NEW ON-SITE TEST-PROCEDURE FOR FIELD INVESTIGATIONS ON GROUNDWATER IN AQUIFER THERMAL ENERGY STORAGE SYSTEMS WITH MOBILE TEST EQUIPMENT

Guido KNOCHE, Michael KOCH and Jörg W. METZGER*

Universität Stuttgart, Germany, Institute for Sanitary Engineering, Water Quality and Solid Waste Management
Bandtäle 2, D-70569 Stuttgart, Germany,
*e-mail: joerg.metzger@iswa.uni-stuttgart.de

ABSTRACT

Operational experience with High-Temperature Aquifer Thermal Energy Storage (HT-ATES) systems sometimes revealed technical problems due to calcite precipitation in heat exchangers. However, no satisfying prediction of scaling behavior in heat exchangers is possible. In order to gain reliable information on the behavior of groundwater in heat exchangers during heating at scheduled HT-ATES sites a mobile test rig has been constructed for preliminary investigations on groundwater for use in HT-ATES plants. Furthermore, a new on-site test procedure - *scaling test* - has been worked out by which an uncritical temperature level in respect to calcite formation in heat exchangers can be evaluated. Up to now, results of experiments with diverse groundwater types have shown both a distinct influence of groundwater chemistry and of temperature level on calcite precipitation in the test rig. It is estimated that carbonate containing groundwater might be heated up to about 60°C (140°F), whereas saline groundwater can be heated up to more than 70°C (158°F) without causing calcite precipitation. However, it is not yet recommended, ~~not~~ to transfer these results on scheduled HT-ATES plants with similar groundwater, but to carry out special investigations.

INTRODUCTION

Seasonal storage of both process or exhaust heat in the underground is a promising technique for a sustainable energy employment and management. In High-Temperature Aquifer Thermal Energy Storage plants (HT-ATES, T >50°C/122°F) ~~plants~~ shallow groundwater is directly used as heat transfer fluid. During the summer e.g. industrial process waste heat, which otherwise would be lost, is stored in the groundwater, in the following winter this thermal energy can be used for heating purposes in residential buildings, greenhouses, etc. (Fig. 1). In the cold season the production well and injection well are operated vice-versa. ATES and HT-ATES plants have been developed and examined since the early 1970s (Sanner, 1999). Up to now, experimental and demonstration plants have been realized, e.g. in Auburn, USA (1975-1982, Auburn University), St. Paul, USA (1980-1990, University of Minnesota), Utrecht, The Netherlands (since 1990, Utrecht University ATES) and Berlin, Germany (since 1997, seat of the German Parliament).
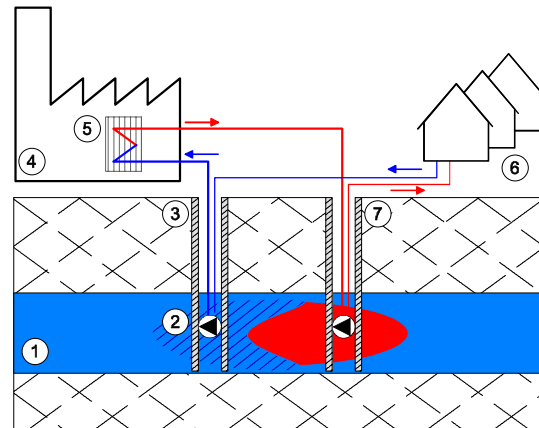

Figure 1. Schematic ATES site
(① Aquifer; ② pump; ③ production well, summer; ④ industrial waste heat, summer; ⑤ heat transfer system; ⑥ residential buildings, winter; ⑦ injection well, summer)

Meanwhile technical guidelines on the "Thermal Use of the Underground" have been evaluated and published; in Germany these guidelines are taken to be authoritative (VDI, 2000, 2001). Unfortunately, operational experience sometimes disclosed technical problems with scale formation, largely calcite precipitation, in heat exchangers and pipe systems of HT-ATES plants. This calcite precipitation is commonly attributed to the displacement of ~~the~~

Tillmans' Equilibrium (Equation 1) to the left side by heating the water.

