Natural manganese deposits as catalyst for decomposing hydrogen peroxide

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Abstract

Drinking water companies ~~more and more~~ implement ~~A~~advanced o~~O~~xidation ~~P~~processes (AOP) in their treatment schemes to increase the barrier against organic micropollutants (OMPs). It is necessary to decompose the excessive hydrogen peroxide after applying AOP to avoid negative effects in the following, often biological, treatment steps. A drinking water company in the western part of the Netherlands investigated decomposition of about 5.75 mg/L hydrogen peroxide in pre-treated Meuse river water with different catalysts on pilot scale.

In down flow operation, the necessary reactor ~~E~~empty ~~B~~bed ~~C~~contact ~~T~~time (EBCT) with the commonly used ~~G~~granulated ~~A~~activated ~~C~~carbon (GAC) and waste ground water filter gravel (MCFgw) were ~~the same~~equal with 149 seconds, corresponding with a conversion rate constant r of 0.021 s^{-1}. The EBCT of the fine coating of ground water filter gravel (MC) was significantly shorter with a little more than 10 seconds (r = 0.30 s^{-1}).

In up flow operation, with a flow rate of 20 m/h, the EBCT of coating MC increased till about 100 seconds (r = 0.031 s^{-1}), from which can be concluded, that the performance of this waste material is better compared with GAC, in both up and down flow operation.

The necessary EBCT at average filtration rate of full scale dual layer filter material (MCFsw) amounted to 209 s (r = 0.015 s^{-1}). Regarding the average residence time in the full scale filters of 700 s, applying AOP in front of the filters could be an interesting alternative which makes a separate decomposition installation superfluous, on the condition that the primary functions of the filters are not affected.

Opmerking [T1]: Comment PLC

Opmerking [T2]: KC

Opmerking [T3]: KC

Opmerking [T4]: KC

Opmerking [T5]: PLC

Key words
Hydrogen peroxide, decomposition, manganese, GAC, AOP, drinking water, Meuse river water

Introduction

All over the world surface water is to some extend contaminated with organic micropollutants (OMPs) (Houtman et al., 2010) It is expected that the amount and concentrations of OMPs will increase, due to population growth, aging and global warming (Wuijts et al., 2013). A drinking water company in the western part of the Netherlands identified the threat of OMPs in their source the Afgedamde Maas, a side branch of the Meuse river. The managed aquifer recharge (MAR) by dune filtration and the dosing of powdered activated carbon (PAC) are currently the main barriers against OMPs. After careful consideration advanced oxidation process (AOP) was selected as the most optimal technique to extend the treatment scheme [Abrahamse, 2007] and research was carried out with ozone and UV based AOP, in combination with hydrogen peroxide. When AOP is installed before MAR it is expected that this two processes will provide a synergistic, hybrid system [Lekkerkerker-Teunissen, 2012].

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Opmerking [T7]: PLC, KC

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A drawback of applying AOP is the remaining hydrogen peroxide in the treated water. After dosing 6 mg/L hydrogen peroxide in the AOP influent water, about 5.75 mg/L hydrogen peroxide is remaining in the AOP effluent water. This AOP effluent water flows out in infiltration ponds which recharge the dunes. It is established that even a concentration of 2 mg/L affects about 80% of the organisms in the infiltration ponds [Reeze, 2010]. Because the infiltration ponds are situated in a protected nature area (Natura 2000), it is of utmost importance to lower the hydrogen peroxide concentration till a level that will not affect the ecology. As a company standard, the maximum allowed concentration of hydrogen peroxide in the infiltrated water is established at 0.25 mg/L.

