WP 1 – Carbon extraction for energy recovery

D 1.3: Compendium of best practices for advanced primary treatment

The project "Full scale demonstration of energy positive sewage treatment plant concepts towards market penetration" (POWERSTEP) has received funding under the European Union HORIZON 2020 – Innovation Actions - Grant agreement° 641661

Deliverable 1.3	*Compendium of best practices for advanced primary treatment*
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Deliverable lead:	Hydrotech
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Abstract	In this report the results of literature research and comparison with data of case studies of full scale enhanced primary treatment units are shown and compared to each other. Specific indicators for the comparison are defined followed by identification of available alternative technologies for primary treatment at municipal wastewater treatment plants (WWTPs). These technologies are described by functionality, efficiency and operational data. Finally an overview of the results is presented in form of a fact sheet for primary treatment processes.

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X	PU	Public
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Glossary

a	Annum (Year)
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
CEPT	Chemically enhanced Primary Treatment
DO	Dissolved Oxygen
DM	Dry Matter
Fil	Filtrated
HRT	Hydraulic Retention Time
N	Nitrogen
NTU	Nephelometric Turbidity Unit
TP	Total Phosphorous
PE	People Equivalents
oDM	organic Dry Matter
Q	Flow
PST	Primary settling Tank
RBF	Rotary Belt Filter
TN	Total Nitrogen
TKN	Total Kjehldahl Nitrogen
TOT	Total
SS	Suspended Solids
WP	Work Package
WW	Wastewater
WWTP	Wastewater Treatment Plant

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Executive Summary

Producing more biogas from sludge digestion is one of the main factors to reach energy-neutral or energy-positive WWTP operation. In the project POWERSTEP a primary goal is to remove as much energy rich primary sludge as possible from the system prior to the biological treatment without having negative effects on downstream processes and effluent quality in terms of nitrogen removal.

Within the project Work Package 1 addresses enhanced carbon extraction in primary treatment with different filtration technologies (drum and disc filters from Veolia Technologie AB - Hydrotech) tested in Case Study 1 (Westewitz, Germany) and 2 (Sjölunda, Sweden). To give scientific proof of the results and benchmark the performance against other competing technologies, process performance data has to be compared with other technologies used for primary treatment.

In this report the results of literature research and comparison with data of case studies of full scale enhanced primary treatment units are shown and compared to each other. Specific indicators for the comparison are defined followed by identification of available alternative technologies for primary treatment at municipal wastewater treatment plants (WWTPs). These technologies are described by functionality, efficiency and operational data. Finally an overview of the results is presented in form of a fact sheet for primary treatment processes.

1. Introduction

The globally growing energy demand has imposed new challenges on wastewater treatment. Wastewater treatment plants (WWTPs) should guarantee purification of wastewater to ever more stringent standards, but should also apply energy efficient treatment as energy is a major cost and environmental factor for WWTP operators.

According to German DWA 2013 municipal wastewater treatment plants (WWTPs) using activated sludge process have an energy demand of about 32-34 kWh/(PE*a), for treatment plants >10.000 PE, and are thereby one of the biggest energy consumers within municipalities.

On the other hand raw sewage has a theoretical energy potential of 175 kWh/(PE*a) (Remy et al. 2014), bringing up the idea of energy producing WWTPs.

In the frame of the European funded project POWERSTEP different approaches and technologies are tested in existing WWTPs (Case Studies) for turning WWTPs into energy producing facilities.

One of these approaches is enhanced carbon removal with advanced primary treatment via microscreen filtration (Work Package 1), tested in Case Study 1 (WWTP in Westewitz, Germany) and 2 (WWTP Sjölunda, Sweden). Detailed information concerning performances can be found in following Deliverables: D1.1, D1.2 and D2.1.

The aim of filtration in primary treatment is to extract as much carbon rich primary sludge as possible before the biological step and making it thus available for digestion (biogas production from primary sludge: 600 NL/kg oDM Biogas at 56% degradation rate; biogas production from excess sludge: 430 NL/kg at 50% at similar mean methane concentration in both sludge types (max. 60%), Remy et al. 2014).

1.1. Necessity of comparing technologies applied in POWERSTEP with other primary treatment processes

To evaluate the results obtained in POWERSTEP, technologies used in the case studies need to be compared with the state-of-the-art (conventional primary treatment) as well as with other already existing alternative enhanced primary treatment processes in respect of technology performance and design.

References for comparison are full scale (pilot) plants operated under European climate conditions.

1.1.1. Primary treatment processes within the process of WWT

To evaluate the different options for primary treatment it is important to understand the function of primary treatment within the process chain of a WWT plant as well as the processes up and downstream of primary treatment.

In a conventional WWTP the first step (prior to primary treatment) is mechanical cleaning by bar racks, coarse screens and grit chambers (Figure 1). The exact implementation and design of the mechanical cleaning stage strongly depends on the size and the influent characteristics of the WWTP.

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For plants with higher content of coarse screenings, meaning debris in form of rocks, branches etc. bar racks / screens with openings > 15mm (Metcalf and Eddy 1991) are used. To remove fine screenings, containing grease and scum, bar racks screens with openings < 15 mm are provided.

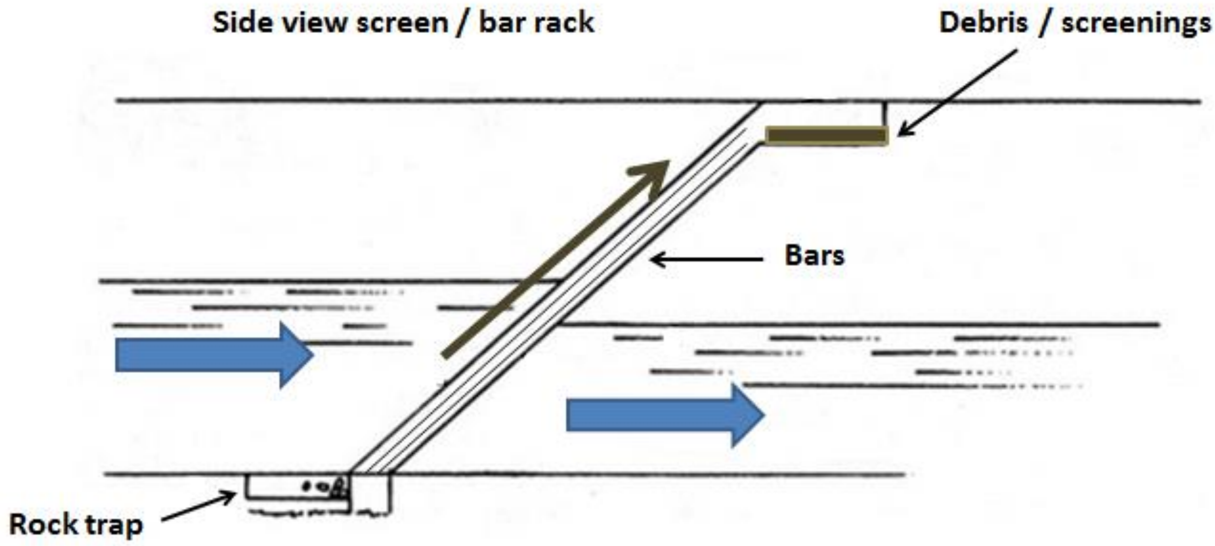

Figure 1: Scheme showing the side view of a screen / bar rack (adapted graphic)[1]

Bar racks or screens are followed by the grit chamber (Figure 2) to separate sand, gravel and other particles > 0.2 mm from the wastewater, as they are often cited as "cause for downstream problems" (Metcalf and Eddy 1991).

