RETHINKING DISSOLVED AIR FLOTATION (DAF) DESIGN FOR INDUSTRIAL PRETREATMENT

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ABSTRACT

Dissolved air flotation (DAF) has been used with increasing frequency in recent decades for the treatment of industrial wastewater. Advances in the technology have expanded the range of applications for DAF; however, engineers and designers frequently use outdated and insufficient design data to design and specify DAF systems for industrial pretreatment. Discussions of advances in DAF design are discussed, including recycle pressurization, improved whitewater systems, enhanced chemical programs, and expansion of manufacturers' base of experience in industrial applications. The need for treatability testing is also emphasized. A case study illustrating these advances is presented, describing the application of DAF at a poultry rendering facility.

KEYWORDS

Dissolved air flotation, DAF, industrial wastewater, industrial pretreatment, poultry rendering

INTRODUCTION

Dissolved air flotation (DAF) has gained widespread usage over the last forty years for the removal of suspended solids (TSS), oils and greases (O&G), and biochemical oxygen demand (BOD) from wastewater and other industrial process streams. DAF systems are frequently used to provide wastewater pretreatment, product recovery, and thickening of biological solids in industries ranging from food processing to pulp and paper to petrochemicals.

Years of experience in specifying DAF systems for industrial applications has shown that many engineers, designers, and end users have come to rely on DAF design information from common reference materials, such as engineering handbooks. Such reference materials base specification of DAF systems on parameters such as recycle rate and pressure, air-solids ratio, hydraulic loading, and surface loading. However, the values provided in common references for these parameters tend to be outdated or inadequate when compared to data from actual operating systems.

In other words, the reliability and performance of DAF systems have improved with increased use of this technology, but there has not been a corresponding change in the standard design criteria for these systems. Moreover, DAF systems have evolved to a point where some of these

parameters are not as critical to the design and are frequently not used for design purposes. This paper will address these issues and provide suggestions for improving the design and specification of DAF-based treatment systems for industrial wastewater.

DAF OVERVIEW

While DAF units come in many forms, the systems most commonly produced today are rectangular-shaped units using recycle pressurization to provide dissolved air to encourage flotation. As illustrated in Figure 1, a DAF system consists of the following primary components:
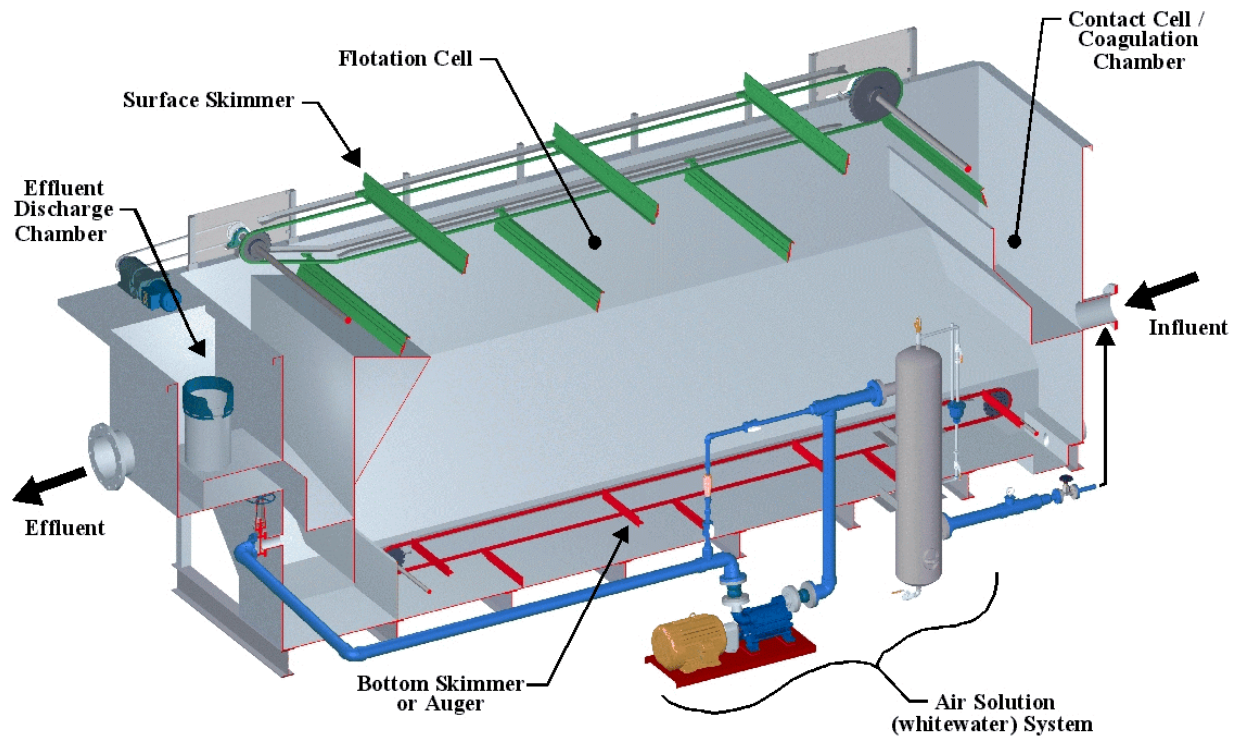
Figure 1. Typical DAF Unit

