Energy, cost and design aspects of coarse- and fine-bubble aeration systems in the MBBR IFAS process
S. Sander, J. Behnisch and M. Wagner

ABSTRACT

With the MBBR IFAS (moving bed biofilm reactor integrated fixed-film activated sludge) process, the biomass required for biological wastewater treatment is either suspended or fixed on free-moving plastic carriers in the reactor. Coarse- or fine-bubble aeration systems are used in the MBBR IFAS process. In this study, the oxygen transfer efficiency (OTE) of a coarse-bubble aeration system was improved significantly by the addition of the investigated carriers, even in-process (∼1% per vol-% of added carrier material). In a fine-bubble aeration system, the carriers had little or no effect on OTE. The effect of carriers on OTE strongly depends on the properties of the aeration system, the volumetric filling rate of the carriers, the properties of the carrier media, and the reactor geometry. This study shows that the effect of carriers on OTE is less pronounced in-process compared to clean water conditions. When designing new carriers in order to improve their effect on OTE further, suppliers should take this into account. Although the energy efficiency and cost effectiveness of coarse-bubble aeration systems can be improved significantly by the addition of carriers, fine-bubble aeration systems remain the more efficient and cost-effective alternative for aeration when applying the investigated MBBR IFAS process.

Key words | aeration systems, energy efficiency, integrated fixed-film activated sludge, moving bed biofilm reactor, oxygen transfer

INTRODUCTION

With the IFAS (integrated fixed-film activated sludge) system, the conventional activated sludge (CAS) process is intensified by the presence of biomass attached to carriers (biofilm) in the reactor. Many variations of the IFAS process have been developed during recent decades. The system mostly applied nowadays is the MBBR (moving bed biofilm reactor) IFAS process, where the biofilm is attached to free-moving carriers in the reactor. The movement of the water body either results from aeration systems or from mixers. Screens retain the carriers within the reactor (Ødegaard et al. 2014).

Typical purposes for the application of MBBR IFAS are the enhancement of nitrification as well as N removal (Randall & Sen 1996), and optimisation of biological P removal (Sriwiriyarat & Randall 2005). Therefore, existing overloaded plants are upgraded frequently by the introduction of this system (e.g. Morper & Wildmoser 1990; Andreottola et al. 2003). Further advantages of the process are improved activated sludge settling properties (Kim et al. 2010) and higher operational stability (Sriwiriyarat et al. 2008). In newer applications, MBBR IFAS is introduced into the deammonification process (Christensson et al. 2013; Malovaný et al. 2015). To facilitate advanced treatment of wastewater, MBBR IFAS has also been combined with membrane bio-reactors (De la Torre et al. 2013).

Due to the small bubble diameter and the related low energy consumption, fine-bubble aeration systems (bubble diameter of 2–5 mm) are predominantly used with the CAS process. To keep the carriers suspended, the MMBR IFAS process requires a stronger grade of turbulence compared to the CAS process. Therefore, some suppliers of MBBR IFAS systems recommend the application of coarse-bubble aeration systems (bubble diameter ≤50 mm). The effect of carriers on the oxygen transfer efficiency (OTE) of aeration systems has been investigated in several pilot-scale (Pham et al. 2008; Jing et al. 2009; Wei et al. 2016) and full-scale studies (Viswanathan et al. 2008; Rosso et al. 2011). Generally, it is assumed that the...
OTE of coarse-bubble aeration systems improves in the presence of carriers. This positive effect can be attributed to the splitting of bubbles when passing through the carrier media, resulting in an increased gas–liquid interfacial area. In addition, the increased retention time of the bubbles in the water body caused by the carriers can positively affect OTE. There have been contrary findings made regarding the effect of carriers on OTE with fine-bubble aeration systems: while Pham et al. (2008) found a negative effect of carriers on OTE with a fine-bubble aeration system in a pilot-scale study in clean water, Viswanathan et al. (2008) concluded in a full-scale study that there is little to no effect.

The objectives of this study are: (a) to compare the effect of carriers on the energy efficiency and cost effectiveness of coarse- and fine-bubble aeration systems in the MBBR IFAS process, in clean water as well as in-process; and (b) to derive design recommendations for respective aeration systems. Therefore, oxygen transfer tests and measurements of the differential pressure in the air pipes were performed in two pilot-scale reactors. Finally, a technical-economic analysis of the investigated systems was conducted.

