The Impact of Magnetite Ballast on Oxygen Transfer and Alpha

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ABSTRACT

A new process, known as mixed liquor ballasting, increases the capacity and treatment efficiency of the activated sludge process by greatly enhancing the mixed liquor settling rate. The BioMag™ system is a ballasted biological treatment system that uses magnetite, a high density, inert form of iron oxide which can be recovered magnetically from the waste activated sludge and reused in the process to maintain an extremely dense, fast settling biomass. As a result, very high biological solids concentrations can be maintained, and the plant footprint can be extremely small. Many studies on other high biomass activated sludge systems have found that the oxygen transfer efficiency of fine bubble diffusers is negatively impacted by high biomass concentrations. While the BioMag system normally operates with very high mixed liquor suspended solids, the magnetite, which typically makes up about half of the suspended solids, is inert and has properties very different than conventional activated sludge biomass. The oxygen transfer efficiency of fine bubble diffusers has not yet been tested in a rigorous manner in a high magnetite, ballasted activated sludge system. The impact of high concentrations of magnetite on fine bubble aeration is vital to know in order to properly size a diffused aeration system in the BioMag® system. To obtain pertinent design information, the field oxygen transfer efficiency of a commercial fine bubble disc diffuser was examined using off-gas measurement in a 3.0 meter deep test column. Various air flow rates and magnetite concentrations were tested, and it was found that magnetite has no negative impact on oxygen transfer efficiency in a fine bubble aeration system.

KEYWORDS: Mixed Liquor Suspended Solids (MLSS), Ballasted MLSS (mixture of magnetite ballast and MLSS), BioMag™, Alpha, and Oxygen Transfer

INTRODUCTION

Ballasting of activated sludge mixed liquor suspended solids (MLSS) is a relatively new process tool within the wastewater treatment industry. This process allows Wastewater Resource Recovery Facilities (WRRFs) to more easily handle increased flow volumes and solids loadings, and/or to be operated at longer sludge ages to achieve enhanced nutrient removal, without physically adding tankage to the plant. The BioMag system is an example of ballasted biological treatment that includes recovery and reuse of magnetite, a fully inert form of iron ore with a specific gravity of 5.2 and a strong affinity for biological solids. In this system, magnetite is added into the return activated sludge (RAS) stream of an activated sludge biological treatment process to create a specific ratio of magnetite to MLSS. The magnetite is embedded into the biological floc, thereby increasing the density of the floc and producing increased settling and thickening rates. It is this increase in settling rate that enables treatment over a wider range of clarifier solids loadings and flow rates. It also allows for operation at increased mixed liquor volatile solids (MLVSS) concentration and corresponding elevated sludge age to achieve enhanced biological nutrient removal. Waste sludge (WAS) is pumped through a shear mixer and then to the magnetic recovery drum, where the ballast is recovered and re-blended with the mixed liquor (see Figure 1).

