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Sludge Dewatering and Aggregate Formation Effects through Taylor Vortex Assisted Flocculation

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Abstract: For polymer induced flocculation processes, the effects of flow patterns in a gap of a conical stirrer on aggregate formation and subsequent sludge dewatering efficiency were analysed. Different flow regimes were identified by lab scale investigations with model substances and summarized in a Ta and Re number plane. An enhancement of sludge dewaterability for polymer induced flocculation processes was identified through post-treatment of flocculated sludge aggregates by the specific flow pattern of stable and wavy Taylor vortices. Photo-optical image analysis of flocculated aggregates shows a clear change of aggregate size distribution with less small particles during aggregate forming by Taylor vortices compared to classical flocculation procedure by stirrer. Results from technical scale dewatering analyses confirmed enhancement of sludge dewatering efficiency for six different dewatering machines using the identified wavy and stable Taylor vortex flow pattern regime.

Keywords: Aggregates, conical cylinder, flocculation, sludge dewatering, Taylor vortex

INTRODUCTION

Flocculation is one of the key processes in water, wastewater, and sludge treatment. It is useful for removing particles and improving sludge dewatering by subsequent mechanical processes such as filtration, sedimentation,

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flotation, centrifugation, etc. The dynamics of polymer induced flocculation processes are complex and include

a. destabilization of primary particles,
b. promotion of floc growth by collision between polymer and particles,
c. floc breakage by shear forces.

Hogg investigated the agglomerate structure in flocculated suspensions and identified aggregate breakage after stopping polymer addition during continuous agitation by decrease of mean aggregate size (1). He also analysed the agglomerate structure in flocculated suspensions and its effect on sedimentation and dewatering (2). The successful use of polymers for flocculation is therefore not only based on selection of reagents, the control the overall system chemistry and the polymer addition and the agitation and mixing are also critical.

An alternative to traditional or classic mixing, e.g. by the agitation in tank or the in-line injection in pipe, is the so-called "pelleting" flocculation, which is a specific type of flocculation obtaining a layered pellet aggregate structure. The pellet aggregate structure can be developed e.g. in a gap of a cylindric- or cone-shape stirrer. Using a cone shape stirrer for pelleting flocculation, Hemme et al. detected

a. an improved solid concentration in dewatered sludge at same polymer addition and
b. a reduced polymer addition at same solid concentration in dewatered sludge compared to traditional flocculation (3).

Schroeder, 2001, investigated the effect of pelleting flocculation in a cone shape stirrer without polymer addition in the pelleting reactor (4). The polymer addition was separated from the pelleting reactor obtaining a two-step process. In this process, additional control parameters enabling better control of appropriate mixing and pelleting conditions are available. Schroeder (4), and Schroeder and Sievers (5), confirmed the improvement of solid concentration by pelleting flocculation for different sludge types in lab and pilot scale, respectively, and found, that different pellet aggregate structures – depending on operational conditions – could be developed and optimally adapted to the subsequent dewatering machine (Sievers et al. (6). However, pelleting flocculation flow patterns are difficult to control, especially for sludge and wastewater treatment due to the fluctuations of sludge and wastewater both in flow rate and composition. A better understanding of hydrodynamic effects on development of layered pellet structure of aggregates is needed.

Continuing the work of Schroeder and Sievers (5), this paper summarizes the experimental results on hydrodynamic flow patterns in a conical gap and its impact on the aggregate size/structure of flocculated sludge aggregates and the subsequent dewatering process. Due to the fact, that Schroeder (4) is in German, this paper gives a brief description about the fundamental concept of the two-step flocculation process.

FLOCCULATION SYSTEM

Figure 1 illustrates the whole two-step flocculation system. The first step is a rapid-mixer where the high concentrated polymer solution is dispersed homogeneously in the incoming sludge in a short period of time. Thus, the primary particles of stable suspension are destabilised and voluminous structured aggregates are generated within the mixing zone. The mean velocity gradient and thus the mixing intensity can be controlled during operation. The voluminous aggregates are treated in a second step. This step is a cone-shape stirring reactor and consists of two concentric conical cylinders with the same apex angle. The flocculated sludge flows from the base (larger diameter) to the top of the conical cylinder. During the reactor operation, it is possible to change the angular velocity of the inner cone and its axial position while the outer cone remains at rest. The forming of flocculated aggregates is carried out within the gap between the conical cylinders. In

