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Investigation of the sludge thickening potential of waste activated sludge using membranes

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ABSTRACT

Sludge thickening with membranes, especially external membranes, is recently emerging. In this study the feasibility of external membranes for thickening of waste activated sludge up to 30 g l^{-1} was studied using a test cell. In batch-wise thickening experiments, the characteristics of the filtration process under various operating conditions (w = 0.8–2 m s^{-1}, TMP = 1–1.8 bar) and with different membranes (four UF membranes, one MF membrane) were investigated. For the different membranes no considerable difference in the sludge thickening behaviour was observed, despite huge variations in membrane pore size and water permeability. By increasing the cross-flow velocity, significant improvements in permeability could be achieved, whereas an increase in TMP at constant cross-flow velocity slightly deteriorated the permeability during the sludge thickening. The obtained permeabilities of 15–20 l m^{-2} h^{-1} bar^{-1} at MLSS concentrations higher than 30 g l^{-1} are economical and, therefore this process is an alternative to conventional sludge thickening processes. In order to investigate the continuous operation of the sludge thickening process, filtration at constant MLSS concentration of approx. 30 g l^{-1} was investigated. During the constant MLSS operation, a slight decrease in permeability was observed. Long-term experiments indicate that batch-wise thickening of sludge is feasible with permeabilities of 10–15 l m^{-2} h^{-1} bar^{-1}.

Keywords: Sludge thickening; External membrane; Permeability; Test cell; Batch experiments

1. Introduction

Large amounts of waste activated sludge are produced in a wastewater treatment plant. For sludge volume reduction, thickening and dewatering are normally applied. The commonly used methods like gravity thickening, dissolved air flotation and centrifugal thickening have some disadvantages like either large footprint combined with a low thickening efficiency or high energy demand.

In some wastewater treatment applications where limited space is available, for example on ships, membrane bioreactors are used for wastewater treatment but still much space is needed for sludge storage. Although the biomass concentration in MBRs is higher than in the conventional activated sludge process, some kind of sludge volume reduction is still needed. By sludge thickening directly on the ships it is either possible to reduce the sludge storage tank or the ships can stay longer at the sea.

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A new concept to save valuable space is the thickening of excess sludge up to 30 g l^{-1} using membranes.

Sidestream MBRs offer a number of advantages [1,2]:

- Easy membrane maintenance without any chemical risk to the biomass.
- It is generally possible to operate sMBRs at higher MLSS levels.
- Fouling has been shown to decrease linearly with increasing cross-flow velocity.
- Better control of hydrodynamic conditions along the membrane.

Nevertheless, sidestream MBRs have a higher fouling potential than submerged MBRs since higher flux operation always results in lower permeabilities because fouling itself increases with increasing flux [1]. Typical reported permeabilities for full scale sidestream MBRs vary between 20 and 40 l m^{-2} h^{-1} bar^{-1} for MLSS concentrations between 8 and 15 g l^{-1} [1].

Wang et al. successfully concentrated activated sludge from a conventional wastewater treatment plant up to 30 g l^{-1}MLSS in a continuously operated submerged membrane bioreactor [3]. The membrane permeability decreased from initially 200 to 20 l m^{-2} h^{-1} bar^{-1} after 30 d. Membrane fouling was mainly due to an increase in apparent viscosity with MLSS and a resulting decrease in cross-flow velocity. Therefore using external membranes could be beneficial due to a better control of hydrodynamic conditions within the system.

Kim et al. operated a submerged MBR for sludge thickening of activated sludge [4]. The plant could be run soundly with a flux of 10–16 l m^{-2} h^{-1} up to 30 g l^{-1}. Additionally, sludge reduction of 60% by aerobic digestion was achieved, due to the long residence time of the sludge in the reactor (64 d). Further increase in MLSS concentration caused a dramatic increase in TMP with simultaneous decline of membrane flux.

Furthermore, better effluent qualities were obtained than those of conventional thickening technologies [3,4].

Wang et al. studied the fouling mechanisms in more detail in a membrane reactor for simultaneous sludge thickening and digestion of activated sludge and worked out that viscosity, capillary suction time (CST), soluable microbial products (SMP) and COD concentration of colloids have significant influence on membrane fouling [5]. The influence of increasing MLSS concentration on sludge viscosity has been shown by many authors [6–8].

