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Numerical Simulation of Freezing-Thawing-Cycles in the Grout of Borehole Heat Exchangers

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ABSTRACT

Borehole heat exchangers (BHE) are a popular and efficient way of regenerative heating. Protection of groundwater has led to legal constraints, in many European countries which require BHEs to be grouted and boreholes to remain sealed under all operating conditions. Borehole heat exchangers operated with fluid temperatures below zero degrees Celsius are required to be grouted with a material that guarantees adequate sealing also under freeze-thaw-stresses. A testing device was developed that measures the hydraulic conductivity of grout specimens after a freely selectable number of cyclic freeze-thaw-stresses. When simulating radial earth-pressure and following in-situ freezing directions the results differ from earlier investigations substantially. Consequently the frost-resistance of the grouts can be assessed.

The temperature distribution during the testing procedure and in-situ are highly influenced by phase change and latent heat effects. For numerical modeling of such processes the FEM flow and heat-transport simulation software FEFLOW was used and extended by a phase change plug-in. The plug-in was validated by numerical benchmarks and comparison with an analytical solution as well as with experimental data.

1. INTRODUCTION

There is a diversity of shallow geothermal system applications. The most common application is the ground source heat pump (GSHP) combined with borehole heat exchangers (BHE). A working fluid streams through a closed loop system made of polyethylene (PE) pipes. For heating cold fluid leaves the heat pump through the return pipe, enters the BHE and collects heat from the surrounding ground. The increase in temperature of the working fluid is used by the heat pump mostly for domestic heating and warm water production. Most borehole heat exchangers are constructed vertically (Figure 1). Common depths are up to 100 m, but there are shallower and as well as deeper BHEs. Due to the depth - typically between 50 m to 100 m - it is very likely that the BHE is in contact with aquifers and eventually penetrates aquicludes. As the working fluid is often a water-monoethyleneglycol-mixture there is a potential hazard if a leakage of the closed pipe system occurs (Mehnert, 2004). This is one of the reasons why the borehole of the BHE needs to be grouted, as the grout embeds the pipes and thus can be understood as a protection layer.

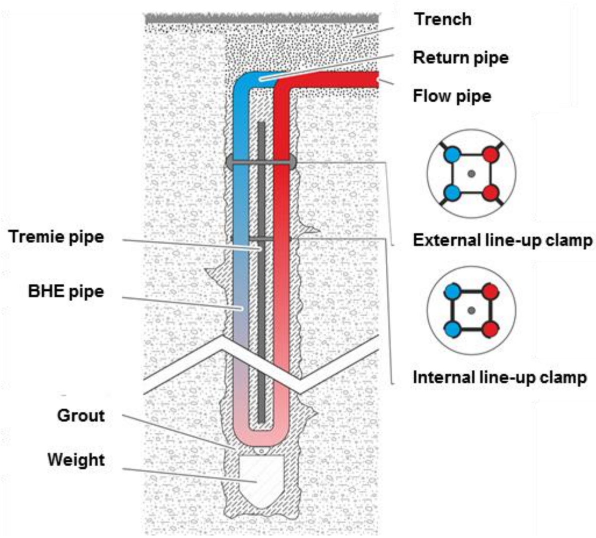

Figure 1: Vertical borehole heat exchanger executed with a Double-U-Pipe (DGG and DGGT, 2014).

Borehole heat exchangers in unconsolidated rocks require grouted boreholes (see Figure 1) because of borehole stability issues as well as thermal and hydraulic needs. In many countries grouting of BHEs is regulated by law. The permission procedures and requirements vary strongly. However the grouting of a BHE in specific geological condition is very useful in terms of systems efficiency and safety against contamination hazards. The grout seals the borehole and is a potential protection layer for the event of pipe leakage. Furthermore it prevents unwanted vertical water flow (Anbergen et al. 2014). Figure 2 shows three potential events of damage due to an unwanted vertical fluid and mass transport caused by improper sealing of the BHE.

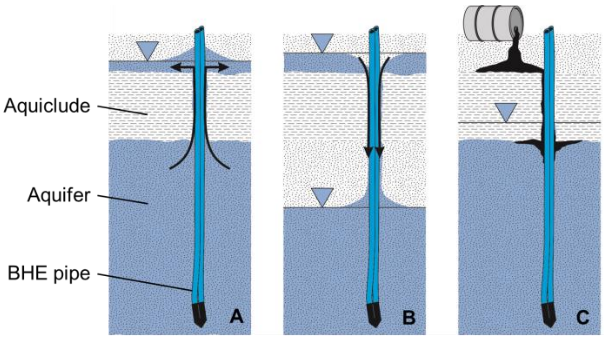

Figure 2: Consequences of an improper sealing. (A) Upstream due to artesian ground water conditions, (B) unwanted water connection of two different aquifers, and (C) vertical contamination from the surface (DGG and DGGT, 2014).

