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Influence of microbial processes on the operational reliability in a geothermal heat store – Results of long-term monitoring at a full scale plant and first studies in a bypass system

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Abstract

This paper describes microbial metabolic processes that are considered to be relevant for the technical reliability of a geothermal heat store. The study reports on changes of the microbial community composition in geothermal well fluids of different temperatures and after plant downtimes monitored by genetic fingerprinting. Stagnant conditions favored the enrichment of bacteria, sulfate reducers (SRB), and sulfur oxidizers (SOB) in the well. Furthermore higher concentrations of DOC, SO_4^{2-}, H_2S, and H_2 were detected in the first fluids produced after plant downtime. The increased abundance of SOB indicated oxygen ingress during plant downtime. The interaction of SRB and SOB might have further enhanced corrosion and scaling processes. A mobile bypass system installed at the site will help to understand the processes occurring in the well and to study biofilm formation and corrosion rates at different temperatures.

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Keywords: Microbial influenced corrosion (MIC), geothermal heat store, bypass system, SRB, SOB, plant downtime

1. Introduction

Up to now, about 250 MW thermal power and 30 MW electrical power are provided by deep geothermal plants in Germany [1]. Experience shows that corrosion and scaling have a huge impact on the operational safety and the economic efficiency of geothermal plants. Despite extreme conditions like high salinity and temperature of the fluids, microbial metabolic processes can accelerate these processes [2,3]. Besides the above ground installations also the borehole, borehole near areas and even the reservoir may be affected or damaged. For instance, in geothermal facilities the use of electrical submersible pumps in expensive designs is necessary. In consequence, pump failures due to corrosion can lead to severe financial strains for the operator.

Deep geothermal reservoir fluids of the North German Basin are characterized by high temperatures and high salt concentrations creating harsh conditions for well installations and plant equipment. Besides the corrosive fluids themselves, also microorganisms inhabiting the saline fluids can increase corrosion rates and scaling up to the emergence of plant operation failures and plant downtimes [4]. In several studies microorganisms mediating scaling, biofouling and corrosion phenomena have been identified reducing the commercial benefits of plants [5,6,7,8,9]. In addition to the regular operation of geothermal plants also downtime phases have to be investigated to evaluate their effects on corrosion and scaling processes.

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Microorganisms, such as sulfate reducing bacteria (SRB), sulfur oxidizing bacteria (SOB), fermentative bacteria and archaea are known to be involved in corrosion and scaling processes [10]. Especially SRB have been identified as one of the main accelerating corrosion factors, although the underlying mechanism of the process is still under debate [11].

In this study, fluids produced from a geothermal plant in Neubrandenburg (North German Basin) used for subsurface heat storage were investigated using molecular biological analyses based on 16S rRNA and *dsr* genes. Samples were taken from the cold well previous and subsequent to downtime phases to monitor their effects on the microbial populations in the well and the reservoir, particularly in the near wellbore area. Therefore the microbial communities in fluids produced during regular plant operation were compared with those in fluids, taken after differently lasting downtime phases, in order to identify specific microbial metabolic groups associated with stagnant conditions during those phases. Comparisons between microbial communities in fluids should provide insight into the processes occurring downhole with respect to corrosion and scaling processes.

Additionally a mobile bypass system is installed on site to understand the processes occurring in the well at different plant operation modes in detail. The bypass allowed modifications of the fluid temperature and the operational regime. Furthermore investigations of corrosion rates and biofilms were conducted by varying the temporal exposure of different steel quality coupons to the fluids.

