Hydraulic characterization of a wastewater treatment clarifier by an acoustic doppler current profiler

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Abstract

Optimization of the solids removal performance of a clarifier requires, in part, a complete understanding of the tank hydraulics. This paper presents velocity measurements obtained by utilizing an acoustic doppler current profiler (ADCP). The latter provides the necessary temporal and spatial scale to understand and analyze in a detailed way density-driven flows in wastewater clarifiers. Velocity profiles and Reynolds shear stresses of a full-scale installation were investigated. Two different clarifiers were investigated that differ in floor slopes and solids removal mechanisms. The ADCP revealed that sloped clarifiers provide significant solids transport towards the central removal sump. Implications in the design of clarifiers are discussed and new insight is provided into the transport of solids and purpose of the solids removal system. The velocity measurements suggest that the analysis of the removal mechanism should be considered from a fluid mechanical perspective. It was also seen that a scraper-equipped, central solids removal design creates non-ideal flow fields compared with a suction, radial removal design. Shear stress corresponded well with simulation results from literature. The paper has to be seen as a first attempt to apply this proven measurement technology in wastewater treatment.

1 Introduction

The clarifier, in which bioflocs are separated from the liquid by gravity, is a crucial operation in biological wastewater treatment systems. If this process does not work properly, suspended solids are flushed out of the tank into the receiving water. The consequences of this are significant. Increased turbidity may restrict plant photosynthesis, and the increased oxygen demand may be detrimental for aquatic life.

Clarifiers are typically large, open, concrete vessels. Their performance is dependent on biofloc properties and hydraulics; recirculation and density currents might be negative for the overall solids removal efficiency. Clarifier velocities typically vary between 0 and 50 mm s^{-1}. Kinnear [1] summarized the factors affecting the hydraulic performance, i.e.

- geometry of the tank (shape, depth,…),
- flow rates through the tank (inlet and recycle flows),
- inlet, outlet and other internal configurations (feedwell and baffles),
- collector mechanism design and operation,
- inlet solids density and settling regime,
- solids blanket depth and density,
- convection currents due to surface heat loss or inlet temperature gradient.

Many modeling but only few validation studies have so far been performed on these topics. Moreover, the few existing studies were mainly focussed on lab-scale clarifiers.

Biofouling, high turbidities, moving structures, etc. make the application of sensors hard. Invasive techniques such as drogues [2-4] are not adequate due to the low velocities prevailing in the tank. It does also not allow to measure multi-dimensionally. Further, it only provides mean velocities and no temporal velocity variance or turbulence. Ultrasonic flow meters have been used in both full-scale and laboratory scale clarifiers [5]. Here too the probe is limited in application by its one-dimensional measurement and wake effects due to the non-invasiveness of the technique. In ocean and estuary research, non-invasive acoustic doppler velocity profilers have been used widely. The device is based on the principles of doppler shift of a sound wave reflected from particles suspended in the fluid stream.

The aim of this paper is twofold. First, the non-invasive acoustic doppler current profiler (ADCP) will be presented shortly with its advantages and disadvantages with respect to the clarifier application. Secondly, the probe will be used in two clarifiers with a different solids removal system. The hydraulic flow pattern will be investigated in order to reveal the mechanism of sludge removal, i.e. hydraulically of mechanically. The recorded velocities will be used for computational fluid model validation in the near future.

2 Principle of acoustic doppler current profiler

The ADCP technology has been applied fruitfully in oceanic research for many years to measure mean velocities and Reynolds stresses. Those applications serve as a basis for applications in (wastewater treatment) clarifiers.

Although the mean velocity measurement is critical to understand the hydraulic behavior, calculation of Reynolds shear stress might be interesting when studying the transfer of momentum. Lohrmann *et al.* [6] played a pioneering role and described the mathematical techniques required to calculate the stresses and kinetic energy from ADCP generated data. A similar mathematical technique was applied by Gargett [7]. To check its accuracy Stacey [8, 9] confronted the ADCP turbulence data with an analytical solution for an unstratified tidal flow and their respective bias matched well.

