Extensive nitrogen removal in a new type of airlift reactor

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Abstract A new type of CIRCOX® airlift reactor was started-up treating anaerobically pre-treated potato-processing waste water. This type of airlift reactor with biofilms on carrier is an airlift reactor extended with an anoxic compartment to obtain total nitrogen removal. This type of reactor was designed in the early nineties and was tested successfully at pilot-scale on brewery and municipal waste water. The 3 m³ pilot reactor was scaled-up to a size of 130 m³. Both the hydraulics and the biological performance were studied. High liquid velocities and equal concentrations of sludge throughout the whole reactor, indicated that the system was well mixed. Up to 5 kg COD/m³/day was removed. Ammonia was almost completely removed (up to 1.0 kg NH₄–N/ m³/day in the aerated compartment). The denitrification efficiency was over 90%. The NOₓ–N concentration in the effluent never exceeded 6 mg/l. The biofilm layers were extremely dense: 30 g/l of VSS with a sludge volume of 220 ml/l. Therefore the particles had high settling velocities and could easily be retained in the reactor. It can be concluded that this new technology has been scaled-up successfully. With this an aerobic technology is available in which extended treatment and nitrogen removal are accomplished in a very compact system.

Keywords Airlift pump; airlift reactor; CIRCOX® airlift technology; denitrification; nitrification; sludge on carrier

Introduction
The CIRCOX®-airlift technology with sludge on carrier has turned out to be an interesting alternative for an aerobic waste water treatment. High quality effluents are produced in the compact system in which conversion rates of 4–10 kg COD/m³/d are achieved. The surplus sludge productions are minimal (2–10% of the COD converted). Due to the relatively long sludge age nitrification is always accomplished. Moreover conversion rates can be relatively high (1–2 kg NH₄–N/m³/d).

In the meantime eight full scale installations have been installed. The international limits for total nitrogen discharge have become more stringent in the last 10 years. As a result denitrification has become an almost standard process in aerobic waste water treatment. Since nitrification is an almost standard process in the airlift reactor it almost seemed a logical step in the development of this technology to extend the system with an anoxic reactor compartment. (Figure 1).

In this new reactor the sludge on carrier is circulated between the oxic and the anoxic compartment by means of an airliftpump (Dutch patent, 1992). This technology was successfully tested on anaerobically pre-treated brewery waste water (Mulder and Bruijn, 1993) in a pilot reactor.

Figure 1 CIRCOX® reactor with integrated anoxic compartment
The technology was also tested on municipal waste water which varies more in flow, temperature and composition (Frijters et al., 1997; STOWA 1997). A good effluent quality was achieved. The biokinetics of the system were studied and it could be concluded that these resembled those of a Carrousel.

In addition the economical aspects were evaluated. In the pilot research an effective oxygen conversion rate of 2.0 kg O₂/kWh could be determined. This rate is comparable to that of a low loaded activated sludge system. Furthermore it could be calculated that the investment costs for a CIRCOX® reactor were significantly lower compared with those of an activated sludge system treating municipal waste water (100.000 i.e.). This is due to the higher conversion capacities resulting in less reactor volume. For both technological and economical reasons it could be concluded that the CIRCOX® airlift-technology is a interesting alternative for aerobic waste water treatment. On top of this the space requirements for this technology are much lower than for an activated sludge system.

Since 1989 the waste water of the potato-processing factory Agrico in Wezep (The Netherlands) is treated in two compact anaerobic IC(internal circulation)® reactors. To reduce costs for discharge it was decided to install aerobic posttreatment. As the authorities accept only relatively high COD/N ratios in discharged waste water, denitrification was necessary. As the characteristics of the airlift technology, mentioned above, fitted well with the situation at Agrico it was decided to chose this technology.

The challenge was to scale-up the 3 m³-pilot reactor to a size of approximately 130 m³.

In December 1998 the reactor was started-up in Wezep. The reactor was designed to remove 3 kg COD/m³/day and 0.2 to 0.8 kgN/m³/day for the present and 6 kg COD/m³/day and 0.4 to 1.6 kgN/m³/day for the future situation.

In this paper the hydrodynamics and the biological performance of this full scale system are discussed.

**Materials and methods**

*The waste water.* The waste water originates from the potato-processing factory Agrico in Wezep. The waste water was pre-treated in two parallel-operating anaerobic IC®-reactors. During start-up both the flow and the concentrations of COD and N in the influent increased. The pH and the temperature of the waste water were more or less constant (Table 1).

*Carrier material.* Basalt (Basalt N.V., Schiedam, Holland), 0.06–0.33 mm, was used as a carrier for biomass. Approximately 40 g/l of basalt was added.

