Model-based monitoring of diffuser fouling using standard sensors

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1. Introduction

Despite technical improvements in fine-pore diffusers and advanced control systems, the aeration system remains the single most energy-demanding operational unit in water resource recovery facilities (WRRFs). Regular cleaning of diffusers is crucial for preventing deteriorating energy efficiency (Garrido-Baserba et al., 2017; Rosso et al., 2008). Garrido-Baserba et al. (2017) reported a 24% increase in energy consumption for the common ethylene-propylene-diene monomer (EPDM) disc diffuser due to fouling and aging the first 14 months of diffuser operation in a low rate loaded WRRF. Fouling progression was reported to be even quicker for high loading rates.

The decrease in energy efficiency has been attributed to fouling and aging of the diffusers (Krampe, 2011; Rosso and Stenstrom, 2006), leading to a decreased oxygen transfer efficiency (OTE). In contrast, the underlying causal effects may differ (Garrido-Baserba et al., 2017; Jiang et al., 2017; Rosso and Stenstrom, 2006). Aging and chemical fouling (scaling) both cause the diffuser membranes to become less flexible and increases the diffuser pressure resistance, i.e., an increase in dynamic wet pressure (DWP) (Rosso et al., 2008; Wang et al., 2020). Both aging and fouling change the membrane properties, for example, by changing bubble size and distribution, which results in a decreased OTE (Garrido-Baserba et al., 2016; Garrido-Baserba et al., 2018; Odize et al., 2017).

1.1. Timely diffuser maintenance is essential but difficult to implement

Timely countermeasures are essential to minimize energy wastage due to deteriorated diffuser efficiency. Fouling can be suppressed through different cleaning actions, such as top-hose cleaning, manual mechanical cleaning, gas sparging, chemical/acid cleaning and reverse flex cleaning (Jiang et al., 2020; Odize et al., 2017; Rosso, 2018). Cleaning actions are costly, resource-demanding and can require a temporary reduction in treatment capacity. For example, top-hose cleaning requires a temporary shutdown of the current activated sludge process (ASP) treatment line.

It is difficult to accurately predict when cleaning is needed since the fouling progression depends on factors that vary between sites (Garrido-Baserba et al., 2017; Odize et al., 2017). Garrido-Baserba et al. (2017) reported a state-of-the-art prediction model for linking diffuser fouling to reduced OTE using deoxyribonucleic acid (DNA) quantification on the diffusor surface. Such DNA analyses are, however, not viable in practice. The use of DNA analysis was motivated by the inconsistent prediction results produced by historically used predictors such as mixed liquor content (MLSS) and solids retention time (SRT). By contrast, monitoring changes in DWP in situ is straightforward (EPA US, 1989; Rosso, 2018), but not sufficient on its own since changes in DWP are only partly correlated with changes in OTE. Thus, direct monitoring of...
the OTE is also needed.

1.2. Assessing diffuser fouling from off-gas measurements

The OTE can be determined directly using off-gas measurements, as Redmon et al. (1983) originally described. Although the off-gas method provides accurate data, it has three drawbacks for diffuser fouling monitoring:

- The method is reliant on dedicated measurement equipment (i.e. a floating hood, vacuum pump and sensors), which are costly and require maintenance.
- A representative hood coverage is representative of only a part of the monitored diffusers. The hood needs to be physically moved to change the monitoring position, which is labour-intensive.
- Changes in OTE obtained from off-gas measurements cannot separate effects from changes in α-value due to changed diffuser properties. The change in OTE for a used diffuser relative to the new diffuser is a factor \( F \) (Metcalf and Eddy, 2004; Rosso, 2018). Note that OTE is proportional to the product αF, and both α and F describe how effective oxygen in the air is converted to dissolved oxygen (DO).

The \( \alpha \)-value relates oxygen transfer rate in clean water and process water (Rosso, 2018). In general, the \( \alpha \)-value is challenging to monitor, as it is influenced by several factors (Amaral et al., 2019), it is dynamically changing (Jiang et al., 2017) and is influenced partly in unknown ways (Rosso, 2018). For this reason, the only established method to separate changed diffuser properties \((F)\) from changes in \( \alpha \) is to conduct clean water OTE measurements on the actual fouled diffuser. This approach is obviously not feasible during real-time operations.

1.3. Estimating oxygen transfer and respiration rate from in situ oxygen dynamics

An alternative and well-studied approach for assessing OTE is to estimate its proxy, the oxygen mass transfer function \((k_{oa})\). This can be done recursively using, for example, a Kalman filter as in (Holmberg and Olsson, 1985; Holmberg et al., 1989; Lindberg, 1997). The main challenge in using this approach is to excite the system (change the airflow rate and DO concentration) sufficiently to make it possible to separate the estimation of respiration rate \((r)\) from \(k_{oa}\). Several approaches have been used to excite the system, including square waves (Holmberg and Olsson, 1985), oscillating DO setpoints (Holmberg et al., 1989) and on/off aeration (Irizar et al., 2009). These approaches have been tested on a full scale, but only for a limited time (several days). There is a lack of long-term studies demonstrating the practicability and usefulness of in situ estimation of \( r \) and \( k_{oa} \).

