Innovative Use of Dissolved Air Flotation with Biosorption as Primary Treatment to Approach Energy Neutrality in WWTPs

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Abstract

This paper presents two types of DAF application together with biosorption (the "Captivator® system") as primary treatments. In the first instance, the Captivator® system is the sole primary treatment for a new plant installation and helps to gain 65% more biogas while requiring only 44% of aeration for COD oxidation, compared to a conventional process with a primary clarifier. In the second application, the Captivator® system is used to enhance the existing primary treatment for plant capacity expansion. With digested anaerobic sludge recycled as an additional adsorbent, the Captivator® system in the second application increases the biogas yield by 52% and only generates 59% excess sludge. Overall, the Captivator® system would help WWTPs to approach energy neutrality by diverting more organics for biogas production and reducing the energy requirements for aeration. In addition, it would help to reduce the installation footprint for primary treatment and save considerable capital cost by eliminating the sludge thickening process.

Keywords

Biosorption, Captivator® System, Dissolved Air Flotation, Energy Neutral, Primary Treatment

INTRODUCTION

In wastewater treatment, biosorption is a physico-chemical step allowing activated sludge to capture organics from wastewater so that they can be "consumed". The A/B (Absorption/Bio-Oxidation) process based on this concept has received increasing attention recently, especially since the Strass WWTP in Austria became the world's first full-scale plant to achieve energy neutrality. The A/B process captures organics from raw wastewater by biosorption in the A-stage, which is typically a high-rate activated sludge (HRAS) process, and then rapidly transfers them to anaerobic digestion (AD) for biogas production. The clarifier following the A-stage biosorption step is a combined unit for both primary and activated sludge. It is between a primary and secondary clarifier in size, and brings new challenges in design and operation with it.

The Captivator® system[1] (1) is intended to help WWTPs to approach energy neutrality. In it, dissolved air flotation (DAF) is used to improve solid-liquid separation after the biosorption process. Either 100% wasted activated sludge (WAS) from the secondary/downstream aeration process or a portion of the anaerobic digester sludge from AD is used as the biosorption adsorbent, instead of HRAS sludge. DAF is often used to thicken waste sludge. In our system, DAF is used as a combined liquid clarifier and sludge thickener, which reduces the primary treatment footprint significantly and eliminates the need for a separate sludge thickener.

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[1] Captivator is a registered trademark in Singapore and pending in The United States.

Typical primary and secondary clarifier surface overflow rates (SOR) are 30 to 50 and 16 to 28 m^3/m^2d, respectively. They are limited by a normal solid settling velocity of approximately 2 cm/min, which corresponds to an upflow rate of 1.2 m/h. In contrast, the floating rise rate of DAF is as high as 12 m/h, leading to a superior SOR, 10 to 20 times that of a gravitational clarifier. Because of this, the DAF footprint is only 5 to 10% that of an A-stage clarifier and retention time is reduced from hours to several minutes.

In this paper, two types of Captivator® system application as primary treatment are presented. In the first (Figure 1), a contact tank for biosorption and a DAF are used as the sole primary treatment for a new plant. In the contact tank, the influent is mixed with WAS from the downstream secondary treatment stage before entering the DAF. The WAS is used as an exogenous biosorption adsorbent, not as in the HRAS process, where activated sludge is endogenously produced in the A-stage contact tank from influent organics. DAF serves the dual purposes here of a solid-liquid separator as well as the only sludge thickener in the process train, doing both jobs at high rates.