*Reactor.* The volume of the reactor is 130 m³. The outer compartment is 78 m³ (60% of the volume) and is divided into two cylinders: the riser (in which the air is brought) and the downer. The inner reactor compartment is not aerated and has a volume of 52 m³ (40%).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>flow (m³/d)</th>
<th>pH</th>
<th>T (°C)</th>
<th>T-COD (mg/l)</th>
<th>S-COD (mg/l)</th>
<th>NKj-N (mg/l)</th>
<th>Total solids (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>average</td>
<td>930 (215)</td>
<td>6.6</td>
<td>35</td>
<td>1160</td>
<td>730</td>
<td>130</td>
<td>375</td>
</tr>
<tr>
<td>minimum</td>
<td>410 (0)</td>
<td>6.3</td>
<td>34</td>
<td>600</td>
<td>400</td>
<td>85</td>
<td>70</td>
</tr>
<tr>
<td>maximum</td>
<td>1250 (250)</td>
<td>6.8</td>
<td>35</td>
<td>1500</td>
<td>1000</td>
<td>165</td>
<td>625</td>
</tr>
</tbody>
</table>
The water/sludge mixture is recirculated over the inner (anoxic) and outer (oxic) compartment by means of an airlift pump (see introduction). The waste water is pumped into the anoxic compartment and is mixed with the recirculated water/sludge mixture.

**Process conditions.** The waste water flow varied from 30 to 45 m³/hour (HRT of 2.9–4.3 hours). During 12 weeks (day 69–156 after start-up) a small flow (1–3 m³/hour) of raw waste water was bypassed to the airlift reactor to provide extra COD (40% of the total load) to the airlift reactor during the start-up. In this period both the waste water flow and the COD concentrations in the water to the airlift reactor were very low due to the fact that the production at the factory was limited because of a poor harvest of potatoes in 1998. To prevent oxygen limitations in the biofilm, the setpoint for the concentration of oxygen was initially set at 4 mg/l and was automatically controlled by the airflow. Two compressors were installed which produced a total of 1000 m³/hour. The minimum flow was set at 215 m³/h. These flows corresponded with 1.1–5.5 cm/s of upflow air velocities in the oxic compartment. The recirculation flow was kept at 240–260 m³/hour.

**Measurements and analyses.** The waterflow to the reactor and in the recirculation pipe were measured on-line. The airflow in the oxic compartment and to the recirculation pipe were measured on-line. The concentrations of oxygen in the oxic compartment and in the anoxic compartment (the latter was measured 1.5 meters from the top of the anoxic compartment) were also measured on-line. The fluid velocities, at different airflows, were measured with an electromagnetic velocity meter, P-EMS with an E-40 probe (Delft Hydraulics, Delft, the Netherlands). The pH of the influent and the effluent of the reactor were measured daily.

The influent and effluent were sampled, proportional to the flow, daily for 24 hours. In these samples the total COD (T-COD), the COD of a centrifuged sample, considered as soluble COD (S-COD) and the total Nkj (T-Nkj) in the influent and the effluent were measured. Twice a week the concentrations of total ammonia (NH₄-N), the nitrite (NO₂-N) and the nitrate (NO₃-N) were measured in the 24 hours samples. Once a week the total suspended solids (TSS) and the volatile suspended solids (VSS) were measured.

The concentrations of COD, NH₄-N, NO₂-N, NO₃-N, were determined using the Dr. Lange method (Dr. Lange Benelux, Tiel, the Netherlands). The T-Nkj, TSS and VSS concentrations were determined using the Dutch NEN-standards.

**Results and discussion**

**Hydrodynamics**

In a previous paper (Frijters et al., 1997) the hydraulics of the system were discussed. Since this is the first full scale airlift reactor with an integrated anoxic compartment the hydraulics of the system were checked and compared with the previous results.

First the fluid velocities in the oxic compartment were measured at different airflows. These fluid velocities were more or less proportional to the superficial air velocities in the range of 1–4.5 cm/s, the latter were calculated on the basis of the total oxic surface area. The circulation times of the liquid over the riser and downer were very short, 30–90 seconds, comparable to the circulation time found in an airlift reactor without anoxic compartment (Heijnen et al., 1993). Therefore the oxic compartment can be considered as completely mixed. Since the circulation times over the anoxic compartment are very short and are only a fraction of the total residence time, the complete system could be considered well mixed.