1.4. Practicability study of the staircase method

As mentioned, reducing energy wastage due to fouled fine-pore diffusers remains a challenge because the existing method to decide a time point for cleaning requires costly and complicated off-gas measurements. Here, we propose a method for in situ condition monitoring of fine-pore aeration diffusers. The goal is to automatically obtain information about the condition of the diffuser during real-time operations using only standard instrumentation.

The proposed method extracts data during an airflow rate sequence used for model parameter estimation. The airflow rate excitation consists of a series of steps similar to a staircase, where the valve position is kept piecewise constant at different magnitudes. This facilitates the estimation of \( \alpha F \) and DWP, which are then related to the diffuser’s condition. The suggested approach is in line with the concept of active fault detection, which has recently been useful for detecting biofilm formation on DO sensors (Samuelsson et al., 2019).

The method’s potential is demonstrated with an 18-month-long experiment, during which fouling and changes in \( \alpha F \) and DWP were monitored in four aerated zones in a full-scale WRRF.

2. Methods and materials

The first section (Section 2.1) describes how the proposed staircase method was studied with the corresponding experimental setting (Section 2.2). Next, the staircase method (Section 2.3) is described and how it facilitates parameter estimation of DWP (Section 2.3.2) and \( \alpha F \) (Section 2.3.3 and 2.3.4), along with a brief summary of the software implementation (Section 2.4).

2.1. Methodology

The proposed staircase method was studied by comparing its parameter estimates of DWP and \( \alpha F \) for diffusers in two parallel ASP lines in a real WRRF. The parameter estimates, which resemble the diffusers condition, were studied for 18 months to separate potential seasonal effects from long-term diffuser fouling. The diffusers were of different ages in the two ASP lines and therefore they were assumed to exhibit different fouling rates.

2.2. Experimental system description

The experiment was performed in the 350,000 p.e. Bromma WRRF, located in Stockholm, Sweden. The WRRF operates at a medium loading rate (SRT 6 days, MLSS 3,600 mg/L) in six parallel ASP lines, each divided into seven zones (Fig. 1). Four positions were selected for the experiment (Fig. 1).

- The Line 1 diffusers were 37 months old at the start of the experiment.
- The Line 2 diffusers were six months old at the start of the experiment.
- Zone 3 was only aerated during winter and therefore expected to exhibit more fouling than zone 4. Zone 4 was aerated as required, depending on the load situation.

The diffusers were made from EPDM (Jaeger, Jetflex HD340) and supplied air at a water depth of 4.07 m, 0.58 m above the basin bottom. The basin had a sloped bottom (1 m slope on each side of the bottom) with a 3.2 m flat area between the sloped sides. The diffusers were supplied air at a water depth of 4.07 m, 0.58 m above the basin bottom. The basin had a sloped bottom (1 m slope on each side of the bottom) with a 3.2 m flat area between the sloped sides. The diffusers were supplied air at a water depth of 4.07 m, 0.58 m above the basin bottom. The basin had a sloped bottom (1 m slope on each side of the bottom) with a 3.2 m flat area between the sloped sides.
mounted on the flat area, with an active diffuser area density of 28% (zone 3) and 30% (zone 4).

The air supply was controlled via a cascade controller with a fixed DO setpoint for each zone, with underlying slave controllers controlling the airflow rate. The sensors used for control included electrochemical DO sensors (Cerlic O2X DUO), thermal gas flow rate sensors (Endress+Hauser, AT770), and a magnetic induction sensor for assessing the current valve position. The butterfly airflow valve (GEFA, K19) was driven by a positioner (Siemens, Sipart PS2). The air was distributed with constant pressure (setpoint 0.51 bar) through a common manifold for the entire ASP.

2.3. Staircase design

A sequence of ten fixed airflow valve positions (Fig. 2), each one ranging from one to ten minutes long (henceforth referred to as slots), were used to facilitate the estimation of DWP and αF. In short, a constant valve position facilitates the estimation of DWP. A sizeable step in the airflow rate causing a large DO change facilitates estimation of kL,a and r, which are needed to estimate αF. The estimation procedure is further described in Section 2.3.2 and 2.3.3.

2.3.1. Diffuser maintenance (airMaint)

In addition to facilitating parameter estimation, a high airflow rate (slot seven, Fig. 2) was applied to retain the diffusers flexible and remove coatings. This so-called airflow maintenance (airMaint) was applied at one aerated zone at the time to avoid pressure drops in the manifold air distribution system. The staircase was repeated at a fixed time and on weekdays (Tuesdays and Thursdays). This was done to only compare influent loads during the same weekday and time, thereby reducing the impact of daily variations in the influent and α.

