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BIOMEDICAL ENGINEERING AND BIOTECHNOLOGY

Automatic batch sedimentation test based on histogram back-projection image analysis

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Abstract. A new method for measurement of sludge blanket height (SBH) based on image analysis is presented. The proposed method uses a histogram back-projection algorithm to distinguish between the settling sludge and supernatant and can be used with sludge possessing different coloring characteristics both in the sludge color and the color of supernatant produced. Individual pixels in the acquired image are compared with a histogram of a representative sludge region. Therefore, the proposed method relies neither on the assumed shape of light intensity profile nor on the dominant sludge or supernatant color. Batch sedimentation tests are presented for different initial sludge concentrations and different background colors to simulate different sludge characteristics. Parameters of a settling velocity function are estimated based on the obtained results. Additionally, an algorithm is proposed that enables the zone settling velocity (ZSV) to be estimated before the batch sedimentation test is completed.

Key words: batch sedumentation test; activated sludge; image analysis; control of recycle in WWTPs.

1. Introduction

Wastewater treatment plants (WWTPs) used to process municipal wastewaters are based on a system of biological reactors designed to process wastewater and a secondary settler to separate the effluent from the activated sludge [1, 2]. The sludge is recycled back into the biological reactor to maintain a desirable concentration of biomass (Fig. 1). Successful treatment of wastewater depends on the maximum capacity of secondary settlers which in turn depends on the settling characteristic of the activated sludge [3]. Although a number of current studies present novel approaches to the modelling of secondary settlers using computational fluid dynamics (for example [4, 5]), simplified models based on settling characteristics are still being developed and used for characterization of settling properties (for example [6, 7]). Measurements in biological and environmental systems often require manual laboratory work, hence automation is required for enhanced control [8]. Moreover, biological systems are always nonlinear and require advanced control strategies [9]. A number of methods have been devised over the decades for the control of the sludge recycle, the majority of which are based on the knowledge about settling characteristics of activated sludge [10]. Settling of activated sludge can occur in different regimes. In low concentrations, when individual flocs rarely touch each other, unhindered settling takes place. In higher concentrations, individual flocs touch each other and move together, developing zone settling regime with fluid moving in the opposite direction. Once activated sludge touches the bottom of the tank, a compression of sludge occurs, and higher concentrations of sludge are developed.

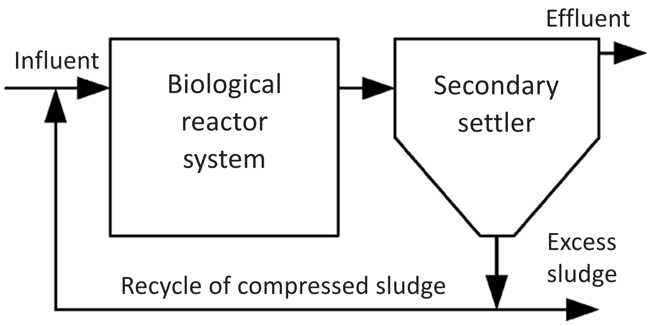

Fig. 1. Continuous biological wastewater treatment plant

Modelling of sedimentation is usually based on a settling velocity function which links the velocity of settling flocs to the local concentration of activated sludge. Higher sludge concentrations result in lower floc velocities [11, 12]. The simplest form of the settling velocity function was proposed by Vesilind [11]:

$$v(X) = v_{max} e^{-nX}, \tag{1}$$

where X (g/l) is sludge concentration; v is settling velocity (cm/min); v_{max} (cm/min) and n (l/g) are parameters. A number of techniques exist for the characterization of settling properties and for the identification of sedimentation model parameters. In most cases, parameters of the settling velocity function are estimated using batch settling curves [13, 14]. On-line quantification of settling properties in application to activated sludge characterization has been presented based on automated set-

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tlometer [15]. This method is based on a moving scanner traveling downwards a backlight settler. When a decrease in light intensity is detected, the level of solid-liquid interface is noted.

Nowadays, methods based on image analysis are gaining popularity due to the abundance of computational power and low-cost cameras. Image analysis methods applied to registration of batch settling curves for both synthetic sludge [16, 17] and activated sludge [18, 19] have been presented.

The works of Kim et al. [18] and Delron et al. [19] present automated procedures for the registration of sludge blanket height (SBH) and settling velocity (SV). The original method by Kim et al. assumes that the activated sludge is brownish and only the red channel of the image is analyzed, as it most sensitively represents the boundary between the settled sludge and the supernatant [18]. The method presented by Delron et al., which is based on the work by Kim et al., exploits the knowledge about an expected shape of the light intensity profile along the vertical dimension of the settling column. Their method rests on the fact that the shape of the profile is known to consist of a downward concave episode followed by a downward convex episode with the transition corresponding to the SBH [19]. In most operational conditions, those methods are sufficient due to the assumed color of the activated sludge and a colorless supernatant. However, the color of the activated sludge may change due to changes in operational conditions [20]. The color of the activated sludge is also linked to biodegradability and heavy metal content [21].

