Recent studies have shown that the control of pond depth can be used to improve the performance of centrifuges used in a wastewater treatment plant.

Centrifuges are widely used in wastewater treatment plants (WWTP) for dewatering and thickening of sludge. Since flow rate but also sludge dewatering properties and composition are subject to large variations in WWTP, automated control of operating parameters is paramount to meet target performance in terms of centrate clarity as well as dry substance of solid product. Besides upstream feed homogenising measures, control of rotational bowl speed and/or differential speed (between scroll and bowl) and polymer dosage, as well as the pond depth level, can be controlled. Within limits the pond depth level can be adjusted by intentionally restricting the natural flow through the weir openings by a choke plate. With a decreasing gap between the weir openings and the choke plate, flow resistance increases resulting in a deeper pond. A deeper pond results in higher residual moisture of the solid discharge fraction under otherwise constant conditions and vice versa. If the centrifuge operates in the mixing regime, a deeper pond results in a better centrate quality, i.e. better clarity. At a WWTP large scale tests reveal that the concentration of the thickened sludge can be improved by a factor of two at otherwise constant performance data when the pond level is reduced.

Introduction

The separation of solid particles from a continuous liquid stream is a common task in many process industries, for example wastewater treatment and the food industry. Depending on the main objective of the separation task, it is the dryness of the solid-rich stream (often termed the product stream or cake), the cleanliness of the liquid-rich stream (referred to as the centrate) or the total capture of solids that is in focus.

A continuous feed stream enters the centrifuge axially where it is redirected and enters a rotating bowl. The separation between the solid particles (disperse phase) and the liquid phase (continuous phase) relies on the principle of sedimentation, which in turn requires a different density between the two phases. In order to improve, i.e. accelerate the sedimentation process, the bowl and with it the introduced suspension, rotate at high speed creating a large gravitational acceleration that acts on the dispersed particles. Due to the high centrifugal forces, the liquid forms a liquid pool that is symmetrical to the rotating axis. Particles move towards the outer wall of the centrifuge where they are collected. Figure 1 displays schematically a side view of the centrifuge cross-section. In a solid bowl centrifuge the solid particles are preferentially moved towards one end by a scroll conveyer which rotates at a different speed to the bowl, while the liquid stream exits at the opposite end.

Generally a centrifuge is geometrically designed for a specific feed which is

![Figure 1: Schematic of a cross-section of a bowl centrifuge with axial feed and separated exit of liquid and solid phases.](image)
Influence of operating parameters on centrifuge performance

The performance of a centrifuge, i.e. the solid/liquid separation, is of often described by the sigma model (but also by the surface flow model, Reuter, H. [8, 9] or Gosele, W. [10]) which is based upon the settling of a single particle in a centrifugal field under cylindrical geometrical constraints. Although the sigma theory does not fully hold in reality due to its inherent simplifications, it is nevertheless widely used for reasons of comparison – for example, Ambler, C. M. [11].

The flow rate Q is given by:

$$Q \propto x_s g z \frac{r_a^2 - r_i^2}{2n_{hiv}}$$

where $x_s$ denotes the cut particle diameter; L is the axial distance between the feed entrance and the liquid discharge; $z$ is the ratio between centrifugal acceleration (based upon the external radius $r_a$) and gravity $g$; and $r_i$ and $r_a$ are the bowl and the weir radii, respectively. In theory, the cut diameter identifies the threshold between particles that exit the centrifuge with the centrate (all the smaller particles $x_s$) and the particle fraction that leaves the centrifuge at the solids discharge end. A smaller $r_a$ for example with a deeper pool, would result in a larger critical cut diameter and therefore more particles in the centrate.

Contrary to these simple theories, tests revealed that the separation efficiency of the centrate is basically independent of the pool depth [9] due to secondary flow phenomena. Moreover, Hilditch & Rushton [12] reported that a deeper pool may result in even better centrate clarity. Stahl & Langeloh [13] suggested that centrate clarity deteriorates significantly when a critical feed rate is exceeded compared to what the sigma theory would predict. They claim that rotation of the scroll conveyer, i.e. solids transport, leads to significant re-entrainment of the solids already settled. For a laminar case the flow rate Q is given by:

$$Q \propto x_s g z \frac{r_a^2 - r_i^2}{2n_{hiv} b_k}$$

where $b_{hiv}$ and $b_k$ denote the pool depth and the width between the scroll conveyer blades, respectively – Stahl [14].

The theoretical (and certainly idealised) theories suggest that under the settling regime, an increase of the feed rate can be compensated for by increasing $r_a$ (decreasing the pond depth) under the premise of the same critical cut diameter of the particle and thus the same centrate quality. However, once a critical feed rate $Q_{crv}$ is exceeded, settling is not the predominant mechanism that determines centrate clarity (separation efficiency), but rather the mixing or re-entrainment regime. Unfortunately, the critical feed flow is difficult to predict. In the mixing regime an increase of the feed rate can be compensated for by decreasing $r_a$ (increasing the pond depth) to allow for the same critical cut diameter. In other words, an improvement of the centrate clarity can be accomplished with increasing pond depth.