1.   Contact cell or coagulation chamber. Provides for the mixing of dissolved air with flocculated particles in the influent to allow for attachment of bubbles to particles. Also provides even distribution of flow across the width of the unit.

2.   Flotation cell. Provides surface area for the flotation of air and flocculated particles (float). Some systems employ the use of inclined plates to augment the separation of

solids in wastewaters with certain characteristics.

3. Surface skimmer. Provides the means for removal of float from the flotation cell for transfer to dewatering or other handling. The most commonly-used system involves a series of flights pulled by a chain drive system with variable-speed, timer-operated drives.

4. Bottoms skimmer or auger. Provides for the removal of settled solids in the bottom of the unit.

5. Effluent discharge baffle and chamber. Provides for physical separation of clarified water from flocculated particles and bottoms prior to discharge from the unit through weirs or similar structures.

6. Air saturation (whitewater) system. Provides the required amount air in the proper form (bubble sizes in the range of 10-100 μm), ideally using minimum recycle flow. The whitewater system uses pump pressurization to force air into solution with either the influent stream or a clarified effluent recycle stream. The air-water solution is then injected into the incoming wastewater stream to encourage bubble-solid contact and flotation.

While the DAF unit is the centerpiece of a DAF-based system design, there are several other supporting systems important to optimal DAF operation. Some of these systems are shown in Figure 2, a typical DAF process design:
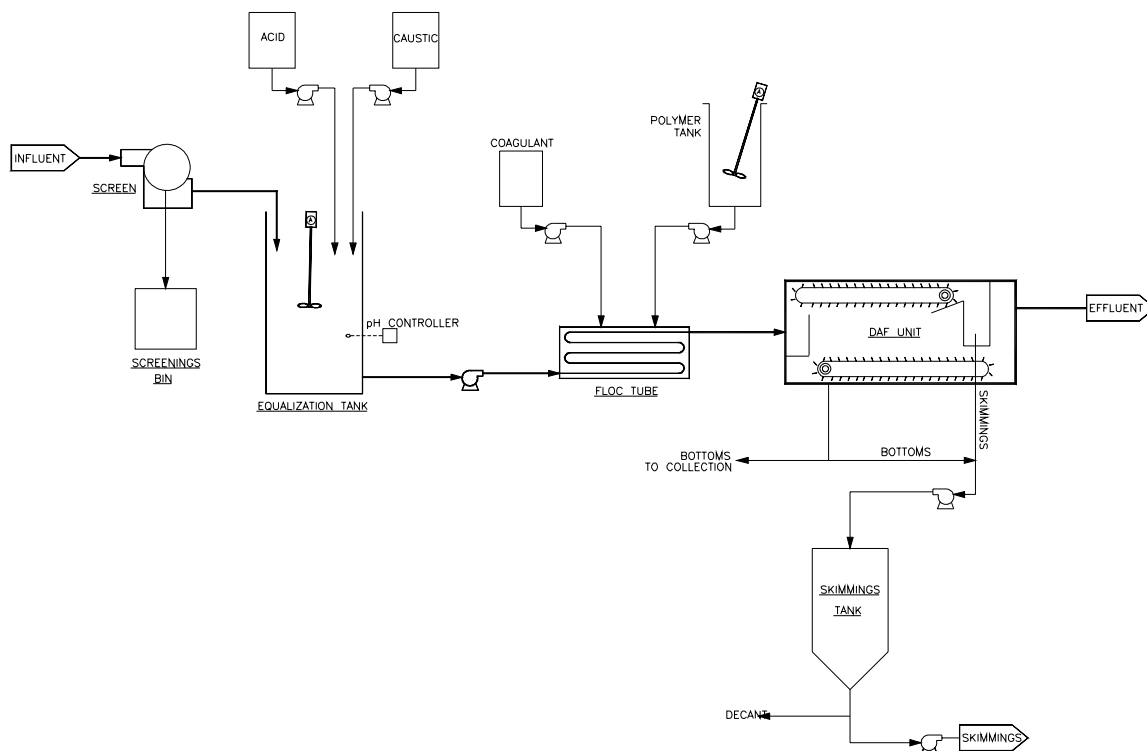

