Comparison of Oxygen Transfer and Uptake Between an Integrated Fixed-Film Activated Sludge (IFAS) Process and a Conventional Activated Sludge Process (ASP)

Sarah Lothman[1*], W. James Gellner[2], Alan Stone[2], Don Howard[3], Paul Pitt[2], Diego Rosso[4]

[1]GHD Limited, Lower Hutt, New Zealand
[2]Hazen and Sawyer, P.C., USA
[4]Dept. of Water Reclamation, Greensboro Water Resources, North Carolina, USA
[6]Department of Civil and Environmental Engineering, University of California, Irvine, USA
*Corresponding author (e-mail: sarah.lothman@ghd.com)

ABSTRACT

Integrated fixed-film activated sludge (IFAS) processes are a combination of biofilm reactors and activated sludge processes, achieved by introducing and retaining biofilm carrier media in activated sludge processes. We tested a full-scale IFAS process equipped with AnoxKaldnes media and coarse-bubble aeration. This process operated independently in parallel with an existing full-scale activated sludge process. Both processes achieved the same percent removal of COD and ammonia, despite the double hydraulic load and double oxygen demand on the IFAS process. In order to prevent kinetic limitations associated with dissolved oxygen (DO) diffusional gradients through the IFAS biofilm and to avoid media coalescence on the reactor surface and promote biofilm contact with the substrate, high DO and high mixing requirements are specified for the IFAS system. These require an elevated air flux in the IFAS process, which was much higher than that of the parallel activated sludge process. Even though the air used per unit load removed should be the same for both processes, the IFAS reactors were characterized by higher air flux and air use per unit load treated due to the high DO and mixing requirements. This directly affected the energy footprint for aeration, which in this case was much higher for the IFAS system than activated sludge.

KEY WORDS - activated sludge; integrated fixed-film activated sludge (IFAS); oxygen transfer; nutrient removal; energy footprint; aeration

NOMENCLATURE

AFR = air flow rate ($m^3\ s^{-1}$)
A_{TANK} = tank bottom area
BHP = power drawn by the blower (kW)
c = molecular weight of air ($kg\ kmol^{-1}$)
COD = chemical oxygen demand ($mg_{O2}\ l^{-1}$)
DWP = dynamic wet pressure (Pa)
h_L = head loss in the air distribution line (Pa)
J_{air} = Air flux ($m\ s^{-1}$)
MCRT = mean cell retention time (d)
MLSS = mixed liquor suspended solids ($mg_{TSS}\ l^{-1}$)
MLVSS = mixed liquor suspended solids ($mg_{VSS}\ l^{-1}$)
OD = oxygen demand ($kg_{O2}\ s^{-1}$)
OTE = oxygen transfer efficiency (%)
OTR = oxygen transfer efficiency ($kg_{O2}\ s^{-1}$)
OUR = oxygen uptake rate ($mg_{O2}\ l^{-1}\ h^{-1}$)
P_d = discharge pressure (Pa)
P_i = inlet pressure (Pa)
Q = influent flow rate ($m^3\ d^{-1}$)
R = universal gas constant ($8.314\ J\ mol^{-1}\ K^{-1}$)
SOTE = standard OTE in clean water (%)
SOTR = standard oxygen transfer efficiency ($kg_{O2}\ s^{-1}$)
T = ambient temperature (K)
W_{air} = ponderal air flow ($kg\ s^{-1}$)
Z = hydrostatic pressure corresponding to diffuser submergence (Pa)

greek letters

α = alpha factor = αSOTE / SOTE (-)
αSOTE = Standard OTE in process water (%)
ε = energy footprint per unit oxygen demand oxidised = ($kWh\ kg_{O2}^{-1}$)
γ = ratio of specific heats at constant pressure and volume (0.283 for air)
η = combined motor and blower efficiencies (-)
ρ_{air} = air density ($kg_{air}\ m^{-3}_{air}$)

1. INTRODUCTION

The integrated fixed-film activated sludge (IFAS) process, introduced over fifteen years ago (Randall and Sen, 1996), integrates the traditional biofilm characteristics and the completely mixed conditions of the activated sludge process (ASP) by introducing floating plastic carriers onto which biofilm can establish. The carriers inside the IFAS reactors are retained by screens which allow the transit of the activated sludge media through the reactor. The introduction of carrier media increases the process biomass inventory, and is expected to allow an increase in organic loading rates without requiring physical process expansion. Thus, the IFAS process poses as an ideal candidate for plant retrofits and process upgrades for land-constrained sites.

The enhanced removal of chemical oxygen demand (COD) and biological nutrient removal have been well-demonstrated in the application of IFAS to ASP. With IFAS, sufficient COD removal can be achieved at higher organic loads, lower hydraulic retention times and with smaller basin volumes (Andreottola et al., 2003; Sriwiriyarat et al., 2008). Enhanced nitrogen removal was accomplished up to full-scale (Randall et al., 1996) and enhanced phosphorous removal was accomplished up to pilot-scale (Sriwiriyarat et al., 2005). Besides improving the level of treatment in the ASP, additional advantages have been reported in IFAS processes including greater process stability (Sriwiriyarat et al., 2008), reduced sludge production and reduced solids loadings on the secondary clarifiers (Stricker et al., 2009), and enhanced sludge settleability (Kim, 2010).

In activated sludge processes, oxygen transfer analyses using the off-gas technique have been extensively practiced for the past 30 years (*inter alia*, Redmon et al, 1983). In moving biofilm reactor technology, fewer published research works on oxygen transfer analyses are available: independent studies on biological aerated filters (BAF) using off-gas analysis were conducted in small scale (Harris et al., 1996) and full depth reactors (Stenstrom et al, 2008), but not for the IFAS process. The oxygen uptake rate (OUR), a key parameter that can be obtained from off-gas testing, is typically used as an indicator of microbial metabolism. The OUR in IFAS systems was previously evaluated (Maas et al., 2008). Those studies suggested that COD and nutrient removal rates can be controlled by determining OUR. Maas et al. (2008) found from OUR tests that the biofilm on the media perform the majority of nitrification in an IFAS system. That study, however, did not measure oxygen transfer efficiency (OTE) and oxygen transfer rates (OTR), two performance parameters that can be measured via off-gas analysis. Off-gas analysis is a direct measurement of oxygen transfer and is based on the mass-balance of the water column under a hood floating on the aerated wastewater surface (Redmon et al, 1983). Off-gas tests were previously performed on an IFAS system by a manufacturer (Viswanathan et al, 2008). To our knowledge, our paper presents the first independent off-gas investigation of a full-scale IFAS system to date.

To compare aeration performance between different aeration systems and for the same system in different process conditions and times, OTE is typically corrected to standard conditions [zero dissolved oxygen, zero salinity, 101,325 Pa, 298.15 K]. Standard oxygen transfer efficiency (SOTE) is typically used to characterize performance in clean water (ASCE, 2007). Due to air bubble geometry, SOTE decreases rapidly with increasing air flow rate per diffuser (Zlokarnik, 1980) and is in general lower for coarse-bubble diffusers than for fine-bubble diffusers (USEPA, 1989). Oxygen transfer efficiency can be affected dramatically by the process conditions: for activated sludge plants, the transfer efficiency is reduced at high F/M or low MCRT operation (Rosso et al, 2005). The parameter employed to quantify the depression of oxygen transfer in process water is the α factor, calculated as (Stenstrom and Gilbert, 1981):

$$\alpha = \frac{\alpha \mathrm{SOTE}}{\mathrm{SOTE}} \tag{1}$$

In aerobic zones, the soluble COD and its readily biodegradable fraction (rbCOD) can depress the α factor for fine-pore diffusers, and therefore depress the SOTE in process condition, or αSOTE (Eckenfelder and Barnhart, 1961; Mancy and Oku, 1968; Hwang and Stenstrom, 1979; Wagner and Pöpel, 1996; Rosso and Stenstrom, 2006). When coarse-bubble diffusers are installed, α is virtually unaffected by the wastewater contaminants (Eckenfelder and Ford, 1968; Rosso et al, 2005). Hence, the coarse bubble diffusers typically employed in IFAS reactors to promote mixing and to meet high oxygen uptake rates are expected to be associated with elevated α factors but low SOTE values (IWA, 2008). Also, it is known that higher MCRT processes using fine bubble diffusers (e.g.: processes performing biological nutrient removal or BNR) have higher α factors throughout the plug flow aeration tank (Rosso et al, 2008). Hence, the oxygen transfer depression in the reactors with fine-pore diffusers is expected to be mitigated by the increased MCRT specified to perform BNR.