In artesian ground water conditions an up streaming flow path through the borehole might lead to erosion effects and eventual settlements in consequence (A). The hydraulic connection of two different aquifers (B) might affect the hydrochemical behavior of the ground water. In several regions ground water provides drinking water supply and needs to be protected from any contaminations or unwanted mixing. Furthermore a vertical contamination from the surface along the borehole might occur (C) in case of loss of sealing properties of the grouting material. These need to be prevented by the hydraulic integrity of the grouting material. This is the main task for the grouting from a hydrogeological point of view. Beneath the hydraulic properties the grout needs to secure a sufficient heat transport. The use of neat cement mixtures leads to high thermal resistances for the heat flow. Thus it is recommended to use thermally enhanced grouts. Furthermore the grouts need to be resistant against shrinkage or cracking as this affects the bonding between grout and probes (Allan and Philippacopoulos, 2000). A loss of bonding leads to reduction of conductive heat transport und thus reduces the efficiency of the whole GSHP system.

This paper focusses on the sealing properties of grouting materials, as they are the most critical from a hydrogeological and approval point of view. To review hydraulic properties of the grout in-situ flow paths have to be taken into account. In the event of piping system leakage the hydraulic conductivity of the bulk grout material has to be low in order to hinder the working fluid from entering the surrounding aquifer. This is a foremost radial flow path. Most directives prescribe a bulk hydraulic conductivity of grouts of $k \leq 10^{-9}\ m \cdot s^{-1}$ (Mehnert, 2004, Skouby, 2010, Anbergen, 2014). Most grouting materials fulfill this requirement. Different to the bulk hydraulic conductivity vertical hydraulic conductivity of the system (Figure 2) is more critical. This axial flow path needs to be assessed in order to quantify the vertical sealing properties. Allan and Philippacopoulos (2000) stated that the system´s hydraulic conductivity is substantially higher than the bulk hydraulic conductivity. The system´s hydraulic conductivity has to remain on a sufficient low level in order to prevent the described events of damage. The low hydraulic conductivity has to be provided under every potential operation status. The most critical operation statuses for BHEs are the potential freezing and thawing processes of the grout during times of extensive heat extraction. In order to cover heating demands during times of long heat extraction periods several BHEs run with negative working fluid temperatures. In this case the working fluid must not be water, but an antifreeze fluid (like water - monoethyleneglycol-mixtures). These thermal stresses and ice building processes may affect the hydraulic integrity of a BHE.

In order to assess this most critical stress on the grout a testing device was developed that is capable to measure the systems hydraulic conductivity before and after cyclic freeze-thaw-stresses (Figure 3).

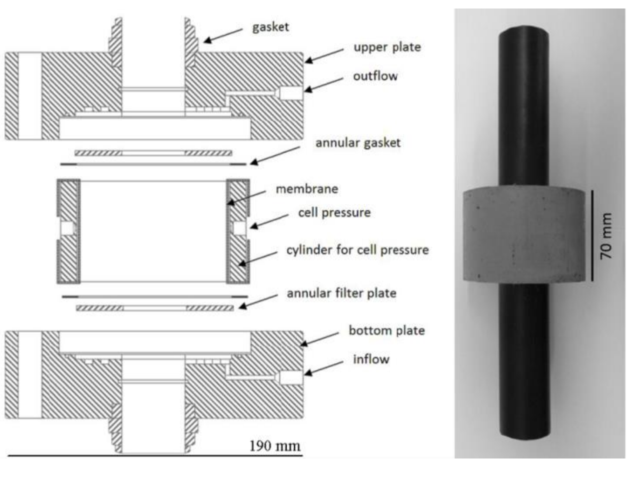

Figure 3: Freeze-Thaw-Testing-Device (left) and specimen composed of a Polyethylene pipe and hollow cylindrical grout body (right) (Anbergen et al., 2014a)

The testing procedure provides three-dimensional mechanical boundary condition and follows the freezing direction from the inside to the outside. Hence a realistic assessment of the hydraulic conductivity before and after cyclic freeze-thaw-stresses is possible. The testing procedure was described in detail by Anbergen et al. (2014a).