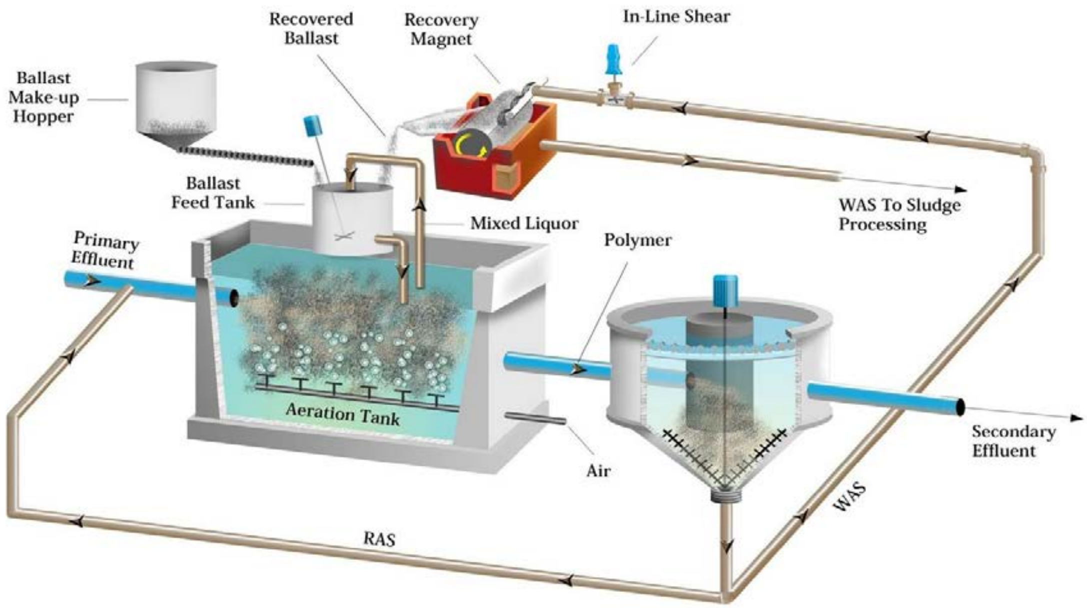

Figure 1 – Biomag^{TM} Process Flow Schematic

Aerobic biological treatment systems require oxygen to perform a variety of biochemical reactions. The supply of oxygen for aeration is the single largest energy consumer in activated sludge wastewater treatment plants (EPA Design Manual Fine Pore Aeration - 1989). It has been estimated that more than 50% of the electrical energy required to operate an activated sludge plant is due to aeration equipment power demand, far more than any other single unit operation (SAIC - 2006). Proper calculation of the total actual oxygen requirement (AOR) is critical to good plant design, and selection of the most energy cost-effective oxygen transfer device is likewise very important in minimizing life cycle costs of the WRRF. In order to provide a uniform methodology of rating oxygen transfer equipment, the American Society of Civil

Engineers (ASCE) has developed Standard ASCE/EWRI 2-06, Measurement of Oxygen Transfer In Clean Water. The oxygen transfer device is tested in tap water or other clean water source, and the transfer rate is standardized at 20 deg. C., 1 atm. pressure, and 0 mg/l dissolved oxygen. This transfer rate can be expressed as:

$$\text{Standard Oxygen Transfer Rate (SOTR, kg/hr)} = \frac{k_L a_{20} * C^*_{\infty 20} * V}{1000} \tag{1}$$

Where:

$k_L a_{20}$ = apparent volumetric mass transfer coefficient (1/hr)

$C^*_{\infty 20}$ = steady state dissolved oxygen saturation concentration at 20 deg. C. and 1 atm (mg/l)

V = process water volume (m^3)

It has generally been recognized that fine bubble diffusers offer the most energy efficient aeration system when evaluated under standard clean water conditions (WEF Manual of Practice 8 - 2009). However, the performance of the aeration system must be translated from the measured transfer efficiency in clean water to actual field conditions in contaminated water, at the operating dissolved oxygen concentration and temperature. There are several field correction factors to be applied (EPA – 1989) including temperature and dissolved oxygen corrections, but usually the most impactful factor, particularly for fine bubble aeration systems, is referred to as the alpha factor (α). This is a correction factor defined as the ratio between the apparent volumetric mass transfer coefficient, $k_L a_f$, in a process solution divided by $k_L a$ in clean water:

$$\text{Alpha } (\alpha) = k_L a_f / k_L a \tag{2}$$

Since the oxygen transfer rate is directly proportional to $k_L a$, alpha will directly impact oxygen transfer rate and efficiency. It can be seen that proper selection of alpha is crucial not only to assure that sufficient oxygen is supplied to the process, but also when making capital and operating cost decisions for plant upgrades.

There are many wastewater contaminants that will impact $k_L a$, but in general these may be classified as 1) inorganic suspended solids, 2) organic suspended solids, 3) dissolved non-surface active agents – usually organic in nature, and 3) dissolved inorganic or non-surface active organics. Because oxygen transfer involves transport across a gas-liquid interface, surface active agents are contaminants of particular importance in fine bubble aeration systems (Doyle, et. al. - 1983). It was at one time a common practice in the UK to conduct oxygen transfer tests on aeration equipment using tap water with surfactants added to simulate municipal wastewater (Boon and Chambers - 1985). While this technique has been shown to provide a good simulation of the impact of soluble organic contaminants, it does not provide an evaluation of the effect of suspended solids on alpha. With the development of membrane biological reactors (MBR), which are usually operated at high MLSS concentrations, it has been found that alpha values are reduced in these systems (Cornel, et. al. – 2003, Krampe and Krauth - 2003). Germain, et. al. (2007) specifically looked at the effects of biomass on oxygen transfer. The conclusions from this study indicated that an increase in suspended solids concentration led to an exponential decrease in both k_La and alpha-factor. The MLSS concentration was the primary controlling factor affecting oxygen transfer efficiency. This finding has very important ramifications for the BioMag system, which typically operates at higher MLSS than conventional activated sludge systems due to the magnetite addition, and very often at elevated biomass concentrations (MLVSS) similar to MBR systems. Magnetite is an inert, inorganic suspended solid, with properties very much different than normal mixed liquor suspended solids, so there is a question as to the effect on oxygen transfer from high magnetite TSS. The impact of high magnetite concentrations therefore needs to be evaluated for proper aeration system design of a BioMag® system. This paper investigates the effect of magnetite ballast on alpha-factor in mixed liquor. The results provide critical oxygen transfer efficiency (OTE) information necessary to better guide process engineers when designing magnetite-ballasted biological treatment systems.