Airflow maintenance, is a diffuser maintenance procedure similar to reverse-flex cleaning (Odize et al., 2017), during which the maximum nominal diffuser airflow rate is exceeded by 20% for 10 min. Here, the originally applied airMaint procedure was slightly modified by applying a fixed valve position, in contrast to the original setting where the airflow rate is fixed.

The airMaint was applied in the middle of the staircase (Fig. 2) to assess its effectiveness by comparing estimated DWP and αF before and after the airMaint.

2.3.2. Estimating diffuser dynamic wet pressure

The diffuser dynamic wet pressure (DWP) change can be obtained by measuring the differential pressure over the diffuser. However, pressure measurements were not available after the airflow valve, as is common in WRRFs. For this reason, the DWP was instead estimated from measurements of the airflow rate through the valve, the valve’s position, the water level above the diffuser, the manifold air pressure, and by using manufacturing data about the valve’s flow characteristics. One DWP estimate was obtained per slot and fixed valve position and airflow rate. Details about the DWP estimation are given in Appendix A.

One reason for using fixed valve positions in the staircase and not data from routine operations (where the valve position and airflow rate continuously vary) was to handle a hysteresis in the valve position. That is, the airflow rates differed for the same valve position depending on the valve’s motion direction. For example, a larger airflow rate was obtained in closing motion compared to when it was opening (compare the airflow rates in slots two and five in Fig. 2). The impact from the valve position hysteresis was handled by only comparing DWP estimates based on the same valve motion direction with each other.

First, an indicator for monitoring long-term changes in DWP was defined as the mean value of the DWP estimates in opening motion (slot five and six) and denoted $DWP_{\text{op}}$.

Second, the effect from airMaint was measured in terms of DWP as the difference between the estimated DWP before (slot two) and after airMaint (slot nine) as $DWP_{\text{clean}}$. Note that both slots produce data with a valve in closing motion.

Changes in the actual valve position hysteresis was monitored by manually choosing the lowest valve position that produced zero airflow rate (in closing motion) for slot three, and the valve position that gave an airflow rate just above zero (in closing motion) for slot ten. Any changes in the airflow rates in either slot three or ten indicate an increasing/decreasing valve hysteresis.

2.3.3. Estimating the alpha fouling factor (αF)

As mentioned in Section 1.2, it is challenging to separate α from the fouling factor F. Therefore, the product αF was used as an indicator for diffuser fouling, where F ranges from zero (fully fouled, with no air passing through the diffuser) to one (unfouled new diffuser).

The αF is defined as the ratio of the oxygen mass transfer coefficient during process conditions, $kL,a_{\text{process}}$, and clean water conditions, $kL,a_{\text{clean}}$, as $αF = \frac{kL,a_{\text{clean}}}{kL,a_{\text{process}}}$.

Here, $kL,a_{\text{clean}}$ was obtained using manufacturer clean water test data and rearranging the standard OTE definition (SOTE), see Appendix A. The $kL,a_{\text{process}}$ was estimated with data from the staircase and is further described in Section 2.3.4. and is henceforth denoted $\tilde{kL,a}$.

2.3.4. Estimating oxygen mass transfer and respiration rate from dissolved oxygen dynamics

The theoretical basis for describing DO dynamics in both continuous and discrete time has been described by, for example, Lindberg (1997) and is briefly given here for clarity.

The DO dynamics in a completely stirred tank with volume $V$ is given by

$$\frac{d DO(t)}{dt} = \frac{Q(t)}{V} (DO_{in}(t) - DO(t)) + \frac{kL,a q_{out}(t)}{V} (DO^* - DO(t)) - r(t) \quad (1)$$

where $DO_{in}$ is the DO entering the tank, $Q$ is the flow rate of the influent and effluent, airflow rate $q_{out}$, $DO^*$ is the DO saturation concentration.

The prediction error method (PEM) described in Söderström and Stoica (1989) was used to estimate both $kL,a$ and $r$ as constants, one estimate per slot. In total, the staircase enabled seven $kL,a$ estimates for the fixed airflow rates during slot two, and slot four to nine and two respiration rates during slot three and ten. Since discrete-time measurements from the WRRF were to be used, (1) was discretized. For simplicity, the Euler forward was used:

$$\frac{d DO(t)}{dt} \approx \frac{DO(k+1) - DO(k)}{Ts},$$

where $Ts$ is the sampling time and $k$ is an integer denoting discrete-time samples.

