Vortex Powered Aeration Standard 6 (VPA-S6) Technical Report

Large Scale Solution Performance in an Abattoir Wastewater Treatment Plant

Executive Summary

The Vortex Powered Aerator Standard 6 (VPA-S6) is a novel wastewater aeration technology that adopts cyclonic flow with advanced flexible control to achieve high treatment efficiency in activated sludge systems. The innovation was recently deployed at an industrial abattoir as part of an onsite wastewater treatment facility upgrade. The challenge at the facility (which processes circa 274 livestock per day) was to provide a low total expenditure aeration solution for an activated sludge system to enhance resource efficiency, reduce trade effluent charges, reduce carbon emissions, and minimise noise pollution. This technical report was prepared to summarise the technical performance of the system over the first year of operation. Technical in-situ performance data pertaining to oxygen transfer, aeration efficiency, process efficiency, noise, aerosols, and maintenance are presented and discussed. The VPA's energy efficiency performance was compared to a similarly sized abattoir facility (owned by the same client) which uses fine bubble diffused aeration (FBDA), and a 30% reduction in specific energy consumption in aeration was noted. In terms of total electricity consumed per unit livestock processed, a 41% reduction was concluded. In addition, a comprehensive carbon equivalent analysis was conducted at the facility, pre- and post-upgrade, which demonstrates a carbon equivalent saving of circa 93,500 kgCO_2-eq/annum through chemical use reductions alone. In financial terms, this report demonstrates that the VPA system will save the client £96,000 per annum against a baseline cost of circa £246,000 (saving of 39%). This saving could increase to potentially £125,000 per annum when the new production line becomes operational. Costs per livestock processed will fall from £3.51 to £2.14, costs per tonne of effluent discharged will fall from £3.41 to £2.08, and there will be a 20-year total lifecycle saving of £1.56 million.

Introduction

Overview and Challenges

An industrial abattoir wastewater treatment plant in the UK recently underwent a major upgrade to include a new activated sludge treatment facility. The abattoir, which processes an average of 274 livestock per day, originally had a basic wastewater treatment facility consisting of a balance tank and dissolved air floatation (DAF), prior to discharge to the local municipality sewer network. Prior to the upgrade, the average biochemical oxygen demand and ammonium concentrations in the final discharged effluent were of the order of 1,500 to 2,500 mg/L and 100 to 250 mg/L respectively. The client identified that continuing operations in this fashion was not sustainable due to several concerns:

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- The effluent concentrations discharging to the sewer were high relative to municipal waste, and furthermore these concentrations fluctuated seasonally. This mounted pressure on the downstream municipal wastewater treatment plant that was required to install supplementary equipment to cater for the increased biological/chemical and nutrient loads discharged by the abattoir. In addition, the ammonium discharge concentrations were in excess of what the site's licence permitted for discharge (circa 100 mg/L).
- Each cubic meter of effluent discharged to the sewer was subject to a trade effluent charge ranging from £1.75 to £1.90 per m^3. With flows through the plant of the order of 200 to 300 m^3/day, the cost of trade effluent alone ranged from £12,000 to £14,000 per month.
- The DAF system was operated at full capacity to maximise BOD removal and to minimise trade effluent charges. The result of this was significant quantities of chemical usage (ferric chloride, liquid poly and dry poly) which also incurred a heavy monetary cost and carbon footprint at the facility. This operation also caused pH levels in the discharged effluent to drop below the compliance limits of the facility.

Based on the above, the client decided to upgrade the existing treatment plant to a full activated sludge treatment facility using sustainable aerobic and anoxic treatment. However, the site posed several unique challenges which influenced the choice of technology at the facility. Some of these challenges are outlined as follows:

- Although an additional electricity expenditure was to be expected when the plant was upgraded to a full activated sludge system, the savings in chemical costs and trade effluent charges were required to outweigh the additional electricity to ensure an economic return. That said, electricity prices had risen considerably, particularly in 2021. With aeration accounting for a significant portion of a typical treatment plant's electricity bill, there was a major priority to consider the most energy efficient aeration system for the upgrade to maximise the return on investment for the facility.
- Domestic dwellings are in the immediate vicinity of the effluent plant, with the nearest house less than 50 m away from the proposed location of the aeration tank. Therefore, noise pollution was a serious consideration.
- The new activated sludge facility was to serve a live abattoir which is operational at least five days a week, with influent loads to the treatment plant active 24 hours per day. The new treatment system was required to be reliable and robust to ensure continuous and sustainable upstream production line operations.
- Pollutant concentrations such as BOD, ammonium and total nitrogen were known to increase at times by as much as 300%. This required an aeration system that was versatile to cater for both average and peak treatment demands efficiently.
- Finally, the installation was to occupy a small plant footprint and construction time was to be minimised to avoid disrupting existing facility operations.

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Solution Overview

The solution was to intercept the DAF effluent line with a new activated sludge system comprising Vortex Powered Aeration (VPA), an aerobic-anoxic fully mixed reactor and clarifier. The balance tank and solids holding tank were also upgraded, with new tanks along with mixers and pumping lines (returned activated sludge, sludge wasting etc.) all contained inside a newly constructed bund. The aerobic-anoxic reactor comprised a 17.05 m diameter glass lined steel tank and base, which was installed by third-party contractors. The liquid depth was 5.1 m, and the aerated volume was 1,168 m^3. A Vortex Powered Aeration Standard-5 (VPA-S6; 63 kW) system and a Flygt submersible compact mixer (10 kW) were installed in the activated sludge tank.

An aerial image highlighting the process flow for the site is outlined in Figure 1. Raw effluent from the facility is forwarded to the balancing tank which homogenises the incoming wastewater and creates a buffer for forward feed to the original DAF system. The DAF is expected to output wastewater with concentrations of COD = 2,500 mg/L, total suspended solids = 500 mg/L and ammonium = 150 mgN/L, which is then pumped to the aeration tank (however, as will be demonstrated later in this report, this can vary significantly). The purpose of the new aeration facility (set by the client) was to ensure that COD and ammonium concentrations leaving the facility are less than 500 mg/L and 10 mgN/L respectively. The average design influent flow is 250 m^3/day, with peak flows of 500 m^3/day. Following the aeration tank, water gravitates to a clarifier where mixed liquor settles, and where the supernatant is discharged to the sewer.

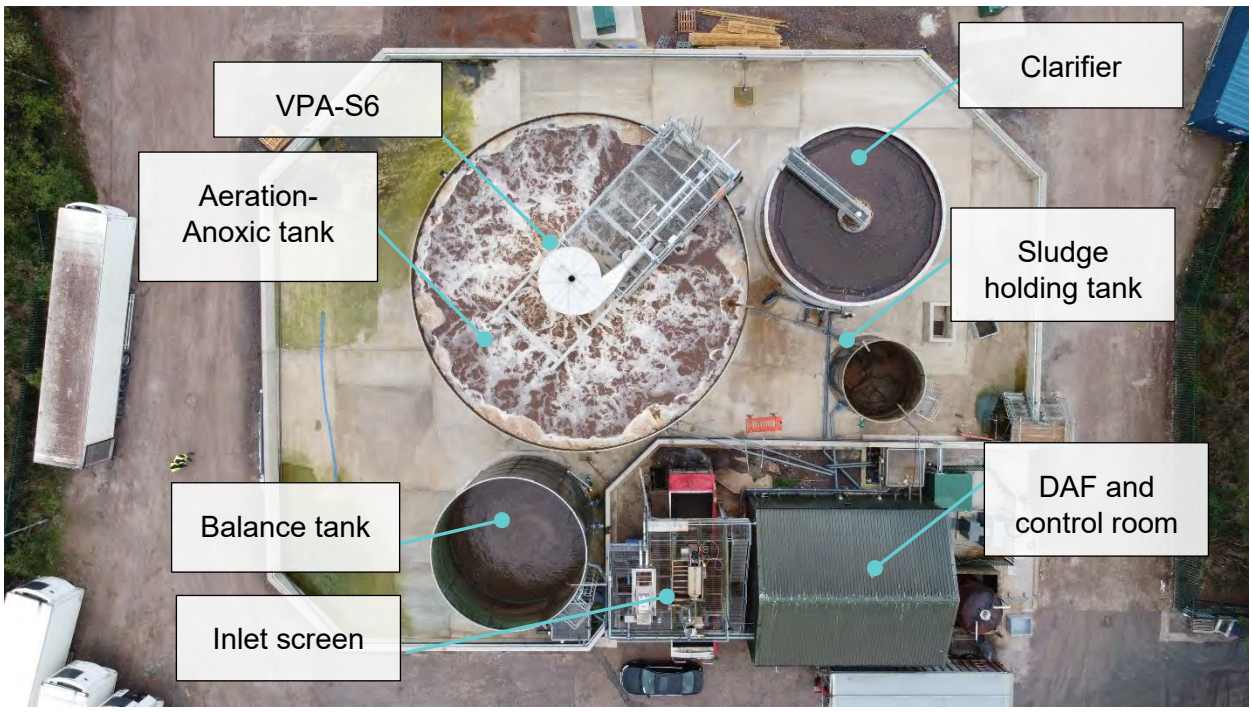

Figure 1: Aerial image of the abattoir effluent facility highlighting key process tanks. **Note:** the image was taken of the plant at start-up stage, therefore the clarifier was not fully stable at the time of the photograph.