In IFAS systems, coarse bubble diffusers for aeration are typically installed to meet the elevated DO and mixing requirements. These diffusers release air through a macroscopic orifice (several millimetres in diameter), and bubbles detach with equivalent diameters of approximately 50mm, which corresponds to the maximum diameter of stability for air bubbles in water (Clift et al, 1978). In coarse-bubble diffusers, the bubble release is dominated by the velocity of the air flow through the orifice. Coarse-bubble diffusers tend to regurgitate air at low air flow rates and stabilize the release of bubbles at higher air flow rates, exhibiting in general a bubble size distribution independent of air flow (Wang and Hung, 2007). Oftentimes, in IFAS systems, the bubbles may be referred to as "medium-bubbles", because it may be evident that the majority of bursting bubbles on the IFAS reactor surface are of the same size as the carrier media or smaller (i.e., below 50mm). It can be inferred that although the diffuser itself releases coarse-bubbles, the transit of bubbles through a well-mixed reactor with solid media must be associated with bubble shearing into smaller bubbles that burst at the tank surface in the "medium" range (with size distribution between 5 and 50mm in diameter).

For a typical IFAS reactor, the air diffuser system consists of stainless steel headers with small holes in the bottom of the header or air spargers mounted to the header top. The design of the system is intended to minimize the need for in-tank maintenance. Because of the presence of the IFAS media, the coarse bubble oxygen transfer efficiency may be expected to increase due to the bubble hold-up in the tank and splitting of the bubbles when passing through the areas filled with IFAS media. In this study we confirmed this phenomenon only visually and no quantitative analysis of bubble size distribution in IFAS reactors is yet published. Also, IFAS systems must be operated with increased DO concentrations relative to ASP reactors to facilitate bulk liquid DO diffusion through the biofilm. Both the coarse bubble system and the increased target DO increase the air requirements for IFAS systems.

Energy use is a growing concern at wastewater treatment facilities and since aeration has been identified as one of the most energy intensive unit operations in wastewater treatment (Reardon, 1995), aeration efficiency monitoring poses as a key candidate for the reduction of energy consumption and operating costs (Leu et al, 2009). It is therefore critical to comparatively quantify the ASP and IFAS aeration efficiencies and energy costs.

The goal of this research is to quantify oxygen transfer and uptake in IFAS systems and to present the results of our comparative energy footprint analysis for the two processes. Due to the unique opportunity afforded by this site's configuration, we tested the hypothesis that the IFAS process can provide a much higher capacity in the same volume, but partially at the cost of a less efficient aeration system.

2. MATERIALS AND METHODS

Process Operations

The T.Z. Osborne Water Reclamation Facility is a 40 mgd plant located in Greensboro, NC (USA). Major unit processes at the plant include influent screening, primary clarifiers, conventional plug flow activated sludge, secondary clarifiers, effluent sand filters, and disinfection. The plant aeration basins are arranged to operate in parallel. Several alternatives are being evaluated as strategies to meet stringent forthcoming regulatory nutrient limits, and consequently a full-scale IFAS unit equipped with AnoxKaldnes media was installed in side-by-side configuration with the existing ASP. The plant performs BNR with a Ludzack-Ettinger configuration (sludge return rate ~ 100% of influent flow). For the IFAS reactors, the previously existing fine bubble disc diffusers (230 mm in diameter) in the three IFAS cells were removed and replaced with the coarse-bubble diffuser system recommended by the manufacturer to promote mixing and maintain elevated DO levels in the IFAS reactors. Throughout Tank 11, the ASP reactor, and in the portion of the IFAS reactor, Tank 12, that followed the IFAS reactors, the fine-pore disc diffusers previously installed were operated. Throughout this paper we refer to ASP as the process in Tank 11 and IFAS as the process in Tank 12. At the time of both tests, there were no unusual plant conditions. Table 1 details the key operating parameters for the plant.

Table 1. Plant Operating Conditions During Testing

	January 2010		**June 2010**	
Parameter	**Tank 11 ASP**	**Tank 12 IFAS**	**Tank 11 ASP**	**Tank 12 IFAS**
Influent Flow (mgd)	2.9	6.0	3.0	6.0
COD, (mg/L)				
Primary effluent	182	182	337	337
Final effluent	37.8	36.8	31.7	35.4
MLSS, (mg_{TSS}/L)	3,110[1]	1,215[1]	2,780	1,655
MLVSS, (mg_{VSS}/L)	2,375[1]	928[1]	N/A[2]	N/A[2]
Temp, MLSS (^{o}C)	14.2	14.5	26.8	26.8
Mixed liquor MCRT, (d)	7.0	4.0	6.0	3.0
NH_4-N, (mg/L)				
Primary Effluent	12.9	12.9	23.8	23.8
Final Effluent	< 0.1	< 0.1	< 0.1	0.2

[1] Average of values collected Tuesday-Friday of testing week since testing day was a holiday

[2] MLVSS not measured for June 16, 2010. June 17, 2010 MLSS values were 2,840 and 1,815 for Tanks 11 and 12, respectively. MLVSS values were 2,220 and 1,390 for Tanks 11 and 12, respectively.

At the time of testing, the two tanks were operating using the same wastewater influent, but with roughly double hydraulic load (Q) and oxygen demand OD ($kg_{O2}\ s^{-1}$) to the IFAS process.

$$OD = Q \cdot \left(\Delta COD + 4.33 \cdot \Delta NH_4^+ \right) \qquad (1)$$

where ΔCOD = COD oxidized in the aerobic reactors (mg l^{-1})
ΔNH_4^+ = ammonia oxidized in the aerobic reactors (mg l^{-1}).

Notwithstanding this, the IFAS had comparable effluent concentrations for COD and ammonia (Table 1). The double hydraulic load on the IFAS implies that the hydraulic retention time there was half than that of the ASP. The plant was able to isolate one aeration basin and one clarifier completely from the rest of the system to allow retrofit with the IFAS process. Aeration tank 12 and a clarifier (No. 7) were isolated and used during the process pilot and this study for the IFAS installation. The ASP and IFAS reactors were hence operated independently, i.e. with separate clarifiers and sludge lines. Aside from the presence of IFAS media and different diffusers in the IFAS reactors, Tanks 11 and 12 were identical (volume = 1.65 MG each), therefore acting as two separate and parallel wastewater treatment processes treating the same wastewater.

Off-gas Analysis

Off-gas analysis was performed in the same fashion as described by the US EPA standard protocol for testing in process water (US EPA, 1989). The off-gas technique is based upon the original method developed by Redmon, et al. (1983). Figure 1 illustrates the testing layout.

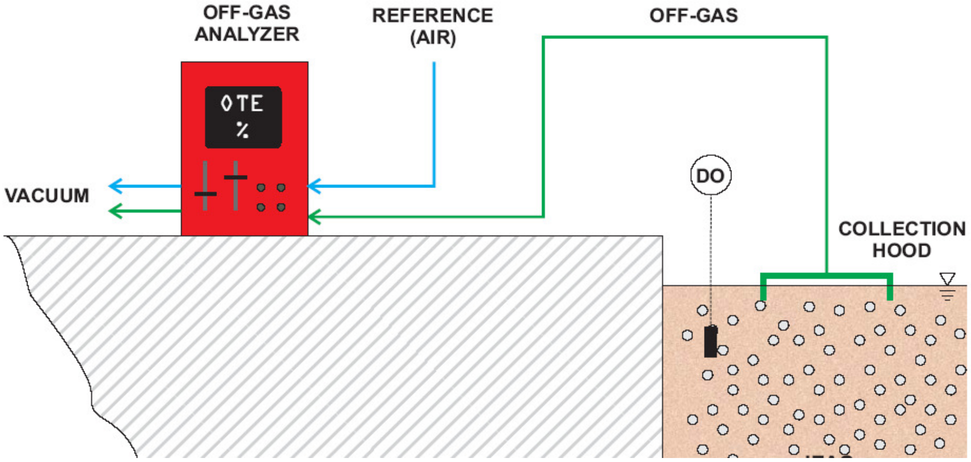
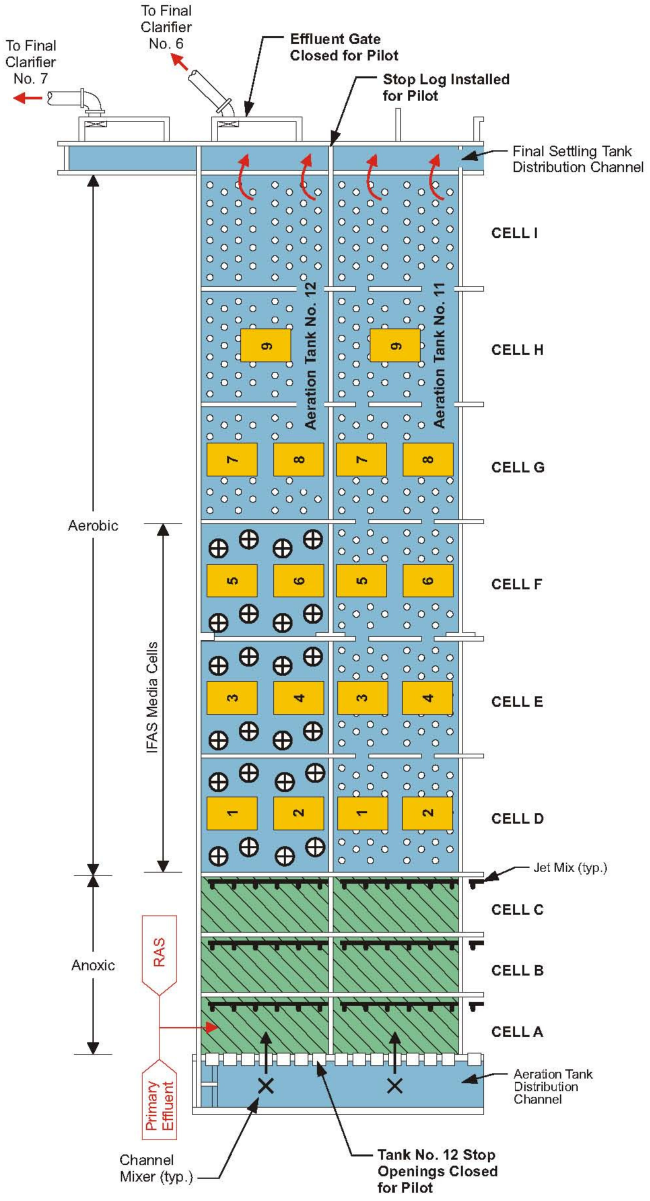


