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Commissioning of a novel in-line rheometery system in a wastewater treatment plant for more efficient polymer dosing

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ABSTRACT

Urbanisation is putting enormous pressure on wastewater treatment plant facilities. Optimising the liquid and sludge process streams in existing plants is one way of prolonging the life span of such installations. Many Wastewater treatment plants (WWTP) have sludge dewatering installations where treated wastewater sludge is dewatered using belt filter presses amongst others, before final disposal. One of the most expensive inputs in these plants is the polymers used as flocculants. Controlling the optimum dosing in the dewatering process cannot currently be done in real-time. It has been shown that huge savings can be made by optimising the dosing rates of polymers based on the sludge rheology.

An Ultrasound Velocity Profiling (UVP) and pressure drop (PD) measurement system was specially designed and commissioned for a WWTP. The system was installed in a WWTP to measure the rheological properties of sludge in-line and in real-time prior to mechanical dewatering using a belt filter press. This non-invasive in-line system was able to accurately measure the rheological parameters in real-time in a 100 mm stainless pipe. It was shown for the first time what the maximum in-line yield stress is that is required for optimum dewatering based on a relationship determined between the yield stress and the total suspended solids in the filtrate exiting the belt filter press.

1. Introduction

Worldwide there is a need for optimisation of wastewater treatment and water treatment plants from an energy, chemical and water saving perspective. Also, to automate processes will result in less manual labour requirements. Vast amounts of liquids and sludges are handled in such facilities consuming large amounts of chemicals (polymers used as flocculants). Tang and Zhang [31] state that because sludges are non-Newtonian, their non-Newtonian behaviour impacts WWTP processes such as fluid transportation, mixing, oxygen diffusion, mass transfer, anaerobic digestion, chemical conditioning and mechanical dewatering. All of these are key factors affecting the operational efficiency and the energy consumption of the entire process.

At belt filter presses in WWTPs polymer is typically dosed at a rate of about 3.5 kg poly per dry ton solids, and at a polymer cost of about 4 USD/kg. Dewatering plants (such as the trial site in this investigation) can process approximately 8000 t dry solids per annum at a polymer cost of 125700 USD which is significant. Measurement and control of the optimal polymer dosage for different sludge solids concentration, is essential during dewatering due to extensive use of the polymer [8]. However, controlling the optimum dosing cannot currently be done in the process in real-time.

Currently, WWTP rely on conventional laboratory tests such as capillary suction time (CST), specific resistance to filtration (SRF), visual observation and time to filter (TTF) to determine optimum polymer doses for good dewatering [23,27]. However, the obtained information cannot be used to predict the performance of full-scale facilities.

As a result, many in-line techniques have been applied for monitoring and controlling polymer dosage in WWTP. These techniques include measuring the electrical conductivity [30], streaming current or potential [1,6,9], electrical impedance tomography [8], UV–vis spectrophotometry [2] and centrate or filtrate viscosity [3]. Although these are promising techniques, their application is still limited; the limitations include the applicability during the variation of sludge inlet concentration and the cost associated to develop such techniques are often high. Other techniques such as a duel slit in-line die has been used by Mazzanti and Mollica [21] to characterise the flow characteristics of wood plastic composites. This technique is however not really

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Notation

D	pipe inner diameter, (m)
K	fluid consistency index, (Pa s^n)
L	unit length, (m)
n	flow behaviour index, (dimensionless)
r	radial position, (m)
R	pipe radius, (m)
R_{plug}	plug radius, (m)
ΔP	pressure drop, (Pa)
Re_2	Reynolds number, (dimensionless)
v	velocity, (m/s)
v_{plug}	plug velocity, (m/s)
V	bulk velocity, (m/s)

Greek letters

τ	shear stress, (Pa)
..	yield stress, (Pa)
ρ	density, (kg/m^3)
$\dot{\gamma}$	shear rate, (1/s)

applicable to the current work as it was developed for the polymer extrusion industry.

It has been shown that large savings can be made by optimising the dosing rates using rheology [9,22]. Örmeci [22] measured rheological properties of the flocculated sludge to optimise polymer dose and mixing intensity in sludge dewatering using a Flocky Tester, which is a torque rheometer type. In this study, two different techniques were presented that can be used for optimisation of polymer dosing and mixing intensity, also for choosing a polymer that performs the best based on rheological data. The first technique is used for polymer optimisation and selection. Uniformly mixed sludge gives a constant torque over time, when a polymer is injected to the sludge, a sharp increase of the torque is observed, reaching a maximum point then decreases afterwards. The maximum torque is correlated to polymer dosage, different polymers and dosage give different torque peaks. The second technique is used for optimising mixing intensity of the flocculated sludge at optimum polymer dosage. Three different polymers were tested by both these techniques at the lab and full-scale WWTPs. These techniques were able to optimise the polymer dosing and mixing intensity with the polymer consumption reduced by 50% at the treatment plant. In addition, the results indicated that torque rheology can be used to determine the total shear intensity imposed to sludge during full-scale conditioning process. The results of this study indicate that well-described rheological properties of sludge offer a reliable tool for the optimisation of dewatering operations and sludge conditioning at WWTPs. However, this method is not in-situ. While a sample is tested, conditions may change in incoming sludge properties.

Salazar and Moreno [26] also attempted to optimise polymer dosage. Their objective was to define the main parameters that affect the overall dewaterability performance in terms of dried solids (DS) content of the final sludge cake. The trials were conducted at a full-scale WWTP that was using filter presses, NALCO polyacrylamide-based polymer was tested and the dosage was optimised in the range of 7–8 ml polymer per 100 ml of digested sludge (7–8% volume per volume). The best capillary suction time values (CST) were obtained at 8.96 and 9.94 s respectively; however, the polymer dosage did not result in any improvements of the DS of the sludge cake.