Eq. 1: $$CaCO_3 + CO_2 + H_2O \leftrightarrow Ca^{2+} + 2HCO_3^-$$
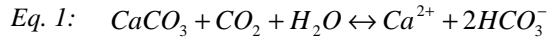
So far, investigations of groundwater suitability for use in ATES plants by means of geochemical models did not yield any satisfying prediction on both scaling behavior and scaling probability in heat exchange systems. Suitable water treatment techniques (e.g. acid-dosage, cation-exchange, etc.) have been developed, but control strategies do not work satisfactorily. A detailed summary of "lessons learned" is given by Sanner (1999).
Within the ongoing Implementing Agreement "Energy Conservation through Energy Storage" Annex 12 "High Temperature Underground Thermal Energy Storage" of the International Energy Agency a mobile test rig (MTR) has been constructed for ~~for~~

preliminary investigations on groundwater in respect to troublesome scale formation in overground ATES installations, e.g. heat exchangers (Sanner, 1999).

OBJECTIVES

The specific goals of the study were (i) to work out a standardized scaling test-procedure for preliminary investigations on groundwater for scheduled HT-ATES plants and (ii) the testing of groundwater at diverse geological sites in respect to a maximum temperature up to which calcite formation in heat exchangers does not occur. Results of these investigations might be referenced to assess the design and the implementation of suitable water treatment techniques at HT-ATES plants.

EXPERIMENTAL SET-UP

In this study it was planned to simulate the ATES loading process - *heating of groundwater* - by means of an experimental set-up which is shown in Figure 2. Therefore the components of the MTR had to be adapted to the heat transfer system of an ATES plant as closely as possible. Thus, the main component of the experimental set-up is a plate-type heat exchanger with titanium plates.

The MTR is completed by a gas boiler, a data logging and control unit and furthermore with a second heat exchanger for heat recovery purposes from the hot groundwater back into the heating cycle (Knoche et al., 2001). The MTR is integrated in a conventional car trailer (Fig. 3), that allows experimental studies with unchanged, real groundwater at scheduled or even at operational (HT-)ATES plant sites.
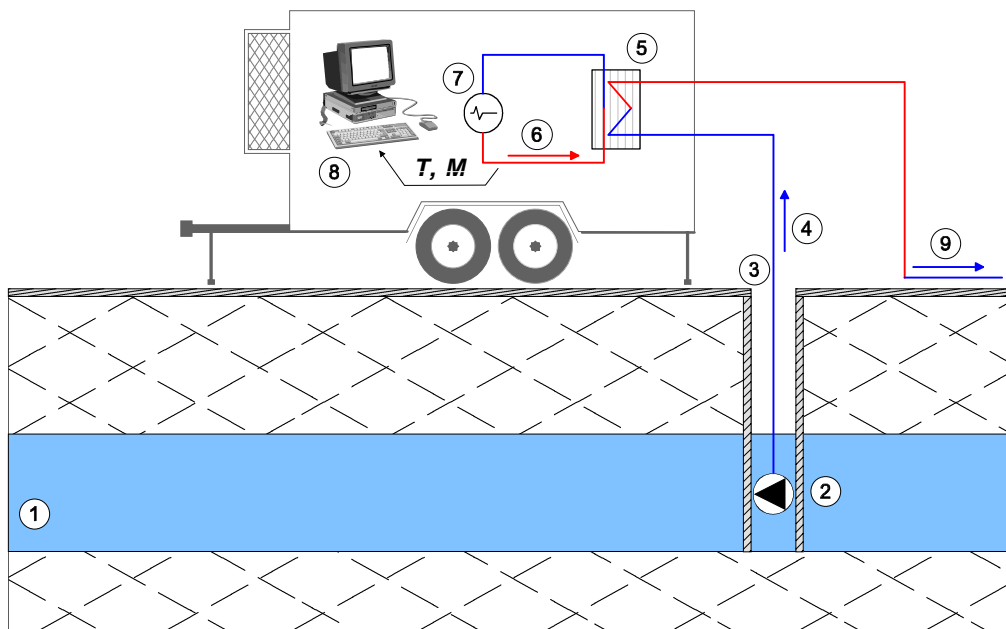