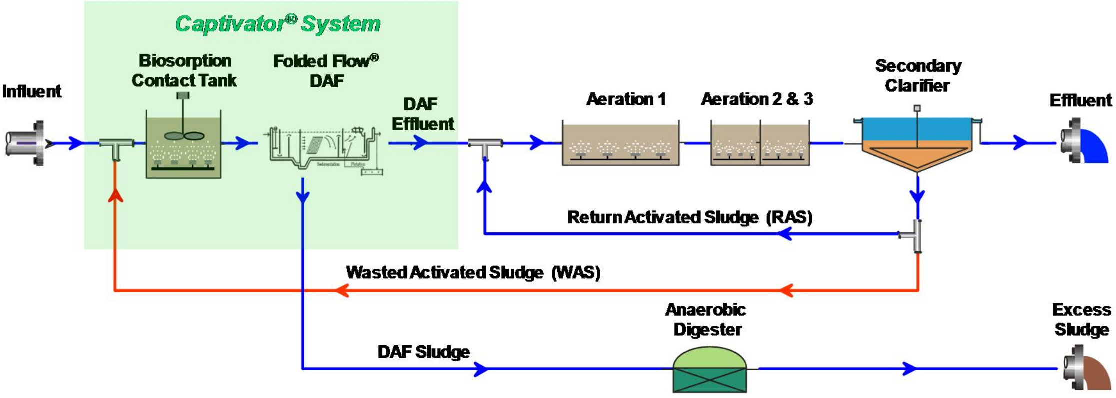

Figure 1. The First Application of the Captivator® System as Sole Primary Treatment for a New Plant Installation

In the second application, the contact tank and DAF are used to enhance the existing primary treatment when capacity needs expansion. There are two options for placement of the contact tank and DAF. One is a parallel installation to the existing primary clarifier, taking the additional treatment capacity as a new, separate installation (this configuration is not shown here). Its performance is similar to that of the first application. The other option is placement in series after the existing primary clarifier (Figure 2). The influent goes into the existing primary clarifier and then to the contact tank, after which the contact effluent is split into two streams: one continuing to the downstream aeration process while the other is diverted to the DAF for solid-liquid separation. Effluent from the DAF enters the final section of the aeration process (aeration tanks 2 & 3 in Figure 2) for polishing. Sludge from the DAF has a solids concentration of 5 to 6% and thus requires no further thickening before being processed by AD.

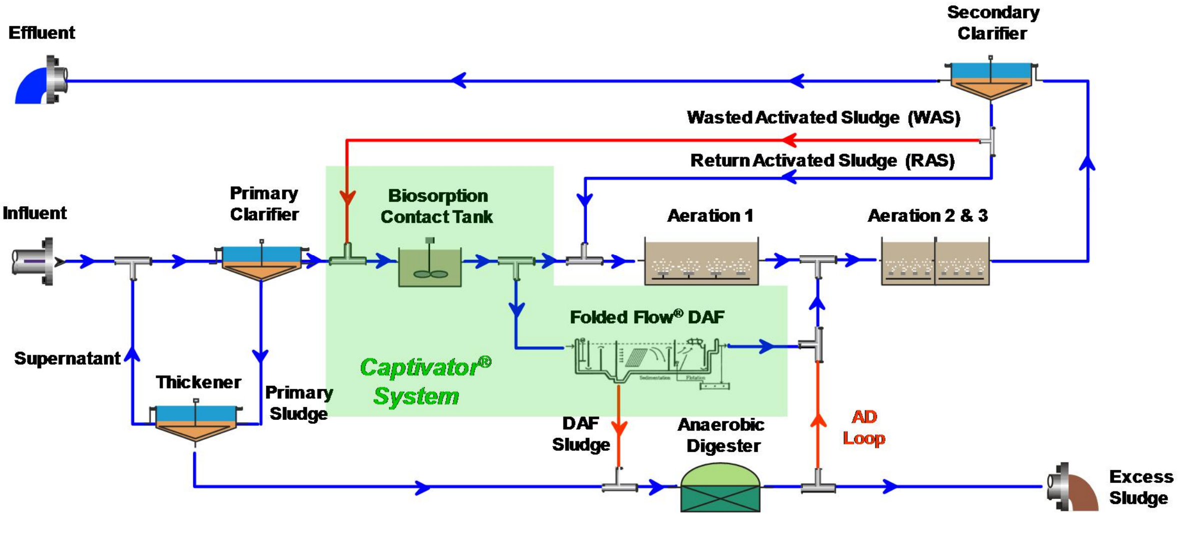

Figure 2. The Second Application of the Captivator® System, as an Enhancement to Existing Primary Treatment

In Figure 2, the flow split ratio after the contact tank depends on the amount of biosorption adsorbent available. It is best to send as much of the contact effluent as possible directly to the DAF, by-passing the main aeration tank (Aeration tank 1) as this gives significant energy savings. However, doing so may reduce the amount of WAS from the aeration process, in turn decreasing biosorption efficiency. This can be overcome by adding an exogenous adsorbent. Evoqua Water Technologies developed a new way of compensating for the WAS loss, by recycling a portion of the anaerobic digested sludge back to the liquid treatment stream (2-3). This is called the AD Loop (Figure 2). The AD sludge is taken first into the aeration process to re-activate its adsorption capacity, because the adsorption capacity of AD sludge is only a fraction of that of activated sludge (2) and aeration is the most convenient method of re-activation. The loop brings benefits beyond the provision of additional biosorption material, as biogas production is significantly enhanced and sludge generation is much reduced (3).