In this study the advantages of external membranes are combined with the new approach of sludge thickening with membranes. In contrast to the sludge thickening with submerged membranes a better control of the hydrodynamic conditions is possible with external membranes so that they are generally be used for higher MLSS concentrations. In a first step, the applicability of 4 different external membranes (UF and MF) for sludge thickening was studied. Furthermore, the influence of operating conditions on the performance of external membranes, that is membrane permeability, for sludge thickening was investigated.

2. Material and methods

In this study, the applicability of external membranes for sludge thickening of waste activated sludge from a membrane bioreactor was investigated using a test cell (*see* Fig. 1). The test cell, which was designed in our laboratory specifically for biological sludges, was operated at variable cross-flow velocities (0.8–2.0 m s^{-1}) and different transmembrane pressures (1–2 bar), which are typical for external membrane modules. All experiments were done at constant pressure with 8 min filtration and 2 min relaxation. The gap width above the membrane was 3 mm which is a typical value of spacing in cushion modules.

Sludge samples were taken from the membrane tank of a decentralised MBR treating municipal wastewater and were screened with a 2.8 mm screen before the experiment. The MLSS concentration of the sludge ranged between 15 and 20 g l^{-1}. The sludge was kept at a constant temperature of 35°C ± 3°C. In small size sidestream MBRs higher temperatures can occur due to the power input by the pumps, moreover, higher temperatures also improve permeability. Transmembrane pressure, cross-flow velocity and flux were monitored continuously and samples for MLSS and viscosity analyses were taken regularly.

For each experiment, a new membrane was used, which was soaked in deionised water for 12 h before the experiment.

To investigate the influence of membrane material and pore size on the sludge thickening process, experiments with four different UF membranes and one MF membrane were performed. Initially, the MBR sludge

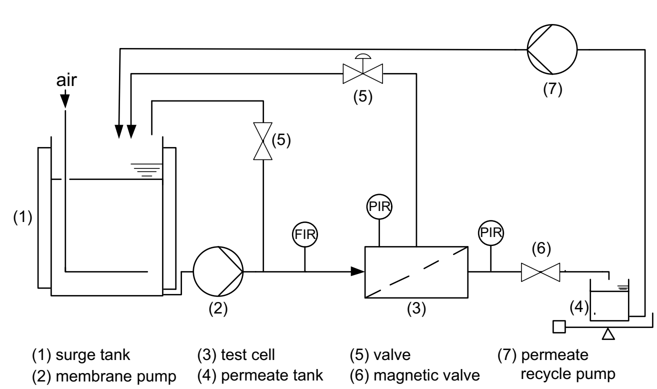

Fig. 1. Experimental set-up of the sludge thickening device.

Table 1
Investigated membrane materials

Notation	Material	Nominal MWCO/ pore size	Water permeability given by supplier [l m^{-2} h^{-1} bar^{-1}]	Measured water permeability [l m^{-2} h^{-1} bar^{-1}]
PS30	PS	20 kDa	1200	1000–1300
PS35	PS	20 kDa	1600	1400–1800
PAN200	PAN	20 kDa	300	600–700
PAN450	PAN	20 kDa	1200	1800–2000
PVDF	PVDF	0.2 µm	1500	n.a.

was concentrated batch-wise at a TMP of 1.8 bar and a cross-flow velocity of 2 m s^{-1} up to a MLSS concentration of 30 g l^{-1}. Then the permeate recycle was switched on for approximately 12 h and the filtration was operated at constant elevated MLSS concentration. As can be seen from Table 1, water permeability of the different membranes given by the manufacturer varied strongly between 300 and 1,600 l m^{-2} h^{-1} bar^{-1}.

The effect of operational parameters on the sludge thickening process was investigated in batch-wise thickening experiments with the membrane PS30. The cross-flow velocity (w = 0.8–2 m s^{-1}) and the transmembrane pressure (TMP = 1–1.8 bar) were varied. However, a constant transmembrane pressure could not be achieved throughout the experiments. The increase of viscosity with time causes a shift of the pump capacity curve. This induced a slight decrease of TMP during the experiment.