It has to be noticed that the technique measures the particle, and not the liquid velocity. Previous research considered particles that were fairly small and mostly experienced a negligible drag. Instead, bioflocs are large and might be very dense especially when flocculants are added to improve their settleability [10]. Hence, their velocity can be expected to deviate from the liquid velocity. The presence of size distributions only worsens the issue. Indeed, the echoed signal is a function of the solids concentration and size distribution, of their properties such as shape, density, compressibility and rigidity and of the particle size to wavelength ratio [11]. But Reichel and Nachtnebel [11] also admit that only a small percentage of the size distribution is dominating the backscatter signal. Finally, high particle concentrations can result in signal shadowing of the ensonified particles.

A typical ADCP transmits and receives signals via four transducers arrayed in the Janus configuration (Figure 1); they are positioned around a horizontal circle every 90 degrees, and are directed outwards at a certain angle to the vertical. The larger the angle, the more sensitive the instrument is for horizontal velocities, but at the same time the probe looses its ability to measure velocities far away. The device can be placed in a down- or up-looking position. It listens to and processes the echoes coming from successive volumes, i.e. bins, along the beam to determine how much the signal has changed. It should be noticed that the measurement uncertainty increases with decreasing depths, velocities and size of the bin [12].

Figure 1. Picture of the ADCP (from RD Instruments).

Due to the time needed for the down-looking ADCP to convert from a transmitter to sound receiver, no measurements are obtained over the first 0.5 m below the water surface. At the bottom too data are lost. When the acoustic signal is transmitted, the signal produces unwanted side-lobes. Some of these travel in a vertical direction, while the primary signal is travelling at a set angle to the vertical. The side-lobes therefore reach the bottom first. These unwanted reflected signals interfere strongly with those returning from the particles, thus overshadowing the actual particle signal.

RD Instruments [13] reviewed the principles of operation of an ADCP. The Janus configuration allows the calculation of the vertical and two horizontal velocities as follows

$$
\begin{aligned}
u &= \frac{u_3 - u_4}{2\,sin\,\theta} \\
v &= \frac{u_1 - u_2}{2\,sin\,\theta} \\
w(u) &= \frac{u_1 - u_2}{2\,cos\,\theta} \\
w(v) &= \frac{u_3 - u_4}{2\,cos\,\theta}
\end{aligned}
\tag{1}
$$

The velocity along the i-th beam is denoted as u_i; u, v and w are the radial, tangential and vertical velocity respectively; θ is the beam angle. Four beams are available, hence, two separate vertical velocities can be calculated. Since each beam samples velocity from a different portion of the flow stream due to the ADCP geometry, error can be introduced in spatially variable flow fields. The difference between the two vertical velocities provides an estimate of this error and checks the flow homogeneity [14].
In addition to the averaged velocities, the Reynolds stresses are important to validate, and calibrate to a certain extent, the Reynolds-averaged Navier-Stokes equations with the corresponding turbulence model. The ADCP does not calculate the stresses directly, but the streamwise and cross-streamwise correlations, i.e. $\overline{u'w'}$ and $\overline{v'w'}$ respectively, are easily calculated as [8, 9]

$$
\begin{aligned}
\overline{u'w'} &= \frac{\overline{u_3'^2} - \overline{u_4'^2}}{4\,sin\,\theta\,cos\,\theta} \\
\overline{v'w'} &= \frac{\overline{u_1'^2} - \overline{u_2'^2}}{4\,sin\,\theta\,cos\,\theta}
\end{aligned}
\tag{2}
$$

The prime superscript indicates the fluctuating component of the velocity while the bar refers to the time-averaging operator.

3 Experimental methodology

Two wastewater treatment facilities were investigated with the ADCP: Central Davis County Sewer District and Central Valley Water Reclamation Facility.

Both are located near Salt Lake City, Utah, USA. Their physical descriptions are given in Table 1. It is clear that both clarifiers differed considerably in terms of floor slopes and solids removal philosophy (Figure 2). At Central Davis, solids were transported to a central sump either by flowing under the force of gravity due to the floor slope or by being pushed by the spiral collector mechanism. In the sump, solids were withdrawn. At the Central Valley clarifier on the other hand, a radial suction mechanism withdrew the solids directly from where it settled down. Due to the flat floor, gravity could not transport solids.

Table 1. Central Davis and Central Valley clarifier physical descriptions.

