Investigation of Clogging Processes on Vertical Filter Wells Using an Experimental Model

Christoph Weidner[1], Sebastian Henkel[2], Stefanie Lorke[2], Thomas R. Rüde[1], Holger Schüttrumpf[2], Wiebke Klauder[3]

[1]RWTH Aachen University, Institute of Hydrogeology (LFH), Lochnerstr. 4—20, 52064 Aachen, Germany, weidner@hydro.rwth-aachen.de
[2]RWTH Aachen University, Institute of Hydraulic Engineering and Water Resources Management (IWW), Kreuzherrenstr. 7, 52056 Aachen, Germany
[3]RWE Power AG, Water Resources Management, Zum Gut Bohlendorf, 50126 Bergheim, Germany

Abstract A large number of wells are required to dewater the aquifers in the Rhenish lignite mining district in Germany. Their performance is often influenced by well ageing due to precipitation of iron oxides. With an experimental model of a well screen section the genesis of Fe oxide incrustations is reproduced in an accelerated way by modification of the pH and the Fe concentration in contrast to the natural values. This model setup aims to gain a general understanding of the clogging processes and to test and develop techniques to prevent or reduce the loss of well efficiency.

Key Words Iron oxide incrustation, chemical clogging, well loss, well ageing, laboratory model test, open-pit dewatering

Introduction

Mining in open pits in the Rhenish lignite district requires large-scale groundwater management including dewatering of reduced (i.e. anoxic) aquifers. To that purpose a large number of vertical dewatering wells with tubing diameters of up to 0.75 m are drilled into depths up to 750 m. More than 550 million m^3 of water is pumped by the mining company (RWE Power AG) every year and well ageing is an important factor. One of the main aspects to be considered is the formation of iron oxide incrustations (ochre) in the gravel pack and well screen, because this affects the well efficiency in an undesirable way (Houben 2003). If a well affected by clogging cannot be regenerated, the only alternative to keep the groundwater level down is to drill a new well.

In contrast to drinking water supply, well operation in open pit mining aims at a complete dewatering of all intersected aquifers above the coal seams in the open pit range. The strong drawdown leads to a mixing of different groundwaters from several aquifer layers. Due to the low operating water level in the well, oxygen inside the well tube can reach reduced groundwater.

Clogging effects generally occur if reduced groundwater with dissolved Fe(II) or Mn(II) ions is brought into contact with the oxygen of the ambient air in the well tube (Holluta and Kölle 1964). In that case, the reduced metal ions react with oxygen to their oxidized forms Fe(III) or Mn(IV) which are insoluble and therefore precipitate as hydroxide minerals, for example FeOOH, including Goethite and Lepidocrocite (Cornell and Schwertmann 2003). In this study only clogging caused by Fe(II) is considered which, in the simplest case, follows the equation:

$$4Fe^{2+} + 6H_2O + O_2 \rightarrow 4FeOOH \downarrow + 8H^+$$

The adsorption of the precipitated minerals to all technical elements of the well system (gravel pack, screen, pump and pipes) results in a significant increase of well losses over time. The progression of the reaction is influenced by the pH value and the concentrations of iron(II) [Fe(II)] and oxygen [O_2] (Houben and Treskatis 2007), as is demonstrated by the following equation:

$$r = k_1 \frac{[Fe(II)] \cdot [O_{2,aq}]}{[H^+]^2} = k_1 [Fe(II)] \cdot [O_{2,aq}] \cdot 10^{2pH}$$

with r = reaction rate in [mol L^{-1} min^{-1}] and k_1 = 1,515·10^{-12} mol L^{-1} min^{-1} after Davidson and Seed (1983). Increasing the concentrations of Fe(II) and O_2 is one possibility to accelerate the reaction. Because the reaction produces protons, its rate also extremely increases with rising pH (quadratic dependency on the proton concentration [H^+]). In addition, the clogging process in wells can be amplified by certain bacteria which use the conversion of dissolved Fe(II) to Fe(III) minerals as source of energy (Hässelbarth and Lüdemann 1967, Ralph and Stephenson 1995, Rinck-Pfeiffer *et al.* 2000).