METHODS

Test Arrangements

Steady-state test equipment was set-up at the Oconomowoc, WI WWRF, and operated by the Redmon Engineering Company to determine the α-factor of various batch samples taken from the plant's aeration tank. The trial utilized the off-gas test method developed by Ewing and Redmon (Redmon et. al. - 1983). Testing was performed in a test column that was 0.76 m (2.5ft) diameter and 3.35 m (11ft) high with a 3.0 m (10 ft.) diffuser submergence. Inside the test column were two 22.9 cm (9 in) diameter membrane diffusers, as well as a 6.8 m^3/hr (30 gpm) circulation pump and two dissolved oxygen (DO) probes. The top of the test column was sealed with a clamping lid, and the air line and cables of the two DO probes and pump were run out of the tank through a sealed, flanged fitting near the top of the test column (above the water level). Air was provided from the primary aeration header. A ballast mix tank was also provided to create the batch samples for the required MLSS concentrations and ballasted MLSS solutions. A 6.8 m^3/hr (30 gpm) submersible pump was used to transfer batch samples to the test column. The pump was also used to remove supernatant from settled sludge that would allow for running high MLSS concentrations. The equipment arrangement is shown in Figure 2.

The test column was filled with a MLSS solution, or ballasted MLSS solution depending upon the trial requirement, while being aerated from the diffusers and mixed by the circulation pump. The airflow rate was corrected for the liquid head conditions and normalized at atmospheric pressure. The DO was monitored by two probes that were connected to a Fluke meter and data logger. One DO probe was located roughly 1/3 depth (~1 meter or 3.33 ft below the water level), while the second probe was roughly 2/3 depth (~2 m or 6.66 ft below the water level). MLSS or ballasted MLSS concentrations from each batch were sampled at the end of each trial. A copy of the plant MLSS data was also secured for reference.

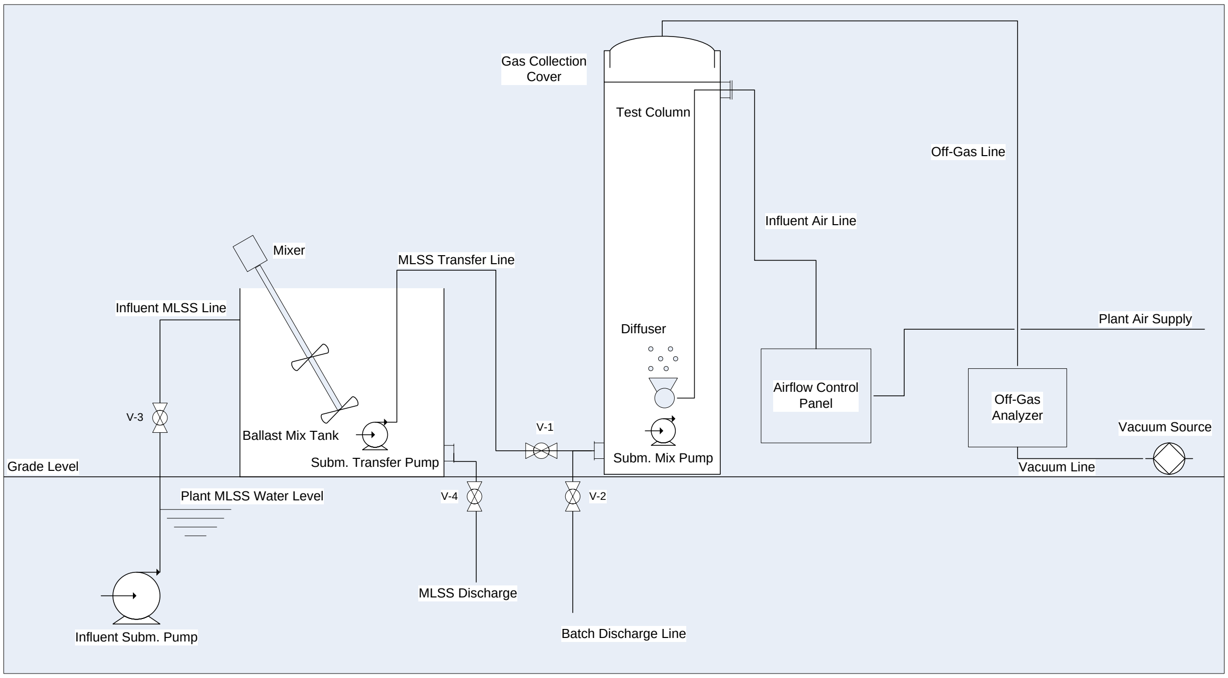

Figure 2: Equipment Arrangement

Test Conditions

The scope of testing included the following batch conditions:

Table 1: Alpha Test: Target Test Conditions*

Variable	Target Value						
MLVSS mg/l	Low (~3000)			High (~ 9000)			
Magnetite:MLSS	0	0.5	1.5	0	0.5	1	1.5
Air Flow Rate m^3/hr/diffuser (SCFM/diffuser)	2, 4 (1.2, 2.4)			2, 4, 6 (1.2, 2.4, 3.6)			