Feature	Central Davis	Central Valley
diameter (m)	24.4	38.1
floor slope (degrees)	9.5°	0°
mechanism	spiral scraper	suction
solids removal system	central sump	radial

Figure 2. Pictures of the spiral scraper (left) and suction (right) solids removal mechanisms in the considered (empty) clarifiers.

The Workhorse Monitor ADCP Direct-Reading 1200 kHz (RD Instruments, San Diego, USA) was deployed downwards from approximately mid-depth in the clarifier while velocities near the surface where measured upwards from the same location. The depth of measurement was limited in favor of measurement resolution; eighty bins of 5-centimeter depth were preferred. Due to the restricted depth unwanted side-lobs were reduced. Sampling was done on a 1-second time interval at a 1 mm s^{-1} accuracy. Both a 2-minute and 10-minute averaging period were initially used to report averaged velocities. Because the averages and standard deviations did not differ, a 2-minute time-average was used.

As acoustical interference limits the ADCP operation, only three velocity profiles were taken along the radius at 7.6, 9.1 and 10.7 m. During the experiments the removal mechanism was turned off for two reasons. First, the attached scum skimmer arm would interfere with the ADCP support mechanism. Secondly, a particular objective of this study was to measure to what extent the solids are removed hydraulically (and not mechanically). Although this research will mainly present results related to Central Davis, a Central Valley velocity profile is utilized to demonstrate the discrepancy in clarifier solids transport. The process conditions for Central Davis at the time of sampling are given in Table 2.

Table 2. Process conditions for the Central Davis clarifier.

Process condition	
inlet flow rate	18925 m^3/day
underflow rate	681 m^3/day
inlet solids concentration	1.6 kg/ m^3

4 Results and discussion

As mentioned before, the ADCP was deployed both downwards and upwards. An overview of the results is shown in Figure 3. Since the ADCP truly measures the velocity of the particles entrained in the fluid, only the measurements at the bottom part of the clarifier are accurate; fluid velocities are high and interparticle contact exist. Near the surface fluid velocities are too low to entrain the particles completely, hence, they settle. This explains the vertical velocities found in the upper part of the clarifier. In this region the probe ability to measure the fluid velocity is definitely restricted, though particle velocities are of interest too for clarifier optimization. Further discussion will focus on the bottom velocities.

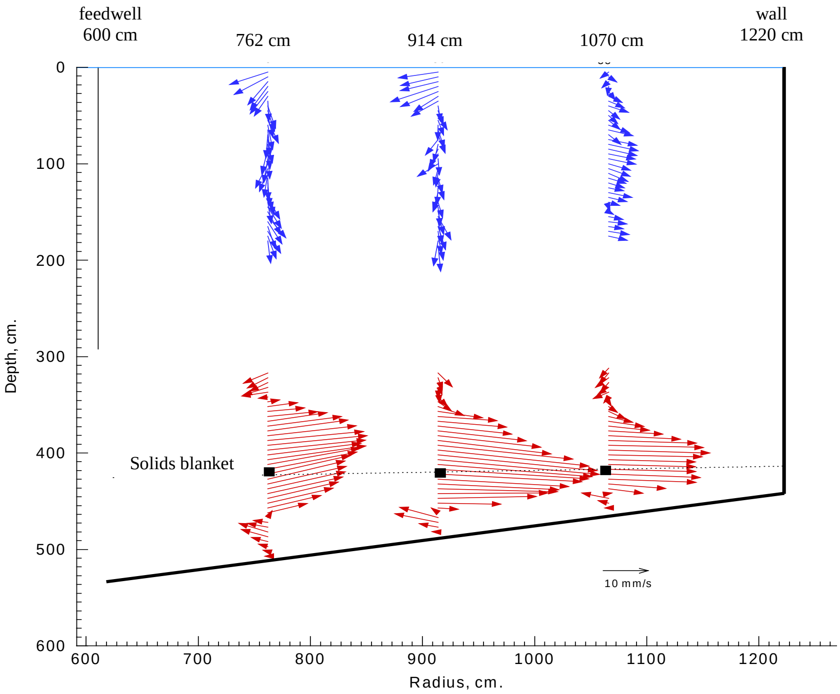

Figure 3. Overview of the velocity measurements at Central Davis clarifier.

