Compact high-rate treatment of wastewater

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Abstract Many cities need to build compact wastewater treatment plants because of lack of land. This paper discusses compact treatment methods. An enhanced primary treatment process based on coarse media filtration is analysed. A high-rate secondary wastewater treatment process has specifically been investigated, consisting of a highly loaded moving bed biofilm reactor directly followed by a coagulation and floc separation step. The objective with this high-rate process is to meet secondary treatment effluent standards at a minimum use of chemicals, minimum sludge production and minimum footprint. It is demonstrated that the biofilm in the bioreactor mainly deals with the soluble organic matter while coagulation deals with the colloidal matter. The bioreactor may, therefore, be designed based on the soluble COD loading only, resulting in a very compact plant when a compact biomass/floc separation reactor (i.e. flotation or direct filtration) is used. The paper reports specifically on the coagulant choice in flotation and filter run time in direct filtration.

Keywords Coagulation; flotation; moving bed biofilm reactor; multimedia filtration

Introduction Traditionally settling has been used for primary treatment and activated sludge for secondary as well as for tertiary treatment. This has resulted in very spacious treatment plants. Now more and more often compact wastewater treatment processes are asked for by cities all over the world as land available for treatment plants is becoming scarce. In the traditional wastewater treatment systems the pollutants are dealt with in “bulk”, i.e. without targeted actions towards specific types of pollutants. In the advanced activated sludge process, for instance, the activated sludge is to deal with soluble organic matter as well as particulate organic matter, autotrophic nitrification as well as heterotrophic denitrification and sometimes enhanced phosphate uptake as well. In order to achieve more efficient and compact plants, it is needed to target the pollutants much more and tailor-make processes according to what we want them to do. In this paper we shall demonstrate the importance and benefit of focusing on particle removal.

High-rate primary treatment

In the area of primary treatment various forms of screens have been used. They need a light opening lower than 0.3 mm in order to meet primary treatment standards. Ordinary primary treatment gives, however, a low treatment efficiency (50% SS-removal and 30% BOD-removal) and the focus has lately been more directed towards enhanced primary treatment where the target is 70–80% SS-removal and 60–70% BOD-removal. This is based on the fact that a large fraction of the pollutants in municipal wastewater is present in the form of particles (Levine et al., 1985, Ødegaard, 1987, Nieuwenhuijzen and Mels, 2002).

Introduction of coagulation/flocculation ahead of the settling (Ødegaard, 1992, 1998) or flotation (Ødegaard, 2000b; Mels et al., 2001) process, results in treatment efficiencies of 80–90% on SS, 65–85% on BOD5 and 85–95% on P.

An alternative approach to settling and flotation for enhanced primary treatment is high-rate, coarse filtration. The main problem with traditional granular media filtration
of wastewater is the rapid head-loss build-up. In the coarse media filters this is avoided by the use of a filter medium with very high porosity that gives the possibility to operate at high filtration rates (10–30 m/h). In addition to slow head-loss build-up, the coarse media filter will also have much higher sludge retaining capacity than that of sand- or similar granular media filters. Various media configurations have been tested with or without pre-coagulation (Okubo et al., 1990; Coma et al., 1991; Mouri and Niwa 1993; Tanaka et al., 1995; Ødegaard et al., 1998). In the coarse media filters that we have developed (Liao and Ødegaard, 2002a,b; Ødegaard et al., 1998, 2003) a plastic medium originally designed as a biofilm carrier for the moving bed process (Ødegaard et al., 1994, 1999) has been used as the filter medium.

Figure 1 shows the design of our pilot plant as well as the design of the filter media used. Various configurations have been investigated, up-flow/down-flow, floating/sinking media, single media/dual media etc. The wastewater has been taken after the grit chamber at Ladehammeren Wastewater Treatment Plant (LARA), Trondheim Norway.

Figure 2 compares the results from up-flow single media filters using the K1 or the larger K2 media (Figure 1) made of polyethylene with density 0.95 g/cm³. The removal efficiencies in the K2 filter was found only slightly lower than in the K1 filter, while the K2 filter had much lower head-loss. This shows that other mechanisms (flocculation, sedimentation, adsorption to biofilms) than those dominant in traditional granular media filtration play the major role in coarse media filtration.