Johnson et al. [13] conducted a series of tests on a new belt filter press at a filtration plant. The operating parameters such as solids feed, sludge flow rate, polymer dosage, and belt speed and tension were identified as being critical to belt filter press efficiency and optimisation. Each belt press control parameter was tested to determine the optimum range of performance in terms of cake production and cake solids percentage. No correlation could be found, with either production or cake solids percentage.

Sludge rheological behaviour can be characterised by the Bingham model which contains a yield stress and Bingham viscosity. These characteristics were related to sludge concentration by many researchers in reviews [11,19,20,28,38]. Viscosity has also been used for optimisation of the flocculation concentration [3,32].

An Ultrasound Velocity Profiling (UVP) system can, together with a pressure drop (PD) measurement, continuously measure the rheological properties of viscous fluids in line and in real time [16–18,25,36]). In this regard, the UVP + PD system has been tested during 2012 and 2014 in a flow loop using secondary sludges with solid concentrations varying between 2% and 6% by weight. The results indicated that it was indeed possible to measure the viscous properties of sludges using the system [15]. The UVP + PD system is however not a plug-and-play system and custom modifications are normally required for each industrial application. This is because each industrial application is unique and has different operational requirements such as pipe dimensions, ultrasound properties of the industrial fluid, pressures, temperatures, flow rates and test environment/location. The Technology Readiness Level (TRL) of the technology therefore varies for different industrial applications.

The objective of this study was to determine the feasibility of using the UVP + PD system to measure sludge rheology in-line in an integrated and operational WWTP environment. If the in-line rheometer was then able to measure the rheological properties in-line and in real time, and if a relationship existed between the rheology just after polymer dosing and the belt press filter operational parameters, this could possibly be used to optimise the polymer dosing.

2. Theory/calculations

2.1. Non-Newtonian laminar pipe flow

This section briefly describes non-Newtonian flow and the associated rheological parameters that were used to characterise the sludges tested in this work.

The equation for the Herschel-Bulkley model is as follows to determine shear stress:

$$\tau = \tau_y + K(\dot{\gamma})^n, \tag{1}$$

where K, n and τ_y are the consistency index, flow behaviour index and yield stress, respectively [7]. These parameters can be obtained by using a curve fitting procedure. Eq. (1) can be integrated to give the velocity (v) profile across the pipe radius (R). For a yield stress fluid the velocity in the plug region as shown in Eq. (2) and for $r \le R_{plug}$ the velocity is as per Eq. (3).

$$v_{plug} = \left(\frac{n}{1+n}\right)\left(\frac{n\Delta P}{2LK}\right)^{\frac{1}{n}}(R - R_{plug})^{\frac{1+n}{n}} \tag{2}$$

$$v = \left(\frac{n}{(1+n)}\right)\left(\frac{\Delta P}{2LK}\right)^{\frac{1}{n}} \left((R - R_{plug})^{1+\frac{1}{n}} - (r - R_{plug})^{1+\frac{1}{n}}\right), \tag{3}$$

where R_{plug} is the plug radius and is related to the fluid yield stress according to:

$$R_{plug} = \frac{2L\tau_y}{\Delta P}. \tag{4}$$

The Herschel-Bulkley model can easily be modified to describe the power-law and Bingham plastic models. For the power law model the yield stress becomes 0 and for the Bingham model $n = 1$ [7].

The fluid yield stress can also be estimated from the UVP + PD data. It can be obtained either directly from the measured plug radius R_{plug} in the velocity profile data or from a model fitting procedure (Eqs. (1)–(4)). Fig. 1 shows a schematic illustration of direct yield stress estimation from the plug velocity profile (using Eqs. (2)–(4)). More information regarding the yield stress measurement can be found in Berta et al. [4]. Yield stress values reported in this study were obtained directly from the plug radius measurement.

The identification of the transition between laminar and turbulent flow is of great importance because the fluid flow behaviour changes fundamentally at the transition zone. Several non-Newtonian Reynolds numbers have been proposed over the years to accommodate the different rheological models. Slatter and Lazarus [29] formulated a Reynolds number (Re_2) for non-Newtonian pipe flow (assumed plug-flow):

$$\mathrm{Re}_2 = \frac{8\rho V^2}{\tau_y + K\left(\frac{8V}{D}\right)^n}. \tag{5}$$

In this work all measurements were conducted in laminar flow. The Reynolds numbers varied between 295.6 and 633.9.

3. Equipment and experimental methods

3.1. Filter belt press at Potsdam WWTW and sludge material

The experimental runs were conducted at a full-scale Wastewater Treatment Plant Facility in Cape Town. The treatment plant handles about 50 Ml of wastewater per day using primary, secondary, preliminary and tertiary treatments. The plant employs an advanced EPBNR process which has three different zones (Solids Technology, Unison 620 model). The thickened waste activated sludge from the holding tank solids concentration feeding the belt filter press was 2.9 ± 0.22%wt. Prior to dewatering, the sludge was conditioned. During this study the treatment facility used a cationic polyelectrolyte polymer which is a polyacrylamide in powder form of very high molecular weight and a charge density of 80%. The BFP at the plant is shown in Fig. 2(a). The polymer conditioning set-up is shown in Fig. 2(b). The rheological properties of the secondary sludge can be affected by the plant process parameters such as the polymer concentration, dosage rate and sludge feed rate.

3.2. The UVP + PD system

Research Institutes of Sweden (RISE) and the Flow Process and Rheology Centre at the Cape Peninsula University of Technology (CPUT) have jointly developed an UVP + PD system over many years from a research prototype to an industrial system. This industrial system based on the UVP + PD methodology is called Incipientus, formerly known as Flow-Viz (see www.incipientus.com). The UVP + PD concept and methodology is well described in several publications; see e.g. Kotzé et al. [14,15–18], Birkhofer et al. [5], Dogan et al. [10], Pfund et al. [24], Wiklund & Stading, [34], Fock et al., [12], Wassell et al. [33], Wiklund et al. [35,36,37]. The Incipientus system is an enhanced in-line rheometer that uses a pulsed ultrasound method that allows true multi-point measurements i.e. to determine instantaneous velocity profiles (velocity distribution) in real-time. When combining the pressure drop measurement with the velocity profile data, a flow curve (rheology) can be derived. This makes it possible to obtain rheological data of complex fluids such as yield stress and viscosity in real time and in line while the process is running. Measurements are done non-invasively through industrial grade stainless steel pipes under realistic field conditions. The instrument sensors therefore do not affect the flow process and give no additional pressure drop (energy losses). Technical specifications (e.g. temperature, pressure ranges) can be modified and are application dependent. Typical pipe diameter sizes can vary from 12 to 200 mm (½" to 8″).