Furthermore the sludge concentrations throughout the system were measured. In accordance with the results of the pilot plant, the concentrations of sludge in the anoxic compartment were equal throughout the whole height and were equal to the concentrations in the
aerated compartment. Dilution of sludge in the anoxic compartment caused by the high settling velocities of the sludge on carrier did not take place. This could be explained by turbulent conditions in the anoxic compartment.

From these results it could be concluded that the hydraulics of the system were similar to that of the pilot plant.

Performance

Biofilm development. The biofilms developed only slowly during the first 70 days because of very low loading rates. From literature is known that the detachment rates of the biofilms in the presence of bare basalt are high (Gjaltema, 1996). To speed up the initial biofilm formation the COD load was increased by opening a small bypass of raw waste water. As the detachment rates of developing biofilms decreased significantly when more and more particles were covered with biofilms, and thus the concentration of bare particles decreased, a significant increase of biomass on carrier could be measured. This was also observed in laboratory experiments (Tijhuis et al., 1994).

Remarkably, when the waste water contained sufficient COD and therefore the bypass of raw waste water was closed, the volume of the biofilm particles in the reactor increased: the size of the particles did not change but the amount of particles increased. By closing the bypass the contribution of easy degradable substrate decreased and the biofilm layer became denser. This is in accordance with results of modelling of biofilm structures described by Picioreanu et al. (1999). They predicted that the structure of the biofilm becomes more compact and homogeneous at low specific substrate consumption rates. These rates will be lower treating more difficult to biodegrade waste water. The basalt particles were covered faster with a biofilm layer because the detachment rate for the dense biofilm was much lower. The amounts of biofilm particles increased in time to 220 ml/l (Figure 2), 30 g/l of VSS. The concentration of sludge on carrier is still increasing. The biofilm particles were small (0.6 mm–1 mm) and had a smooth surface (Figure 3). The biofilm was very compact: at a thickness of the biofilm layer of 100–300 μm, a biomass concentration of 500 mg of VSS/g of carrier was measured. Therefore the sludge settled very well and could easily be retained in the reactor. No sludge on carrier was found in the effluent.

Start-up. As found in other studies (Heijnen et al. 1993, Gorur et al., 1995, Frijters et al., 1997), COD was almost immediately removed after start-up. After two weeks up to 1.0 kg
COD/m^3/day was removed. Since the biodegradable COD load was very low, approximately 1.5–2.5 kg COD/m^3/d, the COD conversion rate did not increase further. To speed up the development of the biofilms the COD load was increased by opening a small bypass of raw waste water (70 days after start-up). The COD conversion rate increased.

The total COD was removed with an efficiency of approximately 30%. The removal rate of soluble COD amounted to 3.1 kg S-COD/m^3/day (50%). The results show that approximately 10–15% of the total converted COD turned into solids. The influent was far more turbid than the effluent. The effluent contained flocs, indicating that flocculation of colloids was enhanced by treatment in the airlift reactor. The solids were easily removed in a post-treatment (dissolved air flotation unit). The effluent produced in the waste water treatment contained a COD concentration less than 60 mg/l.

As a result of very low loading rates the formation of biofilms started only after 70 days, when the small bypass was opened. In the beginning ammonia was mainly used for growth of biomass. After a few weeks ammonia removal significantly increased (Figure 4) indicating that the nitrifying bacteria really developed in the biofilm. It was observed that closing the bypass to the airlift reactor (day 156) resulted in an increase of the nitrification rate. It is known from literature (van Loosdrecht et al., 1995) that if both COD and ammonia are

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**Figure 3** Biofilm particles in the full scale airlift reactor with integrated anoxic compartment

**Figure 4** Removal of NH_4^-N in the system. The removal efficiency was nearly complete after 160 days.
present in a biofilm reactor the slowly growing bacteria (nitrifiers) are present in deeper layers of the biofilm compared with the fast-growing bacteria (heterotrophic bacteria). By closing the bypass, the specific growth rate of the heterotrophic bacteria decreased and the biofilm turnover rates decreased. Therefore the nitrifying bacteria could develop better in the upper-layers.

Similar to the results found on pilot-scale with municipal waste water, nitrification was complete within 90 days after development of biofilm layers started.

After closing the bypass, on average 90% of the ammonia was nitrified (Table 2). The concentration of dissolved oxygen was set at 4.0 mg/l. During operation of the system it was observed that at a concentration lower than 2.0 mg/l O₂ the nitrification rate decreased. Since the amount of biomass on carrier is still growing the setpoint of oxygen was kept at 4.0 mg/l to be sure that oxygen is not limiting for the growth of nitrifying bacteria. It is expected that the setpoint can be decreased as soon as the growth of nitrifying biomass on carrier has stabilised.

