Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2013.846235

53 (2015) 940–950
January

Taylor & Francis
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Dynamic filtration—influence of different precipitation agents on the filtration performance using an inside-out filtration module

Christian Loderer[a,*], Bernhard Gahleitner[a], Anna Woerle[b], Werner Fuchs[a]

[a]*Department for Agrobiotechnlogy, University of Natural Resources and Life Sciences, IFA-Tulln, Konrad-Lorenz-Straße 20, Tulln, Vienna 34030, Austria*
Tel. +43 0 2272 66280555; email: christian.loderer@boku.ac.at
[b]*Institute of Environmental Engineering, University of Innsbruck, Technikerstreet 13, Innsbruck 6020, Austria*

Received 25 April 2013; Accepted 13 September 2013

ABSTRACT

Recently, a new type of wastewater treatment system became the focus of scientific research: the dynamic membrane bioreactor. It is a modification of the membrane bioreactor (MBR), with the main difference that a mesh filter is used instead of the membrane for sludge separation. The effluent is not of the same excellent quality as with MBRs due to the much larger size of the mesh openings. Nevertheless, the new system has all the other advantages of MBRs, including substitution of the settling tank as well as elevated sludge concentration resulting in decreased basin volumes. However, so far little experience on performance under practical conditions is available. In this study, for the first time, results concerning the impact of different precipitation agents on filtration performance are reported. Correlation between precipitation agents, the mesh size and the operational conditions was investigated. For this purpose, dead end and cross-flow filtration tests were carried out using real wastewater samples. According to the experience, flocculation strongly interferes with the dynamic filtration process. In contrast to initial expectations, lower filtrate quality compared with the untreated reference was observed. Despite on the observed impact of flocculation on the filtration performance, dependent on the type of flocculating agent, the dynamic filtration system can be efficiently used for phosphorus removal applications.

Keywords: Dynamic filtration; Precipitant agents; Inside-out module configuration; Different cross-flow velocities; Long-term performance

1. Introduction

The membrane bioreactor (MBR) is an option of choice that has been extensively employed in advanced wastewater treatment [1,2]. MBRs offer two main advantages: a significantly improved effluent quality; and a substantially smaller footprint, due to high mixed liquor suspended solid concentration and the absence of a secondary settling tank [3–5]. So far, unavoidable membrane fouling and the high cost of membranes are major obstacles to the wide application of MBRs [6]. In recent years, there is an increased interest in the development of efficient procedures to mitigate the fouling of membrane in MBRs [7,8]. In this context, low-cost filter materials, including woven and nonwoven fabrics, with lager mesh sizes (10–120 μm) can be considered as a suitable alternative

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*Corresponding author.

to the conventional membrane. The principle of this type of filtration system is as follows: Through filtration of the activated sludge a cake layer is formed on the underlying macroporous material that acts as a new separation membrane called dynamic membrane [9]. Dynamic membrane filtration offers higher flux rates at lower transfilter pressures resulting in less energy consumption. This new type of wastewater treatment system shows also high potential as an alternative to the conventional activated sludge system and to retrofit plants that operate on their hydraulic limits. Different researchers studied the performance of dynamic filtration bioreactors under various conditions to investigate, e.g. the influence of different mesh sizes and different material structures on the effluent quality [10–12], the impact of operational parameters on long-term filtration [12–18] as well as the usage of different module configurations and the correlation on the effluent quality [13].

Most of the studies focused on lab-scale experiments up to 40 L reactor volume using synthetic wastewater. Little information is available about behavior under "real world conditions". In particular, no results concerning how precipitation agents influence the filtration performance have been published. Such precipitation agents are routinely applied in standard wastewater treatments systems for phosphorus removal or to enhance sludge flocculation. In MBR technology, it is known that the addition of precipitants influences membrane performance and fouling occurrence [19,20]. Depending on the type of flocculants and on the operation conditions, both positive and negative effects are described [21–24].

This study should give a first insight into how dynamic membrane filtration can be influenced by precipitation under practical operation conditions.

2. Materials and methods

Different commercially used precipitation agents ($FeCl_3$; $Fe_2(SO_4)_3$; Al-Polymer, and $AlCl_3$) were applied. Dead-end filtration tests were carried out to get a first insight into the correlation between mesh size and effluent quality. These initial investigations were followed by short-term filtration test runs (30 min). Finally, continuous medium-term tests (2 h) using an inside-out filtration configuration ($0.65\,m^2$ filter area and a flux rate of $150\,L/m^2h$) were conducted. The influence of different cross-flow velocities (CFVs) as well as different dosages of precipitation agents on the effluent quality and the trans-filter pressure (TFP) were studied.

2.1. Jar tests to determine impact of flocculants on sludge structure

Initially, jar experiments were carried out in order to investigate the influence of different flocculents on the sludge structure. Activated sludge was taken from a $10\,m^3$ dynamic pilot plant operated at the local wastewater treatment plant (suspended solid (SS) content: 8–9 g/L) without any precipitation agents. The sludge was treated with four commercial precipitation agents ($FeCl_3$, $Fe_2(SO_4)_3$, Al-Polymer, and $AlCl_3$). In a wastewater treatment process, flocculants are applied to remove phosphorus by accumulating in the sludge.