3. Results and discussion

3.1. Typical sludge thickening experiment

In Fig. 2, the characteristics of operational and process parameters for an arbitrary experiment are shown. In this experiment, the PAN450 membrane was used

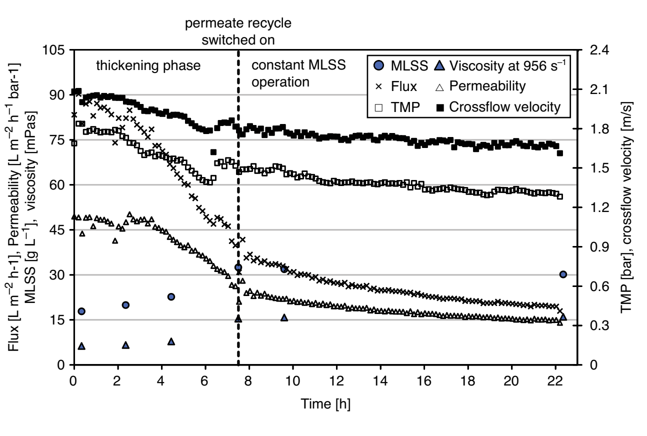

Fig. 2. Typical sludge thickening experiment and the characteristics of operational and process parameters.

and initial set values for TMP and cross-flow velocity were 1.8 bar and 2 m s^{-1}, respectively. After 7.5 h, the batch-wise thickening was stopped at a MLSS concentration of 32.5 g l^{-1} by switching on the permeate recycle to operate the membrane at a constant high MLSS concentration for approx. 12 h.

Differences between measured and calculated MLSS concentrations vary between 2% and 10% and are within the measurement accuracy. Within this short time of experiment digestion is of little importance. At higher cross-flow velocities sometimes foam occurred in the surge tank which resulted in variations of measured and calculated MLSS concentrations of up to 30%. Anti-foam was used sparingly to suppress the formation of foam.

Due to cake formation and the increasing viscosity at higher biomass concentrations, TMP decreases continuously from initially 1.8 to 1.3 bar and cross-flow velocity declines slightly from 2 to 1.7 m s^{-1}.This slight decrease of the cross-flow velocity is caused by a shift in the pump capacity curve. A decrease in cross-flow velocity with MLSS concentration was also observed by Wang et al. [3]. As can be seen from Fig. 2, the viscosity at a shear rate of 954 s^{-1} increases from 6 to 16 mPas when MLSS concentration is nearly doubled. During the first 4 h permeability stays quite constant and then declines continuously, whereas the decrease is more pronounced during the thickening step, but still identifiable during the constant MLSS operation. The constant permeability at the beginning of the experiment is maybe due to the relatively low MLSS concentrations and the still very high cross-flow velocity.

3.2. Rheology of activated sludge

Activated sludge is known to be a non-Newtonian fluid [8,9]. The apparent viscosity μ_a influences the fluid dynamics strongly and is a function of MLSS concentration and shear rate applied. For each experiment five to eight viscosity measurements were carried out. The calculated apparent viscosities corrected to 21°C are shown in Fig. 3 at two different shear rates. In external membrane modules shear rate of about 1,000 s^{-1} appear, due

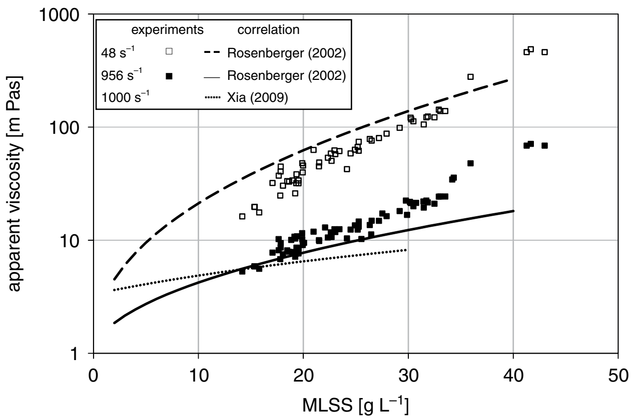

Fig. 3. Apparent viscosity at different shear rates for different MLSS concentrations.