Hydrogen peroxide in water has a tendency to decompose in water and oxygen, because the reaction products are more stable than the hydrogen peroxide itself [Petrucci, 2007]:

$$2\ H_2O_2 \rightarrow 2\ H_2O + O_2$$

H [kJmol^{-1}]~~Σμ° [kG]~~ $2^*{-134.1} \rightarrow 2^*{-237.2} + 0.0$

Overall the chemical drive of this so-called decomposition reaction is 206.2 kJmol^{-1}~~kG~~. However, the decomposition is very slow, the reason why hydrogen peroxide solutions are commercially available. Decomposition is strongly affected by light and catalysts as catalase, (spores of) metal oxides and activated carbon. In full-scale application, homogeneous catalysis (enzymatic with for example catalase or iron) is not practical. The most promising technique is therefore heterogeneous catalysis. Common catalysts include manganese oxide, silver, platinum and activated carbon. The surface of these catalysts provides a favorable environment to catalyze the decomposition, though the mechanism is not well understood~~.~~ According to Masel et al. (2001) the reaction rate is increased as this alternative route has a lower activation energy than without the catalyst~~Apparently the reaction rate is increased as this alternative route has a lower activation energy than without the catalyst [Masel, 2001].~~ Decomposition starts with adsorption of hydrogen peroxide on the catalyst. The rate of adsorption, and with that the decomposition rate, is higher at higher water temperature and with a larger catalyst surface.
Filtration over granulated activated carbon (GAC) is a proven technology to decompose hydrogen peroxide [Kruithof, 2007]. The decomposition reaction with pure manganese dioxide in granular form is slow and time demanding (Bazri, 2008~~). However, it was known that dissolved manganese in surface and groundwater deposits as manganese oxide compounds on grains in sand filters.~~ However, (Miller e.a., 1999) reported decomposition of hydrogen peroxide in the presence of sandy material from an aquifer and riverbed. The sand was naturally coated with metal oxides, from which manganese oxide was most active. It was known that dissolved manganese in surface and groundwater deposits as natural manganese oxide compounds on grains in sand filters of drinking water treatment plants. (Merkle e.a., 1996) measured a high specific surface area of naturally coated filter material, which increase with the amount of manganese coating. Decomposing hydrogen peroxide with existing or waste filter material fowill contribute to a sustainable society. As a proof of principle, 1% hydrogen peroxide solution was add to grains of a full-scale double layer sand filter of a drinking water treatment plant. Microscopic examination yielded promising results: (oxygen)bubbles were formed at the surface of the grains.~~Microscopic examination yielded promising results: at pre-treatment plant, (oxygen)bubbles were formed at the surface of grains of a full-scale double layer sand filter after adding 1% hydrogen peroxide solution.~~

This research focused on the decomposition of about 5 and 10 mg/L hydrogen peroxide till 0.25 mg/L in the pilot plant installation. Three different catalysts were investigated: commonly applied GAC and two types of manganese coated filter material. The main parameter determined for the three decomposing materials was the reactor empty bed contact time (EBCT), based on the conversion rate of the decomposition.

Materials and methods

Column reactors

Catalytic decomposition was investigated in vertical column reactors, with outside diameters of 0.20, 0.40 and 0.60 m, called R20, R40 and R60, respectively. Sample points over the height of the columns made it possible to analyse the hydrogen peroxide after different contact times.
The two reactors R60 were fed with pre-treated Meuse river water, abstracted before the full-scale double layer sand filters. The reactors R20 and R40 were fed with the effluent of these

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Opmerking [T9]: PLC

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Opmerking [T11]: PLC

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full-scale double layer sand filters. The flow through the reactors could be varied between 1.0 and 3.0 m^3/h, which corresponds with flow rates between 4 and 100 m/h. The standard operation was down flow, but up flow operation also was applied with flow rates up till 40 m/h. Before the water flowed in the reactors, 10% hydrogen peroxide was dosed into the water with a membrane pump with a maximum capacity of 3.0 l/h. The applied concentrations were about 5 and 10 mg/L in the influent water.