Plant and DAF performance, and COD balance of the two Captivator® system applications, are presented and discussed here, together with their impact on downstream biological nitrogen removal and overall plant energy self-sufficiency.

METHODS

A 200 m^3/d pilot plant was built at Ulu Pandan Water Reclamation Plant, Singapore (Figure 3). It has three aeration tanks in series: the first is the main aeration tank and its volume is 3 times that of each of the other two tanks, which are of equal size and designed for aerobic polishing. In addition to these two Captivator® system applications, a baseline system using a conventional activated sludge (CAS) process with a primary clarifier (Figure 4) was evaluated using the same aeration tanks in different configurations. The DAF used in both applications is a Folded Flow® DAF[2] (4) (Figure 3) in which the flow is “folded” by removing effluent from the same end of the tank as the influent is introduced, resulting in increased hydraulic loading rates. In the first application (Figure 1), the Captivator® system replaced both the primary clarifier and the sludge thickener of the CAS process. In the second (Figure 2), the Captivator® system was placed between the primary clarifier and the aeration process. Contact effluent after biosorption was split at a ratio of 50/50 between the DAF and the first main aeration tank, and merged later in the second aeration tank. The thickened sludge (from either a decanting centrifuge or the DAF) was sent to a digester with an SRT of 25 days for biogas production. A portion of the AD sludge was sent back to the second aeration tank in the second application.

Figure 3. Photo of Pilot Plant (Left) and Folded Flow® DAF (Right)

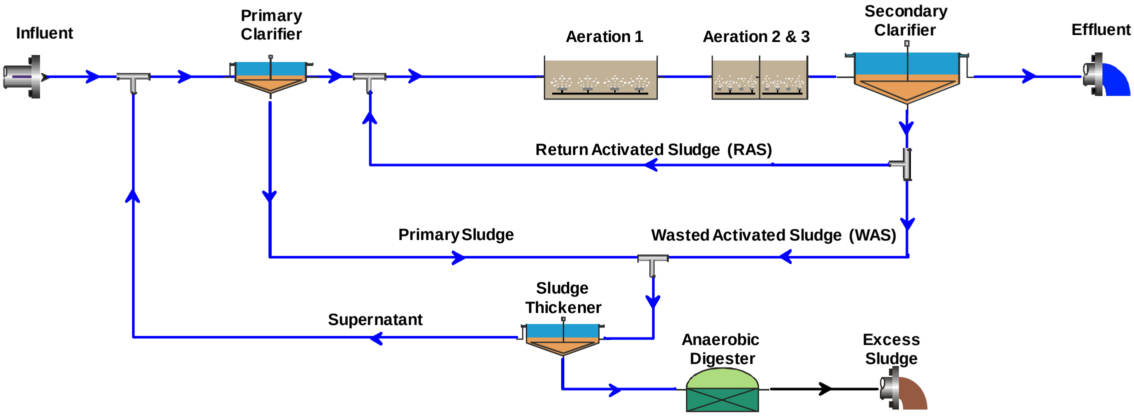

Figure 4. A Baseline Conventional Activated Sludge (CAS) Process

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[2] Folded Flow is a registered trademark in The United States.

The pilot plant received wastewater from the headworks. This was first screened by a fine drum screen before entering primary treatment. Its characteristics are shown in Table 1. The influent and effluent samples were collected by auto-samplers at 4-hour intervals. Other samples – e.g., primary effluent, primary sludge, contact effluent, mixed liquors, thickened sludge, WAS, and digested sludge – were daily grabs. The CAS process in the plant was examined first to collect baseline data for comparison. Then the plant was converted to the two test applications. Plant performance was evaluated mainly on liquid treatment efficiency, biogas production and final excess sludge generation.