A general challenge is that $r$ needs to be estimated simultaneously with $kL,a$, as both quantities, vary in time due to load and sludge activity. Here, the trick was to first estimate $r$ as a constant and separately from


\[ k_a \text{ when the airflow rate was zero (slot three and ten, Fig. 2). This result in zero } k_a \text{ in (1) and enable two estimates of the respiration rate 30 min apart (slot three and ten in Fig. 2). Next, } k_a \text{ was estimated by considering } \tilde{r} \text{ as a constant, where } \tilde{r} \text{ was the mean of the two estimated respiration rates (specifically, the variance weighted least squares mean as described in Gustafsson (2012) was used). To simplify the estimation of the respiration rate, only DO measurements above 2.5 mg/L were considered. This avoids modelling the influence of DO on } \tilde{r}, \text{ which has an effect mainly up to 2 and 3 mg/L (Lopez-Vazquez et al., 2016).}

Note that an accurate } \tilde{r} \text{ is critical as any errors in } \tilde{r} \text{ will be transferred to } k_a, \text{ and in turn to } \alpha F. Variations in load, or any other parameter with influence on the respiration, will however be captured in } \tilde{r}. \text{ How much these aspects induce is not be possible to quantify with the proposed method. This is, however, not needed to obtain the desired parameter estimates.}

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3. Results and discussion

The results are presented and discussed in four sections. The first section (Section 3.1) gives an overview of two experimental disturbances, which had an influence on the diffuser’s condition and the estimated parameters. Next, the key results are presented for the parameter estimates of } \tilde{r} \text{ and } \alpha F, \text{ (including } \tilde{r} \text{ and } k_a, \text{ and their ability to capture changes in diffuser conditions (Section 3.2). The results are evaluated based on the methodology (Section 2.1) and by considering the impact from the mentioned disturbances (Section 3.1).}

3.1. Experimental factors with influence on the diffuser condition

The airflow rate sensors were cleaned from coatings of dust after three months (grey horizontal line, Fig. 3) to improve the accuracy of the airflow rate measurements, and additionally, to study the impact of biased airflow rate measurements on the estimated parameters. The cleaning increased the measured airflow rate by almost 50 % (1,300 Nm\(^3\)/h to 1,900 Nm\(^3\)/h at 20% valve opening) for L2z4, which had the dirtiest sensor. The other positions showed a smaller increase or decrease of 100–200 Nm\(^3\)/h. The operational staff indicated that the airflow rate sensors were not routinely cleaned and had not been cleaned for at least ten years.

Humid air in the manifold air system occasionally caused a ‘flapping valve error’, which in turn prohibited a successful airMaint sequence and the intended diffuser cleaning. Specifically, in L1z2 the targeted maximum airflow rate was not reached during airMaint from June 2019 onwards. The maximum airflow rate was particularly low (<1,000 Nm\(^3\)/h, compared with the desired 6600 Nm\(^3\)/h) between June and October 2019. From January 2020 onwards, the valve was fully open during airMaint in L1z3 without producing the desired airflow rate. The ‘flapping valve error’ is detailed separately in Section 3.2.4 but reported here since the absence of airMaint cleaning impacted the diffuser DWP as will be described in Section 3.2.

\[ DWP_{avg} \text{ (black dots) at all positions and the change in DWP before and after airMaint, } DWP_{cleanoff} \text{ (blue solid line). Vertical grey dashed lines indicate manual cleaning of the airflow rate sensors. The solid red arrow indicates an increase in } DWP_{avg} \text{ due to absent airMaint cleaning, whereas grey dashed line indicates decreased } DWP_{cleanoff} \text{ for the same reason. Line 1 has older diffusers than Line 2. All data are pre-processed and cleaned from known disturbances, as detailed in Section 3.3.}

Fig. 3. DWP_{avg} (black dots) at all positions and the change in DWP before and after airMaint, DWP_{cleanoff} (blue solid line). Vertical grey dashed lines indicate manual cleaning of the airflow rate sensors. The solid red arrow indicates an increase in DWP_{avg} due to absent airMaint cleaning, whereas grey dashed line indicates decreased DWP_{cleanoff} for the same reason. Line 1 has older diffusers than Line 2. All data are pre-processed and cleaned from known disturbances, as detailed in Section 3.3.
3.2. Tracking model parameters reflecting diffuser condition

This section presents the key results, including the estimated DWP and αF (including $\tilde{\alpha}$ and $\tilde{k}_D$) concerning changes in the diffuser’s condition.

3.2.1. Diffuser dynamic wet pressure (DWP)

Detection of absent airMaint cleaning. The estimated average DWP before airMaint, DWP$_{avg}$, was intended to measure changes in the diffuser dynamic wet pressure due to fouling and ageing (Section 3.2.2). Indeed, the results show that DWP$_{avg}$ was clearly affected by the loss of airMaint (Section 3.1), as shown by the marked increase (0.15 bar) in DWP$_{avg}$ during 2019 in L1z3 (black dots, Fig. 3). The increase was unlikely to be caused by aging effects, as L1z4 had diffusers of the same age, but remained able to reach the maximum airflow rate and did not show the same behaviour as L1z3 (compare L1z3 and L1z4, Fig. 3). Compared to the magnitude of the marked increase, the DWP increased with only 0.03 bar in polyurethane diffusers during their first year of operation (Odize et al., 2017).

