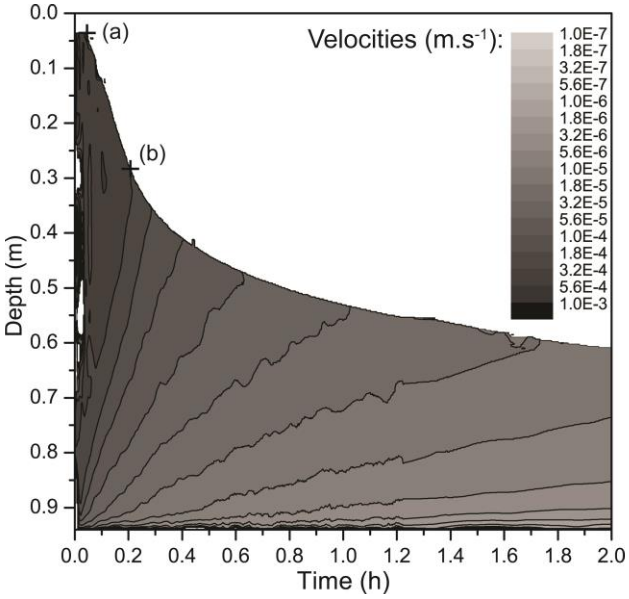

Figure 1: Evolution of the settling velocity profile of an activated sludge suspension as a function of time during 2 hours (initial concentration: 3.9 g.L^{-1}).

Figures 3b, 3c and 2 illustrate the behavior of the sludge during the compression phase. Two phases which hereafter will be called compression phase I and compression phase II are distinguished.

From the beginning of the compression phase and during the three following hours the velocity gradient increases from the bottom to the top of the sludge blanket (Figure 3 (b) compression phase I).

This implies that the densification of the suspension occurs faster in its upper part. This phenomenon compensates progressively the deficit in concentration that had appeared during the settling phase. The concentration profile tends towards a quasi uniform profile around 10gr/l.

After three hours and until the end of the test the curvature of the velocity profiles changes: the velocity gradient has a maximum located at the bottom while it tends to zero at the top (Figure 3 (c) compression phase II). In consequence, the concentration stabilizes around 10gr/l in the upper part of the blanket and increases constantly with time in the lower part.

3.2 Discussion:

In a settled flocculated suspension a fraction of the water present between the flocs, the free water, can migrate under low pressure gradient. Another fraction, trapped inside the flocs, can only be released in case of strong deformation of the floc due to solid stress and, in this way, turn to free water. Each floc on its side is submitted to three forces: relative weight, drag force and a force resulting from solid stress in case of

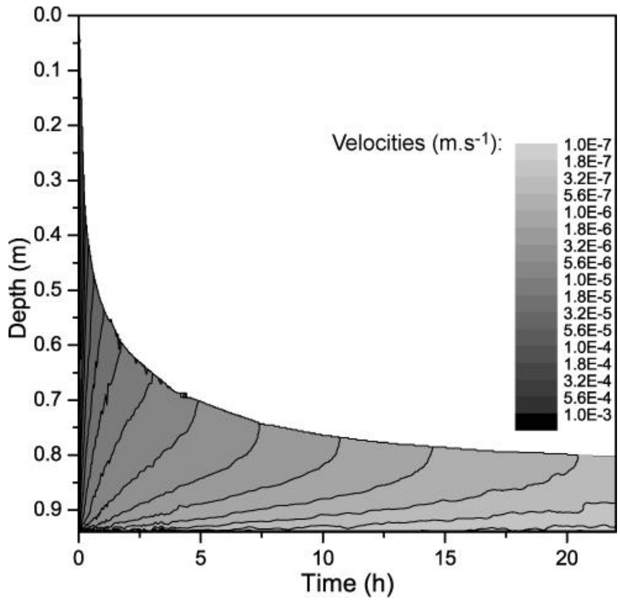

Figure 2: Evolution of the settling velocity profiles of an activated sludge suspension as a function of time during 22 hours (initial concentration: 3.9 g.L^{-1}).