Table 1. Average Characteristics of Screened Influent and Final Effluent and Plant Treatment Efficiencies

Parameters		**CAS**			**First Type Application**			**Second Type Application**		
		Influent	*Effluent*	*Removal*	*Influent*	*Effluent*	*Removal*	*Influent*	*Effluent*	*Removal*
$tBOD_5$	mg/L	316	21	93%	324	13	96%	337	18	95%
$dBOD_5$		82	6	93%	101	5	95%	100	5	95%
$cBOD_5$		37	3	92%	61	3	95%	51	5	90%
tCOD		666	43	94%	704	66	91%	627	46	93%
dCOD		124	34	73%	140	47	66%	133	34	74%
cCOD		119	5	96%	96	14	85%	105	10	90%
TSS		406	13	97%	416	25	94%	347	14	96%
VSS		346	11	97%	352	20	94%	298	12	96%
TN		40	24	40%	47	27	43%	49	32	35%
TP		9.1	3.8	58%	9.8	4.0	41%	8.3	4.1	51%
pH	-	6.7	7.0	-	7.1	7.3	-	7.0	7.3	-
Alkalinity	mg/L	180	155	-	170	156	-	179	152	-

Note: t – total; d – dissolved; and c – colloidal.

RESULTS AND DISCUSSION

Overall Liquid Treatment Efficiencies

Table 1 shows that total BOD and COD removals of both applications were satisfactory and exceeded 90%. The data are average values collected over at least 3 months after the process became stable. Nitrogen removal rates were low for all processes as the pilot plant was not designed for this purpose (sludge age was controlled at 3 to 4 days). Nitrification was limited as indicated by the small decrease in alkalinity level and so it is assumed that most of the oxygen consumed was used for COD oxidation.

DAF Treatment Efficiencies

Preliminary studies. Two preliminary studies were conducted to collect design parameters before full-scale plant operation. The first study evaluated DAF performance for the first application. When all of the WAS from the downstream aeration process was used for biosorption, the DAF achieved very good removal of TSS/BOD/COD (Table 2), significantly better than a typical gravitational primary clarifier with BOD/COD removal of only 25 to 40%. Chemical coagulation with 5 ppm $FeCl_3$ increased the performance substantially further.

Table 2. Preliminary Studies on DAF Performance in Two Applications of Captivator® System

Applications	Biosorption Adsorbent Loading Conditions	DAF Removal Efficiencies, %		
		TSS	*BOD*	*COD*
First Type	100% WAS	73	62	61
	100% WAS + 5 ppm $FeCl_3$	86	79	76
Second Type	100% WAS	98	93	96
	100% WAS + 5 ppm $FeCl_3$	97	96	96

In the second application, primary effluent entered the contact tank and was mixed with WAS for biosorption. Only around 50% of the contact effluent was treated by DAF (see Figure 2). In this case, DAF achieved far better removal (> 90%) of TSS/BOD/COD. This type of DAF effluent, when returned to the secondary treatment stage, would require substantially less aeration energy than that from the first test. Chemical coagulation with 5 mg/l $FeCl_3$ did not significantly improve the performance.

DAF performance in full plant operation. DAF performance was evaluated in both applications for long-term, full plant operation (Figure 5). In the first application, the average BOD, COD, and TSS removals were 64%, 67% and 81%, respectively. BOD/COD removals were similar to those achieved in the preliminary study and TSS removal was much better. In the second application, the average BOD, COD, and TSS removals were 87%, 86%, and 90%, respectively, slightly lower than those achieved in the preliminary study. This may be because the AD sludge used in the second application was not as good a biosorbent as WAS, even after re-activation in the aerobic stage.

