Surface aeration and a small footprint can be combined

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Abstract In densely populated areas new WWTPs will need to be designed on a relatively small area. This paper describes a deep Carrousel® (oxidation ditch) concept resulting in a “small footprint” for the aeration basin combined with an efficient and flexible oxygen input. To enable surface aeration in a deep Carrousel system, the basin was provided with so-called draft tubes, vertical cylinders located underneath aerators, almost extending down to the bottom. A draft tube enables the aerator to draw sludge/water mixture from the bottom of the tank, thereby ensuring proper oxygenation of the tank contents over the entire tank depth. The results of pilot-scale tests for verification of the performance of an aerator equipped with a draft tube are presented.

The full scale WWTP Leidsche Rijn, a compact “wrapped-around” Carrousel-3000 system where the draft tube technology is applied in a 7.5 metre deep basin, is described. Before the plant was put into operation a verification test for the aeration efficiency with clean water was carried out. The test showed that the draft tubes have no negative impact on the aeration efficiency of the surface aerators and justified the chosen design concept.

Keywords Activated sludge; aeration; Carrousel; draft tube; surface aerator

Introduction

Especially in densely populated areas the available space gets limited for building a new wastewater treatment plant (WWTP) or extending an existing plant. In these situations one has to account for a WWTP design with a relatively “small footprint”.

Several “small footprint technologies” have already been developed and some of them are already in operation. Examples are lamella separators for enhanced pre-sedimentation, membranes for sludge-water separation and biological (aerated) filters for COD and nitrogen removal.

In spite of these developments, the activated sludge process can still be seen as the most applied technology for treatment of municipal wastewater. The activated sludge process is robust, hydraulically flexible and capable of removing nutrients in a reliable, efficient and economical way.

In the “heart” of the activated sludge process: the activated sludge basin, numerous developments have been made. Selectors, anaerobic and anoxic tanks were introduced to meet the new stringent effluent requirements regarding levels of phosphorus and nitrogen. Besides these improvements an adequate and efficient aeration is still of major importance for design and operation of the activated sludge process. Aeration in deep tanks by means of fine bubble aeration, reducing the footprint of the activated sludge basins, has already been applied in full-scale plants.

Next to fine bubble aeration, surface aeration is a proven aeration technique. The oxidation ditch-type Carrousel®, where surface aeration is provided by low-speed aerators with vertical axis, is a well known and widely spread activated sludge technology (Janssen, 1996a,b), applied in more than 900 WWTPs world wide. Low-speed vertical shaft aerators have proved to be robust and cost-effective aeration means. This surface aerator combines...
three functions necessary in a Carrousel system: oxygenation, mixing and propulsion.

However, until recently, combination of surface aeration and deep ditches was not available. The maximum ditch depth was limited to approximately 5 metres, a measure determined by the maximum diameter of the aerator and the required oxygenation capacity (OC).

**New aeration concept for oxidation ditches**

The solution to enable surface aerators to be used in a deep ditch-type tank was provided by using so-called *draft tubes*. A draft tube is a vertical cylinder located underneath an aerator, which extends almost down to the bottom. It enables the aerator to draw (oxygen deficient) water from the bottom of the tank, thereby ensuring proper mixing over the entire tank depth (see Figure 1).

This principle has been proven to work well in practice for square and rectangular aeration tanks. However, the necessary propulsion effect of an aerator in a ditch is greatly reduced by the draft tube. The drawback is overcome by installing additional propulsion means, propellers, in the channels of the ditch.

In the following chapters are presented: the initial research regarding draft tubes applied in a deep Carrousel system by means of experimental pilot-scale tests, a description of the Leidsche Rijn WWTP at which the surface aerators with draft tubes are already installed, and the results of a verification test for the aeration efficiency with clean water in this full-scale plant.

**Pilot plant verification tests**

**Introduction**

Pilot-scale tests were carried out in Japan to verify the performance of vertical shaft surface aerators equipped with draft tubes in deep Carrousels, to confirm design assumptions and to determine the precise dimensions of the draft tube in relation to the aerators. A lot of interest has been expressed in the deep Carrousel variant in Japan because of the country’s acute shortage of space. The tests (at scale 1:3) were carried out for a Carrousel basin, both with and without a draft tube.

**Research questions**

The application of the draft tube in a deep Carrousel has a number of uncertainties which

![Figure 1](image-url) Vertical shaft surface aerator and associated draft tube at the Leidsche Rijn WWTP

![Figure 2](image-url) Summary of research questions for the pilot-scale tests
cannot be taken away by theoretical research. Following the recommendations of a desk study, the following questions had to be answered by means of pilot-scale tests:

1. What is the effect of a draft tube on the **oxygenation efficiency** of the aerator?
2. What is the effect of a draft tube on the **power draw** of the aerator?
3. What is the effect of the **mid-wall** on the power draw of the aerator and the flow through the draft tube?
4. Does an **irregular inflow pattern** (like in a Carrousel tank) influence the power draw of the aerator and the flow through the draft tube?