During 2014 and 2015 the technology was evaluated for wastewater by using different ultrasound transducers and prototype electronics. It was found that the instrument can non-invasively measure through a 51 mm (2″) stainless steel pipe in wastewater (secondary sludge). Tests were conducted at Potsdam WWTP, Cape Town, South Africa, in a tube viscometer rig and good agreement was found between conventional tube viscometry and the results obtained using the UVP + PD instrument [15]. The TRL level before this project work was thus determined at level 5. During this work the technology had to be integrated for the first time within an existing belt press at Potsdam Wastewater Treatment Plant. Electronics, ultrasound transducers and software had to be newly designed and modified to improve the TRL of the in-line rheometer for wastewater applications. A spool piece (internal diameter 100 mm) containing one differential pressure and two ultrasound transducers was installed at Potsdam. The sludge rheology was measured in line just after the polymer dosing and before the polymer conditioning zone. Fig. 3 shows the setup at the Potsdam filter press belt.

Table 1 shows the description of the different technology readiness levels and the level where the technology started (marked with X) to where it is after the project finished (marked with C).

3.3. Experimental procedure

The experimental design comprised of the following tests:

- Testing sludge rheology in-line using the UVP + PD system with and without the addition of polymer to the feed sludge, at a sludge flow rate of 12 m^3/h. Polymer was added at a polymer concentration of 0.25% wt and a dosing rate of 0.8 m^3/h.
- Testing sludge rheology variability over time for a total of 6 h. The rheology was measured in-line with the UVP + PD system once every 10 min for an hour, every 30 min for 2 h and every 60 min for 3 h using the above plant operating conditions.
- To determine the relationship between rheology of sludge and plant process conditions, a three factor three level Box-Behnken design was used to design the experimental matrix using Stat-Ease Design-Expert V 10.0.0 software. The software design the experiments in a random manner to ensure that one experimental run neither be influenced by the conditions of the preceding runs nor predict the conditions in the succeeding runs. The variables for the test runs are showed in Tables 2 and 3. In 2016 the higher sludge flow rates was selected, while in 2017 the focus was on the lower sludge flow rates. the rheological parameters were measured in-line just after polymer dosing using the UVP + PD system. The total suspended solids (TSS) in the filtrate was measured on the filtrate stream returning to the plant. At least 20 min were allowed between the runs to ensure that stable conditions were obtained. The origin of solids returned have

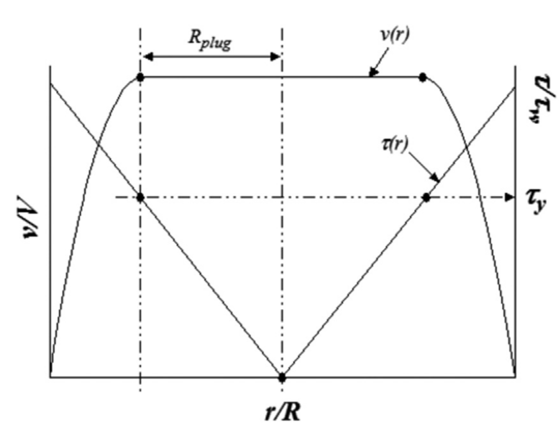

Fig. 1. Schematic illustration of yield stress estimation from the plug velocity profile.

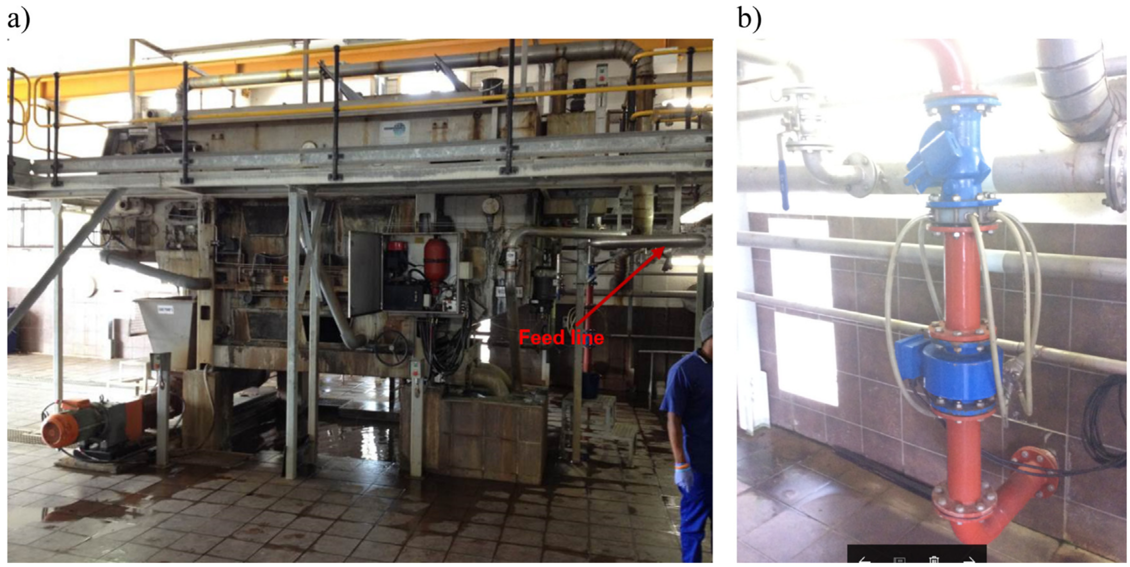

Fig. 2. a) Filter belt press at Potsdam; b) Polymer conditioning zone.