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The VPA-S6 (outlined in Figure 2) was equipped with an access platform to provide easy access to the pumping system using a gantry and electric hoist. WTW dissolved oxygen and total suspended solids sensors were also supplied by VorTech and fitted at platform level to provide enhanced control of the activated sludge reactor. VorTech also provided a motor control centre (MCC) with Smart PLC and operator friendly human machine interface (HMI) to govern the efficient control of the aerobic-anoxic reactor (see Figure 3). Mechanical and electrical installation were provided by Ward and Burke Construction Ltd as outlined in the next section.

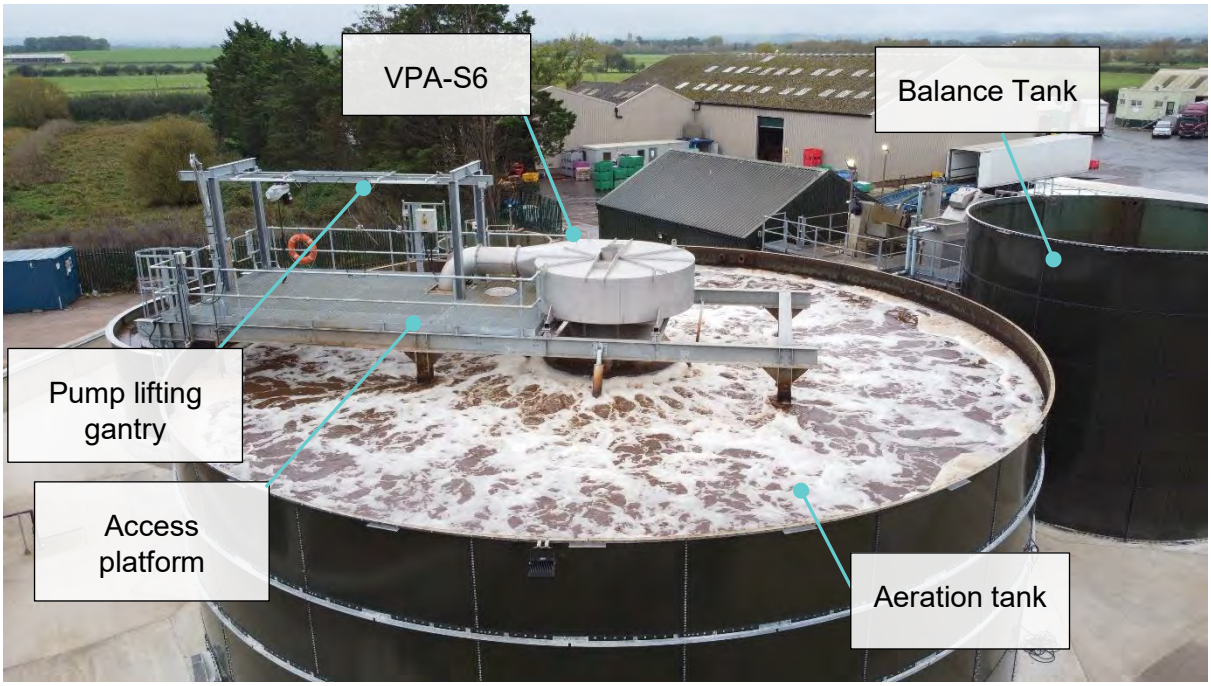

Figure 2: Annotated overview of the VPA aerobic-anoxic reactor.

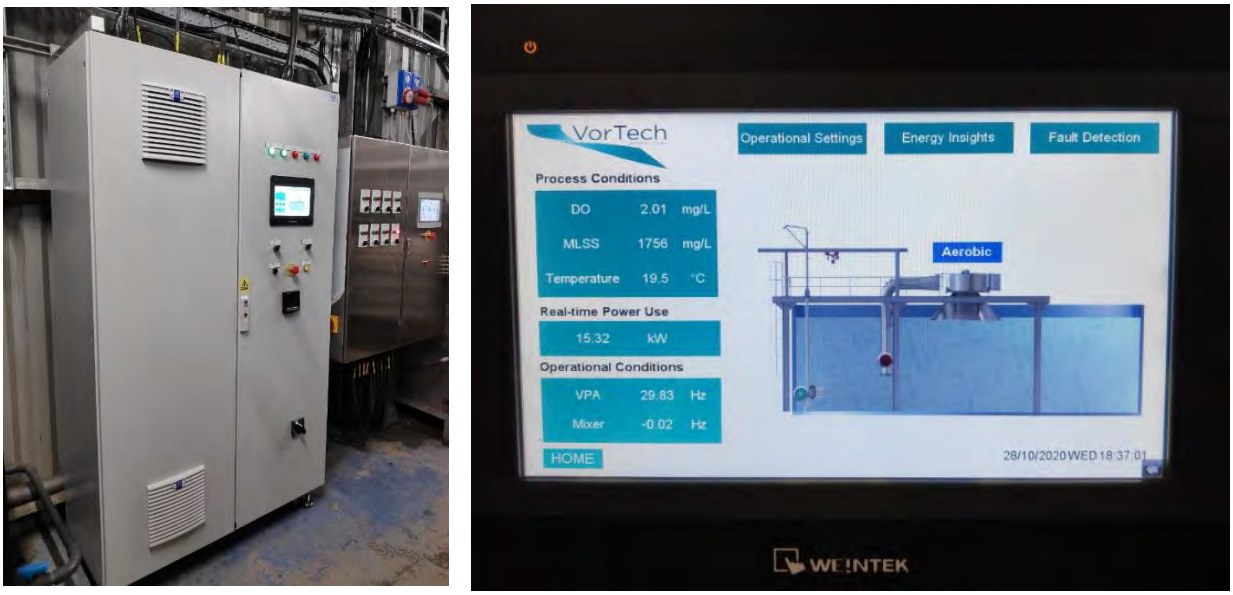

Figure 3: VorTech Smart MCC and HMI control platform.

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Installation

Design for Manufacture and Assembly (DfMA)

VorTech adopt a “Design for Manufacture and Assembly” (DfMA) approach to its delivery of VPA aeration and mixing equipment. The VPA-S6, support and access platform and panel, were all delivered as one pack, ready for assembly on site (see Figure 4 and 5). The installation of the VPA-S6, mixer and support platform were carried out over a two-week period (1 week for mechanical and 1 week for electrical and final fixings) by Ward and Burke Construction. No civil works were required. All equipment was assembled outside the tank, requiring one lift to fit the equipment. A VorTech MCC was installed in the existing control room and was connected to the network for data communications and remote monitoring and control.



Figure 4: VPA-S pack arriving at the facility for installation.



Figure 5: VPA-S assembly by Ward and Burke Construction prior to installation in aeration tank.

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Fluid Dynamics and Mixing Performance

The VPA-S6 can circulate up to 950 l/s of mixed liquor. During operation, the vortex generated in the circulation chamber produces a stable annular jet which plunges into the aeration tank to drive air entrainment and mixing. This in turn triggers additional air flowrates of up to 1,106 l/s. As is demonstrated in Figure 6 and Figure 7, aeration by the VPA system is characterised by an axisymmetric turbulent micro- to fine-bubble plume.



Figure 6: Demonstration of bubble size spectrum resulting from VPA air entrainment mechanisms circa 1 m away from the outlet duct at a power of 53 kW.

Liquid turbulence in the bubble plume is known to limit the effects of gas suppression created by surfactants (i.e., an increased alpha factor can be expected). The effective plume diameter, turbulence and thus the process oxygen transfer rate varies depending on the input flow and power controllable by a variable speed drive as outlined in Figure 7.

The air flow versus power relationship for the VPA-S6 is presented in Figure 8. This data is also compared to the rotary lobe blower and a surface aspirating aerator (spiral aerator). The significant volumes of air entrained with the mixed liquor demonstrates how higher in-process aeration efficiencies can be gained using the VPA technology compared to traditional aeration systems.