Decomposing material

Three different catalysts were investigated: fresh GAC and two types of used manganese coated filter material. The filter materials were collected from full-scale filters at drinking water treatment plants.~~Three different catalysts were used: GAC and two types of manganese coated filter material.~~
The GAC type was extruded activated carbon with a diameter of 0.8 mm, especially suitable for catalytic processes. The manganese coated filter material were obtained from two different drinking water treatment facilities.
The first material was manganese coated filter material from a groundwater treatment plant (MCFgw). This filter material is regularly replaced by fresh sand as a result of the rapid growth of the grain size by the coating, resulting in a lower purification performance. A sample is taken at the end of the filter life time of 7 years. Especially ground water may contain a high content of manganese, which may be makes the replaced grains suitable for decomposing hydrogen peroxide. ~~The first material was manganese coated filter material from a groundwater treatment plant (MCFgw), replaced at the end of the filter life time.~~ The second manganese coated filter material was obtained from a surface water treatment plant (MCFsw). The MCFsw was collected from a double layer sand filter, with a filter life time of 31 years. ~~The MCFsw was collected from the double layer sand filters.~~
In order to clean the grains after filling the reactor, MCFgw was backwashed with water before the first tests. During backwashing, a part of the coating was separated from the grains and formed a top layer. This top layer of fine coating was removed from the reactor and also used as catalyst (MC).~~During the first backwashing of MCFgw, a part of the coating was separated from the grains. This coating (MC) was also used as catalyst~~. ~~With XRD analysis, besides calcium and iron compounds, the manganese containing compounds ramsdellite and birnessite were detected in MC (Hendrix, 2014). Specifications of the manganese containing materials are shown in Table 1.~~

~~***Table 1: Specifications of different tested filter gravels***~~

~~***Parameter***~~	~~***Unit***~~	~~***Course gravel MCFgw***~~	~~***Coating MC***~~	~~***Anthracite/sand, MCFsw***~~
~~***10% Grain***~~	~~***mm***~~	~~***1.01***~~	~~***0.25***~~	~~***2.06/0.97***~~
~~***Uniformity 60%/10%***~~	~~***-***~~	~~***2.26***~~	~~***2.02***~~	~~***1.18/1.13***~~
~~***Manganese content***~~	~~***g/kg***~~	~~***14.0***~~	~~***100.0***~~	~~***0.15/0.09***~~

Analyses

The hydrogen peroxide concentration in water was analysed on site with a spectrophotometer. The measurement is based on the reaction of hydrogen peroxide with titanium(IV)oxysulphate solution, following DIN 38409 H15. Samples were collected and measured in a volumetric flask, after adding 5.0 ML of the titanium(IV)oxysulphate solution by a pipette. When higher concentrations were expected than 6 mg/L, the samples were diluted with milli-q water. The samples were measured at a wavelength of 420 nm and corrected for background absorbance, which were determined by analysing the samples

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without the addition of titanium(IV)oxysulphate solution. At a hydrogen peroxide concentration of 5.8 mg/L the standard deviation σ was 0.02 mg/L.

Results and discussion

Activated carbon

With GAC in down flow operation, 5 mg/L hydrogen peroxide was decomposed completely in just more than 120 s empty bed contact time (EBCT), see Figure 1. In the same EBCT, 10 mg/L hydrogen peroxide was decomposed for about 90 %. This experiment confirmed that activated carbon is well-functioning catalyst for decomposing hydrogen peroxide, even at the low water temperature of 1.8 °C.

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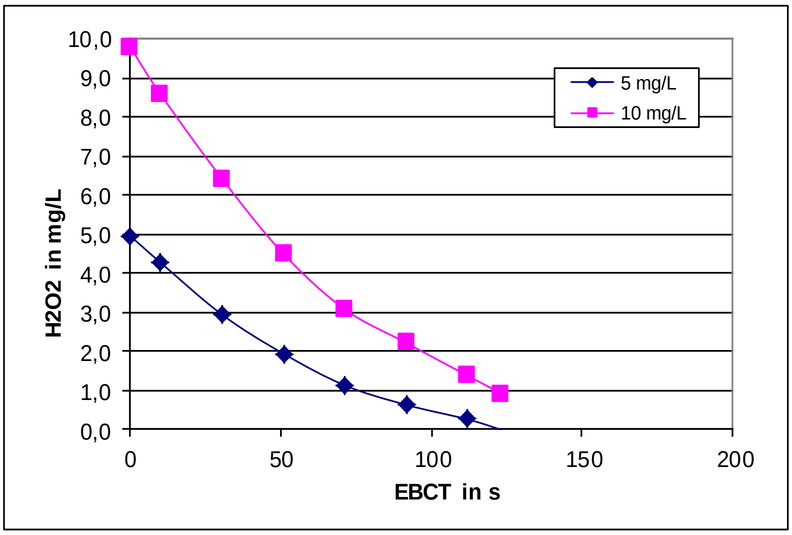

Figure 1: Decomposition of hydrogen peroxide with ROW 0.8 cat in R20 (bed height 1.4 m, flow rate 40 m/u, water temperature 1.8 °C)

Manganese coated filter material

Specifications

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The manganese content of MCFgw is about 100 times higher than from MCFsw due to the higher manganese concentration in groundwater (Table 1). The specific surface area is twice as high. MC is characterized by a high manganese content and specific surface area and small grain size.