An SS-removal efficiency of 60–70% could be achieved without using polymer at an overflow rate of 10–20 m/h and efficiencies as high as 75–95% could be achieved at 20–30 m/h when adding the polymer. Note that the dosage of polymer needed was quite low and dependent on the SS in the influent. The recommended dosage was around 5 mg
polymer/g SS_{influent} (1–2 mg/l for influent SS = 200–400 mg/l). There was little benefit in increasing the dosage above this level.

The fact that the K2 filter runs were normally terminated by breakthrough while the K1 filter runs were terminated by maximum head-loss, indicated that one by the combination of K1 and K2 media (in dual media filters) could achieve both high SS removal and low head loss. A new set of experiments were carried out, in which combinations of the two media, K1 and K2, were used now made in two different plastic materials, polyethylene with density 0.95 g/cm$^3$ (i.e floating – given the index L for light) and PVC with density 1.45 g/cm$^3$ (i.e. sinking – given the index H for heavy).

The average raw water concentrations (+ standard deviations) during the experiments were: 246 $\pm$ 73 mg SS/l and 458 $\pm$ 135 mg COD/l. Figure 3 shows the SS-removal as well as the specific head loss in two dual media filters (the K1L/K2L and the K1H/K2H filters).

It is demonstrated that the two filters gave about equally good SS-removal efficiency but that the head-loss build-up in the sinking media filter (K1H/K2H) was much lower. During backwash the two media were mixed. After backwash termination, however, the majority of the K2H was on top of the filter-bed and the majority of the K1H on the bottom. This kind of coarse to fine media distribution in the direction of flow for the K1H/K2H filter is ideal in a down-flow filter.

An interesting point that can be seen from the K1H/K2H filter (Figure 3b), is that the specific head loss for the higher filtration rate (20 m/h) was not higher than that for the lower filtration rate (10 m/h). This suggests that a more even SS accumulation through the filter bed is achieved at the higher filtration rate caused by the higher hydrodynamic forces giving deeper particle penetration.

**High rate secondary treatment**

In many cities around the world, especially those situated along the ocean coasts, secondary treatment has to be implemented either alone or with additional tertiary treatment. Direct coagulation/flocculation/floc-separation may be sufficient treatment or an appropriate pre-treatment (Ødegaard, 1992; Nieuwenhuijsen and Mels, 2002). However, in order to meet secondary treatment standards it may be necessary to remove low molecular weight, soluble organic matter as well. For this purpose biological processes are most suitable from an economic point of view. When compact treatment plants are looked for, biofilm reactors are the best alternative. However, many of the most compact biofilm reactors (like the granular media biofilters) cannot accept a high load of particulate matter, since this would easily clog the filter and result in too frequent filter washing. It is, therefore, normal to use a
two-step process comprised of a pre-coagulation step followed by a biofilter step. By utilizing lamella-separators for floc separation in the primary step, such treatment plants can be made very compact (Pujol et al., 1994). Nevertheless one is reluctant to use a very high organic load because of the possibility of clogging of the biofilters. An alternative is to combine the moving bed biofilm process with direct coagulation (Ødegaard, 2000a), see Figure 4.

The objective of our research towards this high-rate process is to meet secondary treatment effluent standard at minimum chemical consumption, minimum sludge production and minimum footprint. The lowest sludge production is achieved when a non-precipitating coagulant (i.e. a cationic polymer) is used. Earlier studies of wastewater coagulation (Ødegaard, 1998, 2000b) have, however, demonstrated that a combination of a low metal (Fe) dose and a cationic polymer may also result in very low sludge production combined with improved particle separation and reduced polymer consumption.

In a conventionally designed biological process, both the removal of soluble organics as well as hydrolysis of some particulate matter takes place. The idea behind the high-rate moving bed process is that the biofilm removes the soluble organic matter, while the coagulant is used for the separation of the particulate matter, including colloids. It is not obvious, therefore, whether it is better to add one or both of the coagulants before or after the bioreactor.

