Effective Biofilm Control on High Surface Density Vertical-Flow Structured Sheet Media for Submerged Applications

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ABSTRACT

This study was undertaken to investigate the mixing characteristics and establish aeration mixing criteria for a Vertical-Flow (VF) structured sheet media system. The results demonstrated that the optimized airlift pumping associated with the VF media system using fine bubble diffusers is capable of achieving effective biofilm control for enhanced process performance.

The media scouring velocities of 0.1-0.3 ft/sec obtained at aeration mixing criteria of 0.5-1.0 SCFM/ft^2-media plan view has been shown sufficient for the excessive biomass control in typical municipal IFAS retrofits. The identified scouring air requirements are often exceeded by the process air demand for the upgrade of a conventional activated sludge plant. Tapered aeration has been commonly implemented in the full-scale facilities, enabling a lower mixing air requirement and providing process kinetic benefits and energy savings. Engineering design parameters other than aeration as integrated in the VF media system for effective mixing were also discussed in the paper.

KEYWORDS: Integrated Fixed-Film Activated Sludge (IFAS), Vertical-Flow (VF) Structured Sheet Media, Biofilm Control, Aeration Mixing, Airlift Bioreactor.

INTRODUCTION

Importance of Biofilm Control in Fixed-Film Systems

Maintaining an effective thin biofilm is one of the primary process factors required to achieve optimum performance in a fixed-film system. It has been widely recognized that excessive biofilm growth can result in process impairment by reducing the effective biofilm surface area due to physical clogging, decreasing the biofilm reactiveness due to diffusion limitations of vital nutrients and accumulation of endogenous bacteria, and promoting undesirable nuisance organism growth (WEF, 1998). A number of methods have been used to control excessive biofilm in various fixed-film systems, including air scouring of media in Integrated Fixed-film Activated Sludge (IFAS) systems (Johnson et al., 2004), hydraulic flushing in trickling filters (Alberson, 1995 and Parker et al., 1989), and backwashing in various media bio-filters (Boltz et al., 2009).

In IFAS applications, problems associated with excessive biofilm can occur both in fixed bed and moving bed systems as a result of insufficient or improper mixing patterns (Sen et al., 2007). Coarse bubble diffused aeration systems are often used in free-floating media systems to ensure adequate mixing due to the complication of diffuser maintenance in the presence of floating media and the requirement of unique diffuser orientation to prevent flotation of media in the topmost region of the water column (Johnson et al., 2004). In addition, due to the limited direct air scouring along with the entire surface of media (Ye et al., 2010a), redundant coarse bubble diffusers are also typically required in fixed fabric media systems to control nuisance predators (red worms) associated with thick biomass (Hubbell et al., 2006). In contrast, fine bubble diffusers have been demonstrated to be compatible with structured sheet media in IFAS systems for effective biomass control due to their dedicated airlift pumping and scouring along with the entire surface of media (Ye et al., 2009, 2010a, 2010b).

Excessive Biomass Control on Structured Sheet Media in Trickling Filter Systems

Both Cross-Flow (CF) and Vertical-Flow (VF) structured sheet media have been widely used in trickling filter installations for attached biomass growth since the late 1950's (Bryan, 1982). Considerable studies have been conducted to compare the performance of CF and VF media for various trickling filter applications (Parker and Merrill, 1983 and Harrison and Daigger, 1985). CF media is commonly considered to have better performance for dissolved BOD removal at low organic loadings due to improved wetting of media surface, superior hydraulic residence time, and enhanced oxygen transfer efficiency (Parker and Merill, 1983). However, CF media are more prone to solids retention and fouling because of its more complicated media geometry and reduced flushing effects (WEF, 2000). In contrast, due to the reduced headloss and also an increased void space, VF media has shown its optimum use for applications treating strong wastes with potentially thicker biomass growth (Harrison and Daigger, 1985).

In addition to applying VF media to minimize heavy biomass issues, other methods are also frequently used to control excessive biomass growth in the trickling filter installations. For example, flow recirculation or flooding cycles can provide adequate hydraulics for routine media flushing, increase the wetting efficiency, reduce the clogging tendency (Parker et al., 1989), and can also improve contact efficiency by bringing filter effluent in contact more than once with active biofilm (WEF, 1998). Motorized distributor speed control has also been widely used to achieve proper flushing intensities or instantaneous hydraulic application rates (or SK values) for excess biofilm control (Albertson 1989 and 1995).

Application of Vertical Structured Sheet Media for Submerged Systems

Both CF and VF structured sheet media have also been successfully applied in IFAS applications (Ye et al., 2009, 2010a, 2010b). In comparison to CF media, VF media has been demonstrated with an enhanced biofilm control at a wide variety of organic loads although CF media is also shown applicable at low organic loadings when mixing and scouring becomes less crucial (Ye et al., 2010a).

The effective biomass control and enhanced process performance of the VF media system were attributed to several factors (Ye et al., 2010a). First, VF media has less media structure interruptions in the film flow, therefore less headloss. Second, the recirculation (or the airlift pumping) flow as induced by the diffused air can be significantly higher than the forwarding influent flow, ensuring continuous media scouring. Third, the submerged environment warrants intimate contact between substrates and biofilm even at constant high scouring rates. Lastly, the proprietary distribution media in conjunction with the VF media system enhances continuous air scouring to the entire surface of media.

Existing Aeration Mixing Criteria for CAS and Fixed-Film Systems

Empirical aeration mixing criteria based on air flow per unit area or volume, velocity gradient, power input, and mixed liquor velocity have been well established for conventional activated sludge systems (CAS) (Table 1). For grid configurations, typical values of 0.12 SCFM/ft^2 and 30 SCFM/1,000 ft^3 are often used for fine bubble and coarse bubble aeration systems, respectively to maintain solids in suspension in a CAS system.

Table 1 Empirical aeration mixing criteria for conventional activated sludge systems

References	Aeration Mixing Methods	Mixing Recommendations
(WPCF, 1988) (US EPA, 1989)	Diffused Aeration	Coarse bubble diffusers: 30 scfm/1,000 ft^3 Fine bubble diffusers: 0.12 scfm/ft^2 floor
(Mueller et al., 2002)	Diffused Aeration	Velocity gradient (G value): 45 -125 sec^{-1}
(EDI, 2006)	Diffused Aeration	Fine bubble diffusers: 0.12-0.15 scfm/ft^2 floor
(WEF, 1998)	Mechanical Aeration	0.6-1.15 hp/1,000 ft^3 or 0.5-1.2 ft/sec

Different from a CAS system, aeration mixing for an IFAS system is required to not only keep mixed liquor solids in suspension, but also control the thickness of attached biological growth. There are very limited studies regarding the impact of IFAS media on the aeration mixing requirements to prevent excessive biofilm growth (Table 2). Although mixing air requirements were empirically identified for both fixed and moving bed media systems with coarse bubble diffusers (Sen 2009 and Johnson et al., 2004), no detailed studies were conducted to investigate how these criteria vary with different operating conditions (e.g. organic loading, with or without mixed liquor) and how other engineering aspects (e.g. diffuser layout, media fill or depth) may affect these criteria, especially for a fine bubble aeration system.

Table 2 Minimum air flow required to prevent excessive biofilm in IFAS applications

References	Aeration Equipment	Type of Media	Minimum Air Flow to Prevent Excessive Biofilm
(Sen, 2009)	Coarse Bubble	Fabric Cord Media	50 and 100 scfm/1,000 ft^3 at SCOD less and greater than 50 mg/L, respectively
(Johnson et al., 2004)	Coarse Bubble	Moving Bed Media	30 scfm/1,000 ft^3

Objectives of the Study

The VF structured sheet media has shown a superior performance with enhanced biofilm control; however, the mixing air flow requirements with a fine bubble aeration system have been less quantitatively understood. The primary objectives of this study were to investigate the mixing characteristics (e.g. liquor scouring velocity) at various organic loads and in presence or absence of mixed liquor, establish aeration mixing criteria for effective biofilm control in a VF media system, identify engineering design parameters other than aeration as integrated in a VF media system for effective mixing, and evaluate air scouring requirements in full-scale structured sheet media systems.