*These are target values; actual values will be reported within the Results & Discussion section

Data Analysis

Clean water oxygen transfer tests were conducted in accordance with Measurement of Oxygen Transfer in Clean Water (ASCE - 2006) to determine the standard oxygen transfer efficiency and dissolved oxygen saturation concentration at each test air flow rate. The series of mixed liquor and magnetite ballast tests, as previously described, were then performed. The collected data was compiled and analyzed by Dave Redmon of the Redmon Engineering Company. The important process measurements in this batch test are:

- Feed gas (air) oxygen content, $MV_{(R)}$, millivolt
- Off-gas oxygen content, $MV_{(OG)}$, millivolt
- Water temperature, T, deg. C.
- Operating dissolved oxygen concentration, C, mg/l
- Total dissolved solids concentration, TDS, mg/l
- Barometric pressure

The following equation from the EPA Design Manual for Fine Pore Aeration Systems was used to compare the clean water oxygen transfer rate to the field oxygen transfer rate, and ultimately to calculate the alpha value for each run:

$$\alpha F(SOTR) = (OTR_f\, C^*_{\infty 20}\, \theta^{(20-T)}) \div (\tau\beta\Omega\, C^*_{\infty 20} - C) \quad (3)$$

Where:

F = process water k_La of a diffuser after a given time in service ÷ k_La of a new diffuser in the same process water (F=1 for this testing)

OTR_f = field oxygen transfer rate, kg/hr

Θ = temperature correction factor for k_La = 1.024

T = temperature correction factor for dissolved oxygen concentration

B = oxygen solubility correction factor in process water

Ω = pressure correction factor at local barometric pressure

C^*_f = the field dissolved oxygen saturation value at operating temperature and pressure =

As shown in Ewing and Redmon (1983), the alpha value can be calculated according to the following procedure:

a) calculate mole fraction of oxygen in off-gas, $Y_{OG} = \dfrac{0.2095 * MV_{(OG)}}{MV_{(R)}}$ (4)

b) calculate mole ratio of oxygen/inerts in off-gas, $MR_{OG} = \dfrac{Y_{OG}}{1 - Y_{OG}}$ (5)

c) calculate field oxygen transfer efficiency, $OTE_f = \dfrac{0.265 - MR_{OG}}{0.265}$ (6)

d) knowing that OTR_f / SOTR = OTE_f / SOTE, and C^*_f = field dissolved oxygen saturation concentration = $\tau\beta\Omega\, C^*_{\infty 20}$, substitute into 3) to calculate:

$$\alpha = (OTE_f \;/\; SOTE\; C^*_{\infty 20}\; 1.024^{(20-T)}) \div (C^*_f - C) \quad (7)$$

RESULTS

The results of the batch alpha tests are summarized in Table 2. Two mixed liquor biological solids (MLVSS) concentrations were examined at various levels of magnetite augmentation and two to three air flow rates. The magnetite levels bracketed the typical 1:1 dosage of magnetite to biological solids used in most full scale plants. The air flow rates likewise were intended to cover a very typical range of flows for 23 cm. (9 in.) diameter fine bubble membrane disc diffusers.

Table 2: Alpha Batch Test Results

Trial	AIRFLOW (m^3/hr)	DO CONC. (mg/L)	ALPHA	MLSS (mg/L)	MLVSS (mg/l)	Magnetite Solids (mg/L)	Magnetite:BioSolids ratio
1	2	3.07	0.54	3870	2903	0	0.0
1a	4	5.33	0.64	3870	2903	0	0.0
2	2	3.07	0.60	5777	2903	1907	0.5
2a	4	5.26	0.67	5777	2903	1907	0.5
3	2	3.11	0.63	10176	2903	6306	1.6
3a	4	5.30	0.77	10176	2903	6306	1.6
4	2	0.00	0.36	11415	8561	0	0.0
4a	4	0.00	0.26	11415	8561	0	0.0
4b	6	0.00	0.27	11415	8561	0	0.0
5	2	0.00	0.36	15,750	8561	4,335	0.4
5a	4	0.00	0.26	15,750	8561	4,335	0.4
5b	6	0.00	0.27	15,750	8561	4,335	0.4
6	2	0.00	0.36	22,260	8561	10,845	1.0
6a	4	0.00	0.27	22,260	8561	10,845	1.0
6b	6	0.00	0.26	22,260	8561	10,845	1.0
7	2	0.00	0.36	30,730	8561	19,315	1.7
7a	4	0.00	0.28	30,730	8561	19,315	1.7
7b	6	0.00	0.28	30,730	8561	19,315	1.7