Figure 2. Typical DAF Process Diagram

1. Screening. Although occasionally overlooked by designers, proper screening of large solids (e.g., product solids, trash) from an industrial wastewater reduces the solids loading on a DAF, can improve chemical conditioning downstream, and reduces maintenance requirements due to clogged valves, pumps, and piping.

2. Equalization. Proper equalization of an industrial effluent can provide a more constant and homogeneous flow to the DAF unit. This can improve the effectiveness of the chemical program used for coagulation and flocculation prior to the DAF unit. In addition, equalization reduces hydraulic surging which can be detrimental to system performance. In some cases, equalization tanks can be sized to allow operation of the DAF unit during specific time periods (e.g., a single plant shift), thus reducing operator labor costs.

3. Chemical addition. Most chemical addition systems utilize either flocculation (floc) tubes or flash/floc tanks to introduce chemicals into the process flow. These systems must be designed to provide the proper amount of time and mixing energy for the chemical program employed. In addition, precise pH control will typically improve the performance of most chemical programs.

4. Float handling. The pH adjustment chemicals, coagulants, and polymers used in a chemical program will impact the available methods of disposal and/or utilization of the float generated by a DAF system. The moisture content and volume of material recovered by a system will vary and must be considered when sizing transfer pumps, storage tanks, and dewatering systems.

ADVANCES IN DAF DESIGN

Numerous advances in DAF design over the last 20 years have contributed to the increased efficiency and use of the technology for industrial pretreatment applications. Discussion of shape (i.e., circular vs. rectangular) and other physical design characteristics are the subject of ongoing debate and will not be addressed here. However, there are a number of advances that are common to many of the designs currently marketed for pretreatment applications:

Recycle Pressurization
Over the years, most DAF manufacturers have made a transition from full-flow pressurization to recycle-flow pressurization for the creation of whitewater to induce flotation. Most of the full-flow pressurization systems, which involve pressurizing the total influent to the flotation cell, operate at lower pressures (<50 psig), which limits the amount of air going into solution. Furthermore, in cases where flocculating chemicals are used upstream, full-flow pressurization exposes the floc to high shear forces and turbulence from the pressurization pump, pressurization tank, and pressure control valve prior to entering the flotation cell. This tends to destroy the floc formed prior to pressurization, thereby limiting the effectiveness of the system. In contrast, recycle pressurization involves pressurization of a sidestream of clarified effluent for return to

the flotation cell. Systems which feature recycle pressurization can operate at higher pressures and minimize the destruction of floc formed in the process flow. Generally, the benefits of higher air saturation and undisturbed floc formation outweigh the increased total hydraulic loading that a recycle pressurization system imparts on the flotation system.

Air Saturation (Whitewater) Systems
In addition to the transition from full-flow to recycle-flow pressurization systems, significant advances have also been made in methods for dissolving air into water. These advances have come primarily from injecting air into pumps capable of handling water with entrained air. These pumps operate at higher pressures than standard centrifugal process pumps, increasing both air saturation and volumetric efficiencies. The combined effects of recycle pressurization and improved pumping systems allow the introduction of the same amount of dissolved air into the flotation cell of a DAF using 50 to 70% less recycle flow than earlier whitewater system designs. Additional discussion of whitewater system improvements is provided below.

Chemical Programs
Over the last 20 years, there has been a dramatic increase in the number chemical programs developed for the coagulation and flocculation of contaminants in industrial wastewaters. Industrial pretreatment applications typically rely on chemical programs to improve the destabilization of emulsions, precipitation of proteins, and the destabilization of suspended solids through pH control and the addition of coagulants such as metal salts. Flocculation of the resulting coagulated solids is typically accomplished through the addition of cationic and/or anionic polymers. The resulting floc from these chemical programs can be easier to float than that from many municipal applications, thus requiring less dissolved air. This allows many industrial DAF systems to operate with much lower air:solids ratios and higher solids loading rates than are typically used in municipal applications.