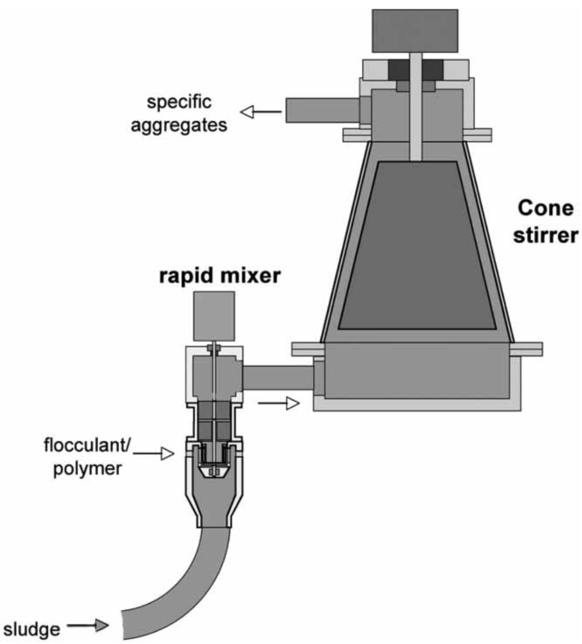

Figure 1. Schematic illustration of the flocculation system with cone-stirring reactor as second step.

this gap different flow mode regimes can be adjusted and therefore the forming of aggregates could be adapted to the subsequent dewatering or particle separation process.

TAYLOR VORTEX FLOW CHARACTERIZATION

Background

Taylor instabilities in the form of spiral vortices can occur within the gap between the co-axial cones, cylinders, spheres etc. This is due to rotation of the inner cone, cylinder etc. which produces a decreasing velocity profile in radial direction and thus an instable centrifugal force layer. Exceeding a critical peripheral velocity, periodical Taylor vortices in the gap do arise arranged side by side in axial direction. This three-dimensional flow pattern was described early by Taylor (7) and Shih-I (8) and provides specific mixing conditions.

The first detected vortex is the so-called First Taylor-Vortex (FTV) that is formed if the local critical Taylor number (Ta_c) is exceeded (6). In literature many different equations to calculate Ta can be found to allow comparison of different geometries e.g. for cones: Noui-Mehidi et al. (9), Wimmer 1994 (10), for cylinders: Reiter (11), Kataoka et al. (12). The square of Ta number Ta^2 can be interpreted as a relationship between the centrifugal and frictional forces and was proposed e.g. by Wimmer (10) employed for concentric cones as

$$Ta^2 = \frac{R_1 d^3 \omega^2}{\nu^2} \tag{1}$$

R_1 is the average radius of inner cylinder/cone, ω is the angular speed inner cylinder/cone, d is the gap between the cylinders/cones, and ν kinematic viscosity of the fluid. This Taylor equation (11) is comparable with the following Ta^* equation often used for concentric cylinders by $Ta^2 \approx Ta^*$, if $d \ll R_1$.

$$Ta^* = 2R_1^2 \frac{(R_2 - R_1)^3}{R_2 + R_1} \frac{\omega^2}{\nu} \tag{2}$$

Above the critical Ta_c, different three-dimensional fluid flow modes could occur depending on Ta and Reynolds number values. For batch-wise operation (without continuous flow-through) the radial Reynolds number

$$Re_{rad} = \frac{R_{1\,max}^2 \omega}{\nu} \tag{3}$$

is used to characterize the different flow pattern regions (e.g. see (10)). For continuous flow-through operations, the axial Reynolds number Re_{ax} is often useful, e.g. corresponding to Reiter (11),

$$\mathrm{Re_{ax}} = \frac{\bar{w}\mathrm{d_h}}{\nu} \tag{4}$$

with hydraulic diameter $d_h = 2 \cdot d$ as characteristic diameter and w as mean axial flow velocity in the gap. For Re_{ax} equal to zero (batch operation, no flow-through) the square of critical Taylor number was theoretically found for cylinders as constant at $Ta_c^2 = 1708$ (e.g. Wimmer, 1988 (13), Chung and Astill (14)). Reiter (11) summarized Ta^* of seven different theoretical and experimental papers for concentric cylinders by function $Ta^* = f\,(Re_{ax})$ and found within a good agreement of all papers that Ta_c^* increases slightly from approx. 1,700 up to approx. 2,000 for Re_{ax} between zero and 20 and increases strongly beyond $Re_{ax} = 30$ up to $Ta_c^* = 100{,}000$ for $Re_{ax} = 1{,}000$. Additionally, all papers summarized by Reiter (11) show that Ta_c^* increases with increasing gap width between concentric cylinders for $Re_{ax} = 0$. This has been confirmed also for concentric conical cylinders by Wimmer (9) by experimentally extracted Ta_c^2 of 1,730 and 2,180 for increasing dimensionless gap width S ($S = d/R_{1,max}$) of 0.11 and 0.25, respectively. $R_{1,max}$ is the radius of the inner cone base.