2. Methods and test site

2.1. Geochemical and microbiological methods

The redox potential, pH and fluid temperature were analyzed on-site using a pH/mV/temperature meter (WTW, Weilheim, Germany). The total organic carbon (TOC) was determined according to the German guideline DIN EN 1484-H3. The quantification of the dissolved organic carbon (DOC) was done by size-exclusion-chromatography with subsequent ultra violet (UV) detection (k = 254 nm). Fluid-soluble anions and cations were determined including ion balances. Quantifications of sulfate, iron and the dissolved gas content as well as the gas composition analyses were done as described before [4]. The dissolved hydrogen sulfide content was quantified using an amperometric H_2S micro-sensor (AMT Analysenmesstechnik GmbH, Germany). The sulfur isotopic composition was measured using an elemental analyzer NC 2500 connected to a Thermo Quest Delta+XL mass spectrometer. The carbon isotopic composition was determined using a mass spectrometer DELTAplusXL (ThermoFischer Scientific). The residues in filters were analyzed using a Scanning Electron Microscope (SEM) Hitachi S-4700 with an Energy Dispersive Spectrometer (EDS).

Genetic fingerprints of bacterial communities in fluids were performed by AMODIA Bioservice GmbH (Braunschweig, Germany) using polymerase chain reaction - single strand conformation polymorphism (PCR-SSCP) [12] as previously described in [4].

Bacteria, SRB and sulfur-oxidizing *Halothiobacillus* were quantified by quantitative real-time PCR (qPCR). Analyses of bacterial 16S rRNA [13], *dsr*A genes for SRB [14,15] and specific *Halothiobacillus* 16S rRNA genes were performed using the StepOnePlusTM real-time PCR System (Applied Biosystems, Carlsbad, CA, USA) with Power SYBR® Green PCR Master Mix (Life Technologies, Carlsbad, CA, USA).

2.2. Site description

The geothermal heat store is located in Neubrandenburg (North German Basin, Germany). The water-bearing sandstone formation is situated at a depth of 1,228 m-1,268 m and is assessed by a geothermal doublet. The distance between the wells GtN 1/86 and GtN 4/86 is around 1,300 m. The season dependent change of the fluid flow direction resulted in an initial increase of the fluid temperature in the aquifer around the “warm” well GtN 1/86 from the original 54 °C to finally 87 °C. Around the “cold” side (GtN 4/86) of the aquifer the temperature decreased to 47 °C. The borehole volume amounts to 35 m^3. The plant is equipped with a filter system to retain solid particles. The fluid flow rate during the plant restart varied between 20 $m^3\ h^{-1}$ to 60 $m^3\ h^{-1}$. At regular operation it was around 80 $m^3\ h^{-1}$. The wells and the topside facility were kept under nitrogen pressure to prevent precipitation, degassing processes and oxygen ingress during plant downtime. Further information on plant design and operation is given in [16,17]. Corrosion damage of the submersible pump and a decreased injection rate in the cold well caused by precipitation and scaling led to downtime phases lasting up to three months.

2.3. Bypass system

The bypass system (Fig. 1) is installed in a container in order to relocate it easily on site or to different sites. All parts of the bypass which are in contact with saline fluids are made out of a nickel based high-performance alloy except the feed pump and the plate heat exchanger. In case of corrosion or clogging they can be exchanged. The bypass system is designed for a maximum pressure of 16 bar at a maximum temperature of 120 °C. Depending on the flow rate and the air temperature a cooling unit allows decreasing the fluid temperature of about 70 °K. The fluid flow can be adjusted between 0.2 and 1 $m^3\ h^{-1}$ and without

cooling up to 5 m^3 h^{-1}. Between flanges two parallel 50 cm long 4" pipes can be equipped with steel coupons or other installations. The sections can be separated by valves and can be removed from the unit for further analysis.

The system is fully automated using a programmable logic controller. Remote access allows for monitoring and control. Physical fluid parameters are measured and recorded online. The design enables the implementation of further sensors e.g. pH, redox potential and conductivity. As a security measure, gas concentrations in the container and fluid leakages are monitored with automatic emergency shutdown.