Significant advancements have been made in the development of polymers with a wide variety of molecular weights and charges (cationic, anionic, and nonionic) and applying them to specific industrial contaminants. This has resulted in the development of single- and multiple-polymer programs that reduce or eliminate the need of some of the more common metal salt coagulants. In many cases, the use of these advanced polymers promotes stronger floc formation, lower float volumes, and lower float moisture content.

Improvements have also been made in the blending of these chemicals into the process flow. While tradition flocculation tanks are still used for this purpose, the use of flocculation tubes has increased in many applications where sequential addition of chemicals is desired and shorter retention times are acceptable.

Application Experience
The most significant advancements in DAF design have come from actual experience in industrial pretreatment. Over the last 40 years, DAF has been tested or implemented in wastewater applications for practically every major industrial category. In fact, it is one of the most common form of pretreatment in the food processing industry. For example, of 30 poultry processing plants in Georgia, 29 use dissolved air flotation as a pretreatment process (Valentine

et al., 1993).

As a result of this experience, DAF manufacturers have developed a considerable knowledge base of appropriate sizing and application of DAF technology for most industrial effluents. When coupled with treatability testing programs, this base of experience allows most manufacturers to design a system for a specific industrial effluent and treatment goal. Unfortunately, much of this design information has not been transferred to many of the engineering design texts for wastewater treatment.

WHITEWATER SYSTEM IMPROVEMENTS

Improvements in whitewater systems have had perhaps the most dramatic effect on the design and specification of DAF systems over the past few decades. As described above, most of the early DAF designs used centrifugal process pumps to force flow into a pressurization tank at a design pressure of less than 50 psig. Compressed air at pressures 10 to 20 psi greater than the recycle pressure was then injected into the recycle stream somewhere between the pump discharge and the pressurization tank. The combined pressure and retention time of the tank forced the air into solution.
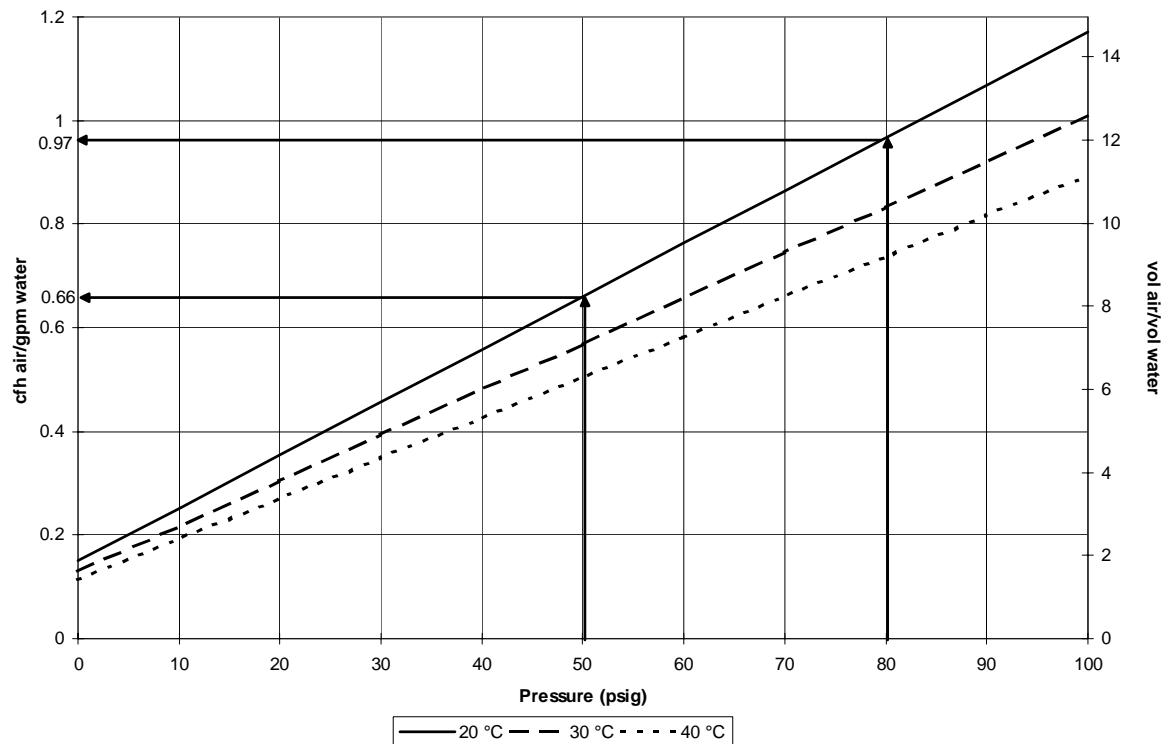

Figure 3. Air Solubility in Water vs. Pressure

Although not noted in most published design criteria, this post-pump air injection system has

given way in recent years to the use of air-handling recycle pumps that can pressurize water with entrained air without causing cavitation or vapor lock. These air-handling pumps include regenerative turbine and special multi-phase centrifugal pumps which can handle limited air injection (10-20% v/v).