Figure 1. Off-gas testing layout. This non-invasive testing method allows the concurrent measurement of the actual oxygen transferred to the water (oxygen transfer efficiency [OTE, %], oxygen transfer rate [OTR, kgO2 h-1], and oxygen uptake rate [OUR, mgO2 l-1 h-1])

The technique consists of an oxygen mass balance on the water column underneath a floating off-gas collection hood. We constructed an analyzer with the same configuration as described in detail by Leu et al (2009). The apparatus self-calibrates at each measurement by zeroing with an initial sample of atmospheric air. The off-gas was collected in two floating hoods providing a capture area of 32 ft^2 each. In the tests performed at this plant, the carbon dioxide and water vapor were removed from the off-gas prior to analysis by using a desiccating column filled with silica gel granules and sodium hydroxide pellets.

The OTE is calculated from the off-gas oxygen mole fraction and the known ambient air mole fraction (20.95%). The gas flow rate is not needed to perform this calculation, although it is useful to calculate flow-weighted averages over an aeration tank or across several aeration tanks. Two testing locations were chosen in each reactor cell in order to gather a representative section of each cell. Only the last cell of each process was tested in the middle. For each testing location, two readings were taken. Figure 2 shows the hood testing locations. The total sampled area exceeded the protocol requirement of 2% tank surface coverage.



30841-004-SC-11.cdr

Figure 2. Testing Hood Positions

The test was first performed in the winter season (January 2010). Winter testing allows the measurements of the aeration efficiency parameters at peak loading in cold water, which is the worst case scenario for aeration efficiency and is the design target for the aeration system. The test was repeated in the summer (June 2010) to verify the aeration efficiency parameters in warm water while the metabolic rates, hence the OUR, are expected to be highest. Also, the coldest weather is the design criteria for blower power and the warmest weather is the design criteria for blower capacity (i.e., AFR), and it is therefore valuable to repeat the test for the two temperatures for a comparison of the normalized performance data, i.e. the energy footprint per unit oxygen demand removed ε (kWh kg_{O2}^{-1})].

3. RESULTS AND DISCUSSION

Table 1 shows the secondary effluent concentrations for COD and ammonia. Both processes [ASP (Tank 11), IFAS (Tank 12)] remove carbonaceous and nitrogenous loads to the same extent, notwithstanding the double oxygen demand (expressed as kg_{O2} s^{-1}) on the IFAS reactor. Figure 3 shows the profiles of nitrogen species along both reactors for the tests in winter and summer.

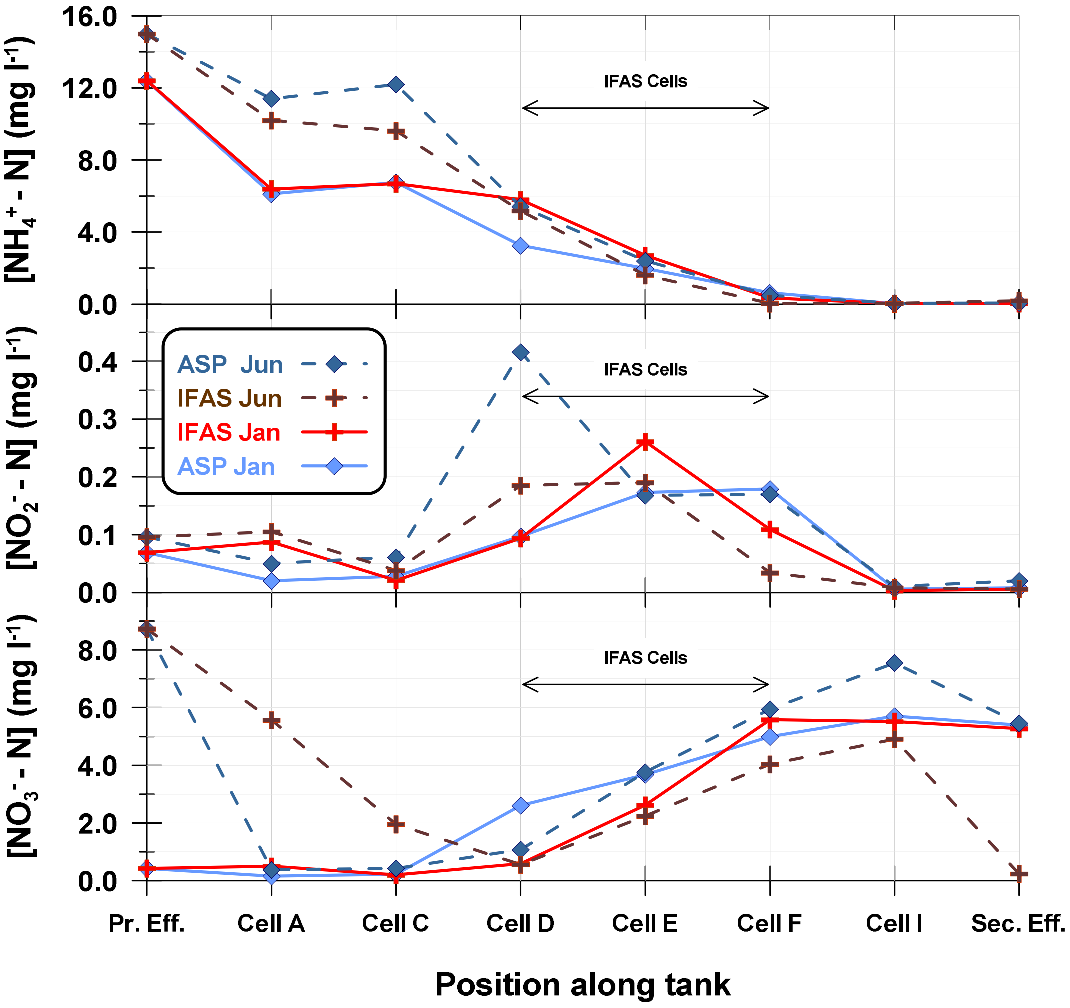


Figure 3. Comparative nutrient profiles during both tests

The ammonia profiles show that the ammonia concentration in the first denitrification zone (Cell A in Fig. 3) during the winter are roughly half when compared to those in the primary effluent, a dilution associated with the mixing between denitrification influent and return activated sludge. In fact, the portion of ammonia assimilated by denitrifiers for synthesis, although usually embedded in the mass balance discrepancy, when not neglected, is calculated by the difference between the ammonia in the reactor influent and its products (Silverstein and Schroeder, 1983; Argaman, 1986). The summer test shows less decrease in ammonia from primary effluent to the first denitrification reactor (Cell A in Fig. 3) despite the higher ammonia assimilation expected with warmer temperature, maybe caused by an increased transformation of TKN to ammonia. In both tests and for both reactors, the bulk of the ammonia is removed in the first two aerated reactors (Cells D and E in Fig. 3) for both the ASP and the IFAS.

