Image analysis procedure to derive bubble size distributions for better understanding of the oxygen transfer mechanism

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INTRODUCTION

Understanding and optimization of the aeration process in the field of biological wastewater treatment is of crucial importance. Aeration typically accounts for more than 50% of water resource recovery facility (WRRF) energy expenditure. In the wastewater field, lab-scale bubble columns have been used by both aerator's manufacturers and researchers for determining aerator performance and improving design in clean water (e.g. oxygen transfer rate), and in the evaluation of predictive models in activated sludge (AS) (Pittoors et al., 2014). In both cases, potential effects of process water characteristics on bubble sizes are too often not considered, while, in the field of chemical engineering the use of imaging tools proved that liquid properties can have important effects on bubble size distribution (BSD) and transfer capabilities (*inter alia:* Anastasiou et al., 2013). This paper proposes a BSD image analysis tool specifically developed for measurements of bubbles in clean water and transparent surrogate liquids mimicking the characteristics of AS. The BSD image analysis tool includes a selection of processing techniques aimed at characterizing changes in bubbles characteristics due to variations in environmental conditions that specifically occur in biological reactors of WRRFs.

IMAGING ALORITHM AND BUBBLE SIZE MEASUREMENTS

A bubble column (160 cm high with an inner diameter of 38 cm) was equipped with a submerged membrane disc aerator (OXYFLEX®-MT 300 Supratec, Germany) to study the effect of bubble size distributions on gas-liquid transfer for wastewater and AS systems. A high speed camera (i-SPEEDLT 600x800 pixels, Olympus) was used to capture high frequency images of the BSD evolution along the height of the column (i.e. 5, 20, 40, 60, 80, 100 and 120 cm above the disc aerator) in different conditions by changing the air flow rate or dosing different concentrations of NaCl and Xanthan TER (Colltec GmbH). Image resolution of 0.095 (+/- 0.005) mm/pixel.
The BSD image analysis tool is developed using the programming language Python (Python Software Foundation, https://www.python.org), relying on functionalities as provided by scikit-image (Pedregosa et al., 2011). The individual processing steps are combined in a python package, giving the user the ability to directly execute the entire processing pipeline or to define a custom processing pipeline. This package is the result of a selection of the best performing processing methods for accurate bubble detection in this specific application. The main steps characterizing the image analysis are listed and described below. A more extensive description of e.g. the filtering parameter choice will be provided in the full paper).
Edge detection and object filling - The red channel of the image is selected as it provides the best contrast with regard to the background incandescent light (Figure 1, left). The Canny method (Canny, 1986), a powerful and flexible edge detection method, is applied on the black and white image for which detects the magnitude and the orientation of the black and white gradients. This, enhancing local maxima, allows high and low gradient thresholds to compose the output binary gradient mask of edges (Figure 1, right).

Selection of complete objects - The dilate function helps enclosing the edges. Closed objects are filled while open lines are removed from the image. The borders of the images are cleared from any object touching the frame perimeter and only entire objects are analysed. Rough edges of the filled objects are eroded to smooth the surface.

Object labelling and measurement - A progressive identification number is given to every object present in the binary image and for each object the values of its perimeter, area and convex area (the area of the convex regions around the object) can be computed.

Filtering for circularity reciprocal and convexity – For each object the circularity reciprocal and convexity are calculated, since they were observed to be effective filtering criteria to select single bubbles in the final BSD

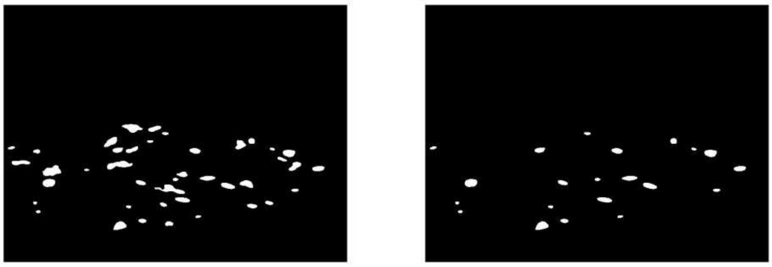

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Figure 2). The circularity reciprocal (-) (Equation 1) gives a measure of zero for ellipsoidal shapes and increases above one when the perimeter of the object is irregular. The convexity (-), gives more strictly a measure of roughness, as the ratio between the internal area of an object and the area of the imaginary elastic band around it.

$$1/C = \frac{Perimeter^2}{4\cdot\pi\cdot Area} \qquad (1)$$

Final BSD - The equivalent diameter (or equivalent projected area diameter) can be computed as:

$$d_{eq} = \left(\frac{Aarea\cdot 4}{\pi}\right)^{\frac{1}{2}} \qquad (2)$$

Finally, the number-based BSD can be built dividing the sizes in classes accordingly with the resolution of the image (i.e. in this work 100 classes spaced 0.2 mm from 0 to 20 mm).