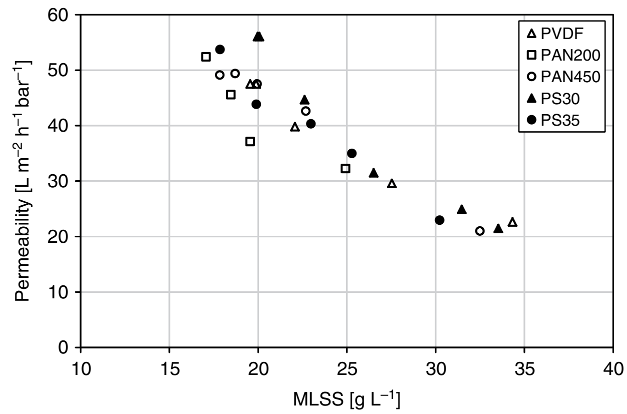

Fig. 4. Comparison of the permeability at different MLSS concentrations for various membrane materials under the same operational conditions (TMP = 1.8 ± 0.4 bar, $w = 2 \pm 0.4$ m s^{-1}).

to the relatively high cross-flow velocities. A duplication of the MLSS concentration from 15 to 30 g l^{-1} results in a triplication of apparent viscosity. In total the apparent viscosity increases exponentially. Thus, the hydrodynamic conditions along the membrane change dramatically at constant pump performance.

Rosenberger et al. [8] analysed the apparent viscosity of many different activated sludges at a temperature of 21°C as a function of MLSS concentration (3–40 g l^{-1}) and shear rate [8]. The apparent viscosity was independent of the operational conditions and the type of wastewater. Based on the Ostwald-de Waele approach they found the following correlation for the apparent viscosity:

$$\mu_a = \exp(2 \cdot \mathrm{MLSS}^{0.41}) \cdot \left(\frac{\mathrm{d}w}{\mathrm{d}y}\right)^{(-0.23 \cdot MLSS^{0.37})}$$

The results obtained with the correlation by Rosenberger et al. [8] at a shear rate of 48 and 956 s^{-1} is also shown in Fig. 3. At a shear rate of 48 s^{-1} the obtained apparent viscosities in this study are slightly lower than predicted by the correlation of Rosenberger et al., [8] whereas at a shear rate of 956 s^{-1} higher apparent viscosities are obtained, especially for elevated MLSS concentrations [8]. The apparent viscosities obtained by Xia et al., are very low, but here the temperature is not known [10].

3.3. Comparison of different membrane materials on sludge thickening process

In order to study the influence of membrane material and membrane properties on the sludge thickening process, four different UF membranes and one MF membrane were tested at the same operational parameters (TMP = 1.8 bar, $w = 2$ m s^{-1}). Measured water permeabilities were in the range given by the manufacturer (*see* Table 1) except for PAN 200 with an experimentally determined water permeability of 600 l m^{-2} h^{-1} bar^{-1}.

Initial MLSS concentrations of the experiments varied between 17 and 20 g l^{-1}. In Fig. 4, the change of permeability for the thickening process is shown. Initial permeabilities are in the same range and vary for the different membranes between 47 and 56 l m^{-2} h^{-1} bar^{-1}, despite a remarkable difference in the water permeability up to a factor of 3. By starting the sludge thickening process, MLSS concentration increases with a simultaneous decrease in permeability. At the end of the thickening process, after having achieved the desired MLSS concentration of 30–35 g l^{-1}, permeability has dropped to 21–23 l m^{-2} h^{-1} bar^{-1}. However, for the different membranes no considerable difference in the sludge thickening behaviour is observable, despite huge variations in membrane pore size and water permeability. Obviously the deposition of foulants limits the flux and permeability.

3.4. Comparison of different operating conditions on the sludge thickening process

The influence of operating conditions on the sludge thickening process was investigated using the PS30 membrane. TMP was varied between 1 and 1.8 bar and cross-flow velocity was shifted between 0.8 and 2 m s^{-1}.

The change in permeability at the different operating conditions for the thickening process is shown in Fig. 5. Sludge thickening up to 30 g l^{-1} could not be achieved with a very low velocity of 0.8 m s^{-1} and a TMP of 1 bar. In this case, initial permeability was very high with 80 l m^{-2} h^{-1} bar^{-1} but dropped very fast to zero when 23 g l^{-1} were reached. By increasing the velocity, permeability values in the thickening process are considerably higher. The sparingly use of anti-foam at higher velocities did not negatively affect the permeabilities, which is sometimes reported in literature. An increase in the velocity from