Therefore, the aggregated flocculants amount is related to the dosage rate but also to the sludge age established in the treatment process. The applied concentrations correspond to the theoretical amount of coagulant dose required to reach a value of 1 mg/L total phosphorus in the effluent (in accordance with the Austrian legal requirements). On average, 5 mg/L phosphorous has to be removed by precipitation. A hydraulic retention time of 3 days, a sludge age of 12 days as well as the following *ß*-values, 1:1.5 for $FeCl_3$; and for $Fe_2(SO_4)_3$; 1:0.8 for $AlCl_3$ were used as a calculation basis. For Al-Polymer, the data sheet from the manufacturer was used as calculation basis. The calculated amounts per litre wastewater were as follows: 2.5 mL FeCl3, 2.8 mL $Fe_2(SO_4)_3$, 0.6 mL $AlCl_3$ and 0.6 mL Al-Polymer. To investigate floc structure change, lower precipitant concentrations, i.e. 1/20, 1/10, and 1/5 of the calculated concentration, were also applied.

Experiments were conducted as follows: After addition of the flocculent, pH was readjusted to ~7.5 with NaOH (0.1 M), and the solutions were stirred at 200 rpm for 2 min (to disperse the coagulant) followed by 15 min stirring at 80 rpm (to allow growth of flocs). Subsequently, the mixture was settled for 30 min to determine the sludge volume. One milliliter sample of the settled sludge was used for particle analysis through a Beckman Coulter LS 13 320. The instrument analyses the particle size distribution by measuring the pattern of light scattered by the particles in the sample with a detection range from 0.04 to 2,000 μm. A second sample was taken from the supernatant using a small outlet valve installed 3 cm below the water surface. The turbidity was determined by a turbidimeter (Turbiquant IR3000).

2.2. Filter material

All experiments were conducted with the same type of filter material. The filter material was made of woven polyester filaments in plain weave, i.e. wires running parallel to the length of textile fabric pass alternately over and under the wires running traversal through the fabric forming a regular mesh structure. Three different sizes of the mesh openings were used i.e. 29, 47, and 70 μm, respectively.

2.3. Dead-end filtration experiments

To evaluate the impact of coagulated sludge using filter material with different mesh sizes small-scale dead-end filtration experiments were carried out. Gravity-driven filtration of 500 mL of sludge was performed. The filter surface area was 0.005 m^2. Sludge derived from the same source as described earlier (jar tests) and also the flocculation step was the same. Detailed description of the experimental setup and handling of the filtration procedure are described in previous investigations [13]. Filtrate was collected on a balance. The amount of filtrate as well as the turbidity was measured every minute over a total period of 7 min. In preliminary experiments, it was shown that within this time frame, the most significant results are obtained. To compare the different test runs, average values of the turbidities were calculated.

2.4. Short-term cross-flow filtration tests

Dead-end filtration tests offer only estimation about filtration behavior using textile filter materials. To get more insight into dynamic filtration using coagulants as well as into quality/floc structure correlation, subsequent experiments with a submerged inside-out module operated in cross-flow mode were carried out. These experiments resemble practical operation conditions and a controlled *"attach/detach effect"* of the dynamic membrane is achieved by a defined CFV. Experiments were conducted in a 200 L reactor. The setup and the module are shown in Fig. 1. For these test runs, the inside-out module configuration with 47-μm mesh size was used. This decision was based on two main reasons: on the one hand, influence of precipitation agents was more pronounced using filter material with a larger mesh size; therefore, the 29-μm mesh was not the option of choice; on the other hand, in a previously published study it was found that mesh sizes ⩽50 μm are the most purposeful for dynamic membrane filtration [13].

The module consisted of 55 parallel filter tubes (47-μm mesh size) encased in a tubular shell for filtrate collection. The total filter length was 535 mm. With an effective filter length of 450 mm and a tube inner diameter of 8 mm, the resulting total filter area was 0.64 m^2. A self-made air diffuser of appropriate dimension was installed below the module to generate the necessary CFV. Module aeration rates were varied in the range of 1−15 L/min which corresponds to CFVs measured to be between 0.02 and 0.27 m/s. Further details on the module and the setup can be found in Loderer et al. [13].

Permeate was sucked by a peristaltic pump (505U, Watson & Marlow, UK). Drawn permeate was recycled to the tank to maintain constant SS concentration. To avoid settling of sludge, a second membrane diffuser was installed at the bottom of the tank. Both tank aeration and module aeration could be regulated independently by flow meters.

The activated sludge used in these experiments derived from a 10 m^3 dynamic membrane pilot reactor operated at the local wastewater treatment plant. No chemical precipitation was installed. Therefore, the sludge was free of flocculants; the SS content was 8–9 g/L.

Filtration experiments were carried out by a stepwise increase in the flocculent concentration starting from 1/20 to the calculated amount. The defined precipitant amount was added, the sludge was agitated for 2 min, and pH was adjusted to ~7.5 (0.1 M NaOH). At each concentration of the precipitant agent filtration performance at three different CFV (0.27, 0.09, 0.02 m/s beginning with the highest) was investigated. Turbidity was measured every minute with a portable photometer (Turbiquant IR 3000). TFP was recorded every 2 min using a u-type manometer for a direct accurate pressure reading. A single test run comprised 30 min of continuous filtration at a flux of 150 L/m^2h. These tests were carried out with all four precipitants so that in total 60 test runs were conducted. All test runs for a certain precipitant were conducted within a single day using a freshly drawn sludge sample. SS, sludge volume and supernatant turbidity after settling were used as control parameters to ensure similar conditions in the experiments.