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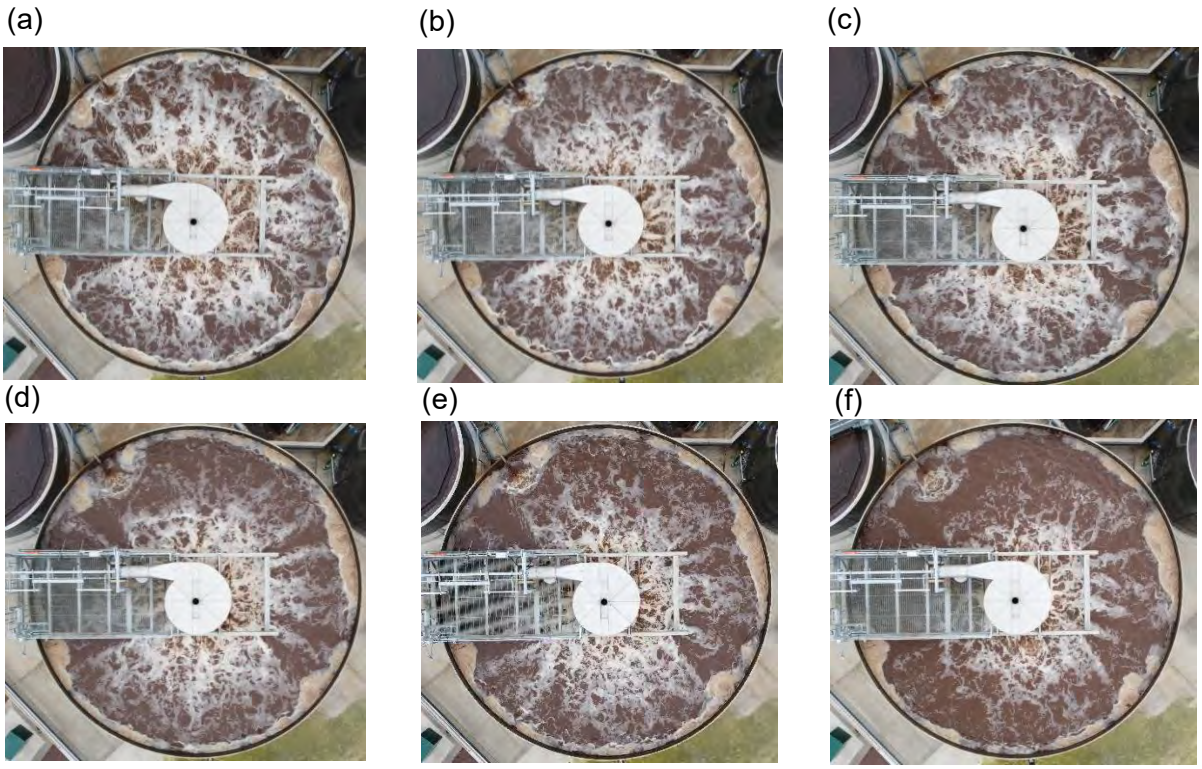

Figure 7: Aerial images of the VPA and reactor outlining mixing conditions at (a) 63 kW, $Q_w \approx$ 950 l/s $Q_a \approx$ 1106 l/s, (b) 54 kW, $Q_w \approx$ 872 l/s $Q_a \approx$ 1058 l/s, (c) 39 kW, $Q_w \approx$ 813 l/s $Q_a \approx$ 875 l/s, (d) 31 kW, $Q_w \approx$ 774 l/s $Q_a \approx$ 673 l/s, (e) 20 kW, $Q_w \approx$ 625 l/s $Q_a \approx$ 337 l/s, (f) 14.8 kW, $Q_w \approx$ 562 l/s $Q_a \approx$ 255 l/s.

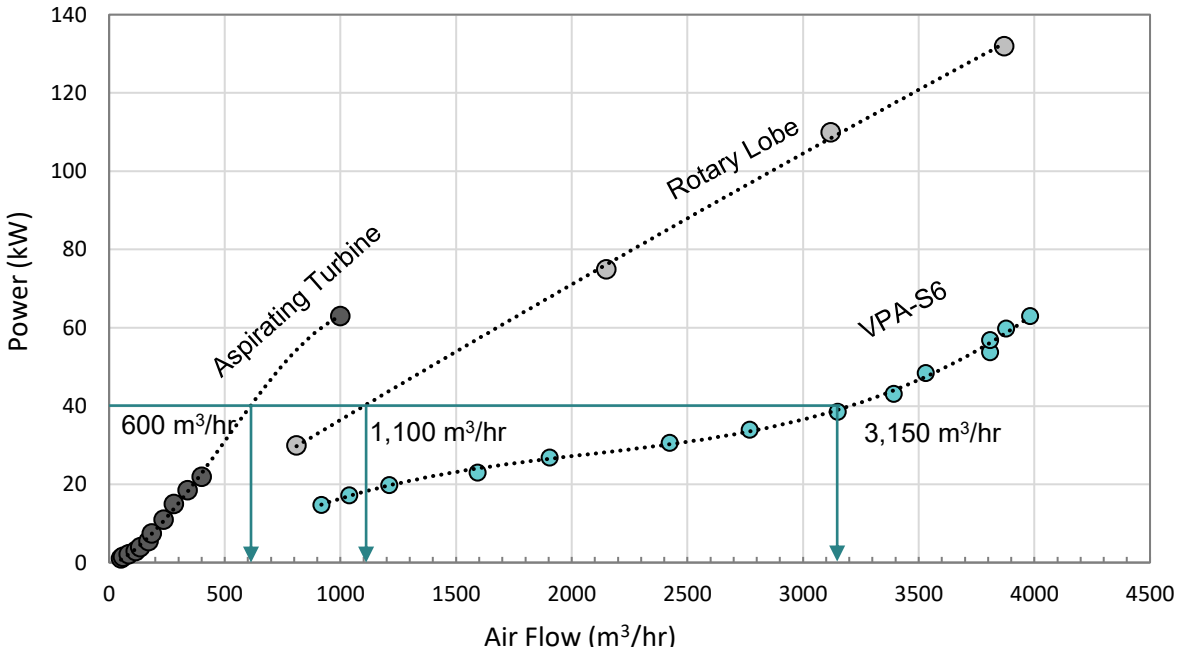

Figure 8: Power versus air flowrate for VPA-S6 compared to a rotary lobe blower and spiral aerator.

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A computational fluid dynamics (CFD) model of the reactor was also developed to support the observations made at the facility. Figure 9 outlines a side by side physical and numerical comparison of the VPA-S6 operating at a water flow rate of 950 L/s, where the contours represent the surface water velocities in the reactor.

(a) (b)

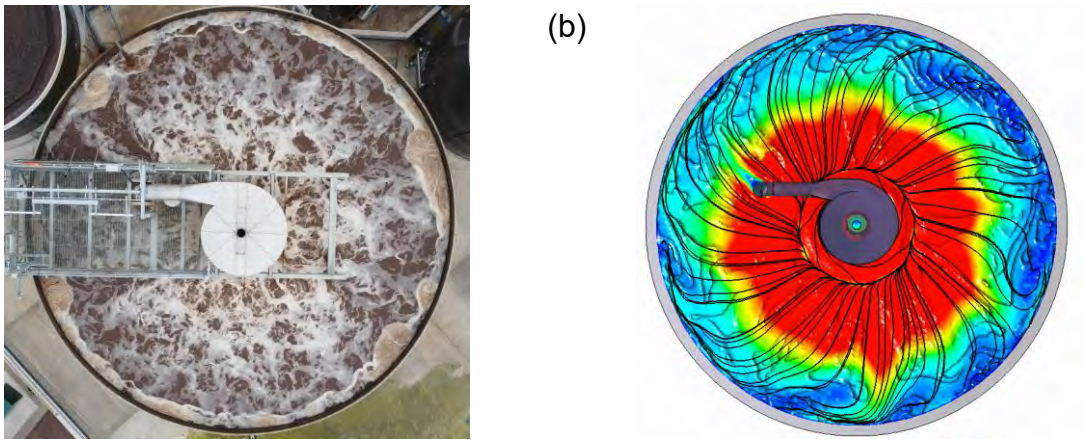
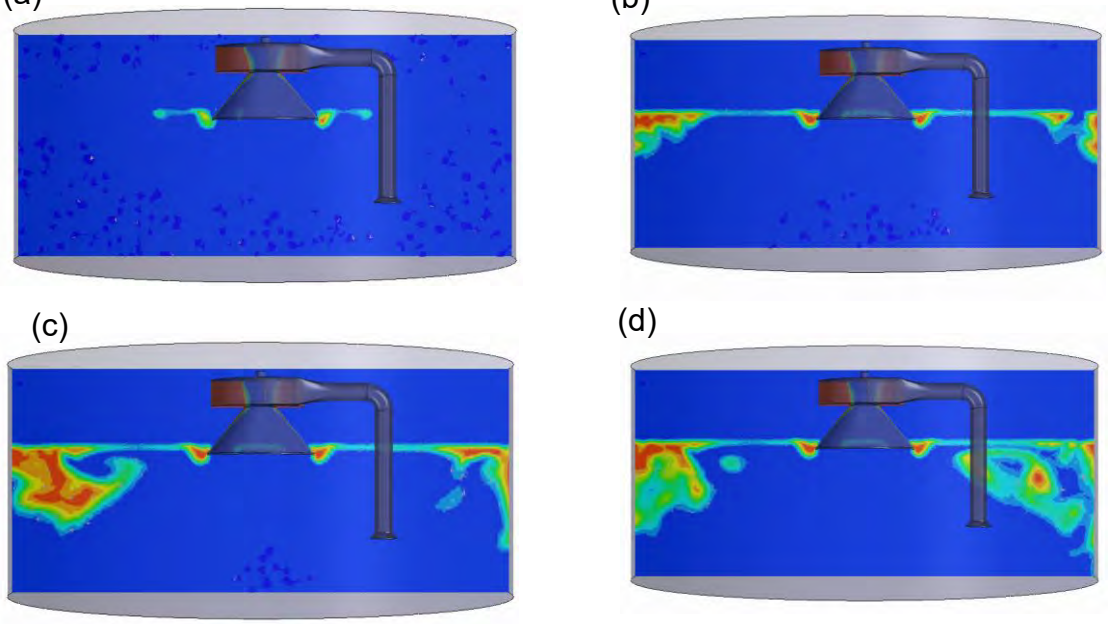


Figure 9: VPA-S6 unit in operation and CFD simulation of operation during aeration.