The two processes have consistent profiles for all nitrogen species for both tests. In the IFAS reactor (Tank 12), the reactor zones with IFAS media (Cells D, E, and F in Fig. 3) show no different behaviour than their parallel ASP zones in Tank 11. The overall effect is secondary effluent values for nitrogen species for IFAS are consistently lower or equal to those of ASP. One nitrate measurement, the primary effluent concentrations for the summer test in Figure 3 appears unusually high for an L-E process (i.e., without internal recycling) and can be considered an outlier. Although no samples upstream of the primary effluent were collected, this outlier may be due to a non-representative variation of the primary effluent at the time of sampling. The nitrate profiles in the winter increase regularly along the process train, and appear consistent with the expectations for a plug-flow L-E process. The off-gas results are summarized in Table 2. The results from both tests confirmed that the IFAS is characterized by elevated air flux due to mixing requirements specified by the process manufacturer, with associated lower OTE.

Table 2. Comparative summary of results for the off-gas tests performed in January and June 2010. All values are airflow-weighted except for DO.

Tank No.	**OTE** (%)	**αSOTE** (%)	**Air Flux** ($m\ s^{-1}$)	**DO** ($mg\ l^{-1}$)	**OUR** ($mg\ l^{-1}\ h^{-1}$)
			JANUARY 2010		
11 (ASP)	11.7	15.7	1.53×10^{-3}	1.0	36.5
12 (IFAS)	6.3	11.0	5.11×10^{-3}	3.6	80.0
			JUNE 2010		
11 (ASP)	11.3	15.3	2.15×10^{-3}	2.2	53.4
12 (IFAS)	7.8	13.5	4.74×10^{-3}	3.8	105.4

For Tank 12, only the IFAS reactor cells (Cells D, E, F as shown in Figure 2) contain coarse bubble diffusers, while the remaining aerobic cells after the IFAS process in Tank 12 (cells G, H, I) contain fine bubble diffusers. Our results are also normalized as air flux (air flow per unit tank bottom area) and air use (air volume per unit oxygen demand removed). In Table 2, the results for each tank are reported as airflow-weighted averages (except for DO). Flow-weighing is necessary to calculate an appropriate average for a process where the air flow may be variable for the different sampling locations. This is the case of the process tested here, where the IFAS has an air flux several times higher than that of the ASP at some of the sampling locations.

Due to the high DO values specified for the IFAS design by the manufacturer, the average DO in the IFAS process was 1.7 – 3.6 times higher than the average DO in the ASP. The air flux (air flow per unit tank bottom area) and air use (air volume per unit oxygen demand removed) of IFAS vs. ASP are 1.4 – 3.1 times and 1.6 – 2.0 times higher, respectively. The OUR is approximately double for the IFAS, corresponding with the double oxygen demand being removed in the IFAS process. The OTE, αSOTE, OUR, and Air Flux for both the IFAS and the ASP for both tests are shown in Figures 4-7. IFAS media is installed in Tank 12 aeration basins cells corresponding to positions 1-6 (cells D-F); positions 7-9 (cells G-H) are ASP for both tanks. Figure 4 shows the OUR profiles.

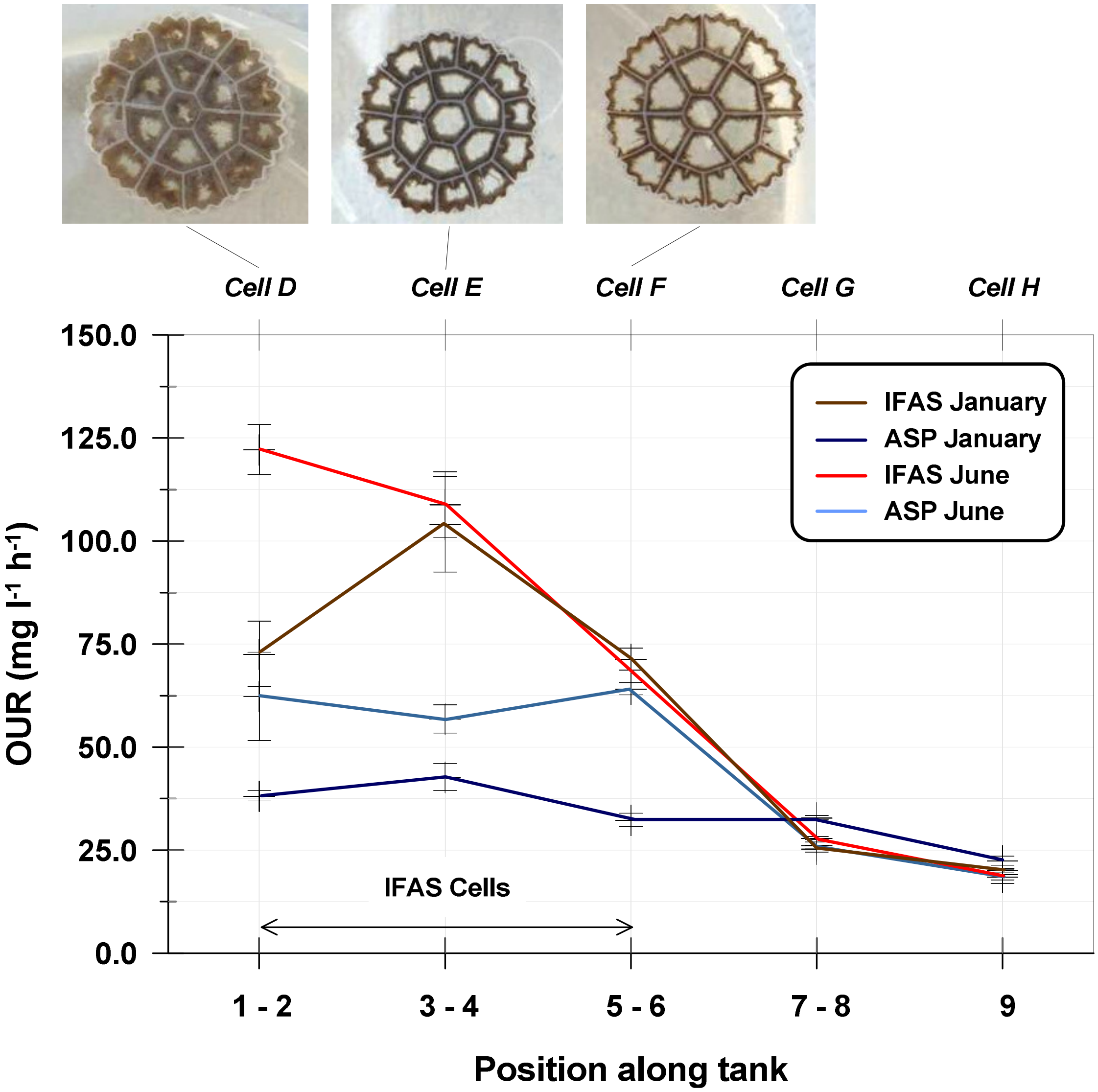


Figure 4. Comparative OUR profiles for ASP and IFAS during the January and June tests. IFAS cells are installed only at testing positions 1-6, and positions 7-9 are ASP for both tanks.

The IFAS zones in Tank 12 are characterized by very high OUR values, unusual for municipal wastewater treatment processes, a result of the ability by the increased IFAS biomass inventory to remove twice as much oxygen demand as the ASP in the same reactor volume. The OUR values for both tanks are virtually indistinguishable outside the IFAS zone in Tank 12 (positions 7-9). Figure 4 also shows images of sample biofilm carriers for each of the three IFAS cells in Tank 12. The images of the carriers show different biofilm thicknesses and suggest potentially different abilities for bubbles and liquid to penetrate the biofilm and reach the inner portion of the carrier. Differences in nitrification throughout the biofilm thickness should be the object of future research activities. The OTE for the ASP cells corresponding with the IFAS cells (testing positions 1-6 in Figure 5) are higher for both tests, but this is driven by high DO.