MATERIAL AND METHODS

MBBR IFAS pilot-scale reactors

The energy efficiency of aeration in the MBBR IFAS process was investigated in two pilot-scale test reactors with a volume of 8.5 m³ each (length 1.2 m; width: 1.2 m; water depth: 5.9 m). One reactor was equipped with coarse-bubble diffusers (four PVC tubes, each with 14 holes of 3.5 mm in diameter), the other with fine-bubble diffusers (two disc aerators, Roflex, Aqseptence Group, Germany). For testing, the reactors were filled with plastic carriers SPR-1 (Spring Water-Treatment Ltd, P.R. China) with a specific surface area of 500 m²/m³ and a density of 0.96 g/m³ to 0, 17, 33, and 50 vol.%. Higher volumetric filling rates were not considered, as complete mixing of the carriers within the reactor could not be guaranteed.

Clean water oxygen transfer tests

Oxygen transfer tests in clean water were conducted in batch tests using the desorption method with pure oxygen (Wagner et al. 1998). The test set up is illustrated in Figure 1,
(left). The air flow rate was measured with a thermal flow sensor TA 16 (Hoentzsch, Germany). The concentration of dissolved oxygen (DO) was measured with four electrochemical sensors Oxymax W COS51D (Endress + Hauser, Germany). The signals were recorded on a programmable logic controller (PLC) every 5 s. For the clean water tests, new carrier media were used. Prior to testing, the new carriers were soaked in tap water for several days in order to remove buoyancy forces, which, in unused conditions, prevent the media from mixing. The mass transfer coefficient \( k_{La} \) (1/h) was calculated for each DO sensor by nonlinear regression using the software OCA (Fröse & Olderdissen, Germany). The mean calculated \( k_{La} \)-values were converted prior to testing. Each volumetric components from the MBBR IFAS part of a full-scale aeration tank attached biomass used for the in-process tests were taken were recorded on a PLC every 30 s. The carriers with the particles were removed from the off-gas stream. The signals of complete coverage, only a fraction of 0.75 m of the tank equals that of O\(_2\) absorbed and that N\(_2\) is conservative (Redmon et al. 1985), there is no difference between the in-gas and the off-gas air flow rate. (b) To enable easier installation and removal of sensors to the reactors, instead of complete coverage, only a fraction of 0.75 m × 0.75 m of the reactor was covered by an off-gas hood.

The wastewater containing activated sludge was taken from an aeration tank of WWTP Licunhe in Qingdao (P.R. China). Table 1 details the key operating parameters for the WWTP during testing. Due to high chemical oxygen demand (COD) concentrations in the influent, the WWTP was operated at high concentrations of mixed liquor suspended solids (MLSS). Particularly sludge retention time and floc volume of activated sludge influence \( \text{oSSOTE} \) at in-process oxygen transfer testing. Floc volume of activated sludge correlates roughly with the MLSS (Henkel et al. 2009). Sludge retention time and MLSS of the investigated

<table>
<thead>
<tr>
<th>Plant operating conditions during testing (mean values, coefficients of variation in brackets, ( n = 18 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD influent mg/L</td>
</tr>
<tr>
<td>COD effluent mg/L</td>
</tr>
<tr>
<td>NH(_4)-N influent mg/L</td>
</tr>
<tr>
<td>NH(_2)-N effluent mg/L</td>
</tr>
<tr>
<td>MLSS g/L</td>
</tr>
<tr>
<td>Temperature influent °C</td>
</tr>
<tr>
<td>Sludge retention time d</td>
</tr>
</tbody>
</table>

With the measured parameters, the specific standard oxygen transfer efficiency in-process \( \text{oSSOTE} (\%/m) \) can be calculated according to DWA (2007).

The SGV to the pilot-scale reactors was adjusted manually once a day in order to meet a DO of ~2 mg/L, since this was the set value in the full-scale aeration tank from which the activated sludge was taken. The SGV was maintained on that level for ~24 h and the DO fluctuated around the set value throughout the day. With the coarse-bubble aeration system, the SGV ranged between 10 and 14 m/h, and with the fine-bubble aeration system, it ranged between 7 and 9 m/h. At such SGVs, complete mixing of the carrier media was observed in the clean water oxygen transfer tests at all investigated volumetric filling rates.