The novelty of the method presented in this paper is that neither assumptions about the color of the activated sludge nor about the color of the supernatant are needed. Consequently, the presented method is not dependent on an expected shape of light intensity profiles in any color channels. Instead, it is based on a histogram back-projection algorithm that detects the presence of the activated sludge on different levels of a settling column by making a comparison to the histogram of a sludge containing the region obtained at the start of the settling process.

Additionally, in order to validate the SBH measurement method, an online algorithm is proposed to estimate the zone settling velocity (ZSV) without the need to perform the full 30-minute settling experiment. This method is based on online SBH measurements and detects the maximum settling velocity (SV_{max}) that represents the ZSV. The recording of SBH can be performed using the proposed histogram back-projection method as well as other online methods proposed in the literature (for example [18, 19]). Once ZSV is estimated, it can be used by the control system to modify the recycle rate in a WWTP. Therefore, real-time control of secondary clarifiers can be enhanced by shortening the delay between commencing the test and obtaining the results.

The paper is organized as follows. In Section 2.1 the activated sludge plant used in the experiments and the setup used to acquire images are presented. Details of the proposed image processing algorithm are given in Section 2.2 and determination of ZSV is presented in Section 2.3. Experimental results demonstrating SBH measurements are presented in Section 3, detailing the ZSV estimation in Section 3.1 and identification of settling velocity function parameters in Section 3.2. In Section 3.3 sensitivity of the proposed algorithm to different coloring and backlight conditions is investigated to verify robustness of the proposed algorithm. Results are discussed and general conclusions are presented in Section 4.

2. Materials and methods

2.1. Experimental setup. The batch sedimentation tests have been performed using an activated sludge obtained from a commercial WWTP, feed and purified for a couple of months, maintained in 5 separate two- or four-liter reactors aerated and mixed constantly (Fig. 2). For batch sedimentation tests biomass from different reactors was drawn, mixed together, and thickened or diluted to obtain different concentrations. In every case, initial biomass concentration was independently measured using a dry-weight method (Radwag WPS 50/SX/1).

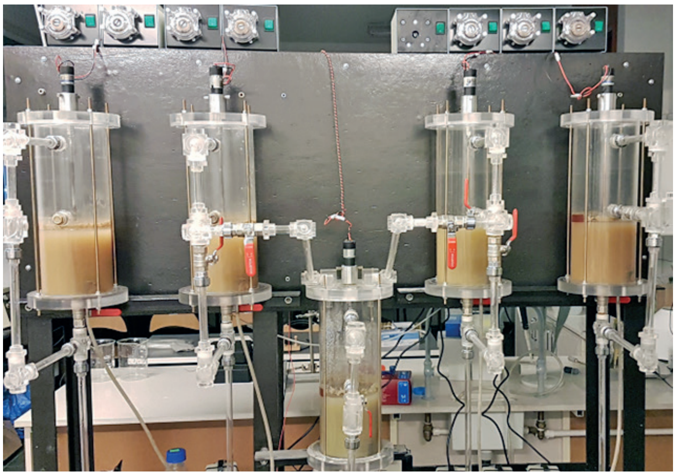

Fig. 2. Reactors used to maintain, feed, aerate and mix the activated sludge for batch sedimentation experiments

In total, 11 batch tests have been performed in a one-liter cylinder for different concentrations and numbered post factum according to the decreasing initial biomass concentration (Table 1). Two tests with the highest initial concentrations (1 and 2) resulted in batch tests in which the compression of sludge started right after the beginning of the experiment. The tests were carried out over a period of one week, thus it was assumed that the settling characteristics of the activated sludge remained unchanged.

Images were acquired using Nikon D5300 DSLR camera with AF-S Nikkor 18–140 mm lens, set to about 55 mm to obtain a field of view containing the whole cylinder and the numbered markers denoting a particular batch experiment (Fig. 3). Distance from the camera to the settling column was 200 cm and the camera was placed on a tripod at the level of the 500 ml mark. A white background for the cylinder was provided for regular tests. Additionally, different background colors were used to test the robustness of the proposed method.