In order to observe the temperature distribution during the testing procedure the Finite Element Simulation Method (FEM) software FEFLOW was used. FEFLOW is a common software for heat and mass transport simulation. Unfortunately FEFLOW does not take effects of phase change into account. The change of the thermal properties of water and the latent heat is not incorporated according to the knowledge of the authors. This is why a plug-in for FEFLOW was written that enables the FEM software to simulate freeze-thaw-cycles in porous media. The relevant thermal background and a benchmark of the programmed plug-in will be presented in this paper. Furthermore the application of the plug-in for the simulation of the temperature distribution in the testing device will be provided.

2. BACKGROUND

2.1 Grouted Borehole Heat Exchangers

Grouting materials for BHEs mostly contain cement, water and thermal enhancements. Cement is necessary for the prevention of erosion and constant volume properties. Furthermore cement builds a rigid protection layer for PE pipes. For the enhanced thermal properties additives such as silica sand are added because of its thermal conductivity increasing effects. The enhanced grouts have thermal conductivities around $2\ W \cdot m^{-1} \cdot K^{-1}$ or even higher. Unfortunately most of these mixtures are prone to cyclic freeze-thaw-stresses (Figure 4), wet-dry-cycles, and other mechanical deformations as they tend to crack. The cracks become hydraulic relevant and the sealing effect of the grout body decreases, eventually to an inacceptable level.

Figure 4: Oven dried grout specimen of a cement-sand-mixture (water/solid substance ratio 0.82) frozen and thawed out radially in the developed testing device (Anbergen et al., 2014a). The vertical cracks increased the axial hydraulic conductivity.

As seen in Figure 4, the cracks are foremost vertical. These are typical frost induced cracks, as structural disruptions form perpendicular to the direction of the frost front.

In order to reduce the bleeding of the cementitious suspension swelling clays are added to the mixtures (Allan and Philippacopoulos, 2000). Beside the stabilization of the suspension, the bentonite particles are capable to reduce the water flow through the flow tubes in the structure. Thus the system hydraulic conductivity is reduced substantially. Small amounts of bentonite are sufficient for a substantial reduction of hydraulic conductivity. When cracking occurs there is enough swelling potential that the bentonite reduces the loss of sealing to an acceptable level. These mixtures of a rigid cement matrix with sealing bentonite contents are generally suitable for the grouting of BHEs.

For the assessment of the hydraulic integrity of BHE grouts it is necessary to consider the in-situ flow directions inside the system of the backfilling. The idealized system of a BHE backfill is axial pipe system with a surrounding grout body (Figure 3, right). It is obvious that the system's hydraulic conductivity is anisotropic. The axial hydraulic conductivity will be higher than the radial hydraulic conductivity. The contact area between grout and pipe is a preferred flow path. In general the radial flow path corresponds with the bulk material hydraulic conductivity. The axial flow path (here referred to as *system hydraulic conductivity*) corresponds with a hydraulic conductivity that is about two orders of magnitude higher than the bulk material conductivity (Allan and Philippacopoulos, 2000, Anbergen, 2014). Hence a regular hydraulic conductivity test of the bulk material will not reflect the hydraulic integrity of the in-situ system. The developed testing device (Figure 3, left) considers the higher system hydraulic conductivity correctly and is able to simulate a wide range of thermal stresses on the grout specimens, simulating the operation modes of GSHPs. Furthermore the in-situ heat flow directions are respected as they differ substantially from existing freeze-thaw-test procedures for fine grained soils, concrete or natural stones (Anbergen et al., 2014a).

2.2 Freeze-Thaw-Cycles in Borehole Heat Exchangers

In cold climates, especially in regions with long heating periods it is reasonable to run the GSHP with temperatures below 0 °C. With an increasing amount of heat extraction the temperature of the surrounding ground of the BHE will decrease. The decrease is strongly dependent on the geological boundary conditions and the total working fluid temperatures in the BHE. In soils with low permeability the heat transport is foremost conductive, so is the heat recharge. Due to the lowered soil temperature the GSHP needs to lower the return flow temperatures as well in order to extract sufficient thermal energy. For most heat pump devices the difference between return flow and flow of the GSHP needs to be approx. 3 - 4 K. By using return flow temperatures below 0° C it is possible to reach the required temperature difference even when the surrounding soil temperature is far below 10 °C. A plot of a GSHP with BHEs is shown in Figure 5.