The influence of the differential speed on the clarity of the centrate is quite complex and an optimal differential speed can be identified – Alt, C. [15]. When the differential speed is too high, the phenomenon of re-entrainment due to mixing prevails and the clarity of centrate deteriorates. But when the differential speed is too low, the solids quantity and therefore the volume with a higher solid concentration increases. Consequently particle sedimentation may worsen resulting in a lower clarity of the centrate.

An increase of the bowl rotational speed (higher $z$ results in better/faster settling. This correlation is valid in both the settling and mixing regimes (see Table 1).

Final dewatering of the product occurs during the stage when the solid cake leaves the pond until it exits the centrifuge. The differential speed between the conveyor and the bowl sets the retention time for the solids in the bowl. An increase in the rotational speed means a

**Table 1: Trends of operational measures on few problem situations.**

<table>
<thead>
<tr>
<th>Situation</th>
<th>Rotational speed</th>
<th>Differential speed</th>
<th>Gap distance (settling regime)</th>
<th>Gap distance (mixing regime)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower feed rate</td>
<td>Cake too dry</td>
<td>↓</td>
<td>↑</td>
<td>(deeper pool)</td>
</tr>
<tr>
<td>Higher feed rate</td>
<td>Cake too wet</td>
<td>↑</td>
<td>↓</td>
<td>(shallow pool)</td>
</tr>
<tr>
<td>Higher feed rate</td>
<td>Centrate clarity too low</td>
<td>↑ (optimal)</td>
<td>↑ (shallow pool)</td>
<td>↓ (deeper pool)</td>
</tr>
<tr>
<td>Lower feed rate</td>
<td>Centrate clarity too high</td>
<td>↓ (optimal)</td>
<td>(deeper pool)</td>
<td>(shallow pool)</td>
</tr>
</tbody>
</table>

characterised by the flow rate, solids content, particle size distribution, densities of liquid and solid, and the targets, i.e. cake dryness and centrate quality. Under changing conditions rotational speed and differential speed between the bowl and the scroll conveyer represent the main operating parameters that can be adjusted for meeting the separation task. But restrictions apply for the maximum rotational speed due to mechanical constraints and the motor, and for the differential speed due to the gear unit used. (Of course, the centrifuge’s geometry could be changed, for example feed tube length, scroll conveyer geometry, pond level control plate, or the length of cylindrical or conical sections. However, this would require substantial work and are not appropriate measures to cope with temporary changes.)

As well as rotational speed, the pond depth represents another operating parameter to cope with changing conditions. Different concepts have been proposed to change the pond depth during operation. When two V-shaped weir plates are rotated against each other, the weir height and thereby the pond level can be adjusted gradually, which can also be accomplished during operation – Gaessler, v. W. & Fink, E. [1]. A similar system proposed by Schilp, R. & Epper, E. [2] involved a continuous liquid pool level system that adjusts the apertures of the weir laterally from the outside. In addition, Kellnberger, A. [3] used the same concept but instead of having the weir adjusting part rotating, he suggested two adjacent weir plates with the inner weir plate rotating with the drum and the outer one basically fixed and only laterally adjustable. The pond level adjustment is accomplished by rotating the outer weir plate eccentrically. A stepwise change of the weir level can be accomplished by having two weir plates with different diameters available. The smaller inner one determines the pond level until the axial gap between the two plates vanishes by moving the larger outer plate axially – Ostkamp, W. [4]. Figgener, H. & Brüning, P. [5] and Seaburg, R.A. & Hanson, J.D. [6] proposed a non-rotating choke plate that is laterally adjusted towards a rotating weir. With the gap decreasing, resistance to flow increases in the channel and consequently increases the pond level, allowing for continuous pool level adjustment. Feldkamp, B. et al. [7] refer to a non-rotating liquid discharge weir that contains an annular cup containing one or more openings which are located such that the flow of the centrate can exit either in the axial or radial direction.

This contribution elaborates on the potential to control the pond depth for coping with varying feed conditions. Consequently a concept is investigated where a choke plate is laterally adjusted towards a weir, and both, choke and weir plate, rotate with the same speed.
lower residual moisture of the solids discharge as a consequence and vice versa. An increase of the differential speed reduces the solids residence time in the centrifuge, giving a cake with higher moisture content. A similar effect is accomplished when the pond level increases in the conical discharge section, which reduces the residence time of the cake outside the pool. The trends are indicated in Table 1 and are also discussed by Alt, C. [15] and Day, N. [16]. Of course, the pool depth of the conical section is linked with the one in the cylindrical section, i.e. a shallow pond in the cylindrical section also results in a shallow pool in the conical one and vice versa.