The CFD model was used to also demonstrate the sub-surface mixing in the reactor as outlined in Figure 10 where the aerated flow and the reactor volume are mixed over a 300 second real time duration from startup.

(a) (b)

(c) (d)



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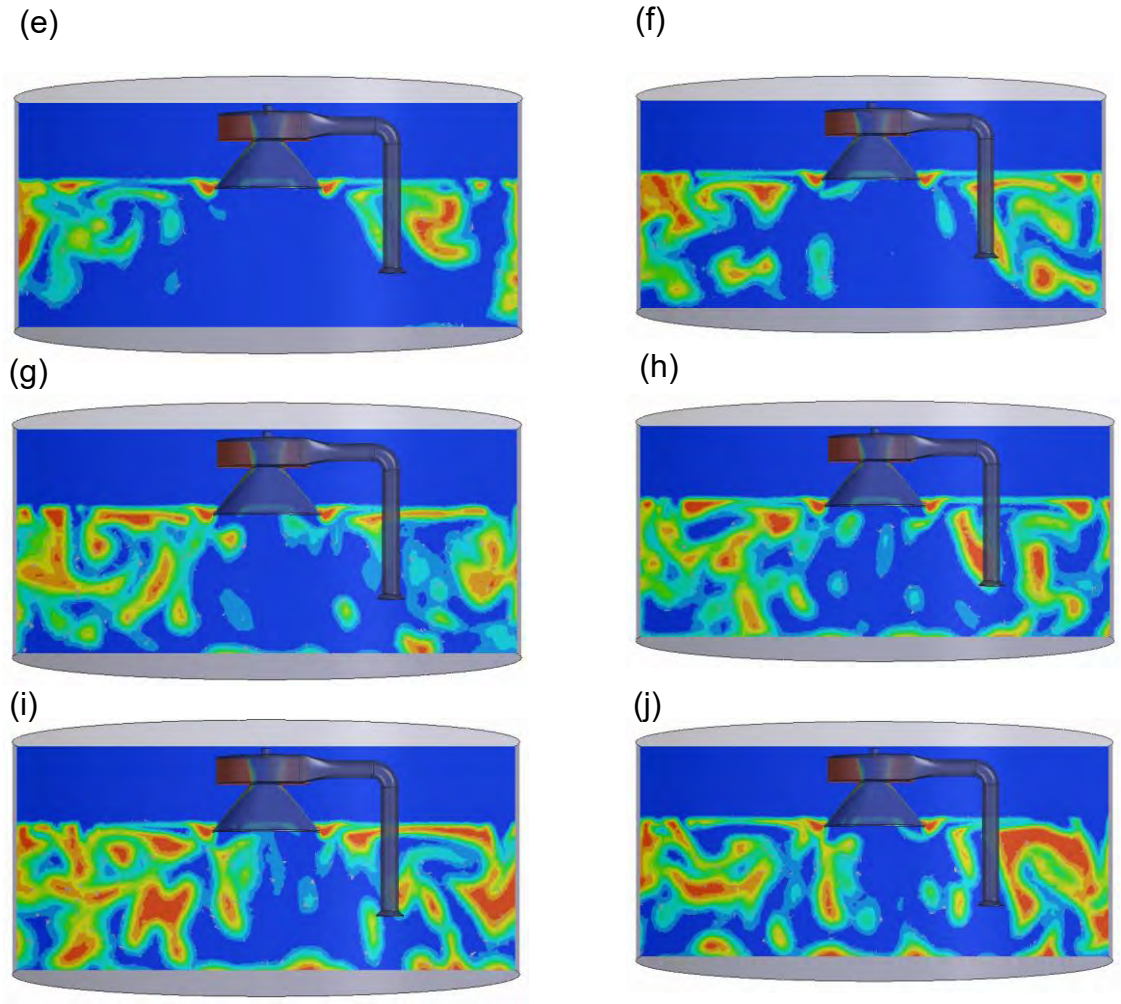

Figure 10: Cross sections of CFD simulation through a 17.05 m diameter, 5.12 m deep tank for aerated flows using the VPA-S6 at 960 l/s at (a) 0 s, (b) 30 s, (c) 60 s, (d) 90 s, (e) 120 s, (f) 150 s, (g) 180, (h) 210, (I) 240 s, (j) 270 s, (k) 300 s.

Oxygen Transfer Performance

Following installation, the activated sludge tank was filled with raw influent (1,168 m^3). Initial concentrations for COD and ammonium in this volume were +2,500 mg/L and +250 mgN/L respectively, and the total suspended solids was circa 400 mg/L. After the first day of aeration, when the dissolved oxygen level in the tank had been raised, 90 to 120 m^3 of seed activated sludge from a nearby abattoir facility was pumped into the tank, increasing the suspended solids content to 1,800 mg/L. Aeration tests were then conducted by monitoring the oxygen uptake rate and reaeration curves.

Oxygen Uptake and Oxygen Transfer Rates

After start-up, an assessment of aerator performance was conducted by measuring the oxygen uptake rate (OUR) of the system by turning off the aerator, maintaining mixing, and measuring the rate of depletion of oxygen over time. Table 1 summarises test data on OUR measurements and aerator power. By measuring the OUR and subsequent re-

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aeration, we can infer minimum oxygen supply that must be achieved to raise the dissolved oxygen in the tank. Figure 11 and Figure 12 display the oxygen curves for each test. These oxygen uptake rates (as outlined in Table 1) infer high, in-process oxygen transfer rates accordingly.

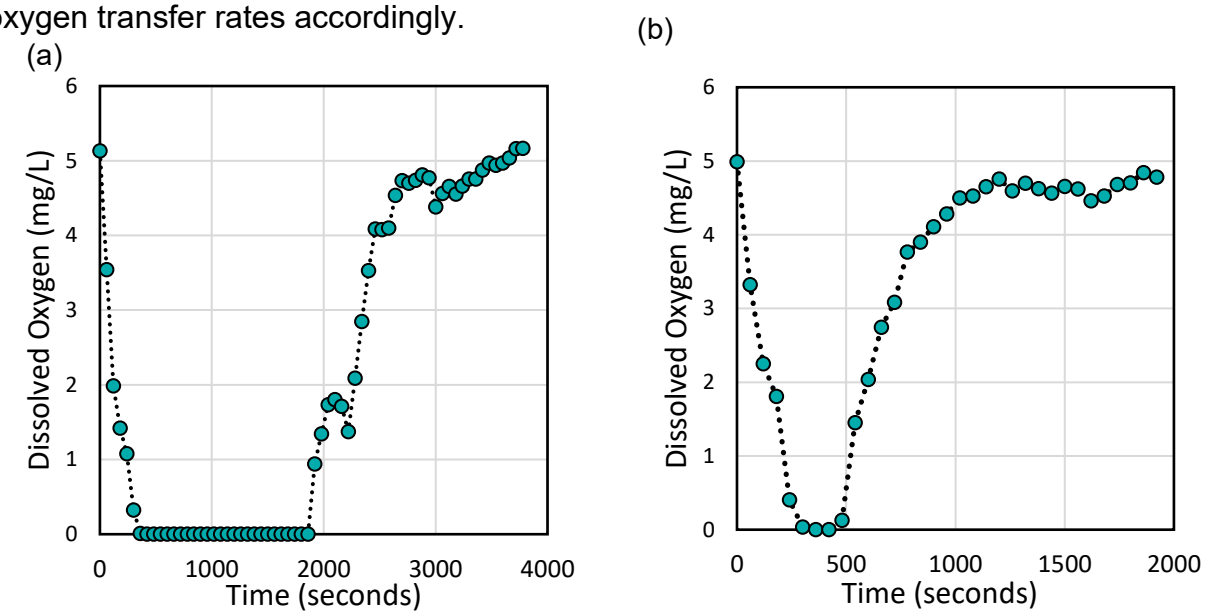

Figure 11: (a) Test 1 - OUR at 110.20 kg O_2/hour and re-aeration at 51 Hz and (b)Test 2 - OUR at 80.29 kg O_2/hour and re-aeration at 45 Hz.