Low MLVSS Tests

The first series of tests were conducted at an MLVSS concentration of approximately 2,900 mg/l (unamended MLSS = 3,800 mg/l), with dry weight magnetite to initial MLSS ratios of roughly 0.5 to 1, 1 to 1, and 1.6 to 1. At an air flow rate per diffuser of 2 m^3/hr (1.2 SCFM), this test indicated a slight, but distinct, rise in alpha as the magnetite concentration was increased, as shown graphically in Figure 3. The highest magnetite dosing boosted the total TSS to 10,100 mg/l, with no change in MLVSS, while alpha rose by 16.6% from 0.54 to 0.63. As the air flow per diffuser was increased to 4 m^3/hr (2.4 SCFM), a similar increase in alpha was noted at increasing magnetite to MLSS ratios, as illustrated in Figure 4. A 20.3% increase in alpha was seen at the air flow rate per diffuser of 4 m^3/hr as the MLSS was raised from 3,800 mg/l to 10,100 mg/l. Again, there was no change in MLVSS as magnetite dosage increased.

High MLVSS Tests

A second series of tests were conducted using mixed liquor at an MLVSS concentration of approximately 8,600 mg/l (unamended MLSS = 11,400 mg/l), with dry weight magnetite to initial MLSS ratios of roughly 0.4 to 1, 1 to 1, and 1.7 to 1. Figures 3 through 5 demonstrate the negligible effect of magnetite ballast on alpha over an air flow rate range of 2 – 6 m^3/hr/diffuser (1.2 - 3.5 SCFM/diffuser).

For the starting MLSS concentration of 11,400 mg/l (MLVSS = 8,600 mg/l), the alpha factor remained steady at 0.36 as the magnetite concentration increased. Magnetite ballast addition for the high MLSS/MLVSS runs increased the combined suspended solids from roughly 11,400 mg/l to 30,700 mg/l while the MLVSS was constant at 8,600 mg/l. The airflow rate for these tests was maintained at 2 m^3/hr (1.18 scfm) per diffuser.

Figure 4 demonstrates a similar effect, while operating at a constant airflow rate of 4 m^3/hr (2.35 scfm) per diffuser. In the high initial MLSS runs of 11,400 mg/l TSS (MLVSS constant at 8,600 mg/l), alpha was steady at 0.26 - 0.28. Magnetite ballast addition for the high MLSS runs increased the combined suspended solids from roughly 11,400 mg/l to 30,700 mg/l, as in the testing at the lower air flow/diffuser. Again, there was no change in MLVSS as magnetite was added to increase the MLSS.

Lastly, Figure 5 shows the results for a high starting MLSS condition of 11,400 mg/l (MLVSS = 8,600 mg/l), with an airflow rate of 6 m^3/hr (3.50 scfm) per diffuser. As magnetite ballast was added the combined suspended solids again was increased from 11,400 mg/l to 30,700 mg/l, while the MLVSS was constant, and the alpha factor held steady at 0.27.