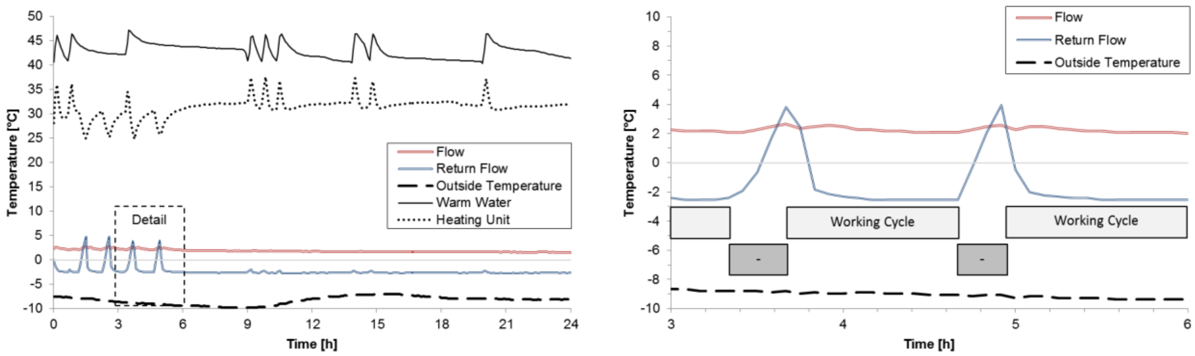

Figure 5: Temperature log of a GSHP installation with BHEs, February 2014 (Anbergen, 2014)

Usually a heat pump runs in relative short operation cycles. In this case the demand for heating and warm water is so high that the heat pump runs constantly. Even though this is not a proper design for a heat pump, such GSHP behavior happens quite often. In consequence there is a nearly constant frost milieu in the vicinity of the return pipes. The grout eventually freezes. Phase change of the pore water will start directly beneath the return pipes and the frost front will propagate in radial direction. The positive temperature value of the flow pipe will cause an asymmetric propagation of the frost front.

As there is not enough water supply for the formation of big ice lenses, the ice lenses beneath the return pipe will remain small. With increasing distance from the return pipe the diameter of ice lenses will increase as well. The forming mechanisms of ice lenses in fine grained soils (Konrad and Morgenstern, 1980) and grouting materials correspond (Anbergen et al., 2014a). As the heat flow is primary of a radial shape, the ice lenses form perpendicular to the heat flow which leads to axis parallel cracking (Figure 4).

2.3 Heat Transport

The effective heat transport in porous media is determined by the convective and conductive part of heat flow. The general heat equation is written as

$$(\rho \cdot c)_{eff} \frac{\partial T}{\partial t} = \nabla \cdot \left(\vec{\lambda}_{eff} \nabla T - (\rho \cdot c)_{fluid} \vec{q} T \right) \qquad (1)$$

where ρ, c, T, t, λ, q are density, gravimetric heat capacity, temperature, time, thermal conductivity and flow rate, respectively. The thermal conductivity and the flow rate are directed. The indices $_{eff}$ and $_{fluid}$ define the effective (bulk) specific heat or thermal conductivity and the fluid specific heat, respectively.

Even if a BHE is a highly dynamic thermal system, most analytical and numerical solutions simplify the model to an axisymmetric calculation, such as the line source approach or cylinder source approach (Sass and Lehr, 2011). While observing the heat transport in a grouted BHE it is important to define in which geological formations the observation takes place. The hydraulic integrity of the grout body is of special importance in aquicludes (Figure 2). There, only very limited convective heat transport occurs. Thus the heat transport is foremost conductive. Figure 6 shows the dimensions of directed heat flow.

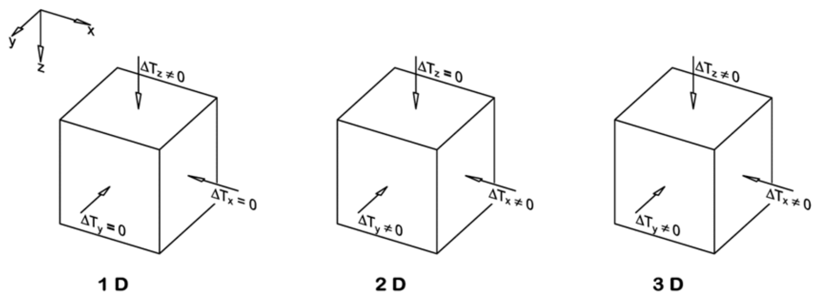

Figure 6: Dimensions of directed heat flow (Anbergen, 2014)

Following the common calculations of BHEs the heat flow is two-dimensional (or radial). Observing the BHE piecewise in test volumes of only small vertical length, this approach is reasonable. Consequently a testing procedure has to follow this heat flow direction as well. For the numerical implementation of such a model, a two-dimensional axisymmetric approach is sufficient, as the change in z-axis is small.