2.5. Long-term cross-flow experiments

In subsequent long-term filtration experiments, the filtration behavior of sludge without and with flocculants was explored in continuous filtration over a 2-h period. For these tests, two of the flocculants, $FeCl_3$ and Al-Polymer, were chosen. The reasons are (1) that these flocculants are the most commonly applied precipitate agents in Austria and (2) that the experiments conducted before showed similar behavior within the two groups of flocculants (ferrous and alumina based, respectively). As in the experiments before, the flux rate was set to 150 L/m^2h, the investigated CFVs were 0.02

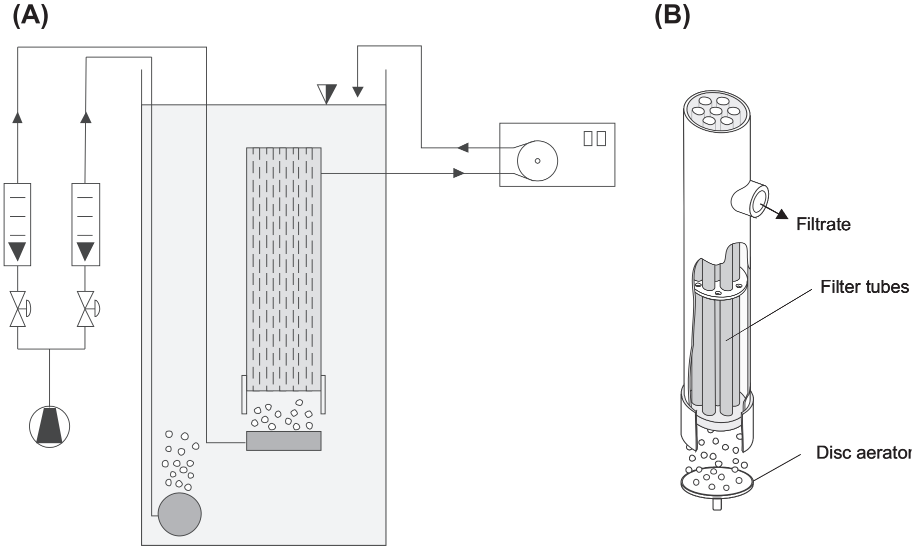

Fig. 1. 200 L lab reactor with submerged inside-out module for controlled CFV tests (A); configuration of the inside-out module (B).

and 0.27 m/s. Turbidity was measured online during the whole filtration period, pressure loss was determined as described above.

After each experiment (short term and long term), the module was mechanically cleaned by intensive flushing of the mesh surface with a water jet to remove all deposits. In addition, between the short-term and the long-term filtration experiment, a chemical cleaning with sodium hypochlorite (1,000 ppm for 2 h) and citric acid (0.5% v/v for 1hour) was applied.

2.6. Determination of the filter cake resistance

The TFP increase during dynamic filtration due to establishment of the filter cake can be analyzed with the resistance in series model. The theoretical basis is represented by the general form of Darcy's law:

$$J_V = \frac{\mathrm{TFP}}{\mu \cdot R_t} \tag{1}$$

In Eq. (1), J_v is the permeate flux, R_t corresponds to the total hydraulic resistance, and μ is the dynamic viscosity of the wastewater. The value for μ, 1.1 kg/m^2 s^2, was taken from literature [25].

According to the resistance in series model, the total resistance R_t is composed by several resistances and can be calculated by means of the following equation:

$$R_t = R_C + R_M + R_H \tag{2}$$

Hereby R_C is the resistance of the dynamic membrane (in membrane filtration usually termed R_C, cake resistance), R_M the intrinsic resistance of the filter material (typically termed R_M, deriving from membrane resistance), and R_H is the hydraulic resistance of the filtration setup due to unavoidable pressure losses in pipes and connections. In membrane filtration, this pressure loss is frequently ignored, because it is relatively low in comparison with the resistance of the membrane. In the case of dynamic membranes, the intrinsic resistance of the filter material is extremely low due to the large mesh size. In these experiments, the sum of R_M and R_H was determined in initial water tests for each filter material and flux rate. Knowing $R_M + R_H$, R_C can be easily calculated.

3. Results and discussion

3.1. Effect of different precipitation agents on the floc structure

The effect of different precipitation agents on the floc structure is shown in Fig. 2. The average increase in particle size compared with the reference sample is low but still recognizable. Aluminum-based agents produce slightly higher average particle size than the ferrous ones. Similar results were obtained by Turchiuli and Fargues [26]. They also pointed out that aluminia flocs are larger and more compact than ferric ones.

Beside the particle size analysis, sludge volume and turbidity in the supernatant were monitored. The sludge volume can be taken as an indicator of