Methods

An experimental model of a well screen section (fig. 1) was set up to reproduce the natural situation and processes under controlled boundary conditions and to contribute to the understanding of the clogging processes of vertical filter wells (Rüde *et al.* 2010). In natural situations, the ageing

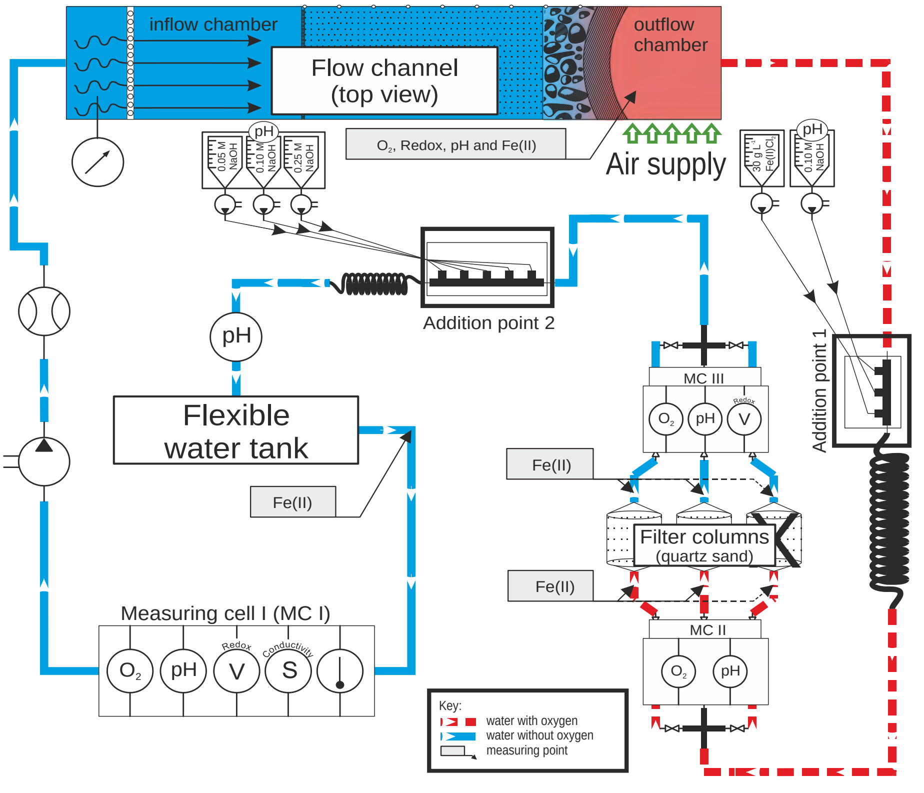

Figure 1 *Experimental setup with illustration of the flow direction and the zones of O_2-bearing and O_2-free water. During the test period each of the filter columns can be exchanged by a third one. A 150 L flexible water tank is used as a storage reservoir for volume fluctuations and for buffering the effects of addition point 2.*

process extends over several years. In order to run the tests in an appropriate time frame, we accelerated the process in the model by increasing the pH and the concentration of dissolved Fe(II). Additionally the water in the outflow chamber is aerated. In contrast to the natural situation, the individual factors that affect the clogging process can be investigated separately. Firstly, the purely chemical clogging by iron oxides is considered.

The experimental setup can be divided into two parts. The main part is the flow channel, where the experimental investigations are performed. The ancillary part is the peripheral water cycle which is designated as a water processing chain to reprocess the water for the flow channel.

In the flow channel a section of a typical dewatering well in the Rhenish lignite mining district is installed. To reach a high similarity to the natural situation, original aquifer material from the open pit Garzweiler in Germany was applied. The aquifer material was taken from the Frimmersdorf-Sand (Horizon 6B after Schneider and Thiele 1965) which forms a sandy interlayer in the main seam group of the upper Miocene Ville-strata (Walter 2010). Horizon 6B separates the two coal seams Morken (Horizon 6A) in the lower bed and Frimmersdorf a (Horizon 6C a) in the upper bed (German Institute for Standardization 2001). The gravel pack and the well screen are original well assembling materials, allocated by RWE Power AG. In the channel the water flows from left to right (fig 2) through the aquifer material and then enters the well with gravel pack and screen. The walls of the channel consist of acrylic glass (PMMA), enabling an optical documentation of the clogging process.