These pumps have a number of advantages over the traditional centrifugal pump design:

•   Pressure. Air-handling pumps can typically operate at pressures of 80 to 120 psig, versus 50 psig for traditional centrifugal pumps. This higher pressure significantly increases the amount of air that can go into solution, as illustrated in Figure 3. For example, at 20ºC, the maximum amount of air that can be saturated in water at 80 psig is 46% greater than the amount at 50 psig.

•   Saturation efficiency.   Whitewater systems based on air-handling pumps draw air into the suction or volute of the pump, subjecting the mixture to the high shear forces of the pump impeller(s) to force air into solution more rapidly and efficiently. In addition, studies on various DAF saturator configurations by Valentine et al. (1993) have indicated that mixing at higher pressures (>50 psi) significantly increases saturation efficiency over systems without mixing at lower pressures.
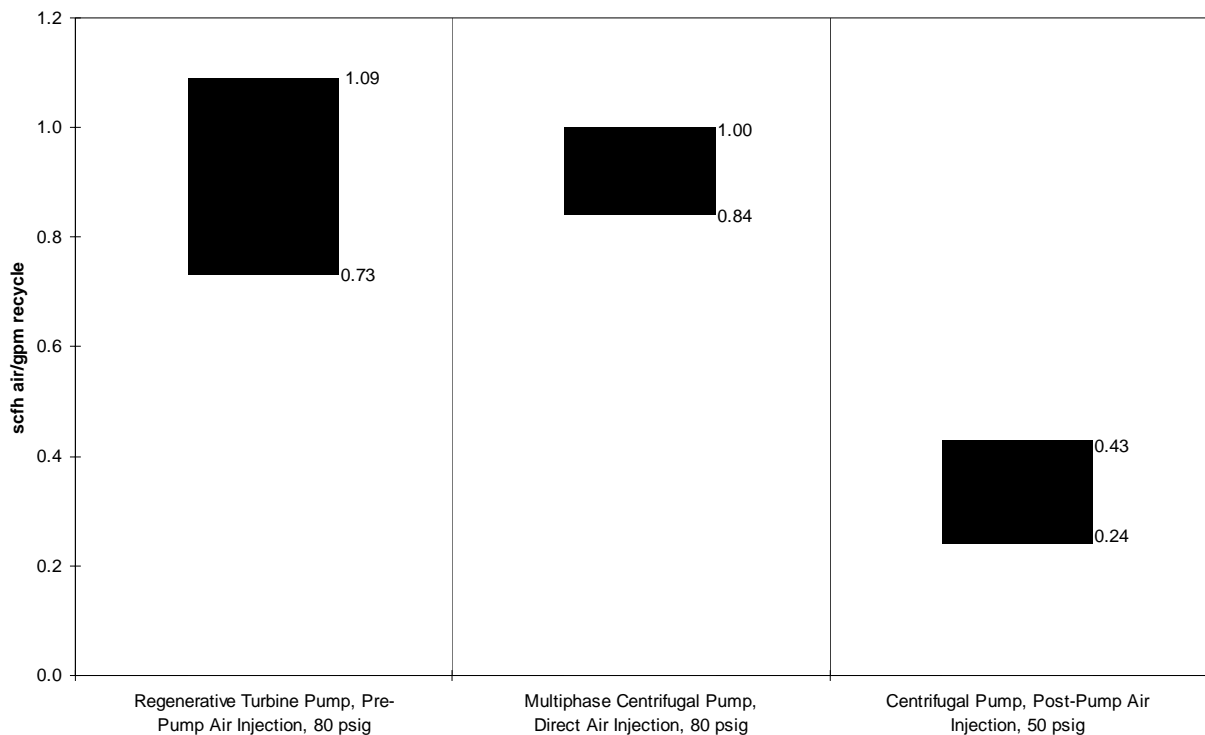

Figure 4. Comparison of Saturator Efficiencies for Different Types of DAF Recycle Pumps

- Volumetric efficiency. Since air-handling pumps operate at higher pressures and achieve higher saturation efficiencies, they provide a higher mass of air per unit volume of recycle flow. This is illustrated in the bar graphs in Figure 4 for data collected from three different types of recycle pump systems. Regenerative turbine and multi-phase centrifugal pumps operating at 80 psig provided over 230% more dissolved air per unit volume of recycle (scfh air/gpm recycle) than a standard centrifugal pump operating at 50 psig. In some cases, the upper saturation efficiencies for the vapor pumps exceeded the theoretical air solubility at a given temperature and pressure. These air injection rates that exceed theoretical saturation rates can be attributed to the mechanical energy of the pump producing small undissolved air bubbles in the pressurized solution, in addition to the air that is actually in solution.