In earlier studies about the hydraulic behavior of grouting materials under cyclic freeze-thaw-stress the heat flow directions of BHEs were not respected sufficiently. One-dimensional or three-dimensional freezing and thawing leads to different ice lens formations which do not reflect the in-situ process. Thus only two-dimensional freezing from the inside to the outside can lead to realistic results (Anbergen and Sass, 2013)

2.4 FEFLOW

The finite element method (FEM) software FEFLOW is a tool for ground water simulation in porous media including heat and mass transport. The code is often used for numerical simulations of shallow geothermal systems in every size. FEFLOW uses linear interpolations for the effective thermal conductivity and heat capacity as shown in Eq. (2) and (3).

Assuming fully water saturated conditions the thermal conductivity is calculated weighted by the porosity of the matrix.

$$\vec{\lambda}_{eff} = \varepsilon \cdot \vec{\lambda}_{fluid} + (1 - \varepsilon) \cdot \vec{\lambda}_{\text{solid}} \tag{2}$$

where λ *and* ε are directed thermal conductivity and porosity, respectively. The indices define the effective, fluid and solid components.

In general fluid thermal conductivity is isotropic; in difference the thermal conductivity of the solid structures can be highly anisotropic.

The specific heat capacity is calculated respectively.

$$(\rho \cdot c)_{eff} = \varepsilon \cdot (\rho \cdot c)_{fluid} + (1 - \varepsilon) \cdot (\rho \cdot c)_{\text{solid}} \tag{3}$$

By default FEFLOW does not take phase changes into account. Neither it is capable of defining amounts of water and ice in the model parameters. In order to enable FELOW for such simulations a plug-in was developed using FEFLOW´s programmable interface IFM. The presented plug-in is freely available from the authors upon request.

3. MATERIAL AND METHODS

3.1 Incorporation of Phase Change Effects

There exist several approaches for the incorporation of phase change effects in the equations for heat and mass transport. One frequently applied method is the modification of the fluid heat capacity. A temperature interval is defined, in which the phase changes from liquid to solid or vice versa. During this transformation process thermal energy is released in form of an apparent heat capacity. The apparent heat capacity incorporates the weighted heat capacity of the phases and an amount of crystallization heat (latent heat). The increase in heat capacity reduces the velocity of heat transport in the transition zone of phase change. Thus the thermal impact of the phase change is considered mathematically. For the transition zone of phase change a relative saturation of liquid water content can be applied. The boundary temperatures of the transition zone are defined as T_w (temperature water) where pore water is fully liquid, T_i (temperature ice) where pore water is fully solid. In between these two temperatures there exist both, liquid and solid pore water (water and ice). For now it is assumed that all pore water freezes to solid, so there is no residual water content even though it is easy to implement. In a fully saturated environment the content of liquid water S_w at T_w is equal to 1. At the Temperature T_i the saturation of liquid water S_w is equal to 0. In between a transition function is implemented; for example linear or exponential transition functions. Detailed information for such implementations is published by Mottaghy and Rath (2006), McKenzie et al. (2007), Anbergen et al. (2014b), and others.

Besides the effect of latent heat release, the thermal properties of water and ice differ substantially. So do the hydraulic properties. The temperature dependency of both, thermal and hydraulic properties needs to be taken into account in order to simulate the effects of phase change correctly.

3.2 Temperature Dependent Thermal Properties

The thermal conductivity and heat capacity of water are highly temperature dependent as seen in Figure 7. The thermal conductivity of frozen water is about four times higher than the thermal conductivity of liquid water. In difference the heat capacity of ice is about 50% lower than the heat capacity of water. For the implementation in FEFLOW literature data was evaluated and the formulations of Alexiades and Solomon (1993) were found to have a nearly perfect fit. Thus FEFLOW´s thermal properties of the fluid were modified according to Figure 7. In this case a linear ramp function was applied.