Figures 4-6 show the recorded velocity components in a cartesian coordinate system for the Central Davis clarifier. It is clear that some difference exists between the two vertical velocities w, hence flow homogeneity may be questioned. Accurate measuring is hard due to the beam spread and turbulence. The figures also indicate a strong radial flow u, which is normal for clarifiers. The tangential flow v magnitude remains approximately the same throughout the radial cross-section and exceeds the radial velocity in the most outer location. This velocity is important to consider in computational model setup since most circular clarifier models assume a tangential homogeneous flow. Future measurements should check this crucial assumption.

In every profile, a radial-outward density current develops in the vicinity of the solids blanket, i.e. at equal buoyancy [15, 16]. From a hydraulic point of view this density effect has a greater impact on the solids removal efficiency than the settling process. Indeed, ambient water is entrained by the particles and thus the flow rate of this bottom current is increasing. Increased shearing scours the blanket. At the inlet the suspension is characterized by a high potential energy (due to buoyancy) as compared to the inlet kinetic energy, if the inlet is not considered as a jet [17]. Hence, the potential energy is converted to the bottom current. At the interface of the solids blanket, momentum transfer to the layer below occurs due to high shearing. For that reason, it is seen that the density current translocated downwards while moving radially outwards. As a consequence of this short circuit from the inlet to the outlet, a reverse top current is induced. The upward looking ADCP does not record this since the flocs move independently of the liquid. In view of CFD validation it is important to note that the ADCP does not give fluid velocities. Immediately above the density current the vertical velocities are still (mostly) downwards. Again, this is due to settling; solids concentrations are fairly low and do not restrict the settling velocity. Remarkable is the observation of an upward oriented vertical velocity for the flocs in the density current itself. A possible cause is still unclear but might be attributed to resuspension of flocs.
It is also seen that the radial velocity becomes negative right above the density current. Since the ADCP was located at half-depth, it is not known from Figures 4 and 5 if the velocity becomes again positive when moving to the surface. Instead, at the outer location in the clarifier (Figure 6) the velocity is negative only over a small distance above the density current. This suggests that at least two recirculation zones exist above the solids blanket. Otherwise, this sequence of negative and positive radial velocities right above the blanket can never be retained. This likely explanation is supported by simulations [16] and measurements [18] from literature.

In the Central Davis velocity profiles, the no-slip velocity boundary condition at the floor is clearly seen. Further, a density-driven radial-inward flow developed below the radial-outward flow. This flow originates from the sloped floor and is driven by gravitational forces. This demonstrates that hydraulic phenomena play a significant role in solids transport towards the central sump since no solids removal occurred. Lakehal *et al.* [16] concluded from simulations that the scraper's function is to overcome the slurry's yield stress and to make it flow. It

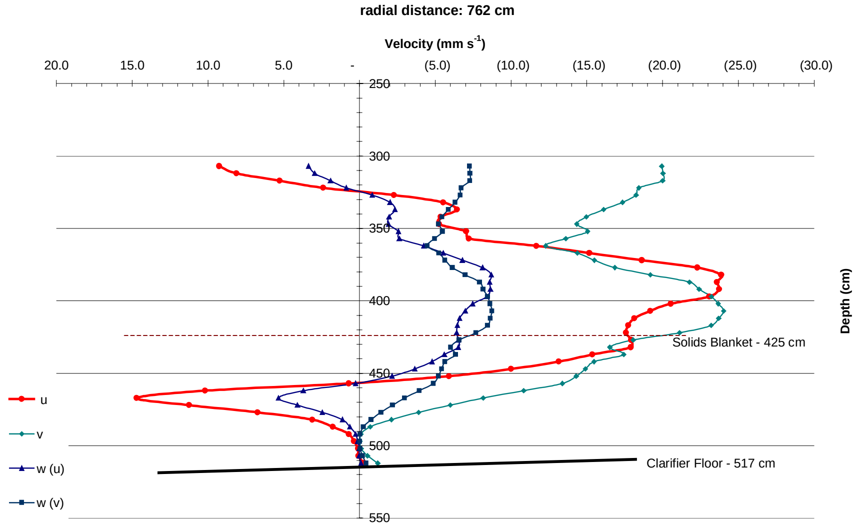

Figure 4. Profiles of radial, tangential and vertical velocity at a radial distance of 762 cm of the Central Davis clarifier.