The absence of airMaint cleaning are similarly captured by DWP$_{cleaneff}$ (solid blue line, L1z3, Fig. 3), which measures the change in DWP before and after airMaint (Section 2.3.2). These results indicate that the diffusers in L1z3 were fouled, likely due to the absent airMaint cleaning.

Diffuser age and incorrect measurements impact on estimated dynamic wet pressure. The effect from cleaning the airflow rate sensors is seen as a dashed line, Fig. 3) in all positions. This demonstrates the importance of accurate airflow rate measurements.

Considering only data from the cleaned airflow rate sensors, there is a larger trend for increasing DWP$_{avg}$ for Line 2 compared to L1z4 (disregarding L1z3 due to the insufficient cleaning action). The DWP$_{avg}$ is also on average larger in Line 1 than in Line 2. This agrees with our expectations that newer diffusers in Line 2 would show a more apparent aging effect and increase in DWP compared to Line 1.

The results, however differed from our expectations regarding the absolute values of DWP$_{avg}$. All positions showed negative DWP$_{avg}$ on the order of –0.05 bar (Fig. 3). This indicates a general bias in either model assumptions (1) or in a joint measurement (air temperature and air distribution pressure). The offset could also have been caused by bias in the individual measurements at the four positions (airflow rate and valve position), although this is less likely because it assumes that the bias was similar in magnitude at all positions. Ultimately, we cannot identify the root cause for the offset in DWP$_{avg}$ since one faulty measurement alone could not have caused such large bias. Therefore, in future studies, it would be interesting to quantify the DWP bias for new (unfouled) diffusers.

3.2.2. The alpha-fouling factor ($\alpha F$)

The trends for $\alpha F$ partly differed from those for DWP$_{avg}$ (compare Figs. 3 with 4). Notably, there was no change in $\alpha F$ for L1z3 due to the absent airMaint cleaning as was seen for DWP$_{avg}$. This observation is in line with (Odize et al., 2017), in which an increased DWP was not linked to a decrease in aeration efficiency. The sudden change in airflow rate due to manual cleaning was not as clear in $\alpha F$ at L2z4, as for DWP in Fig. 3. Considering only data after cleaning of the airflow rate sensors, there is a slight trend towards increasing $\alpha F$ at all positions apart from L1z3. This contrasts with our expectations, as we assumed there would be an increase in fouling and thus a decrease in aeration efficiency over the experimental period (due to ageing and fouling). Such decrease was observed in Garrido-Baserba et al. (2017) and the contradicting results here could either be that the suggested method was incapable of assessing changes in aeration efficiency, or that the decrease in aeration efficiency was negligible. Furthermore, we assumed that the newer diffusers (Line 2) would show a larger (better) $\alpha F$ than Line 1, which was not observed. The $\alpha F$ was also above 1.0 (its theoretical maximum) for short periods. Since the current WRRF has a medium loading rate leading to extensive sensor fouling (Samuelsson et al., 2018), we suggest that the unexpected results indicate model or measurement errors, rather than negligible diffusor fouling. Note that any error in the

Fig. 4. Estimated $\alpha F$ values without disturbances for all positions. Slot five (grey dots) had a higher airflow rate than slot four (back dots). Dashed lines indicate cleaning the airflow rate sensor. All data are pre-processed and cleaned from known disturbances detailed in Section 3.3.
estimated underlying parameters \((\hat{r}, \hat{k}_L a, k_{L,a_{clean}})\) would be reflected in the \(\alpha F\).

It is likely that also large variations in the \(\alpha \) factor — due to influent composition variations — mask changes in \(F\). The \(\alpha F\) is expected to lie in the interval; \(\alpha F = 0.11 - 0.79\) (Metcalf and Eddy, 2004). It is known that variations in \(\alpha\) are large, and occasionally periodic. We still expected a slow trend in \(\alpha F\) due to diffusor fouling, that would have been clear despite periodic variations as indicated in L2x4 (Fig. 4). Therefore, further studies are needed to assess whether changes in the fouling factor \(F\) can be distinguished from influent variations with the proposed method. Such assessment would require extensive measurements including off-gas, respirometry, laboratory analyses, and clean water tests of fouled diffusers.

3.2.3. Respiration rate (\(r\))

The estimated respiration rate indicated an uneven load distribution between Line 1 and 2 and a higher respiration rate for zone 3 than for zone 4. These interesting process-related observations are detailed in the Supplementary Materials as they do not directly relate to the diffusers condition. A reliability check of the estimated respiration rates (Supplementary Materials) indicated normal rates in all positions apart from L2x4, which was in the lower range as measured by the sludge activity scale (Henze et al., 2002).