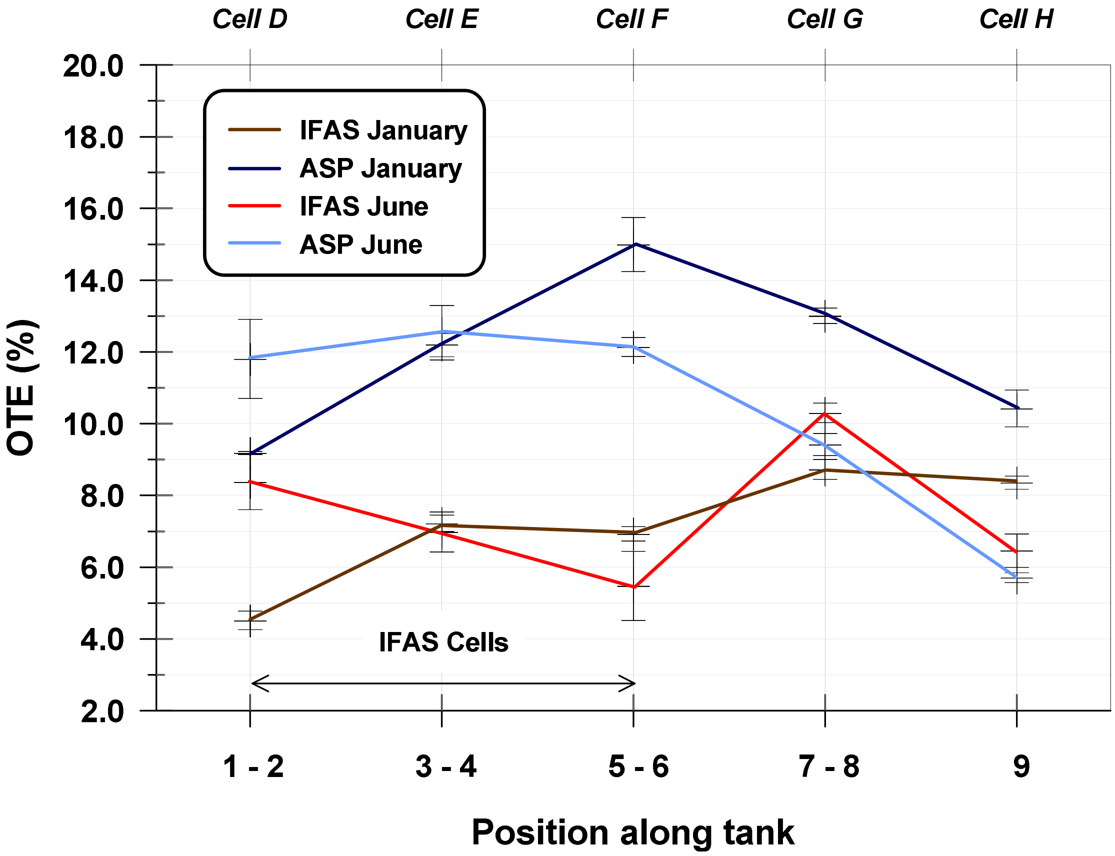


Figure 5. Comparative OTE profiles for ASP and IFAS during the January and June tests. IFAS cells are installed only at testing positions 1-6, and positions 7-9 are ASP for both tanks.

In order to reach such elevated DO, the air flow rate required is high, therefore lowering the OTE for IFAS. Also, OTE at high DO is lower since the DO is closer to oxygen saturation. The IFAS process is disadvantaged on the basis of OTE due to the lower driving force for oxygen transfer, but αSOTE is compensated when a zero DO correction is applied to OTE (ASCE, 1996). Therefore, the αSOTE, as shown in Figure 6, appears similar for both processes.

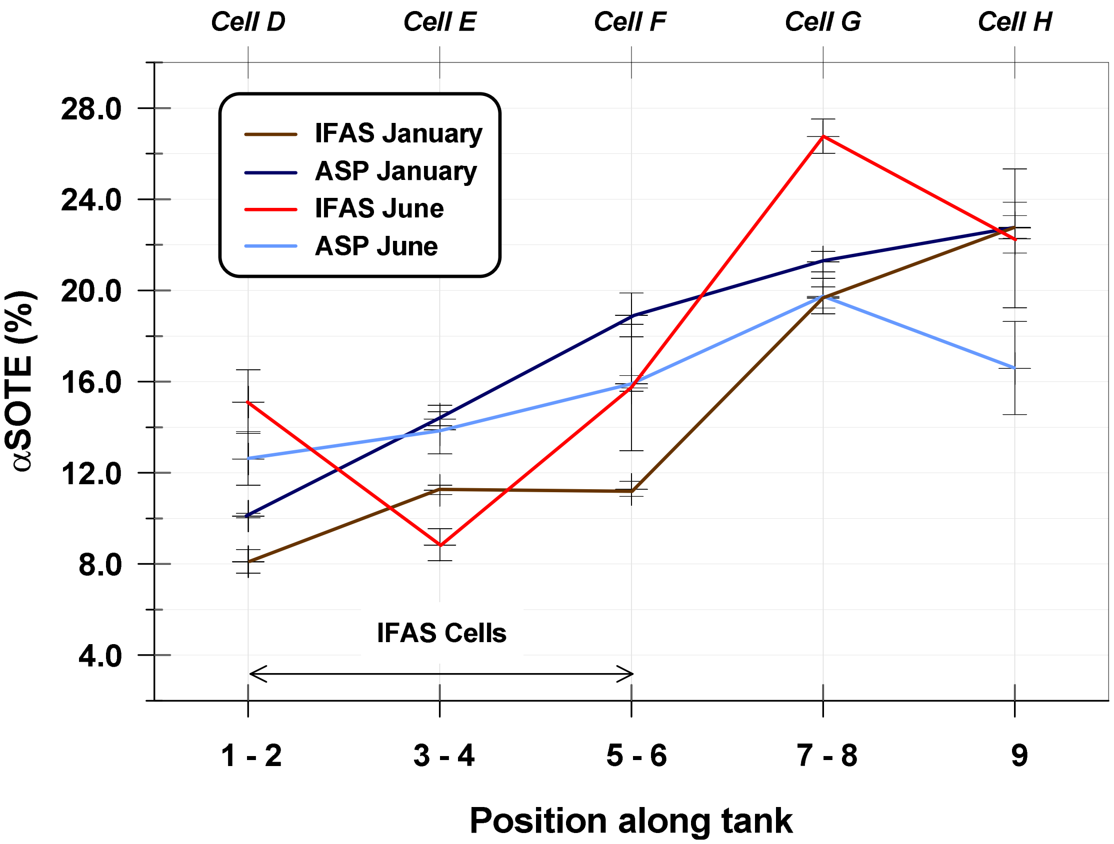


Figure 6. Comparative □*SOTE profiles for ASP and IFAS during the January and June tests. IFAS cells are installed only at testing positions 1-6, and positions 7-9 are ASP for both tanks.*

Energy footprint considerations can be concluded directly from the datasets plotted in Figure 7. For both IFAS and ASP, the energy footprint is dominated by the power requirements of the air blowers.