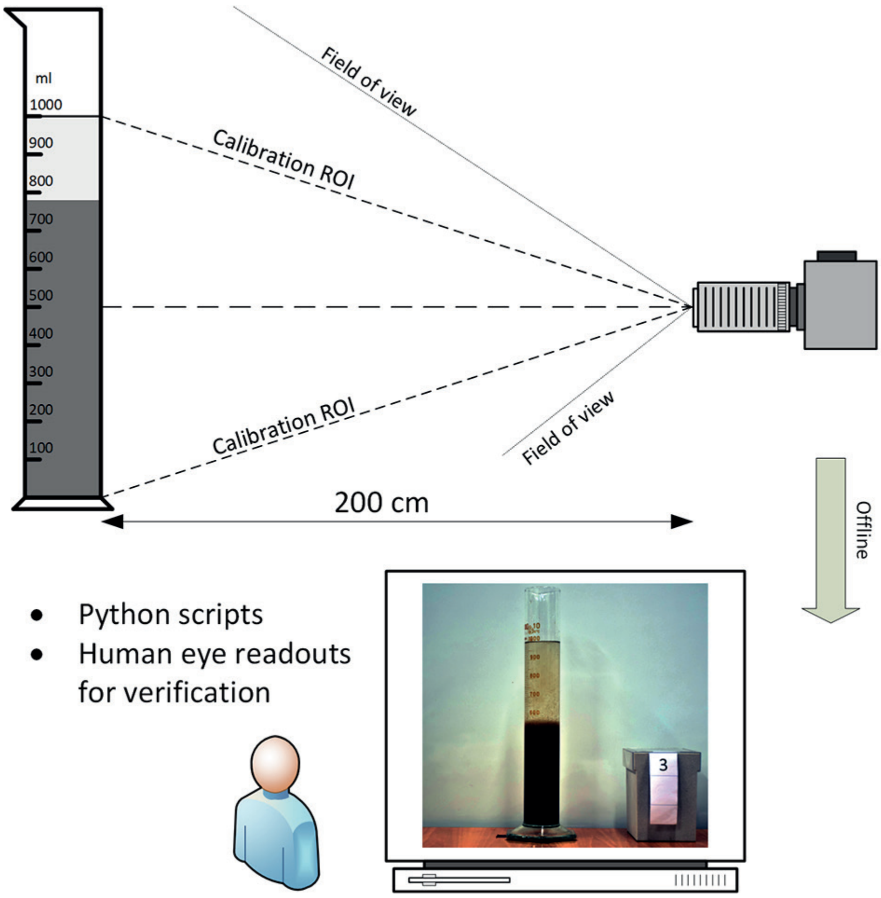

Fig. 3. Image acquisition setup

Pictures were acquired every 10 seconds for up to 60 minutes using the camera timing function and saved in JPEG format (basic quality and resolution of 6000×4000 pixels). Autofocus function was disabled to prevent slight variations in the acquired images.

For the detection of SBH and SV, a Python script was developed. It provides a basic interface for selecting the sequence of images, asks the user to mark the necessary regions of interest and boundaries of the settler on the first image from the sequence and saves all results.

The necessary markings are: (1) general outline of the settler to reduce the amount of processed data. This outline should preferably avoid any markings or labels on the cylinder, and it should point to the region in which the settling sludge is present. However, any background area that does not belong to the settler will be automatically rejected by the algorithm and will not influence the result in any significant way; (2) a region of interest (ROI) marking the activated sludge for model histogram determination; (3) liquid level in the settler and (4) bottom of the settler (Fig. 4).

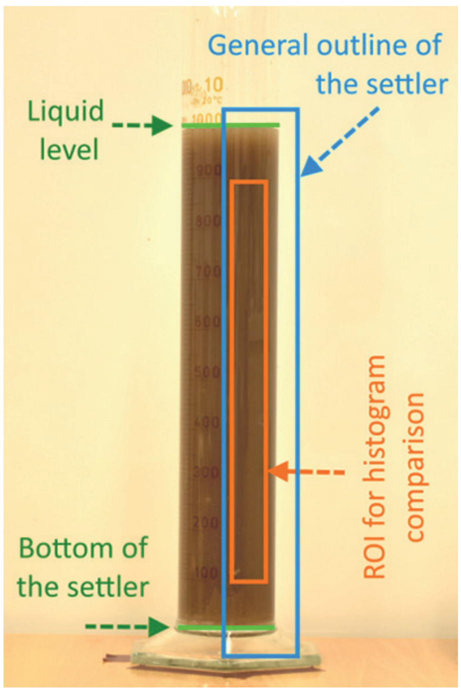

Fig. 4. User selected markings and regions of the first picture in a sequence: 1) General outline of the settler; 2) ROI for histogram comparison; 3) Liquid level; 4) Bottom of the settler

2.2. Algorithm for sludge blanket height determination. The algorithm for automatic measurements of SBH is based on histogram back-projection and was developed using Python and the OpenCV module (Fig. 5):

