Measuring oxygen transfer efficiency (OTE) at the Eindhoven WWTP using real-time off-gas analysis in circular aeration tank

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Abstract

Aeration efficiency in the activated sludge basin of the Eindhoven wastewater treatment plant was monitored during two off-gas measurement campaigns using the ASCE method for oxygen transfer testing. Different locations were sampled and revealed differences in αSOTE values both in tangential as in radial direction. The highest values were found at the end of the aeration zone (ca. 38%), the lowest at the start (ca. 30%) and intermediate values in between. Differences in the radial direction were negligible at the start of the aeration zone, but became more significant towards the end. This hints that homogeneity in terms of OTE can be assumed at the start of the aeration zone, but does not longer hold at the end of the aeration zone.

Keywords
Activated sludge model; Aeration; Off-gas test; Oxygen transfer efficiency

INTRODUCTION

As one of the most economically important contributors to operational costs of daily operation of a wastewater treatment plant (WWTP), to aeration has been given ample attention with regard to its contribution to process energy footprint (Reardon, 1995). Several methods for aeration efficiency measurements (steady-state, non steady state, with and without the addiction of chemicals) have been presented in literature and reviewed in US EPA (1989) and STOWA (2009). The steady-state testing is described in detail by the ASCE standard protocol for off-gas testing (ASCE, 1997). This test gives the possibility to a modeller to compare plant aeration efficiency (expressed as oxygen transfer efficiency OTE and its standardised form SOTE) with the existing process models and evaluate discrepancies or lack in model structure. The currently available models are typically based on the product of the gradient between local dissolved oxygen (DO) and the DO concentration at saturation (i.e. DO*), with the oxygen transfer coefficient k_la (i.e. mass transfer coefficient k_l multiplied by the gas-liquid interfacial area a). This approach accounts for the influence of process conditions by correcting DO* and k_la as function of temperature. Correction for other influences like barometric pressure and salinity is not routinely done. Compared to the more elaborated bioprocess models, the current aeration models are very simple, and do not fully take into account the complexity of the oxygen transfer mechanism. This process depends on different conditions, both configurational and operational (Gillot and Heduit, 2008). The former includes diffuser submergence (Capela et al., 2002), surface area, diffuser layout and placement (Gillot et al. 2005) while the latter includes physical factors like salinity, atmospheric pressure, elevation, reduction of efficiency due to dissolved contaminants in the process water (surfactants, inorganics) (Capela et al., 2002; Rosso and Stenstrom, 2006), membrane fouling (Frey and Thonhauser, 2004; Wagner and Loock, 2007; Gillot and Heduit, 2008), and sludge retention time (Rosso et al, 2005). The goal of this research is twofold: (1) apply the measurement technique and (2) investigate the dynamic nature of oxygen transfer with regard to the location in the aerated zone, including the impact of influent load and aeration control. The novel aspect is the application in a deep orbital ditch process with high internal recirculation and horizontal liquid velocity. This information is to be used to decide whether a constant or dynamic OTE is to be used in the Eindhoven WWTP model.

MATERIALS AND METHODS

Off-gas testing

Aeration efficiency was monitored in the aerated zone of the Eindhoven WWTP by means of the off-gas test (Redmon et al., 1983), using the process water testing protocol (ASCE, 1997). The off-gas equipment was composed of a reinforced polyethylene hood floating on the wastewater surface (1.5 m x 1.5 m x 0.3 m, LxWxD). The hood was connected to the off-gas analyser (evolution of the analyser in Leu et al, 2009) through a flexible hose (diameter ~ 40mm). By means of a vacuum pump a small fraction of the off-gas was diverted from the main hose to a desiccator/adsorption unit to remove water vapour and CO_2, and then circulated inside a zirconium oxide fuel cell (AMI Model 65, Advanced Micro Instruments, USA) to measure oxygen partial pressure. Ambient air was sampled by means of a three-way valve at the start and end of each experiment as reference for the efficiency evaluation. The percentage of oxygen transferred to the liquid phase (i.e. OTE) was calculated from the oxygen content measured in the off-gas and the reference fraction in the ambient air as follows:

$$OTE = \frac{O_{2in} - O_{2out}}{O_{2in}} \tag{1}$$

where O_{2in} is the mass flow of oxygen measured in the influent air supplied and O_{2out} is the mass flow in the off-gas.

Dissolved oxygen was recorded by means of an LDO probe (Hach-Lange) attached underneath the floating hood, in order to correct for variable DO gradients during the oxygen transfer process. A schematic of the off-gas set-up is shown in Figure 1.