The flow through the channel was controlled by pumps at the in- and outflow and kept at a constant rate of 1.06 L min^{-1}. To simulate an infinite groundwater reservoir, the inflow chamber was kept under hydrostatic overpressure during the tests. In the downstream part of the aquifer material the flow conditions change from confined to unconfined characteristics due to the low water level in the outflow chamber which is not covered. The water comes into contact with the oxygen of

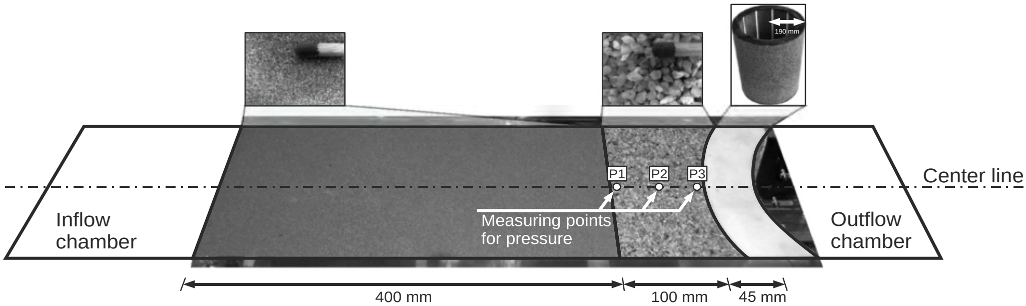

Figure 2 *Perspective top view of the material assembled in the flow channel. The flow direction is from left to right. The width and height of the channel are 200 mm each. The pressure measurement points P1-P3 actually lie on the bottom of the channel and are projected to the top for illustration purposes only.*

the ambient air in the gravel pack, the well screen and the outflow chamber, leading to aeration of the water. The oxidation of Fe(II) takes place in these parts of the system only.

In the peripheral water cycle the discharge from the flow channel is continuously enriched with Fe(II) by addition of a 30 g L^{-1} Fe(II) solution of $FeCl_2 \cdot 4H_2O$ at a rate of 1 mL min^{-1}. To keep the Fe(II) ions in solution and to prevent untimely oxidation, the solution is acidulated with 1 mL HCl (25 %) per L of Fe solution. This Fe(II) input is sufficient to chemically bond all of the residual oxygen that is not dissipated by the oxidation reaction in the flow channel. At this point the water is "re-enriched" with Fe to obtain a level in between 40 and 80 mg L^{-1}. To keep the O_2 detracting reaction running, the pH value has to be raised by continuous addition of NaOH. Then, the oxygen is entirely consumed by the generation of iron hydroxides or Green Rust I (Refait and Génin 1993), which in a following step are filtered by columns of quartz sand. Subsequently, the pH value of the O_2-free water is adjusted to a level of 7.8 to ensure a constant high reaction rate in the channel outflow. To prevent the generation of green rust, which will clog the aquifer material at the channel inflow, the pH value should not exceed a threshold value of 8. Altogether, there are three aspects that were consciously modified in comparison to the natural conditions to achieve an accelerating effect in reproducing the clogging process: The natural water from Garzweiler has average pH values of 6.7 to 7.2 and Fe(II) contents of 0 to 9^{-1} mg L^{-1} (RWE Power AG 2008), whereas in the model a pH value of 7.8 and an Fe content in between 40 and 80 mg L^{-1} are applied. The third accelerating effect is the active air supply, which raises the DO (Dissolved Oxygen) in the outflow chamber to about 1 mg L^{-1}.