The flow characterization for conical cylinders has been less analysed where experiments are mostly carried out under batch conditions (Wimmer 1988 (13, 10); Noui-Mehidi et al., 2001 (9), 2002 (15); Ohmura et al., 2004 (16)). While batch conditions are not useful for flocculation applications, experimental fluid flow analysis as described below have been carried out for applicable flow-through conditions.

Experimental Fluid Flow Mode Analysis

To allow visual observations of fluid flow modes, the outer cone has been built of Plexiglas® and aqueous solutions with 2% Kalliroscope (see (9)). For the flow characterisation, the kinematic viscosities of water and a water-glycerol mixture (66 mass-% glycerol) of 1.1 and 14.82 mm^2/s, respectively, have been used. The lab-scale reactor geometry used for fluid flow mode investigations and also for lab-scale dewatering experiments is as follows: Average radius of inner cone 45 mm, height of inner cone 144 mm, gap width between outer and inner cone adjustable between 2 and 10 mm.

The experiments to detect different flow patterns in the reactor were carried out with the operational parameters for angular speed between 50 and 600 1/min, the continuous flow rate was set between 0 and 200 L/h and the gap between 2 and 10 mm. Based on papers cited above, different fluid flow modes were identified for the cone-stirrer reactor and summarized in the Re_{ax}–Ta^2 plane.

In batch operation ($Re_{ax} = 0$), similar flow patterns as documented in previous research were found e.g. Wimmer (10). With continuous flow-through ($Re_{ax} \neq 0$) as well as with different Ta, one additional flow pattern, the so-called Wavy Angular Flow (WAF) was observed in this reactor. The different identified fluid flow modes are photographically summarized in Fig. 2.

Table 1 is summarizing the visually observed critical Taylor number Ta_c for axial Reynolds number of both Zero and 14. For $Re_{ax} = 0$, an increase of Ta_c number was found for increased gap which is in agreement with the cited papers above. The critical Taylor number Ta_c is between 16 and 25 for a dimensionless gap width of 0.024 and 0.06, respectively. However, these Ta_c values are lower compared to (9). This difference is subjected to the differences of system configuration and its boundary conditions: One of the differences between (10) and this paper is the position of the conical cylinder. In (10), the base of the conical cylinder was above. In this study the base of the conical cylinder is below. Further differences are the apex angle and the influence of friction force and its balance with centrifugal forces, especially at the ends of the conical cylinder. The first Taylor vortex is detected at the base of the conical cylinder due to the highest centrifugal force at this location. Wimmer (10) used discs at both cone ends for closing the ends. This will for instance lead to additional friction forces at discs surface compared to the open ends of the system used for this paper. Therefore, in open cone systems lower centrifugal forces and Taylor number values could be needed to produce the first Taylor vortex.

Increasing the rotation speed of the inner cone at a constant gap width from first Taylor vortex detection has almost led to wavy Taylor vortices (WVF picture in Fig. 2). Further increase of rotation speed will stabilize the wavy vortices and lead to horizontal Taylor vortices (TVF in Fig. 2). Table 1 contains the "stable" Taylor numbers Ta_S for the first detection of stable Taylor vortex flow (TVF).

Compared to findings of Wimmer (10), the Ta_S values for $Re_{ax} = 0$ are four to five times higher. Below the gap width $S = 0.12$, there is a good agreement in increasing of Ta_S with increased gap width. However, in this

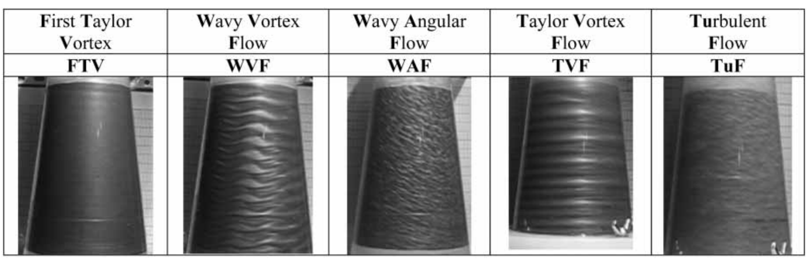

Figure 2. Identified fluid flow modes in the cone-stirring reactor with cone base located at bottom.