- Pressurization tank size. In contrast to a traditional whitewater system which requires a pressurization tank detention time of at least one minute for good saturation efficiency, an air-handling pump negates or minimizes the need for a pressure tank, except as a means for venting excess air to the atmosphere. Therefore, the size of the pressurization tank can be greatly reduced over that needed with a traditional centrifugal pump.

- Air supply. Because the location of air injection on air-handling pump systems is under low pressure or vacuum conditions found in the pump suction or volute, air can be supplied by low-pressure compressors or drawn from the ambient air without the need for an air compressor. This contrasts with a traditional centrifugal pump design, where compressed air must be supplied at 10 to 20 psi greater than the pump operating pressure (60 psig or greater).

However, in spite of their many advantages, whitewater systems based on air-handling pumps have a number of disadvantages which should be considered by the engineer or system designer:

- Greater horsepower requirements. Operation at higher pressures requires higher horsepower motors, although this effect is partially offset by the reduced recycle flow that is required.

- Closer tolerances. Regenerative turbine pumps have closer tolerances than typical centrifugal pumps. Wear caused by solids in the clarified effluent can reduce pump effectiveness over time.

- Excess air. Since air-handling pumps can draw air in excess of what can be dissolved in the recycle stream, excess air can result in large, disruptive bubbles in the flotation cell if not vented from the system.

After considering both these advantages and disadvantages, many DAF manufacturers have opted to include in their designs whitewater systems based on air-handling pumps.

IMPACTS ON DAF DESIGN CRITERIA

Although DAF has been in use for over 40 years, the design criteria available to engineers and system designers for industrial applications is limited in the more popular design manuals. As illustrated in Table 1, criteria provided in these references has either gaps or wide ranges, some of an order of magnitude or greater (e.g., air/solids ratio). Much of the early design criteria were developed using municipal wastewater or waste activated sludge (WAS) thickening data. As shown in Table 1, even the more recently-published criteria appear to focus on municipal applications with little data input from industrial applications and do not reflect the advances in DAF technology over the last 20 years.

Recycle Pressure
The typical recycle pressure shown in Table 1 of 15 to 75 psig for a DAF whitewater system is based on a post-pump air injection system with a standard centrifugal pump providing pressurized flow. Higher-pressure air-handling pump systems are more prevalent today. As discussed above, these systems typically operate at 80 to 120 psig, resulting in much higher volumetric efficiencies (scfh air/gpm recycle flow).

Saturation Efficiency
While design saturation efficiencies of 50 to 90% are suggested in Table 1, most of the traditional centrifugal pump based systems operate in the range of 45 to 65% (Valentine et al., 1993). Recycle systems based on air-handling pumps have demonstrated saturation efficiencies up to 100% due to the mechanical mixing of air within the pump.

Recycle Percentage
DAF recycle rate as a percentage of throughput through the system is considered by many in the industry as an outdated parameter to use when sizing a system. With volumetric efficiencies ranging from 0.24 to 1.09 scfh air/gpm of recycle flow (Figure 4), the actual percentage of recycle is inconsequential.

Pressurization Tank Detention
While Table 1 suggests pressurization tank detention times of 0.5 to 3.0 minutes, Valentine et al. (1993) noted that with traditional centrifugal pump designs, the detention time was less important than the physical configuration of the tank. Most whitewater systems based on air-handling pumps do not require significant detention time for air saturation and as a result use either small tanks or none at all.

Hydraulic Loading Rate
DAF hydraulic loading rate (HLR) is typically the primary design parameter for most industrial applications. As indicated in Table 1, published suggested values range from 0.2 to 5.5 gpm/ft^2; however, most references do not indicate whether or not this includes the recycle rate in addition to the influent wastewater stream. Given that some DAF systems use the post-pump air injection system with high recycle rates, it is important make this distinction since high recycle flows can significantly increase the hydraulic loading of a DAF system. Generally, a HLR of 2.0 gpm/ft^2, without recycle, is considered a good starting point in a design. Other factors, including

chemical programs, the nature of the contaminants being removed, and prior treatment experience, will have an effect on the final design value.