3.2.4. Oxygen mass transfer coefficient (\(k_L a\))

Line 2 showed the most stable \(k_L a\) and close to the expected values, especially in slots four and five when compared with other positions (Fig. 5(a)). See Supplementary Materials for a complete set of figures. There was a temporary increase and periodic variation in \(k_L a\) for the period July to October (empty circles, Fig. 5(a), which was not predicted from the theoretical clean water value \(k_{L,a_{clean}}\) (grey line, Fig. 5(a)). This sudden increase was seen at all positions (Supplementary Materials), indicating that it reflects a change in the water composition (either influent or activated sludge) rather than in the diffusers.

The effect of cleaning the airflow rate sensor is shown as a step increase in the theoretical \(k_{L,a_{clean}}\) in the beginning of April in all slots (Fig. 5(a)).

Note that, in general, the predicted variations in \(k_{L,a_{clean}}\) are small compared to \(\hat{k}_L a\). Also, the impact from \(k_{L,a_{clean}}\) (and cleaning airflow

![Fig. 5. \(\hat{k}_L a\) for a) L2x4 in the different slots on the staircase (Fig. 2). Note that slots seven and nine have a different Y-axis scale compared to other slots. b) L1x3 with slot six.](image-url)
rate sensors) has a much smaller impact on $\Delta F$ than the variations in $k_0a$ (compare the dip in $\Delta F$ in early March, with the manual cleaning in end of March for L1z4 and L2z4, Fig. 4). This supports the indication that influential variations causing variations in $a$ may be too large, and mask the smaller variations in $F$. This difficulty that can severely limit the usage of $k_0a$ to represent OTE of diffusors has not been demonstrated in previous studies (Holmberg and Olsson 1985; Irizar et al., 2009; Lindberg, 1997) most likely because they only evaluated their approach for a short time (days).

In addition to the variations assumed to be caused by the influent, all positions and slots were also affected by sensor measurement disturbances (filled markers, Fig. 5(a)). The disturbances, however, could be explained and are analysed in Section 3.3.

### 3.3. Practical experimental problems related to the staircase method

#### 3.3.1. Flapping valve error

A large variation, or flapping, in both airflow rate and valve position was observed for several measurements, as shown in Fig. 6 and by the black dots in Fig. 5. The root cause for this disturbance was that the airflow rate sensor was biased by humid air, which made the measured airflow rate exceeding its maximum value. This, in turn triggered the control system to close the valve rapidly. Once closed, the valve was opened again, which caused an excessive airflow rate that was repeated until the airflow sensor was dried out or the staircase entered a slot with a lower airflow rate. The impact from humid air was concluded with a separate experiment where the flapping valve error disappeared when water condensate was removed from the aeration system.

The flapping valve issue was mainly seen in slot two, probably when the air distribution system contained the largest condensate water volume, and in slot six when the airflow rate was high and close to the maximum limit (see Supplementary Materials for plots equivalent to Fig. 5(a) for all positions).

Surprisingly, the flapping valve was unsuccessful in suppressing DWP despite the resulting frequent changes in airflow rate (compare the black dots around July in Fig. 5(b) with $DW_{P\text{avg}}$ in L1z3 in Fig. 3). This indicates that the maximum airflow rate was more important than the variation for effective reverse-flex cleaning. This suggestion is reinforced by the observed negative correlation between lowered maximum airflow rate during airMaint and $DW_{P\text{avg}}$ (Supplementary Materials, Fig. 1).

#### 3.3.2. Erroneous airflow rate

During the period from June to October, the $k_0a_{\text{clean}}$ in L1z3 exhibited a series of peaks followed by a dip (grey diamonds, Fig. 5(b)). Similar events were seen for several slots in zones 3 and 4, Line 1 (Supplementary Materials). These were caused by a seemingly erroneous airflow rate that had a direct impact on $k_0a_{\text{clean}}$. We identified two different reasons for the deviating airflow rates.

First, the peaks in Fig. 5(b) were caused by a confusion in the slot identification algorithm induced by the flapping valve. Due to the flapping valve, the valve position variations were large, making it difficult to identify when a new slot began. As mentioned in Section 2.4, data for the different slots were extracted based on a change detection algorithm that identified the different slots from valve position data. As a result, the airflow rates from the wrong slots were used, which showed as ‘erroneous’ airflow rates.

Second, the period with low or zero $k_0a_{\text{clean}}$ in L1z3 was caused by a low airflow rate. In the staircases, it was clear that the airflow rate was zero at all valve positions, indicating either a frozen or broken airflow rate sensor or a closed valve with faulty position indication. The DO measurement oscillated between zero (or very low concentration) and normal values. This somewhat mysterious behaviour was explained by a play in the airflow rate sensor, which was solved in November by replacing the sensor, resulting in expected values for $k_0a_{\text{clean}}$.