Table 1. Visually observed critical and "stable" Taylor number values and comparison with literature

	S										
Re_{ax}	0.04	0.06	0.08	0.1	0.12	0.14	0.17	0.18	0.25	Source	Geometry
Ta_c											
0	16	19	21	25	*n.d.	*n.d.	*n.d.	*n.d.	—	This paper	Conical
14	28	29	27	28	*n.d.	*n.d.	*n.d.	*n.d.	—	This paper	Conical
0	—	—	—	41.6	—	—	—	46.7		Wimmer 1994	Conical
0	41	—	—	42	—	—	—	44	—	Recalculated from Reiter 1983	Cylindrical
Ta_s											
0	*n.d.	233	286	350	395	414	—	405	—	This paper	Conical
14	*n.d.	*n.d.	*n.d.	300	296	414	—	405	—	This paper	Conical
0	—	—	—	75	84	—	90	—	117	Wimmer 1994	Conical

*n.d. - not detected (Rotation frequency of cone stirrer was restricted).

study, a value of $Ta_S = 400$ is reached at $S = 0.12$ and not increasing for higher gap width.

In the flow-through mode at $Re_{ax} = 14$, the critical Ta number values are found to be higher than for $Re_{ax} = 0$. This is in good agreement with all the papers summarized by Reiter (11) for cylinders. However, the Ta_c value for $Re_{ax} = 14$ was found to be constant at $Ta_c = 28$ for different gap width up to $S = 0.1$. Also the Taylor number for stable Taylor vortex flow was found to be constant at $Ta_S = 300$ and independent from gap width at $Re_{ax} = 14$.

Corresponding to the findings for rotating cylinder (Kay and Elgar (17)), Figure 3 summarizes four fluid flow modes in the $Ta^2 - Re_{ax}$ plane of flow-through cylindrical cones: (1) WVF-wavy vortex flow, (2) WAF-wavy angular flow, (3) TVF-Taylor vortex flow, (4) TuF-turbulent flow. This diagram includes all variations of investigated operational parameters (angular speed, gap between the concentric cylinders, fluid viscosity, and axial flow). Four principal regions are detected. The transitions from one flow pattern to another are separated qualitatively.

It is obvious that the patterns do not only depend on Ta as could be predicted but also on the flow through the reactor. In batch operation ($Re_{ax} = 0$) and $Ta > Ta_c$ three flow patterns were observed (WVF, TVW, and TuF). The WVF, TVF, and TuF patterns were also observed for $Re_{ax} < 100$. For $150 < Re_{ax} < 300$ an additional pattern was detected (WAF). At these Re_{ax} values, the axial flow has a significant influence. At high axial flow ($Re_{ax} > 350$) only the WAF and TuF patterns were observed. Here, the flow pattern's transition takes place at $Ta^2 \approx 1.2 \times 10^5$. An additional observation is that the TuF pattern was always found at high angular speed ($Ta^2 > 1.2 \times 10^6$) independently of the Re_{ax} value.

For the sludge conditioning processes, the cone stirring reactor has been designed to operate at $Ta^2 > 0.5$ to 5×10^5 and $100 < Re_{ax} < 400$. At these

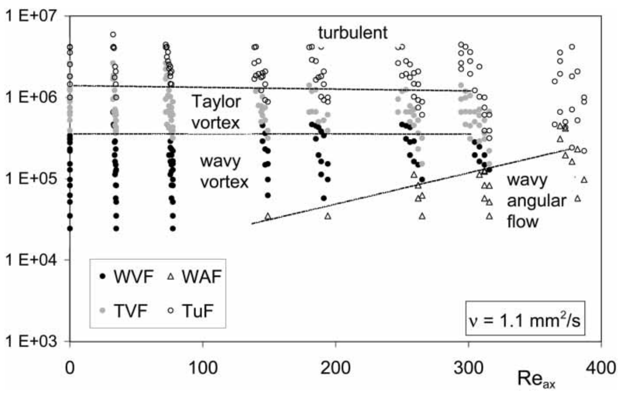

Figure 3. Fluid flow mode regions of the flow-through cone-stirring reactor (laboratory scale; cone base below) in Ta^2-Re-plane.

operational conditions, the correlation of the four detected flow patterns (WAF, WVF, TVF, and TuF) with the sludge conditioning has to be analysed.