Solids Loading Rate
The solids loading rate (SLR) is determined by dividing the mass flow rate of solids and/or O&G by the available surface area in the flotation cell. As illustrated in Table 1, only two of the five references include this parameter, with a range of 0.80 to 2.8 lb/ft²-hr. As with the HLR, the optimum SLR is dependent on a number of other operating conditions. The fact that these published ranges apply only to a small range of primarily municipal applications raises questions of whether they can be applied to industrial applications at all.

Table 1. Comparison of Published DAF Design Parameters

	WPCF MOP-8 (1977)	Metcalf & Eddy (1991)	WEF MOP-8 (1992)	WEF MOP-FD-3 (1994)	Corbitt (1999)
Reference treatment category	Wastewater	Sludge	Sludge thickening	Industrial	Wastewater
Recycle pressure, psig	15-45	40-75	75	15-45	25-70
Saturation efficiency, %		50-95	50-90	80	
Recycle, %		15-120	100		5-120
Pressurization tank detention, min				3.0	0.5-3.0
Hydraulic loading rate, gpm/ft²		0.20-4.00	0.50-2.00	1.0-2.00	0.35-5.50
Solids loading rate, lb/ft²-hr	1.0-2.8		0.80-2.00		
Air-solids ratio, lb air/lb solids	0.010-0.200	0.005-0.060	0.020-0.060	0.006-0.070	0.010-0.200

Air-to-Solids Ratio
The air-to-solids (A:S) ratio is the ratio of the mass of dissolved air delivered by the whitewater system to the mass of solids in the influent entering the flotation system (lb air/lb solids). The values provided in Table 1 range from 0.005 to 0.200 lb air/lb solids, representing a range greater than an order of magnitude. As one would expect, it would be difficult to specify an A:S ratio with such a range to choose from. Choosing a high A:S ratio can lead to large recycle systems which will in turn affect the HLR and overall size of the DAF system. Typically, systems are sized initially with A:S ratios in the lower range (0.005 to 0.010), especially when influent TSS concentrations are less than 2,000 mg/L and the HLR is the predominant design criteria. Higher

solids loading may or may not require an increase in the amount of air supplied to maintain the design A:S ratio. This will depend greatly on the characteristics of the contaminants and the chemical program used to coagulate and flocculate. The use of bench- and pilot-scale treatability testing would be very beneficial under these conditions.

In general, the design criteria for DAF design provided by the most common environmental engineering design manuals are short in specifics and represent data that do not correspond with most industrial applications. While DAF treatment programs are well-established for some industries, data are limited for many industrial effluents. Moreover, variability in wastewater characteristics and the introduction of new chemical programs can make it difficult to optimize the sizing of a DAF system.

This stresses the need for treatability testing prior to sizing DAF systems for many industrial applications. Testing can range from simple jar testing to bench-scale batch tests to on-site pilot tests. Pilot testing is particularly effective for determining the optimum size of a full-scale DAF system so that under-sizing (unrealized performance) and over-sizing (increased capital cost) can be avoided.

CASE STUDY- RENDERING PLANT

In 1998, Environmental Treatment Systems, Inc. conducted a series of pilot-scale treatability tests on the screened effluent from a poultry rendering plant prior to biological treatment. The testing was deemed necessary due to the very high levels of TSS and O&G in the wastewater (approximately 35,000 and 25,000 mg/L, respectively) and the need to determine the most economical chemical program for coagulation and flocculation.

Prior to the pilot test, jar testing showed that the most effective chemical program was pH adjustment to pH 4.5-5.5 to precipitate proteins, followed by flocculation using a cationic polymer dosed at 15 to 20 ppm. For the pilot test, a side-stream of screened and equalized wastewater was neutralized to the target pH using PID-based pH control and sulfuric acid in a small equalization tank. The conditioned wastewater was then pumped through a flocculation tube, where cationic polymer was added and blended in prior to entry into the pilot DAF system.

A summary of the pilot test operating conditions and performance results is provided in Table 2. The pilot DAF unit had 15 ft^2 of surface area and was nominally loaded at 25 gpm, or a HLR of 1.7 gpm/ft^2 not including recycle. Air was supplied to the whitewater system by a regenerative turbine pump using pre-pump air injection at an average rate of 10 scfh, with a recycle flow of 10 gpm at 80 psig (1.0 scfh/gpm). As illustrated in Table 2, TSS, O&G, and COD removals were 98.6, 99.2, and 89.3%, respectively, during the test.