#### 3.3.3. Insufficient DO excitation

Slots seven to nine showed insufficient DO excitation (blue dots, Fig. 5(a)). This was found to be caused by the intensive aeration during airMaint. The airMaint resulted in a DO concentration close to or above the maximum saturated value, limiting the available increase in DO concentration in subsequent slots. This made it difficult to estimate $k_0a$ accurately as the model (1) may provide a poor estimate when $\Delta k_0a_L$ is small. The other positions showed similar results, with insufficient DO excitation as in L2z4 (Supplementary Materials).

When the DO is close to its saturated value, the related problem is that the oxygen is transferred to the off-gas instead of the water. This is not captured in (1) and introduces a bias in $\hat{k}_0a$. From Fig. 5(a), it is not clear whether the high DO concentration caused a sufficiently large bias to be problematic, as there is no clear difference between normal (empty circles) and potentially biased estimates (blue circles), for example, in slot two to five.

#### 3.3.4. Biased DO measurements

Occasionally, the measured DO was even above its theoretical saturated concentration. This result in a negative difference $DO^* - DO(t)$ in (1), which in turn produce negative $\hat{k}_0a$ (slot seven and nine in Fig. 5(a)).

DO measurements above the theoretically saturated value (more than 1 mg/L above) were flagged as biased measurements (red dots, Fig. 5(a)). The biased measurements were mainly found in L1z4 (39% in slot seven, see Supplementary materials, Fig. 5(b)), which indicates that the DO sensor in L1z4 produced inaccurate measurements. For comparison, the L2z4 showed 8% biased measurements for the same slot (Supplementary Materials Fig. 5(d), slot seven). The effect of the biased DO sensor on the estimated $\hat{k}_0a$ values was unclear because we lacked information about the bias type and magnitude.

Similarly, as for the erroneous airflow rates, we note that the staircase method can detect data quality issues here in terms of a biased DO sensor. The biased DO sensors were not noticed in the WRRFs everyday routines, which shows the potential for the staircase method also to indicate data quality issues.

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**Fig. 6.** The effect of humid air condensation on the airflow sensor. The effect of the flapping valve causing fast variation in airflow rate is evident.
3.4. Suggested method and experimental improvements

3.4.1. Improving the staircase

The many disturbances with a negative impact on $k_c a$ are expected to be mitigated if the following improvements to the staircase are made.

- The AirMaint should be positioned at the beginning of the sequence to remove as much condensate water as possible and reduce the risk of a flapping valve.
- During AirMaint, the valve should be controlled to an airflow rate setpoint instead of a predefined valve position. This would also avoid the flapping valve error during AirMaint.
- A sufficient DO excitation could be obtained if the DO was allowed to settle to about 4 mg/L between each aeration slot. For example, the second slot with zero airflow rate (slot ten) should be placed directly after the AirMaint to lower the DO concentration sufficiently.

3.4.2. Recommendations for replicating the implementation

In a future implementation, the results would be less uncertain if the observed challenges in this study were considered. We recommend:

- Obtaining baseline parameter estimates when new diffusers are installed.
- Measuring variations in temperature and humidity both before and after the blowers (close to the valve) to estimate the impact of condensate water. An even better solution is to automatically remove the condensate water early in the air distribution system.
- Verifying that the airflow rate sensors are clean and provide accurate measurements, as this is not commonly part of sensor maintenance procedures.
- After calibrating and validating the DO sensors, comparing the measured maximum DO saturation concentration in buckets with clean and process water. This will be an additional validation of the measured accuracy at the (abnormally) high DO concentrations used for estimating $k_c a$.

The method should be further validated by comparing estimated values with suitable reference measurements such as pressure measurements (before and after the diffuser), respirometry, and off-gas measurements.

3.4.3. Extending the method to additional applications

The staircase method was inspired by the active fault detection concept (Puncochar and Skach, 2018). In line with that concept, the staircase could be used to obtain additional information about the process and sensors.

Estimating respiration rate has many potential applications, as exemplified in (Olsson, 2012), and the suggested method would be applicable for in situ respirometry at several (all) zones and lines without the need for additional instrumentation.

As indicated previously, the maximum DO concentration is reached (or can be assumed to be reached) during AirMaint. This value could be used to assess the deviation in DO measurements to quantify bias direction and magnitude in the DO sensor.

Finally, the large change in DO during AirMaint can be considered to be a controlled disturbance that will impact the DO in the subsequent zones. By monitoring how quickly the subsequent DO controllers suppress the disturbance, a measure of their disturbance-rejection ability could be obtained using the method by Petersson et al. (2002).