Figure 2. Test design during field investigations
(① aquifer; ② submersible pump; ③ well; ④ groundwater; ⑤ heat exchanger; ⑥ heating cycle; ⑦ gas boiler; ⑧ data logging and control unit, T: temperature, M: mass flow; ⑨ groundwater to sanitary sewer after heat recovery)

SCALING TEST-PROCEDURE

The simulation of the ATES loading process is carried out by means of single short-term *(up to 24 h)* and long-term *(up to 72 h)* experiments.

Therefore groundwater is pumped *(mass flow* M: 0.13 to 0.24 kg*s^{-1}) into the test rig and heated up to temperatures between 50°C (122°F) and 90°C (194°F).

During the experiments the data logging unit records continuously temperature data at the in- and outlets of the heat exchanger and mass flow data of both the heating cycle and the groundwater.

After each experiment the heat exchanger is opened and cleaned.

Calcite precipitation is then directly determined by means of visual inspection of the heat exchanger plates and by chemical analysis of calcium in the cleaning solution. The absolute content of calcium in the cleaning solution serves as an indicator for potential calcite precipitation on the heat exchanger plates and is given as calcite equivalents in millimoles (Fig. 6, 7, and 8).

If necessary, solid precipitates are analyzed by means of x-ray-diffractometry and scanning electron microscopy of selected samples to get information on the formed precipitates.

RESULTS AND DISCUSSION

Preliminary experiments were carried out to evaluate the test conditions (e.g. duration, mass flow of groundwater). Therefore groundwater GW1 was used, which originates from a groundwater lowering well on the terrain of the Institute for Sanitary Engineering in Stuttgart, Germany.

Figure 3. MTR in operation at groundwater test site GW1

Within the first test sets (**M_1**: 0.17 kg*s^{-1}, 15 h; **M_2**: 0.13 kg*s^{-1}, 18 h) different mass flow and equal temperature conditions (80°C [176°F]) were adjusted for the calculation of the heat transfer coefficient k, which can be expressed by Equation 2.

Eq. 2:
$$k = C_p \times \Delta T \times \frac{1000 \times M}{A_{HE} \times LTD} ,$$

k *in W*m^{-2}*K^{-1}*

where:

C$_p$: Specific heat capacity, *in J*kg^{-1}*K^{-1}*

ΔT: T$_{warm}$ - T$_{cold}$, *in K*

M: Mass flow, *in kg*s^{-1}*

A$_{HE}$: Heat exchanger surface, *in m^2*

LTD: Logarithmic of the temperature difference between heating and groundwater cycle, *in K*

As shown in Figure 4 the calculated heat transfer coefficients k corresponded within each test set at the beginning, even after repeated opening and assembling of the heat exchanger, and in addition complied with the predicted k computed in advance by the manufacturer for diverse mass flow conditions. Furthermore, the absolute content of calcium in the cleaning solution of the heat exchanger largely showed good agreement within each test set M_1 and M_2. This means, that even under field conditions reproducible results can be achieved.

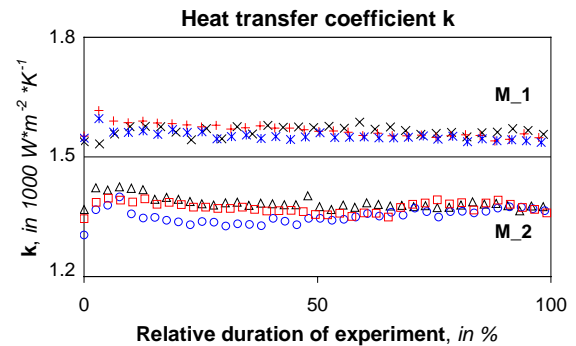*Figure 4. Heat transfer coefficient k at 80°C (176°F) during test sets M_1 and M_2*

Within further test sets under variation of the gauge pressure *(1, 2.5, 4 bar)* in the test rig no distinct influence of increasing pressure levels on the extent of calcite formation in the heat exchanger was observed. This was attributed to the low content of free CO$_2$ *(~ 1 mmol*L^{-1})* at the groundwater test site GW1.