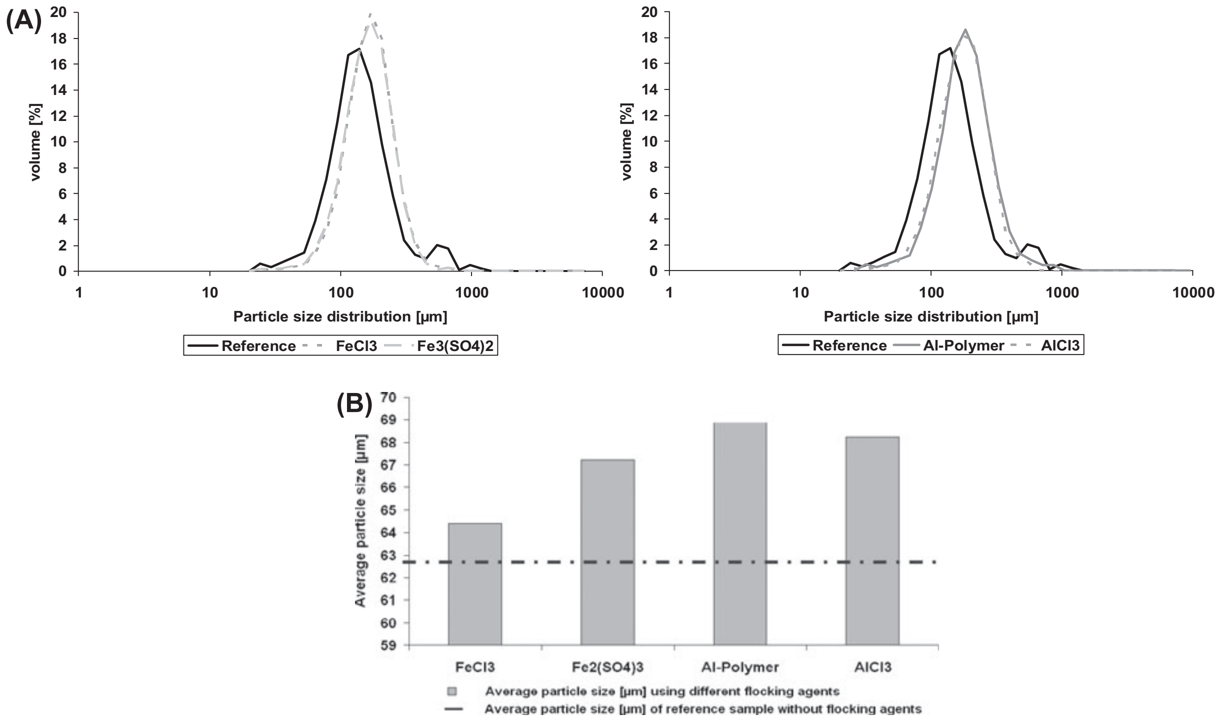

Fig. 2. Particle size distribution of ferrous (*left hand side*) and aluminous (*right hand side*) precipitation agents compared to the reference (A); average particle size [µm] to the reference sample (*dashed line*) (B).

compactness of the obtained sludge flocs, whereas the turbidity is related to the concentration of unsettled microparticles.

Fig. 3 shows results of both parameters (exemplarily for $FeCl_3$ and Al-Polymer). In case of $FeCl_3$, the addition of the precipitation agent finally led to a small increase in the sludge volume (12% increase compared with the reference sample). The probable reason is that the settleability of the reference sludge was already quite good (sludge volume index 80 mL/g) and no further improvement was achieved. Moreover, the addition of precipitants leads to extra sludge production due to mineral precipitates as well as the agglomeration of colloidal particles [26]. Little effect on the sludge volume was observed using Al-Polymer, presumably because in this case, improvement of settleability was balanced by the formation of extra sludge. In regards of dynamic filtration, it can be expected that the observed differences in sludge volume influence thickness of the formed cake layer. Another point of interest is the high impact on supernatant turbidity; 50 up to 76% lower NTU values were measured after precipitant addition. In dynamic filtration processes, the enlargement of microflocs and the creation of agglomerates should positively influence permeate quality.

The effects observed for $Fe_2(SO_4)_3$ were very similar to the behavior of $FeCl_3$. This was also the case for the two types of aluminous flocculants.

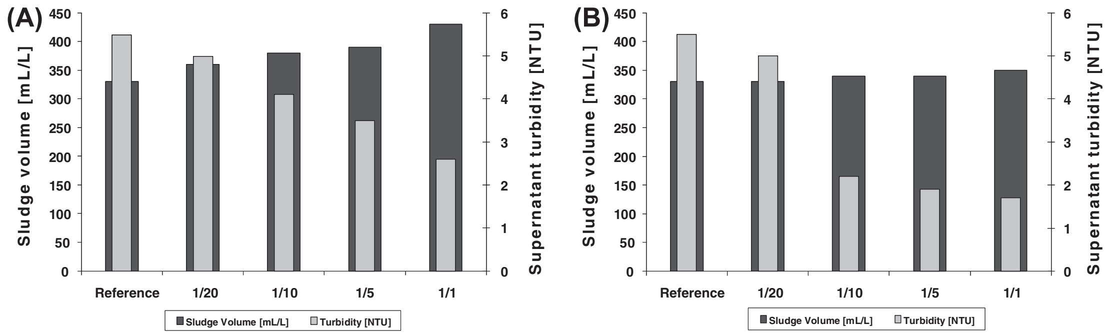

Fig. 3. The supernatant turbidity [NTU] (*gray bars*) and sludge volume [mL/L] (*black bars*) of precipitant samples at increased dosage after 30 min settling: $FeCl_3$ (A); Al-Polymer (B).

To investigate the relation of the identified change in sludge characteristics and dynamic filtration, the subsequent experiments in dead-end as well as in continuous cross-flow mode were conducted.

3.2. Dead-end filtration experiments

This simplified experimental setup can be a helpful tool for first screening tests in dynamic membrane filtration as demonstrated in previous works by the authors and other investigators [13,27–29]. Fig. 4(A) shows typical filtration behavior over time gained by such a test. Depending on the applied conditions the filtrate amount obtained within the first minute varied between 15 and 150 mL. The bigger the mesh size, the longer it takes until a first cake layer is established over the mesh openings and the dynamic membrane can start to build up. Hence, a bigger mesh size lead to higher initial filtrate volumes. On the other hand, the filtrate quality is worse due to the higher content of small particles. This has been confirmed by Kiso et al. [10] and Loderer et al. [13]. The other way round, at a given mesh size an increase in the sludge flocs through precipitation should lead to a similar effect.

To give an overview of results of the high number of dead-end filtration tests with different precipitation agents, a standardized presentation was chosen. The average turbidity and the average amount of filtrate over 7-min filtration period were calculated. These data were compared with results achieved for a reference sample without precipitation agent as shown in Fig. 4(B).

Concerning the quality of the filtrate, the expected positive effect of coagulant addition on the turbidity was observed. In general, no matter that agent was used, the average turbidity values were 10–50% lower than the reference. The quality improvement was pronounced when bigger mesh sizes were used. The reason for that is that independently from the mesh size relatively similar turbidities were measured, whereas in the reference samples effluent quality decreased with increasing mesh size as described above.