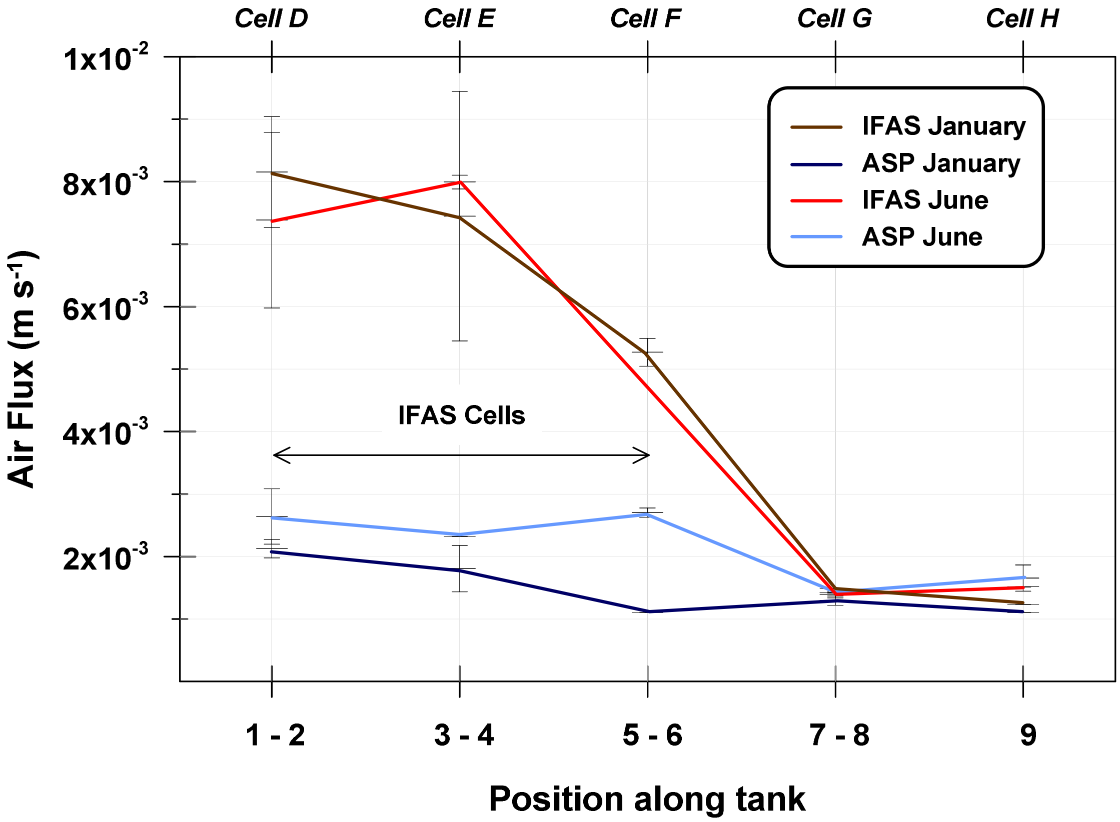


Figure 7. Comparative Air Flux profiles for ASP and IFAS during the January and June tests. IFAS cells are installed only at testing positions 1-6, and positions 7-9 are ASP for both tanks.

The relationship between blower power (BHP), air flow rate (AFR), and air flux (J_{air}) can be described using the adiabatic formula (Metcalf and Eddy, 2003):

$$BHP = \genfrac{}{}{0pt}{}{r_{air}\ x\ AFR\ x\ RT}{cgh}\ x \left[\left(\genfrac{}{}{0pt}{}{Z + h_L + CWP + P_i}{P_i}\right)\quad 1\right]$$

$$BHP = \frac{rair\ x\ A_{TANK}\ x\ J_{air}\ x\ RT}{cgh}\ x \left[\left(\frac{Z + h_L + DWP + P_i}{P_i}\right) - 1\right]$$

(2)

where BHP = power drawn by the blower (kW)
ρ_{air} = air density ($kg_{air}\ m^{-3}{}_{air}$)
AFR = volumetric air flow ($m^3\ s^{-1}$)
A_{TANK} = tank bottom area
J_{air} = Air flux ($m\ s^{-1}$)
R = universal gas constant (8.314 $J\ mol^{-1}\ K^{-1}$)

T = ambient temperature (K)
c = molecular weight of air (kg kmol^{-1})
γ = ratio of specific heats (0.283 for air)
η = combined motor and blower efficiencies (-)
P_d = discharge pressure (Pa)
P_i = inlet pressure (Pa)
Z = hydrostatic pressure corresponding to diffuser submergence (Pa)
h_L = head loss in the air distribution line (Pa)
DWP = dynamic wet pressure (pressure drop across the diffusers, Pa)

Since, in this case, the tank bottom area for both the ASP and the IFAS is known and identical, the air flow rate can be calculated from the air flux (plotted in Figure 7 and averaged in Table 2). By assuming an appropriate dynamic wet pressure for the air diffusers (5,475 Pa for the fine-pore diffusers and 1,490 Pa for the coarse-bubble diffusers), the blower power requirements BHP can be calculated. In this case, the oxygen demand is very different between the two processes, and therefore the process with higher load (the IFAS) would be unfairly disadvantaged if only the BHP were calculated. Therefore, we also introduce the energy footprint per unit oxygen demand oxidized ε:

$$e = 3600\frac{\mathrm{BHP}}{\mathrm{OD}} \tag{3}$$

where ε = energy footprint per unit oxygen demand (kWh/ kg$_{O2}$)
OD = oxygen demand (kg$_{O2}$ s^{-1}), defined in eq. 1

It is evident from Figure 7 that the IFAS cells (Cells D-F), due to their design specifications to promote mixing and high DO, are characterised by elevated air flux. For cells G-H where both basins have fine bubble diffused aeration, the air flux for both basins is similar in the summer test and is slightly lower for the IFAS during winter. This may be related to a more rapid removal of the oxygen demand in the IFAS zones upstream from Cells G-H. This may suggest that the remaining reactor volume may be unnecessary. The relative ratios of the flow-weighted averages of air flux, air use, and energy footprint are reported in Table 3.

Table 3. Summary of relative process performance in terms of air use, blower power requirements, and energy footprint

	Process Influent Flow	**Oxygen Demand**	**Air Flow**	**Air Use**	**Energy Footprint**
	Q	**OD = ΔCOD + 4.33ΔNH_4^+**	**AFR**	**AFR/OL**	**ε = BHP/OL**
(IFAS / ASP)$_{winter}$	2.06	1.97	3.33	2.08	2.00
(IFAS / ASP)$_{summer}$	1.99	1.34	2.20	2.11	2.09

In theory, when OTE is the same, the air required per unit mass of oxygen demand removed should be the same, regardless of the process. Yet, the requirement for elevated mixing and DO requirements impact air use significantly. Throughout the coarse bubble aeration zones [positions 1-6 in the IFAS process (Figure 7)], the IFAS has elevated air flux which reflects directly in its energy footprint. The energy footprint per unit load oxidized ε of the IFAS exceeds twice that of the ASP (Table 3).

Since mixing is a crucial component of the IFAS process, and since the elevated air flow rate for the IFAS process is driven by manufacturer's specifications for mixing, an attempt to quantify the fraction of aeration energy used for mixing was made. Although the exact fraction of air flow used for mixing cannot be quantified, it is possible to calculate the fraction of air flux used for oxygen transfer from off-gas data, then calculate the fraction of air flux used for mixing by subtraction from the off-gas air flux:

$$\left(\text{Air Flux}\right)_{\text{Mixing}} = \left(\text{Air Flux}\right)_{\text{Off-gas}} - \left(\text{Air Flux}\right)_{\text{Oxygen Transfer}} \quad (4)$$

Figures 8 through 11 present the calculated air flux required for mixing for the January and June tests for the IFAS and ASP processes.

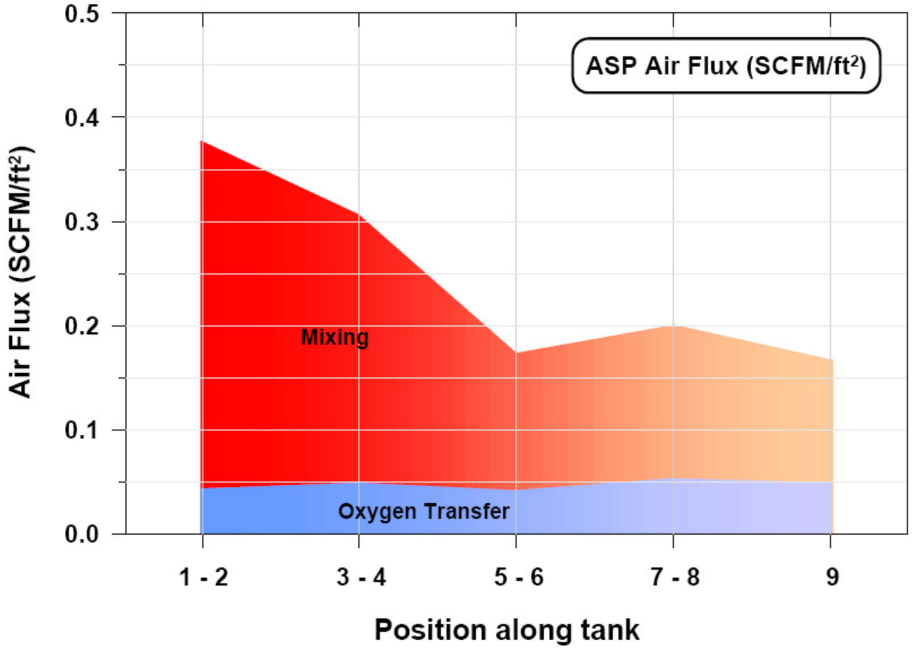


Figure 8. Air flux profiles for the ASP (Tank 11) in the January test.