The number based distributions obtained from the image analysis can then be used, along with the column gas holdup, to separately calculate the oxygen transfer coefficient (k_L) and the available area for exchange over the total volume (*a*) contributing to a better understanding of which parameter (k_L or a) dictates the oxygen transfer (Amerlinck et al., 2016).

Consistency of the results was checked verifying the performance of the BSD image analysis tool on different subsamples from the same image set. The BSD image analysis tool was able to detect true bubbles with no false positive objects in all different transparent solutions tested with the presented experimental setup. Furthermore, it was able to detect at all heights the effects of hydrostatic pressure and air flow on the equivalent diameter of the bubbles in both clean water (Figure 3) and slightly enhanced viscosity medium mimicking AS (Figure 4). In Figure 4 the relative changes of the distributions in high viscosity medium with respect to the clean water reference case show consistent results highlighting: (i) the sensitivity and capabilities of this measuring method and algorithm (ii) the importance of understanding the effect of viscosity in AS systems.

CONCLUSIONS AND PERSPECTIVES

The BSD image analysis tool returns consistent results in the different conditions tested. Effects of hydrostatic pressure, air flow and fluid characteristics on bubble sizes can be detected if the image resolution allows. The BSD image analysis tool proved to be a potential help in unravelling the dynamics behind oxygen transfer in wastewater applications. The code will be available on github.com, which allows other researchers to use and adapt the functionalities for their needs and provides an environment to discuss issues or questions. This enables an interactive and collaborative further development among different users.

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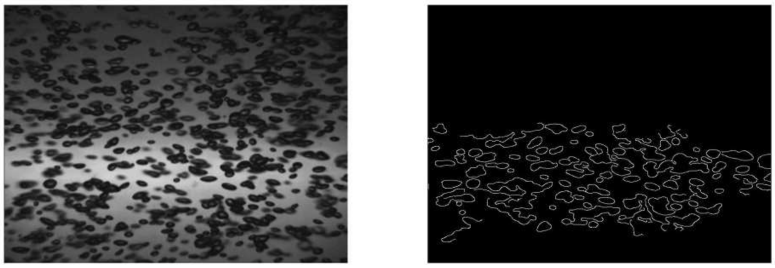

Figure 1 - Red channel of the original image (left) and the binary gradient mask (right) resulting from the edge detection function

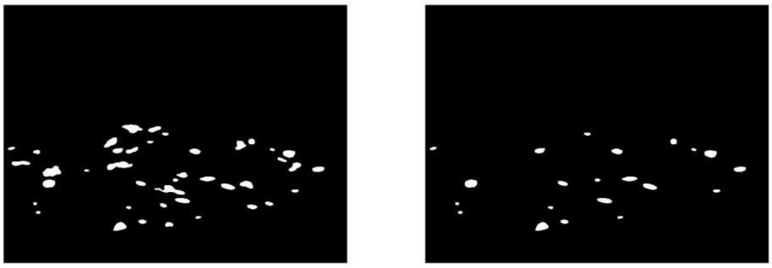

Figure 2 - Outlined original image before (left) and after (right) the application of the filter based on circularity and convexity.

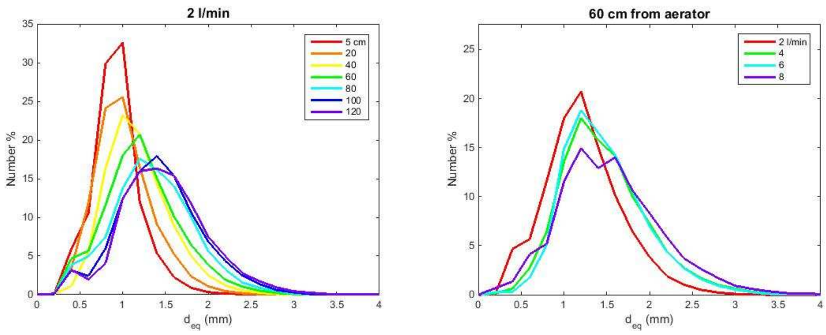

Figure 3 – Example number-based cumulative bubble size distributions in clean water at different heights (left) and air flows (right).

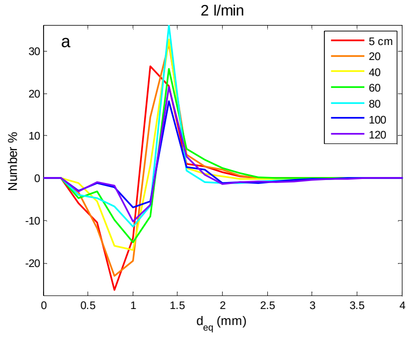

Figure 4 – Number-based distribution of the solution mimicking AS viscosity, shown in percentage of deviation from the reference clean water case. The air flow is given in the figure title.