METHODOLOGY

The performance of the VF media was evaluated at various aeration mixing and organic load conditions in both pilot-scale and full-scale facilities. In the pilot study, the mixing characteristics for the VF media system were primarily examined in a Fixed Bed Biofilm Reactor (FBBR) operating mode without mixed liquor recycle. In the FBBR process, the organic removal achieved in the aerobic tanks will solely rely on the attached biomass, which is therefore directly related to the extent of biofilm growth on the media. This eliminates the complication to determine the extent of organic removal occurred on the biofilm (e.g. biofilm thickness) in an IFAS process. However, mixing characteristics as identified in the FBBR process were also extrapolated to an IFAS process by comparing to the mixed liquor velocities and air flow rates as observed in both pilot and full-scale IFAS facilities.

Description of the Pilot Facility

Figure 1 is a simplified schematic of the pilot facility in a FBBR operating mode, which consists of one swing tank under anoxic condition as shown and two staged aeration tanks furnished with fine bubble diffusers in a MLE process. The media fill fraction in each aerobic tank was approximately 46 % (by vol.), with one (1) 1.0-ft layer of distribution media module at the bottom and one (1) 2.0-ft layer of VF media module on the top. The VF structured sheet media was created by joining adjacent corrugated PVC sheets with solvent bonding and forming them into modules and has a specific surface area of 96 ft^2/ft^3 (315 m^2/m^3) (Figure 2). The swing tank was also filled with about 80% CF media in order to retain denitrification populations with the MLE process for nitrate removal in the other testing phases, rather than the purpose of this paper for investigating mixing air requirements at high organic loads and low HRTs with minimum nitrification and TN removal. The influent to the pilot was drawn from the effluent channel of a primary clarifier in the City of Reading, PA wastewater treatment plant.

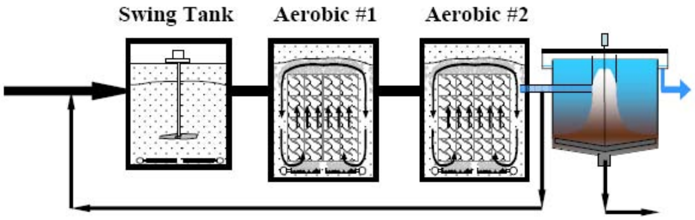


Figure 1 Simplified process schematic of the pilot facility in a FBBR operating mode

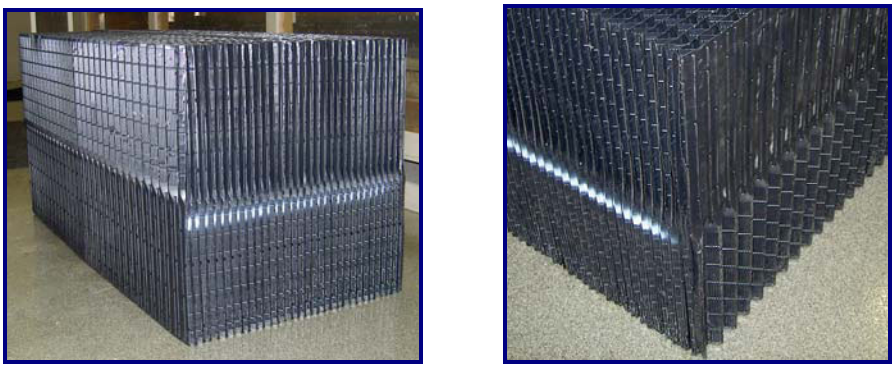


Figure 2 High surface area density VF structured sheet media

Mixing characteristics, such as mixed liquor velocity and air flow rates, were also measured in an IFAS process, similar as the pilot FBBR process but with returned activated sludge. Table 3 summarizes the pilot design operating conditions of both FBBR and IFAS processes.

Table 3 Pilot design operating conditions of FBBR and IFAS processes

Parameters		FBBR	IFAS
Process		MLE	MLE
Flow rate, lpm (gpm)		4.92 (1.3)	4.92 (1.3)
RAS/influent ratio		N/A	65%
IMLR/influent ratio		3.0	3.0
MLSS, mg/L		120	3,000
HRTs	Swing Tank	23-min (Anoxic)†	20-min (Anoxic)†
	Aerobic #1, hrs	2.24	2.24
	Aerobic #2, hrs	2.24	2.24
Media Fill	Swing Tank	80%	N/A
	Aerobic #1	46%	46%
	Aerobic #2	46%	46%

†Anoxic HRTs were calculated based on the total flow, including influent, RAS, and IMLR.

Analytical Methods

Composite samples from the influent and effluent of the pilot plant were routinely collected and analyzed for TSS, ammonia, TN, TP, and soluble COD to determine the overall system performance. Grab samples from each stage of the pilot process (including influent and effluent) were also taken frequently for the concentrations of different nitrogen species (e.g. ammonia, nitrate, and nitrite) and soluble COD to establish performance profiles across the pilot reactors. Comparison between composite and grab samples confirmed the consistency of the influent and effluent data of the pilot. Diurnal sampling of primary effluent (data not shown) indicated that the grab samples (with the consideration of the HRT lags) was conservative in terms of evaluating the system performance when compared to the composite samples.

In addition to the above parameters, suspended solids (MLSS), dissolved oxygen (DO), and temperature in each aerobic stage were also continually monitored with Hach SOLITAX and LDO probes and SC100 controllers. A dissolved oxygen (DO) concentration of 3-5 mg/L was maintained in the aerobic media tanks by using the DO probe to signal a VFD-controlled blower to speed up and down in response to fluctuated process air demands. Air flow to each aerobic tank and liquid velocities in "downcommer" regions with no media were routinely measured to understand the relationship between scouring velocities in media, air flow requirements, and organic loads.

RESULTS AND DISCUSSIONS

Enhanced SCOD Removal in the VF Media FBBR System

Enhanced SCOD removal rates (e.g. up to 30 g/m^2-day) were consistently achieved even when the 1st aerobic stage was continuously stressed with high organic loads (e.g. greater than 10 g/m^2-day) and a low HRT of approximately 2-hr (Figure 3). No flow restriction due to biomass overgrowth on the media was encountered and thin and uniform biofilm was observed on the entire surface of the VF media (Figure 4). The thin biofilm as maintained on the VF media has contributed to favorable SCOD removal rates over a Moving Bed Biofilm Reactor (MBBR) system due to enhanced substrate and oxygen diffusion efficiency (Ye et al., 2010a).