Some slight modifications of the test setup have been made compared to Appendix E of ASCE (1997): (a) Due to the more stable conditions in the air supply pipe to the reactors, the in-gas volumetric air flow rate was measured instead of the off-gas volumetric air flow rate. Since it can be assumed that the volume fraction of CO\(_2\) generated in the tank equals that of O\(_2\) absorbed and that N\(_2\) is conservative (Redmon et al. 1985), there is no difference between the in-gas and the off-gas air flow rate. (b) To enable easier installation and removal of sensors to the reactors, instead of complete coverage, only a fraction of 0.75 m × 0.75 m of the reactor was covered by an off-gas hood.

The wastewater containing activated sludge was taken from an aeration tank of WWTP Licunhe in Qingdao (P.R. China). Table 1 details the key operating parameters for the WWTP during testing. Due to high chemical oxygen demand (COD) concentrations in the influent, the WWTP was operated at high concentrations of mixed liquor suspended solids (MLSS). Particularly sludge retention time and floc volume of activated sludge influence \( \text{oSSOTE} \) at in-process oxygen transfer testing. Floc volume of activated sludge correlates roughly with the MLSS (Henkel et al. 2009). Sludge retention time and MLSS of the investigated
activated sludge varied only slightly during testing. This can be seen in the low coefficients of variation for these parameters in the table.

Biodegradation in attached biomass requires DO levels of 3 mg/L to 5 mg/L (Ødegaard et al. 2014). Since such DO levels were undercut frequently during the tests, the effect of attached biomass on oxygen uptake, which can also be measured with off-gas testing, is not discussed in this study.

**In-process energy efficiency**

The energy efficiency of the coarse- and the fine-bubble aeration system was compared using the energy difference factor $\Delta E$ fine/coarse (-). The following applies:

$$\Delta E_{\text{fine/coarse}} = \frac{\alpha_{\text{SSOTE, fine}}}{\alpha_{\text{SSOTE, coarse}}} \div \frac{\Delta p_{\text{fine}}}{\Delta p_{\text{coarse}}}$$

The input parameters for the calculation are the mean $\alpha_{\text{SSOTE}}$- and $\Delta p$-results obtained in the in-process tests described above.

**Technical-economic analysis**

A technical-economic analysis of the two investigated aeration systems with the MBBR IFAS process was conducted via dynamic cost comparison according to DWA (2012). Thereby, cash values of investment, reinvestment and energy costs are compared. According to the common service lifetime of blowers, a time period of 15 years was considered. The analysis is based on an exemplary calculation of an aeration system for a WWTP with a capacity of 100,000 population equivalents (PE). With both types of aeration systems, investment costs for blowers were considered. With the fine-bubble aeration system, additional investment costs for diffusers were taken into account. Reinvestment costs for the full replacement of the diffusers every five years were considered. A conversion factor $f_1$ accounts for the impact of the rate of interest after a certain time on the cash value of the reinvestments:

$$f_1 = \frac{1}{(1+i)^n} \quad (-)$$

$i$ = rate of interest (here, 3% respective 0.03 is assumed); $n$ = period of time.

Energy costs were considered with both types of aeration systems. A conversion factor, $f_2$, accounts for the impact of the rate of interest after a certain time and the annual growth rate of the energy price on the cash value of the energy costs:

$$f_2 = \frac{(1+r)(1+i)^n - (1+r)^n}{(1+i)^n \cdot (1-r)} \quad (-)$$

$r$ = annual growth rate of the energy price (here, 2% respective 0.02 is assumed).

**RESULTS AND DISCUSSION**

**Test results**

The results of the oxygen transfer tests are illustrated in Figure 2, separately for clean water and in-process conditions. It can be seen that with equal volumetric filling rates, OTE of the fine-bubble aeration system is always greater than OTE of the coarse-bubble aeration system. However, the difference becomes smaller with increasing filling rates. In clean water at 50 vol.-%, for instance, SSOTE is almost equal in both types of aeration systems. Except for the fine-bubble aeration system in-process, OTE increases linearly with the addition of carriers.