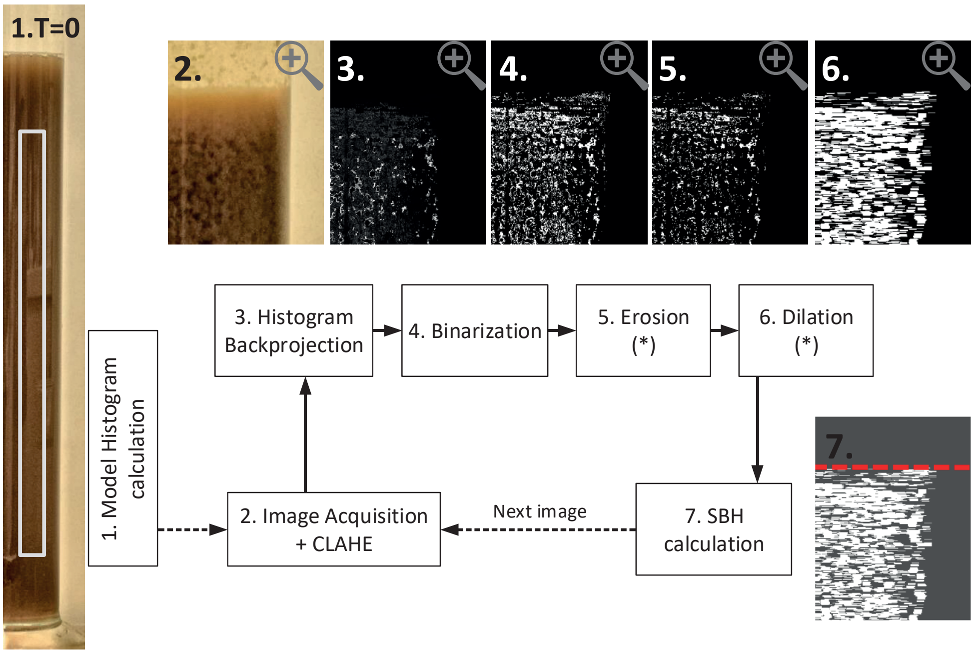

Fig. 5. Image processing algorithm for sludge blanket height (SHB) calculation. (*) Steps not required in a well-controlled environment

1. Model histogram of the sludge is obtained from the ROI indicated by the operator, based on the first image in the acquired sequence.
2. Contrast of an image is additionally improved to differentiate areas containing sludge more accurately from the rest of image. For this purpose, the Contrast Limited Adaptive Histogram Equalization (CLAHE) procedure is applied [22].
3. Histogram back-projection algorithm is performed [23]. The result is a single channel pixel map in which pixel values are interpreted as the probability that the given pixel represents the sludge corresponding to the model histogram. All pixels that significantly differ from pixels contained in the ROI used for model histogram determination form a homogenous background, significantly reducing the amount of irrelevant data on the image. Additionally, top 1% of tank height is cut out to eliminate the sludge that often floats on the surface and may be incorrectly detected by the algorithm as the top of the sludge blanket.
4. The obtained image is then binarized. Niblack's local binarization is used [24] due to the presence of disturbances originating from light reflections, high heterogeneity of the sludge texture and because the top of the sludge is usually brighter than the rest of the sludge region.
5. The obtained binarized image is eroded using pixel-wide horizontal line as a structuring element. The purpose of using this morphological operation is to get rid of incorrectly detected pixels that are usually parts of free sludge flocs suspended in water.
6. Dilation is then used to rebuild the remaining, horizontally oriented pixel groups that represent the level of the activated sludge. The structuring element used for dilation has a form of a horizontal line that is longer than the one used for erosion; therefore, the remaining horizontal pixel structures are additionally highlighted.
7. The sum of pixels representing the sludge is calculated for each row and the obtained vector is normalized to a 0–255 range. This vector represents the cumulative probability that the activated sludge is present at the given level in the settler. The highest row in which the sum is above the threshold value is considered to be the sludge blanket height (SBH). The threshold value is calculated as a percentage of the highest amount of sludge representing pixels in a given row (75 or about 30%) and was obtained experimentally. In general, using large threshold values results in stable measurements, but with a larger constant offset, while usage of smaller threshold values reduces the constant offset but results in larger errors.

The ROI used for histogram comparison may indirectly influence results of SBH measurements. Therefore, the ROI should be selected in a region that is representative of the activated sludge and does not include the effects like significant light reflections or markings on the cylinder. The size of the ROI should preferably cover the widest area possible in order to cancel any irregularities in the image. In practice, however, the same results were obtained for square ROIs half the size of the column width and the highest possible ROIs not containing unwanted effects.

In a controlled environment where free floating flocs are not significant, erosion and dilation in steps 5 and 6 can be omitted and simple binarization method can be used (global thresholding, for example). However, those steps are added for the increased algorithm reliability in a wide range of conditions.