Basically there are three reasons for grit removal:

1. To prevent abrasion of moving mechanical equipment
2. To reduce formation of heavy deposits in pipelines etc.
3. To reduce frequency of digester cleaning due to the above mentioned reason

[1]original from the environmental department of Pennsylvania: www.slideplayer.com/slide/5731767/

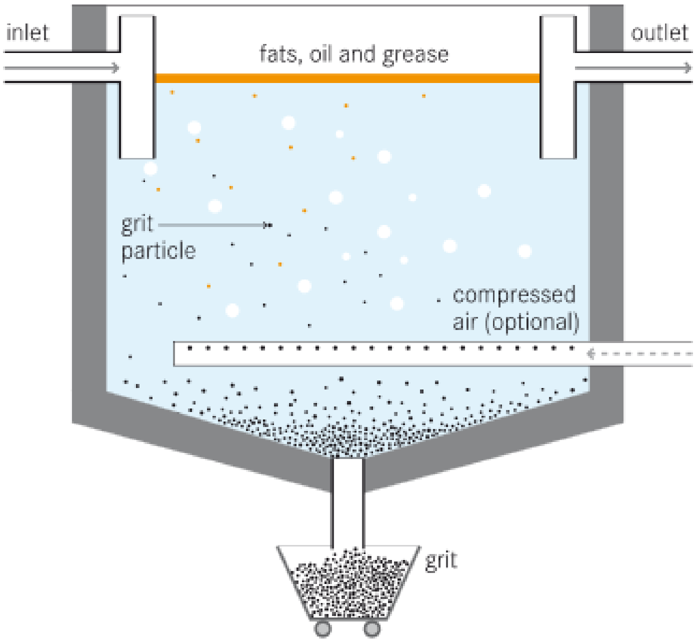

Figure 2: Schematic description of a grit chamber[2] (other tank designs possible).

After the grit removal primary treatment of the wastewater takes place. Thereby performance of primary treatment is not limited to carbon extraction. The removal of settleable solids, which could form sludge deposits, is also a vital function.

In addition suspended and colloidal solids have to be taken out of the process upstream of biological treatment reducing the organic load and thereby optimizing biological nutrient removal and saving costs. *Metcalf* & *Eddy* (1991) state suspended solids (SS) removal of 50-70% and BOD_5 removal of 25-40% for efficient primary treatment with settling tanks.

TSS, COD removal and reduction of organic load in primary treatment have to be considered when choosing indicators for evaluation of performance and design.

1.2. Procedure of comparison and evaluation

In the first step parameters were defined which reflect the technology performance and show the advantages and disadvantage of technology design (s. Chapter 2)

In a second step relevant technologies were selected. Literature was screened and case studies were searched for giving information on the chosen parameters (s. Chapter 3 and 4).

The selected parameters were applied to compare the already existing alternative primary treatment processes with the state-of-the-art (conventional primary settling tanks as baseline) as well as with micro screen filtration tested within the POWERSTEP project.

[2] Source: http://ecompendium.sswm.info/sanitation-technologies/pre-treatment-technologies

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Every alternative primary treatment process is described and evaluated in the following manner:

- Technology description
  - Principle
  - Plant construction
- Evaluation of performance and design
- Case Studies

In a final step the results of research as summarized in a factsheet (Chapter 4).

2. Indicators for comparison and evaluation

In order to compare identified technologies for primary treatment standardized indicators have to be chosen.

2.1. Indicators for Performance

As the most important indicators for performance removal efficiencies (given in %) the following were chosen: TSS (total suspended solids); COD (chemical oxygen demand); BOD (biological oxygen demand); TN (total nitrogen); TP (total phosphorus) as well as the related production of primary sludge. The European Commission has stated in its Urban Waste Water Directive (Article 2, paragraph 7) that 50% TSS and 20% BOD_5 have to be removed by primary treatment.

2.1.1. Total suspended solids (TSS)

Together with the BOD, TSS is the main indicator that is measured in primary treatment. Suspended solids are defined as solids that are removed by filtration of centrifugation under defined conditions (ISO11923:1997). Discharging large amounts of suspended solids into the environment can have negative impacts on water quality and the aquatic biota (Bilotta & Brazier, 2008). Early removal of these substances can decrease the load on subsequent biological treatment stages and hence contribute to the minimization of their footprint and resource use (e.g. oxygen or energy) (Siegrist, 2008).

2.1.2. Biological Oxygen Demand (BOD)

BOD is one of the oldest and common indicators for organic pollution in water treatment. It indicates the amount of oxygen which bacteria and other micro-organisms consume in a water sample at a temperature of 20°C to degrade the water contents aerobically. Standardized methods are ISO 5815-1:2003 and ISO 5815-2:2003. It is measured as BOD_n, where n is the incubation time equal to 5 days or 7 days (ISO 5815-1:2003). Often BOD_5 is reported. So BOD is an indirect measure for all biodegradable organic substances in the water and thereby an indicator for treatment quality of WWTPs concerning organic pollution.

2.1.3. Chemical Oxygen Demand (COD)

COD is a sum parameter used to measure the concentration of organic matter in wastewater and is correlated with BOD, which is more difficult to measure (5-7 days). COD is giving the mass concentration of oxygen equivalent to the amount of dichromate ($Cr_2O_7^{2-}$) consumed by dissolved and suspended matter when a water sample is treated with that oxidant under defined conditions (ISO 6060:1989). For this report TSS and COD are important because they indicate the amount of organic matter that can be sent to anaerobic digestion for producing a maximal amount of biogas. COD is also a suitable parameter for modelling carbon balances in WWTP models.

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2.1.4. Total Nitrogen (TN)

TN is the sum of all nitrogen fractions or the sum of total Kjeldahl-nitrogen (organic N + NH_4^+), nitrate-nitrogen (NO_3^--N) and nitrite-nitrogen (NO_2^--N). Standardized methods are described in ISO 29441:2010 and ISO 11905-1:1997. TN is usually removed by the biological treatment, as most nitrogen is in soluble form in the incoming wastewater and nitrogen is an essential building block in the synthesis of proteins and thereby biological growth. TN is typically only removed in a small amount in primary treatment.

2.1.5. Total Phosphorus (TP)

TP is the total amount of phosphorus in a sample, including free phosphates or bound to organic compounds (Hach, 2015). Standardized methods are ISO 15681 and ISO 6878:2004. Like nitrogen, phosphorus is a nutrient and known to be a limiting factor for the growth of algae. Phosphorus is present in soluble and particulate form, and is typically removed in biological treatment via enhanced biological P uptake (EBPR) or chemical precipitation with metal salts. TP is only partially removed in simple primary treatment due to the removal of particulate matter containing phosphorus, but can be removed by precipitation to a large extent.