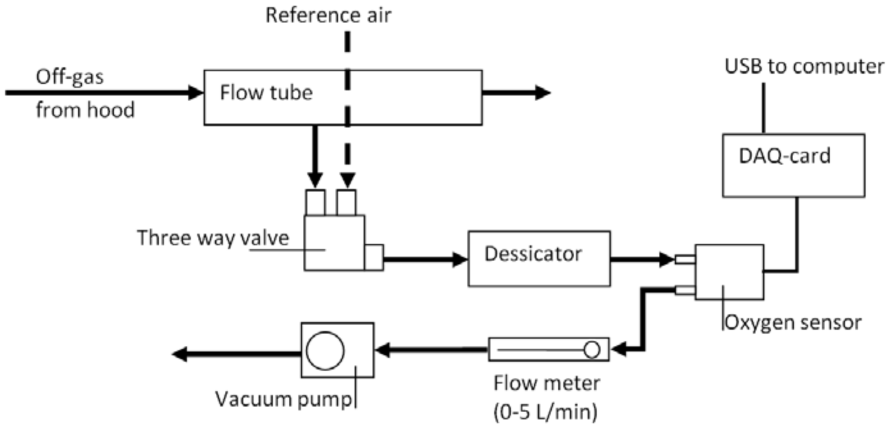

Figure 1 – Schematic diagram of the off-gas set-up

Eq 1 allows the calculation of OTE without the need of knowing the airflow rate. The standard oxygen transfer efficiency in process water (αSOTE, %) can be computed as:

$$\alpha SOTE = OTE \cdot \frac{DO^*_{S20}}{(\beta \cdot DO^*_{S_T} - DO)} \cdot \theta^{(20-T)} \tag{2}$$

where standard conditions (i.e. 20°C, mean atmospheric pressure, zero dissolved oxygen and zero effect of salinity) have been defined from ASCE (1984, 1991, 2007) and included here as multiplication factors. In particular β is the factor that quantifies the process water salinity effect on transfer efficiency and is defined by Stenstrom and Gilbert (1981) as the ratio of oxygen saturation in process water to clean water or $DO^*_{\infty}/DO^*_{\infty cw}$. This coefficient is indeed used to adjust the calculated oxygen value (Baca and Arnett, 1976) at half of the depth (Metcalf & Eddy, 2003) at saturation (DO^*_{ST}) to the process water conditions. The α factor is the correction coefficient for the effect of contaminants on transfer efficiency in particular this is defined as the ratio of process water to clean water mass transfer coefficient (i.e. K_La_{pw}/K_La_{cw}). The value of oxygen saturation in clean water at 20°C has been calculated as DO^*_{S20} and the correction factor that relates to standard water temperature is here reported as the temperature correlation coefficient θ. The process water temperature in the activated sludge basin T has been directly recorded using the LDO probe.

Field Experiments

Field tests have been performed at the full-scale WWTP of Eindhoven (Netherlands) which operates according to the UCT configuration (Figure 2) with pre-settling. The full-scale Eindhoven WWTP treats the wastewater of 750000 inhabitant equivalent (IE) with a load of 136 g COD day^{-1} IE^{-1} through the use of three parallel lines, each consisting of a primary settler, a biological tank and four secondary settlers. The pre-settled wastewater enters the biological tank in the central anaerobic compartment (i.e. Inner Ring in Figure 2) which is a plug flow reactor with four compartments in series. After the last compartment, the mixed liquor enters the anoxic ring (Middle Ring in Figure 2) and then to the outer ring where the activated sludge is kept in motion by three pair of mixers and aeration is supplied by fine pore membrane plate aerators in a continuous aerobic/anoxic ring. The aerators are divided in two main zones defined as summer package (the larger diffuser grid in Figure 2) and winter package (the smaller diffuser grid Figure 2). The summer package is constantly in use and controlled by a DO-NH_4 cascade controller while the winter package is activated during particular environmental and/or biological conditions (e.g. low water temperatures, rain events, low biomass activity) in order to enlarge the aerobic zone. Figure 2 shows the location in which aeration efficiency is monitored. Locations were chosen in both radial as tangential direction.