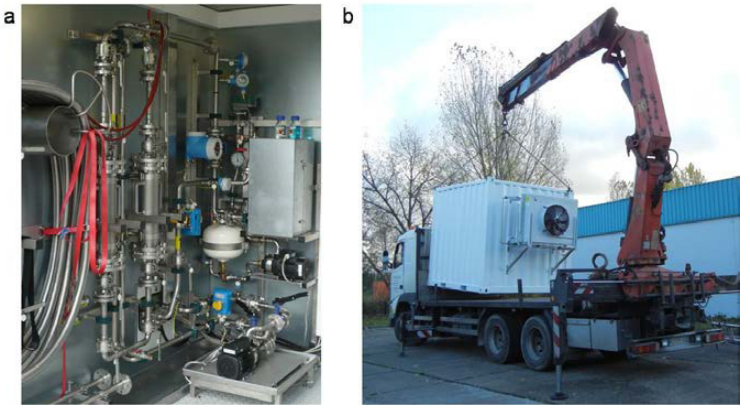

Fig. 1 Mobile bypass system: (a) interior of the container; (b) container transportation.

3. Results and Discussion

The geothermal fluid was classified as Na-Cl type with a mineralization of 130 g L^{-1}, a sulfate concentration of 900 to 1,000 mg L^{-1} and a pH of 6. The redox potential of less than -50 mV represented anoxic conditions. The total gas content of the fluids amounted to 7 % with carbon dioxide (86.2 vol.-%) and nitrogen (13.8 vol.-%) as main components. The hydrogen content of the fluids produced from the warm and cold well of the aquifer was approximately 0.03 vol.-% and 0.21 vol.-%, respectively. In addition, hydrogen sulfide was only detected in fluids produced from the cold well, with average values of 0.2 vol.-% [4]. After heat extraction the filter residue in topside facility consisted mainly of iron sulfide (FeS, ~ 90 %), with a particle size of less than 1 µm. The minority of mineral residues consisted of rust, calcium carbonate, and reservoir materials. The average concentration of DOC was 3.5 mg C L^{-1} with low concentrations of short-chain fatty acids, ranging between 0.1 mg L^{-1} and 1.9 mg L^{-1} [9].

The reduction of the fluid temperature during heat extraction affected the bacterial communities in numbers and composition [4]. Cell counts, 16S rRNA and *dsr*A gene copy numbers were higher in fluids produced from the cold well than in hot fluids from the warm well (data not shown) and indicated that microorganisms were favored by the lower fluid temperatures [4]. Temperature reduction resulted in a higher diversity of fermentative bacteria in cooled fluids originating from the warm well [4]. The predominance and higher diversity of SRB in the cold well (Fig.2) was in accordance with the higher FeS content and a slightly lower sulfate concentration. Furthermore, the isotopic signature in the fluids of above 32 ‰ CDT indicated microbial turnover of sulfur components in the fluids, as values of 13-18‰ CDT would be expected without microbial activity. Altogether, genetic fingerprinting, quantification of gene copy numbers as well as chemical data analysis of the fluids and filter residues indicate that the sulfate reducing community influenced corrosion processes and affected thereby the operational reliability of the plant seriously [4].

Genetic fingerprinting indicated that the microbial community composition of fluids originating from the cold well was dominated by different genera of SRB and fermentative *Halanaerobiaceae* in the 47 °C tempered fluids during regular operation, whereas after shut-down phases sequences of SOB were detected additionally [18]. The effects of shut-down on the operational reliability were studied after several up to three months lasting downtimes. Stagnant conditions favored the enrichment of biomass and particles in the well. After plant restart, SOB decreased quickly after production of 1-2 borehole volumes to background levels, which led to the assumption that the SOB abundance was limited to the well bore (Fig. 3). It is assumed that the interaction of SRB and SOB during plant downtimes enhanced corrosion processes and scaling. Increase of SRB and SOB during stagnant conditions went along with higher concentrations of DOC, sulfate and hydrogen sulfide [18].