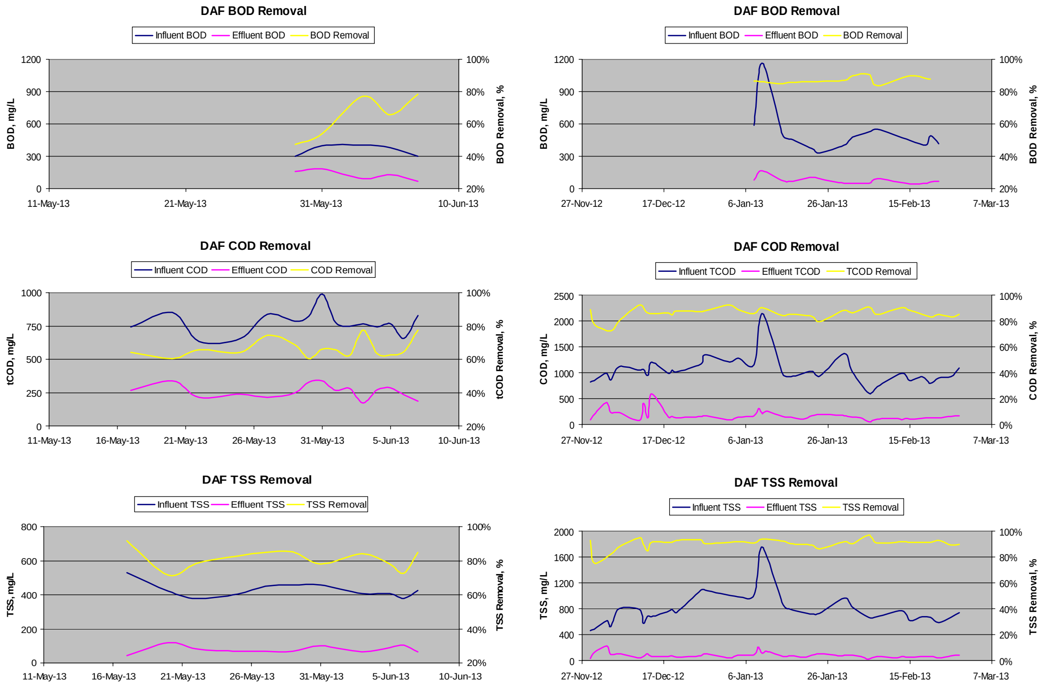

Figure 5. DAF Performance in the first (Left) and second applications (Right) of the Captivator® System

Biogas Production

Daily biogas production rates are shown in Figure 6. Average production was 15.0 m^3/d in the first application and 11.9 m^3/d in the second. Both were much higher than the 8.3 m^3/d achieved by the CAS process operating on its own. This shows that biosorption and DAF together can capture raw organics efficiently and divert them from aeration "burning" to energy gas production in the digester.

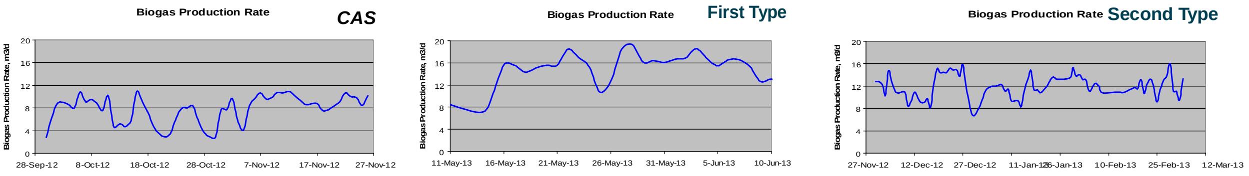

Figure 6. Biogas Production in CAS (Left), and first (Middle), and second applications (Right)

COD Balance

The daily analytical results were collected and used to carry out a COD balance in order to try to understand the impact of the Captivator® system on the process train. Figure 7 shows the COD balance for the CAS process. The primary sludge captured 30% of the influent COD. The centrifugal decanter delivered 55.1% of it in the thickened sludge for biogas production. Of this 55.1% COD, 22.9% was converted to methane and 32.2% discharged as excess sludge, indicating a VS (volatile solids) destruction efficiency of 42% in the digester. Some 38.9% of the influent COD was oxidized in the aeration tanks. The overall COD balance for the CAS process is very close to the simulated result using BioWin® software (EnviroSim Associates Ltd), so it is a reasonable baseline to compare with the two Captivator® system applications.