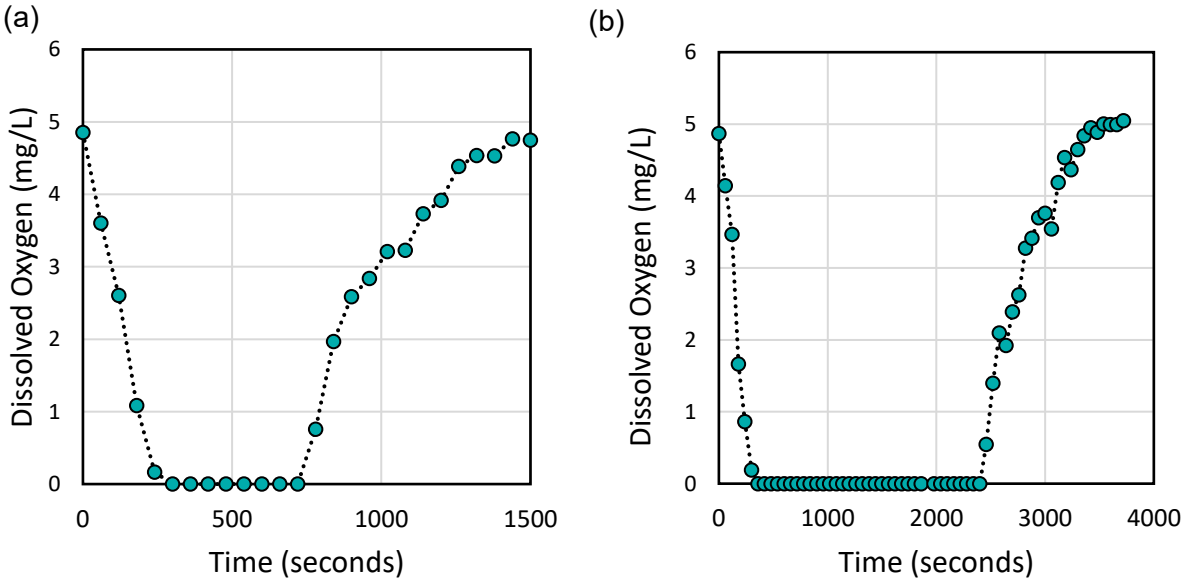

Figure 12: (a) Test 3 - OUR at 89.74 kg O_2/hour and re-aeration at 51 Hz and (b) Test 4 - OUR at 70.18 kg O_2/hour and re-aeration at 45 Hz.

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Table 1: Summary of OUR and re-aeration tests performed.

Test #	Frequency (Hz)	Power (kW)	Standard oxygen uptake rate (SOUR) (kg O_2/h)
1	51	56	110.20
2	45	41	80.29
3	51	56	89.74
4	45	41	70.18

Process Performance

Overview and Wastewater Characteristics

Physicochemical characteristics of the facility wastewater are outlined in Table 2, for the raw balance tank influent, the DAF, and the clarifier final effluent respectively. The table highlights characteristics that are unique to this facility, including high chlorides and high total Kjeldahl nitrogen, which is largely converted from organic nitrogen to ammonium during treatment.

Table 2: Results of physicochemical testing of wastewater before and after treatment at the abattoir facility.

Parameter	Balance Tank (Raw)	DAF (Morning and Afternoon Average)	Final Effluent (Morning and Afternoon Average)
BOD_5 + ATU (5 day) (mg/L)	> 4,000	2,466	19.5
COD (Total) (mg/L)	19,800	3,875	379
Total Suspended Solids (mg/L)	8,160	340	126.5
Total Nitrogen (mg/L)	395	569.5	17.9
Total Kjeldahl Nitrogen (mg/L)	395	569.5	14.6
Ammoniacal Nitrogen as N (mg/L)	293	222	3.2
Total Oxidised Nitrogen as N (mg/L)	<1	<0.5	3.2
Nitrate as N (mg/L)	<0.7	<0.7	<0.7
Nitrite as N (mg/L)	<0.08	<0.08	2.0
Phosphorus, total as P (mg/L)	107	32	2.4
Phosphate, Ortho as P (mg/L)	92.1	27.7	0.7
pH	6.3	6.2	6.3
Chloride as Cl (mg/L)	2,790	2,830	4,385
Anionic surfactants (MBAS) (mg/L)	0.088	0.1035	0.08
*Exceeded testing limit			

Removal Efficiencies

The removal efficiency of BOD_5 and ammonium over the course of the first nine months of operation is outlined in Figure 14 and 15. An image of the visual difference between

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influent and effluent colour and suspended solids is outlined in Figure 13. During this period, two process instability issues occurred which disrupted optimal activated sludge conditions. However, these events enabled the team to monitor adverse process conditions (shocks) on the VPA system performance. These are outlined as follows:

- A process malfunction resulted in solids wasting from the clarifier to the sludge holding tank (biomass inventory removed). Due to issues with sludge treatment, all solids had to mix with raw influent and pass through the DAF with limited solids removal back to aeration resulting in a significant shock event which increased the oxygen demand and severely impacted the activated sludge process. This essentially resulted in a restart of the activated sludge process. BOD removal rates were negligibly affected during this period; however, the ammonium increased from values of less than 1 mg/L to between 15 and 20 mg/L after this period (see day 17 on graph).
- The pH in the influent began to drift downwards from day 45 - 50 due to DAF acid control issues. This problem became progressively worse over time and resulted in pH values as low as 4.35 entering the aeration tank, which inhibited nitrification activity.
- On day 89, the aeration tank had to store excess activated sludge temporarily from a nearby abattoir aeration facility which was undergoing heavy maintenance works. This caused an increase in mixed liquor suspended solids. In general, values as high as 8,000 mg/L have been noted at the facility.

Despite the above, oxygen supply and dissolved oxygen levels were being maintained within appropriate ranges, and BOD removal efficiency was consistently above 95% with average values of 98% being achieved (see Figure 14). Figure 15 outlines the ammonium removal efficiency through the aeration tank. Due to low pH conditions being experienced in the tank, poor conditions for nitrification caused the effluent ammonium to rise.

However, once the DAF control was optimised and when the pH returned to levels above 6 on day 113, average values for ammonium removal of circa 99% were consistently achieved at the facility.

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Figure 13: Influent versus effluent visual comparison of removal efficiency. **Note:** The yellow tinge in the effluent is said to be a mixture of hard (inorganic) COD and/or chemical such as ferric and poly.

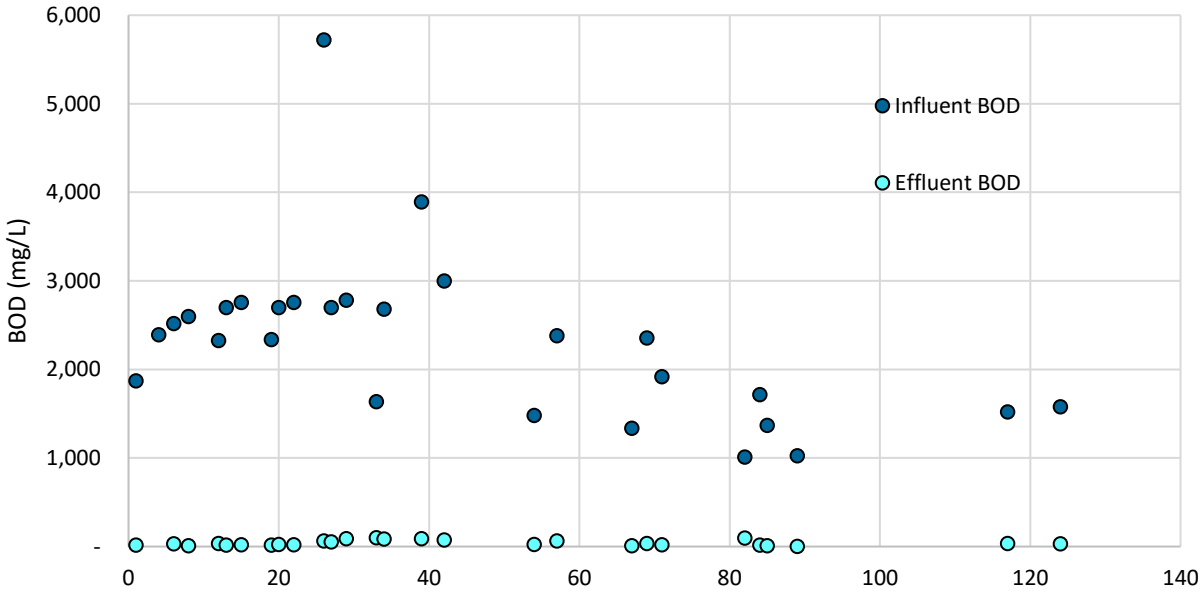

Figure 14: Influent and effluent BOD concentrations at the abattoir facility.