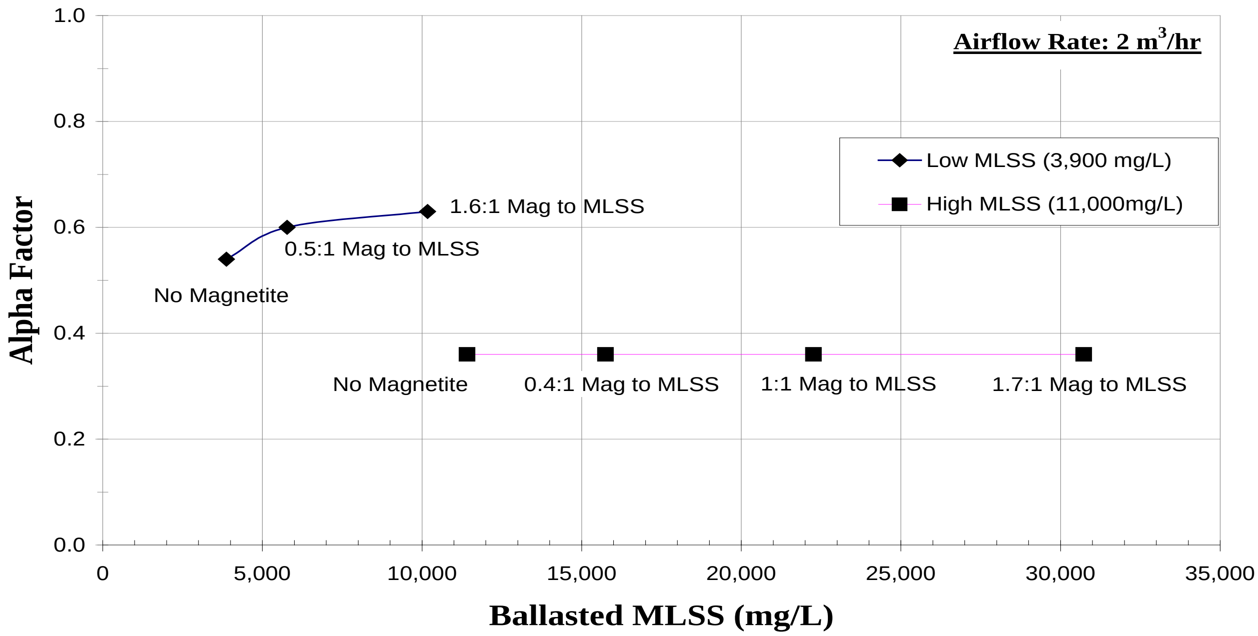

Figure 3: Magnetite Effect on Alpha @ 2 m^3/hr Air Flow

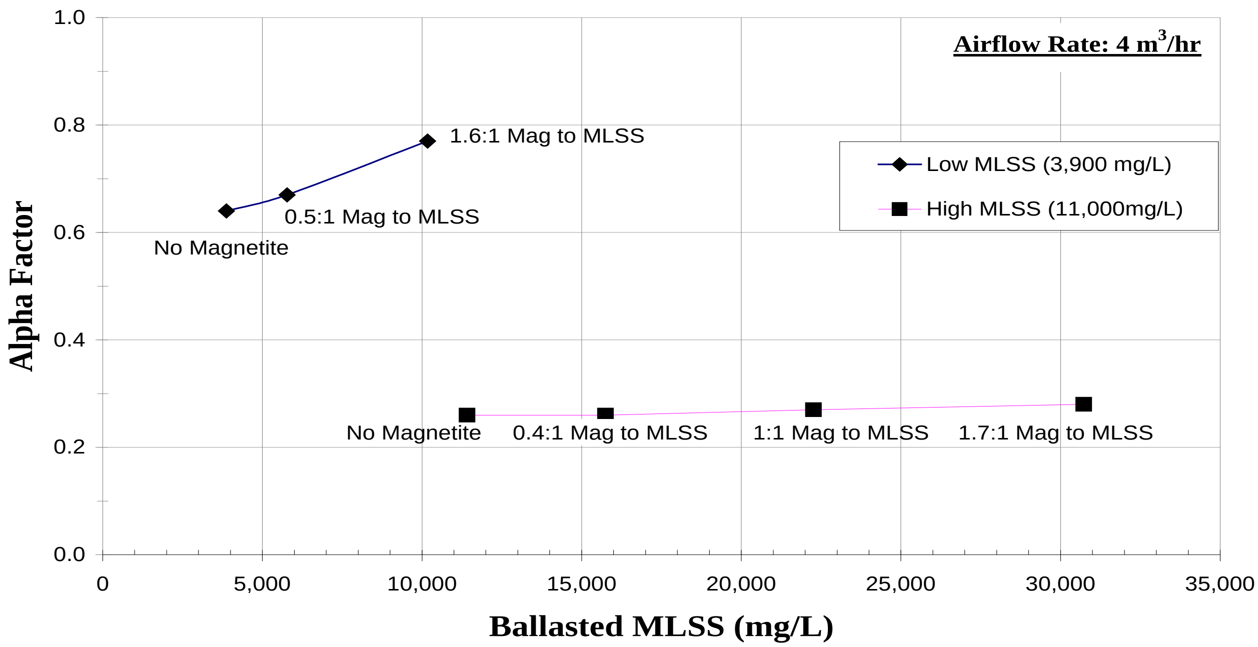

Figure 4: Magnetite Effect on Alpha @ 4 m^3/hr Air Flow

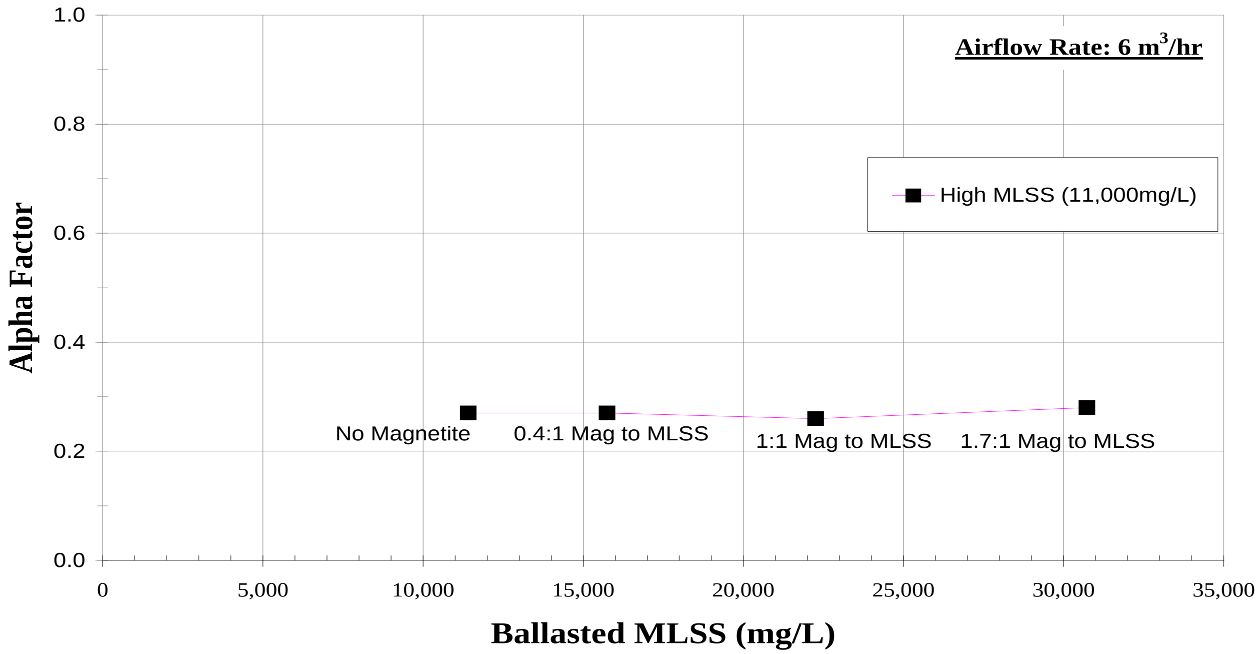

Figure 4: Magnetite Effect on Alpha @ 6 m^3/hr Air Flow

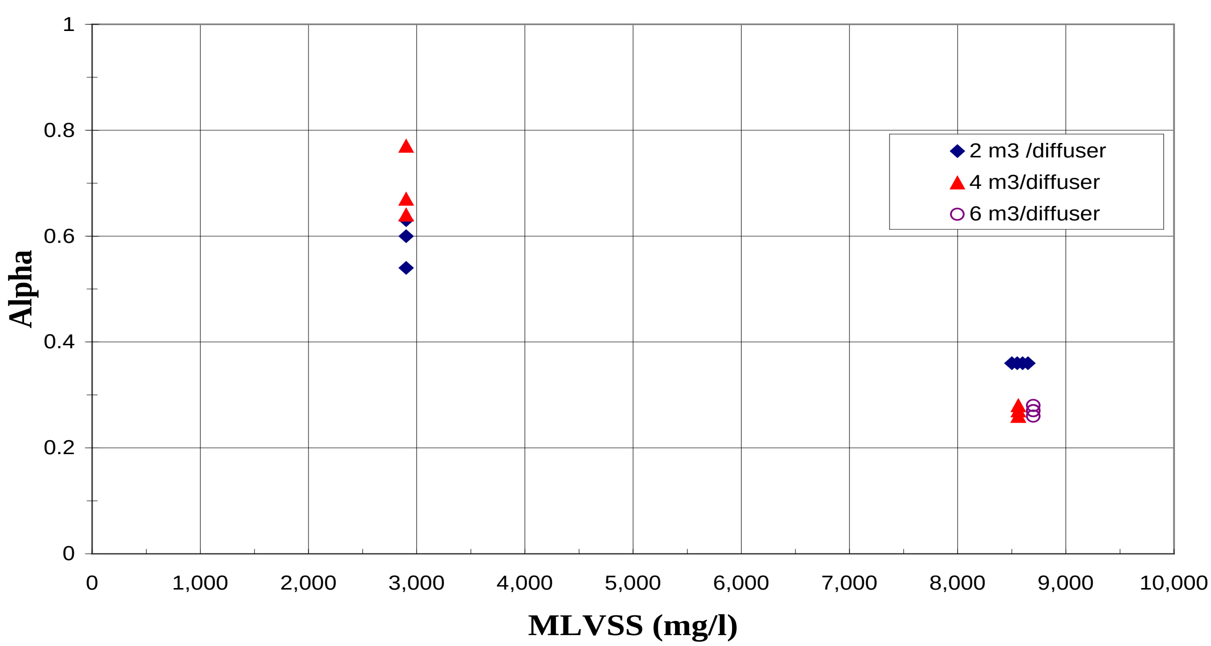

Figure 6: MLVSS Effect on Alpha

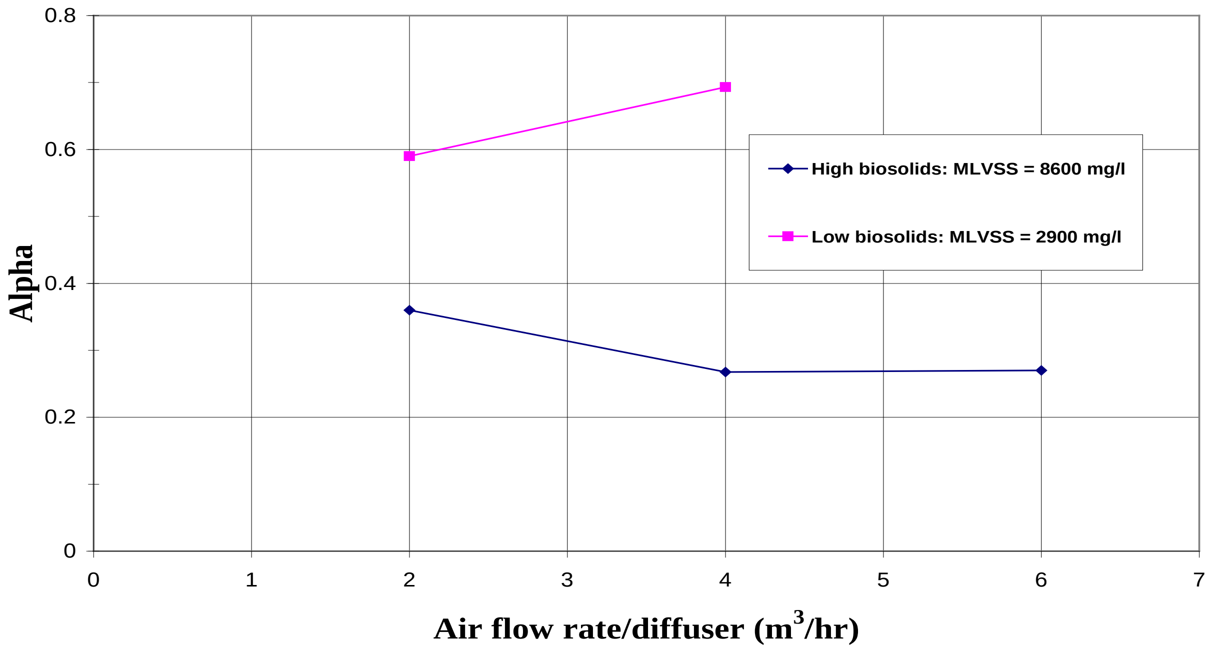

Figure 7: Air Flow Rate Effect on Alpha

DISCUSSION AND CONCLUSIONS

The results of these tests indicate little to no impact by magnetite ballast on the value of alpha in a fine bubble diffuser system over the range of air flow rates and MLSS values investigated, as long as MLVSS was constant. This finding may seem contradictory to observations by Germain, et. al. who recommended that MLSS should be held < 10,000 – 15,000 mg/l so as not to reduce oxygen transfer efficiency so drastically. However, it must be recognized that their studies were conducted with mixed liquor biological solids with a constant volatile fraction so that as MLSS increased, MLVSS also increased. Krampe and Krauth found that it was MLVSS, and corresponding viscosity, that correlated best with alpha in fine bubble aeration across different systems. The impact of increased MLVSS was verified in this study as alpha dropped by 