At last, experiments without heating of groundwater *(blank experiments)* were carried out in order to estimate potential contamination of heat exchanger plates during opening and assembling the heat exchanger. It was found that values from 0.2 to 0.8

mmoles calcium have to be accepted as a blank value during the handling of the heat exchanger plates.

After this test phase the scaling test-procedure was provisionally set for each temperature experiment to a duration of 24 hours and a groundwater volume of 10 to 15 m^3 to be heated. In order to prevent physical CO_2 degassing during heating the groundwater is kept under a gauge pressure of 2.5 to 3 bar.

The MTR has been operated at four test sites with diverse groundwater types (Table 1). These locations were chosen due to their different geological background and are not scheduled for any ATES application.

The tested groundwater (Table 2) are roughly classified as calcium-bicarbonate type (GW1, GW4, GW5) and sodium chloride type (GW2, GW3).

Table 1.   Geological classification of test sites

	Stratigraphy	Lithology	Aquifer
GW1	Holocene	Alluvial	Pore aquifer
GW2	Pleistocene	Sand	Pore a., confined
GW3	Rhaet	Limestone	Joint a., confined
GW4	Pleistocene	Gravel, Sand	Pore a.
GW5	Skyth	Sandstone	Joint a.

Table 2.   Physico-chemical properties of the tested groundwater

	GW1	GW2	GW3	GW4	GW5
Temperature, in °C (°F)	12 (53.6)	11 (51.8)	20.5 (68.9)	11.4 (52.5)	13.2 (55.7)
Ionic strength, in $mmol*L^{-1}$	14	291	51	7.4	11
Carbonate h.*, in $mmol*L^{-1}$	3.2	7	2.6	1.6	2.2
Total h.*, in $mmol*L^{-1}$	4.6	35.3	2.6	2.2	2.9

*Carbonate hardness, total hardness

In general, GW1, GW2 and GW3 show distinctly higher concentrations of carbonate (HCO_3^-) and total hardness than GW4 and GW5. In addition, GW2 and GW3 are characterized by a high ionic strength compared to the other tested groundwater types.

Before the field investigations a potential calcite formation was computed as the saturation index of calcite for each groundwater by means of geo-chemical modeling with PHREEQC (Ver. 2, Parkhurst and Appelo, 1999). Values above 0 indicate a supersaturation in respect to calcite, values below 0 undersaturation.

As exemplarily shown in Figure 5 a huge risk of calcite formation during heating up had to be expected during heating of groundwater GW1 and GW2, already even at temperatures of 50°C (122°F) and lower. Calculations for GW3, GW4, and GW5 showed a similar trend, but particularly GW4 and GW5 to a lower extent.
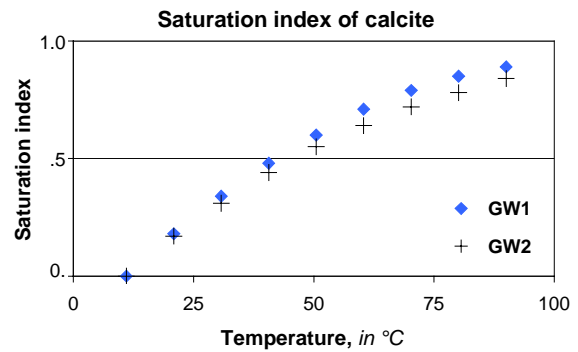

Figure 5. Saturation index of calcite during heating of groundwater GW1 and GW2, computed with PHREEQC

First experiments under field conditions have been undertaken at test sites GW1, GW2, and GW3.