The influence of plant downtime and stagnant fluid flow on corrosion processes was further investigated in a bypass system. Hereby, carbon steel and stainless steel coupons were exposed to the saline brine. The initial fluid temperature was approximately 78 °C and cooled down to 40 °C and 30 °C (Tab.1). The TOC concentration ranged between 3 and 22 mg L^{-1} (Fig. 4) dependent on time and temperature. After an exposure time of 34 days a black biofilm was observed on the carbon steel coupon (Fig. 5a, 5b) and SEM studies showed the shape of microorganisms covered with minerals (Fig. 6a). In contrast, on the stainless steel coupon no macroscopic biofilms were observed, however SEM pictures showed some microorganisms on the surface (Fig. 6b).

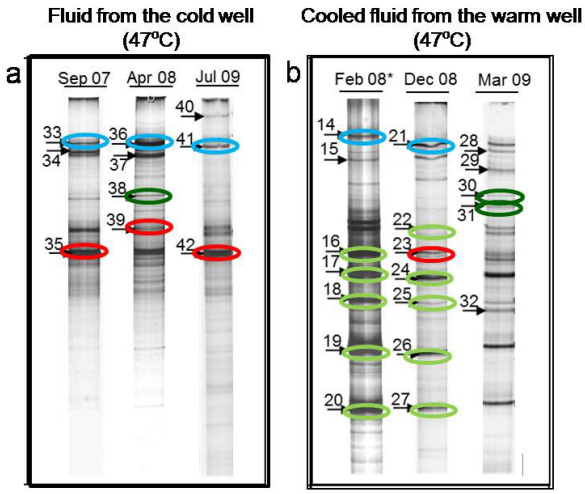

Fig. 2. SSCP-analysis of 16S rRNA gene fragments of fluids from the warm and cold well. Due to long-term monitoring, genetic profiles were generated individually for each sample and subsequently arranged. The highlighted bands indicate the positions that were sequenced. Blue and red marked bands are affiliated to SRB and green ones are assigned to fermentative bacteria. (a) Fluid produced from the cold well dominated by SRB; (b) cooled fluid produced from the warm well dominated by fermentative bacteria. Modified after [4].

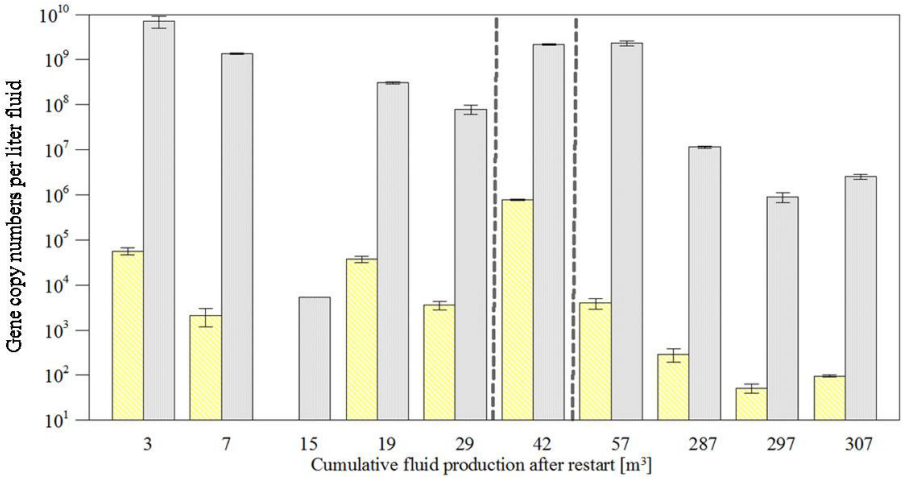

Fig. 3. Abundance of SRB (grey column) and *Halothiobacillus* sp (yellow column) in fluids taken after 32 days downtime with respect to cumulative fluid production. Dashed grey lines indicate short term stops (< 2 hours) during plant restart.

Table 1. Characteristics of the bypass experiments: material, exposure time and temperatures.