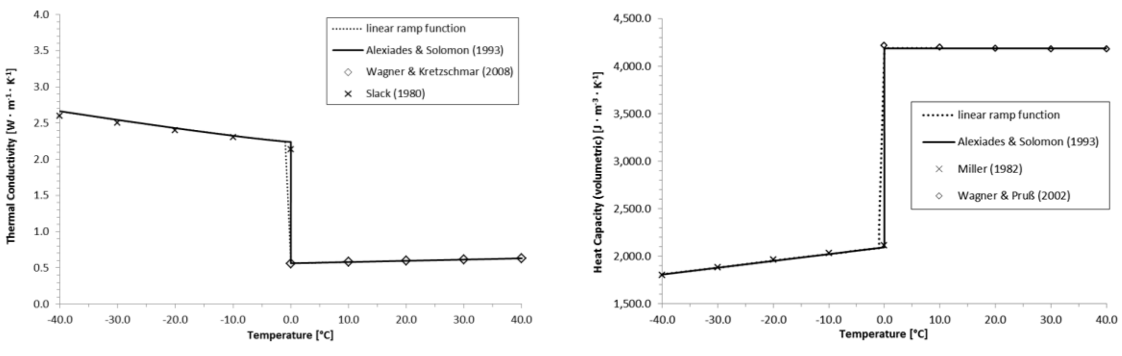

Figure 7: Temperature dependent fluid thermal conductivity (left) and fluid gravimetric heat capacity (right). Comparison of different approaches (Anbergen et al., 2014b)

As the thermal properties of the solid structure (here: soil or rock) are nearly constant in the evaluated temperature regions, they are not considered here in order to keep the calculation effort to a low level. The resulting failure is negligible.

3.3 Temperature Dependent Hydraulic Properties

The hydraulic properties of water and ice change with temperature as well. Thus FEFLOW´s fluid density and viscosity are modified, as well as the systems hydraulic conductivity. Again different approaches were reviewed and implemented (see Anbergen et al., 2014b). For the modification of the hydraulic conductivity it is assumed that flow is reduced to nearly zero when water starts freezing. Even though there is still limited water flow even in frozen regions, this is neglected for the implementation. The water movement in frozen soils very low, so is the convective heat transport. By assuming a no flow restriction at temperature below T_w, heat flow is under estimated slightly. Thus a conservative freezing process is simulated.

4. BENCHMARK AND APPLICATION

4.1 Benchmark with Analytical and Numerical Solutions

The plug-in was compared to different numerical and analytical solutions for freezing and thawing processes. Here a benchmark to the analytical *Neumann Solution* and a numerical solution with SHEMAT is presented. The *Neumann Solution* is frequently considered for freezing and thawing processes. The calculations are based on the thawing mechanisms of ice in oceans described by Stefan (1891). As the mathematical formulations are based on Neumann, the solution is often referred to as the *Neumann Solution* (Mottaghy and Rath, 2006). For the benchmark a calibration model was used according to McKenzie et al. (2007) as shown in Figure 8.

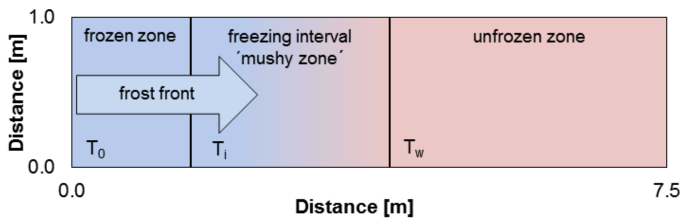

Figure 8: Model for the benchmark of the FEFLOW plug-in for freeze-thaw-cycling based on McKenzie et al. (2007)

For the numerical model a semi-infinite half-space is chosen in order to fulfill the requirements of the analytical solution. The model has an initial Temperature of T_w. At time $t = 0$, a temperature of $T_0 < T_i$ is applied at the left side ($x = 0$). Thus the temperature of the pore water decreases and the frost front (location of T_i) propagates from left to right with increasing time.

The propagation of the frost front can be calculated as a function of time.

$$X_i(t) = 2 \cdot \gamma \sqrt{a_i \cdot t} \tag{4}$$

where X_i, γ, a_i, t are Location of the frost front, a form factor, thermal diffusivity of ice, and time, respectively.