46%, on average, when compared to the trials with or without magnetite, as shown graphically in Figure 6. Although viscosity measurements were not made in this testing, it has generally been noted that bulk fluid properties such as viscosity do not seem to be impacted at the magnetite dosages used in this study.

There were some other observations of note that resulted from this study. There was a noticeable increase in alpha (18%, on average) that occurred with the addition of magnetite at the low operating MLVSS concentration of 2,700 mg/l, as shown in Figures 3 and 4. However, at the high MLVSS concentration of 8,600 mg/l, the impact of magnetite on alpha was neutral. The change in alpha as air flow rate was varied at a given MLVSS could also be evaluated from this work. As air flow was increased from 2 m^3/hr (1.18 scfm) per diffuser to 4 m^3/hr (2.35 scfm) per diffuser in the high MLVSS tests, the alpha value dropped. This is contrary to traditional experience where increases in airflow to a fine bubble aeration system tend to increase the alpha value (despite lowering the oxygen transfer efficiency). The low MLVSS concentration testing demonstrated a more typical result, with alpha increasing as airflow was increased. The impact of air flow rate on alpha for the low MLVSS and high MLVSS tests are shown in Figure 7. These findings suggest that further trials may be necessary to better understand these secondary observations.

Based upon the results of this study, the following conclusions may be drawn:

- The impact of magnetite ballast on alpha in fine bubble aeration is slightly positive-to-neutral, depending upon the MLVSS concentration. There is no negative impact on alpha as magnetite concentration increases.
- The alpha factor dropped appreciably as the MLVSS concentration increased, as has been commonly observed in high biomass activated sludge systems.
- Increasing air flow rate had a variable effect on alpha, depending on the MLVSS concentration. However, the impact of air flow rate at a given MLVSS was small compared to the influence of MLVSS itself.

It is recommended when designing a magnetite-ballasted mixed liquor aeration system with fine bubble diffusers that the increase in suspended solids from the magnetite not be considered, and that the MLVSS be the factor of importance regarding selection of alpha for high suspended solids activated sludge systems. Further study is required to better understand the actual fluid dynamic interactions between magnetite and biological floc in aerated conditions for other types of aeration devices.

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