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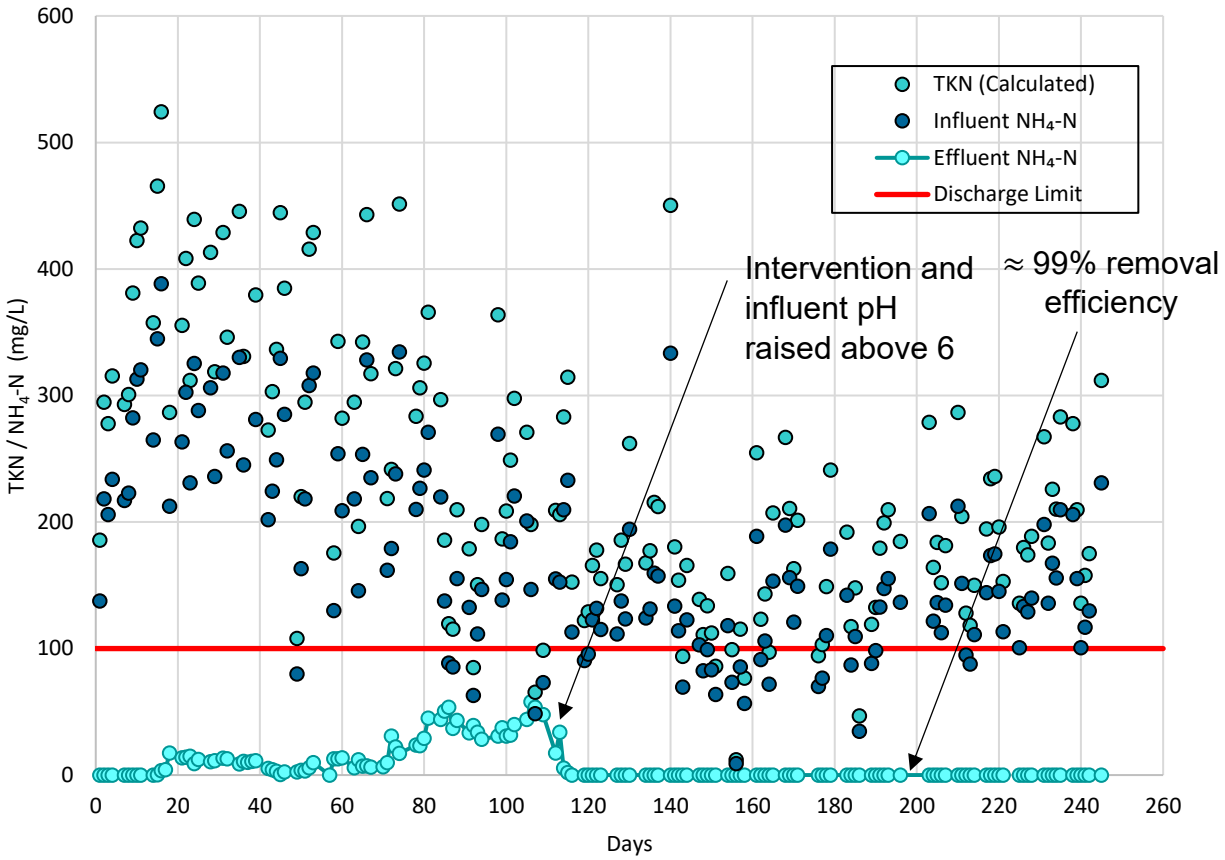

Figure 15: Influent and effluent ammonium concentrations at the abattoir facility.

Specific Energy Efficiency

The specific energy efficiency is an important key performance indicator being adopted across the wastewater industry to evaluate efficiency of treatment plants. Specific energy consumption can be expressed either in terms of kWh/kgBOD_5 removed or kWh/PE/Annum. As the current case study is an industrial treatment facility, the latter per capita based KPI was not considered. The BOD_5 based specific energy consumption was determined by computing the BOD_5 load removed (including BOD_5 load in the return activated sludge) and BOD_5 relative to the aeration energy (excluding mixing power). For 28 data points from July to November 2021, a specific energy consumption of 1.54 kWh/kgBOD_5 removed was determined with a standard deviation of 0.49 kWh/kgBOD_5.

Note: 22 BOD_5 samples were not tested immediately upon collection due to a transit time for testing of circa one week. Therefore, actual BOD_5 concentrations and thus removals may be larger implying that the specific energy consumption may be lower than as presented (conservative values). Further testing is being conducted to uncover this uncertainty.

This specific energy consumption value, as presented, is however not fully representative of true efficiency conditions due to the large demands associated with simultaneous ammonium removal (where the relatively high standard deviation is likely attributed to

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variations in ammonium load). As an example, the average ammonium concentration at this facility was 162 mg/L which can be as much as eight times larger than concentrations experienced in municipal facilities and significantly higher than that often observed at dairy wastewater treatment plants. Instead, the specific energy was normalised to also include the demand with respect to ammonium removal (using a coefficient of oxygen demand of 4.34 $kgO_2/kgNH_4$-N). During aerobic degradation of BOD_5 (assumed 1.0 kgO_2 per kg BOD_5), approximately 4.5% of the total BOD removed is assimilated as NH_4-N and accounted for in the calculation. As the requirement for endogenous respiration and oxygen demand associated with biomass maintenance will be site specific and controlled by the operators, it is excluded from this analysis and only the contaminant load to be removed by the treatment plant is considered. The adjusted KPI is herein termed the BOD load equivalent, or BOD_{Equiv}, and is calculated as follows:

$$kgBOD_{Equiv} = ((1.0 \times kgBOD_5) + (4.34 \times ((kgNH_4\text{-}N-(kgBOD_5 \times 4.5\%))))/1.0$$

A data set was available for comparison from Site (1) which is an abattoir activated sludge facility using FBDA (owned by the same client as the current study). The specific energy consumption was evaluated for each facility using the BOD_5 equivalent removed through the aeration system. In Site (1), the aeration energy was estimated to be 60% of total plant energy to be conservative. The results are outlined in Figure 16 and demonstrate that the VPA system has a 30% lower specific energy consumption than Site (1).

Technology	VPA Abattoir*	FBDA Abattoir
Data Points	28.000	32.000
Mean	**1.257**	**1.801**
Median	1.170	1.803
STD Dev	0.408	0.360
5th Percentile	0.731	1.333
95th Percentile	1.950	2.317
Min	0.469	1.084
Max	2.025	2.846

* Note: 22 BOD_5 samples were not tested immediately upon collection due to a transit time for testing of circa one week. Therefore, actual BOD_5 concentrations and thus removals may be larger (specific energy consumption may be lower)

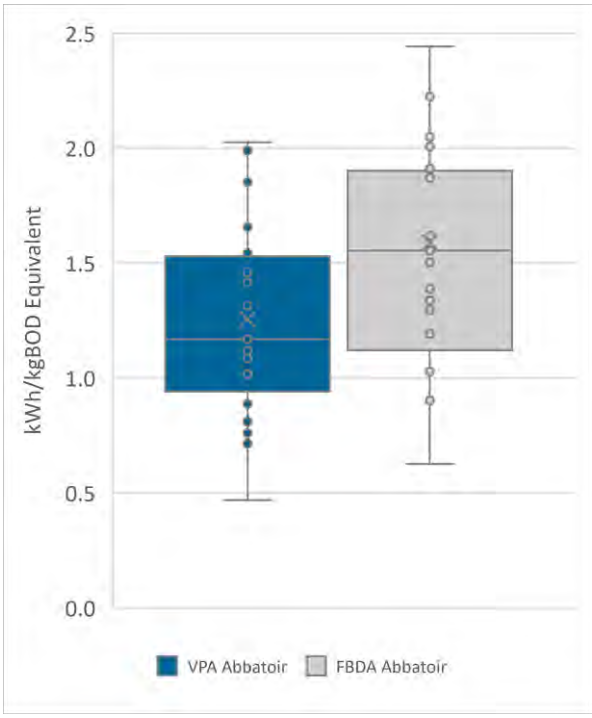

Figure 16: Specific energy comparison between Abattoir WWTP using VPA, Abattoir WWTP using FBDA. Outliers were removed from each data set according to the box plots.

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An additional KPI was developed for evaluating this facility and assessed total plant electricity consumption based on numbers of livestock processed. Values for specific energy consumption on this basis were in the range of 4.5 to 5.8 kWh/livestock processed, or £0.57 to £0.72 /livestock processed, using a price per unit electricity of £0.125/kWh. For comparison, similar values at Site (1) were in the range of 8.8 kWh/livestock processed, or £1.1/livestock processed. Therefore, the VPA-S6 activated sludge facility has a 41% lower electricity and carbon footprint compared with the traditional FBDA activated sludge facility in Site (1).

Noise and Aerosols

During operation, the VPA-S6 air-water interface remains below the water surface, resulting in minimal aerosols. As a result of all parts being submerged, including the outlet duct, this also keeps the noise emissions from the unit very low. To date, there have been no complaints about aerosols, smells, or noise from the unit, despite the nearest smell and noise sensitive receptor (domestic dwelling) less than 50 m away from the aeration tank.

Maintenance

After 6 months of operation, the VPA-S6 had circulated circa 5 million tonnes of activated sludge with no failures reported. At that point the pump was lifted, as required, for routine pump inspection. No solids or fibres were observed or present on the blades. The inside of the vortex chamber vessel was examined, particularly in locations where high velocity, turbulence and abrasion could occur, and no evidence of wear or biofouling was present, and the surface demonstrated a “like new” stainless steel surface. Furthermore, the vessel pressure to power relationship at (1) commissioning in November 2020, (2) December 2021 (before inspection), and (3) December 2021 (after inspection) outlined in Figure 17 demonstrates negligible variation (average 3%) in pump hydraulics and thus performance. Going forward, a single annual inspection will be required by the operator with more detailed inspections and maintenance programs after three years and six years accordingly. The overall time spent conducting the inspection on this occasion was 2.5 hours.