![Figure 2](https://iwaponline.com/wst/article-pdf/75/4/890/454838/wst075040890.pdf)

**Figure 2** Specific standard oxygen transfer efficiency (mean values with coefficients of variation) of the coarse- and fine-bubble aeration systems with different volumetric filling rates of carriers in clean water (left) and in-process (right).
In clean water, the addition of carriers increases SSOTE with both types of aeration systems in the investigated range of volumetric filling rates from 0 to 50 vol-% (Figure 2, left). The effect is much greater with coarse-bubble aeration, where SSOTE increases from 2.9%/m to 5.6%/m, i.e. with a mean specific rate of approx. 1.9%/vol-% of added carriers. In contrast, with fine-bubble aeration, SSOTE increases only by 0.4%/vol-%.

In-process and with the coarse-bubble aeration system, αSSOTE increases in mean from 2.4 to 3.7%/m in the investigated range of volumetric filling rates from 0 to 50 vol-%; i.e. ~1%/vol-% (Figure 2, right). With the fine-bubble aeration system, there was no clear effect of the carriers on αSSOTE. Here, the differences in the mean values of αSSOTE can be attributed predominantly to the variations of other parameters with impact on αSSOTE, such as sludge retention time and floc volume of activated sludge (cf. Table 1).

The energy efficiency of diffused aeration systems is affected by αSSOTE as well as Δp. In-process, Δp was ranging between 594 and 596 mbar with the coarse-bubble aeration system and between 614 and 621 with the fine-bubble aeration system. This difference of ~20 mbar can be attributed to the additional air resistance of the fine-bubble diffusers’ membrane.

In clean water, the influence of SGV on oxygen transfer at different volumetric filling rates was evaluated (Figure 3). For the fine-bubble aeration system, no effect was observed. For the coarse-bubble aeration system, slightly lower SSOTE values were measured at all filling rates at the low investigated SGV of 4 m/h. This can be attributed to incomplete mixing of the carriers in this setting and was also observed visually on the water surface. This effect can also be seen in the pronounced coefficients of variation in Figure 2 (left) for the coarse-bubble aeration system in clean water.

In a pilot-scale study with clean water, Pham et al. (2008) found a positive effect of carriers on OTE with a coarse-bubble aeration system. This study confirms those findings. In contrast, for a fine-bubble aeration system, Pham et al. (2008) found a negative effect of the carriers on OTE. These observations are not in accordance to those here, since a positive effect of carriers on OTE was measured with the fine-bubble aeration system. This positive effect was only slightly pronounced in clean water and was no longer evident in-process. The latter observation confirms the findings made by Viswanathan et al. (2008), who investigated an MBBR IFAS process equipped with a fine-bubble aeration system at full-scale, and concluded that the effect of the carrier media on OTE was negligible. Rosso et al. (2011) found that the OTE of a CAS process with fine-bubble aeration was similar to that of an MBBR IFAS system with coarse-bubble aeration. Here, the in-process OTE of the coarse-bubble aeration at a volumetric filling rate of 50 vol-% is still lower by more than 1%/m compared to that of fine-bubble aeration without carriers. However, the OTE of a coarse-bubble aeration system in the MBBR IFAS increases significantly with the volumetric filling rate of carriers. It can be hypothesised that the investigations of Rosso et al. (2011) were carried out at higher volumetric filling rates then in this study, and that the different results can be explained by that circumstance. The partially contrary findings in the literature show that the effect of carriers on OTE strongly depends on the properties of the aeration system, the volumetric filling rate of the carriers, the properties of the carrier media, and the reactor geometry.

The effect of carriers on OTE is much less pronounced in-process compared to clean water conditions in this study. This is a typical observation made in oxygen transfer tests: in-process, there are many effects – positive and negative – on OTE at the same time. Single effects are therefore often overlapped or cancelled out by others, and in total, their impact on OTE is weaker than in clean water, or not observable at all.

In-process energy efficiency

The in-process energy efficiency of the coarse- and the fine-bubble aeration systems with the MBBR IFAS process is calculated via the determined mean values of αSSOTE and Δp (Table 2). With a volumetric filling rate of 0 vol-%, the fine-bubble aeration system shows an αSSOTE double that of the
coarse-bubble system. At the same time, $\Delta p_s \sim 3\%$ higher. Altogether, the positive effect on $\alpha_{SSOTE}$ prevails, i.e. the fine-bubble aeration system shows a 93% better energy balance. With increasing volumetric filling rates, the energetic advantage of the fine-bubble aeration system decreases significantly due to the considerable improvement of $\alpha_{SSOTE}$ with the coarse-bubble aeration system. With a carrier volume of 50 vol-%, the fine-bubble aeration system is still superior energetically, but the energy balance is only 31% higher.