Experiment	Coupon material	Exposure time [d]	Fluid temperature from the well [°C]	Fluid temperature in the bypass system [°C]
N1prod40-C	Carbon steel (1.0038)	34	~78	40
N1prod30-S	Stainless steel (1.4301)	55	~78	30

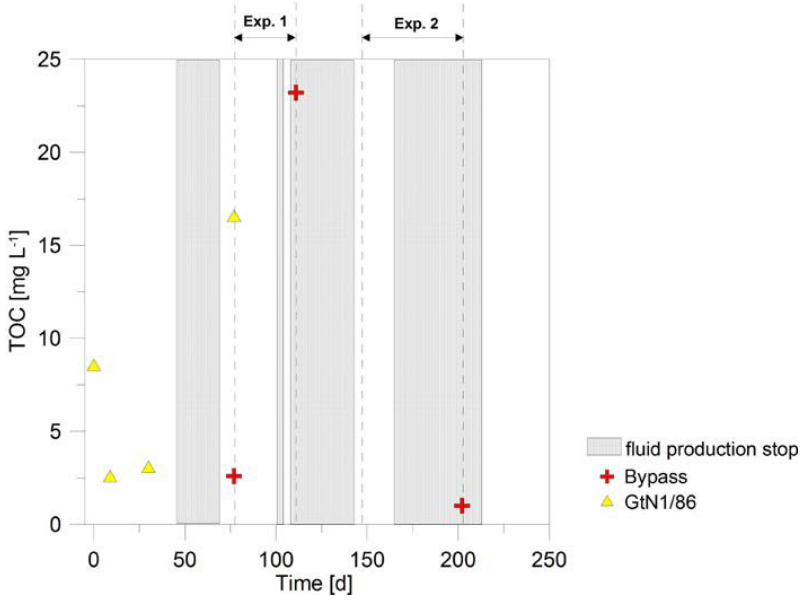

Fig. 4. TOC concentration in the bypass system and in the warm well during regular operation and shut down phases.

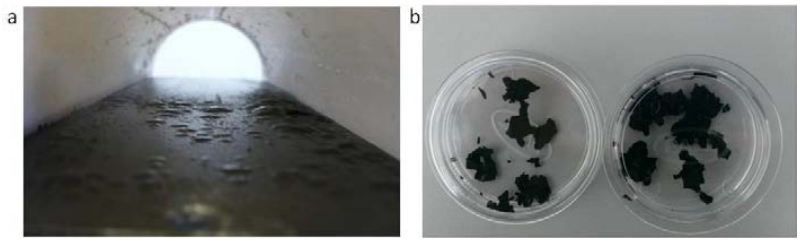

Fig. 5. (a) Black biofilm on a carbon steel coupon after 34 days of exposure in the bypass system; (b) biofilm sample for SEM/EDS-analyses.

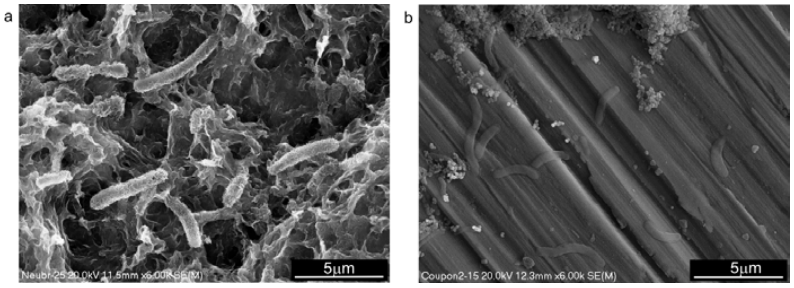

Fig. 6. (a) SEM-picture of the black biofilm with microorganisms covered with minerals; (b) SEM-picture of the stainless steel coupon with microorganisms.

4. Conclusion

SRB were highly abundant in geothermal fluids of the cold well with temperatures of 47 °C as monitored over several years. The detection of SOB after plant downtimes is regarded as an indication for oxygen ingress in the highly reduced fluids. That was also evidenced by elevated sulfate concentrations in fluids taken immediately after the restart of fluid production. The interaction of SRB and SOB might have enhanced corrosion and scaling processes relevant for the operational reliability of the plant.

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