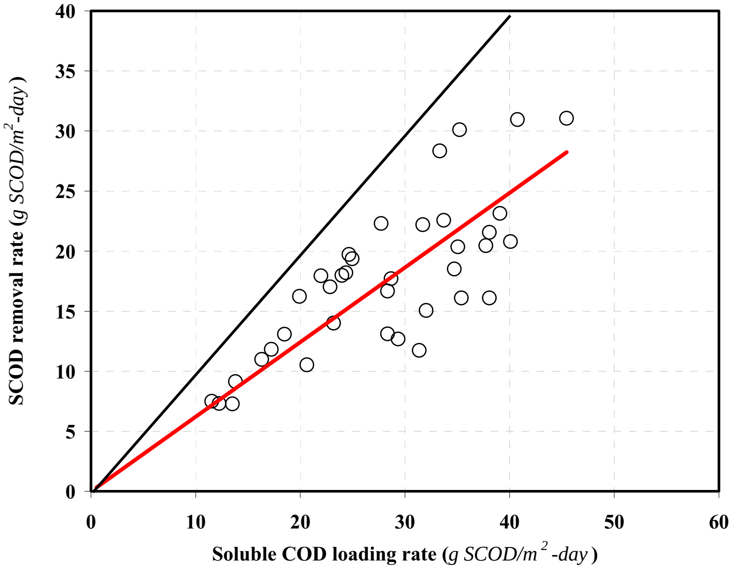
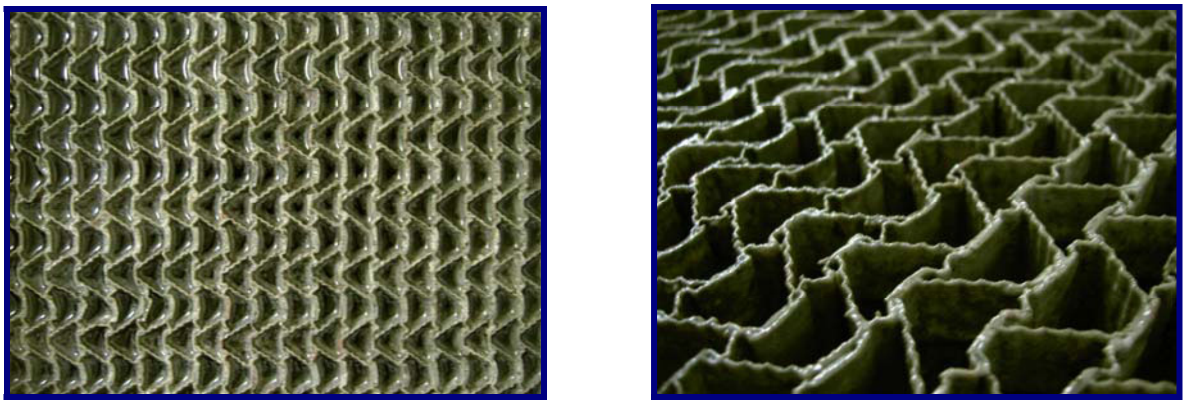


Figure 3 Media surface SCOD removal rates versus media surface SCOD loading rates in the 1st aerobic stage during FBBR operation



(a) Biofilm on the VF media when submerged

(b) Biofilm on the VF media when drained

Figure 4 Thin and uniform biofilm on the surface of the VF media in the 1st aerobic stage at high SCOD removal rates between 10-30 g/m^2-day

Unique Features of the VF Media System for Enhanced Biofilm Control

In addition to the SCOD removal rates, favorable nitrification and denitrification rates were also reported in the VF structured sheet media system (Ye et al., 2010a). Several features of the VF media system have enhanced the control of biofilm thickness for better performance.

First, the application of distribution media in the VF media system ensures air delivery from discrete sources of diffusers to the entire surface of media (Ye et al., 2010a). This helps maintain uniform biofilm thickness and also maximize the use of media surface.

Second, the vertical orientation of the VF media reduces the headloss through media, therefore minimizing the potential for excessive biomass buildup due to the increased shearing in the vertical layers. In addition, unlike the CF media where air leaking to the downcomers (or areas between media assemblies) may occur if not appropriately baffled, the VF media consists of self-baffled or isolated vertical tubes, therefore maximizing the airlift pumping velocity and scouring through media. Comparable or greater fluid scouring velocities were observed in the VF media even with viscous wastewater as compared to CF media in a clear water experiment (Figure 5).

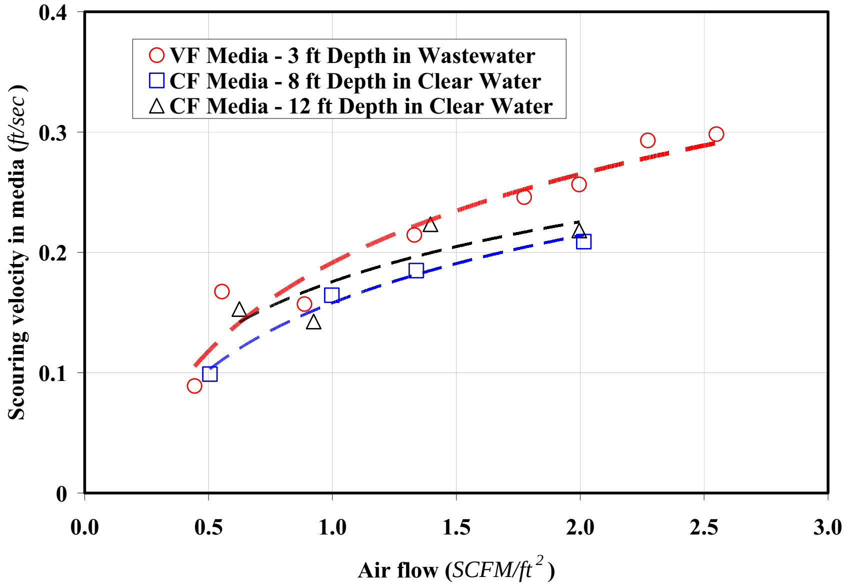


Figure 5 Fluid scouring velocities in the VF and CF systems at different air flow rates over media plan view surface area

Third, the dedicated airlift pumping along the biofilm surface of the VF media promotes direct scouring and also intimate contact between substrates/oxygen and biofilm. In contrast, the erratic tumbling action of the free-floating media or the limited horizontal scouring in the fabric media system may prevent efficient contact between biofilm and substrates/oxygen (Ye et al., 2010a).

Process-determined Scouring Velocities and Air Flows in the VF Media FBBR System

Figure 6 identifies air/wastewater scouring velocities in the VF media at various organic loads during the FBBR operation. An air/wastewater souring velocity ranging between 0.1-0.3 ft/sec (or 0.03-0.09 m/sec) was measured at a SCOD removal rate of 100-500 lbs/1,000 ft^3-day (or approximately 6.0-30 g SCOD removed/m^2-day) in the VF media. In addition, the air/wastewater scouring velocity increased as more SCOD was removed due to the increase of SCOD uptake rate when the aeration requirement in the pilot was controlled by the process air demand.

The media scouring velocity of 0.1-0.3 ft/sec appeared to be low when compared to the empirical mixing requirement of 0.5-1.2 ft/sec (or 0.15-0.36 m/sec) with a mechanical aeration device for a CAS system. However, the enhanced SCOD removal with uniform and thin biofilm growth on the VF media confirmed that media scouring velocities as resulted from the process demand were sufficient to maintain effective biofilm for an enhanced performance. It has been reported that the re-suspension of settled biological solids could occur at a scouring velocity as low as 0.067 ft/sec (Theroux and Betz, 1959). In comparison to apply VF media to minimize bio-solids buildup in the roughing trickling filters, the liquid scouring velocities obtained in the submerged VF media system were about 2-6 times of those observed in the trickling filters where even more favorable conditions were used to maximize the flushing rate, such as applying more open media flute size (e.g. 50-mm), no flow interruption (or distribution) media, and significantly less organic loads (Table 3). Although the scouring appeared to be more intensive in the submerged VF media system, intimate and sufficient contact between substrates and biofilm was still maintained because of the submerged environment and the high recirculation (or the airlift pumping) flow as induced by the diffused air.