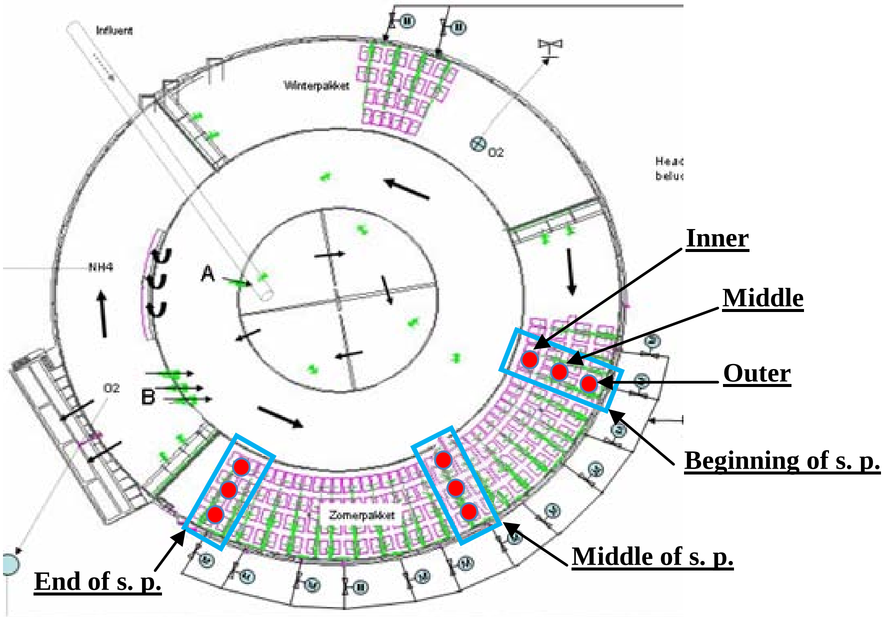

Figure 2 – ATII with hood main sampling locations (blue rectangle) and sub-locations (red circles) on the summer package (s. p.).

RESULTS AND DISCUSSION

Experiment A

A 2-days experiment was performed to test the newly built off-gas setup. During the first day the hood was placed in the middle of the summer package. Fairly constant values of OTE, αSOTE and DO were obtained during the first part of the experiment (Figure 3). It should be noted that the noise in the αSOTE signal is caused by noise in the DO measurement (due to the bubbles; this cannot be avoided). A sudden activation of feedforward control resulted in a peak of DO up to 8 mg/l. This increased air flow rate had a significant impact on the OTE which dropped by 50%.

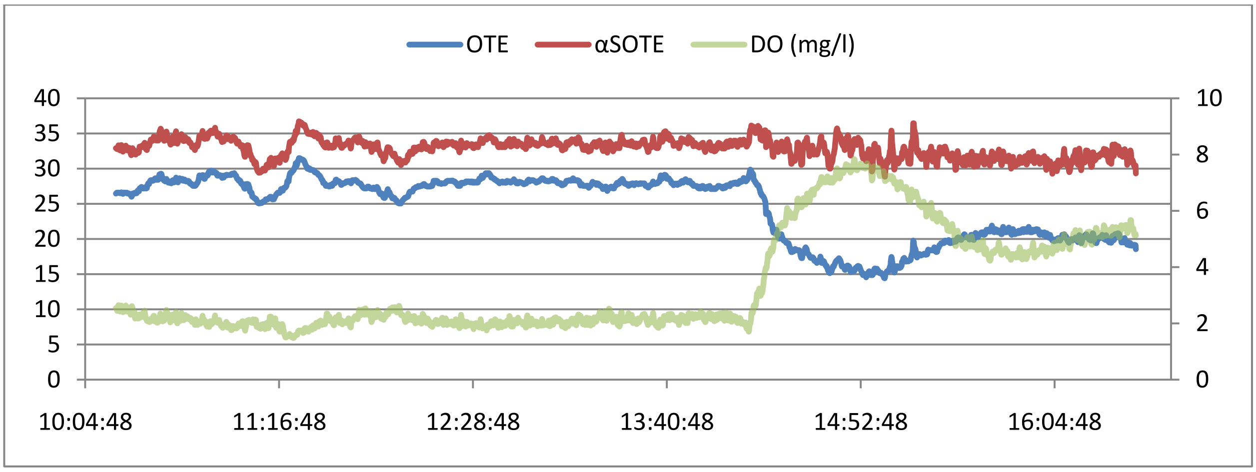

Figure 3 – Results of day 1 of exp. A.: OTE, αSOTE on left axis (%), DO on right axis (mg/l)

The αSOTE time series did not sag because the correction to zero DO compensates for low oxygen transfer when the driving force (i.e. the difference between DO and DO_s) is low. Air flow rate and incoming flow rate for the same time period are given in Figure 4.