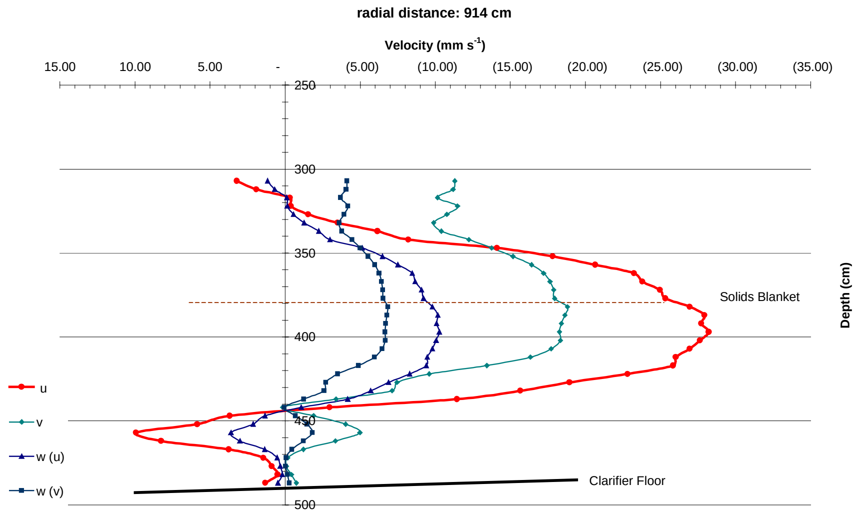

Figure 5. Profiles of radial, tangential and vertical velocity at a radial distance of 914 cm of the Central Davis clarifier.

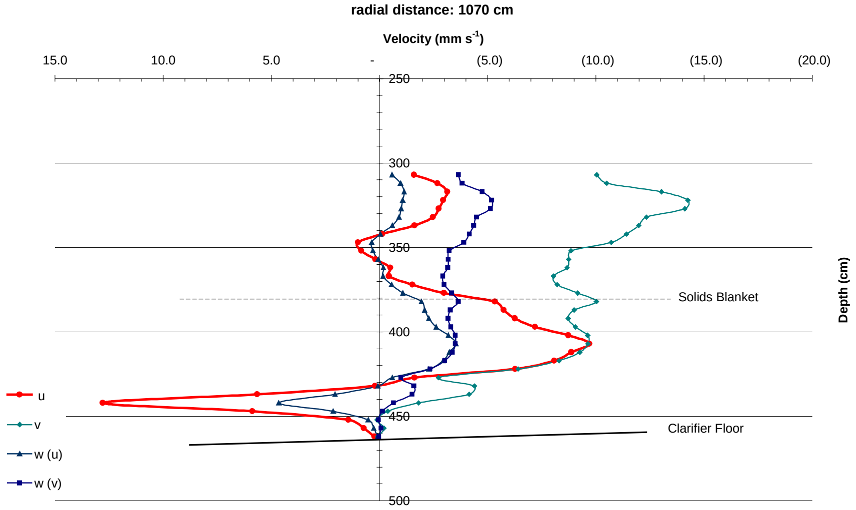

Figure 6. Profiles of radial, tangential and vertical velocity at a radial distance of 1070 cm of the Central Davis clarifier.

does not induce the transport to the center as such. Instead, Narayanan *et al.* [19] and Albertson [20] stated that mechanical transport dominates. The ADCP data does not suggest that the clarifier would operate successfully without any solids removal mechanism. Due to the no-slip condition at the bottom, a region of low velocities near the floor must exist, which limits proper solids transport.

A high residence time for the slurry may result in rising solids; nitrogen bubbles may be formed in the flocs by biological reactions. Hence, an equal clarifier residence time for all solids is crucial and plug-flow conditions are favored inside the blanket. From the figures, it is clear that this is not the case. The scraper overcomes the yield stress, mixes the slurry and moves it from the low to the high velocity region. As can be observed in Figure 7 this mixing is absent with a flat-bottomed clarifier. Here, the suction mechanism removes the solids equally across the tank. The shorter solids residence time as compared to a scraper-equipped clarifier was experimentally confirmed by Audic *et al.* [21]. A no-slip condition was not observed, but a reversed flow was obviously present.