In all experiments, the aluminous agents show a slightly better effect on turbidity decrease than the ferrous ones. A probable explanation is the larger and denser floc structure that formed a more homogenous cake layer on the mesh filter.

Generally, also higher filtrate volumes were observed. While this is somehow inconsistent to the before stated faster development of a filter cake, the obvious reason is a change in cake structure.

It is already reported by Massé et al. [21] that increase in the particle size is associated with a less compact filter cake structure and hence lower cake

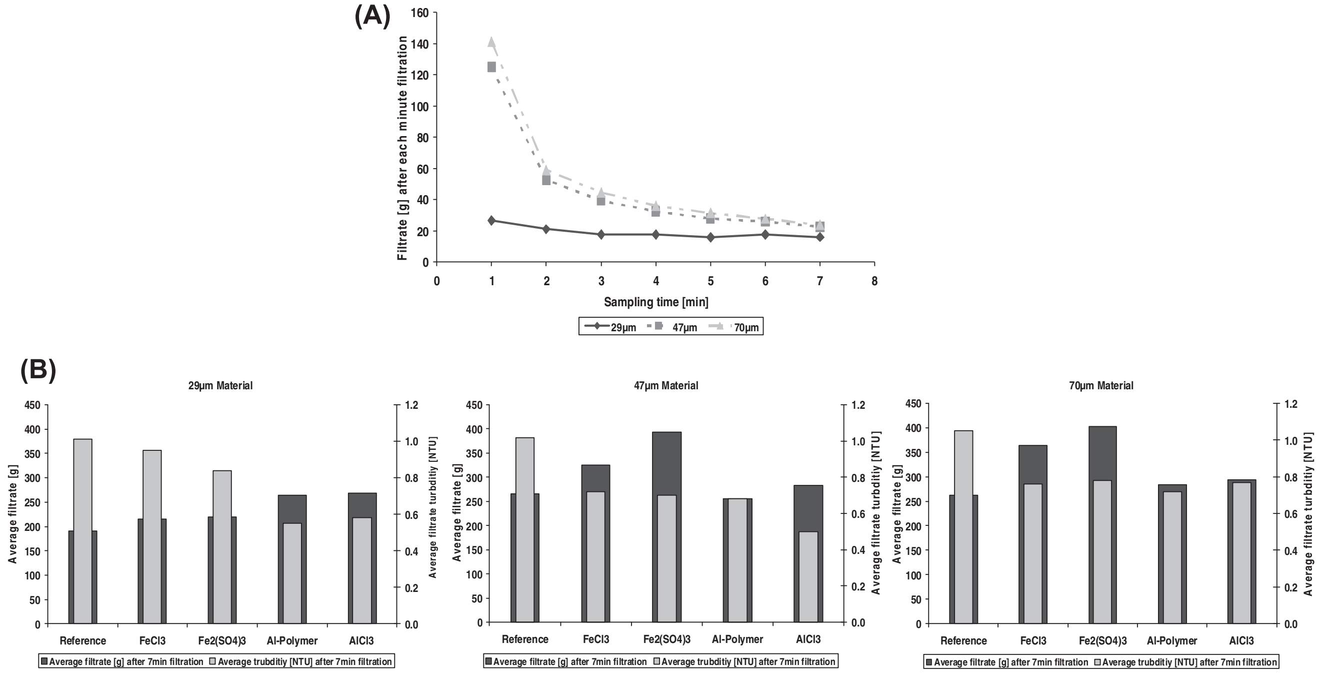

Fig. 4. Filtrate behaviour of a mesh material with different mesh sizes (29, 47, 70 µm) adding $FeCl_3$, (A); summary of all carried out dead-end filtration experiments concerning quantity and quality of the filtrate using 29, 47, 70 µm mesh size (B).

resistance. However, the reason why also mesh size played a role in how different flocculents improved filtrate volume remains unknown.

3.3. *Short-term cross-flow filtration experiments*

Subsequently, submerged cross-flow filtration experiments were carried out, because these experiments resemble practical operation conditions and a controlled *"attach-detach effect"* of the dynamic membrane is achieved by a defined CFV. For these test runs, the inside-out module configuration with 47-μm mesh size was used. This decision was based on two main reasons: on the one hand, influence of precipitation agents was more pronounced using filter material with a larger mesh size, and therefore, the 29-μm mesh was not the option of choice; on the other hand, in a previously published study, it was found that mesh sizes $\leqslant 50\,\mu m$ are the most purposeful for dynamic membrane filtration [13].

3.4. *Effect on turbidity*

As a general observation and as expected, an increase in CFV leads to an increase in turbidity. The obvious cause is a reduction of the filter cake thickness during dynamic filtration at higher shear stress [12,27]. It should be noted that some of the turbidities obtained are relatively high and are significantly above the values reported in earlier investigations [13]. The reason is that high CFVs, i.e. high shear rates, were applied to allow better differentiation of potential effects of the coagulant.

In Fig. 5, results of the 30-min filtration trials carried out under different CFV and increasing dosage rates of $FeCl_3$ and $Fe_2(SO_4)_3$ are presented. Again the average turbidities over 30 min were calculated and compared with the reference value. It can be seen that reference values are different. This is caused by the fact that each set of experiments (for one specific flocculent) was conducted on a single day using a fresh sludge sample. Although all other monitored values, SS content, pH, sludge volume, as well as particle size distribution, were almost similar quite high variations in filterability occurred. Nevertheless, it is presumed that at least within each data set comparability of the obtained results is given.