2.3. Zone settling velocity determination. The determined values of SBH are used on-line to determine the maximum sludge velocity (SV_{max}) during the batch test. The SV_{max} velocity is equivalent to the zone settling velocity (ZSV) which quantifies the settling properties of the activated sludge [10]. Sludge blanket velocity at any given time is calculated using the following equation:

$$SV_i = -\frac{(SBH_i - SBH_{i-5})}{(t_i - t_{i-5})}, \tag{2}$$

where SBH_i is the sludge level height in the i-th measurement and t_i is the timestamp of that measurement. Because images are taken every 10 seconds, SV is measured based on the current SBH and the SBH 50 seconds before. In the next step, the obtained velocity value is filtered using Savitzky-Golay's filter with the first order polynomial and window length of 7 measurements. Because this filter requires the usage of symmetrical window, the given velocity value is filtered after 3 new velocity measurements are acquired.

Mean values are used to detect the maximum sludge velocity (SV_{max}). The algorithm calculates the mean velocity for the last minute. The highest mean velocity is remembered for the whole experiment, and when the current velocity falls below 80% of the already calculated maximum value, the searching is stopped, and the current maximum velocity value is returned as ZSV.

In the cases of high initial concentrations of the activated sludge, no zone settling will be observed. SBH will decrease slowly and no maximum sludge velocity will be detected. In such cases, the algorithm stops after 30 minutes and SV_{max} is determined by calculating mean SV value from a 10-minute window located symmetrically around the detected maximum velocity value. If that window exceeds 0–30-minute time range, its length is reduced. The obtained mean SV value is then returned as ZSV.

3. Experimental results

Figure 6 presents the obtained sedimentation curves for the 11 batch tests and the plot of differences between automatic and manual (visual) SBH values. White background was used. Manual and automatic readings agree consistently. However, a constant error, which is less than 2% of the measurement