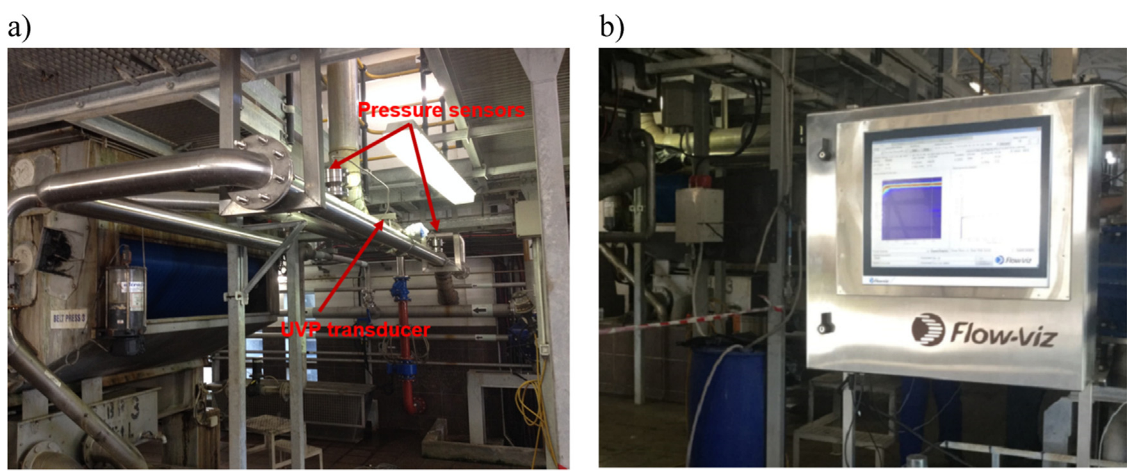

Fig. 3. a) Spool piece on feed line with pressure transducers and ultrasound transducers; b) Incipientus operator's panel at Potsdam.

Table 1
The stage of development or the Technology Readiness Level (TRL) that the UVP + PD technology was before the project (X); and the TRL level of the technology at the end of the project (C).

Technology Readiness Level		Description	X = before project, C = after project (current)
1	Basic Technology research	Basic science. Not application-focussed. Principles are observed and reported on.	
2	Concept formulation	Some practical applications identified materials or processes required and confirmed. Technology and hypothesis formulated. Research plans and protocols are developed, peer reviewed and approved.	
3	Analytical and experimental critical function or research proof of concept established	Laboratory measurements validate analytical predictions of separate technology elements. Hypothesis tested.	
4	Validation in laboratory environment	Test results confirm design and meet technical performance. Hypothesis refined. Formulations tested.	
5	Laboratory scale validation in relevant environment	Validation under relevant operational conditions, mimicked in the laboratory.	**X**
6	Integrated prototype system verified in relevant environment	Prototype demonstration in the operational environment. E.g. Phase 1 trials	
7	Integrated pilot system demonstrated in operational environment	Integrated full scale pilot systems demonstrated in an operational environment or site.	**C**
8	Actual system completed and validated through test and demonstration	Actual product completed and qualified through certification, tests and demonstrations.	
9	Proven system and ready for full commercial deployment	Product proven ready through successful operations in operating environment.	

Table 2
Factorial trial design for September 2016.

Variables	Factors (X)	Levels used		
		Low	Medium	High
Polymer concentration (%wt)	A	0.2 (−1)	0.25 (0)	0.30 (+1)
Polymer dosing (m^3/h)	B	0.7 (−1)	0.8 (0)	0.9 (+1)
Sludge feed (m^3/h)	C	10 (−1)	15 (0)	20 (+1)

Table 3
Factorial trial design for February 2017.

Variables	Factors (X)	Levels used		
		Low	Medium	High
Polymer concentration (%wt)	A	0.2 (−1)	0.25 (0)	0.30 (+1)
Polymer dosing (m^3/h)	B	0.6 (−1)	0.8 (0)	1.0 (+1)
Sludge feed (m^3/h)	C	10 (−1)	13 (0)	16 (+1)

to be mentioned. Solids carryover from belt, solids not scraped of belt but captured in pores and washed off, solids in feed (if not properly filtered), solids in filtrate all contribute to the TSS.

3.4. Challenges experienced during commissioning

3.4.1. Pressure transducers

A pressure transducer with a rating of 6 kPa and large membranes with remote capillaries for transmitting the pressure from the pressure ports (measuring points) was used. The pressure transducer setup also came with a chamber where the test fluid fills and eventually presses on the membrane which is installed on the top of the setup (see Fig. 4). A large length of 2.8 m was used to ensure adequate pressure drops that are measurable. However, even with a length of almost 3 m the pressures measured were below 1 kPa for the highest flow rate. The sludge also tended to clog inside the pressure chamber where the membrane is situated. In order to mitigate the clogging effect, the chamber was removed (see Fig. 4). Unfortunately, this did not solve the issue and therefore an alternative differential pressure transducer (also 6 kPa rating) and setup was used. Instead valves were installed at the bottom of the pipe (as shown in Fig. 4) and these pressures were transmitted to the alternative pressure transducer using water tubes. Good results were still obtained, but the latest solution needs to be replaced with in-line pressure sensors for future validations in different wastewater treatment plants.

3.4.2. Measurement interference due to fouling layer inside process pipe

It was found that the ultrasound energy was attenuated more over time and as a consequence noise was present during measurements. The noise levels increased with time until it was not possible to measure any velocity profiles at all. It was suspected that a fouling layer could be forming during pumping of the sludge. Fig. 5(a) shows the inside of the stainless steel pipe and it can be seen that a thick fouling layer was indeed present. Fig. 5(b) shows the significance of this fouling layer on the Doppler spectra and velocity profile measurement. It can be observed that there was not enough energy and no velocity profile measurement was possible.