In the trials with $FeCl_3$, the following phenomenon was observed: At high CFV, 0.27 m/s, a stepwise increase in the precipitate dosage led to a slight turbidity decrease, whereas running the experiments with lower CFVs, 0.09 and 0.02 m/s, led to a decline of effluent quality.

Using $Fe_2(SO_4)_3$, no clear trend is recognizable. In addition, at the lowest CFV, total filter blocking occurred and no results could be obtained. However, at least at high flocculent concentration, an improvement of filtrate turbidity was observed.

In Fig. 6, the results for Al-Polymer and $AlCl_3$ are shown. Generally, the impact of the two aluminum-based flocking agents was quite similar. In comparison to the experiments with ferrous agents, the positive effect of precipitant addition was more pronounced at high CFV (0.27 m/s). At lower CFVs, no filtrate quality improvement was achieved. At least under conditions of high CFV, these results fit well to the observations made in the dead-end filtration tests where alumina-based precipitants also demonstrated a higher effectiveness on turbidity improvement.

3.5. *Effect on filter cake resistance*

To characterize the influence of flocculants on dynamic membrane filtration, the transfilter pressure

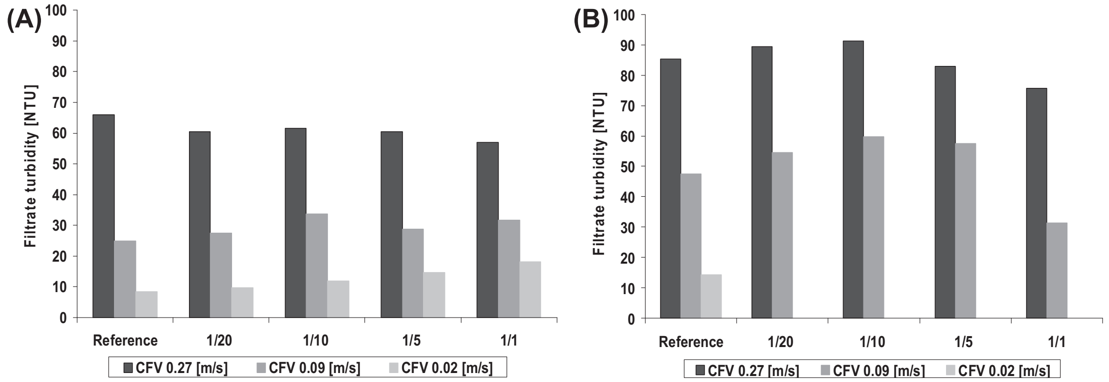

Fig. 5. Effluent turbidity behavior with $FeCl_3$ at increasing flocculant dosage and CFV rates (A), effluent turbidity behavior with $Fe_2(SO_4)_3$ at increasing flocculant dosage and CFV rates (B).

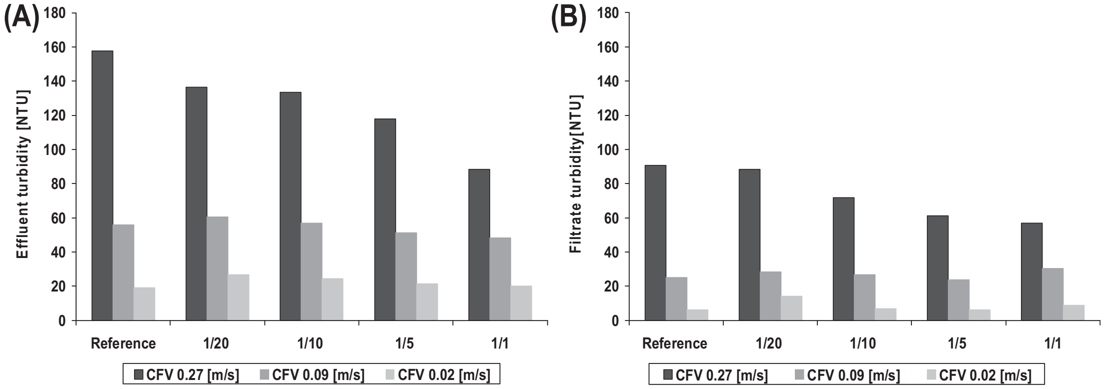

Fig. 6. Effluent turbidity behavior with Al-Polymer at increasing flocculent dosage and CFV (A); effluent turbidity behavior with $AlCl_3$ at increasing flocculent dosage and CFV rates (B).

(TFP) and the calculated resistance (R_C) were monitored. Results for the experiments with the ferrous precipitant are presented in Fig. 7. First, it has to be pointed out that TFP values were in a very low range during all experiments. Values between 2 and 18 mbar were measured at high flux rates of 150 L/m^{2}h. A certain difference in TFP was already observed for the initial reference values. In particular, the reference TFP using $FeCl_3$ was lower than in the other experiments. Nevertheless, the trend observed for the two ferrous coagulants was the same: with increasing flocculents dosage a significant rise in TFP occurred. At the highest flocculants dose, a TFP increase in 8–11 mbar, depending on the CFV, was measured for $FeCl_3$, using $Fe_2(SO_4)_3$ the TFP increase was 4–7 mbar.

This is in sharp contrast with the results gained with aluminum-based flocculants as presented in Fig. 8. In these experiments, only a slight increase in TFP $\leqslant 3$ mbar was observed. The calculated R_C values were in the range between 5.0×10^9 and $4.5 \times 10^{10}\,m^{-1}$. It has been described before that in dynamic filtration the intrinsic filter resistance (R_M) is very low, whereas the cake resistance (R_C) is a major factor of the total resistance. At typical operation conditions, the R_C values reach more than 90% of the total filtration resistance [29], R_C values reported in other studies are similar to the values found in our investigations, the typical range is 1.0×109–1.0×10^{12} [28–32].