FLOCCULATION AND DEWATERING

Analytical Methods

The total solids (TS) of sludge were measured according to the German standards (DIN). The TS of both the sludge before flocculation and the dewatered sludge were analysed.

The sludge aggregate size distribution of flocculated sludge was measured using a sensor based on a Charge-Coupled Device (CCD) line scan camera, a light source and an image processing software. The flocculation analyser is described in Sievers et al. (6). For practical purposes and based on previous experiments the aggregate size analyser is calibrated individually according to the needs of each sludge and WWTP. By means of this optical measuring system, the sludge is automatically scanned and evaluated on-line. With this particle-oriented measurement technique, specified distribution characteristics of the aggregates are determined (i.e. cumulative, density, and relative distributions).

Experimental Lab-scale Methods

The sludge of three different wastewater treatment plants (WWTPs) was collected and treated. The polymer type was ZETAG 7631 and the dose was changed in steps of 1 g polymer (as active substance) per kg TS between the range of 5 to 10 g/kgTS.

For the classical laboratory flocculation, the suitable polymer type with concentration of solution of 1 mass-% was dosed by pipette in a stirred sludge volume 500 mL (cylindric glas vessel). The mixing time was at 100 to 120 rpm for about 30 seconds before dewatering. This mixing time was selected as best before aggregates breakage as described in (1) will start. This was found using the mentioned aggregate size analyser. For the flocculation with conical cylinders in lab scale the classical flocculation was done first in the same manner as described. Secondly this sludge was treated with the lab scale cone-stirring reactor for additional 30 s and without any further polymer addition. The lab scale cone-stirring reactor was operated in the WVF fluid flow mode region with Taylor number of about 30 to 40 and Re_{ax} close to zero.

The influence of both, the classical and the new type of flocculation on the dewatering efficiency as well as on the sludge aggregate size structure was investigated. The dewatering efficiency was measured with the filtration test method as follows. A filtration cell of 500 mL volume was filled up with flocculated sludge and closed. At time zero the pressure was switched to 3 bar by opening a magnetic valve in the pressured air pipe. The system was operated automatically while the filtrate volume was registered continuously by analytical balance. Either the filtration time of 60 seconds or the filtrate volume of 50% were used for evaluation. Additionally, a hydraulic sludge press cell (diameter 50 mm, pressure 10 bar) has been used to dewater 100 ml of flocculated sludge within a time of 30 min. This dewatering test leads to thin filter cakes (approx. 5 mm) and should provide realistic values of total solids in dewatered sludge which may be comparable with dewatering applications.

Aggregate Size Structure

Compared to classic flocculation, the number of aggregates smaller than approx. 1,500 μm is drastically reduced for all three sludge types by post treatment of flocculated sludge with the cone stirring reactor, as presented exemplary for two types of sludge in Fig. 4. In all cases, the polymer dose was about 7.5 g/kgTS. These results indicate that the post-treatment by the cone-stirring reactor improves the flocculation by low shear forces leading to an additional aggregation of smaller aggregates compared to classical flocculation systems.

Dewatering Efficiency

Table 2 shows a comparison of filtration time for classic and cone-stirring flocculated sludge measured by the lab filtration test cell. The same three sludge samples mentioned above and the same polymer dose of 7.5 g/kgTS were used. The filtration time represents the time for filtration of 50% of sludge volume (=250 mL). The cone-stirring reactor improves the filtration process since it leads to a time reduction between 15 and 28%. Taking into account the results of Fig. 4, the change in aggregate size structure with cone-stirring reactor seems to be the main reason for improving the solid-

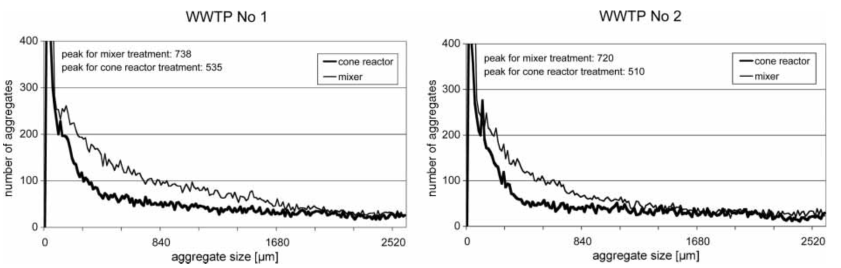

Figure 4. Aggregate size distribution of flocculated sludge for different flocculation procedures and sludge types for constant polymer dose of 7.5 g/kgTS.