Physico-chemical parameters (pH, eC, DO and redox-potential) are monitored at several points in the model. The Fe(II) concentration is determined photometrically in more or less irregular intervals using a pinkish Fe(II)-1,10-phenanthroline complex after the German Institute for Standardization (1983). The average decay of Fe(II) in the outflow chamber is calculated to estimate the average Fe_{tot} content of the gravel pack.

To quantify the progress of the incrustation growth, the piezometric profile in the gravel pack is continuously monitored using a high resolution pressure gauge device. The water level in the outflow chamber can be adjusted to certain heights above the channel bottom because of their large effect on the pressure losses in the gravel pack. As there is a stable pressure in the inflow chamber a different outflow level automatically influences the hydraulic gradient. Additionally, other measuring points can be triggered to measure the pressure losses in the aquifer material.

After finishing a test, the gravel pack material is excavated in layers of 2 cm. Each layer is charted, photographed and sampled. The samples are analyzed by an sequential extraction procedure (SEP) focusing on poorly-crystalline and well-crystalline iron hydroxides according to fractures 6 and 7 after Wenzel *et al.* (2001). X-Ray Diffraction (XRD) methods are to be used to determine the type of generated Fe minerals.

Results

The contiuous measurements (tab. 1) show the system to be free of dissolved oxygen except for the outflow chamber. In the outflow chamber the redox potential rises rapidly due to the oxygen input. The Fe(II) content and the pH decrease in the outflow chamber as a consequence of the oxidation reaction.

The growth of incrustations at three distinct test times is shown in figure 3. The first picture shows the initial situation before addition of Fe(II).

Parameter	*Unit*	*Measurement Point*	*m*	*s*	*n*	*Mode*
O_2	[mg L^{-1}]	outflow chamber	2.64	0.35	81,165	auto
		MC II	0.01	0.01	382	man
		MC III	0.24	0.08	377	man
		MC I	0.03	0.01	1.3 Mio.	auto
pH	[-]	outflow chamber	6.35	0.24	393	man
		MC II	7.60	0.33	379	man
		MC III	7.48	0.21	382	man
		bA2	7.82	0.10	1.6 Mio.	auto
		MC I	7.77	0.08	1.6 Mio.	auto
Redox	[mV]	outflow chamber	-76	67	395	man
		MC I	-439	21.2	1.6 Mio.	auto
eC	[mS cm^{-1}]	MC I	5.01	0.21	1.6 Mio.	auto
Fe(II)	[mg L^{-1}]	outflow chamber	46.6	14.6	212	man
		MC II	55.1	14.7	211	man
		MC III	53.0	14.0	431	man
		MC I	50.3	13.9	218	man

Table 1 *Long term arithmetic means (m), standard deviations (s) and value numbers (n) of the parameters, measured automatically (auto) or manually (man) at the points in the model defined in figure 1. bA2: behind addition point 2.*

The second picture shows the effects of clogging after a test period of 17.5 hours using the lowest possible outflow water level (about 4 mm). It becomes clear that the clogging reaction takes place in the vadose zone of the gravel pack only. In the phreatic zone the concentration of dissolved oxygen apparently is too low to produce visible incrustations and above the vadose zone, of course no Fe(II) bearing water is available.

At the upstream boundary of the gravel pack (left) the water obviously has a vertical flow component, allowing the incrustations to reach the top of the flow channel.

At a later stage of the experiment, the water level was actively raised in steps of 20 mm up to 120 mm in order to induce clogging effects at the top of the flow channel in the downstream parts of the gravel pack as well (fig. 3, right picture).

The clogging processes caused an increase of the pressure loss in the gravel pack of about 30 % (tab. 2). However, because the measuring cycle was modified during the test to concentrate the investigations on the measuring points P1, P2 and P3 (fig. 2), this value should be considered to be a first approximation which has to be verified by another test.