Table 1: Specifications of different tested filter gravels

Parameter	***Unit***	***Course gravel MCFgw***	***Coating MC***	***Anthracite/sand, MCFsw***
10% Grain	mm	1.01	0.25	2.06/0.97
Uniformity 60%/10%	-	2.26	2.02	1.18/1.13
Manganese content	gkg^{-1}	14.0	100.0	0.15/0.09
Specific surface area*	m^{2}g^{-1}	4.0	64	1.9/2.1

** BET surface area by N_2 adsorption*

Opmerking [T19]: KC

With XRD analysis, besides calcium and iron compounds, the manganese containing compounds ramsdellite and birnessite were detected in MC (Hendrix, 2014).

Decomposition rate

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The decomposition rate of the different manganese containing materials are investigated in down flow operation. The decomposition of 5 mg/L hydrogen peroxide with anthracite and gravel MCFsw is plotted in Figure 2.

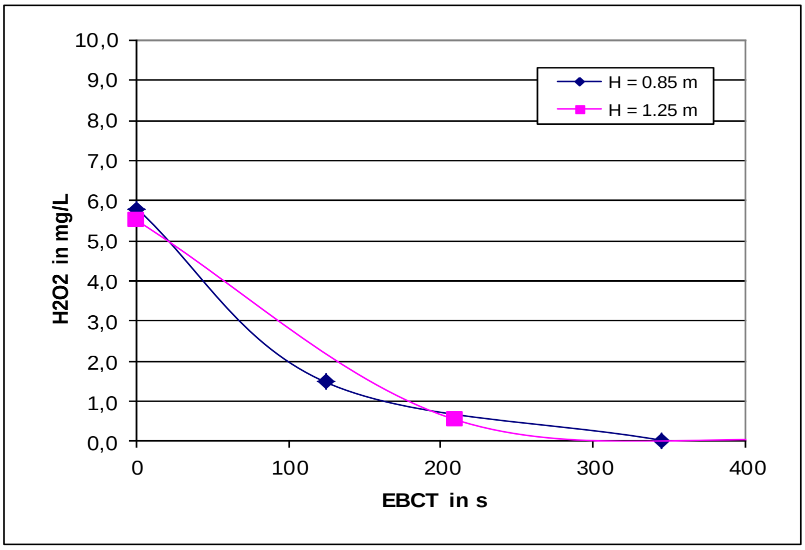

Figure 2: Decomposition over MCFsw in R60s with a bed height of 0.85 m (0.6 m gravel 0.8–1.2 mm & 0.25 m anthracite 1.4-2.4 mm) and a bed height of 1.25 m (1.0 m gravel 0.8–1.2 mm & 0.25 m anthracite 1.4-2.4 mm), a flow velocity of 4.4 m/h, and a water temperature of 12.4 °C

In about 250 till 350 s the hydrogen peroxide in both reactors was decomposed completely. The EBCT of the 0.25 m anthracite layer was about 200 s, which means that the anthracite had a major contribution to the decomposition. The total EBCT of 700 s of the 0.85 m bed layer was the same as the average EBCT in the full scale filters, which means that at least 400 s EBCT remains for the primary functions of the rapid sand filters (removal of iron and manganese, nitrification and mineralization). This observation confirms that applying AOP in front of the rapid sand filters can be an interesting option in practice and could make a separate decomposing installation superfluous, provided that the primary filter functions are not disturbed.
Decomposing with the coarse gravel MCFgw was investigated with a dose of 5 mg/L and 10 mg/L (Figure 3).