2.1.6. Sludge production

Daily volume and concentration of produced sludge also need to be taken into consideration as the sludge has to be thickened and digested before disposal. For thickening, various options are available. The produced sludge can be either thickened by gravity (long retention time, adding to the spatial requirements (footprint) of the WWTP) or actively with polymer dosing and e.g. belt thickeners (which require energy and chemicals, i.e. higher costs.

2.2. Indicators for process design

To evaluate and compare the different primary treatment technologies their technological design operational indicators are analysed. In contrast to the indicators for performance these cannot be measured directly, but need to be calculated from design assumptions, balances and observations made during the planning and operation of a WWTP.

In terms of operational indicators the following parameters were chosen:

- **Energy consumption:** The energy consumption gives the amount of energy (kWh) that is needed to treat the wastewater. Specific energy consumption (energy per removed kg of TSS) is not only important for economically reasons, it is most important for optimisation of energy balance of the WWTP, which is a key task within POWERSTEP.
- **Chemical consumption:** chemicals can be added in primary treatment to improve removal efficiencies for small particulate matter and partly soluble substances. Coagulation agents (i.e. metal salts such as Fe or Al-based products) and flocculation aids (i.e. polymer) are typically used to enhance efficiency of primary treatment.

- **Spatial requirements (footprint):** Spatial requirements play a vital role especially for big WWTPs in urban areas. Footprint: The footprint is mostly dependent on the specific construction environment, targeted removal efficiencies, and quantities of wastewater
- **Investment and operation costs:** Investment and operating costs have to be looked into to design a realistic WWTP. The total capital costs are depending on many different factors such as engineering/ construction work, land preparation, infrastructure, investment in equipment and so on. Operating costs include chemicals as well as energy and employee costs for maintenance and operation. In Deliverable 1.3 only costs for building the technology and chemical costs for operating it are important, because other factors are assumed to have too much fluctuation and depend on geographical circumstances.

Often data are not given in absolute values, but as categories or values per amount of TSS or BOD_5 removed. So in this case the following definitions are applied to do comparison of different technologies:

Definitions for spatial requirements used by Lema (2017)

- Large = Standard PST
- Medium (up to 70 - 80% less of standard PST)
- Small (up to 90% less than standard PST)

Definitions for capital and operating cost used by Lema (2017)3

- High (50 - 120€ per (m^3/d) treated wastewater)
- Medium (25 - 70€ per (m^3/d) treated wastewater)
- Low (< 10€ per (m^3/d) treated wastewater)

For calculation of removal related costs a "standard" wastewater inflow to the WWTP is assumed according to DWA A131 with the characteristics shown in Table 1 and the arithmetic mean value minimum and maximum removal rates given in the references.

Table 1: Definition of "standard" wastewater inflow for calculation of removal related costs

Inflow volume	Water quality parameter	Influent Concentrations	Influent Loads
[L/(PE*d)]		[mg/L]	[kg/d]
120	BOD_5	500	0.06
	COD	1000	0.12
	SS	583	0.07
	TKN	92	0.11
	TP	15	0.0018

Emission of odorous and greenhouse gases are also taken into consideration in this report if data are available.

[3] Based on a 90,000m^3/d site

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3. State-of-the-art: Primary Settling Tanks (PST)

Mechanically-treated wastewater after screening, grit chamber and fat, oil and grease (FOG) removal still contains a large amount of suspended solids. A simple way to separate these solids is through sedimentation. Sedimentation is a gravity-driven process where particles settle when having a higher density than the surrounding media. PSTs are mainly constructed in two different shapes, rectangular and circular basins (Figure 3).

For rectangular shaped PSTs the influent enters the basin at one side and the effluent leaves on the other end, following a horizontal flow pattern. Chain- and flight sludge collectors or travelling-bridge type collectors are used and scraped into hoppers or transverse troughs to collect the primary sludge. The sludge is usually collected at the influent side of the tank and the scum at the effluent side. The advantage of using rectangular shaped PSTs in comparison to circular is the more compact footprint when requiring multiple basins.

Circular shaped PSTs have a radial flow pattern. The influent can enter the PST in two ways. The most common is the centre-feed design, where the influent is pumped into a central well and the flow is distributed equally into all directions. The other is (rim)-feed design, where the water is entering from the basin wall with a circular baffle. While flowing spirally around the basin the clarified water is transported to the centre of the basin and skimmed off over weirs. The scum is transported to an annular area close to the basin wall where it is removed. Metcalf & Eddy mentioned problems of the peripheral design with flow distribution and scum removal. The bottom of both types is sloped, so that the sludge can be scraped into a smaller hopper near the centre of the PST. The cleaning mechanism of circular PSTs is two or four arms with scrapers near the bottom of the basin to remove sludge and surface skimmers to remove scum.

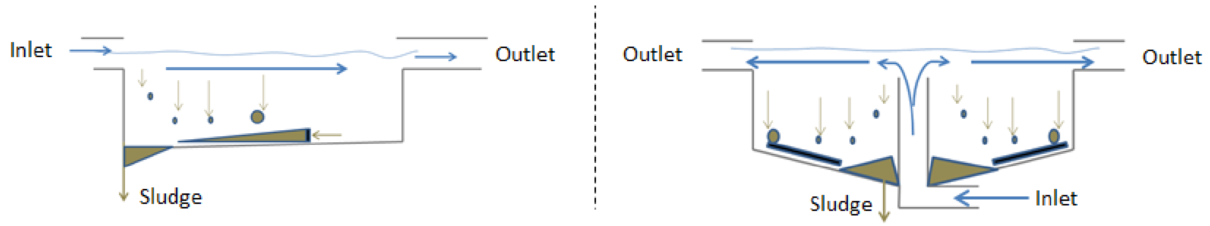

Figure 3: Schematic description of rectangular and circular PSTs.

Table 2 summarize the important parameters comparing rectangular as well as circular PSTs.

Table 2: Typical dimensions for rectangular and circular PSTs

Rectangular		Circular	
Depth	3 - 4 m	Depth	3 - 4 m
Surface area	120 - 400 m²	Surface area	117 - 1590 m²
Flight speed	1 m/min	Flight speed	0.01 m/min
Width	5 - 10 m	Diameter	12 - 45 m
Length	24 - 40 m	Bottom slope	83 mm/m

The surface overflow rate ranges from 0.6-4 m/h (Kemira, 1990), typically designed for 1-2 m/h (Ødegaard 1992). The hydraulic retention time is between 0.5 and 2 h (Ratnaweera et al. 1994). Depending on the TSS removal efficiency Jover-Smet et al. mentioned overflow rates ranging from 0.8-1.45 m/h resulting in a TSS removal rate of 55-65% (Jover-Smet et al., 2017).

Metcalf & Eddy reports that efficiently designed and operated PSTs lead to 50-70% TSS and 25-40% BOD removal rates. Similar efficiencies have also been reported by Lema & Suarez (2017). It is also possible to achieve higher removal efficiencies by reducing the surface overflow rate thus increasing the hydraulic retention time. Similar or lower (< 50%) removal results have also been published by Misund et al. (2004). **Fehler! Verweisquelle konnte nicht gefunden werden.** shows a summary of removal efficiencies gained by PSTs.