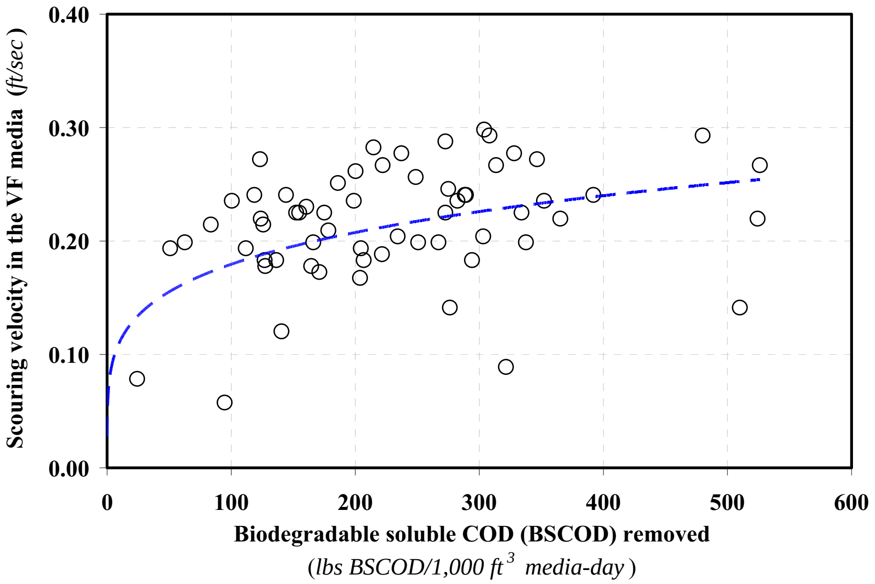


Figure 6 Air/wastewater scouring velocity in the VF media at various SCOD removal rates during the FBBR operation

Table 3 Comparison of liquid flushing and scouring velocities in the VF structured sheet media trickling filter and FBBR applications

	Trickling Filter[1]	FBBR
Type of Structured Sheet Media	Vertical-Flow	Vertical-Flow
Use of Distribution Media	No	Yes
Typical Pore Size of Media	50-mm	19-mm
Media Specific Surface Area, ft^2/ft^3 (m^2/m^3)	30 (101)	96 (315)
Hydraulic Load, gpm/ft^2 (m^3/m^2-hr)	1.0-1.7 (2.4-6.2)	N/A
Organic Load, lbs/1,000 ft^3-day (kg/m^3-day)	81 (3.6)	500 (8.0)
Liquid Scouring Velocity Induced by Gravity or Airlift Pumping, ft/sec (m/sec)	0.05-0.08 (0.015-0.024)	0.10-0.30 (0.03-0.09)

[1] (Richards and Reinhart, 1986)

Figure 7 shows the scouring air flow rates in SCFM per ft^2 of media plan view area at various SCOD removal rates in the VF media system during the FBBR operation. The air flow rates were calculated based on the measured scouring velocities as shown in Figure 6 and also the correlation between air flow rate and the scouring velocity as shown in Figure 5. A wide variety of air flow rates were estimated even at similar SCOD removal rates due to the challenges of the D.O. process control in the pilot (e.g. probe fouling and the limitation of the blower capacity). However, a general increasing trend of scouring air flow rates was obtained as more SCOD was removed, consistent with the overall process air demand.

A scouring air flow rate of 1.0-2.0 SCFM/ft^2 (or 0.005-0.01 m/sec) appeared sufficient to support the scouring and mixing requirement for effective biofilm control at a SCOD removal rate up to 500 lbs/1,000 ft^3-day (or 30 g/m^2-day) on the VF media (Figure 7). The applied scouring air flow rate was also comparable to the gas superficial velocity (or gas volumetric flow rate per unit of cross-sectional area) (e.g. 0.005-0.012 m/sec) used in an airlift bioreactor with free-floating biomass carrier (Merchuck and Shechter, www.aqwise.com). For a tertiary nitrification process with a typical SCOD loading rate less than 3.0 g/m^2-day (or 60 lbs/1,000 ft^3-day), the scouring air flow rate may be significantly less (e.g. less than 0.75 SCFM/ft^2) due to the low biomass yield associated with the nitrification process.

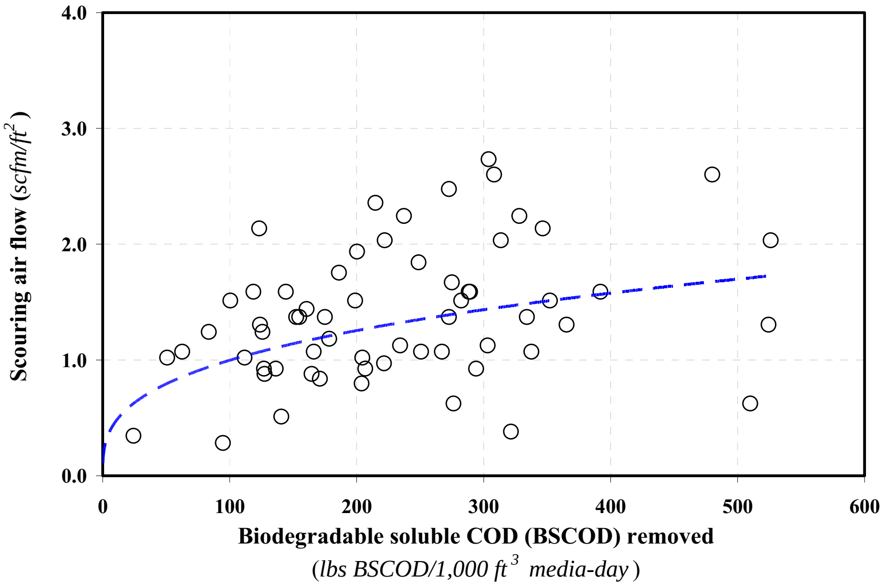


Figure 7 Scouring air flow rates versus SCOD removal rates in the VF media system during the FBBR operation

Scouring Velocities and Air Flows in the VF Media IFAS System

Compared to the FBBR process, lower media scouring velocities (e.g. 0.1-0.2 ft/sec or 0.03-0.06 m/sec) were measured in the 1st aerobic tank for an overall SCOD removal rate up to 200 lbs/1,000 ft^3-day (or 12 g/m^2-day, including removal occurred in the mixed liquor) when the pilot was operating in an IFAS mode (Figure 8). This may be primarily due to the increased viscosity in the mixed liquor and also the reduced air flow rates applied as a result of the lower SCOD loads during the IFAS period. The media scouring velocity of 0.1-0.2 ft/sec also corresponds to a scouring air flow rate of approximately 1.0 SCFM/ft^2 or less (Figure 9). Despite the lower scouring velocities in the 1st aerobic tank, no biomass overgrowth was observed on the VF media (Figure 10) and a complete SCOD and ammonia removal was also consistently achieved over a period of four months in the IFAS system (Figure 11), suggesting that the scouring aeration requirement can be less than 1.0 SCFM/ft^2 even in the presence of mixed liquor for an IFAS application.

The reduced aeration mixing requirement in the VF media IFAS system can be also rationalized as follows. First, biofilm on the VF media may only account for half of the total SCOD removal in the IFAS system with a MLSS concentration of approximately 3,000 mg/L (Ye et al., 2010a). The solids yield of the biofilm is relatively low at a low organic load or during a nitrification process, therefore requiring less scouring air to maintain thin biofilm. Second, the CAS system is often designed with a volumetric BOD loading rate of 20-40 lbs/1,000 ft^3 (tank)-day (Stephenson et al., 2009), which is equivalent to about 40-80 lbs/1,000 ft^3 (media)-day in a 50% media fill IFAS retrofit. The typical low organic load and nitrification requirement in the IFAS retrofits may ease the scouring air requirement to be as low as 0.5 SCFM/ft^2.