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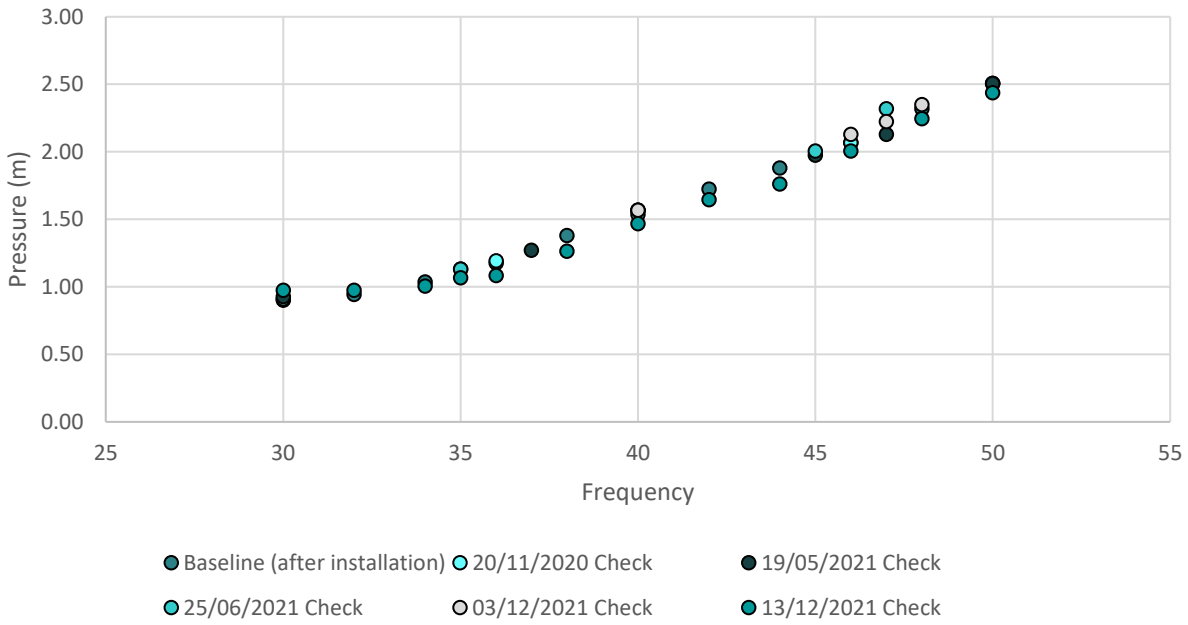

Figure 17: Pressure to power relationship at plant commissioning, prior to inspection and after inspection.

Total Lifecycle Cost Assessment

A total lifecycle assessment was conducted for the new wastewater treatment plant where the VPA-S6 costs were compared to (1) a do-nothing scenario (which represents costs incurred prior to upgrade) and (2) a hypothetical FBDA system upgrade. The breakdown and assumptions for operational costs, maintenance and capex are outlined in the following sections.

Opex

The annual operational expenditure (opex) at the facility consists of three aspects:

- Chemical costs (ferric chloride, liquid poly and dry poly) required for DAF and solids processing.
- Electricity costs.
- Trade effluent charges.
- Maintenance Costs

Data for chemical usage, electricity and trade effluent charges prior to upgrade were provided by the plant operator and plant manager as a baseline (do nothing scenario) condition. The values were remeasured post upgrade and averaged over seven months. The averages developed were used to project the annual costs/savings before and after upgrade as outlined in Table 3. As described earlier, electricity costs increased post upgrade due to the presence of the new treatment facility, however total costs will be

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significantly reduced due to improved overall resource efficiency and reduction of trade effluent charges.

Table 3: Plant average monthly opex as of 2021.

		Before Upgrade	VPA Aeration Upgrade	Savings
Chemical (£/month)	Ferric Chloride	£2,968.00	£517.42	£2,450.58
	Liquid Poly	£4,800.00	£1,260.00	£3,540.00
	Dry Poly	£1,140.63	£637.20	£503.43
Electricity (£/Month)		£795.82	£3,136.62	-£2,340.80
Effluent Volume/Month (m^3/month)		6,010.80		6,010.80
Trade Effluent Charge (£/m^3)		£1.80	£1.16	£0.64
Total Volumetric Cost (£/m^3)		£3.41	£2.08	£1.33
Cost/Livestock Processed (£/animal)		£3.51	£2.14	£1.37
Projected Annual Cost (£)		£246,316.86	£150,285.23	£96,031.63

The data in Table 3 is based on the 2021 facility operations of 1,369 livestock processed per week. It is understood that the facility has recently expanded its operations to include a new processing line, resulting in the capacity to increase production by 33%. It is assumed that this production will be fully operational in 2023. Therefore, a hypothetical case summarising the impact of the new facility in terms of savings for the increased capacity and load is outlined in Table 4.

Table 4: Plant average monthly opex as of 2023 following increased production.

		Do Nothing	VPA Aeration Upgrade	Savings
Chemical (£/month)	Ferric Chloride	£3,947.44	£908.51	£3,038.93
	Liquid Poly	£6,384.00	£1,675.80	£4,708.20
	Dry Poly	£1,517.03	£847.48	£669.56
Electricity (£/Month)		£1,058.44	£4,171.70	-£3,113.26
Effluent Volume/Month (m^3/month)		7,994.36		7,994.36
Trade Effluent Charge (£/m^3)		£1.80	£1.16	£0.64
Total Volumetric Cost (£/m^3)		£3.41	£2.11	£1.30
Cost/Livestock Processed (£/animal)		£3.51	£2.17	£1.34
Projected Annual Cost (£)		£327,601.43	£202,523.40	£125,078.03

FBDA Comparison

To compare against a hypothetical case where FBDA was installed instead of VPA, Table 5 was developed to demonstrate how the energy requirement could be estimated. Here,

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the average power demand for aeration using average loading conditions (40 kgO_2/kWh) is developed using the in-process oxygen transfer equations.

Table 5: FBDA versus VPA energy comparison.

Fine Bubble Diffused Aeration (FBDA)	Vortex Powered Aeration (VPA)
	
FBDA SAE = 3.5 kgO_2/kWh as defined by manufacturer. In process conditions, an average alpha factor of α = 0.45 is declared[5]. The in process aeration efficiency (AE) can be calculated as follows: $AE = SAE \frac{\alpha(\beta C_{ST} - C)}{C_{S20}} \theta^{T-20}$ *Where;* Temperature = 25 °C β = 0.9 α = 0.45 C_{ST} = 8.05 mg/L C_{S20} = 9.08 mg/L C = 1 mg/L θ = 1.024 process AE can be calculated to as: AE =1.22 kgO_2/kWh At an OTR requirement of 40 kgO_2/hr, the average power input for the overall FBDA system will be: $P_{in(aeration)}$ =OTR/AE =40/1.22= 32.8 kW	VPA SAE = 2.5 kgO_2/kWh as defined in previous studies. Alpha factor used in this analysis was reduced from measured values to be conservative to α = 0.9 (measured in process). The in process aeration efficiency (AE) can be calculated as follows: $AE = SAE \frac{\alpha(\beta C_{ST} - C)}{C_{S20}} \theta^{T-20}$ *Where;* Temperature = 25 °C β = 0.9 α = 0.9 C_{ST} = 8.05 mg/L C_{S20} = 9.08 mg/L C = 1 mg/L θ = 1.024 process AE can be calculated as: AE =1.74 kgO_2/kWh At an OTR requirement of 40 kgO_2/hr, the average power input for the overall VPA system will be: $P_{in(aeration)}$ =OTR/AE =40/1.74 = 23 kW
Annual energy = 32.8 x 24 x 365 = 287,464 kWhs	Annual energy = 23 x 24 x 365 = 201,225 kWhs
Average energy savings usng VPA is ≈ 30% as confirmed from specific energy consumption analysis	

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Maintenance and Replacement

Routine maintenance for all three cases in the lifecycle assessment is assumed to be the same; however, ongoing specific maintenance and replacement costs are described and costed as follows in Table 6 in the lifecycle assessment.

Table 6: FBDA versus VPA maintenance.

Equipment	Repair or Overhaul Requirements	Frequency	Cost
FBDA	Diffuser fouling*	Cleaned every 5 years to maintain high efficiency	£30,000
	Diffuser failure (membrane leakage, tears, bursts, pipe failure, grid failure) *	Can occur anytime throughout equipment lifespan	£30,000
	Overhaul including replacing diffuser grid, pipework and blowers	Every 15 years	£150,000 to £200,000
VPA-S	Pump overhaul*	After 6 years of operation	£5,000
	Pump replacement	After 15 years of operation	£16,000
*Cost not included in lifecycle assessment to be conservative			

Totex

In discussions with the client and feedback from contractors active in the wastewater sector, total upfront capital costs for lifecycle assessment purposes have been estimated for (1) the actual upgrade with VPA and (2) a notional upgrade with FBDA. This results in estimated total upgrade costs for both options (1) of circa £925,000 and (2) of circa £995,000 (based on approximate capex provided by the client).