The research questions are schematically depicted in Figure 2.

**Description of the test procedure**

The tests were run at a newly built testing facility of Taiyo Toyo Sanso Co. Ltd. in Sakai, Japan. The testing facility consists of a square tank of $6.5 \times 6.5 \text{ m}^2$ with a maximum depth of 2.3 m. By using steel baffles the size and the shape of the tank was adjusted to a Carrousel basin.

Figures 3 and 4 provide schematic drawings of the test tank in top and cross-section views showing the general arrangement of the surface aerator, the draft tube and the location of DO probes (type: COS CD480S). No bottom baffles were installed.

The surface aerator consisted of a motor (Little King, Meidensha El. Co; power: 7.5 kW; frequency: 50–60 Hz), a gearbox (Philadelphia Mixer; efficiency: 0.94) and an impeller (Oxyrator® 1000; diameter 1.00 m; speed range: 58–90 rpm). A mixer (Flygt SR464.410 with jet ring, diameter 847 mm; speed range: 0–850 rpm) was installed to create flow velocity. To measure the flow in the draft tube a flow meter was installed (Marsh-McBirney Inc.; flow-mate model 2000).

The water used in all tests was taken from the Osaka municipal water supply (pH: 7.1; conductivity: 0.15 mS/cm; hardness 45 mg CaCO$_3$/l; TSS: 1 mg/l). The chemicals used for de-oxygenation of the test water were cobalt(II)chloride hexa-hydrate and hydrous sodium sulphite. The meteorology at the test site was as follows: air temperature: 22°C (first tests) – 31°C (last tests), barometric pressure 101.3 kPa (approx.) and site elevation (10 m + MSL).

The measurements of the OC were based on the ASCE-standard procedures (1993).

**Test results**

Numerous tests have been carried out. A summary of the test results is presented, referring to the research questions as formulated before. Also the translation to full-scale application is made.

**Oxygenation capacity**. The measured oxygenation efficiencies are depicted in Table 1. As can be seen, no notable increase or decrease in efficiency is measured when applying a draft
From these results it was concluded that the application of a draft tube does not have a significant effect on the oxygenation efficiency of the surface aerator. The measured efficiencies were lower than the normally expected values of 2.0–2.2 kg O$_2$/kWh. Besides “small scale side wall“ effects, a good explanation for this lower value was difficult to find.

Although the effect proves not to be significant it is clear that the draft tube is a resistance in the flow towards the aerator. Additional flow boosters are required because the aerators loose their propulsion capacity.

Power draw. The flow pattern near an aerator and the submergence of the impeller will both influence the power draw. With a draft tube the water will flow evenly in the vertical direction towards the aerator. Furthermore the water level near the aerator will drop because of the acceleration of the water. Both effects might result in a reduced power draw of the aerator.

Tests have been carried out with and without draft tube. Both bottom clearance and top clearance of the draft tube have been varied during the tests. The motor power has been measured. The results are depicted in Figure 5.

The tests showed that the power draw of the aerator with a draft tube was in general higher than the power draw of the aerator without draft tube. When the flow through the draft tube was restricted because of a small bottom clearance of 0.25 m, the power draw of the aerator was reduced. When compared with an aerator without draft tube the power draw is more steady and smooth.

Mid-wall effect. It is expected that the mid-wall of the Carrousel influences the inflow pattern of the draft tube. Inflow cannot take place equally from all sides. This could have a reducing effect on the power draw and flow through the draft tube.

The test results showed that the flow velocity through the draft tube with or without mid-wall was equal. Due to the fact the test tank was equipped with partly transparent sidewalls, it was possible to see the movement of air bubbles below water level. It could clearly be seen that as soon as the air bubbles hit the side- or mid-wall, a strong downward flow took the bubbles to a depth of about 1.0–1.5 m, dependent on the speed of the aerator.

### Table 1  Measured oxygenation efficiencies, pilot tests

<table>
<thead>
<tr>
<th>Aerator speed rpm</th>
<th>Efficiency kg O$_2$/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Draft tube</td>
</tr>
<tr>
<td>60</td>
<td>1.6</td>
</tr>
<tr>
<td>75</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Figure 5  Pilot-scale test results. Influence of draft tube and clearance on power draw
phenomenon should have a positive effect on the oxygen transfer, because the contact time of air and water is increased. It was concluded that a mid-wall does not negatively influence the flow through the draft tube.

Effect of irregular flow pattern. With a second submersible mixer an irregular flow pattern was created near the draft tube.

The test results showed that a large horizontal flow was created in the tank, which reflected against the walls and returned via the top and the bottom. This showed a visible surface flow towards the aerator, which was larger than the flow thrown away by the aerator. As a result the flow through the draft tube was reduced to zero.