As shown in Figure 6 the heating up of these groundwater types leads to great distinctions in respect to scaling in the heat exchanger. Particularly groundwater GW1 and GW2 were assumed to have a great calcite precipitation risk during heating, GW3 slightly lesser. But in contrast to GW2 only GW1 reached the predicted extent of scaling. This rough disagreement between simulation and field experiment for GW2 is attributed to ionic interactions in the system, which might result in theoretical supersaturation of calcite without scale formation.

Moreover only in the case of GW1 at 80°C (176°F) and 90°C (194°F) and GW3 at 90°C was the visual inspection of the heat exchanger plates positive for calcite. This result was verified afterwards by means of mineralogical analyses. Absolute calcite contents

of under 1 mmol~~e~~ are attributed to a possible contamination during the handling of the heat exchanger plates. It is estimated that heating of saline groundwater such as GW2 and even GW3 up to a temperature level around 70°C (158°F) will not lead to any scale formation.
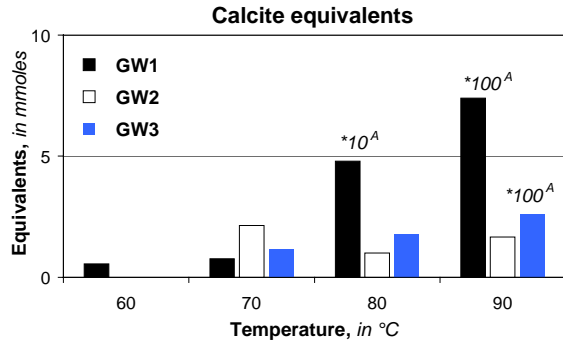
Calcite equivalents

Figure 6. *Calcite equivalents after experiments at test sites GW1, GW2, and GW3 (M=0.13 kg*s^{-1}; GW1, GW3: 24 h; GW2: 48 h; GW2, GW3 not with 60°C; ^{A}: multiply with factor 10 or 100)*

Further experiments under field conditions were carried out after optimizing the test procedure *(duration, groundwater volume)* at groundwater test sites GW1, GW4 and GW5.

Therefore the scaling test was standardized from one up to three short-term temperature experiments over a period of 18 hours (each 15 m^3, M=0.23 kg*s^{-1}) and one or more long-term experiments over a period of 72 hours (60 m^3, M=0.24 kg*s^{-1}). Within the latter a temperature level was adjusted in the test rig, which did not yield calcite precipitation ~~as~~ in the previous short-term experiments. For the first a heating temperature of the groundwater was adjusted to 70°C and in addition to 55°C *(131°F)* and 60°C *(140°F)* at test site GW1.
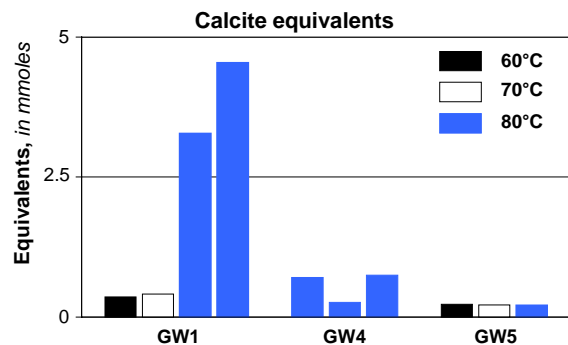
Calcite equivalents

Figure 7. *Calcite equivalents after short-term experiments at test sites GW1, GW4, and*

GW5 (M=0.24 kg*s^{-1}; t=18h; GW4 only 80°C)

Again great differences between the tested groundwater in respect to scale formation in the heat exchanger were observed (Fig. 7).

Scale formation increased from 60°C (140°F) to 80°C (176°F) within the scaling test on GW1 by a factor of approximately 10. In contrast to this observation experiments with GW5 did not show any increase in scale formation in the heat exchanger with increasing the temperature. Three experiments at test site GW4 showed a very good agreement in respect to calcite equivalents with values from 0.25 to 0.75 mmol~~es~~.