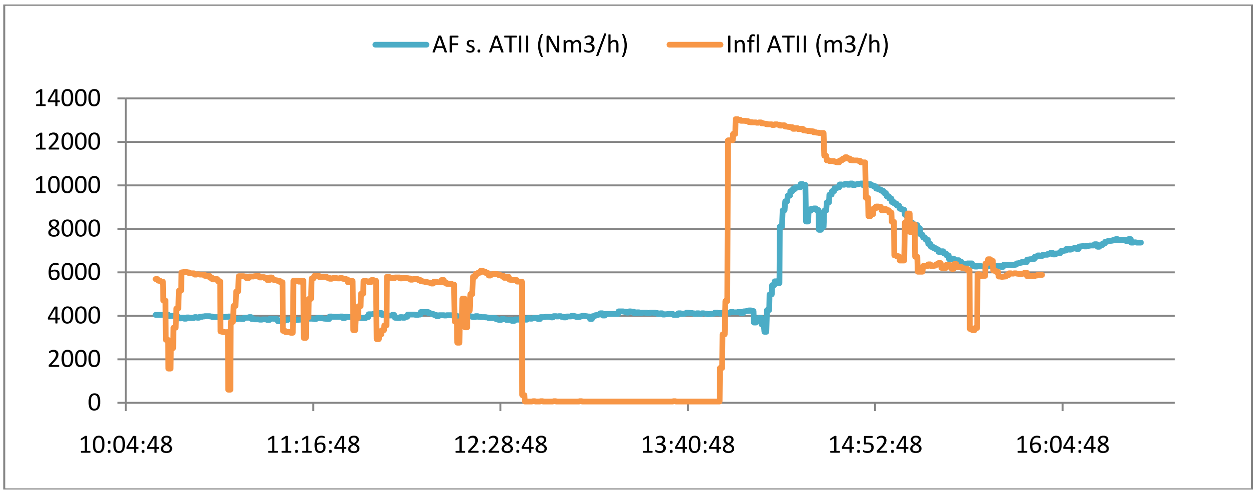

Figure 4 – Summer package air flow (AF s. ATII) and the incoming flow (Infl ATII) for AT II

A slightly negative but poor correlation between air flow rate and αSOTE was found (Figure 5), in agreement with literature. The extreme increase in air flow rate due to the feedforward control causes the scatter and poor correlation.

During the second day of exp. A (Figure 6), different locations were monitored. The hood was located in the middle of the summer package but was now moved in the radial direction. It should be noted that during these changes, unavoidably the load of the system changed. Hence, the observations are a combined effect of this. Again, a fairly constant behaviour was found in the morning hours (this is normal since the elevated load from the morning peak enters the plant only late due to a large residence time in the sewer system). When moving the hood radially to the outer part of the ring, a slight decrease in αSOTE (about 1%) could be observed. When moving the hood to the inner part of the ring, an increase could be observed. The slight decrease in αSOTE in the next part (when the hood was moved back to the middle of the ring) can be attributed to the increased load entering the plant. This can be observed from the increase in DO and increase in air flow rate due to the cascade controller action (Figure 7).

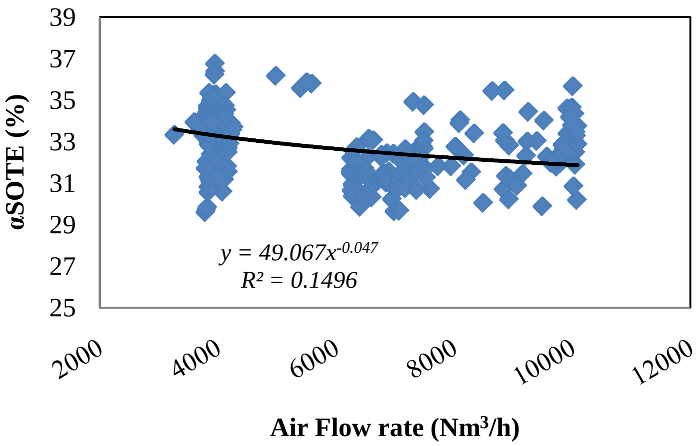

Figure 5 – Phase plane of Air flow rate and αSOTE, illustrating the poor correlation