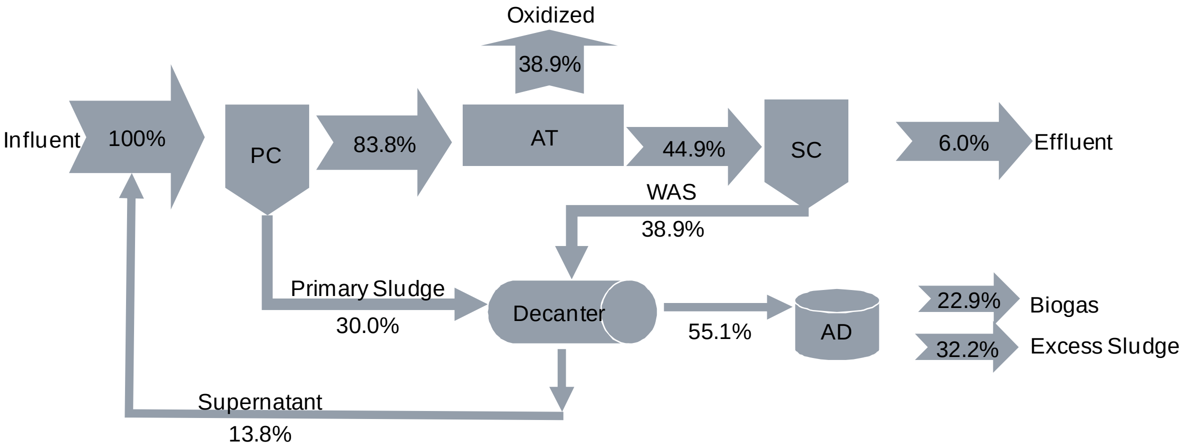

Figure 7. COD Balance for the Baseline Conventional Activated Sludge (CAS) Process

Note: PC – Primary Clarifier; AT – Aeration Tanks; SC – Secondary Clarifier.

Figure 8 shows the COD balance for the first application of the Captivator® system in the treatment train. The DAF in this application captured and sent 71.2% of the influent COD for biogas production. Around 78% of the VS mass in the DAF sludge came from primary solids. In the digester, 38.0% of the influent COD was converted to methane and 33.2% discharged as excess sludge. This corresponds to a high VS destruction efficiency of 53%. There was some COD oxidation loss (around 1.9 % of the influent COD) in the contact tank, where coarse bubble aeration was installed to re-activate the WAS for biosorption. The main aeration tank oxidized 15.2% of the influent COD. The final effluent contained quite high COD concentrations, because of poor clarifier performance at a low SRT of 3 to 4 days. If a better clarifier had been used, part of this COD would have been captured for biogas production via the WAS route to the DAF and then to AD.

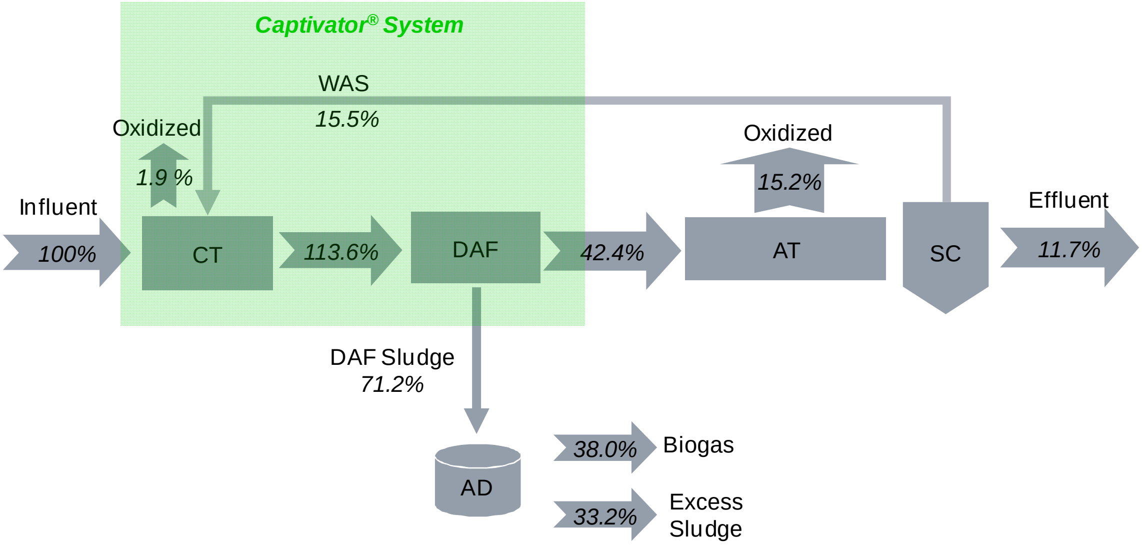

Figure 8. COD Balance the First Application of the Captivator® System

Note: CT – Contact Tank; AT – Aeration Tanks; SC – Secondary Clarifier.