Table 3: Removal efficiencies for primary settlers in municipal wastewater treatment

Removal efficiencies [%]					Sludge concentration [kg/m³]	References
TSS	COD	BOD	TN	TP		
40 - 70	25 - 35	25 - 40	< 10	16 - 20	10 – 40	Metcalf & Eddy (2014), Lema & Suarez (2017), DWA BIZ 11.4 (2008)

PSTs are designed in a way to ensure satisfactory performance even at unfavourable conditions such as heavy rainfall (high flow) or low temperatures. They can be upgraded with chemical dosing to chemically enhanced primary treatment (CEPT) or with inclined plates. A main drawback of PSTs is the large amount of footprint required (s. Table 4). On the other hand one of PSTs biggest advantages is their simple operation and low maintenance needs. There are no costs for chemical cleaning and PSTs have a low energy usage. When multiple PSTs are necessary rectangular tanks get cheaper due to the possibility of using the walls for two tanks instead of one. Multiple circular basins are often arranged in groups of two to four.

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Table 4: Operational indicators for PSTs

Operational indicators				References
Spatial requirements (Footprint)	Energy-consumption [kWh/m³] [4]	Invest Costs	Operating Costs	
Large	0.016 – 0.029	High 50 - 100€ per (m³/d) treated wastewater =4.5 Mio. €[5]	-	Lema & Suarez (2017)
Large	0.002 - 0.003	High 67€ per (m³/d) treated wastewater = 400k€ for 50,000 pe plant (560 m³ tank)	-	POWERSTEP data

[4] Treated wastewater
[5] Assuming a 90,000 m³/d site

4. Advanced Primary Treatment Technologies

4.1. Chemically Enhanced Primary Treatment (CEPT)

To enhance the efficiency of treatment units and reach higher removals or treatment capacities without consuming more space, the wastewater can be treated with chemicals upstream of the primary treatment unit. The chemicals are used to (a) precipitate dissolved matter and (b) to increase the size/density of the particles. Chemical addition increases particle density (using metal salt coagulants or ballast) and size by allowing small particles form larger flocs and subsequently achieving higher sedimentation velocities. Particles in wastewater mainly have a negative charged surface. By dosing positively charged metal ions electrostatic repulsion is reduced and micro-flocs can be formed. The binding of micro-flocs and destabilized colloids by long-chain molecules (polymers) into macro-flocs is called flocculation.

Since the 1870's it is known that CEPT represents an upgrade of traditional technology for primary sedimentation tanks (Metcalf & Eddy, 2014).

Figure 4 gives a schematic description of a CEPT upstream of a PST. In the first process step the coagulant (Fe or Al salt) is added before the "Parshall Flume" working as a jet and providing the necessary high flow speed for coagulation. After the "Parshall Flume" flocculent (polymer) is added at lower flow velocities and therefore less sheer forces, giving a suitable condition to form stable macro-flocs.

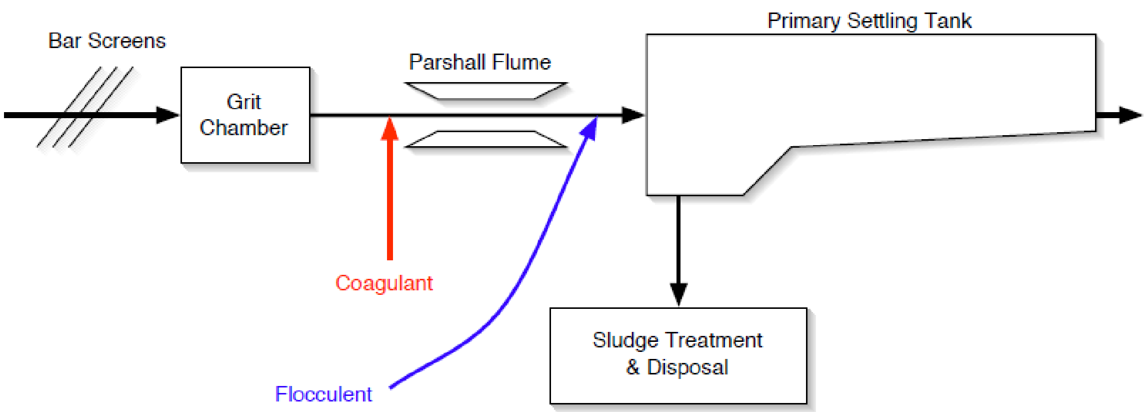

Figure 4: Scheme of mechanical treatment followed by CEPT (Chagnon et al, 2002)

Since wastewater conditions depend on location, dilution through rain events, daily time windows and the presence of industrial facilities, etc. in the catchment of the WWTP, it is recommended to run jar tests before designing a CEPT to find the optimal combination of chemicals and doses prior to putting the CEPT process in operation. The objective of the jar tests is to find the optimum chemical combination and dose required to achieve the desired treatment performance at the lowest possible chemical usage. With CEPT significantly higher removal rates can be achieved compared to simple sedimentation tanks.

Table 5 presents expected removal efficiencies using CEPT.

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Table 5: Expected removal rates for CEPT

Removal rates [%]					Chemical dosing [mg/L]	Sludge concentration [kg/m³]	Reference
TSS	COD	BOD	TN	TP			
80 - 90	55 - 75	40 - 80	10 - 20	60 - 80	20 - 60 mg/L coagulant 0.5 - 2 mg/L polymer	20 - 70	Metcalf & Eddy (2014) Lema & Suarez (2017) DWA BIZ 11.4 (2008)

In terms of operational indicators CEPTs show similar characteristics as primary settling tanks, but require a dosing station and chemical storage. Energy demand is slightly higher due to dosing of chemicals, which is also the main driver for higher operating costs. Table 6 shows a summary of expected values of the main operational indicators.

Table 6: Operational indicators for CEPT

Operational indicators				References
Spatial requirements (Footprint)	Energy-consumption [kWh/m³]	Invest Costs	Operating Costs	
Large	0.01 0.036	High 50 - 120€ per (m³/d) treated wastewater	0.01 - 0.074 €/m³ treated wastewater	Lema & Suarez (2017)
Medium up to 70 - 80% less of standard PST	0.006	High 133€ per (m³/d) treated wastewater = 800k€ for 50.000 pe WWTP (multiflo configuration)	1 mg/L polymer (active substance) 15 mg/L Fe = 0.026 €/m³	POWERSTEP data

4.2. Lamella Settler

In the lamella settler particles settle to the surface of the inclined plates or tubes and form a layer of sediment that is cleared by gravitation as long as it is small enough to slide down. Biological growth can occur on the plate layer or chemical flocs can accumulate on the plates if flocculent is dosed upstream which both can lead to a decrease of lamella settlers performance. As a protection measurement self-cleaning mechanisms can be installed to reduce the above issues.