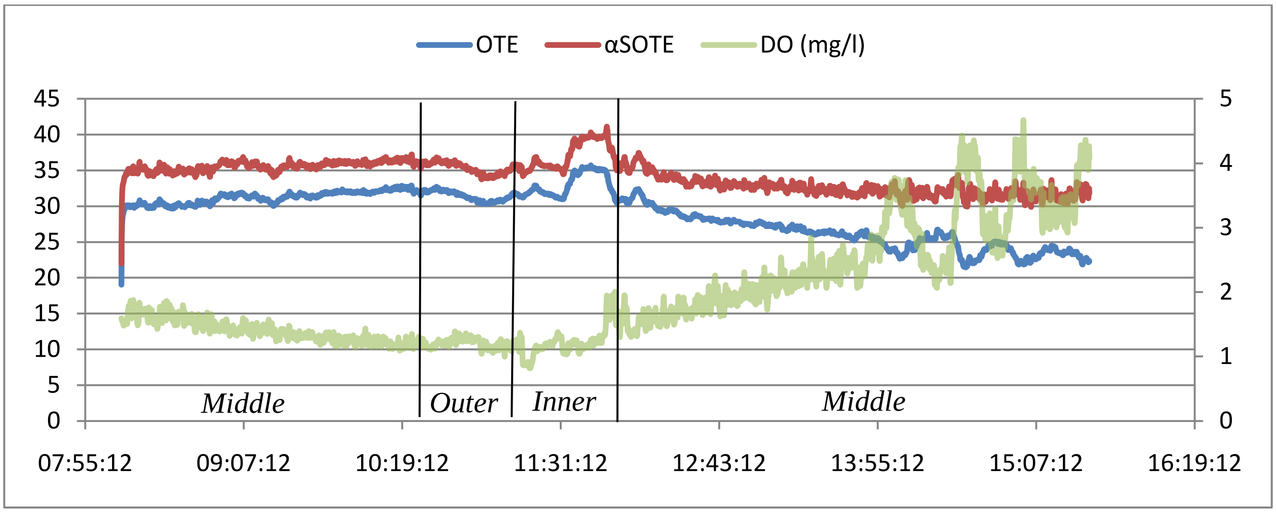

Figure 6 – Results of day 2 of exp. A.: OTE, αSOTE on left axis (%), DO on right axis (mg/l)

When plotting αSOTE versus air flow rate, one can now observe a steeper decreasing trend in the correlation (Figure 8).

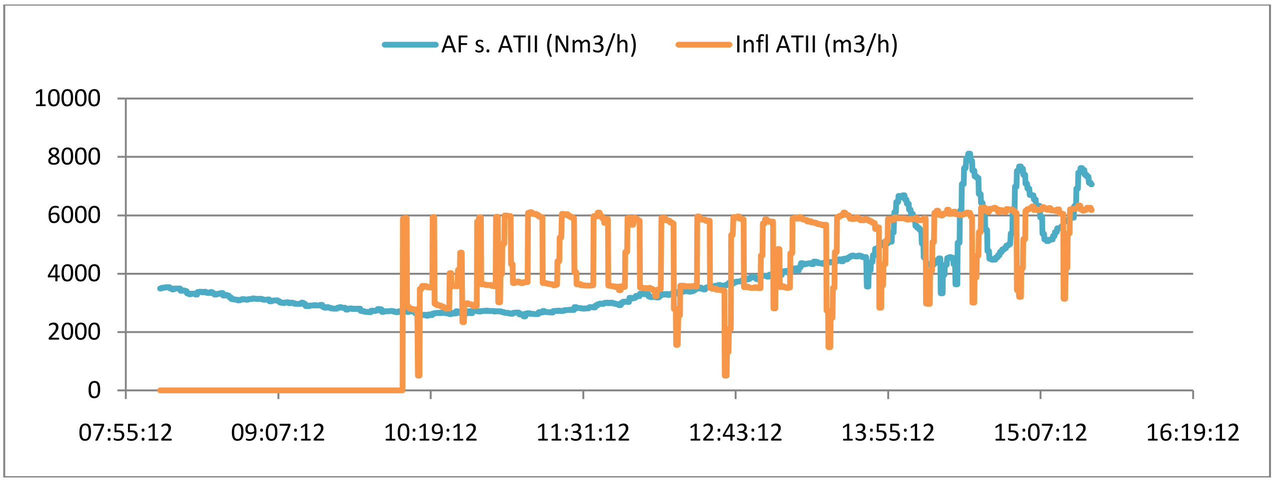

Figure 7 – Air flow rate and influent.