To solve this problem a valve was installed on the opposite side of the non-invasive ultrasound sensor. A hose pipe was then connected and water was jetted to flush the fouling layer from the inner surface of the pipe. This worked very well and once the fouling layer was flushed it was possible to measure for several hours afterwards. Fig. 6 shows the valve installed on the pipe (a) as well as the Doppler spectra measurement (b) after the flushing process. A significant improvement on the velocity profile measurement can be observed. This step is very important for accurate rheology measurements (e.g. yield stress) during the monitoring process and should be integrated into the UVP + PD technology for the wastewater industrial application. This solution will

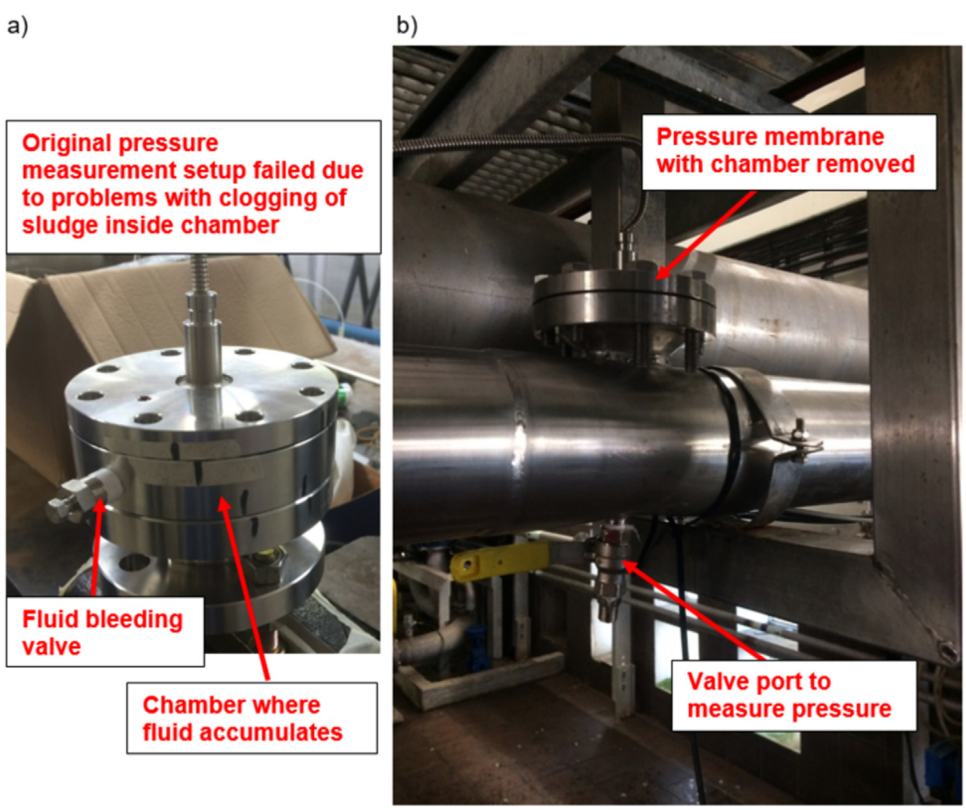

Fig. 4. Pressure measurement setups used during the work.

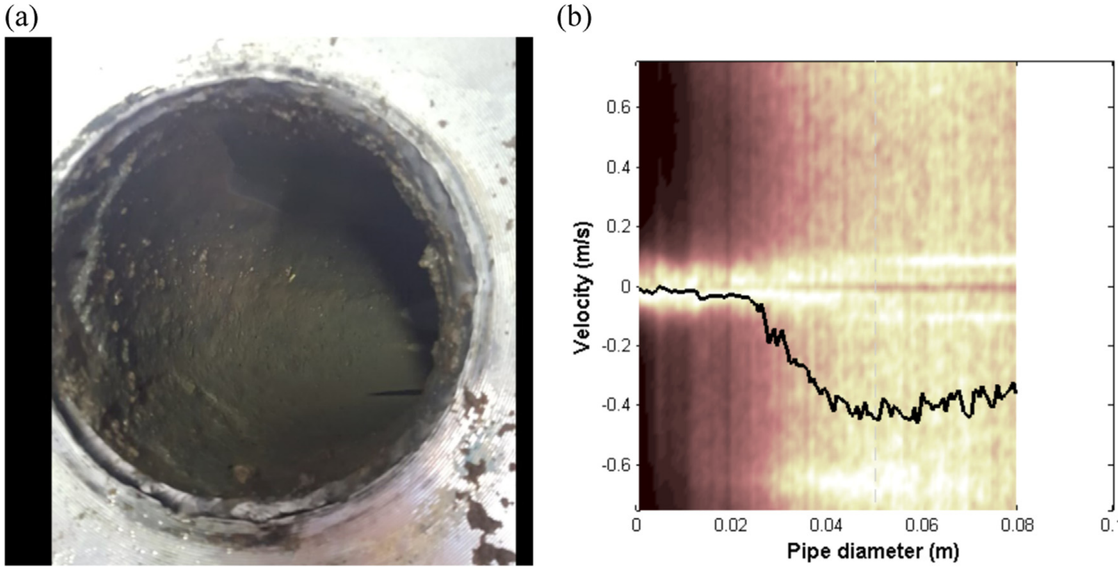

Fig. 5. (a) Process pipe removed showing large fouling layer around the inner pipe circumference; (b) Doppler spectra measurement during the presence of fouling layer.

also not disturb the flow process as the hole in the pipe quickly fills with sludge sealing the pipe wall and flushing is only required a few times per day.