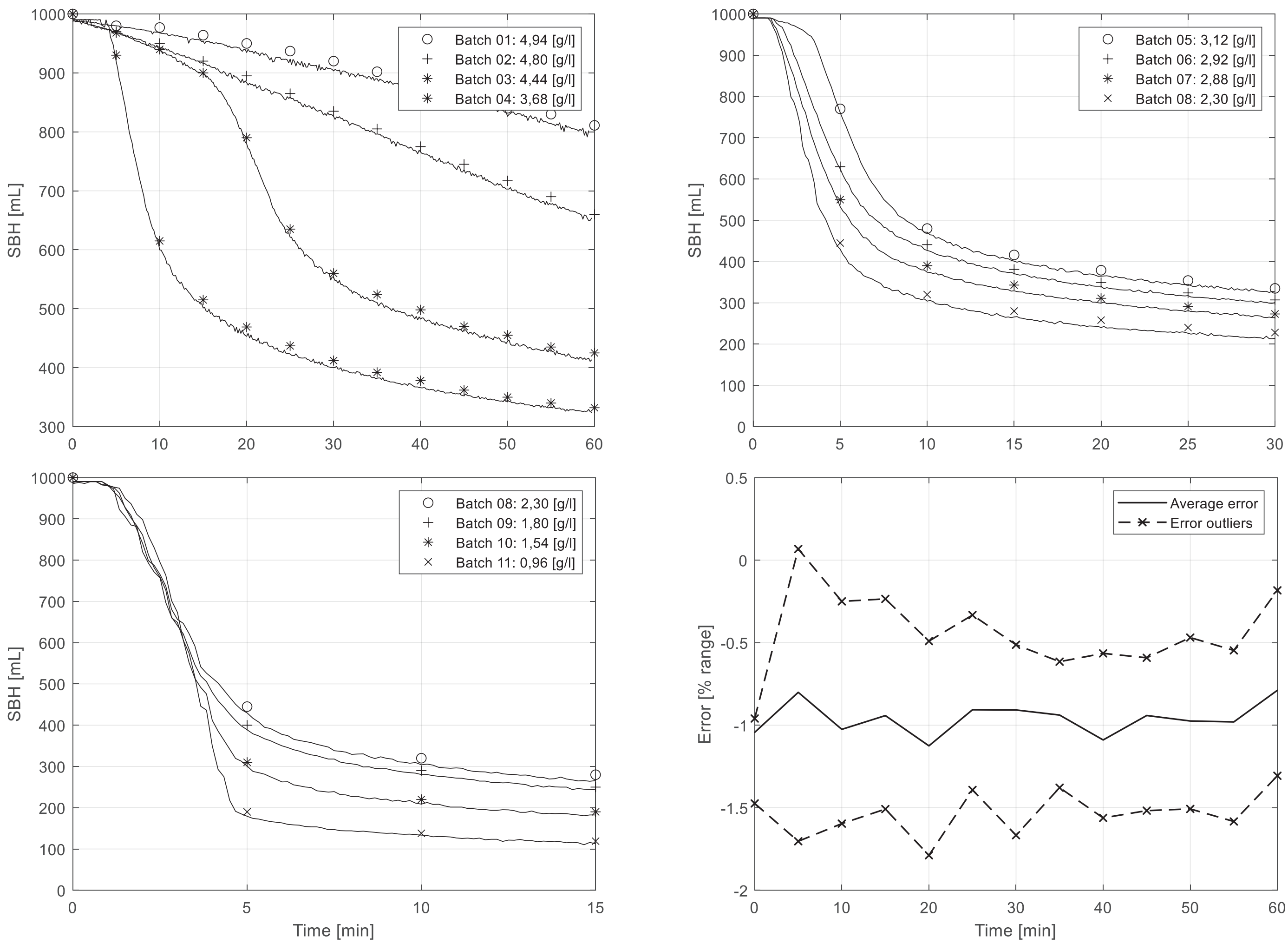

Fig. 6. Sludge blanket height measured by the proposed algorithm (lines) and comparison with manual data (points)

range, is visible. The calculated mean error is −9,74 mL, which is about 1% of the range. This bias results from the nature of the image processing method because the area of the activated sludge near the border of the sludge area has a lower probability of belonging to the sludge region, usually due to the higher light intensity. This bias can be estimated and compensated when accurate SBH values are needed for the precise identification of the sedimentation model parameters based on the settling curve. On the other hand, a constant SBH bias does not influence the velocity estimate and is within the expected error due to differences in calibration and discrepancies caused by parallax in the acquired pictures.

3.1. Determination of zone settling velocity. Figure 7 and Table 1 present estimates of ZSV for the selected tests. For high initial sludge concentrations (4,94 g/l and 4,80 g/l), the settling regime goes straight into sedimentation with compression. Therefore, no peak of SV is identified. For tests exhibiting zone settling behavior, a peak SV is clearly visible, and enables SV_{max} and thus ZSV to be estimated. The slope of the dashed lines in Fig. 7 corresponds to the calculated ZSV and intersects the point on the SBH plot corresponding to the detection of the

Table 1
Calculated zone settling velocities (ZSV) and times of ZSV determination

Batch test number	X_0 [mg/l]	ZSV [mL/min]	Time of ZSV determination [min]
1$^{(*)}$	4.94	4.2$^{(*)}$	30$^{(*)}$
2$^{(*)}$	4.80	6.2$^{(*)}$	30$^{(*)}$
3	4.44	36.6	21.5
4	3.68	78.8	5.83
5	3.12	115.9	4.83
6	2.92	112.2	3.3
7	2.88	139.5	3.0
8	2.30	174.3	2.6
9	1.80	180.3	3.0
10	1.54	221.6	3.3
11	0.96	301.6	3.7