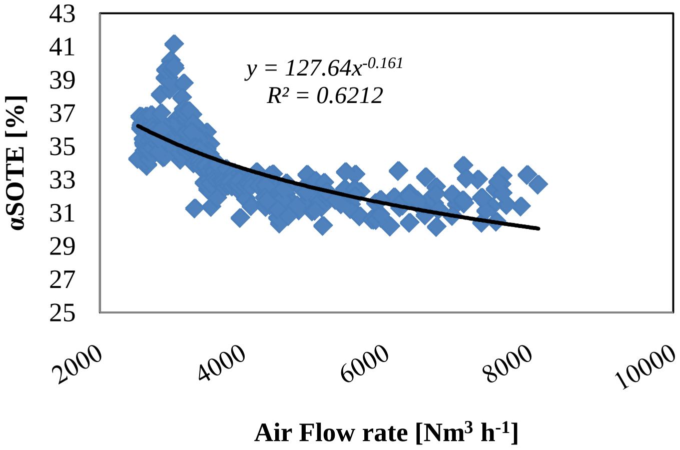

Figure 8 – Phase plane of Air flow rate and αSOTE during day 2 of experiment A.

Experiment B

During exp. B, OTE was measured at different locations tangentially along the length of the summer package. Each location (i.e. beginning, middle and end) was monitored at three radial locations (Figure 2). The first day the middle of the summer package was monitored, followed by the beginning and the end during the second day.

The αSOTE level was found to be significantly lower at the beginning of the summer package (approx. 5%) compared to the one obtained in the middle of the summer package (Figure 9). Moving the hood in the radial direction seems to have some impact. However, this coincides with the increase in load and both effects cannot be separated from the data. However, it can be noted that the DO level is almost zero at the outside of the ring, whereas it is higher at the inside of the ring. In the afternoon an increase in DO can be observed resulting from the cascade controller. Again, this results in a decrease in αSOTE at increasing air flow rate. Unfortunately this cannot be checked due to a lack of air flow data from the SCADA system of the treatment plant during this experimental campaign.

Therefore, also the high value of DO registered in the middle of the summer package (Figure 10) cannot be explained in the present work but attention can be given to the αSOTE behavior which again rises moving the hood in the inner side of the section. Furthermore, although the variability of DO seems to be higher, αSOTE is practically once again constant from the middle toward the outer location.

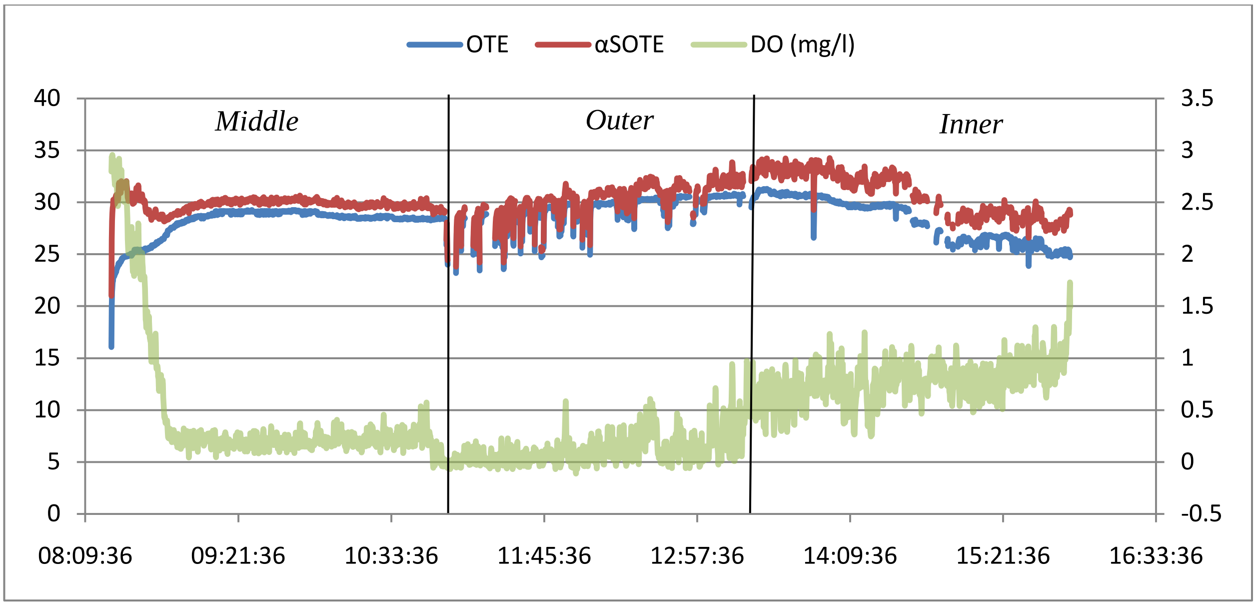

Figure 9 – Results of experiment B **(**beginning of summer package). OTE, αSOTE on left axis (%), DO on right axis (mg/l).