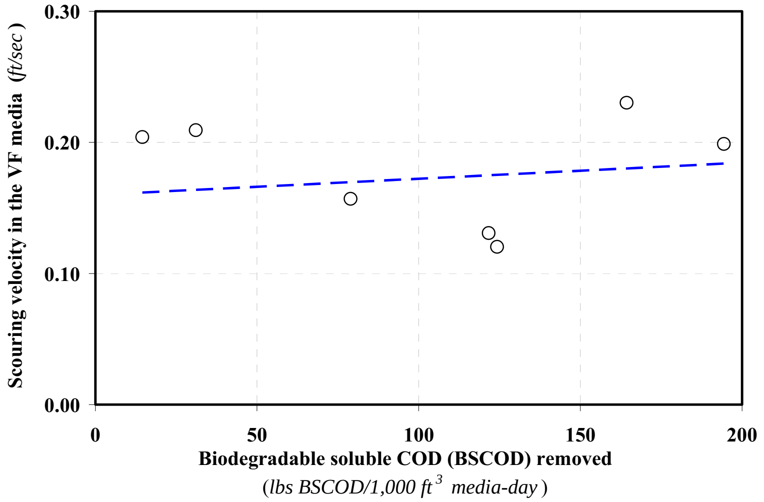


Figure 8 Scouring velocities at various SCOD removal rates during the IFAS operation

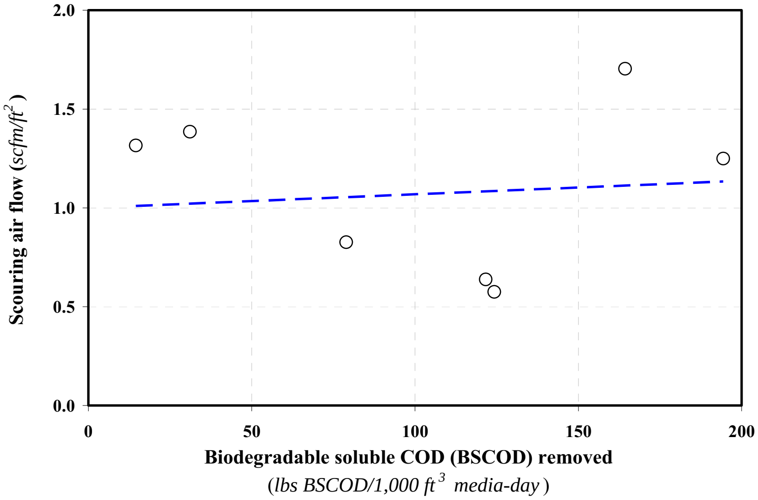


Figure 9 Scouring air flow rates at various SCOD removal rates during the IFAS operation

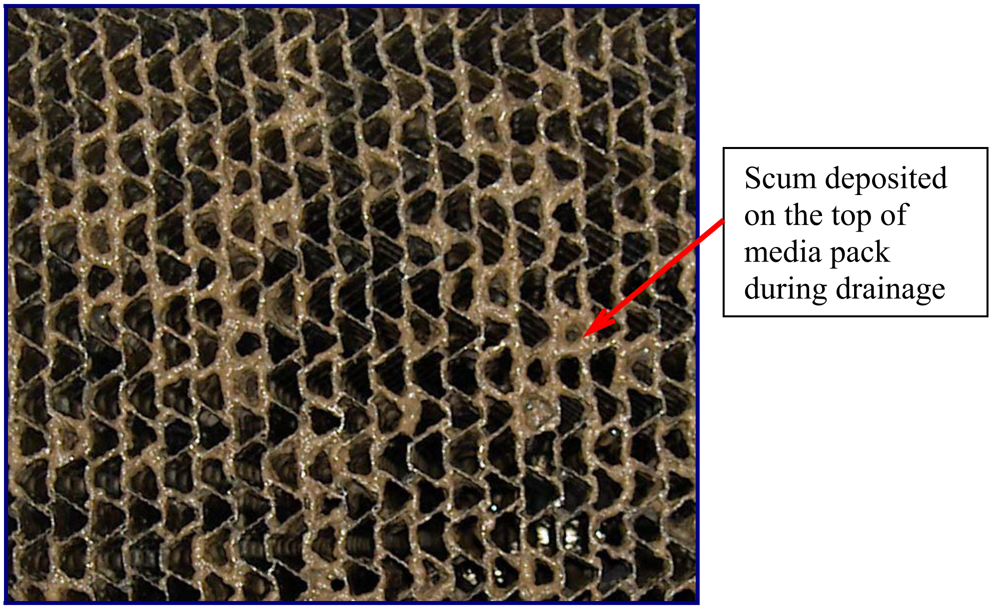


Figure 10 Biofilm on the VF media after the IFAS operation

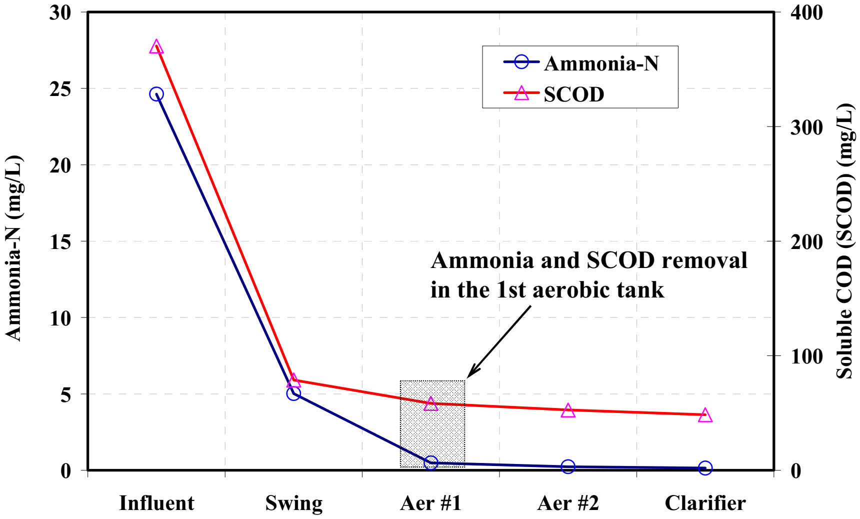


Figure 11 Ammonia and SCOD profiles across the pilot facility during the IFAS operation

The aeration mixing requirements (e.g. 0.5-1.0 SCFM/ft^2-media plan view) for the retrofit of a CAS system with the VF media appeared to be significantly higher than the typical mixing air requirement of 0.12 SCFM/ft^2-floor or equivalent 0.24 SCFM/ft^2-media plan view (assuming a 50% media plan area in the retrofit) for a CAS system. However, these mixing requirements are often exceeded by the process air demand for the upgrade of the CAS plants due to the needs for the treatment capacity increase (therefore requiring additional process air) or the nitrification improvement to meet new regulatory limit at relatively low organic loads (Figure 12). The theoretical process air in Figure 12 was calculated based on both BSCOD and ammonia loads, assuming a typical TKN/BOD ratio of 0.2 (U.S. EPA, 1993) in the municipal raw wastewater, a typical 50% media fill and a media depth of 10-ft for the VF media system, and a typical Actual

Oxygen Requirement (AOR) versus Standard Oxygen Requirement (SOR) ratio of 0.3 for a fine bubble aeration system (www.sanitaire.com). In full-scale facilities, an average scouring air flow rate less than 0.5 SCFM/ft^2-media plan view may be used because the required media scouring can be achieved locally by tapered aeration in the typical plug-flow configuration associated with the VF media IFAS system.

Although the process air often dictates the overall aeration requirement in an IFAS retrofit application with the VF media, caution should be taken to properly size the aeration equipment in the case of pure oxygen systems where mixing aeration requirement may exceed the process oxygen demand.