The average Fe_{tot} content in the gravel pack, estimated on the basis of the Fe(II) balance, reaches levels up to 10 g kg^{-1}. For the sequential extraction procedure different clogging zones were sampled, which were distinguished optically by the colouring of the gravel. Three samples from dark red zones showed average values of about 13.3 g kg^{-1} Fe_{tot}, five samples from light red to dark orange zones 3.4 g kg^{-1} Fe_{tot} and three samples from light orange zones 0.96 g kg^{-1} Fe_{tot}. The percentage of well-crystalline Fe(III) minerals in all 11 samples ranged from 34 to 97 % and averaged 74 % (Henkel *et al.* 2011).

Discussion and Conclusions

The results show that the pressure loss in the gravel pack significantly increased due to chemical clogging of iron oxides. A change in the hydraulic conductivity of the filter gravel occurs within 295 hours of Fe(II) bearing water flowing through the channel. Therefore, the acceleration of the clogging processes works quite well and the tests can be accomplished in an appropriate time period. With the proposed model it is possible to investigate the clogging processes with or without considering several influencing factors. Hence the clogging tendency can be compared for different settings of gravel pack materials, well screens and hydrochemical settings (e.g. input solution on the basis of $Fe(II)SO_4$). Different types of regeneration and the corresponding re-ageing can be studied.

The laboratory reproduction of the chemical

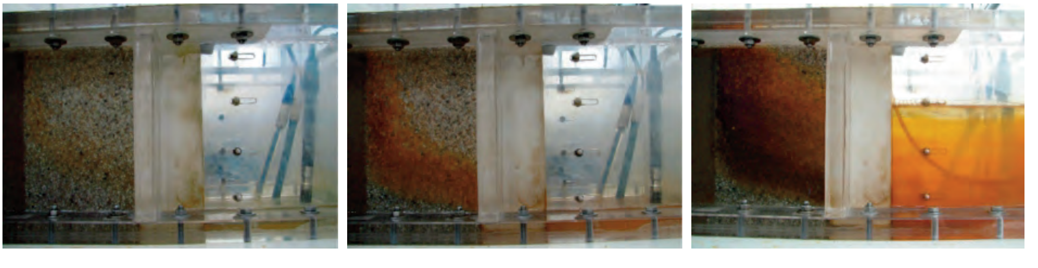

Figure 3 *Front view of the outflow chamber with the well screen section, gravel pack and aquifer material (from the left to the right of each picture; height: 200 mm). Progress of incrustation growth at 0 h (left), 17.5 h (middle) and 123.0 h (right) after the first breakthrough of Fe(II) through the flow channel.*

***Table 2** Pressure losses (ΔPi-Pj) at the end of the test in comparison with the initial values (Start) at different water levels H (n: Number of values). The increase is calculated from the start and end values of ΔP1-P3.*

Time	n	H [mm]	ΔP1-P2 [mm]	ΔP2-P3 [mm]	ΔP1-P3 [mm]	Increase [%]
Start[1]	32	138.9 ± 2.1	2.1 ± 0.2	2.1 ± 0.1	4.2 ± 0.2	10.64
End[2]	39	135.6 ± 0.6	2.2 ± 0.1	2.5 ± 0.1	4.7 ± 0.1	
Start[1]	36	84.0 ± 2.4	2.2 ± 0.1	2.3 ± 0.1	4.4 ± 0.1	21.43
End[2]	43	82.6 ± 3.0	2.5 ± 0.6	3.1 ± 0.1	5.6 ± 0.2	
Start[1]	50	54.2 ± 2.8	2.9 ± 0.1	2.3 ± 0.6	5.0 ± 0.6	29.58
End[2]	36	60.9 ± 1.7	3.0 ± 0.1	4.1 ± 0.1	7.1 ± 0.1	
Start[1]	44	30.6 ± 4.4	2.9 ± 0.1	3.6 ± 0.2	6.6 ± 0.2	19.51
End[2]	35	40.1 ± 1.3	3.3 ± 0.6	5.0 ± 0.3	8.2 ± 0.5	

[1] Measuring cycle 1, measurement of any possible point in the flow channel in a row

[2] Measuring cycle 2, only measuring points P1, P2 and P3 (compare figure 2)

iron clogging process with the introduced model has been successful and seems promising to provide contributions to a detailed understanding of the process taking place during the growth of incrustation.