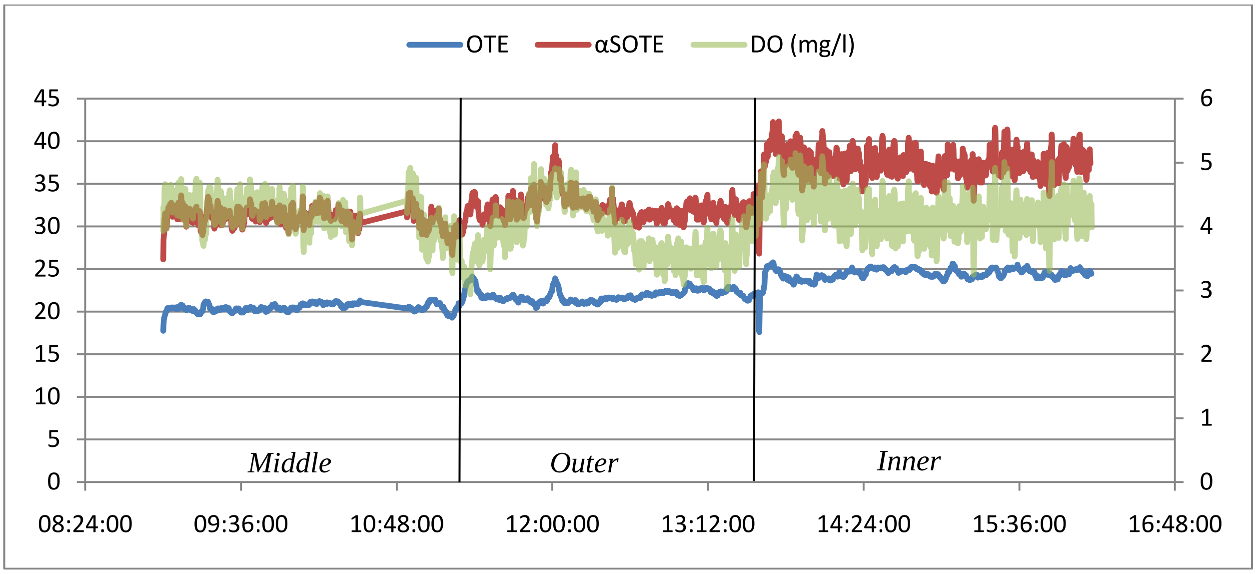

Figure 10 – Results of experiment B **(**middle of summer package). OTE, αSOTE on left axis (%), DO on the right axis (mg/l).

Moreover, during the measurements at the end of the summer package (Figure 11), a similar αSOTE behavior from the one in Figure 10 has been recorded but lifted to an higher efficiency level. Again the efficiency from the middle toward the outer locations are practically coincident, rising then, when the hood arrives in the inner part. Indeed from Figure 12, one can see how the efficiencies are higher in the inner part of the measured section validating the fact that lower horizontal velocities correspond to higher efficiencies (Gillot, 2000). On the other hand, it should be pointed out that inner sub-locations were always visited during afternoon hours when the load reaches its peak and the aeration cascade control system increases the air flow (which also impacts horizontal velocity). Therefore, a decrease in the αSOTE profile was expected. The results along the length are consistent with an increase in αSOTE of about 70% for the inner part, 27% for the middle and 35% for the outer location between the beginning and the end of the summer package. The constant value of αSOTE among the sub-locations at the beginning of the summer package could suggest that the vicinity of the impellers package provides a well mixed environment with well distributed flow velocity. However, towards the end of the aeration system the gap in αSOTE between sub-location increases, probably due to the fact that the velocity becomes heterogeneous due to inertia effects that occur further away from the mixers. In the outer sections and especially at the end of the summer package the higher velocity leads to a lower efficiency value. The fact that αSOTE is not rising linearly towards the radial section is probably due to turbulence effects. These findings need to be considered when attempting a more detailed modeling of aeration in the EH WWTP.