In the moving bed biofilm reactor (MBBR) the biomass grows on carriers that move freely in the reactor, but kept within by a sieve arrangement at the reactor outlet (Ødegaard et al., 1994). The moving bed biofilm process has been used for many different applications (Ødegaard et al., 1999). This paper will focus on the high-rate moving bed biofilm process which is currently not used in practice.

The fate of particles in biofilm reactors is not totally clear, but it is obvious that particulate matter to a far lesser extent is being degraded in a high-rate biofilm process than in a standard activated sludge process. When operating at such a high soluble organic loading that the maximum COD degradation rate prevails, the COD-removal will primarily be due to consumption of soluble organic matter. The following conclusions were drawn from earlier work (Ødegaard, 2000a).

On biodegradation: The maximum biodegradation rate of soluble COD in our wastewater was found to be around 30 g SCOD/m²d (at 12°C). The maximum rate was reached at a loading of about 60 g SCOD/m²d corresponding to a bulk biodegradable, soluble COD concentration of around 100 g BSCOD/m³. Below this the rate was limited by the availability of biodegradable COD. The biodegradation rate of soluble COD did not depend much upon residence time within the range of 15–60 min. The results indicate that bulk hydrolysis of colloidal COD did not play an important role at short residence times contrary to longer residence times.

Recent results indicate, however, that if the SCOD-loading is low, adsorption of colloidal and particulate COD to the biofilm can lead to hydrolysis of colloidal and particulate COD. At short residence times one has to be especially aware of the importance of the residence time distribution.

**Figure 4** Schematic flow diagram for the high-rate process discussed
**On floc and biomass separation:** The potential for meeting secondary effluent standard with a high rate moving bed process depends strongly upon the separation of the biomass. The settleability of the biomass decreased with increasing organic load on bioreactor and was quite poor at high loads. However, a small dose of metal (5–10 mg Fe/l) or cationic polymer (1.5–2 mg/l) for coagulation of the fine particles, improved settleability considerably.

The earlier work lead, therefore, to new research in which we have analyzed flotation and filtration as floc separation alternatives. Part of this research shall be presented here.

**High rate process based on moving bed combined with coagulation and flotation**

A very interesting floc separation alternative is flotation. Standard flotation in wastewater treatment is operated at overflow rates of 5–10 m/h (Ødegaard, 2000b). New high-rate flotation reactors are now being marketed, like the lamella flotation unit (Hedberg *et al*., 1998) and the turbulent flotation unit (Kiuru, 2001), in which flotation rates in the range of 15–30 m/h have been reported. A project is, therefore, underway in our group where we study the process depicted in Figure 5 (Melin *et al*., 2002).

**Selection of coagulant**

In this process we may choose different coagulant alternatives, i.e. metal (Al, Fe) salt alone, cationic polymer alone or combinations of the two. To minimize sludge production, the polymer alone alternative is the most attractive since no precipitation takes place. It has earlier been demonstrated (Ødegaard, 1998), however, that a very limited precipitation takes place when a very small metal dose (< 0.2 mmol/l) is combined with a low dose of the cationic polymer.

Designed experiments were used to evaluate the effect of polymer properties and polymer and iron dosages on the treatment results. A laboratory-scale MBBR was used to treat domestic wastewater from a nearby residential area. The MBBR loading was very high with a detention time of only 15 min. A flotation jar tester was used for flotation tests. One-litre samples collected from the MBBR outlet were used in each jar.

The iron and polymer were dosed with syringes under rapid mixing (400 rpm) which was continued for 0.5–1 min. The water was then flocculated for 20 min while mixing with 80 rpm. In the flotation step, 150 ml of dispersion water (15% recycle) was used, saturated with air under 5 bar pressure. The samples from clarified water were taken 10 min after dispersion water was applied.

Iron was dosed as JKL (FeCl$_2$SO$_4$). 14 PAMs were tested with molecular weight (MW) ranging from 0.3 to 14.5 × 10$^6$ g/mol and charge densities from 0.25 to 4.2 meq/g. Three different low MW, high charge density polyDADMACs (~ 6.2 meq/g) were also tested.

The low iron dosages varied from 0 to 0.2 mmol Fe/l and polymer dosages from 0.5 to 3 mg/l. With poly-DADMACs additional dosages of 0.3 mmol/Fe/l and 3.4 mg/l polymer were also tested. Since a real wastewater was used in the experiments, the quality of the wastewater itself could not be used as a design variable.