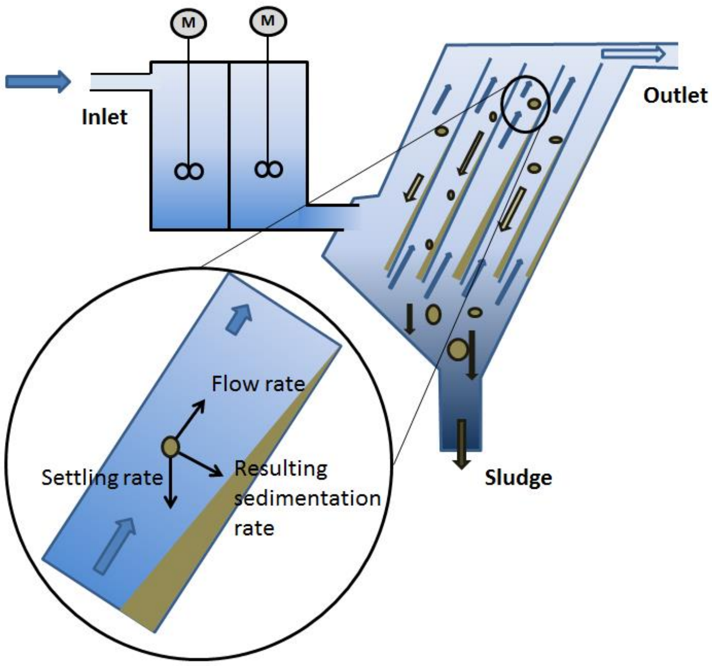

Figure 5: Schematic description of a cross-current lamella settler including chemical dosing, adapted graphic[6]

Another important point for a good operation is the disturbance of the water to be treated to the sedimentation of the separated substances. There are 3 different operation options: Counter-current, co-current or cross-flow. Figure 5 shows counter-current, meaning the water and the sediment flow are opposite, resulting in a high separation. Counter-current is the most common mode of operation among the three options. Co-current describes an equal water and sedimentation flow direction. It is recommended if the sedimentation rates are high as they are less likely to clog the pipes or plates, due to the better self-cleaning of the water flow. Cross-flow is a mode of operation in which the water flow is introduced vertically to the sedimentation flow, allowing for better separation if both sediment and floated are to be removed.

For further improvement of the removal rates it is possible to implement chemical dosing upstream. There is also the option to use recycled sludge as ballasted-sludge to increase sedimentation or flotation rates, reducing significantly the hydraulic residence times, and reduce the chemical consumption. The lamella settler technology is not common in municipal wastewater treatment. However, they are used for storm water treatment to avoid discharge of high loaded runoff into receiving waters.

Typical inclined plates are 1-2 meter long, 1.2 meter wide and have a 55° installation angle. Tubes are normally 1.8–2.4 meter long, have 0.3-0.6 meter diameter and feature 45-60° angles (Hendricks, 2011) resulting in a 6-12 times larger effective sedimentation surface area (Lema & Suarez, 2017). Plate/ tube packs can be integrated into existing PSTs if an increase of clarifier capacity is necessary. Achievable removal rates for lamella settlers are represented by Lema & Suarez (2017) and shown in Table 7.

[6]Original: http://encyclopedia.che.engin.umich.edu/Pages/SeparationsMechanical/ThickenersClarifiers/ThickenersClarifiers.html

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Table 7: Reported removal rates for lamella settlers

Chemical Dosing	Removal rates [%]					Chemical dosing [mg/L]	Sludge concentration [kg/m³]	Reference
	TSS	COD	BOD	TN	TP			
without	50 - 70	-	30 - 50	10 - 30	30 - 40	-	15 – 25	Lema & Suarez (2017)
with	60 - 90	-	40 - 60	15 - 20	60-75	20 - 60 mg/L coagulant 0.5 - 2 mg/L polymer	20 - 35	Lema & Suarez (2017)

In terms of operational indicators Table 8 shows a summary of expected values of the main operational indicators.

Table 8: Operational indicators for lamella settlers

Operational indicators				References
Spatial requirements (Footprint)	Energy-consumption [kWh/m³]	Invest Costs	Operating Costs	
Medium Up to 70 - 80% less of conventional clarifiers	0.016 – 0.028	Medium 25 - 40 € per (m³/d) treated wastewater =2.25-3.6 Mio. €[7]	-	Lema & Suarez (2017)
-	-	25 - 40[8] € per (m³/d) treated wastewater	-	Brinkmann (2016)

4.3. Microscreens

Micro-screens (also referred to as micro-sieves) are gravity driven self-cleaning units designed for solid separation with minimal footprint and low energy consumption. The removal of suspended solids is achieved by pore sizes of the filter material below 1000 µm. Due to their construction, thickening and/or dewatering can be achieved internally, i.e. in one unit. Common micro-screen design includes drum, disc and rotary belt filters.

[7] Assuming 90,000m³/d site
[8] Depending on the capacity of the plant

4.3.1. Drum- & Discfilter

Drum- and discfilter have a similar functional principle. Water flows into a central drum, which supports the woven media fixed to custom-made panels mounted directly to the drum (Figure 6).

During filtration, solids are caught on the filter panels, leading to an increase of the filtration resistance and to a rise of the water level in the central drum. When the water level between the inside (feedtank) and the outside (filtratetank) of the drum (s. Figure 6, left illustration), reaches a maximum value the drum starts rotating and backwash is initiated and the filter media is cleaned with filtrated water being pumped with approx. 6-8 bars through a set of backwash nozzles aligned outside the filtration elements. The backwash water permeating through the filter media washes the solids retained on the inner side of the drum off and the drum rotation lifts them into the tray mounted inside the drum, from there they are flushed into a sludge collection tank (not shown in the illustration). Filtration is not stopped during backwashing. Normally (as described above) the filtrate is used to rinse the filter media, but alternatively WWTP effluent can also be used depending on the type of unit installed.

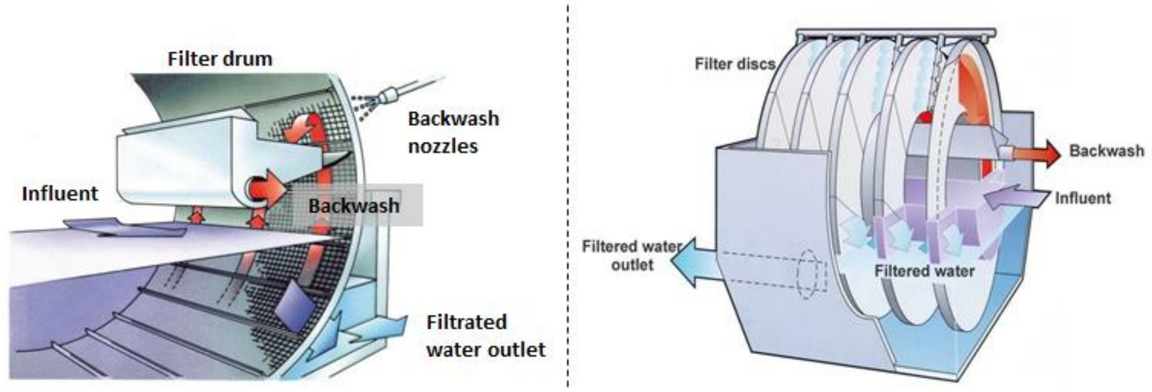

Figure 6: Schematic illustration of a drum- (left) and a discfilter (right)[9]

In case of filter overloads, the water, which cannot be processed, is by-passed via a set of weirs installed at the filter inlet or through a separate bypass channel. These overflows can be either mixed with filtrate or disposed separately. Coagulants in combination with polymer can be added prior to the microscreen in to improve the filterability and effluent quality. However such high removal can impact the performance of the biological stage downstream, especially the lack of phosphorus can become problematic for bacterial growth. Therefore the dosing in primary treatment with nutrient removal downstream is lower. Generally a chemical dose of 1-3 mg/L polymer is required to have a balanced removal of TSS in primary treatment. Polymer dosing can be combined with low coagulant dosing of about 1-4 mg Me3+/L for improved TSS and phosphorus removal (Väänänen et al. 2016).