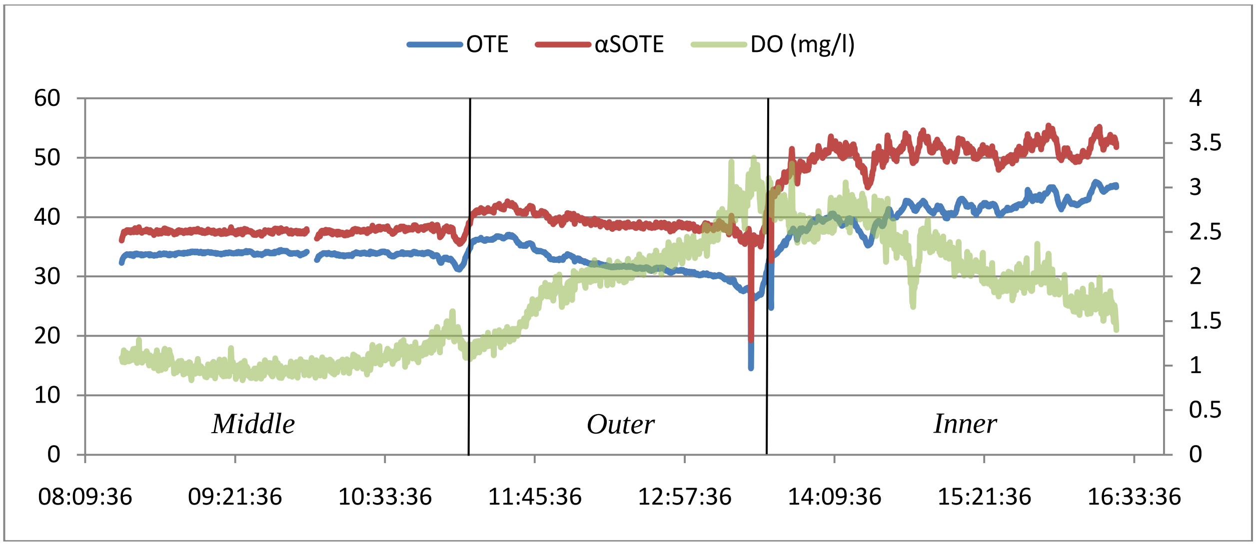

Figure 11 – Results of experiment B **(**end of summer package). OTE, αSOTE on left axis (%), DO on right axis (mg/l).

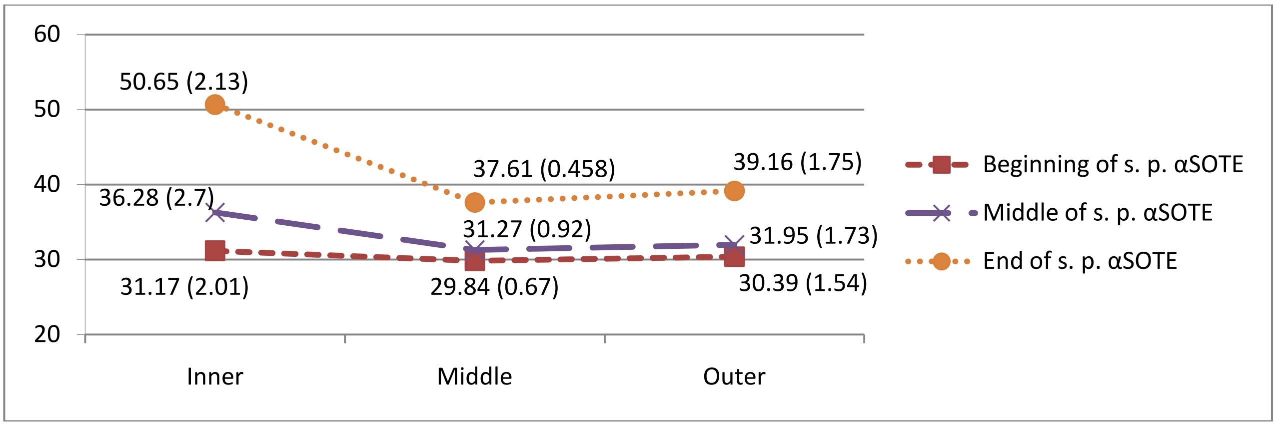

Figure 12 – Efficiency averaged values and standard deviations for each radial location

CONCLUSIONS

Oxygen transfer efficiencies were measured at the WWTP of Eindhoven under different circumstances and at different locations in the aerated zone. The main finding was that αSOTE is not constant along the length of the summer package. Higher values (ca. 38%) were measured towards the end of the aerated zone compared to the beginning of that zone (ca. 30%). Furthermore, homogenous OTE was observed at the start of the aerated zone, whereas heterogeneity can clearly be observed towards the end. This will have to be accounted for in the aeration model of the EH WWTP model. The present activated sludge basin seems to have a plug flow based behavior with respect to oxygen transfer, which might be different from the mixing behavior of other dissolved components.

ACKNOWLEGMENTS

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