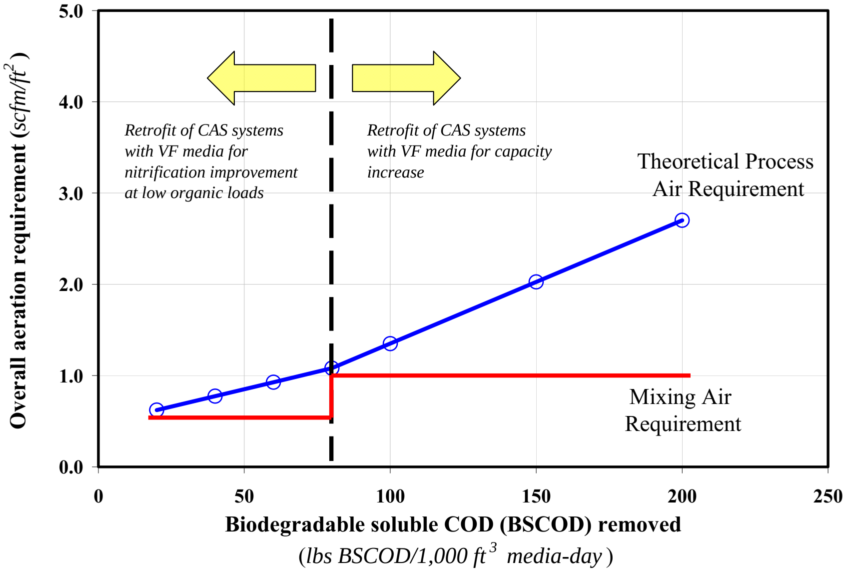


Figure 12 Process and mixing aeration requirements (in SCFM per ft^2 of media plan view area) in the retrofit of CAS systems with VF media for IFAS applications

Prediction of Liquor Scouring Velocity in the VF media Using Airlift Reactor Theory

Although the VF media system has been qualitatively characterized as an airlift bioreactor (Ye et al., 2010a), it is still unknown whether the well-established airlift reactor theory can be applied to predict the liquor scouring velocity in the VF media at various scouring air flow rates, such as 0.5-1.0 SCFM/ft^2 for the typical municipal IFAS retrofits and 1.0-2.0 SCFM/ft^2 for high organic loading rates in the FBBR application.

Equation (1) is a theoretical equation developed to predict liquid circulation velocity in airlift reactors (Chisti et al., 1988), which has been repeatedly validated by other independent investigators (Cai and Nieuwstad, 1991, Choi and Lee, 1991).

$$U_{Lr} = \left[\frac{2g \cdot h_D \cdot (\varepsilon_r - \varepsilon_d)}{K_B (\frac{A_r}{A_d})^2 \cdot \frac{1}{(1-\varepsilon_d)^2}} \right]^{0.5} \qquad (1)$$

Where,

U_{Lr} = superficial liquid velocity in media, m/sec
U_{Gr} = superficial gas velocity in media, m/sec (or equivalent scouring air in SCFM/ft^2)
g = gravitional acceleration, m/sec^2
h_D= height of the gas-liquid dispersion, m
ε_r= fractional gas holdup in the media (or riser), is calculated using the equation (2)

$$\varepsilon_r = \frac{U_{Gr}}{0.24 + 1.35 \cdot (U_{Gr} + U_{Lr})^{0.93}} \qquad (2)$$

ε_d= fractional gas holdup in the downcomer, is linearly related to ε_r with a relationship of $\varepsilon_d = k \cdot \varepsilon$ (Chisti, 1989), where $k \approx 0.7$ at typical downcomer velocities of 0.3-0.65 ft/sec
A_r= cross-sectional area of media plan view, m^2
A_d= cross-sectional area of downcomer, m^2
A_b= cross-sectional area for flow under media, m^2
K_B= friction loss coefficient for the bottom zone of the reactor, is given by the empirical equation (3)

$$K_B = 11.402 \cdot ({}^{A_d}\!/\!{}_{A_b})^{0.789} \qquad (3)$$

In the pilot VF media system, the predicted liquid velocities in the media at various scouring air flow rates appears correlated very well with the measured data (Figure 13), confirming that the hydrodynamic characteristics of the VF media system were similar to the typical airlift bioreactors.

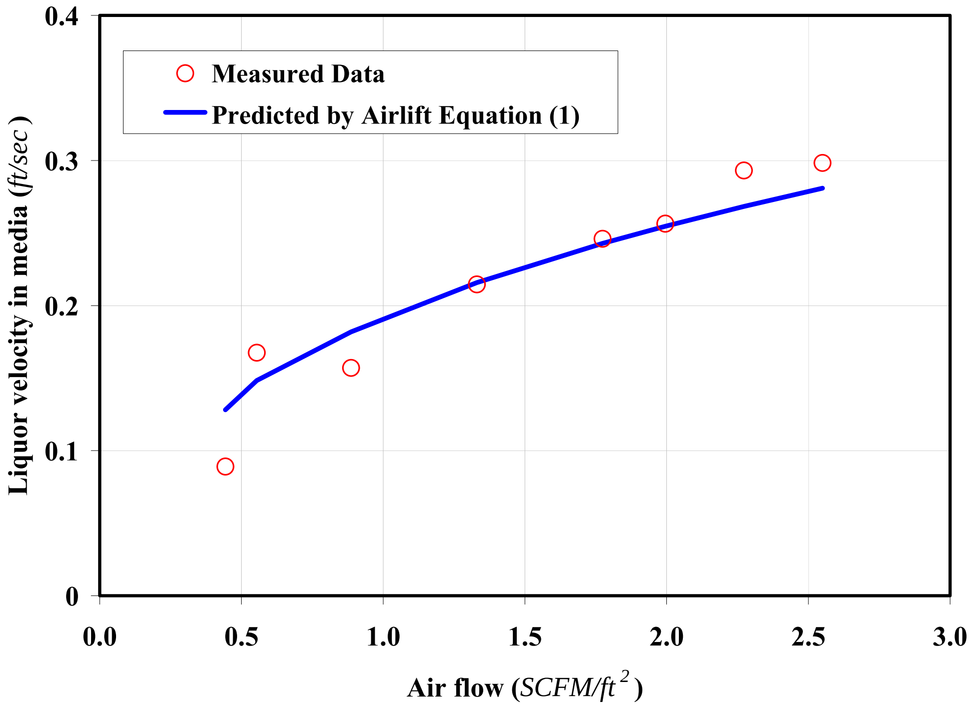


Figure 13 Comparison of predicted and measured liquid velocities in the VF media at various applied air flow rates

Other Design Parameters Integrated in a VF Media System for Effective Mixing

Similar to a typical airlift bioreactor, the VF media system consists of four (4) distinct regions, (a) vertical media tubes for air/wastewater upflow (Riser), (b) downcomers between VF media towers for the downflow (Downcomer), (c) the top wastewater free board (Gas Separator), and (d) the bottom wastewater free-board (Base) (Figure 13). The design of each of these regions will determine the fluid circulation patterns in the reactor, therefore controlling important system performance parameters, such as mixing, turbulence, mass transfer rates (e.g. substrates and oxygen), and so on (Chisti and Moo-Young, 1987, 1993 and Chisti, 1989). In the VF media system, all the aspects as identified above for a typical airlift bioreactor should be properly engineered in order to optimize the air/wastewater circulation for enhanced biofilm control and performance.