The total hydraulic retention times for the microscreens are minimized to a few minutes allowing for real-time process control (Väänänen et al. 2017). Due to the short retention

[9] Source: Veolia Water Technologies, Hydrotech Microsceen Filters

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time for the sludge handling, lower greenhouse gas emissions and maximization of the energy recovery from the organic carbon can be expected by using microscreens in primary treatment. Real time process control can also enhance minimizing the chemical dose required. Research and operational efforts (POWERSTEP Deliverable 1.1) have proven that the pore size of the filters can be adjusted to target specific removal efficiencies in primary filtration applications as shown in Figure 7**Fehler! Verweisquelle konnte nicht gefunden werden.**. For the purpose of treating wastewater after screening, grit, oil, grease and fat removal, drum micro screens with pores of 100 µm are common/ recommended. Larger pores (200-500 µm) are can be suitable if chemical dosing is used upstream or a reduced effluent water quality is accepted (Väänänen, 2017).

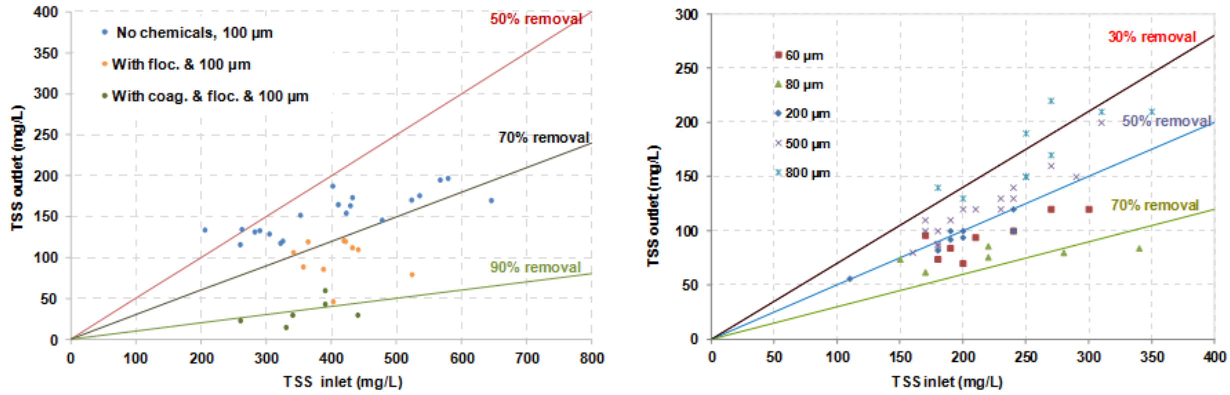

Figure 7: right: TSS removal in the filter depending on the pore size of the filter material; left: TSS removal at different chemical pre-treatment options (WWTP Lynetten, Denmark, data collected in the "Avera Project")

Hydrotech, as a one of different providers of micro-screens, delivers self-contained microscreens in steel or plastic tanks with an integrated control system and hardware to initiate, maintain and stop the self-cleaning mechanism. microscreens (drum or discfilters) allow loading rates 10-20 times higher than in PSTs and still achieve similar or even greater TSS removals. As the area in a microscreen is optimally packed within the footprint of the equipment, the space required for installation can be substantially reduced to be up to 90% smaller then PSTs. These options make drum and discfilters turnkey options for water treatment with low construction and operation costs.

As mentioned above, micro-screens can be used as a compact and cost-effective solution for primary treatment of municipal wastewater. Without chemical addition, removal efficiencies of about 50% of the TSS (equivalent to the removal efficiency obtained in primary clarifiers) are attainable. This percentage typically corresponds to 20-30% in BOD-removal. TSS removals can be enhanced by adding polymer in a flocculation stage upstream of the microscreen. With a correctly designed flocculation process, TSS removal in the order of 70-90% can be achieved this without increasing the sludge production (no chemical sludge is formed). The reduction of particulate organic fractions will follow accordingly. Additionally, this configuration allows for dissolved fractions of phosphorus to remain in the water, which could be of interest in certain applications. It is possible to consider a microscreen for a phosphorous pre-precipitation process. With a properly-designed coagulation and flocculation step more than 90% reduction of TSS and total P can be expected (Väänänen et al. 2016).

Table 9: Reported removal rates for drum- and disc filters

Chemical Dosing	Removal efficiencies [%] for 100µm pore size					Sludge production [kg/m³]	References
	TSS	COD	BOD	TN	TP		
without	40 - 60	up to 60	15 - 30	5 - 10	0 - 40	6 -14	Lema & Suarez (2017) Libhaber & Jaramillo (2012) Väänänen et al. (2016) Powerstep Data
with	80 - 90	up to 80	50 - 60	5 - 10	50 - 90	up to 25	

Microscreens need around 10-20% of PSTs footprint while maintaining equal, if not even better clarification of water. While operating the energy consumption can range from 0.005 to 0.03 kWh/m³ treated water depending on the type of filtration cloth used (10-1000 µm pores), the type of chemical pre-treatment applied, and the total suspended solids (TSS) loading pattern (Kängsepp et al., 2016, Remy et al., 2014)

Table 10: Operational indicators for drum- and disc filters

Operational indicators				References
Spatial requirements (Footprint)	Energy-consumption [kWh/m³] [10]	Invest Costs	Operating Costs	
Small up to 90% less of clarifiers	0.005 - 0.03	Medium 25 – 40€ per (m³/d) treated wastewater	-	Lema & Suarez (2017)
-	0.01[11]	-	-	Hey (2016)
Small	0.006 - 0.01 (incl. chemical dosing)	High 187 € per (m³/d) treated wastewater = 1.12 Mio € for 50.000 pe WWTP (incl. coagulation tanks, 456 m² filter surface)	13 mg/L Fe, 2.5 mg/L polymer (active substance) = 0.03 €/m³	POWERSTEP data

[10] Treated wastewater
[11] Including stirrers for flocculation and coagulation

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Piloting results demonstrate that both filter types are viable options for primary treatment of municipal wastewater, with minimal footprint, however discfilters might need a higher degree of pre -treatment due to the present of rags and larger objects and tests have been important in order to create sound design data and for establishing the technology in full-scale in municipal WWTPs.

4.3.2. Rotary Belt Filter (RBF)

As mentioned in the previous chapter microscreens can be provided as drum-, disc- or as rotary belt filters (RBFs). RBFs consist of a removable filter material attached to a moving belt of wire cloth (Lema & Suarez, 2017). The wastewater is filtered by pores in the filter material, which the water can pass through vertically. As the water flows through the belt, a filter cake (also referred to as sludge) forms on the surface of the material. By the rotation of the moving belt the particles get filtered and separated from the wastewater continuously. A typical unit structure and flow of wastewater through the RBF is shown in Figure 8.