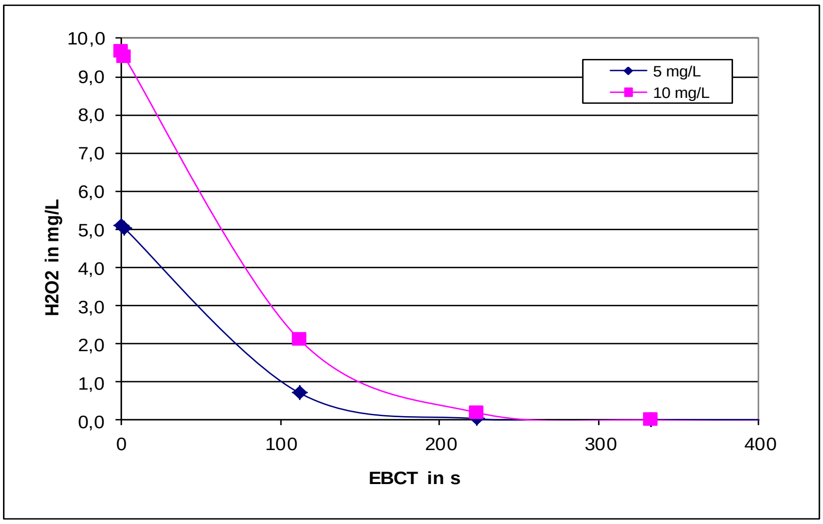

Figure 3: Decomposition over MCFgw in R40 (bed height 2.3 m, flow rate 25 m/h, water temperature 3.3 °C)

A dose of 5 mg/L hydrogen peroxide was completely decomposed in an EBCT of 180 s. A dose of 10 mg/L was decomposed in 260 s. Despite the manganese content of MCFgw of 14 gkg^{-1}, about 100 times higher compared to MCFsw, and twice as large specific surface area, 4.0 m^2g^{-1} compared to 1.9/2.1 m^2g^{-1}, the difference in the decomposing time between MCFgw and MCFsw was no more than 30%. Possibly a part of the manganese oxides in MCFgw were enclosed and did not contribute to the decomposition.~~Despite the manganese content of MCFgw of 14 g/kg, about 100 times higher compared to MCFsw, the difference in the decomposing time between MCFgw and MCFsw was no more than 30%.~~

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The results of decomposition with the fine coating MC was investigated with a dose of 5 mg/L hydrogen peroxide and printed in Figure 4.

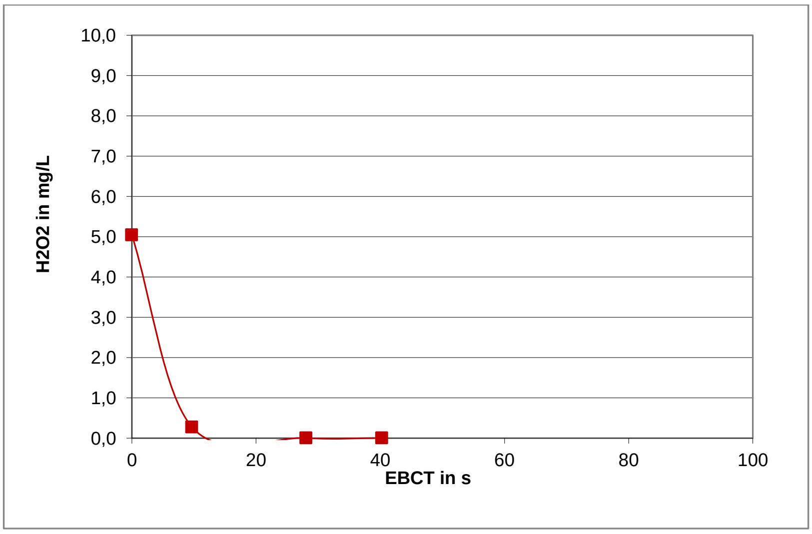

Figure 4: Decomposition over MC in R20 (bed height 0.36 m, flow rate 40 m/h, water temperature 11.7 °C)

Already within 10 s 95% of the hydrogen peroxide was decomposed. Clearly the coating with a relatively high manganese content of 100 g/kg had a positive effect on the rate constant of decomposing hydrogen peroxide, conform literature [Bazri, 2008]. In addition, the small particles and high specific surface area (Table 1) form a large catalyst surface.