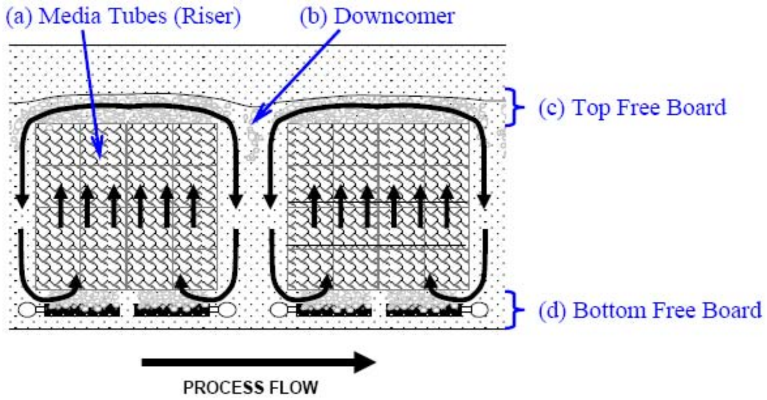
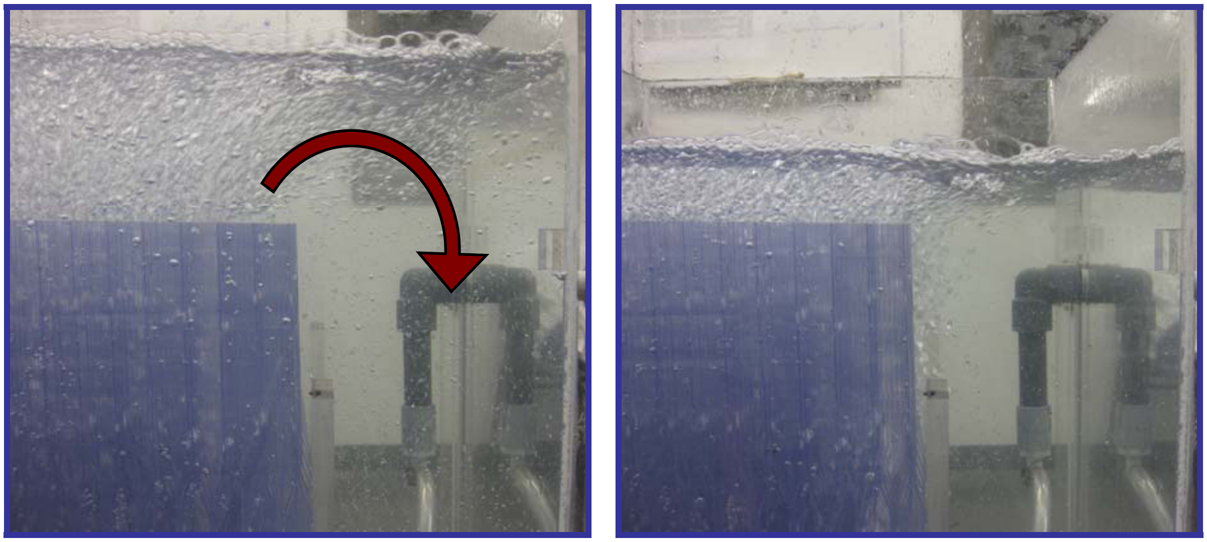


Figure 14 Different regions in a VF media airlift bioreactor

First, the typical diameters of the VF media flutes for submerged applications ragne 19-50 mm. It was reported that surface tension effects were negligible (or small) for the airlift pumps with a diameter greater than 19-mm in air/water systems (Reinemann et al., 1990, Reinemann and Timmons, 1989). However, the growth of biofilm on the tube surface of the VF media may increase the surface tension and retard the fluid circulation rate. Depending on the specific treatment objectives (e.g. BOD removal or tertiary nitrification), different sizes of the VF media shall be properly selected along with an appropriately sized scouring air to maximize the airlift pumping efficiency.

Second, the downcomer region with no diffusers is an essential component of the VF media airlift bioreactor in order to facilitate the liquid circulation. The full coverage or 100% media fill of structured sheet media in the aeration basin (e.g. like the submerged aerated filters) may compromise the benefit of the flow re-circulation associated with a typical airlift bioreactor. In addition, the A_r/A_d ratio (or the cross section ration between riser and downcommer) should be carefully considered to avoid a either too wide or narrow downcomer region. A wide downcomer region not only limits the maximum media fill and treatment capacity, but also potentially creates unmixed zones between media towers, causing solids settling and buildup. A narrow downcomer may cause inconveniences for diffusers maintenance. The increased downcomer liquid velocity as a result of a narrow channel will also increase air bubble traps in the downcomer and reduce the differential pressure between the riser and downcommer regions, therefore decreasing overall airlift pumping efficiency. In full-scale implementation of the VF media systems, a typical 3-ft wide downcomer region in conjunction with the standard 8-ft long media tower along the direction of the flow has shown good mixing patterns (e.g. with a liquid velocity of 0.3-0.8 ft/sec) and easy access to diffusers.

Third, the influence of the top water free board on the liquid velocity in the VF media system can be interpreted into two aspects. On the one hand, a higher top water free board will give a longer residence time in the region between the riser and downcomer (or the gas separator), therefore increasing the gas disengagement in the gas separator and the differential pressure between the riser and downcomer. On the other hand, the increased liquid velocity as resulted from a higher top free board will enable more air bubbles to be trapped in the downcomer region, until the system eventually reaches a steady state. In a clear water demonstration test at the same air flow rate, higher downcomer velocity was observed as evidenced by the fact that more air bubbles were entrapped in the downcomer when the media was covered with more water (Figure 15). Increase of top free board in the full-scale facilities (e.g. Spring Township, PA and Coldwater, MI) has shown improvements of liquid scouring velocities and system performance. In order to maximize the circulation flow as well as the media fill, a typical 1.0-ft top water free board over the VF media should be maintained. This is also consistent with the observation that a maximum differential pressure was achieved between riser and downcomer at a top water clearance of about 1.0-ft in an airlift bioreactor (Merchuk et al., 1994).



(a) Aeration rolling pattern at a higher top water clearance

(b) Aeration rolling pattern at a lower top water clearance

Figure 15 Aeration rolling patterns at different top water clearances with the same air flow rate in a clear water experiment with the VF media

Fourth, although it is usually believed that the bottom free board does not significantly affect the overall behavior of an airlift reactor (Merchuk et al., 1994, Koide et al., 1984), special design considerations should be taken to prevent solids settling and buildup on the tank floor. In the VF media system, a typical 1.5 ft bottom clearance is used to achieve sufficient scouring velocity (e.g. 0.6-1.6 ft/sec, comparable to the mechanical air mixing criterion of 0.5-1.2 ft/sec) to keep the solids suspended. In addition, the diffusers are typically mounted as close to the basin floor as possible to agitate the settled solids, normally within 1.0-ft off the floor as recommended by the Design Manual of Fine Pore Aeration Systems (US EPA, 1989). This also leaves about 6-inch spacing between the bottom of media and the top of the diffusers.

Lastly, the air flow rate is often considered as the only manipulable variable in the operation of an airlift bioreactor (Merchuk and Gluz, www.chem.engr.utc.edu). In the VF media plug-flow system, proper design of aeration grids can ensure flexible air flow control to each individual media towers to achieve high oxygen transfer efficiency during normal operation as well as high-intensity air scouring if necessary for maintenance. In a clear water experiment with an air flow rate of approximately 1.0 SCFM/ft^2, observation of the motion of small gas bubbles suspended in the liquid showed erratic behavior, confirming the presence of turbulence in the liquid flow (Figure 16a). The observed turbulent flow could be partially due to the interruption of microstructures and also the middle-module splash slopes of the VF media. Apparent bubble coalesce was not observed within the single 1.0-ft layer of the VF media in the clear water test, indicating a potential high oxygen transfer efficiency maintained in the VF media system with the fine bubble diffusers. However, further studies should be conducted to understand the impact of full-scale media stacking (e.g. multiple layers, cross orientation between layers) and growth of biofilm on the behavior of the air bubbles and oxygen transfer efficiency. At a higher air flow rate up to 3.0 SCFM/ft^2 in the clear water experiment, large slug air bubbles were formed, providing an enhanced mixing efficiency. This supports the concept that advanced aeration manipulation (e.g. individual media tower scouring) can be applied to maintain thin biofilm in the VF media system.

(a) Small air bubbles in the VF media at an air flow rate of 1.0 SCFM/ft^2

(b) Large slug air bubbles formed in the VF media at an air flow rate of 3.0 SCFM/ft^2

Figure 16 Behavior of air bubbles in the VF media at 1.0 and 3.0 SCFM/ft^2 air flow rates, respectively

Air Scouring in Full-Scale Structured Sheet Media IFAS Systems

The aeration mixing requirements were also examined in four (4) full-scale facilities upgraded with structured sheet media for either performance improvement or capacity increase. Table 4 lists the IFAS media system information (e.g. flow, source of wastewater, type of media and diffusers, and air scouring velocities and flow rate) of the full-scale installations. No aeration rolling pattern change as a result of biomass overgrowth on the media was observed at a wide range of organic removal rates (e.g. 65-200 lbs/1,000 ft^3-day) as obtained in the first media towers towards the inlet of the aeration basins. Enhanced performance has also been consistently observed in the full-scale facilities (Ye et al., 2010b).