The COD balance for the second application is quite complicated (Figure 9) as the AD Loop recycled additional digested sludge (containing 25.3% of the influent COD) into the liquid treatment stream. The DAF here captured 98.8% of the influent COD as DAF sludge, while the existing primary clarifier collected 34.8% of it as primary sludge. The existing decanting centrifuge thickened the combined sludge and sent 79.7% of the influent COD for biogas production. This proportion could be increased by sending the DAF sludge directly to the digester, by-passing the decanter to avoid COD loss to the supernatant. Apart from the 25.3% of COD recycled in AD Loop, 35.1% was converted to methane and 18.6% discharged as excess sludge. The digester had a moderate VS destruction efficiency of 44%. Some 7.7 and 33.3% of the influent COD were oxidized in the contact and aeration tanks, respectively.

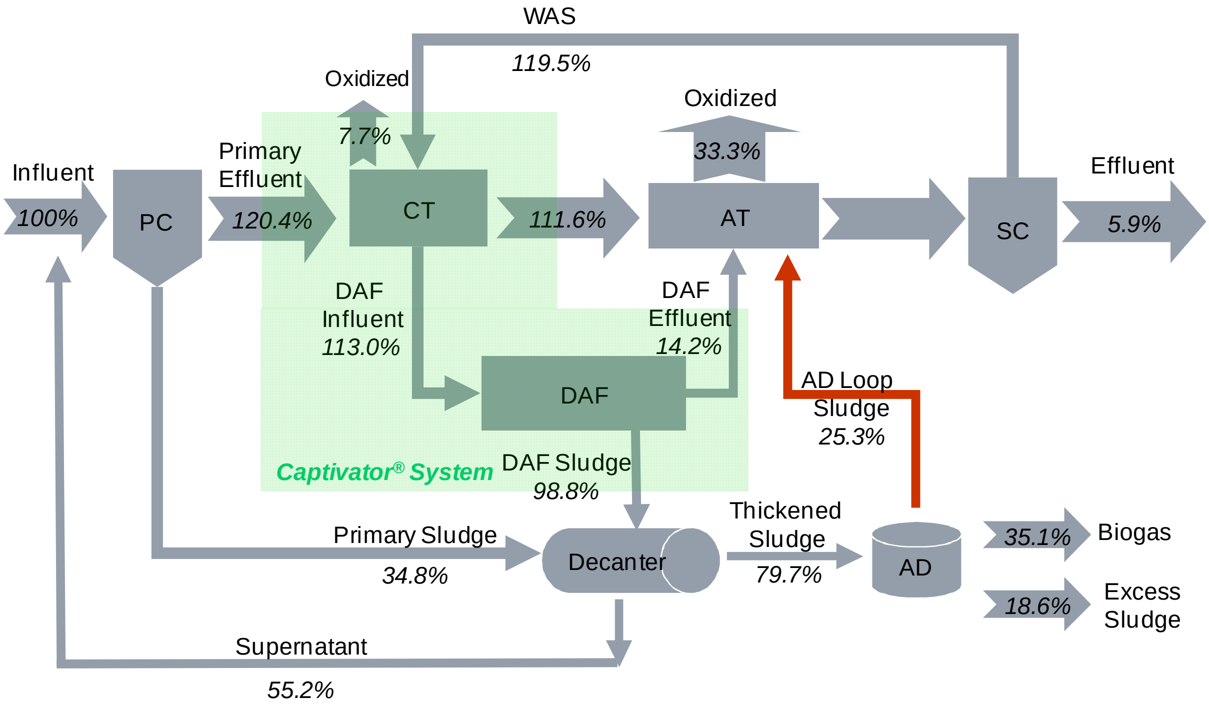

Figure 9. COD Balance for the Second Application of the Captivator® System

Note: PC – Primary Clarifier; CT – Contact Tank; AT – Aeration Tanks; SC – Secondary Clarifier.