Table 2. Filtration time results for 50% water remove by the laboratory filtration test

Sludge type	Classic	Cone stirring reactor	Relative improvement (time reduction)
WWTP No 1	111 s	94 s	15%
WWTP No 2	204 s	146 s	28%
WWTP No 3	154 s	114 s	26%

liquid separation efficiency, because the lower number of small aggregates should lead to higher filter cake drainage efficiency.

Table 3 summarizes the results of the press test for the same three sludge types. Three different polymer doses were analysed and for all polymer doses the post treatment with conical stirrer lead to an improvement of the dewatering efficiency in terms of TS in dewatered sludge by more than 3%-points. Only one test run shows smaller improvement (test run 7.0 g polymer/kgTS for WWTP No. 3). This difference is subjected to the difference of charge condition of sludge water and a minimum of 7.5 g polymer/kgTS is needed for destabilisation of aggregates.

These achievements are only based on post treatment of flocculated sludge with cone stirrer. All other parameters were kept constant and the useful flow mode region of cone-stirring reactor is the wavy vortex flow (WVF).

Link between Aggregate Structure and Filtration Efficiency

The diagram in Fig. 5 left hand gives the filtrate volume produced by filter test method for the same three sludge types within a constant time of 60 s. The

Table 3. Dewatering results based on flocculation procedure

Sludge type	Polymer dose [g/kg TS]	TS dewatered sludge [%]		Improvement [%-points]
		classical	cone stirrer	
WWTP No 1	7.0	27.2	30.6	3.4
	7.5	28.2	31.4	3.2
	8.0	28.4	31.5	3.1
WWTP No 2	7.0	29.3	33.1	3.8
	7.5	29.9	33.5	3.6
	8.0	30.5	34.1	3.6
WWTP No 3	7.0	17.1	18.3	1.2
	7.5	28.6	32.3	3.7
	8.0	29.1	32.5	3.4

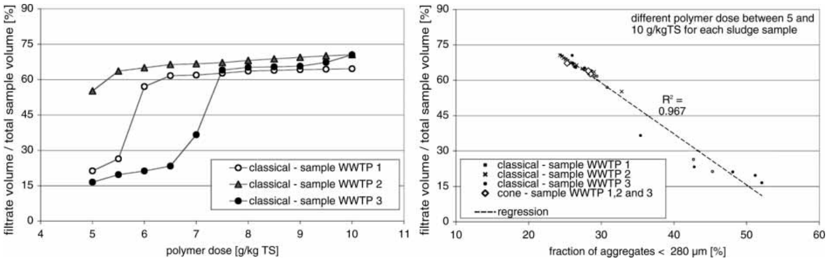

Figure 5. Filtration test results as a function of specific polymer dose (left hand) and as a function of corresponding aggregate size fraction (right hand) for different sludge types and flocculation procedures.

three different curves are obviously characterizing different types of sludge. For these three sludge types, the aggregate size distribution was measured during mixing and flocculation in the cylindrical glass vessel. The measured filtrate volume of Figure 5 left hand is plotted as a function of corresponding fraction of aggregates smaller than 280 μm at the end of flocculation in Fig. 5, right hand. There is a very good agreement between filtration efficiency and the number of aggregates smaller than 280 μm. This agreement seems to be valid independently of the flocculation procedure since the aggregate size structure resulting from the Taylor vortex assisted flocculation fits also the linear regression line but more close to the results of classic flocculation obtained at higher polymer dosing rates.