Technical-economic analysis

Table 3 summarizes the results of the technical-economic analysis of coarse- and fine-bubble aeration systems with the investigated MBBR IFAS process at a volumetric filling rate of 50 vol-%.

The in-process energy efficiency of the fine-bubble aeration system did not change considerably with the volumetric filling rate of carrier media. Therefore, conventional design recommendations for diffused aeration systems (DWA 2013) were used for the design of the fine-bubble aeration system with the MBBR IFAS in the exemplary calculation:

For a WWTP with a capacity of 100,000 PE, a mean required standard oxygen transfer rate of $\sim 3,700,000$ kg O$_2$/a was estimated. To supply this amount of oxygen with a fine-bubble aeration system, blowers for $\sim 100,000$ € and diffusers for $\sim 50,000$ € were estimated. Reinvestments, considering the conversion factor $f_1$, were assumed for the full replacement of the diffusers every five years. Under the assumption of a standard aeration efficiency of 3 kg O$_2$/kWh and specific energy costs of 0.15 €/kWh, annual energy costs of 185,000 €/a can be calculated for the fine-bubble aeration system. For the calculation of the cash value of the energy costs, the conversion factor $f_2$ has to be taken into account. Considering these components, the exemplary calculation shows a total cash value of $\sim €2,800,000$ for the fine-bubble aeration system.

The investment costs for the blowers and the energy costs of the coarse-bubble aeration system are calculated by dividing the corresponding costs of the fine-bubble aeration system with the energy factor $\Delta E_{fine/coarse}$ at a volumetric filling rate of 50 vol-%, which is 1.31 (cf. Table 2). No investments and reinvestments for diffusers are required with the coarse-bubble aeration system. In total, the exemplary calculation shows a cash value of $\sim €3,500,000$ results for the coarse-bubble aeration system.

This cash value exceeds that of the fine-bubble aeration system by $\sim 25\%$.

Costs for additional agitators were not included in the analysis, since no difference in mixing could be observed between the two investigated types of aeration systems.

CONCLUSIONS AND OUTLOOK

Although the energetic efficiency of the coarse-bubble aeration system can be improved significantly by adding carrier material, the fine-bubble aeration system remains the more
cost-effective technical solution when applying the investigated MBBR IFAS carrier media. However, in this study, only one type of carrier material was observed and costs for additional agitators were not included in the analysis. With other MBBR IFAS applications, the advantage of fine-bubble aeration might not be evident anymore.

When designing new carriers in order to improve the positive effect of carriers on OTE further, suppliers should take into account that this effect is less pronounced in-process compared to clean water conditions. The small improvements observed with clean water conditions may not be observable in-process any longer. It is therefore recommended to investigate the effect of carriers on OTE always in-process.

For the coarse-bubble aeration system, the investigated carriers improve αSSOTE by ~1% per vol.% of added carrier material. This rate of increase should be taken into account when designing respective systems. It might also serve as an orientation value for applications using other types of carrier media than in this study. When applying fine-bubble aeration systems, the effect of the investigated carriers on energy efficiency is negligible, and the same design approaches as with CAS plants may be used.

In this study, only one type of carrier material was investigated. Future studies should include the properties of different carrier media, such as the effect of the specific surface area on oxygen transfer.

ACKNOWLEDGEMENTS

We thank the German Federal Ministry of Education and Research (BMBF) for funding the research project EXPOVAL ‘Technology transfer-oriented research and development in the wastewater sector – validation at industrial-scale plants’ – subgroup 2 ‘Validation and optimization of fine bubble aeration systems depending on the water temperature’ (Research Grant 02WA1252E). We also thank our project partners Aqseptence Group and Qingdao Technological University for their cooperation.

REFERENCES


Randall, C. W. & Sen, D. 1996 Full-scale evaluation of an integrated fixed-film activated sludge (IFAS) process for...