The form factor γ is calculated according to Eq. (5)

$$\frac{e^{\frac{(a_i - a_w)\cdot\gamma^2}{a_w}} \cdot \mathrm{erfc}\left(\gamma \cdot \sqrt{\frac{a_i}{a_w}}\right)}{\mathrm{erfc}(\gamma)} = \frac{(T_w - T_i)\cdot\lambda_s\cdot\sqrt{a_i}}{(T_i - T_0)\cdot\lambda_i\cdot\sqrt{a_w}} \tag{5}$$

where a_i, a_w, γ, T_w, T_i, T_0, λ_i, λ_s, are thermal diffusivities of ice and water, the form factor, boundary temperatures of fully liquid and fully frozen phase, temperature of heat sink, and thermal conductivities of solid and ice, respectively.

The thermal diffusivities can be calculates weighted arithmetically or geometrically. In this case the geometric mean was applied.

For the benchmark not only the analytical solution is compared, but also a numerical solution using SHEMAT. SHEMAT is a simulation code for heat and mass transport as well. It is commonly used and is capable to calculate phase change processes (Mottaghy and Rath, 2006). The input parameters for the SHEMAT solution are published by Mottagh and Rath (2006), the FEFLOW input date is shown in Table 1.

Table 1: Parameters for the benchmark simulation in FEFLOW (Anbergen et al., 2014b)

Parameter	FEFLOW	Unit
Fluid specific heat (grav.)	4 187	$J\ kg^{-1}\ K^{-1}$
Fluid thermal conductivity	variable	$J\ s^{-1}\ m^{-1}\ K^{-1}$
Density of fluid	variable	$kg\ m^{-3}$
Ice specific heat	variable	$J\ kg^{-1}\ K^{-1}$

Ice thermal conductivity	variable	J s^{-1} m^{-1} K^{-1}
Density of ice	920	kg m^{-3}
Solid grain specific heat (vol.)	2.06	MJ m^{-3} K^{-1}
Solid grain thermal conductivity	2.9	J s^{-1} m^{-1} K^{-1}
Porosity	0.05	-
Permeability / Darcy flux	6.5 x 10^{-4} [c]	m s^{-1}
Latent heat of fusion	334 000	J kg^{-1}
Maximum Step Size	0.25	h
Total Simulation Time	2	d

The results of the three solutions are compared in Figure 9.

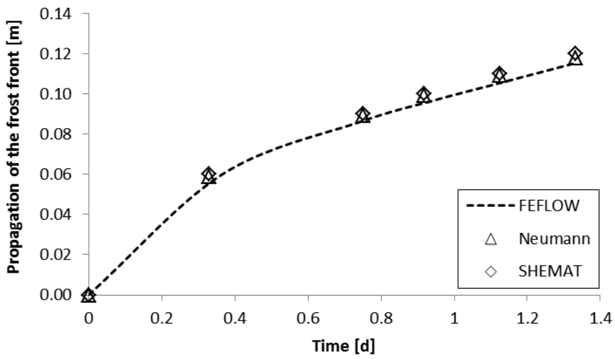

Figure 9: Propagation of the frost front in the benchmark model. Comparison of the analytical Neumann Solution, the numerical Solution with SHEMAT, and FEFLOW.

It can be observed, that the three solutions (Neumann, SHEMAT, and FEFLOW) are in good fit. The propagation of the frost front is calculated with only little errors and thus it can be stated that the plug-in provides good predictions on the temperature distributions under phase change conditions. Further benchmarks of the model are published in Anbergen (2014) and Anbergen et al. (2014b).

4.2 Application of the Plug-In and Experimental Observations

As the benchmark with the literature worked well, a comparison with experimental data was executed. Therefore three specimens (see Figure 3, right) were casted, cured under exact same conditions, transferred to the testing devices, and saturated. After full saturation and the determination of the hydraulic conductivity the freeze-thaw-cycle (FTC) was commenced. One FTC is composed of 20 hours of freezing with working fluid temperatures of – 10 °C and 20 hours of thawing with working fluid temperatures of + 8 °C. The working fluid flows through the axial pipes of the specimens whilst the specimen remains inside the testing device. During the FTC simulation the temperature at the outer edges of the specimens was recorded.

The thermal process of the FTC simulation was simulated using FEFLOW. The input data is shown in Table 2. Therefore a model of the testing device and the specimen was set up. On the one hand the model was simulated without any modifications of the FEFLOW code, on the other hand the developed plug-in was activated. The testing device was modeled as a two-dimensional axisymmetric setup according to the components shown in Figure 3 (left).