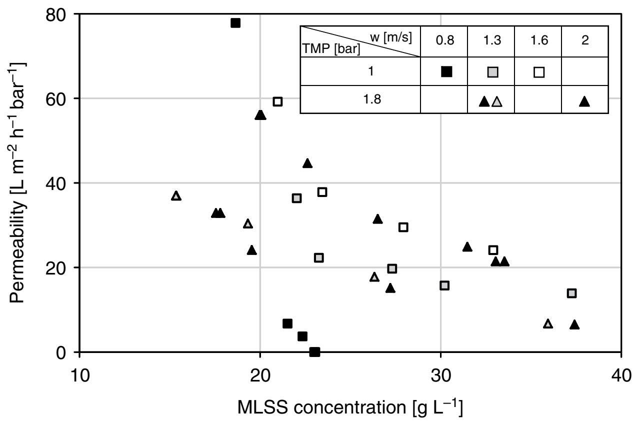

Fig. 5. Variation of permeability with MLSS concentration for different cross-flow velocities and transmembrane pressures.

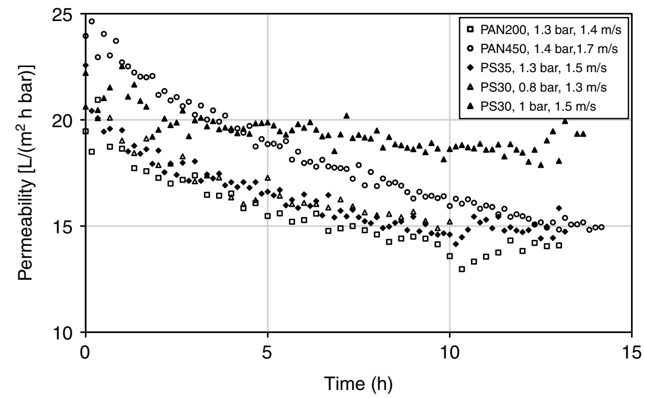

Fig. 6. Variation of permeability with time for continuous thickening at constant MLSS concentration.

1.3 to 1.6 m s^{-1} caused an increase in the permeability of 50% for the sludge thickening process. This could be explained by a more permeable filter cake at higher velocities.

An increase in the TMP did not have a strong effect on the thickening process. Comparing the two experiments at a cross-flow velocity of 1.3 m s^{-1} and different transmembrane pressures of 1 and 1.8 bar, respectively, an increase in TMP slightly decreased the permeability. Also the experiment done at 1.8 bar and 2 m s^{-1} did not improve the permeability compared to the experiment performed at 1 bar and 1.6 m s^{-1}.

Although an increase in TMP at constant cross-flow velocity slightly deteriorates the permeability during the sludge thickening - higher fluxes are still obtained at higher transmembrane pressures. At higher TMP more energy is required to maintain operating conditions, while at lower pressures more membrane area is needed. The optimal operational conditions are therefore dependent on costs for energy and membrane material.

3.5. Constant MLSS operation

In order to investigate the continuous operation of the sludge thickening process, the permeate recycle was switched on after reaching the desired MLSS concentration of approx. 30 g l^{-1} in the batch-wise thickening step. The operational conditions of cross-flow velocity and TMP during this process results from the operational conditions set in the batch-wise thickening step and the influence of rising viscosity with increasing MLSS concentration on these parameters. In Fig. 6, the change in permeability with time for the continuous thickening process at constant MLSS concentration is shown. Initial MLSS concentrations vary between 29 and 32.5 g l^{-1} for the different experiments and fluctuate by 7% within one experiment.

As can be seen from Fig. 6, the initial permeability at MLSS concentrations of approx. 30 g l^{-1} varies between 20 and 25 l m^{-2} h^{-1} bar^{-1}, which does not correlate with the initial MLSS concentration. The initial permeability is just a result of the batch-wise thickening step before and the sludge characteristics. However, during the continuous thickening process a slight decrease in permeability can be observed for all experiments independent of the operational conditions. Sometimes the decrease in permeability is more pronounced like for the experiment with the PAN450 membrane showing a decline of 0.64 l m^{-2} h^{-1} bar^{-1} per hour and sometimes it is less distinct as for the PS30 membrane with a decline of permeability of only 0.31 l m^{-2} h^{-1} bar^{-1} per hour. It seems that after 10 h a constant permeability is reached for all experiments except for the one with the PAN450 membrane.

Compared to literature values for sidestream membranes, the obtained permeabilities of 15–20 l m^{-2} h^{-1} bar^{-1} at MLSS concentrations higher than 30 g l^{-1} are in an acceptable range. Typical reported permeabilities for full scale sidestream MBRs vary between 20–40 l m^{-2} h^{-1} bar^{-1} for MLSS concentrations between 8 and 15 g l^{-1}. In submerged MBRs Wang et al. obtained permeabilities of 30–70 l m^{-2} h^{-1} bar^{-1} at 35 g l^{-1} due to lower fluxes applied [5].