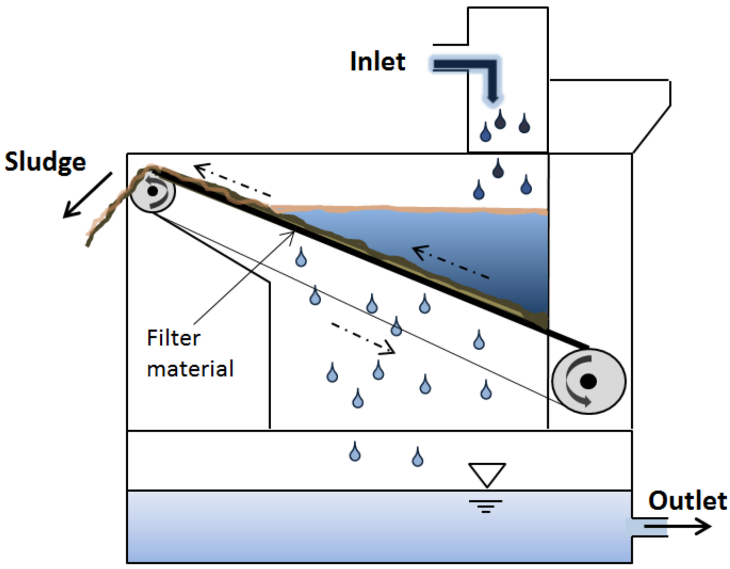

Figure 8: Simplified schematic illustration of a rotary belt filter

This filter cake is then removed by additional aid of a dedicated self-cleaning mechanism, which can be an air knife, water jet or mechanical devices that are cleaning the belt continuously (Lema & Suarez, 2017). Since particles are filtered not only on the surface of the belt but also in the belt, RBFs usually have the ability to backwash the belt with hot water to remove grease and oil accumulations and contaminants in the filter net. The self-cleaning of the RBF is applied after a filtration zone and is spatially in an elevated separated position of the filtration zone. While the RBF is working and wastewater is flowing into the screening chamber it is possible for the wastewater to rise and overflow the unit. To prevent this there is an overflow weir located on the upstream side of the belt (Franchi & Santoro, 2015). Typically RBFs are connected to a control mechanism to prevent over flow of the RBF by increasing the belt speed. By this the control mechanism enables and controls a proper self-cleaning and a control of overflow. In addition to the filtration of wastewater, RBFs provide the possibility of particle dewatering for easier removal and treatment of the filtrate. After removal from the belt by the cleaning mechanism, the separated filtrate is collected in a receiver in which it is simultaneously dried, compressed and removed dewatering within the RBF.

The mesh is available in different materials and openings. Most common for municipal applications are sieve pore sizes of 50-500 µm (Franchi & Santoro, 2015). Mesh openings below 500 µm are the most economically ones for primary treatment and 250-500 µm are normally proper choices for typical municipal wastewater. But the right size should be determined by screening tests before. Once a filter mat is formed on the sieve there is practically no difference in the performance of sieve cloths within the size range (Rusten & Ødegaard, 2006).

Depending on the requirements of the plant, the removed filter cake can be assumed to contain 20-30% of dry matter (Franchi & Santoro, 2015). Rusten & Ødegaard (2006) have even reported that 17-37% (average 27%) are possible and there is no significant difference between the mesh opening size or the operation with or without addition of chemicals.

RBFs are not subject to occurrences such as thermal stratification, wind, density currents, and high flow rates and biological activity (Franchi & Santoro, 2015). In order for wastewater to be treated satisfactorily in the RBF it should meet a few conditions: At least 20% of the SS should consist of particles larger than 350 µm and have a ratio of over 0.4 COD_{fil} to COD_{tot} (Rusten & Ødegaard, 2006). If these conditions are not met, it is necessary to implement chemical dosing upstream the RBF. The addition of coagulants and flocculants show less optimal results. This occurs due to fast agglomeration and particle growth during coagulation, which results in seemingly more TSS (for example) in the water to be treated and ultimately give the false impression of poor filtration performances (Franchi & Santoro, 2015). Achievable performances are presented in Table 11.

Table 11: Filtration performance of "Salsnes" rotary belt filter in municipal primary treatment with and without chemical dosing

Chemical dosing	Removal performances [%]					Sludge production [kg/m³]	Reference
	TSS	COD	BOD	TN	TP		
without	25 - 60	15 - 40	15 - 30	<10	0	30 - 200	Franchi & Santoro (2015) Lema & Suarez (2017)
with	65 - 75	46	41	-	15 - 20		

For chemical dosing numbers are represented of studies with polymer addition. Removal performances of RBFs depend highly on the mesh size of the filter mesh, the filtration rate (m³/m²/h) and the amount of particles to be filtered. It has to be mentioned, that recent studies show average removal performances of TSS around 45-55 %, COD around 30%.

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The main advantages for considering of RBF include low energy usage of estimated to ≈ 0.002 kWh/m³ treated water (Franchi & Santoro, 2015), compact foot print (up to 90% less than PSTs), modular installation, limited operation and maintenance requirements, and no requirement for further thickening of collected solids. Depending on the location of the prospect installation and process configuration additional potential advantages of RBF may include reduced capital and operation costs, energy savings, and overall reduction of CO_2 emissions.

Table 12: Operational indicators for rotary belt filters

Operational indicators				References
Spatial requirements (Footprint)	Energy-consumption [kWh/m³]	Invest Costs	Operating Costs [€/m³]	
Small 20 - 70 m²/unit up to 90% less of clarifiers	0.037 - 0.056[12] 0.061 – 0.103[13]	Medium 25 - 70€ per (m³/d) treated wastewater	0.016 - 0.04 chemical costs	Lema & Suarez (2017)
-	-	50% of conventional primary clarifiers	50% of conventional primary clarifiers	Rusten & Ødegaard (2006)

4.4. Dissolved Air Flotation (DAF)

In contrast to sedimentation, where particles accumulate gravity driven on the bottom of a tank, during in the process of flotation particles are lifted to the surface by introduction of fine air bubbles, which attach to the surface of the particles, reducing their density and enhancing the buoyant force.

Especially smaller solids, that settle slowly, or liquid particles (e.g. fat, oil and grease) can be removed "more completely in a shorter time" (Metcalf and Eddy, 1991)

In WWT different flotation processes are known, which differ in the way of air injection:

1. **(Dispersed) Air flotation:** Air is directly induced in the liquid phase by a revolving impeller or through diffusors, which is not very effective about flotation of solids, because of the large bubble size (100-1000 µm).
2. **Vacuum flotation**: The wastewater is first saturated with air either directly in the tank or by allowing air to enter the suction side of the pump feeding the wastewater into the tank. A vacuum is created at the suction side of the pump to achieve super saturation and to ensure that the air exits the solution in fine bubbles. As there is a limitation in pressure difference of one atm, there is also a limitation to the amount of air available for flotation

[12] Without chemical dosing
[13] With chemical dosing

3. **Dissolved air flotation:** The wastewater is saturated with air in a pressure tank (275-350 kPa) and retained in that tank for a couple of minutes so the air can dissolve in the water. In the next step the solution is fed via a pressure reducing valve into the flotation tank, where the air degases in fine bubbles (30 -120 µm) through the entire volume, attaching to the particles and enabling flotation of the particles.