With the results available from the plant's current and projected future operational expenditure, maintenance and replacement costs, and the aforementioned upfront capital costs, the output from the total lifecycle costs is presented in Figure 18. This shows that the plant should pay for itself within 8 years. After 20 years, the VPA aeration system will have reduced the total lifecycle costs from circa £7 million to £5.46 million resulting in a total lifecycle saving of approximately £1.56 million. Regarding FBDA, due to the larger aeration energy demand, a longer pay back of 10 years can be expected.

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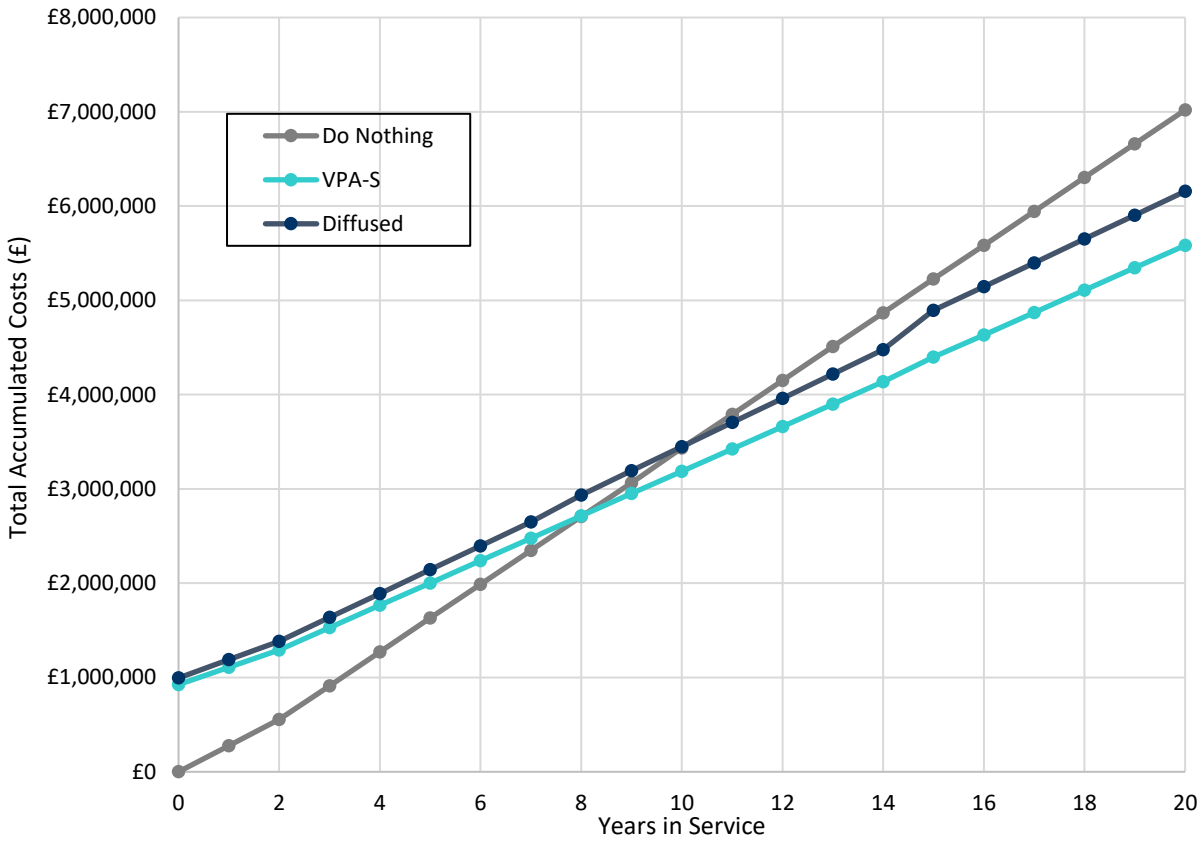

Figure 18: Totex for (1) do nothing, (2) FBDA upgrade and (3) VPA upgrade options.

Chemical Carbon Reductions

The chemicals ferric chloride, liquid polymer and dry polymer are known to have a heavy carbon emissions equivalent ($kgCO_2$-eq) associated with their production and use (transport, water, electricity, steel, diesel use etc.). Through the project, a 66%, 74% and 15% reduction in ferric chloride, liquid polymer (polyacrylamide) and dry polymer respectively was noted by the operator. A carbon emissions equivalent analysis was therefore conducted using the EcoInvent v3.8 2021 Global Database. The following assumptions and omissions were noted:

- Figures for production of Ferric Chloride are based on a detailed analysis done in Quebec which has been statistically interpolated for global use. Density of ferric chloride is 1.4 kg/L as per material safety data sheet supplied.
- For Liquid Polymer (polyacrylamide) the data is a global dataset which effectively averages various production sources globally.
- Dry polymer has not been included due to (i) the relatively low usage and low overall impact on emissions on the site and (ii) the need for more detailed ingredients/process investigation to fully model the substance. This contributes to a conservative total emissions output.
- Carbon emissions associated with transport has been omitted. This contributes to a conservative total emissions output.

The results of the analysis are outlined in Table 7.

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Table 7: Chemical carbon emission equivalent savings summary (as of 2022).

Chemical	Chemical Saving (%)	Chemical Saving (kg/month)	$kgCO_2$-eq/kg	$kgCO_2$-eq/annum
Ferric Chloride*	66%	7,381	0.41	36,313
Liquid Polymer (polyacrylamide)	73%	1,475	3.23	57,171
Dry Polymer	15%	47	Omitted from analysis	
			Total $kgCO_2$-eq/annum	93,484
* Ferric Chloride 40% (12% iron state solution)				

The total carbon emissions saving of 93,484 $kgCO_2$-eq/annum is significant and represents a livestock based (carbon handprint) reduction of at least 1.33 $kgCO_2$-eq/livestock processed at the facility. Therefore, the combination of reduced chemical use and reduced pollutant production (and consequently a lowered impact on eutrophication and toxicity, both upstream and downstream) using energy efficiency VPA and activated sludge technology demonstrates the high impact of such projects when striving to approach net zero emissions.

Conclusion

The Vortex Powered Aerator Standard 6 (VPA-S6) is a novel wastewater aeration technology that adopts cyclonic flow with advanced flexible control to achieve high treatment efficiency in activated sludge systems. The innovation was recently deployed at an industrial abattoir as part of an onsite wastewater treatment facility upgrade. The challenge at the facility (which processes circa 274 livestock per day) was to provide a low total expenditure aeration solution for an activated sludge system to enhance resource efficiency, reduce trade effluent charges, reduce carbon emissions, and minimise noise pollution. This technical report was prepared to summarise the technical performance of the system over the first year of operation. Technical in-situ performance data pertaining to oxygen transfer, aeration efficiency, process efficiency, noise, aerosols, and maintenance are presented and discussed. Figure 19 provides a high-level summary infographic of the key impacts at the facility due to the upgrade.

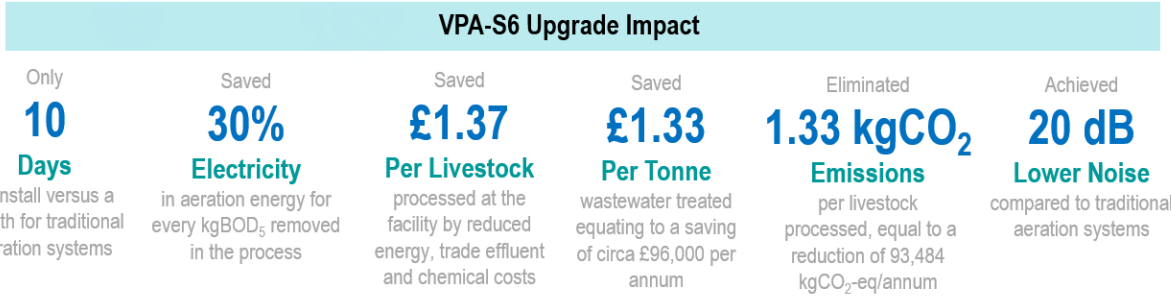

Figure 19: Infographic outlining the impact of the VPA activated sludge system at the site

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The VPA's energy efficiency performance was compared to a similarly sized abattoir facility using fine bubble diffused aeration (FBDA), and a 30% reduction in specific energy consumption was noted. In terms of total electricity consumed per unit livestock processed, a 41% reduction was concluded. In addition, a comprehensive carbon equivalent analysis was conducted at the facility, pre- and post-upgrade, which demonstrates a carbon equivalent saving of circa 93,500 $kgCO_2$-eq/annum in chemical use alone. In financial terms, this report demonstrates that the VPA system will save the client £96,000 per annum (against a baseline opex of approximately £246,000), increasing to potentially £125,000 per annum when the new production line becomes operational. Costs per livestock processed will fall from £3.51 to £2.14, costs per tonne of effluent discharged will fall from £3.41 to £2.08, and there will be a 20-year total lifecycle saving of £1.56 million.

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