4. Results and discussion

4.1. Measurement of velocity profile with and without polymer addition

It is a routine technique in WWTPs to dose polymers into piping systems that transfer and discharge dewatered sludge in order to reduce wall friction and ensure dry cake can be pumped to the storage silos. A test was conducted with no polymers added and after polymer addition in the primary and secondary sludge (see Section 3.3). This was done to see whether the instrument after commissioning was able to detect a change in the flow behaviour and rheological properties of the sludge. Fig. 7 shows the comparison between velocity profiles (Doppler spectra) measured in secondary sludge with no polymers (a) and with polymers (b) added. The yield stress and pressure drop values are shown below the velocity profile measurements. Note that the velocities are negative due to the direction of flow relative to the ultrasound beam inside the pipe. This does not affect any results, but can be useful for some industries, e.g. cleaning applications.

It can be observed that the profile shape is very different between the two conditions. When no polymers are added the plug-flow is significantly less than when compared to measurement in sludge with polymers. However, it is interesting to note that when the polymers were added, the plug of the profile increased, but the pressure drop decreased. With polymer addition, there will be less pressure drop due to lower friction. This resulted in a significant drop in yield stress when compared to the yield stress of the sludge with no polymers added. Similar results were found in the primary sludge when comparing polymer addition vs. no polymers addition and therefore those findings are not included here. From these results, it is clear that the UVP + PD instrument is able to detect variations of the flow profile and rheology when certain processing conditions are changed or stopped, in this case polymer dosing. This is the first time that the effect of polymer addition

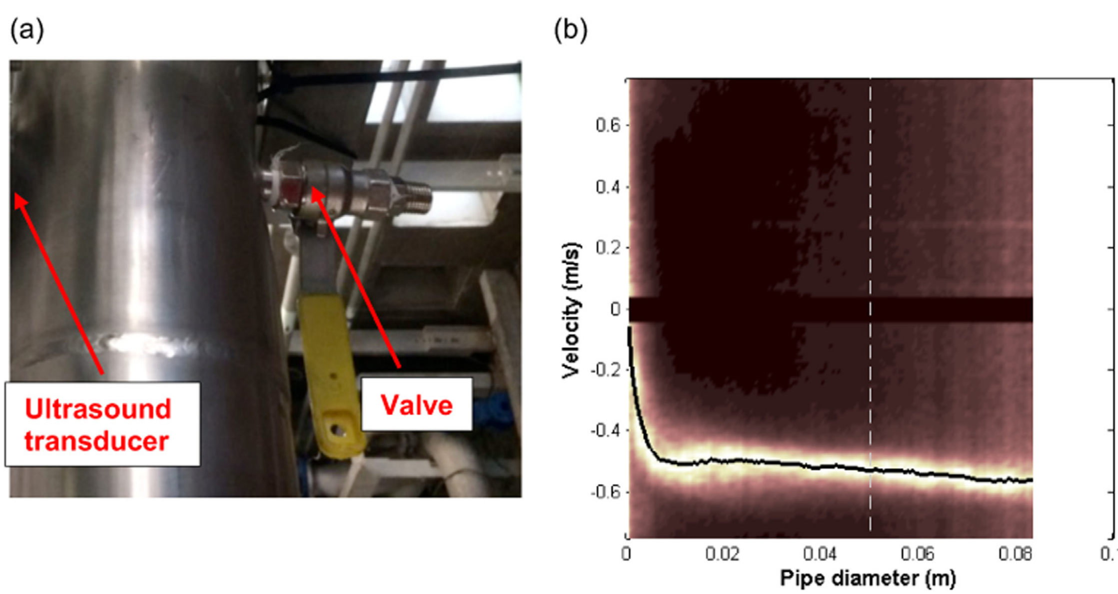

Fig. 6. (a) Valve installed on the pipe opposite to the ultrasound transducer; (b) Doppler spectra measurement after the fouling layer was flushed with water.

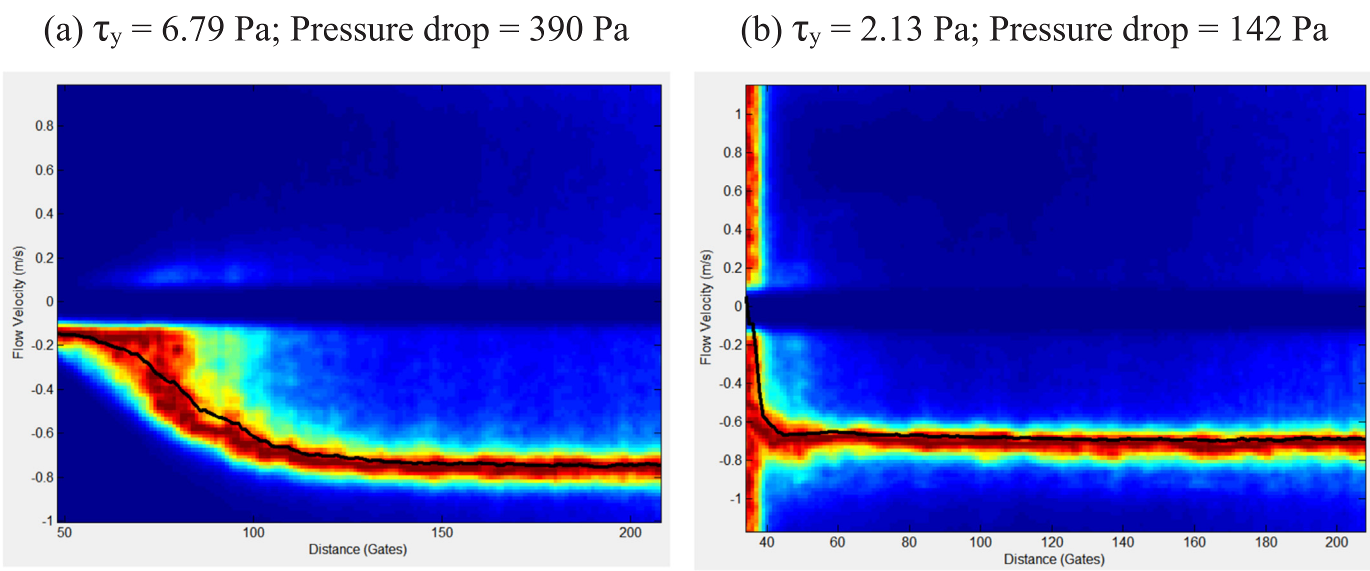

Fig. 7. Velocity profile measurements of secondary sludge flow (a) with no polymers and (b) with polymers added.

on the rheology of the sludge is measured in line and in real time. Previous yield stress values measured for Potsdam WWTP sludge ranged from 9.2 ± 1.3 Pa.