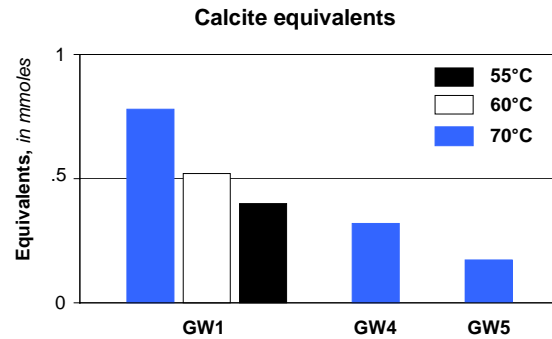The following long-term experiments with a temperature of 70°C (158°F) confirmed the preceding assumptions.

Calcite equivalents

Figure 8. *Calcite equivalents after long-term experiments at test sites GW1, GW4 and GW5 (M=0.24 kg*s^{-1}; t=72h; GW4, GW 5 only 70°C)*

As shown in Figure 8 calcite precipitation in the heat exchanger could be reduced by decreasing the temperature of the groundwater from 70°C to 55°C. In contrast to GW1 scale formation within the tests of GW4 and GW5 occurred to a negligible extent. In the case of GW5 there was no increase in scale formation observable, even compared to the short-term experiments (Fig. 7).

In general, these experiments showed that carbonate containing groundwater as GW4 and GW5 could be heated up to a temperature level around 60°C (140°F) without causing any calcite precipitation in heat exchangers. Due to its higher carbonate and total hardness the maximum temperature level for heating of groundwater GW1 should be not much higher than 50°C (122°F).

CONCLUSION

A mobile test rig has been constructed for pre-liminary investigations in respect to scale formation

on groundwater for use in High-Temperature-ATES plants. It has been successfully operated under field conditions.

A new scaling test procedure has been worked out and applied *on site* on diverse groundwater types. Potential scaling products are directly detected by visual inspection and chemical analyses of the cleaning solution of the heat exchanger. A complete scaling test consisting of three to four experiments between 18 and 72 hours takes at least one week. Compared to the overall duration of an operational construction of building projects this period is not that much, taking into account subsequently possible technical problems in overground ATES installations due to scale formation.

The tested groundwater types showed distinctly diverse results after each scaling test in respect to calcite formation.

In contrast to the results of preceding geochemical modeling for each groundwater, the experiments on saline groundwater types led only to little calcite precipitation. This is attributed to ionic interactions in the heated groundwater.

The scaling test on carbonate containing groundwater types showed diverse results, too. While a carbonate type with higher carbonate and total hardness results in considerable scale formation during heating at temperatures around 60°C (140°F) to 70°C (158°F) carbonate containing groundwater with lower hardness values showed even at higher temperatures (80°C [176°F]) no or only negligible scale formation within the test period. It is assumed that different CO_2 partial pressures in the groundwater body might affect the scale formation process in the heat exchanger.

Up to now, it is estimated that saline groundwater types might be heated to temperatures around 70°C (158°F) without causing a considerable calcite precipitation.

Carbonate type groundwater with a low carbonate (~ 2 mmol*L^{-1}) and total (< 3 mmol*L^{-1}) hardness might be heated up to temperatures around 60°C (140°F) or even higher, whereas carbonate type groundwater with higher hardness values should not be heated up to more than 50°C (122°F) without any water treatment.

Nevertheless, at present it is recommended, not to transfer these results on scheduled HT-ATES plants with similar groundwater, but to carry out special investigations at these HT-ATES sites.

OUTLOOK

In order to create a greater data base with more groundwater types and to confirm the present results further work is necessary at diverse test sites in respect to the geological background. First scaling tests have been carried out commercially, further tests are projected.

Future work will also focus on other scaling products (e.g. silicates, ferric oxide hydrates, etc.) during heating in the heat exchanger.

In addition, it is intended to integrate a water treatment module (e.g. CO_2-dosage) into the experimental setup.

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