3.6. Long-term operation

The long-term behaviour of serveral successive sludge thickening experiments was studied using the membrane PS30 at a TMP of 1.8 bar and a cross-flow velocity of 1.3 m s^{-1}. Between two thickening cycles the membrane was cleaned with water for 5 min. After cleaning, the membrane stayed in water over night, that is for approximately 12 h before the next thickening cycle was started. New sludge was taken after the fourth and the ninth cycle and the sludge was kept aerated in a stored tank. Thus the influence of sludge properties of the excess sludge on the thickening process is negligible over the time of the experiment.

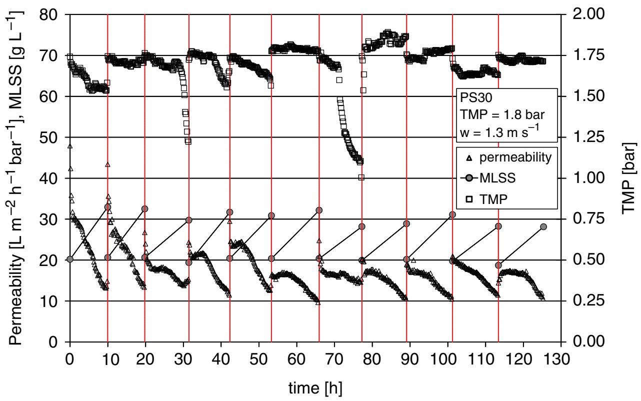

Fig. 7. Evolution of TMP, permeability and MLSS concentration over several successive thickening experiments.

In Fig. 7 the change of TMP, permeability and MLSS concentration is shown for repeated successive thickening experiments. The cross-flow velocity was nearly constant over the time of experiment and varied only by about 5% around the desired value of 1.3 m s^{-1}. In each thickening cycle the sludge was concentrated from initially 20 to 30 ± 2 g l^{-1}. Within the first five cycles the initial permeability dropped from 48 to 24 l m^{-2} h^{-1} bar^{-1}. Nevertheless the final permeability at a MLSS concentration of about 30 g l^{-1} stayed nearly constant at 11–13 l m^{-2} h^{-1} bar^{-1}. After the fifth cycle, the thickening behaviour changes hardly. The strong decrease of the TMP in the 7th cycle is due to a restriction in a tube.

A continuous batch-wise sludge thickening is feasible with permeabilities of 10–15 l m^{-2} h^{-1} bar^{-1}. By an optimization of the cleaning strategy may be higher permeabilities could be achieved. Therefore further experiments are needed.

4. Conclusions

The feasibility of using external membranes for sludge thickening of waste activated sludge was studied using a test cell. In batch-wise thickening experiments, the characteristics of the filtration process under various operating conditions (w = 0.8–2 m s^{-1}, TMP = 1–1.8 bar) and with different membranes (four UF membranes, one MF membrane) were investigated. It was shown that:

- Sludge thickening up to 30 g l^{-1} using external membranes is feasible at permeabilities of 20 l m^{-2} h^{-1} bar^{-1}, which are the lower limit of external membranes.
- Permeability continuously decreases with increasing MLSS concentration and time due to the formation of a filter cake.
- For the different membranes no considerable difference in the sludge thickening behaviour was observed, despite huge variations in membrane pore size and water permeability.
- Increasing cross-flow velocity results in significant improvements in permeability.
- Increase in TMP slightly deteriorates the permeability during the sludge thickening process.

In order to investigate the continuous operation of the sludge thickening process, filtration at constant MLSS concentration of approx. 30 g l^{-1} was investigated for 12 h. During the constant MLSS operation, a slight decrease in permeability can be observed for all experiments independent of the operational conditions. Repeated thickening experiments over five days showed that permeability remained between 10–15 l m^{-2} h^{-1} bar^{-1}.

Symbols

COD	—	chemical oxygen demand
CST	—	capillary suction time
MF	—	microfiltration
MLSS	—	mixed liquor suspended solids
SMP	—	soluble microbial products
TMP	—	transmembrane pressure
UF	—	ultrafiltration

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