4.2. Sludge rheology variability over time

A variability study was conducted to see how the sludge rheology changes with time. The test procedure is summarised in Table 4. Tests were conducted every one minute for ten minutes, every ten minutes for an hour, every 30 min for two hours and hourly for five hours. One velocity profile, rheogram (shear stress vs. shear rate) and yield stress value were recorded during each test.

Fig. 8 shows a typical velocity profile measured in secondary sludge during the variability study. A large plug flow was present and this profile shape was measured during all other processing conditions, except for the fact that the pressure drop measurement varied. Due to the large pipe diameter (100 mm ID) only velocity data could be measured up to a distance of 57 mm inside the pipe. This is a memory limitation of the instrument, however, only data across the pipe radius is required for determining rheology. Fig. 8(b) also shows the instantaneous rheogram calculated from the velocity profile and pressure drop measurement. The yield stress for this particular measurement was 2.55 Pa.

Fig. 9 shows a summary of velocity profiles (normalised) measured using the in-line rheometer. The sludge temperature was stable around 19 °C. The measured velocity profiles did not change with time. It can be concluded that both the feed conditions and the operational conditions were consistent over the time of measurement.

4.3. Relationship between rheology of sludge and process conditions

The effect of BFP operating parameters such as polymer concentration, polymer dosing rate and sludge flow rate on the yield stress and the resulting total suspended solids in the filtrate from the belt filter press was investigated. The trial conditions and results are provided in Table 5. The range of the operating conditioned were within the belt filter press specification.

The objective of this work was to find if a relationship exists between the rheology of the sludge after polymer dosing (depending on belt press process conditions) and the total suspended solids in the filtrate (TSS filtrate). A plot (Fig. 10) of the total suspended solids in the filtrate and yield stress revealed that there is a relationship between the total suspended solids in the filtrate and yield stress. Trial 1 was conducted over a large range of sludge flow conditions up to 20 m^3/h. Due to the fact that at high sludge flow rates, lateral spreading will occur, and some sludge might drop off the sides of the belt and increase the TSS in the filtrate in that way, which is not necessarily due to insufficient flocculation, the second trial was run up to a maximum of 16 m^3/h. It was observed in both trials that the TSS in the filtrate increases with increasing yield stress. The increase in TSS could either be due to insufficient flocculation and some fines are forced through the pores of the belt or when the sludge feed rates are excessive.

The in-line results revealed that the yield stress in the pipe ranged from 2 to 20 Pa clearly showing the sensitivity of the system to measure changes in polymer dosing conditions by the resulting change in yield stress. However, these conditions produced a filtrate with too high suspended solids concentration. The process conditions were therefore limited to a range of conditions that would deliver a TSS in the filtrate within the acceptable range. The comparison of the results indicates that there is good agreement between the different trial runs as shown in Fig. 10. Over the range of yield stresses measured, it was found that the target value for TSS in the filtrate of 1 g/ℓ was obtained at yield stress values less than 5 Pa. This means that any combination of process conditions that will produce sludge in the pipe with a yield stress of less than 5 Pa will produce a TSS in the filtrate of an acceptable level. A critical yield stress of 5 Pa is identified as the maximum yield stress where acceptable levels of TSS filtrate are achieved. Of course, to obtain yield stress values of lower than 5 Pa, more polymer has to be added, either by increasing polymer concentration or polymer dosing that will ultimately increase the cost. Therefore, a control system can be developed around these criteria.

5. Conclusions and recommendations

5.1. Conclusions

The UVP + PD system was custom designed for WWTP applications for measuring the yield stress of sludge in the supply feed pipe just after

Table 4
Test matrix for in-line sludge rheology variation using UVP + PD instrument.

Run	No of measurements	Total time (minutes)
Once every 10 min for an hour	6	60
Once every 30 min for 2 h	4	120
Once every 60 min for 3 h	3	180

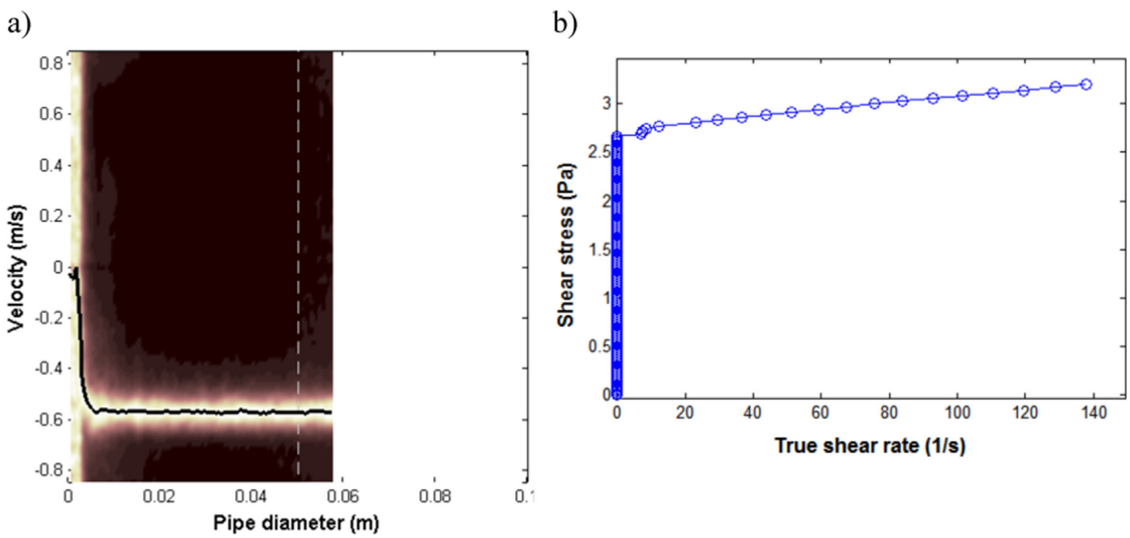

Fig. 8. (a) Velocity profile measurement of secondary sludge flow; (b) instantaneous rheogram showing shear stress vs. shear rate.