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Decomposition of hydrogen peroxide is a first order reaction in a heterogeneous environment. Because the reaction does not take place under homogenous circumstances, the decomposition rate is not expressed in a reaction rate constant, but in the conversion rate constant r [Coulson, 1996]. The conversion rate constant is not only depending of temperature and pressure (as in homogeneous milieu), but also on contact surface of the catalyst and hydraulic conditions in the reactor. In case of a first order reaction, a linear relation exist between the negative natural logarithm of the quotient of the effluent hydrogen peroxide C and influent concentration C_0 and the reaction time (-ln C/C_0 versus t). The relations of the different investigated catalysts are printed in Figure 5.

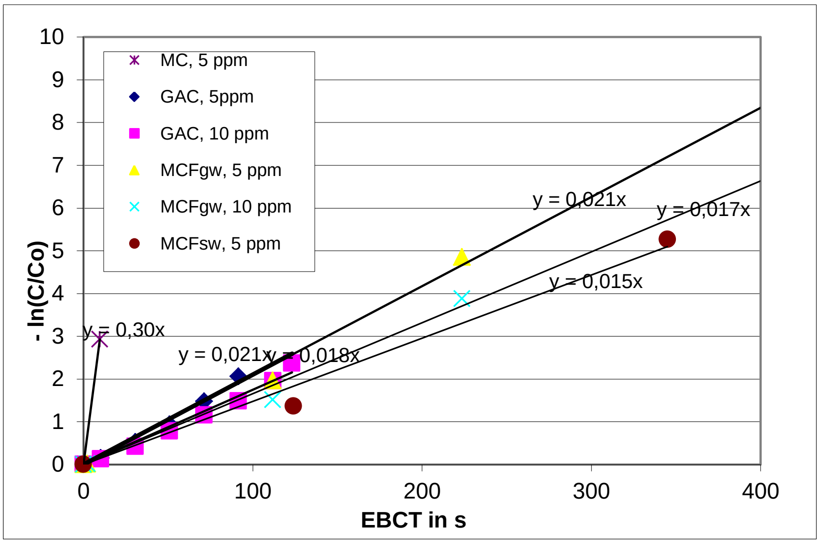

Figure 5: Conversion rate constants of the different tested catalysts

~~The slope of the lines is the value of r.~~ MC had the highest conversion rate constant (note that the value of r is only based on one sample point, because the water in the second sample point did not contain hydrogen peroxide anymore) and much higher compared to the other catalysts~~.~~ The high specific surface area of 64 m^2g^{-1}, the high manganese content in the form of (partly) ramsdellite and small grain size, all three factors contributed to the high conversion rate. Páez et.al. (2011) also reported high conversion rate constants with synthesized small nano-needle particals ramsdellite (ø = 10 nm, L = 180 nm). In batch operation a conversion rate constant was measured of 0.015 s^{-1} after addition of only 0.374 gL^{-1} particles. The conversion rate constant of 0.015 s^{-1} of MCFsw is in line with the reported conversion rate constant of 0.007 s^{-1} during column experiments with sandy aquifer material with different metal deposits, from which manganese appeared to have the biggest contribution to the decomposition (Miller e.a., 1995). Not only the manganese content of 0.06 gkg^{-1} of the sandy aquifer material was comparable with MCFsw (0.15/0.09 gkg^{-1}), but also the specific surface area of 1.75 gm^{-2} (MCFsw 1.9/2.1 gm^{-2}). In addition, the conversion rate

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of the same catalyst depended on the initial hydrogen peroxide concentration. This observation is reported earlier under heterogeneous conditions by Coulson [1996]. In Table 2 the necessary EBCT is calculated for the investigated catalysts with an initial concentration C_0 = 5.75 mg/L (corresponding to a dose in the AOP influent of 6 mg/L) and an effluent concentration C = 0.25 mg/L (the allowed concentration in the infiltration ponds), which means that ln C_0/C = 3.135 and t = 3.135/r. Here, it was assumed that the calculated conversion rate constants at about 5.0 mg/L hydrogen peroxide will not differ much from the conversion rate at 5.75 mg/L.