FULL-SCALE FLOCCULATION AND DEWATERING

For full-scale experiments, an up-scaled cone-stirring reactor with following reactor geometry was used: Average radius of inner cone 400 mm, height of inner cone 700 mm, gap width between outer and inner cone adjustable between 2 and 20 mm. This reactor was placed onsite in the sludge dewatering treatment line of six wastewater treatment plants (WWTP). The continuous flow rates of sludge through the flocculation system were adapted to the common operating point of existing dewatering machine of each WWTP and therefore set between 3 and 10 m^3/h. The sludge was pumped from a stirred sludge storage tank enabling constant sludge properties for every test run. The flow rates of sludge and polymer and all mixing parameters of flocculation system were automatically controlled and kept constant during the test run. To evaluate the potential of the new conditioning system, a repeated mode switching between classical and the two-step flocculation process was realized for the continuous application. Each mode was operated constantly for several hours and representative dewatered samples were collected after at least 30 minutes with respect to the solid retention time in the used dewatering machines. Samples for TS analyses were collected at two different times and measured twice for each mode. For comparison of different flocculation procedures, the average TS values were calculated over all modes repeated. The full-scale cone-stirring reactor was operated in terms of Ta^2 and Re numbers of approx. 2×10^5 and 200, respectively. This will lead to a flow mode close to the stable Taylor vortex flow mode region showed on Fig. 3. The classical flocculation was done with existing system at optimised operational parameters based on previous experiences of staff from each WWTP.

The results of these experiments in terms of polymer dosage and dewatering efficiency are summarized in Table 4. It can be seen that the post treatment according to Taylor vortices leads to higher TS in the dewatered sludge of approx. 3 to 5%-points. The results at WWTP Telgte showed lower increase of TS by 1.6%. At these experiments, the Ta^2 and Re were approx. 2×10^4 and 200 respectively and the flow mode region given in Fig. 3 seems to be close to a wavy angular flow mode instead of stable Taylor vortex flow mode. The results of Hayingen WWTP show no increase of TS due to the cone-stirring reactor but a drastically reduced polymer dose needed for

Table 4. Full-scale sludge dewatering results - comparison of classic to Taylor vortex induced post aggregation in cone-stirring reactor

		Classic		Cone-stirring reactor	
WWTP	Dewatering system	Polymer dosage (kg/t TS)	TS (%)	Polymer dosage (kg/t TS)	TS (%)
Bernburg, D	Flottweg Decanter Z4D-4/454	15.0	21.2	13.5	26.3
Effretikon, CH	HUBER ROTOMAT Centrifuge RoD 1500	17.0	25.0	14.8	28.1
Oelde, D	Westfalia Decanter AD1220	7.4	24.8	6.9	29.5
Scharzfeld, D	HUBER ROTOMAT Screw Press RoS 3Q	12.8	24.0	12.8	27.3
Hayingen[a,b], D	HUBER ROTOMAT Screw Press RoS 3	32.0	20.7	15.0	20.6
Telgte, D	HUBER ROTOMAT Centrifuge RoD 1500	13.1	25.2	13.7	26.8

[a]Extremely low temperature approx. 2°C.
[b]Low flow rates (10 m^3/h system used for 3 m^3/h).
D – Germany, CH – Switzerland.

achieving the same dewatering efficiency. This time, the sludge temperature was extremely low (2°C) and Ta^2 and Re were approx. 6×10^4 and 30, respectively. These lower numbers are based on the approximately three times higher sludge viscosity and lead to a wavy Taylor flow mode region far from stable Taylor vortex flow mode region (TVF) in Fig. 3. However, it should be noted that the scale-up of the used Ta and Re number calculations has not been experimentally confirmed yet and is subject of future research.

CONCLUSION

A post flocculation in a gap of conical cylinders as second step after classic polymer induced flocculation was investigated. This posttreatment allows both improvement of aggregate formation in terms of lower number of small aggregates, e.g. smaller than 280 μm, and enhancement of sludge dewatering process efficiency in terms of both increased TS of dewatered sludge and reduced polymer doses. Key of the successful posttreatment for enhanced sludge dewatering efficiency seems to be the flow mode region of stable Taylor vortex flow. A good linear regression between the aggregate fraction smaller than e.g. 280 μm extracted from aggregate size measurement of flocculated sludge and sludge filtration test results confirms that post treatment by the Taylor vortices in the gap of conical cylinders is more efficient to reduce the fraction of small aggregates at less polymer dose. This is subjected to lower and more uniform shear rates under the Taylor vortex flow regime and has been confirmed both for lab-scale and full-scale investigations by characterization and identification of different flow mode regions in a Taylor-Reynolds number plane. However, it should be noted, that the flow mode regions of full-scale reactor in the Ta-Re number plane need experimental confirmation to ensure correct Ta and Re calculations for up-scaling.

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