![Figure 5](image_url) **Figure 5** The flow scheme of a high rate process based on moving bed, coagulation and flotation

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The results were evaluated using Partial Least Squares Regression (PLSR), a multivariate analysis method based on analysis of the variation in the data (Martens and Naes, 1989). The method helps to separate important or real effects from small variations in the data that can be caused by less important effects or noise.

**Effect of dosing point**

Four different alternatives for dosing point of iron and polymer were tested. The iron dosage was 0.2 mmol Fe/l in most of the experiments. The following conclusions were drawn.

When the polymer dosage was 2 mg/l or higher, there were no clear differences between situations when iron and polymer was dosed before the MBBR, iron before and polymer after the MBBR, or both iron and polymer were dosed after the MBBR. In some experiments, better results were obtained when dosing iron (and polymer) before the MBBR at polymer dosages <2 mg/l. We have not been able to identify a clear reason (for example changes in wastewater properties) why this happened only occasionally. Dosing the polymer before the MBBR and iron after was clearly an inferior dosing strategy compared to the other alternatives. It was chosen to continue dosing both iron and polymer after the MBBR. In the future, it may be interesting to study in more detail whether dosing coagulants before the bioreactor allows using lower coagulant dosages.

**Effect of polymer and iron dosage**

The multivariate analysis shows that the treatment results were primarily governed by the coagulant (polymer and iron) dosages. Figure 6 shows the effect of iron and polymer dosage.
dosage on the SS concentration in clarified water. The figures present response surfaces calculated with the multivariate regression model for average wastewater quality and polymer properties.

It is demonstrated that the effect of polymer dosage was linear for both types of polymer while the response for iron dosage showed curvature, i.e. the effect of iron on the treatment results becomes smaller with increasing iron dosage. Without metal coagulant, only moderate removal of SS was achieved. With PAMs, increasing iron dosage from 0.1 to 0.2 mmol Fe/l did not increase removal efficiency as much as demonstrated between no iron and 0.1 mmol Fe/l, explaining the curved response in the model. With polyDADMACs the effect of iron became smaller at slightly higher dosages (over 0.15–0.2 mmol/Fe/l).

Generally, the removal efficiency was quite similar between the best PAMs and polyDADMACs but polyDADMACs gave slightly higher SS removal with 0.2 mmol Fe/l. However, because of the variation in the wastewater quality, it cannot be concluded that polyDADMACs in general gave better results than PAMs.

**Effect of polymer properties**

Figure 7 depicts the effect of molecular weight and charge density of the PAM-polymers (together with iron dose) at a polymer dose of 3 mg/l. The model indicates that with PAMs there is an effect of the molecular weight that depends on the iron dose. The model predicts that when iron is not used or the dosage is low, it is a benefit to have a high molecular weight polymer.

When a PAM is used together with iron, the best choice seems to be a medium molecular weight, high charge density polymer.
The model for PAM indicates that a high charge density is a benefit. The results for both molecular weight and charge density demonstrate that although these polymer properties probably have an effect on the removal efficiency, they are small compared to the effect of dosage and wastewater quality. There were no significant differences between the tested polyDADMACs. Also, the best PAMs performed equally with polyDADMACs.

**Effect of wastewater composition**

Two important parameters in coagulation of wastewater are pH and soluble COD. Only minor SCOD removal was observed in the tests without metal coagulant and it was shown that iron improves SCOD removal which is probably due to coagulation of the colloidal fraction.

The multivariate analysis indicated that the raw water SCOD and pH influenced SS concentration in flotated water with PAMs while the polyDADMAC results were affected by raw water COD and SS-concentration. The raw water pH varied only in a very narrow range (from 7.4 to 7.9) and therefore the pH-results are not very conclusive.