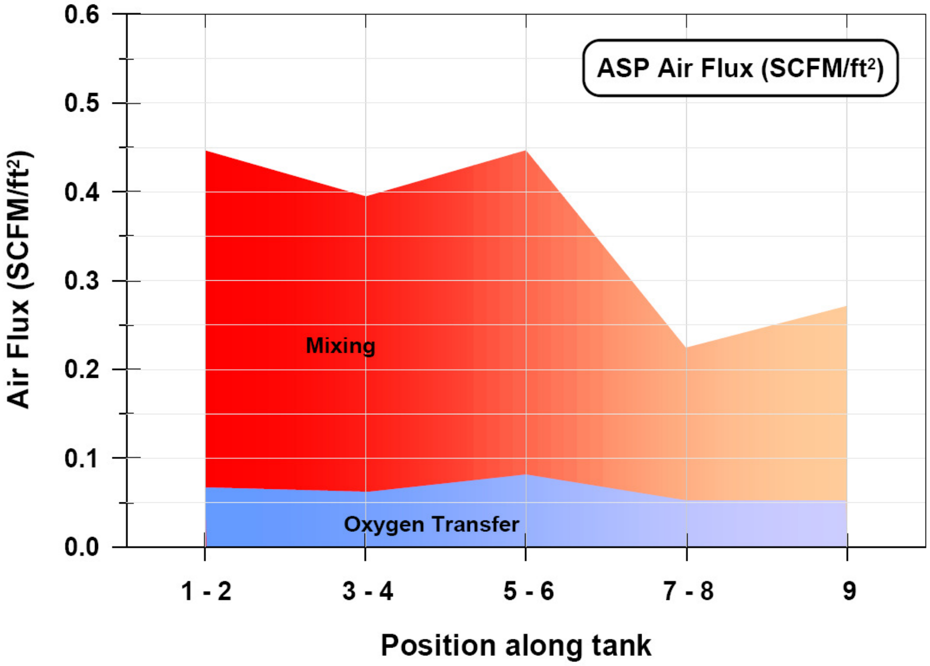


Figure 9. Air flux profiles for the ASP (Tank 11) in the June test.

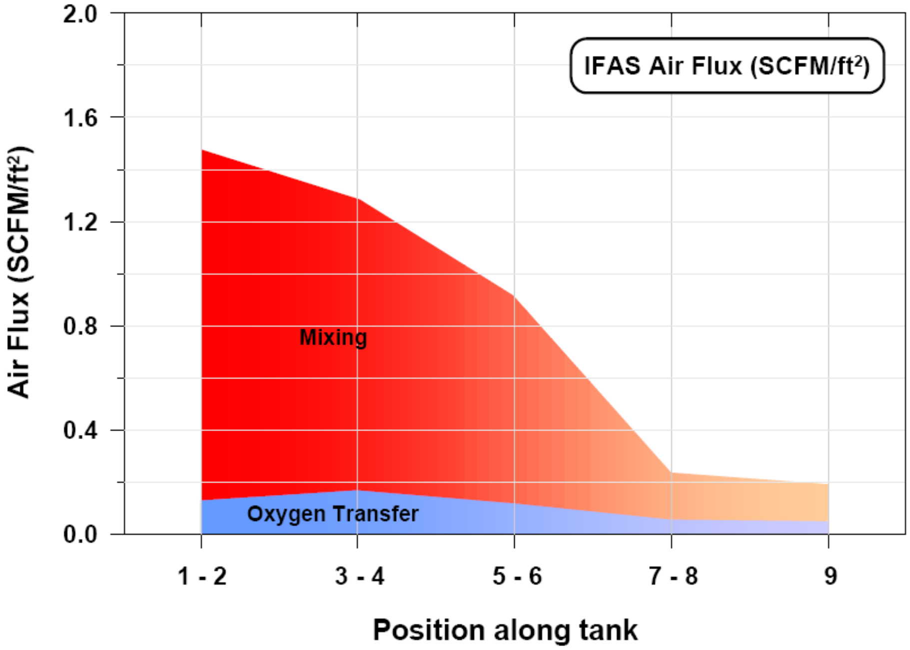


Figure 10. Air flux profiles for the IFAS (Tank 12) in the January test.

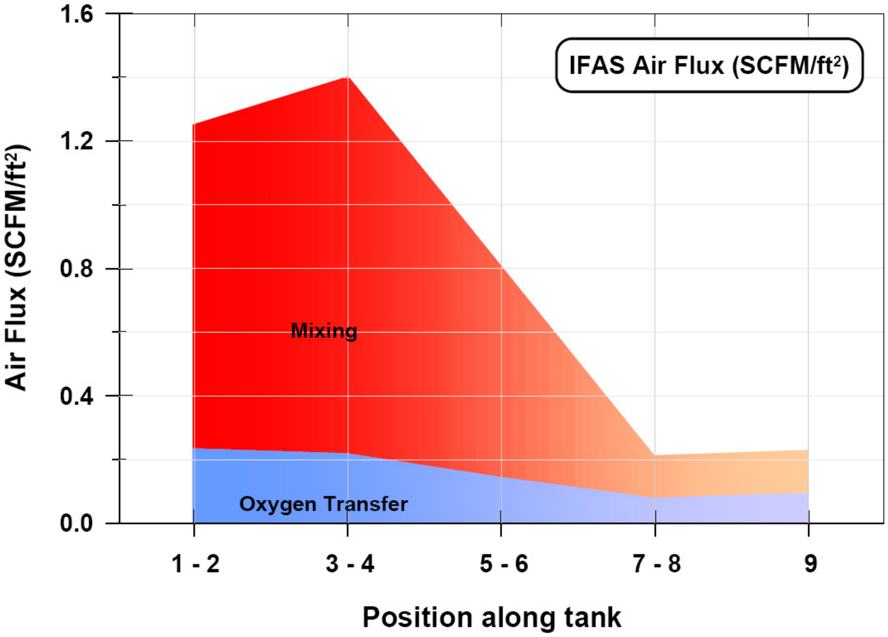


Figure 11. Air flux profiles for the IFAS (Tank 12) in the June test.

The IFAS process, due to its roughly double hydraulic load compared to the ASP, had a halved hydraulic residence time since the IFAS and ASP tanks were identical. This makes the IFAS a viable alternative for land-constrained sites where the hydraulic flow, hence the total tankage, may be the deciding factor for process selection. The enhancement in oxygen demand removal came at an elevated energy cost (shown by the air flow per unit oxygen demand removed). The elevated air use associated with the IFAS process directly relates to the energy footprint increase. Presence of mechanical mixing in the IFAS cells and minimization of aeration required for mixing could potentially decrease the energy footprint. The energy footprint of IFAS compared to ASP is consistent between the January and the June tests. The elevated energy use to promote mixing may suggest that the testing of mechanical mixers combined with reduced air flow or with fine-pore diffusers for oxygen transfer should be the subject of future research.

4. CONCLUSIONS

Off-gas testing was conducted in summer and winter on parallel, independent activated sludge (ASP) and integrated fixed-film activated sludge (IFAS) processes to determine the comparative oxygen transfer efficiency, oxygen uptake rate, and air use for the two processes, and to quantify temperature effects on the aeration performance parameters. Our results show that in both tests the IFAS had higher DO, OUR, and air flux than the ASP. The IFAS process was characterized by higher oxygen transfer efficiency (OTE). The standard oxygen transfer efficiency in process water (αSOTE) was comparable between the two processes after correction to zero DO. The hydraulic load and the oxygen demand applied to the IFAS process was approximately twice that of the parallel ASP, yet the percent removal of COD and ammonia was approximately the same for both processes. This suggests that the IFAS is a viable process for process expansion, especially for land-constrained sites. The increased oxygen demand removal for IFAS is associated with an elevated air use (i.e., air flow per unit oxygen demand removed), which exceeds that of the ASP by a factor of 2, corresponding to the same excess for energy footprint.

ACKNOWLEDGEMENTS

The authors thank the staff at the T.Z. Osborne Water Reclamation Plant in Greensboro, NC for the help during field testing.

REFERENCES

Alleman, J.E. (1983) *The history of fixed-film wastewater treatment systems*, Available on: http://web.deu.edu.tr/atiksu/ana52/biofilm4.pdf.

Andreottola, G., P. Foladori, G. Gatti, P. Nardelli, M. Pettena and M. Ragazzi (2003). "Upgrading of a Small Overloaded Activated Sludge Plant Using a MBBR System," *Journal of Environmental Science and Health, Part A*, **38**: 10, pp. 2317-2328.

Argaman, Y. (1986) Nitrogen removal in a semi-continuous process, *Wat. Res.* **20**(2), 173-183.

ASCE (1984, 1991, 2007) ASCE Standard: *Measurement of Oxygen Transfer in Clean Water*, ISBN 0-87262-430-7, New York, NY.

ASCE (1997) ASCE Standard: *Standard Guidelines for In-Process Oxygen Transfer Testing,* ISBN 0-78440-114-4, New York, NY,.

Clara, M., N. Kreuzinger, B. Strenn, O. Gans and H. Kroiss (2005) "The Soilds Retention Time – A Suitable Design Parameter to Evaluate the Capacity of Wastewater Treatment Plant to Remove Micropollutants," *Water Research*, **39**, pp. 97-106.