   Often 15-120% of the DAF effluent is recycled, pressurized, semi saturated with air and mixed with the unpressurized main stream before fed to the flotation tank (s. Figure 9), because flocculent suspended solids are sensitive to direct aeration (too high sheer forces) and larger quantities of air can be introduced by a greater recycle flow than influent.

   Due to the advantages over the air and vacuum flotation it is the most important flotation process, which is going to be focused on in this report.

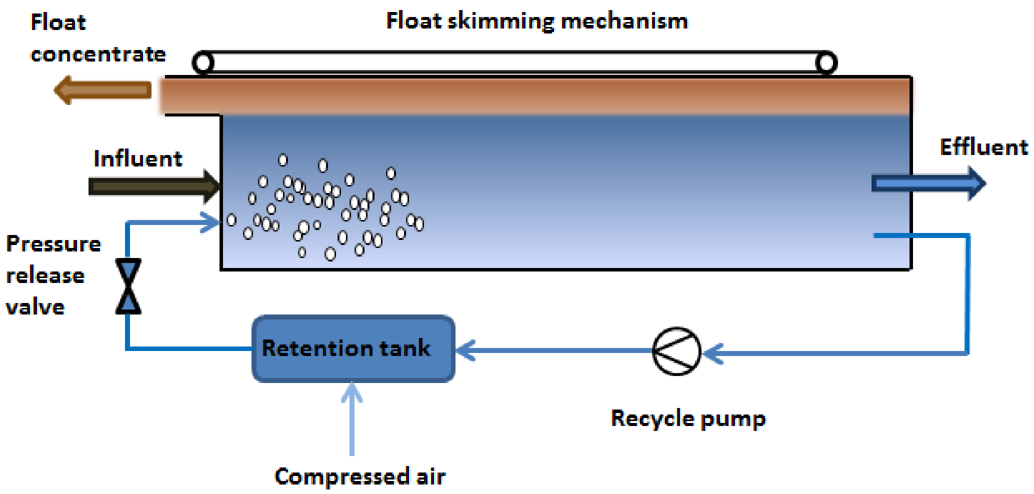

Figure 9: Schematic description of dissolved air flotation (DAF) with effluent recycling, adapted graphic[14]

In the process of DAF chemicals can be added to create a better structure for absorbing the air bubbles.

In addition metals salts and activated silica can be used to enhance binding of particulate matter as well as polymers to change the air-liquid and/or liquid solid interface.

Design of DAF systems depends on the following parameters:

- Pressure in retention tank
- Fraction of dissolved air at pressure in retention tank
- Retention time in flotation tank
- Ratio A/S (air available for flotation/ mass of influent solids)
- Feed flow rate
- Recycle flow rate

[14] Original: http://www.komline.com/products/dissolved_air_flotation.html

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Dissolved air flotation can be performed with and without chemicals (see Table 13). Maximum TSS removal without chemicals is about 82% over 97% when using chemicals. COD removal can be enhanced from 71% to 84% by chemical dosing. BOD, TP and TN elimination are around 50%.

Table 13: Reported removal rates for DAF

Chemical dosing	Removal performances[15] [%]					Sludge production [kg/m³]	Reference
	TSS	COD	BOD	TN	TP		
without	32 - 82	71	51	44	53	-	Kim (2015) Johnson (2014) Bratby (1982) Ødegaard (2001)
with	50 - 97	30 - 84	-	-	92 - 96	approx. 6.5	

Concerning operational parameters an advantage of dissolved air flotation is the relatively small footprint. Energy demand ranges between 0.02 and 0.05 kWh/m³. Table 14 show a summary of operational indicators presented in different references.

Table 14: Operational indicators for DAF

Operational indicators					References
Spatial requirements (Footprint)	Energy-consumption [kWh/m³]	Invest Costs		Operating Costs [k€/year]	
40m * 25m[16]					Johnson (2014)
-	0.0206	Capacity m³/h 1000	25€ per (m³/d) treated wastewater = 0.61 Mio. €	61 - 98	Brinkmann (2016)
		10000	5€ per (m³/d) treated wastewater =1.2 Mio. €	610 - 980	
Small	0.05	-	-	-	POWERSTEP data

[15] Removal rates strongly depend on plant size (full scale or pilot scale) and flotated media

[16] 120 m³/d plant capacity

5. Overview

Table 15 summarizes the important steps (e.g.: chemical dosing) as well as the different removal performances of the presented technologies for standard (PST) and different advanced primary treatment technologies.

Table 15: Summarized performance indicators for evaluated technologies

Technology	Chemical dosing	Removal performances [%]					Sludge production [kg/m³]
		TSS	COD	BOD	TN	TP	
PST	-	40 - 70	25 - 35	25 - 40	<10	16 - 20	10 – 40
CEPT	+	80 - 90	55 - 75	40 - 80	10 - 20	60 - 80	20 - 70
Lamella Settler	-	50 - 70	-	30 - 50	10 - 30	30 - 40	15 – 25
Lamella Settler	+	60 - 90	-	40 - 60	15 - 20	60 - 75	20 - 35
Drum- and Disc filter	-	40 - 60	Up to 60	15 - 30	5 - 10	Up to 40	6 - 14
Drum- and Disc filter	+	80 - 90	Up to 80	50 - 60	5 - 10	50 - 90	Up to 25
RBF	-	25 - 60	15 - 40	15 - 30	<10	0	30 - 200
RBF	+	65 - 75	46	41	-	15 - 20	
DAF[17]	-	32 - 82	71	51	44	53	-
DAF[18]	+	50 - 97	30 - 84	-	-	92 - 96	6.5

Table 16 summarizes the operational indicators (e.g.: footprint, energy consumption, investment as well as operation costs) the presented technologies for standard (PST) and different advanced primary treatment technologies.

Table 16: Summarized operational indicators for evaluated technologies

Technology	Operational indicators			
	Spatial requirements (Footprint)	Energy-consumption [kWh/m³]	Invest Costs €/(m³*d) treated wastewater	Operating Costs
PST	large	0.016 – 0.029	High, 50 – 100	-

[17] including industrial wastewater treatment
[18] including industrial wastewater treatment

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CEPT	Medium - Large	0.006 - 0.036	High, 50 – 133	0.01 – 0.074
Lamella Settler	Medium Up to 70% less of conventional clarifiers	0.016 – 1.5	Medium 25 - 40	-
Drum- and Disc filter	Small up to 90% less of clarifiers	0.005 - 0.03	Medium – High 25 - 187	-
RBF	Small 20 - 70m²/unit up to 90% less of clarifiers	0.037 - 0.103	Medium 25 - 70 50% of conventional primary clarifiers	0.016 - 0.041 €/m³ chemical costs
DAF	-	0.02 – 0.05	Capacity m³/h 1000 25 10000 5	k€/ a 61 - 98 610 - 980

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