Finally, the shear stresses $\overline{u'w'}$ and $\overline{v'w'}$ were calculated (Figure 8) in the Central Davis clarifier. It is observed that the peak values of shear stress correspond to the position of the peak velocity gradients. Lakehal *et al.* [16] also observed a similar profile in their simulations though highly dependent on the solids concentration profile. Apparently, the shear stress was present to a greater degree in the sloped-floor clarifier. This definitely will have an influence on particle resuspension at the surface of the blanket. The fluctuations in Figure 8 superimposed on the main stress profile are still unclear. The issue of turbulence definitely needs more attention in future studies.

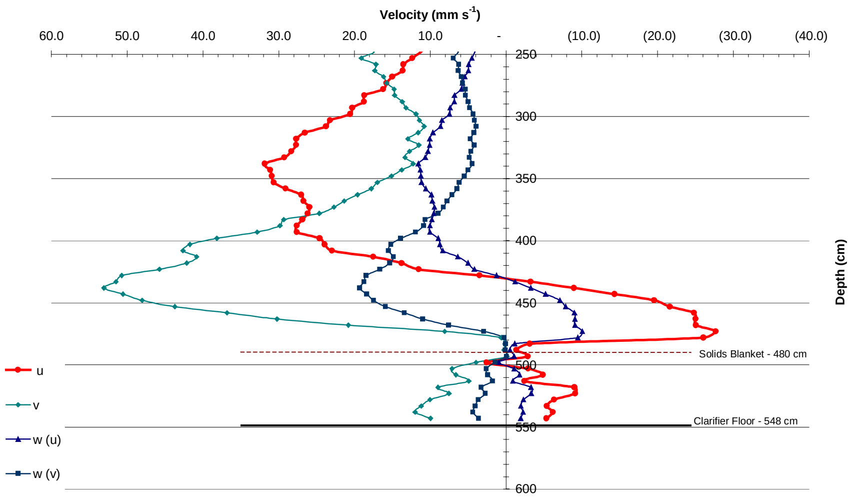

Figure 7. Profiles of radial, tangential and vertical velocity at the middle of the radius of the Central Valley Clarifier.

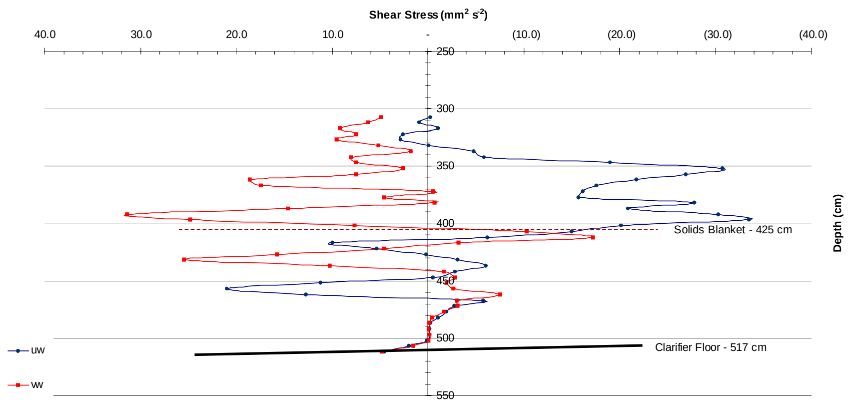

Figure 8. Shear stresses $\overline{u'w'}$ and $\overline{v'w'}$ in the Central Davis clarifier.

5 Conclusions

Unwanted hydraulics in clarifiers can be detrimental for the solids removal performance. Hence, design retrofitting might be desired and is aimed at by computational fluid dynamics. Model validation and calibration are crucial. In this respect, the ADCP technique provides an improved method for measuring on-site average velocities and Reynolds stress profiles in clarifiers.
Using the ADCP, this paper presented new insights in solids transport and solids removal mechanisms. The measurements suggest that the analysis of the removal mechanism should be considered from a fluid mechanical perspective. Further, the scraper-equipped, central solids removal design creates non-ideal flow fields inside the blanket as compared to the suction-based solids removal system.
Besides the technique itself, turbulence aspects of the clarifier still require a lot of future work.

6 Acknowledgement

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