4. Conclusions

Diffuser condition and the reverse flex cleaning effect (AirMaint) can be monitored using only existing sensors in combination with the proposed staircase method. An increase in the dynamic wet pressure due to insufficient reverse-flex cleaning was detected as changes in the related parameter estimates $DWP_{avg}$ and $DWP_{cleanoff}$. These estimates of the dynamic wet pressure are therefore suggested as promising early warning indicators for diffuser fouling. By contrast, the estimated alpha-fouling factor showed no trends of increasing diffuser fouling. Instead, large variations were seen in alpha-fouling factor, which were suspected to originate from influent composition variations, and in turn the estimated oxygen mass transfer coefficient. This crucial challenge for using the oxygen mass transfer coefficient for diffuser condition monitoring has, to the best of our knowledge, not been emphasized before and needs to be considered in future studies. Ultimately, this study demonstrates that:

- The staircase method is a promising strategy since it is available and straightforward with minor costs.
- The staircase method can also be valuable for data quality assessment. Disturbances causing bias in airflow rates and DO sensor measurements were found, which would have gone undetected without analysing the data produced by the staircase method.
- Further research is motivated on how modelling in combination with repetitive process disturbances can provide useful information without additional instrumentation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.wroa.2021.100118.

Appendix A. Estimation of diffuser dynamic wet pressure

The pressure drop over most commercial valves is experimentally assessed and indirectly available in the form of a $k_v$ table provided by the valve manufacturer. The $k_v$ table consists of $k_v$ values for different valve positions. The standard expression relating $k_v$ to airflow rate $Q$ and differential pressure $Δp = p_1 − p_2$ over a valve during subcritical flow (Nesbitt, 2007) is given as
\[ k_v = \frac{Q}{5.14} \sqrt{\frac{\rho T}{\Delta p}} p_2 \]  

(2)

The product of air density \( \rho \) and absolute air temperature \( T \) is assumed to be constant at an estimated yearly average \((T = 288 K, \rho = 1.2 \text{ kg/m}^3)\). Note that an increase in temperature results in a decrease in air density, which in effect makes their product (essentially constant) in the range 0–40°C.

The pressure \( p_1 \) before the valve is the manifold pressure of the air distribution system (both \( p_1 \) and \( p_2 \) are expressed as absolute pressure in (2)). The \( k_v \) table for the airflow valve was obtained from the manufacturer and \( p_2 \), the absolute pressure after the valve was obtained by rearranging (2) and solving the resulting second-order equation. The DWP due to fouling and ageing during slot \( s \), \( DWP_{slot,s} \), was finally obtained as

\[ DWP_{slot,s} = p_2 - p_{am} - p_{wate} - DWP_{diff} \]  

(3)

where the water pressure \( p_{wate} \), and the diffuser pressure resistance at the current airflow rate for a new diffuser \( DWP_{diff} \) (obtained from the manufacturer) were subtracted from the gauge pressure, \( p_2 - p_{am} \). The ambient barometric pressure \( p_{am} \) was assumed to be constant at 1 bar.

Appendix B. Derivation of SOTE and \( k_{\alpha} \) during clean water conditions

The SOTE is given by

\[ SOTE_{sto} = k_{\alpha_{clean}} (20, q_{sto}) \frac{DO_{20\text{ atm}}}{{W_{O2\text{ net}}}} - V_{sto} \]  

(4)

In (4), \( W_{O2\text{ net}} \) is the oxygen mass flow, \( V_{sto} \) is the tank volume and \( DO_{20\text{ atm}} \) is the average saturated DO obtained during SOTE clean water tests. Note that \( DO_{20\text{ atm}} \) is usually higher than the surface DO saturation in clean water, \( DO_2 \), due to the liquid column pressure of water above the diffuser. \( DO_2 \), but not \( DO_{20\text{ atm}} \) was available from the supplier’s clean water test data; therefore, \( DO_{20\text{ atm}} \) was estimated by assuming that the effective saturation depth, \( d_e \), was 50% of the basin depth (Metcalf and Eddy; 2004); \( d_e \) is defined as “the depth of water under which the total pressure (hydrostatic + atmospheric) would produce a saturation concentration equal to \( DO_{20\text{ atm}} \)” (EPA US, 1989). The subsequent conversion is straightforward: \( DO_{sto} = \frac{DO_{20\text{ atm}}}{2} \), where \( \frac{1}{2} = \frac{1}{2} \text{ atm} \) and \( p_{sto} \) is the atmospheric pressure. By further compensating for temperature \( T \) with the common correction factor \( \varphi = 1.024 \) (Metcalf and Eddy, 2004; Rosso 2018), the \( k_{\alpha_{sto}} \) is obtained as

\[ k_{\alpha_{sto}} (T, q_{sto}) = \sqrt[20]{\frac{\theta(T, q_{sto}) W_{O2\text{ net}}\text{process}}{V_{sto}\text{process} \Delta DO_{sto}}} \]  

(5)

In (5), the \( SOTE_{sto}(q_{sto}) \) was obtained by interpolating SOTE test measurements at five airflow rates provided by the manufacturer.

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