The increase in the cake resistance caused by dosage of aluminum was significantly lower than the one obtained with ferrous agents. It must, therefore, be assumed that either the dynamic membrane formed after aluminum precipitation sludge is less compact or, alternatively, that the formed cake layers are of different thickness. The latter can occur if, e.g. lower interaction forces between the single particles exist and enhanced detachment due to dynamic shear forces occurs.

The described results are in a certain contradiction to the experience gained in dead-end filtration tests. The flux should be indirectly proportional to the filter resistance. Nevertheless, the filtrate yield after

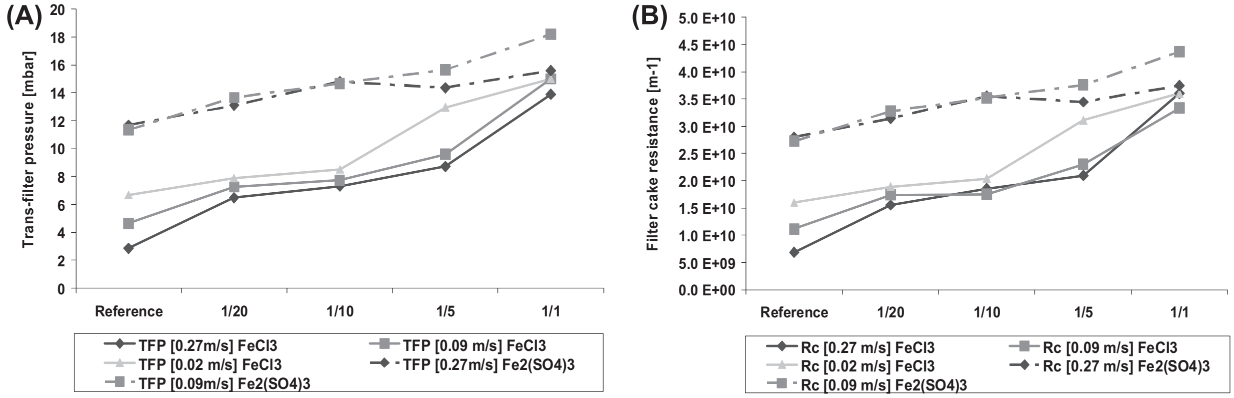

Fig. 7. TFP behavior of $FeCl_3$ (*full lines*) and $Fe_2(SO_4)_3$ (*dashed lines*) at different CFV and increasing flocculent dosage (A); corresponding filter cake resistance (R_C) for $FeCl_3$ (*full lines*) and $Fe_2(SO_4)_3$ (*dashed lines*) (B).

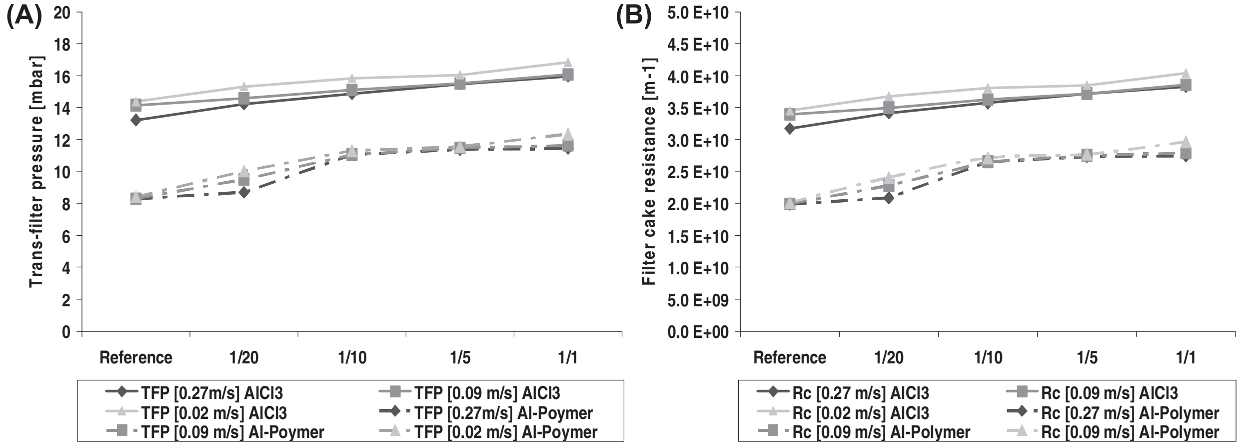

Fig. 8. TFP behavior of Al-Polymer (*full lines*) and $AlCl_3$ (*dashed lines*) at different CFV and increasing flocculent dosage (A); corresponding filter cake resistance (R_C) for Al-Polymer (*full lines*) and $AlCl_3$ (*dashed lines*) (B).

flocculation observed in the dead-end experiments was generally higher. The reasons for that remains unknown, however, it demonstrates the limitations of the simple dead-end filtration experiment where the conditions for cake layer formation are different compared with cross-flow filtration.

Summarizing all 30 min test runs, it can be pointed out that the behavior of the two ferrous agents is relatively similar. The same is the case for the two types of alumina-based agents. However, among these two groups, there is clear difference in impact on dynamic membrane filtration. Using ferrous coagulants, a decrease in turbidity was only observed at high CFV moreover, it was associated with a strong increase in TFP. In the case of $Fe_2(SO_4)_3$, even filter blocking occurred. Looking at the alumina-based coagulants, the beneficial effect on filtrate quality was more pronounced. Furthermore, even high doses of the coagulant had an almost neglectible impact on TFP.