Table 2: EBCT of catalysts to decompose a peroxide concentration of C_0 = 5.75 mg/L till C = 0.25 mg/L

Catalyst	***r (s^{-1})***	***EBCT (s)***
MCFsw	0.015	209
GAC	0.021	149
MCFgw	0.021	149
MC	0.30	10.4

The necessary EBCT in the full scale dual layer filters (MCFsw) amounts about 200 s. The EBCTs of GAC and MCFgw equals about 150 s. The EBCT of MC is much lower with approximately 10 s.

Mode of operation

Opmerking [T25]: KC

~~All experiments were carried out in down flow operation.~~ For full scale operation~~, however,~~ down flow operation over fine material has the disadvantage of fast clogging of filter material with suspended particles and potential increase of the resistance due to oxygen bubble formation, depending of the oxygen saturation degree of the water. These disadvantages could be solved by up flow operation.
Up flow operation of the coating MC was investigated using three different flow rates. A flow velocity of 40 m/h appeared to be the maximum velocity, without carrying the coatings with the effluent of the reactor. The coatings became in fluidised state at a flow velocity of 4 m/h. The decomposition of 5.8 mg/L hydrogen peroxide is plotted in Figure 6.

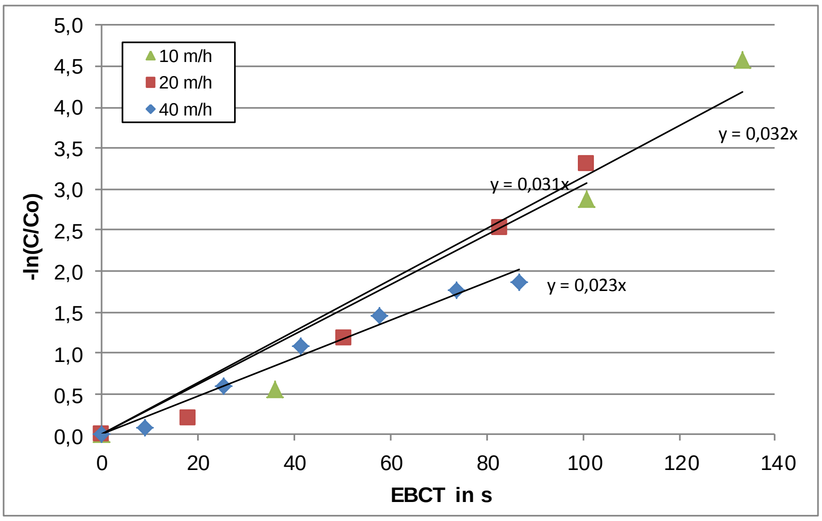

Figure 6: Up flow decomposition with MC in R20 (static bed height 0.36 m, water temperature 5.8 °C)

From Figure 6 it was concluded, that the decomposition was sufficient, which means ln $C_0/C \geq 3.135$, with up flow velocities of 10 m/h and 20 m/h. The necessary EBCT was approximately 100 s. At a velocity of 40 m/h the decomposition goal could not be achieved. Presumably, the adsorption of hydrogen peroxide on the catalyst was inadequate due to the increased expansion of up to 170%, which resulted in less catalyst surface in the same reactor height.~~Presumably, the adsorption of hydrogen peroxide on the catalyst was inadequate due to the increased expansion, see Figure 7, which resulted in less catalyst surface in the same reactor height.~~