The design criteria drawn from the pilot test was used to design a full-scale DAF system, as shown in Table 2. The rectangular DAF system was sized at 1.8 gpm/ft^2 to treat a flow of 330 gpm with a whitewater recycle rate of 90 gpm at 80 psig and an air injection rate of 65 scfh (0.72 scfh/gpm). The system was installed in 1998 and has operated as shown in Table 2. Although initial influent COD and TSS concentrations were higher than those observed during the pilot

test, the system provided TSS, O&G, and COD removals of 99.4, 99.6, and 91.7%, respectively.

Table 2. Operating Parameters and Performance - Rendering Plant Case Study

	Pilot DAF	Full-Scale DAF	Published Ranges
Operating Parameters			
DAF surface area, ft^2	15	180	
Influent flow, gpm	30	330	
Recycle rate, gpm	12	90	
Recycle pressure, psig	80	80	
Air injection rate, SCFH	10	65	
Air solution rate, SCFH/gpm	1.0	0.72	
Influent TSS, mg/L	34,975	43,706	
Influent COD, mg/L	63,446	113,864	
Influent O&G, mg/L	25,219	18,568	
Hydraulic loading rate, feed only, gpm/ft^2	2.0	1.8	
Hydraulic loading rate, incl recycle, gpm/ft^2	2.8	2.5	0.2-5.5
Solids loading rate, lb/ft^2-hr	35.0	40.1	0.8-2.8
Air-solids ratio, lb air/lb solids	0.0015	0.0006	0.005-0.200
Performance Data			
Effluent TSS, mg/L	505	263	
TSS removal, %	98.6	99.4	
Effluent COD, mg/L	6,765	9,400	
COD removal, %	89.3	91.7	
Effluent O&G, mg/L	191	72	
O&G removal, %	99.2	99.6	

Most notable of the operating parameters for both the pilot-scale and full-scale systems was the SLR, which was significantly higher than the published values. The full-scale DAF operating SLR of 40.1 lb/ft^2-hr was roughly 13 times greater than the maximum published value of 2.8 lb/ft^2-hr. More importantly, the DAF A:S ratio of 0.0006 lb air/lb solids was roughly one-tenth the minimum value found in Table 1, indicating that the flocculated solids in this waste stream could be effectively removed with this type of DAF system at a much lower A:S ratio than that suggested in the design literature.

If either of the less-stringent values for SLR or A:S ratio in Table 1 had been used in sizing the unit based on the wastewater characteristics alone, the DAF system would have been much larger than it actually needed to be. If the maximum allowable SLR in Table 1 had been used as the primary design criterion, instead of the 180 ft^2 of surface area provided, the DAF unit(s) would have needed greater than 1,800 ft^2 of surface area. In addition, using the minimum A:S ratio in Table 1 would have resulted in a recycle flow of at least 900 to as much as 1,800 gpm instead of the 90 gpm used.

The capital cost using these published design values would have been $1.5 to $2.0 million higher, and the operating and maintenance costs would have been proportionally higher. The pilot testing and resulting installation confirms the need to conduct treatability testing on industrial wastewater prior to selecting design criteria. It also calls into question the wisdom in using some of the published design data reflected in Table 1.

CONCLUSIONS

1. The increased use of recycle pressurization, advances in whitewater systems and chemical programs, and expansion of DAF manufacturers' base of experience in industrial applications has not been accompanied by a corresponding change in standard published design data commonly used by engineers and designers.

2. Many design references commonly used by engineers and designers provide wide ranges in data, or no data at all, for many common design parameters. While it may not be the intention of the authors of these references for these ranges to be used in actual designs, it has become fairly common practice to use such references as sources of firm design data. This practice can result in sizing systems incorrectly, which can also lead to false elimination of DAF as an economically feasible treatment alternative. Since DAF is still used in municipal wastewater treatment and sludge thickening, these design references should still include data for these applications. However, these references should also emphasize that the data they supply should be used with caution and restraint and stress the need for further investigation when treating industrial wastewaters.

3. Treatability testing, both on a bench scale and pilot scale, is often overlooked as a step in design of DAF-based wastewater treatment systems. Experience has shown that such testing can markedly improve the economic feasibility of a treatment project. While it may complicate the traditional design-bid-build process, testing should be included in any industrial treatment system design where the engineer, designer, or equipment supplier

does not have substantial experience in the particular industry.

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