Acknowledgements

The authors thank Christian Forkel, Wilhelm Schlegel and Gero Vinzelberg (RWE Power AG) for the pleasant cooperation, for their contribution to the project's funding, and for creating the unique opportunity to take samples in the open pits. We sincerely thank Sebastian Roger (RWTH Aachen University) for a long time of pleasurable collaboration on this project. Andre Banning and Thomas Demmel (RWTH Aachen University) are acknowledged for their help in analytical and technical questions. Furthermore, we appreciate the inspiring correspondence with Christoph Treskatis (Bieske und Partner Beratende Ingenieure GmbH).

References

Cornell RM, Schwertmann U (2003) The iron oxides: structure, properties, reactions, occurences and uses. Wiley-VCH, Weinheim, 604 pp

Davidson W, Seed G (1983) The kinetics of the oxidation of ferrous iron in synthetic and natural waters. Geochimica et Cosmochimica Acta 47:67—79

German Institute for Standardization (2001) DIN 21919—3: Bergmännisches Risswerk – Stratigraphie – Teil 3: Regionale und lokale Gliederungen Braunkohle. Beuth, Berlin, 11 pp

German Institute for Standardization (1983) DIN 38406—1: Deutsche Einheitsverfahren zur Wasser-, Abwasser- und Schlammuntersuchung – Kationen (Gruppe E) – Bestimmung von Eisen (E 1). Beuth, Berlin, 9 pp

Hässelbarth U, Lüdemann D (1967a) Die biologische Verockerung von Brunnen durch Massenentwicklung von Eisen- und Manganbakterien. bbr 18:363—368 & 401—406

Henkel S, Weidner C, Roger S, Schüttrumpf H, Rüde TR, Klauder W, Vinzelberg G (2011) Untersuchung der Verockerungsneigung von Vertikalfilterbrunnen im Modellversuch (Investigation of the clogging affinity of vertical wells using an experimental model). Grundwasser (submitted)

Holluta J, Kölle W (1964) Über die Oxydation von zweiwertigem Eisen durch Luftsauerstoff. gwf 105(18):471—474

Houben GJ (2003) Iron oxide incrustations in wells. Part 1: genesis, mineralogy and geochemistry. Applied Geochemistry 18:927—939

Houben GJ, Treskatis C (2007) Water Well Rehabilitation and Reconstruction. McGraw-Hill Professional, New York, 391 pp

Ralph DE, Stevenson JM (1995) The role of bacteria in well clogging. Water Research 29(1):365—369

Rinck-Pfeiffer S, Ragusa S, Sztajnbok P, Vandevelde T (2000) Interrelationships between biological, chemical, and physical processes as an analog to clogging in aquifer storage and recovery (ASR) wells. Water Research 34:2110—2118

Refait P, Génin J-MR (1993) Mechanisms of formation and structure of green rust one in aqueous corrosion of iron in the presence of chloride ions. Corrosion Science 40(9):1547—1560

Rüde TR, Banning A, Klauder W, Roger S, Vinzelberg G (2010) Improving the effectiveness of wells for lignite mine dewatering. In: Wolkersdorfer C, Freund A (2010) Mine Water and Innovative Thinking. CBU Press, Sydney, Nova Scotia:89—93

RWE Power AG (2008) Bericht zur Grundwasserbeschaffenheit – Vorfeld. Bericht 2.4, unpublished

Schneider H, Thiele S (1965) Geohydrologie des Erftgebietes. Ministerium für Ernährung, Landwirtschaft und Forsten des Landes Nordrhein-Westfalen, Aachen, 185 pp

Walter R (2010) Aachen und nördliche Umgebung. Sammlung Geologischer Führer Band 101. Gebr. Borntraeger, Stuttgart, 214 pp

Wenzel WW, Kirchbaumer N, Prohaska T, Stingeder G, Lombi E, Adriano DC (2001) Arsenic fractionation in soils using an improved sequential extraction procedure. Analytica Chimica Acta 436(2):309—323