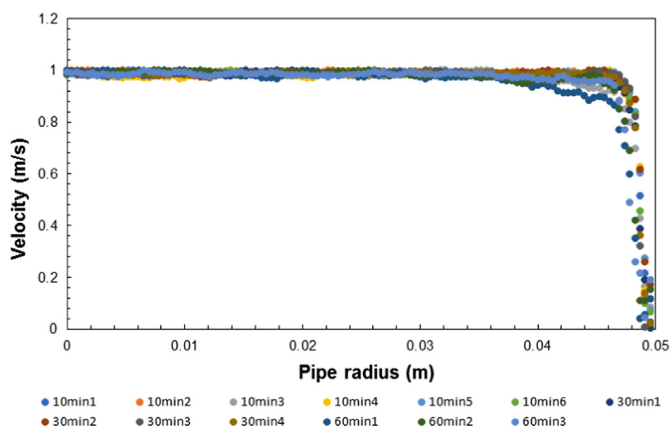

Fig. 9. Normalised velocity profiles measured using Flow-Viz technology with time.

polymer addition during a full-scale dewatering process to determine the optimum belt filter press operating parameters. The practical challenge experienced that had to be resolved was the presence of a fouling layer on the pipe wall which distorted Doppler measurements significantly. This problem was solved by installing a valve on the pipe opposite to the ultrasound sensor position and by jetting water to flush the fouling layer away. Tests were conducted to ascertain if the system was sensitive to differentiate between the sludge with and without polymer addition. The profile shapes were significantly different as well as the corresponding yield stress values.

The variation of the flocculated sludge rheology under constant plant conditions was tested over six hours and no variation of yield stress could be observed over this test period. A unique relationship between process parameters, in-line yield stress in the pipeline just after flocculation and the total suspended solids in the filtrate was established for the first time. A critical yield stress of 5 Pa was identified as the maximum yield stress where acceptable levels of TSS filtrate are achieved. This implies that any combination of process conditions (polymer concentration, polymer dosing and sludge flow rate) that will result in yield stress of less than 5 Pa will produce an acceptable filtrate. Should a polymer dosing system be designed around the measurement and control of this optimum yield stress, possible savings in polymer could be realized.

Table 5
Factorial trial measured response.

Run order	Polymer concentration	Polymer dosing	Sludge feed	FlowViz yield stress pipeline	Total suspended solids in filtrate (discharge)
	%wt	m^3/h	m^3/h	Pa	g/ℓ
Trial 1: September 2016					
1	0.25	1.0	16	5.19	0.69
2	0.30	0.8	16	5.21	0.80
3	0.25	0.8	13	3.52	0.72
4	0.30	0.6	13	3.98	0.77
5	0.20	0.8	16	7.56	1.79
6	0.25	0.8	13	2.8	0.69
7	0.20	0.8	10	2.22	0.74
8	0.20	0.6	13	3.18	1.43
9	0.25	0.6	16	7.64	1.94
10	0.20	1.0	13	2.94	0.66
11	0.30	0.8	10	3.42	0.53
12	0.25	1.0	10	3.37	0.62
13	0.25	0.6	10	2.13	0.85
14	0.25	0.8	13	3.27	0.67
15	0.30	1.0	13	4.04	0.12
Trial 2: February 2017					
1	0.25	0.8	15	5.20	0.85
2	0.25	0.9	20	7.13	6.62
3	0.25	0.7	15	7.13	1.46
4	0.25	0.8	15	9.13	2.53
5	0.25	0.8	15	6.37	1.27
6	0.20	0.7	15	16.80	6.39
7	0.25	0.9	10	4.67	2.17
8	0.30	0.8	15	8.05	9.63
9	0.20	0.8	15	13.37	4.99
10	0.20	0.8	20	18.13	9.70

5.2. Recommendations for future research

The in-line rheological tests should be extended to more WWTP's using alternative polymers, belt filter presses and different feed solids concentrations. The application of the UVP + PD system is limited to plants where the sludge is thickened. This is due to the low pressure drop that can be obtained in the large pipes of at least 100 mm diameter feeding the belt filter presses. The effect of shear as a function of pipe size on the floc structure and subsequent rheological parameters should be evaluated. If the effect on rheology is negligible, then it will enable the use of smaller diameter pipes for higher pressure drops. Both UVP sensors and the pressure sensors will also be cheaper for smaller pipe

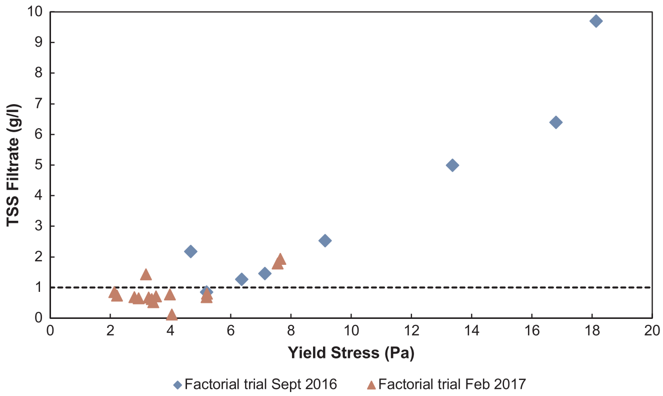

Fig. 10. Relationship between TSS filtrate and yield stress in the pipe.

sizes. However, the flow in the selected pipe size must be laminar to enable rheological measurements.

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