COD distribution in the final effluent, oxidation, biogas, and excess sludge streams is summarized for comparison in Table 3. The first application produced 65% more biogas than the CAS and required only 44% of the aeration energy needed by the CAS for COD oxidation. The second application produced 52% more biogas than the CAS and generated only 59% of the excess sludge that came from the CAS. Significant sludge reduction arose because of the recycling of AD sludge (3). In the second application, recycled, digested sludge was oxidized in the liquid treatment stream because of the AD loop, so there was no saving in aeration energy for COD oxidation. If there had been no AD loop, the aeration process would have needed more contact effluent with a different split ratio from the 50/50 used in the study, to produce more WAS. Certainly, the loop concept can be applied, on its own, to any WWTP to reduce sludge disposal costs.

Table 3. COD Balance Summary of the Captivator® System Applications vs. the CAS Process

	CAS	Type 1	Δ	Type 2	Δ
Final Effluent	6%	12%	-	6%	-
Oxidized	39%	17%	-56%	41%	+5%
Biogas	23%	38%	+65%	35%	+52%
Excess Sludge	32%	33%	+3%	19%	-41%

Impact on Nitrogen Removal and Plant Energy Self-Efficiency

This study shows that the Captivator® system is capable of capturing a significant proportion of the organics from wastewater and diverting it to anaerobic digestion for biogas production. However, it creates carbon-limited conditions, bringing new challenges for downstream biological nitrogen removal. In this study, a low BOD/N ratio of around 3 (average BOD = 128 mg/L and TN = 42 mg/L) was commonly found in the DAF effluent of the first application. This is considered too low to enable conventional nitrification and denitrification (required BOD/N > 6) for biological nitrogen removal. Recently, some special, short-cut nitrogen removal pathways have been discovered, with lower BOD/N ratios – e.g., the nitrite-shunt or deammonification. These can complete biological nitrogen removal to meet stringent nitrogen discharge limits, and are efficient in both carbon and energy terms, being ideal downstream treatments following the Captivator® system, to achieve plant energy self-efficiency.

A recent investigation showed that biological nitrogen removal in aerated anoxic processes performs well in carbon-limited conditions. One such example is the aerated anoxic Orbal® system[3] (5) at Port Washington WWTP, USA. The low influent carbon condition was attributed to the under-loaded primary clarifier, which removed a high proportion of the BOD. Although the influent BOD/N ratio was as low as 3.3 (average BOD = 100 mg/L and average TN = 30 mg/L), the ammoniacal nitrogen in the effluent was mostly undetectable and effluent nitrate concentrations have been between 1 and 2 mg/L for the last two years. When plant operation began, the energy provided for treatment was 100 *e*HP but this has now been reduced to 60 *e*HP.

The performance data for the Captivator® system and the Port Washington WWTP give credence and confidence to the proposed new A/B configuration with respect to its ability to achieve energy neutrality. In this proposed configuration, the first stage uses the Captivator® system to capture and divert organics for much improved biogas production while the second stage is an aerated anoxic process like the Orbal® system, designed to achieve excellent nitrogen removal with much reduced aeration energy. For a wastewater of 300 mg-BOD/L, 300 mg-TSS/L and 30 mg-TKN/L to be nitrified, this new A/B process configuration would have an estimated total power consumption of 0.21 to 0.23 kWh/m^3 of treated wastewater, depending on the short-cut biological nitrogen removal pathways used. At the same time, it would produce between 0.25 and 0.27 kWh/m^3 of treated wastewater for use in the plant. Because of this, WWTPs designed around this new A/B configuration would have a good chance of being energy neutral.

CONCLUSION

This study demonstrates the performance of the Captivator® system used as primary treatment in either a new installation or an existing plant. The system has a significant impact on the COD balance of WWTPs, by diverting more organics for biogas production and reducing the amount of aeration required for COD oxidation. It has also shown that recycling digested sludge to the liquid stream via an AD Loop, as an additional biosorbent, not only improves biogas production but also reduces the final amount of sludge for disposal. Through this study, a new A/B process configuration for future plant installation is proposed. It consists of a Captivator® system as the first stage and an aerated anoxic process as the second, and will help WWTPs to approach energy neutrality. In addition, the Captivator® system can significantly reduce the installation footprint and save considerable capital cost by eliminating the requirement for a separate sludge thickener.

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[3] Orbal is a registered trademark in the United States.