Table 2: Parameters for the simulation of the freezing and thawing process of the testing device (Anbergen and Sass, 2013)

Material	Porosity [-]	Thermal Conductivity [W m^{-1} K^{-1}]	Vol. Heat Capacity [MJ m^{-3} K^{-1}]
Probe	$1 \cdot 10^{-6}$	0.40	1 900
Grout	0.60	2.00	4 560
Filter plate	0.54	60.00	3 318
Upper and lower plate	$1 \cdot 10^{-6}$	0.17	2 100
Membrane	$1 \cdot 10^{-6}$	0.16	1 587
Insulation	$1 \cdot 10^{-6}$	0.04	66

A comparison of three temperature logs of the freeze-thaw-process, the FEFLOW simulation without application of the plug-in, and the FEFLOW simulation with the plug-in is shown in Figure 10.

It can be observed that the simulation with latent heat incorporation fits the measured temperature date very well. The freezing and thawing temperatures are simulated correctly and the simulated and measured latent heat effects correspond. In difference the simulation without phase change modifications does not reflect the experimental results.

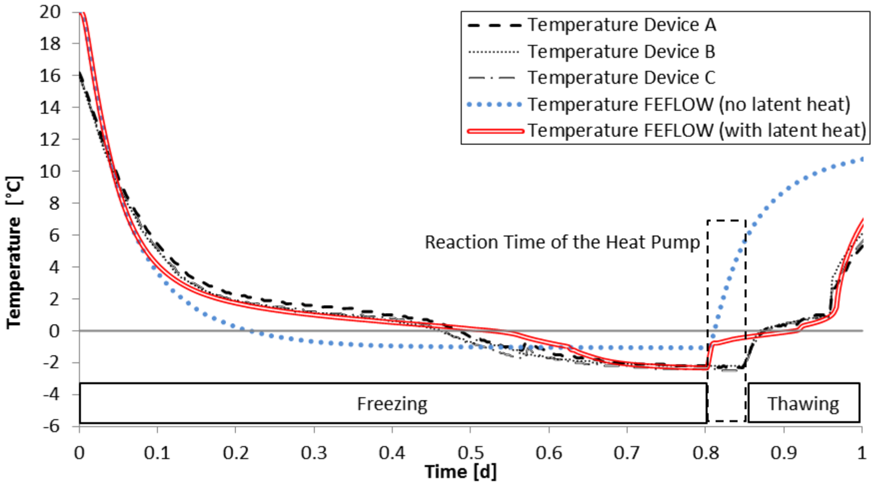

Figure 10: Temperature at the lateral surface of a specimen during FTC simulation. Measured temperature (black), simulated temperature with/without latent heat incorporation (red / blue).

4. DISCUSSION

The FEFLOW plug-in calculates satisfactorily the temperature profiles of the benchmark model and the testing device. The comparison to the experimental data shows a shift of the temperature log after 0.8 d of freezing before thawing fully starts. This is because of the reaction time of the heat pump. The heat pump cannot increase the working fluid temperature instantaneously as the model does. The heat pump needs time to increase the temperature slowly in order not to damage the internal heat exchanger. Consequently the measured temperature at the lateral surface of the specimen remains on a low level until the heat flow reaches the measurement point. Despite this shift, the fit between temperature simulation and experimental date is very good. Further verifications with thermography measurements of frozen specimens are published in Anbergen et al. (2014b).

5. CONCLUSION

With the developed testing procedure the hydraulic integrity of BHE grouts can be assessed while simulating the relevant in-situ boundary conditions. Measuring the system hydraulic conductivity while providing consistent radial earth pressure simulations and following the in-situ freezing directions, the results differ substantially from earlier investigations on the freeze-thaw-behavior of BHE grouts. The thermal processes of the testing procedure and BHEs under operation correspond. By modifying the FEM software FEFLOW with a latent heat plug-in, the temperature distribution inside the testing device under operation could be successfully simulated. The apparent heat capacity approach of the plug-in leads to good benchmark results with numerical and analytical solutions.

Besides the study of FTCs on BHE grouts a potential future application of the plug-in is the modeling of permafrost. The rising atmospheric temperatures reduce the extent of permafrost globally, causing reduced slope stability due to thawing ground. The plug-in could also be combined with regional ground water models to improve predictions, for instance with respect to recharge. A more advanced application of the plug-in are integrated models coupled with appropriate soil-vegetation-atmosphere-transfer (SVAT) schemes (Mölders and Romanovsky, 2006), surface run-off and atmospheric models (Mölders and Rühaak, 2002) which are valuable tools for identifying the most relevant parameters and processes. An extension to the plug-in will be developed based on Rühaak et al. (2014) in order to incorporate mechanical stress into the FEFLOW simulations.

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