3.6. Long-term filtration experiments

As the name implies, the formation of the dynamic membrane is an evolutional process [9–13,27–29]. During cross-flow filtration, there is a permanent exchange of sludge particles with the bulk fluid through deposition and detachment. Furthermore, with increasing filtrate amount smaller particles get trapped inside the cake layer and cake compaction and cake compression occurs. To study these effects, long-term filtration tests for 2 h were carried out. $FeCl_3$ and Al-Polymer were chosen as they are most frequently used flocculation agents for P-removal in standard WWT operation. CFV was set to 0.02 and 0.27 m/s, respectively; the flux rate was 150 L/m^{2}h. Results are shown in Fig. 9.

Using the reference sludge without precipitant and a low CFV (Fig. 9(A)), the turbidity dropped rapidly and a good effluent quality was constantly achieved. Under the same conditions, the sludge flocculated with Al-polymer showed a similar behavior; however, the turbidity always remained at a slightly higher level. In contrast, using $FeCl_3$, after the initial drop, a continuous increase in turbidity was observed. At the higher CFV (Fig. 9(B)), the picture was somehow different. At least in the first minutes, effluent quality was better after the addition of flocculants. Nevertheless, both with $FeCl_3$ and Al-polymer, the turbidity increased again and soon it exceeded the turbidity of the reference experiment. These somehow surprising results, which, however, were already indicated by the short-term experiments, might be explained in the following way: The mesh was already selected with respect to providing high effluent quality. That means the size of the mesh opening fits the typical size of the sludge flocs which therefore rapidly form the secondary layer acting as the filter barrier. Therefore, an increase in floc size due to the addition of coagulants does not bring any significant advantage. Also, the expected effect that flocking agents minimize the number of very fine particles which might pass through this layer could not be confirmed. It rather seems that the addition of coagulants leads to a more tightly packed cake layer, which leads to the observed increase of filter resistance. It could be expected that a tighter filter cake decreases the turbidity, however, we presume that the increase in filter resistance lead to an inhomogeneous filtration where locally high flux rates occur. Similar to the phenomenon of channeling as it is observed in blocked sand filters this leads to an overall decline of the retention capacity for small

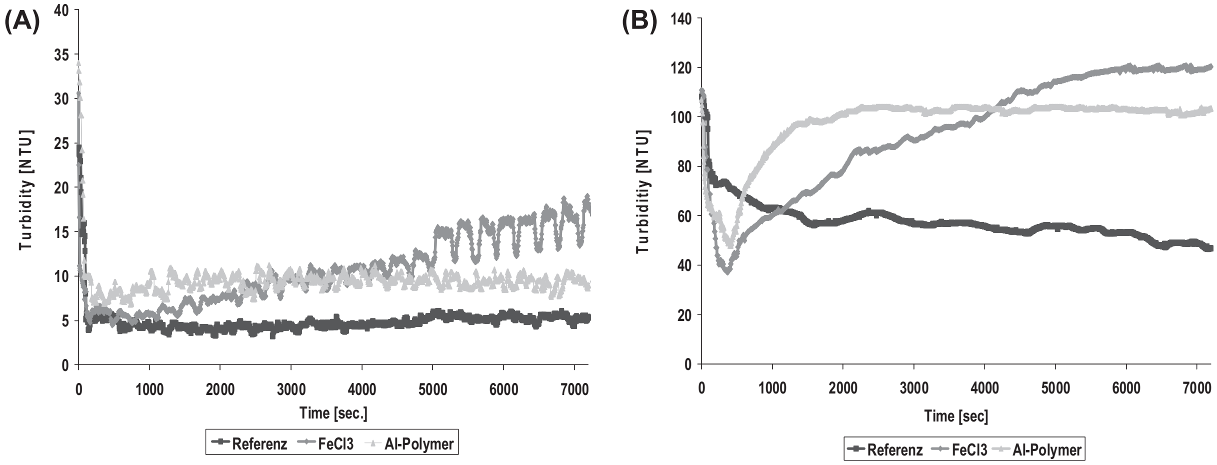

Fig. 9. Flux and turbidity behavior over 2 h with $FeCl_3$ (*dark gray line*) and Al-Polymer (*gray line*) at a CFV of 0.02 m/s versus the reference trial (*black line*) (A); flux and turbidity behaviour over 2 h with $FeCl_3$ (*dark gray line*) and Al-Polymer (*gray line*) at a CFV of 0.27 m/s versus the reference trial (*black line*) (B).

particles. In the experiment with the elevated CFV where the high shear forces minimize the formation of the secondary membrane, it can be seen that the flocculation initially helps to form the cake layer. But again after a short period, the above-described phenomenon led to an increase in turbidity.

4. Conclusions

Just as MBRs the dynamic filtration system process gets seriously influenced by flocculation. The right choice of agents (e.g. ferrous or aluminous) as well as the right dosage can affect the filtration performance. In contrast to initial expectations and summing up the experiments carried out, the addition of precipitation agents did not improve the efficiency of the dynamic filtration process. So far the exact impact on cake layer formation must largely be hypothesized. Nevertheless, the results have significant practical implication. In many wastewater treatment plants, addition of the tested chemicals arises from the need to precipitate phosphorous in order to meet the given legal limits. According to the experience, made this measure strongly interferes with the dynamic filtration process. Our results also indicate that the application of alumina-based precipitation agents seem to be preferable.

But it should also be stated that the observed relationship cannot be generalized and that it is depended on complex interaction of several parameters in particular the sludge condition and last but not least the type and nature of the filter mesh used. Also, in MBR systems, the impact of flocculation agents is controversially discussed [32,33]. Dynamic membrane bioreactors are not an established treatment process at the moment, and based on this first experience, we suggest that attention as well as further research should be given to the investigated issue.

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