Kjeldahl and ammonia analyses showed that organically bound nitrogen was not nitrified (Table 2). Differences in removal of NKj and NH₄ could be explained by the production of suspended biomass. During start-up small amounts of nitrate were measured in the effluent. Accumulation of nitrite caused by limited oxygen in the biofilm (Garrido et al., 1997) seemed very unlikely since the dissolved oxygen concentration in the bulk was higher than 4 mg/l. In laboratory studies (Tijhuis et al., 1995; van Benthum et al., 1998) and pilot studies (Frijters et al., 1997) with nitrifying systems, nitrite was found during start-up. As expected the concentration of nitrite in the effluent dropped below 0.4 mg/l N in time.

**Denitrification.** Results showed that the efficiency of the denitrification was optimal (table 3) and amounted to 94 %. In the anoxic compartment the dissolved oxygen concentration was always lower than 0.2 mg/l. The NO₃–N measured in the effluent never exceeded 6 mg/l. The average concentration of NO₃–N measured (4 mg/l) in the effluent was even lower than would be expected on basis of the recirculation ratio (220 m³/h: 260 m³/h=0.85; (1–0.85)*(74–8)=0 mg/l/). A part of the N was assimilated into biomass.

**Evaluation of the system**
In fixed filter systems with biofilms high conversion capacities are also achieved. However, for nitrogen this only applies to tertiary treatment (Lazarova and Manem, 1994). On top of

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average in kg/m³/day (%)</th>
<th>Range in kg/m³/day (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T–COD load</td>
<td>9.4</td>
<td>6.5–13.3</td>
</tr>
<tr>
<td>T–COD removed</td>
<td>2.7 (29)</td>
<td>1.3–5.2 (17–47)</td>
</tr>
<tr>
<td>S–COD load</td>
<td>6.4</td>
<td>3.8–10.9</td>
</tr>
<tr>
<td>S–COD removed</td>
<td>3.1 (49)</td>
<td>1.7–5.2 (39–70)</td>
</tr>
<tr>
<td>NKj–N load*</td>
<td>1.7</td>
<td>1.5–1.8</td>
</tr>
<tr>
<td>NKj–N removed*</td>
<td>0.7 (42)</td>
<td>0.6–0.8 (38–47)</td>
</tr>
<tr>
<td>NH₄–N load*</td>
<td>0.9</td>
<td>0.7–1.1</td>
</tr>
<tr>
<td>NH₄–N removed*</td>
<td>0.8 (90)</td>
<td>0.7–1.0 (79–98)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average (range) concentrations in mg/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>NKj–N</td>
<td>137 (118–163)</td>
</tr>
<tr>
<td>NH₄–N</td>
<td>74 (56–96)</td>
</tr>
<tr>
<td>NO₃–N</td>
<td>0</td>
</tr>
<tr>
<td>NO₂–N</td>
<td>0</td>
</tr>
<tr>
<td>VSS</td>
<td>264 (205–356)</td>
</tr>
</tbody>
</table>
An additional process unit would be required for denitrification. For concomitant carbonaceous and nitrogenous conversions, the capacities in biofilters are much lower (Boller et al., 1994). In biofilters solids are removed in the same process unit. This, itself an advantage, makes the design and operation of such systems however more complicated.

An important feature of the CIRCOX® system described here is that operational attention for the biomass is not required. Sludge age (in case of AS systems) and back washing (for biological filters) do not need to be controlled in the CIRCOX® technology. In this system an equilibrium is established between biomass concentration and loading rate applied.

With the development of the CIRCOX® airlift reactor with integrated denitrification a compact system is available allowing high removal rates for both organic carbon and nitrogen. Biological sludge production at the same time is relatively low. High effluent qualities can be attained, allowing discharge on surface waters. An additional process unit is required for solids removal. In the waste water treatment system discussed here, a flotation unit with polymer dosing was applied for that purpose. COD concentrations lower than 60 mg/l and total nitrogen concentrations lower than 10 mg/l were obtained in the final effluent.

Conclusions

The reactor was scaled-up successfully. The hydrodynamics corresponded with those of the pilot plant. The average COD removal rate amounted to 3 kg/m³/day and more than 1 kg/m³/day of ammonia was nitrified. The efficiency of denitrification was over 90%.

A concentration of 30 g/l of biofilm-VSS was measured. The particles were very smooth and extremely dense resulting in good biomass retention in the airlift reactor.

It can be concluded that this new technology has been scaled-up successfully. With this an aerobic technology is available in which extended treatment and nitrogen removal are accomplished in a very compact system.

Acknowledgements

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References