**COD fractions in the flotated water**

In some tests, COD was analysed from water samples that were filtered through filters having different pore size. Figure 8 shows the COD fractions in raw water and flotated water. In the experiment, polyDADMAC was used at variable dosages (0.6–3.4 mg/l) and the iron dosage was 0.2 mmol Fe/l. The results show that particles above 11 µm are effectively removed by flotation. The truly soluble COD fraction (<0.1 µm) is the largest fraction in the clarified water and is not removed very well. Since the aim is removal of particulate organic matter, this size fraction is of no interest. The preceding biological process should be operated so that the truly soluble fraction is removed to desired levels. The results show that the observed SCOD removal is mostly the removal of colloidal material (size fraction 0.1–1 µm). The 1–11 µm size fraction is, however, critical for successful particle removal and further process optimization should concentrate on this size range.

**Separation of biofilm in a multi-media filter**

The key issue if one is going to separate the biomass directly in a filter, is the filter run time. We have earlier shown (Ødegaard et al., 2003) that the filter run time is primarily dependent upon the sludge loading rate (kg SS/m²h) which is the product of filtration rate (m/h) and SS-concentration (kg SS/m³). Based on the ideas that we have got from the primary filter (see above), we decided to investigate the use of coarse media filtration also as the final particle separation step in high-rate secondary treatment using a new multi-media KFS-filter (Figure 9).

The new multi-media filter, the Kaldnes-Filtralite-Sand (KFS) filter, was designed as shown in Figure 10. It is a down-flow filter with a 1m mixed K2H/K1H layer on top of a...
0.5 m expanded clay aggregate layer (Filtralite, density: 1.65 g/cm³) over a 0.3 m sand layer (density: 2.65 g/cm³) and a support layer. Grain sizes are shown in Figure 10. A coagulant was dosed in an in-line static mixer. The experiments were carried out at filtration rates of 10–20 m/h with and without coagulant dosing (iron or iron and polymer). During the test period the raw wastewater was rather dilute and cold because of snow melting, with SS of 167±43 mg/l and COD of 273±53 mg/l. A 1 m³ moving bed biofilm reactor (MBBR) using K2 Kaldnes carrier (effective media surface is 220 m²/m³ reactor volume) was used at 30 min HRT. Figure 11 shows an example of the filtration results at 10 m/h filtration rate at no dosage, 2 mg polymer/l dosage and at 10 mg Fe + 2 mg polymer/l dosage.

The figure demonstrates the benefit of the coagulant in this process. The ripening period was far less significant when a coagulant was used. The results show that the process should not be used without coagulant addition. The additional sludge caused by Fe-precipitation resulted in a slightly lower filter run time before a given head-loss was reached, but the difference was not dramatic. The average SS-removal efficiency and effluent SS-concentration during over 24 hr filter run at 2 mg/l polymer dosage was > 90 % and 11 mg/l respectively. The accumulated sludge mass at about 1.5 m head-loss was 20 kgSS/m²_filter. This makes the KFS-filter a very interesting alternative as separation reactor for a high rate biofilm process.

When operating at 20 m/h, the results were poorer with an average SS-removal efficiency of about 85% and effluent SS-concentration of about 25 mg/l during the 6 hr filter run at 2 mg/l polymer dosage. The accumulated sludge mass at about 2.0 m head-loss was 15 kgSS/m²_filter.

Filter run time is probably the most important design criteria for a filter like this and it may be determined based on the sludge loading rate and the necessary removal (i.e. the
The most striking feature when comparing the results from the two filters is that for the same filter run time and head-loss, the KFS-filter may be loaded several times higher than the single media filter. For instance, the KFS filter could run about 24 hrs before 1 m head-loss at 1 kg SS/m²h compared with around 5 hrs at the same SS-loading with the single media filter. This clearly demonstrates the advantages of the multi-media filter.

Conclusions
A very compact wastewater treatment can be achieved when utilizing the following basic principles in the design of treatment plants.

- Since a very considerably portion of the pollutants in wastewater is associated with particles, enhanced primary treatment should be used. Coarse media filtration is an interesting method.

- A combination of colloids coagulation and soluble organics biodegradation in biofilms can effectively remove organic matter to secondary treatment standard within a total residence time less than 1 hour, if a high rate floc separation process (i.e. flotation or multimedia filtration) is used

- Cationic polymer can replace metal coagulants (at least partly), resulting in less sludge production and good floc/biomass separation.

References