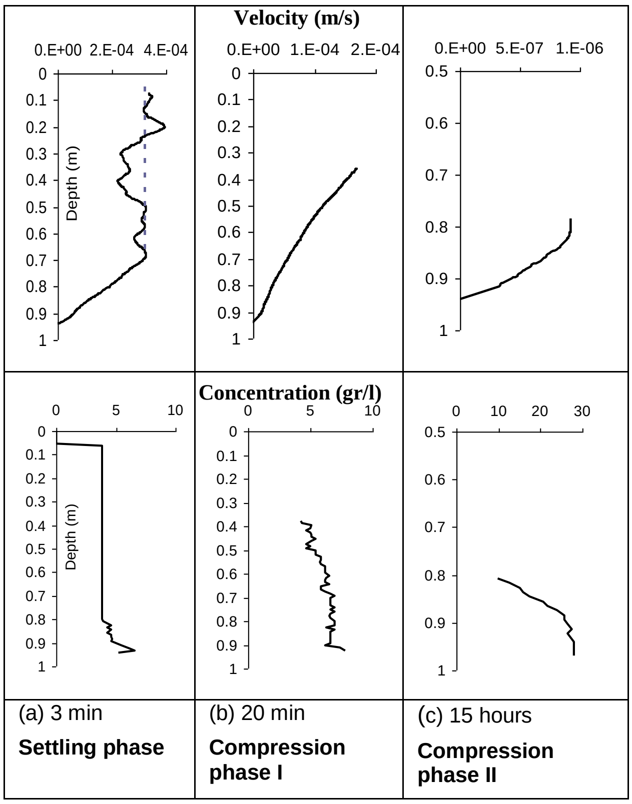

Figure 3: Settling velocity and concentration profiles obtained at three different instants during the settling of an activated sludge suspension (initial concentration: 3.9 g.L^{-1}).

continuous contact between flocs from the tank's bottom. The successive phases of settling can be interpreted in the following way. In the settling zone velocity fluctuations, probably induced by heterogeneities of the concentration field prevent the creation of permanent links between flocs. At the tank's bottom velocity is zero permitting the creation of permanent links and a loose particle matrix, having in its upper part a concentration close to the initial one, propagates upward until it reaches the sludge interface. In the meantime in the core of the matrix free water migrates upward while particles rearrange until maximum compaction at initial floc size is obtained. During this phase relative weight is mainly balanced by drag force so that solid stress remains low and no water is released from the flocs. At the end of this compression phase I, the concentration is, following our measurements, around 10g/l. As compaction approaches maximum, water velocity and therefore drag force decreases and solid stress is no longer negligible which induces a floc deformation and a release of the trapped water. Solid stress depending upon the depth concentration increases with depth. At the end of this compression phase II, relative weight is totally balanced by solid stress induced force. This ultimate state of the suspension could not be obtained over the duration of the present test.

3.3 Direct phase shift measurement:

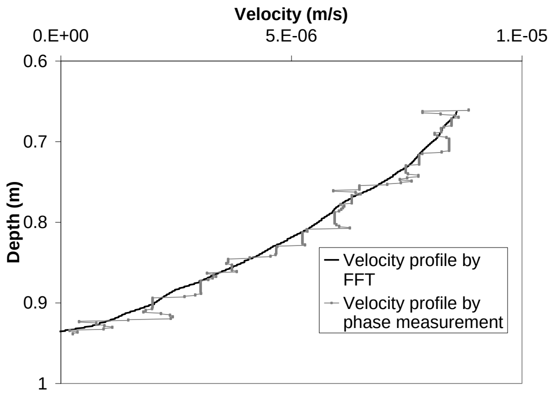

Figure 4: Comparison of velocity profiles obtained by FFT analysis and phase shift derivation (4 hour rest).

As formerly stated, direct phase measurements permits a better time resolution than FFT analysis. Figure 4 shows a comparison between velocity profiles obtained by the two methods. The profile by phase shift measurement exhibits velocity jumps that are not present with FFT analysis due to time averaging. It is hoped that this method will permit a better understanding of floc to floc interaction and will lead to better physical model of compaction.

4 CONCLUSION

The experimental method applied in this study allowed validating the potential an ultrasonic transducer to provide detailed activated sludge settling velocity profiles. The settling velocity inside of the sludge blanket has thus been successfully measured. Such data is particularly useful for the understanding of the behaviour of activated sludge suspensions and the calibration of numerical models.

In addition the existence of two phenomenon's, usually totally neglected in numerical models has been shown: the existence of velocity fluctuations in the settling zone and a phase of compaction without solid stress due to free water migration and particle rearrangement. A better understanding of compaction mechanism is expected from the analyse of detailed velocity profiles obtained by direct phase shift measurements

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