It was concluded that the distance between aerator and the top of the draft tube (top clearance) should be kept minimal to reduce aeration of water from the top of the basin instead of (more oxygen deficient) water coming from deeper layers.

Draft tube design derived from the pilot tests. Derived from the test results the following design approach was suggested.

Any restrictions in the flow towards the aerator should be avoided as much as possible. The draft tube diameter should be as large as the aerator impeller diameter. The bottom clearance should be large enough to assure that water can be drawn from the bottom of the basin. The distance between aerator and draft tube should be small to prevent drawing of water from the upper layers of the basin. There should be however be sufficient space in order to prevent the creation of additional hydraulic resistance.

In full-scale operation the creation of a so-called “vortex” inside the draft tube will be likely. This is not desirable because it may lower the water level near the aerator, resulting in a drop in power draw. To prevent development of a vortex inside the draft tube, the latter should be equipped with vertical anti-vortex baffles. These baffles also may add to the strength of the tube, enabling construction of tubes with a moderate wall thickness.

WWTP Leidsche Rijn

Design and implementation of the draft tube technology

In the new residential and industrial area Leidsche Rijn, located west of the Dutch city of Utrecht, a new WWTP has been built. Final effluent discharged from the treatment plant has to comply with stringent discharge requirements for phosphate (< 1 mg P\text{total}/l) and nitrogen (< 10 mg N\text{total}/l), even at low temperatures (7°C). The biological and hydraulic capacities of the first phase of realisation are 70,000 population equivalents (p.e.) and 1,600 m³/h respectively.

Water pre-treatment comprises screening and degritting. Following are two low-loaded deep Carrousel tanks (so-called Carrousel-3000 systems), each tank being 49 m in diameter. From the centre, the following consecutive ring-shaped process components are integrated in the system design: an inlet well and splitterbox for return activated sludge; a selector tank and an anaerobic tank, each consisting of four compartments. In the outer ring both the main Carrousel tank with three aerators (type Oxyrator) and the smaller pre-denitrification tank are located. As the main Carrousel tank only has two “heads”, the third aerator and accompanying draft tube was incorporated in the mid-wall of the tank. The nett water depth in the main Carrousel tank amounts to 7.5 metres. Both a general layout of the Carrousel-3000 system and an overview during plant construction are presented in Figures 6 and 7.

A final sedimentation stage follows the Carrousel 3000 systems. The waste activated sludge is thickened mechanically and thereupon transported to the central WWTP Utrecht, for digestion and dewatering. The requirements call for a “zero nuisance” plant, not at least
because residential houses will be built right next to the WWTP. Therefore all process units, except the final sedimentation tanks, are covered and ventilated. The ventilation air is biologically treated in biofilters. Besides the fact that the Leidsche Rijn Carrousel-3000 tanks are much deeper than conventional aeration tanks, a “wrap-around” design was chosen to further save on civil costs and area requirement.

The main relevant characteristics of the WWTP Leidsche Rijn and the Carrousel-3000 tanks are listed in Table 2. Before the plant was put into operation, full-scale Oxygen Capacity (OC) measurements and additional flow velocity measurements were carried out.

**Test procedure full-scale verification tests**

Before carrying out the full-scale tests, the selector, anaerobic tank and pre-denitrification tank were closed from the main aeration tank. The aeration tank was filled with chlorinated surface water.

The OC-measurements were carried out in accordance with the Dutch guidelines for the re-aeration method (STORA, 1980). Sodium sulphite and cobalt chloride were added to remove all dissolved oxygen in the water. At different locations in the aeration tank the oxygen concentration was measured at the cross-section. The probes (type WTW Oxi 196) where installed at depths of 2, 3, 4 and 6 metres.

Prior to the measurements in the aeration tank the oxygen saturation value of the