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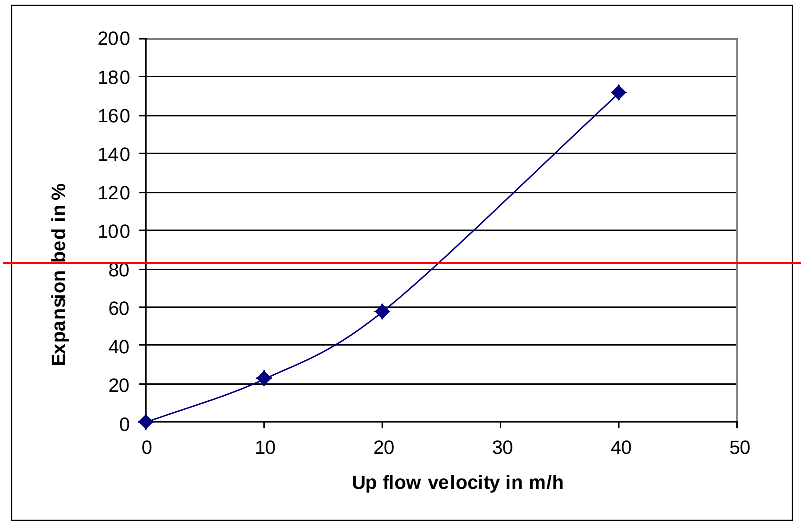

~~*Figure 7: Expansion of the 0.36 m MC-bed as a function of the flow rate*~~

Opmerking [T27]: PLC

~~In one way or another p~~Pelleting MC till a diameter of about 2 mm would make higher flow velocities possible, and with that a smaller reactor footprint. However, changing the diameter or the surface area of the catalyst or the hydraulic conditions in the reactor, will have impact

Opmerking [T28]: PLC

on the value of the conversion rate constant and consequentially on the design criteria. In addition, the decomposition of hydrogen peroxide depends on the water temperature and will be faster with increasing water temperature. This is visible in Figure ~~8~~7, wherein the decomposition is plotted of experiments with GAC at 1.8 °C and 10.7 °C. The concentration of hydrogen peroxide was always lower after the same contact time at a higher water temperature.

Opmerking [T29]: PLC

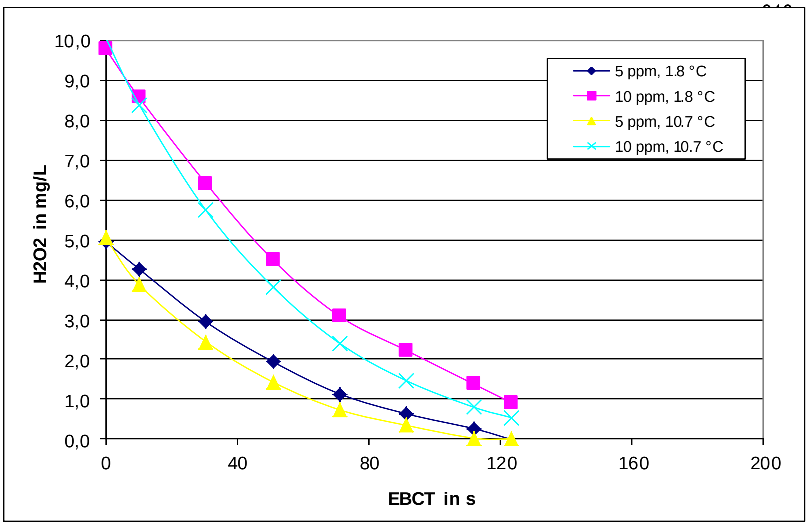

Figure 7~~8~~: Decomposition with GAC at different water temperatures

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Conclusions

In down flow operation, the necessary EBCT to decompose 5.75 mg/L hydrogen peroxide in pre-treated Meuse river water with the commonly used GAC and waste groundwater filter gravel (MCFgw) were the same with about 150 s, corresponding to a conversion rate constant r of 0.021 s^{-1}. The EBCT of the coating of groundwater filter gravel (MC) was much shorter with a little more than 10 s (r = 0.30 s^{-1}).
MC was suitable for up flow operation till a flow velocity of about 20 m/h. The necessary EBCT was about 100 s (r = 0.031 s^{-1}). At an up flow rate of 40 m/h the decomposition goal could not be achieved, probably due to the increased porosity in the fluidized bed. Pelleting MC till a diameter of about 2 mm would make higher up flow velocities possible.
The necessary EBCT at average filtration velocity of dual layer filter material (MCFsw) amounted to about 200 s (r = 0.015 s^{-1}). Regarding the average residence time in the full scale filters of 700 seconds, applying AOP in front of the filters could be an interesting alternative making a separate decomposition installation superfluous, on the condition that the primary functions of the filters are not affected.

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