Note $^{(*)}$: No peak zone settling velocity detected

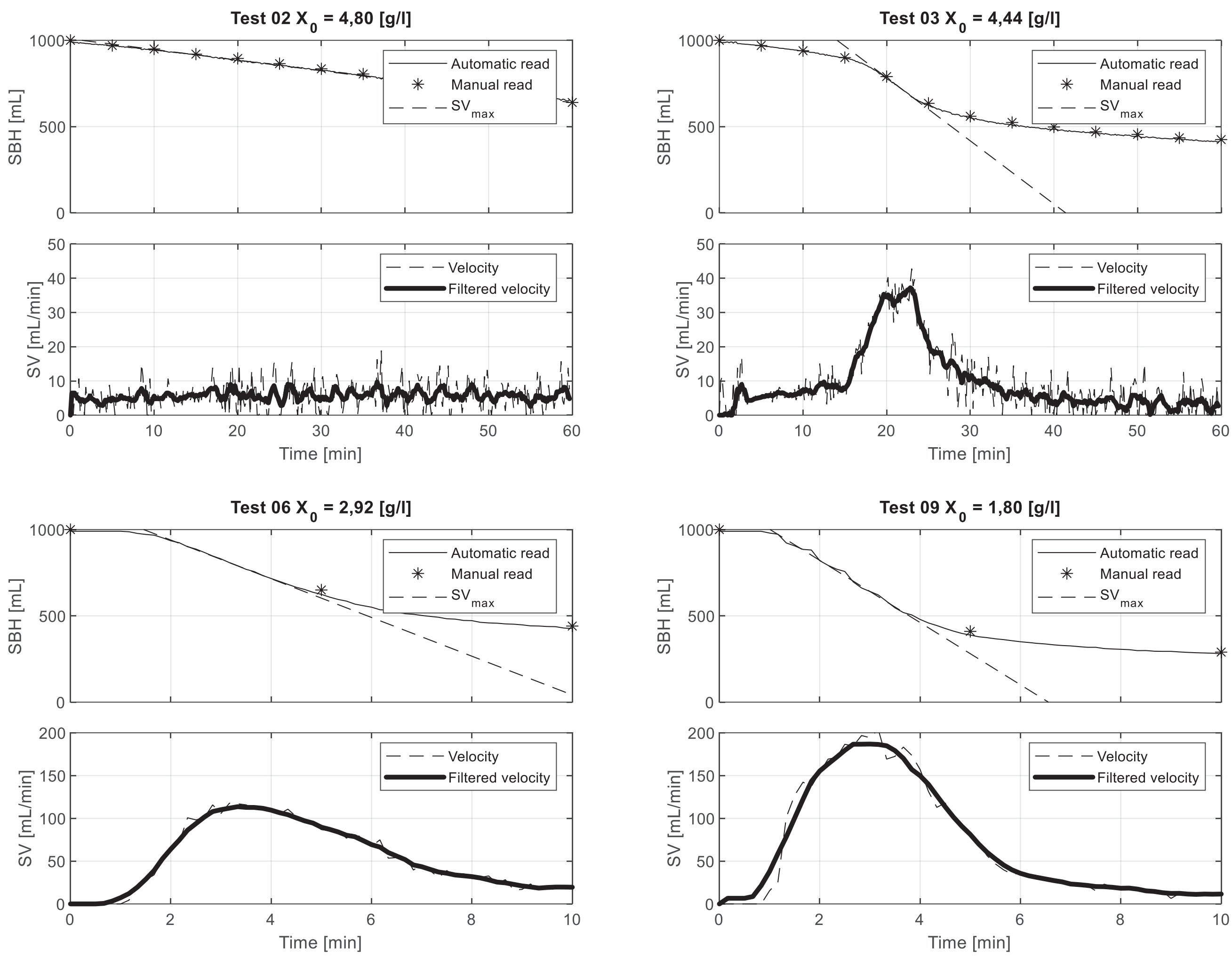

Fig. 7. Selected results visualizing maximum SBH rate of change and measured sludge velocities (SV)

maximum settling velocity. As can be seen, the detected maximum velocities closely match the slope of SBH, thus validating the proposed method of ZSV calculation.

3.2. Determination of settling velocity function parameters. Table 1 presents the calculated zone settling velocities. The obtained zone settling velocities expressed as a function of initial activated sludge concentration form the basic dependency behind the models of the sedimentation process and facilitate the identification of the settling velocity function parameters (Eq. 1). For the identification, only tests with the detected peak of settling velocity were used (3–11), as only those experiments represented the zone settling behavior of the activated sludge. Figure 8 presents this dependency for the identified parameters $v_{max} = 467$ mL/min, $n = 0.47$ l/g. The mean square error (MSE) of approximation was 11,34 mL/min.

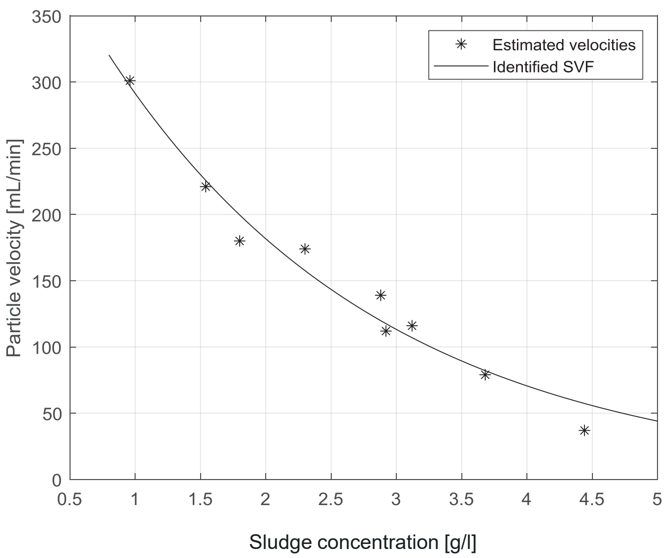

Fig. 8. Settling velocity function based on tests 1–11 ($v_{max} = 467$ mL/min, $n = 0.47$ g/l). MSE: 11.34 mL/min

3.3. Sensitivity to different light intensity profiles. The main advantage of the histogram back-projection algorithm is its robustness with respect to the changing light intensity profiles for different colors of sludge and/or supernatant. To simulate such situations, 4 batch tests were performed with red, green, blue, and orange backgrounds, respectively. Figure 9 shows the sludge blanket interface regions with the horizontal line in each image representing the SBH calculated using the proposed method, while Fig. 10 presents red, green, and blue color intensity profiles for the four background colors used. As can be seen, depending on the dominant color in the upper region of the settler, the shape of the individual light intensity profiles changes significantly especially for the red channel.

Figure 11 presents the obtained settling curves and the differences between SBH values obtained by the algorithm and values obtained by visual inspection. The differences between SBH estimation for different background colors are less than 2%.