**Table 2** Main characteristics of the Leidsche Rijn WWTP

<table>
<thead>
<tr>
<th>Process part</th>
<th>Number</th>
<th>Volume/diameter/capacity each</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selector tank</td>
<td>2</td>
<td>400</td>
<td>m³</td>
</tr>
<tr>
<td>Anaerobic tank</td>
<td>2</td>
<td>1,100</td>
<td>m³</td>
</tr>
<tr>
<td>Pre-denitrification tank</td>
<td>2</td>
<td>2,700</td>
<td>m³</td>
</tr>
<tr>
<td>Aeration tank</td>
<td>2</td>
<td>8,100</td>
<td>m³</td>
</tr>
<tr>
<td>Water depth</td>
<td>–</td>
<td>7.5</td>
<td>m</td>
</tr>
<tr>
<td>Flowboosters</td>
<td>4</td>
<td>4.2</td>
<td>kW</td>
</tr>
<tr>
<td>Aerator</td>
<td>6</td>
<td>90</td>
<td>kW</td>
</tr>
<tr>
<td>Diameter</td>
<td>–</td>
<td>3.25</td>
<td>m</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>–</td>
<td>15–40</td>
<td>min⁻¹</td>
</tr>
<tr>
<td>Design OC (total)</td>
<td>–</td>
<td>920</td>
<td>kg O₂/h</td>
</tr>
<tr>
<td>Final sedimentation tank</td>
<td>2</td>
<td>46</td>
<td>m</td>
</tr>
<tr>
<td>Excess sludge thickener</td>
<td>2</td>
<td>30–60</td>
<td>m³/h</td>
</tr>
</tbody>
</table>
aeration tank contents was measured with the different oxygen probes in a separate vessel that had been extensively oxygenated. Also, after each measurement by means of probes of the oxygen level in a sample that was saturated with oxygen, the oxygen level was simultaneously determined by means of the Winkler method (NEN, 1982). For each measurement the different $C_s$ values as measured by the probes were adjusted for the decrease of the saturation value as determined by means of the Winkler method.

It was verified that the $C_s$-values, taking into account the alpha-factor, which was determined to be 1.0, corresponded with the theoretical saturation values of oxygen at the current temperature and pressure. The OC measurements were carried out for two operating conditions, viz. three aerators at half speed (normally 20 rpm) and three aerators at high speed (normally 40 rpm).

**Test results**

*OC-measurements*. The mixing of the aeration tank contents proved to be good. From the oxygen level measurements it can be derived that the oxygen levels start to increase simultaneously and equally at the different oxygen probe locations over the tank depth. This equal distribution will be partly facilitated by the operating submersed mixers or flowboosters.

The results of the OC-measurements are summarized in Table 3. The tender documents specified that the OC for each aerator needed to be 160 kg O$_2$/h with an absorbed power at the shaft of the aerator of 80 kW. The specific efficiency therefore needed to be 2.0 kg O$_2$/kWh for the aerators. During the measurements the absorbed power at shaft aerator was approximately 75 kW as a maximum with an aerator speed of 40 rpm.

Based on the measurements, the conclusion can be drawn that at 40 rpm the aerators have a capacity of 75 kW. By adjustment of the impeller speed to 42 rpm the power draw will increase to 80 kW resulting in an OC per aerator of 160 kg O$_2$/h at the specific efficiency of 2.0 kg O$_2$/kWh.

**Additional flow velocity measurements**

By using an Ott mill the flow velocity in the outer channel was measured at the complete cross-section during various operating conditions. These conditions may vary from only flow boosters in operation to both flow boosters and surface aerators (at high speed) in operation.

As expected, the flow velocity in the outer loop proved higher than in the inner loop. With only flow boosters in operation the average flow velocity measured 0.31 m/s. When the aerators were also put in operation at high speed the flow velocity increased to 0.47 m/s. By adjusting the number of flow boosters in operation to the capacity of the surface aerators it is thus possible to maintain a necessary minimum flow velocity of approximately 0.3 m/s at all load conditions.

**Table 3** Results OC-measurements Leidsche Rijn WWTP

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Speed (rpm)</th>
<th>OC (kg O$_2$/h)</th>
<th>Efficiency (kg O$_2$/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>20</td>
<td>140</td>
<td>2.01</td>
</tr>
<tr>
<td>1B</td>
<td>20</td>
<td>138</td>
<td>2.02</td>
</tr>
<tr>
<td><strong>Average 1</strong></td>
<td><strong>20</strong></td>
<td><strong>139</strong></td>
<td><strong>2.02</strong></td>
</tr>
<tr>
<td>2A</td>
<td>40</td>
<td>458</td>
<td>2.03</td>
</tr>
<tr>
<td>2B</td>
<td>40</td>
<td>424</td>
<td>1.88</td>
</tr>
<tr>
<td><strong>Average 2</strong></td>
<td><strong>40</strong></td>
<td><strong>441</strong></td>
<td><strong>1.96</strong></td>
</tr>
</tbody>
</table>
Conclusions
From the pilot tests in Japan it was concluded that draft tubes can be applied in deep Carrousel basins. Additional flow boosters are required for maintaining sufficient propulsion capacity. The mid-wall, characteristic for ditch systems is likely to have a positive effect on the oxygenation capacity in combination with a draft tube.

The pilot tests as well as the full-scale test showed no significant influence in the oxygenation efficiency when draft tubes are applied. The prescribed efficiency of 2.0 kg O₂/kWh can be achieved.

The power draw of an aerator equipped with a draft tube is more steady and smooth compared with an aerator without a draft tube. This will have a positive effect on the lifetime of the mechanical equipment (gearbox and motor).

References
NEN (1982). Water-Iodometric determination of the oxygen content according to Winkler Dutch Standards for the determination of water (NEN approved October 1982).