Three different operating parameters can be adjusted to cope with a varying feed situation in terms of quantity and separation properties: rotational speed of the bowl, differential speed and pool depth. For sludge treatment, polymer addition is commonly used, which impacts strongly on centrifuge behaviour. Generally there is an optimal polymer dosage which results in improved settling and therefore high centrate clarity. This flow situation cannot be described adequately by the Bernoulli equation, since stream lines do not remain parallel. Nevertheless it has been used for an incompressible fluid, for a simplified geometry and an axis-symmetric pond level, i.e. the radial fluid velocity vector at the pond level surface is negligible. Correction factors are introduced that account for the supplementary increase of pressure and velocity.

Tests with three different settings were performed with an ANDRITZ D7 series solid bowl centrifuge, with a bowl diameter of 750mm. Water was used with a density \( \rho = 1000 \text{ kg/m}^3 \) and dynamic viscosity \( \mu = 0.001 \text{ Pa} \cdot \text{s} \). The rotational speed was 2200 rpm. The head wall of the bowl has four openings. Figure 3 shows the experimental parameters and results, together with the simulation. The agreement is excellent given the simplistic flow description. The adjustment parameters, especially the pressure coefficient, depend upon the actual geometrical situation and they need to be determined based on the experimental tests.

### Wastewater treatment plant tests

At a wastewater treatment plant, a test series #1501 was performed with an ANDRITZ D7 series centrifuge where the geometrical setting remained the same except for the size of the gap. The feed concentration was between 6.6 and 7.2 g/l solids. The tests focused on the thickening performance – the cake dryness and centrate clarity. Qualitatively it was observed that a reduction of the gap (through an increase of the pond depth) resulted in a better capture rate and consequently better centrate clarity. This indicates that the centrifuge operated in the mixing regime rather than the settling regime. Tests also confirmed that an increase of the bowl speed through the rotational velocity or a decrease of the throughput, gives an increase in the cake dryness (results not shown here). These tests showed that for thickening applications the Easy Pond System is very useful to cope with varying sludge concentrations and flow rates.

Figure 4 shows the concentration of the thickened sludge versus the operational range of the total crest in percentage terms, together with the influence of the differential speed in rpm. Clearly with increasing differential speed, the concentration of the thickened sludge decreases. Moreover with decreasing crest height through a decrease of pool depth, the concentration of the thickened sludge increases substantially. This is accomplished by a wider gap. When the gap is reduced the pool depth increases, which results in a lower concentration of the thickened sludge, i.e. a lower fraction of dry substance. But the influence becomes almost negligible beyond 60% of the set operational range. Thus the control of the centrifuge performance is very sensitive within a range of 20-60% at least for low differential speeds.

### Natural and enforced crest – model and experimental test

A natural crest develops in a centrifuge as the centrate flows over the weir. A further increase of the crest height can be accomplished when a disc or choke plate, called an Easy pond™ disk, is brought laterally close to the weir or bowl plate. The flow is redirected and forced through the ‘Easy pond gap’. The entire weir adjustment system is termed Easy pond System. The actual flow resistance depends on the gap and weir geometries. Friction results in pressure loss causing an increase of the liquid pond depth beyond the natural crest height. This flow situation cannot be described adequately by the Bernoulli equation, since stream lines do not remain parallel. Nevertheless it has been used for an incompressible fluid, for a simplified geometry and an axis-symmetric pond level, i.e. the radial fluid velocity vector at the pond level surface is negligible. Correction factors are introduced that account for the supplementary increase of pressure and velocity.

### Figure 2: Schematics of the centrate flow through the weir and the choke plate at different spacings. Left: natural crest – choke plate not in contact with the fluid. Right: enforced crest – choke plate in contact with the fluid.

### Figure 3: Volume flow versus gap distance as a comparison between tests and model simulations for different total crest heights (TCH) and perimeter weir openings (PWO). (For a given crest height, a 100% gap distance represents natural cresting.)

### Figure 4: Concentration of the thickened sludge versus the total crest height of WWTP test series #1501 in percentage terms, with a set operational range of a rotational speed of 2000 rpm, a feed rate of 58 m³/h, and a centrate quality of ≥ 90% (without polymer). Filled symbols denote a differential speed of 5 rpm, whereas open symbols show the dependence of the rotational speed on the concentration of the thickened sludge at a constant total and height of around 25%.
**Conclusions**

Controlling the pond depth through a change of the gap between the weir opening and a choke plate during operation gives an additional degree of freedom for better centrifuge operation. Such a feature is particularly valuable for large thickening centrifuges where it is very time consuming to stop the centrifuge, adjust the weir plate and start-up the machine again. This control parameter is combined with a control of the rotational speed of the bowl, the differential speed of the bowl and the amount of polymer provided to account for feed quantity and property variations. Thus the target of obtaining stable product streams in terms of thickened sludge concentration, capture rate and centrate quality can be accomplished even during large changes of the sludge characteristics and/or flow rate variations. Energy and polymer consumption are reduced in operating the centrifuge at its optimum performance. Since the rotating centrate flows out on a rotating choke plate, the Easy Pond System does not increase power consumption.

**References**


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