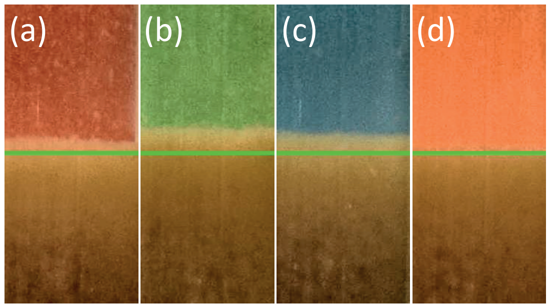

Fig. 9. Images of sludge interface for: a) red; b) green; c) blue and d) orange background. Detected SBH marked by a horizontal line

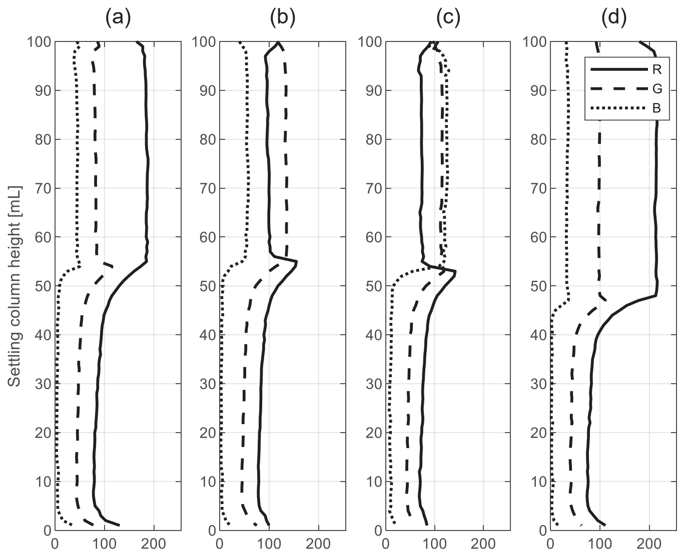

Fig. 10. R, G, B intensity profiles for different background colors. Backgrounds: a) red; b) green; c) blue and d) orange

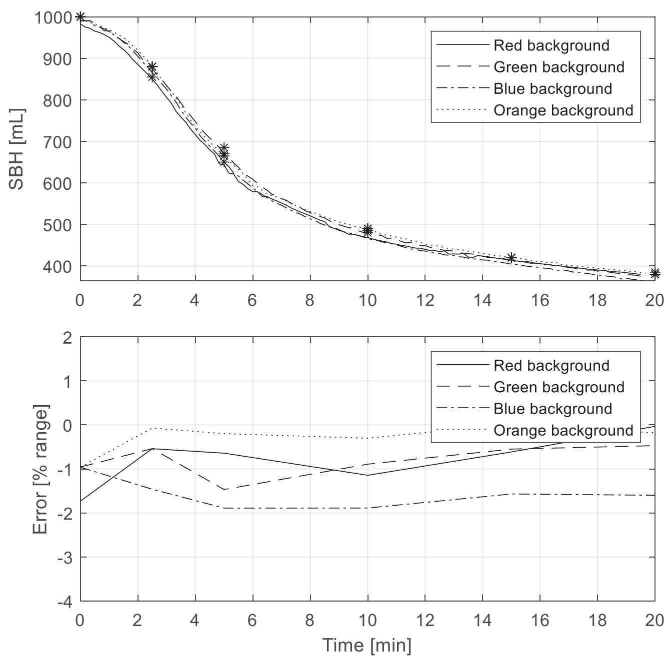

Fig. 11. Batch tests and errors with respect to visual observations (*) for different background colors

4. Concluding remarks

The paper presented and verified a method for automatic measurement of the sludge blanket height (SBH) during a batch sedimentation test based on image analysis. The presented method complements the suite of methods used for this purpose and has the following advantages:

- By employing the histogram back-projection algorithm, the proposed method can be used with different kinds of sludge, possessing different coloring characteristics, both in the sludge color and the color of supernatant produced, as long as the sludge has different visual characteristic with respect to the supernatant.
- Because individual pixels in the acquired image are compared with the histogram of the representative sludge region, the method neither relies on any assumed shape of the light intensity profile nor on the dominant sludge or background color. The histogram is acquired at the beginning of every sedimentation test.
- The method utilizes off-the-shelf image processing algorithms available in programming languages that support libraries for image acquisition and processing. Therefore, implementation of the proposed method is straightforward and does not require advanced mathematic computations to be additionally coded and tested.
- No calibration is required with respect sludge characteristics. Initial marking of the bottom and top of the settler are needed and a region containing a representative view of the sludge at the beginning of settling needs to be specified by the user.

Additionally, an algorithm for the zone settling velocity (ZSV) estimation during the batch settling experiment has been proposed. It enables the result to be obtained before the batch experiment is finished. Therefore, real-time control of the secondary clarifier and the recycle of the activated sludge can be enhanced by minimizing the delay caused by the measurement. Although, the algorithm has been verified together with the proposed histogram back-projection algorithm, other methods for SBH measurement can also be coupled with this algorithm.

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