The media scouring velocities (e.g. 0.1-0.3 ft/sec) measured in both full-scale CF and VF media systems using either tubular membrane or ceramic disc fine bubble diffusers were consistent with the pilot observations, confirming the identified scouring velocities of 0.1-0.3 ft/sec would satisfy the mixing and scouring requirement to maintain thin biofilm in a structured sheet media system. In addition, the VF media system demonstrated an improved scouring velocity over the CF system even at a much higher organic removal rate in an industrial application (e.g. Stevens, PA). However, as previously reported (Ye et al, 2009 and 2010a), the CF media has also shown its applicability in the retrofits with relatively low organic loads, therefore less mixing requirement.

Tapered aeration has been commonly implemented in the full-scale structured sheet media IFAS facilities due to their typical plug-flow configurations. Higher organic loads are typically observed in the media towers on the influent side of an aeration basin, therefore demanding more process air. This also leads to heavier biomass growth in the first media towers, requiring more scouring air for biofilm control (Figure 17). In addition to the benefits of kinetic optimization and process energy savings associated with a plug-flow configuration using tapered aeration (Daigger and Parker, 2000), the structured sheet media IFAS system may also use overall lower aeration mixing requirements as those identified in the pilot study (e.g. 1.0 SCFM/ft^2) due to the tapered aeration. For example, a scouring air flow rate of 1.25 SCFM/ft^2 was resulted from the tapered aeration for the 1st two media towers although the overall scouring air was about 0.85 SCFM/ft^2 in Coldwater, MI IFAS system. This was equivalent to approximately 30% reduction on the overall mixing aeration requirement when compared to the scouring air requirement for the 1st two media towers.

Table 4 Scouring air flow rates and liquid scouring velocities observed in the full-scale structured sheet media IFAS systems

Installations	**Hopedale, MA**	**Spring Township, PA**	**Coldwater, MI**	**Stevens, PA**
Flow, MGD	0.588	1.25	3.22	0.02
Type of Application	Domestic	Domestic	Domestic	Industrial
Type of Media	Cross-flow	Cross-flow	Cross-flow	Vertical-flow
Type of Fine Bubble Diffuser	Tubular membrane	Tubular ceramic	Disc ceramic	Tubular membrane
MLSS, mg/L	~2,500	~1,800	~3,500	~1,700
SCOD removed in the 1st tower (lbs/1,000 ft^3-day)	100	65	80	200
Scouring velocity in the 1st tower (ft/sec)	0.10	0.17	0.12	0.18
Airflow in the 1st tower (scfm/ft^2)	0.50	N/A	1.25	1.50
Airflow in the last tower (scfm/ft^2)	0.16	N/A	0.50	0.88
Overall airflow (scfm/ft^2)	0.40	1.0	0.85	1.15

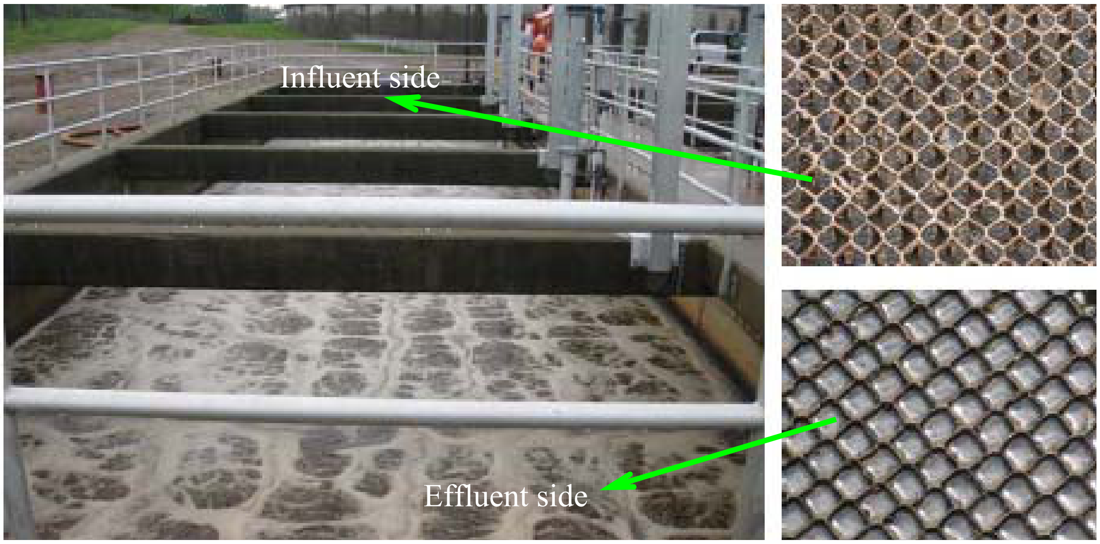


Figure 17 Biomass growths on the structured sheet media in Coldwater, MI WWTP

CONCLUSIONS

The study has demonstrated that the optimized airlift pumping associated with the VF media system using different types of fine bubble diffusers is capable of achieving effective biofilm control for enhanced ammonia and BOD removal in IFAS/FBBR applications. The unique features of the VF media system, including the use of a proprietary distribution media to ensure air distribution to the entire surface of the media, the vertical orientation of the VF media to reduce headloss and minimize excessive biomass buildup, and the dedicated airlift pumping along the biofilm surface to promote direct scouring and intimate contact, has contributed to its enhanced control of heavy biomass growth. As a typical airlift bioreactor, the VF media system is also carefully engineered in order to maximize the liquid scouring velocity in the vertical tubes of the media, including selecting different sizes of the VF media for specific treatment objectives, determining an appropriate downcomer region for easy diffuser maintenance and adequate aeration rolling patterns, and also integrating proper top and bottom water free boards for circulation flow optimization and solids settling prevention on the tank floor.

As confirmed by the enhanced process performance, the scouring velocity of 0.1-0.3 ft/sec (or 0.03-0.09 m/sec) observed in the VF media system has been shown to be sufficient for the control of excessive biomass growth at an organic removal rate up to 30 g SCOD removed/m^2-day. This observed liquid scouring velocity could be equivalent to 2-6 times of the flushing rates as typically used in the roughing trickling filters with open VF media, therefore providing an enhanced biofilm control in the submerged VF media system. This also corresponded to a scouring air flow requirement of 1.0-2.0 SCFM/ft^2-media plan view in the FBBR application with organic removal rates greater than 10 g SCOD/m^2-day and 0.5-1.0 SCFM/ft^2-media plan view in the typical municipal IFAS retrofits with relatively low organic loads. Significantly less aeration mixing requirement (e.g. less than 0.5 SCFM/ft^2) may be applied for a tertiary nitrification process due to its low biomass yield. The identified scouring air criteria for the VF media systems are often exceeded by the process air requirement for the upgrade of a CAS plant.

However, caution should be taken to properly size the aeration equipment in the case of pure oxygen plants where mixing aeration requirement may exceed the process demand.

Tapered aeration has been commonly implemented in the full-scale structured sheet media IFAS facilities. The measurement of liquid scouring velocities in the full-scale facilities confirmed the pilot observations that the scouring velocity of 0.1-0.3 ft/sec would satisfy the mixing and scouring requirement to maintain thin biofilm in a structured sheet media system. As a result of tapered aeration, lower overall scouring air flow rates than 0.5-1.0 SCFM/ft^2-media plan view may be used in the full-scale plants because the required media scouring can be achieved locally in the typical plug-flow configuration associated the VF media IFAS system. In addition to providing process kinetic optimization, tapered aeration also reduces the overall process and mixing air requirements for energy savings.

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