Clift, R.; Grace, J. R.; Weber, M. E. (1979). *Bubbles Drops and Particles*. New York: Academic Press

Eckenfelder, W.W., Barnhart, E. L. (1961) The Effect of Organic Substances on the Transfer of Oxygen from Air Bubbles in Water, *AIChE J.*, **7**(4), 631-634.

Eckenfelder, W. W., Ford, D. L. (1968) New concepts in oxygen transfer and aeration, *Advances in water quality improvement, E. F. Gloyna, and W. W. Eckenfelder Jr. (eds.)*, University of Texas Press, Austin, Tex., 215-236

Gonsior, M., Tseng, L.Y., Jeung, M.K., Cooper, W.J., Hertkorn, N., Schmitt-Kopplin, P., Pitt, P., Rosso, D. (2011) Differential analysis of the removal of organics in parallel IFAS and activated sludge reactors using ultrahigh resolution mass spectrometry, *Proc. IWA NOM/DOM/EfOM Conf.*, Costa Mesa, CA, USA.

Harris, S.L., T. Stephenson and P. Pearce (1996) "Aeration Investigation of Biological Aerated Filters Using Off-Gas Analysis," *Wat. Sci. Technol.*, **34**(3-4), pp. 307-314.

Hwang, H.J., Stenstrom, M.K. (1979) *The Effect of Surface Active Agents on Oxygen Transfer*, UCLA-ENG-79-30 Report, University of California, Los Angeles.

IWA (2008) *Biological Wastewater Treatment – Principles, Modelling and Design*, IWA Publishing, London, UK.

Joss, A., H. Anderson, T. Ternes, P.R. Richle and H. Siegrist (2004) "Removal of Estrogens in Municipal Wastewater Treatment under Aerobic and Anaerobic Conditions: Consequences for Plant Optimization," *Environmental Science and Technology*, **38**, pp. 3047-3055.

Kim, H., J.W. Gellner, J.P. Boltz, R.G. Freudenberg, C.K. Gunsch and A.J. Schuler (2010). Effects of Integrated Fixed Film Activated Sludge Media on Activated Sludge Settling in Biological Nutrient Removal Systems, *Wa.r Res.,,* **44**, 1553-1561.

Leu, S.-Y., Rosso, D., Larson, L.E., Stenstrom, M.K. (2009) Real-Time Aeration Efficiency Monitoring in the Acvivated Sludge Process and Methods to Reduce Energy Consumption and Operating Costs, *Wat. Environ. Res.* **81**, 2471-2481.

Maas, C.L.A., W.J. Parker, R.L. Legge (2008). "Oxygen Uptake Rate Tests to Evaluate Integrated Fixed Film Activated Sludge Processes," *Water Environment Research*, **80**, No. 12, pp. 2276-2283.

Mancy, K.H., Okun, D.A. (1960) Effects of Surface Active Agents on Bubble Aeration, *J. Wat. Poll. Cont. Fed.*, **32**(4), 351-364.

Metcalf, L., Eddy, H.P. (1914) *American Sewerage Practice*, 1st ed., McGraw-Hill, New York.

Metcalf and Eddy, Inc. (2003) *Wastewater Engineering: Treatment and Reuse*, 4th ed., ISBN 0-07041-878-0, McGraw-Hill, New York

Ort, C., M.G. Lawrence, J. Rieckermann and A. Joss (2010) Sampling for Pharmaceuticals and Personal Care Products (PPCPs) and Illicit Drugs in Wastewater Systems: Are Your Conclusions Valid? A Critical Review," *Environ. Sci. Technol.*, **44**, 6024-6035.

Plano, S., Rosso, D., Benedetti, L., Weijers, S., De Jonge, J., Nopens, I. (2010) Towards dynamic activated sludge modelling without need for calibration, *Proc. IWA World Water Congress*, Montreal, QC, Canada.

Randall, C.W. and D. Sen (1996) Full-Scale Evaluation of an Integrated Fixed-Film Activated Sludge (IFAS) Process for Enhanced Nitrogen Removal, *Wa.r Sci. Technol.*, **33**(12), 155-162.

Reardon, D. J. (1995) Turning down the power, *Civ. Eng.* **65**(8), 54–56.

Redmon, D.T., Boyle, W.C., and L. Ewing. L.(1983). "Oxygen Transfer Efficiency Measurements in Mixed Liquor Using Off-gas Techniques," *J. Wat. Poll. Cont. Fed.*, **55**, pp.1338.

Rosso, D., and Stenstrom, M.K. (2005) Comparative Economic Analysis of the Impacts of Mean Cell Retention Time and Denitrification on Aeration Systems, *Wat. Res.* **39**, 3773-3780.

Rosso, D., Stenstrom, M.K. (2006) Surfactant effects on alpha-factors in aeration systems, *Wat. Res.* **40**(7) 1397-1404.

Rosso, D., R. Iranpour and M.K. Stenstrom (2005). "Fifteen Years of Off-Gas Transfer Efficiency Measurements on Fine Pore Aerators: Key Role of Sludge Age and Normalized Air Flux," *Wat. Environ. Res.*, **77**, 266-273.

Rosso D., Larson L.E., Stenstrom M.K. (2008) Aeration of large-scale municipal wastewater treatment plants: state of the art, *Wat. Sci. Technol.* **57**(7), 973-978.

Silverman, J., Schroeder, E.D. (1983) Performance of SBR activated sludge process with nitrification/denitrification, *J. Wat. Poll. Cont. Fed.* **55**(4), 377-384.

Soliman, M.A., Pedersen, J.A., Park, H., Castaneda-Jimenez, A., Stenstrom, M.K., Suffet, I.H. (2006) Human pharamaceuticals, antioxidants, and plasticizers in wastewater treatment plant and water reclamation plant effluents, *Wat. Environ. Res.* **79**(2), 156-167.

Sriwiriyarat, T., C.W. Randall (2005). "Performance of IFAS Wastewater Treatment Processes for Biological Phosphorous Removal," *Wa.r Res.*, **39**, pp. 3873-3884.

Sriwiriyarat, T., K. Pittayakool, P. Fongsatitkul and S. Chinwetkitvanich (2008). "Stability and Capacity Enhancements of Activated Sludge Process by IFAS Technology," *J. Env. Sc. and Hea. Part A*, **43**, pp. 1318-1324.

Stenstrom, M.K., G Masutani (1990). *Fine Pore Diffuser Fouling - the Los Angeles Studies,*UCLA Engr. Report No. 90-02, Los Angeles, CA.

Stenstrom, M.K., R.G. Gilbert (1981). "Effects of Alpha, Beta and Theta Factors in Design, Specification and Operations of Aeration Systems," *Water Research*, **15**, pp. 643-654.

Stenstrom, M.K.(1990) "Upgrading Existing Activated Sludge Treatment Plants with Fine Pore Aeration Systems," *Water Science and Technology*, **22**, No. 7/8, pp. 245-251.

Stenstrom, M.K., Rosso, D., Melcer, H., Appleton, R., Langworthy, A., Wong, P. (2008) Oxygen Transfer in a Full-Depth Biological Aerated Filter, *Wat. Env. Res.* 80(7), 663-671.

Stricker, A.E., A. Barrie, C.L.A. Maas, W. Fernandes and L. Lishman (2009). " Comparison of Performance and Operation of Side-By-Side Integrated Fixed-Film and Conventional Activated Sludge Processes at Demonstration Scale," *Water Environment Research*, **81**, pp. 219-232.

US. EPA (1989) *Design Manual - Fine Pore Aeration Systems*, Risk Reduction Laboratory, Cincinnati, Ohio, EPA/625/1-89/023.

Viswanathan, S., Pham, H., Kelly, R.F., Redmon, D.T., and Fernandes, W. (2008) Evaluation of Oxygen Transfer Efficiency via Off-gas Testing at Full Scale Integrated Fixed film Activated Sludge Installation, *Proc. WEFTEC 2008 Conference.*

Wagner, M., Pöpel, H.J.(1996) Surface active agents and their influence on oxygen transfer, *Water Sci. Technol.* **34**(3-4), 249-256

Wang, L.K., Hung, Y.-T. (2007) *Advanced physicochemical treatment technologies (Vol. 5)*, Humana Press, Totowa, NJ, USA.

Zlokarnik, M. (1980) Eignung und Leistungsfähigkeit von Volumenbelüftern für biologische Abwasserreinigungsanlagen, *Korrespondenz Abwasser* **27**(3) 194-209.