SOIL-WATER PIT HEAT STORE WITH DIRECT CHARGING SYSTEM

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1. GRAVEL-WATER VS. SOIL-WATER HEAT STORE

In the case of large pit heat stores (10 000 m³) with small area to volume ratio (A/V) the thermal storage medium embodies a significant cost reduction potential. If there is no gravel available at or near the construction site of the store, and if the excavated soil can be refilled, it can be used as a very cheap heat storage medium. Both the money for the landfill and the costs for the gravel can be saved. An indirect charging system designed similar to a floor heating system using plastic piping (see figure 1) is required in the case of a soil/sand pit heat store. This is the main disadvantage of this concept, because the length and as a consequence the cost of the plastic piping increase linearly with the size of the store. Thus the cost reduction potential of the storage medium is compensated by the complicated and consequently costly plastic piping system. In table 1 an overview of realised gravel-water and soil/sand water pit heat stores is given:

Figure 1: Heat exchanger - plastic piping of the gravel-water store in Steinfurt-Borghorst (1999)

Table 1: Selection of projects with gravel-water and soil/sand-water heat stores in comparison with BTES in Neckarsulm, Germany

location	country	date	volume in m³	medium	charging	HX-length in m	A_{HX}/V in m^{-1}	literature
Stuttgart	D	1983	1 000	GrW	D + I	4 853	0.24	Giebe 1989
Vaulruz	CH	1983	3 500	SoW	I	1 200	n/a	Hadorn 1985
Chemnitz	D	1996	8 000	GrW	D	-	-	Urbaneck 2003
Marstal	DK	1996	3 500	SaW	I	5 000	n/a	Heller 2000
Augsburg	D	1997	6 000	GrW	I	20 000	0.16	Hausladen 1998
Steinfurt	D	1999	1 500	GrW	I	7 000	0.23	Pfeil 1999
Neckarsulm	D	1997	63 360	BTES	I	15 840	0.44	Nußbicker 2003

GrW: gravel-water, SaW: sand-water, SoW: soil-water, BTES: borehole thermal energy storage (borehole length and diameter); HX: Heat Exchanger; I: indirect, D: direct charging system; n/a: not available

An important criterion for a successful operation of seasonal thermal storages in solar assisted district heating systems is that the heat generated by solar collectors during the day can be charged into the store at the same time (in combination with a buffer store during 24 h). Consequently, not only the amount of thermal energy has to be taken into consideration but also the store's maximum thermal power input, resulting in the values of the heat exchanger length (HX-length) and area (A_{HX}). The length of the plastic piping and the heat exchanger area to storage volume ratio (A_{HX}/V) of gravel or soil/sand heat stores are listed in table 1.

2. OUTDOOR EXPERIMENTS: RESEARCH SOIL-WATER HEAT STORE

In the framework of the research project “Further Development of the Pit Heat Storage Technology”, funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, outdoor experiments and tests on different concepts of hot-water-, gravel-water- and soil/sand-water heat stores are carried out (see Ochs 2005). A new concept for a soil/sand water pit heat store with a direct charging system is realized in a research scale. Instead of the complicated and costly plastic piping, horizontal and vertical gravel layers are placed between the soil/sand layers (compare figure 2). The water is pumped through these gravel layers.

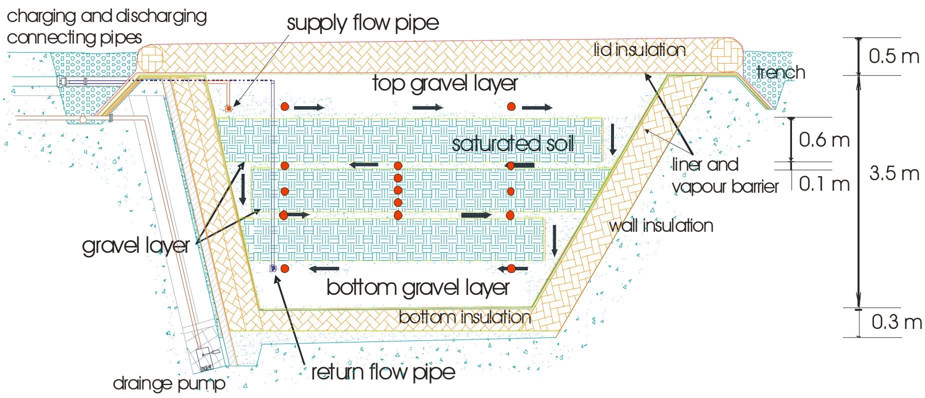

Figure 2: Scheme of the research soil/water pit heat store with gravel channels for the water flow (arrows mark the charging direction, dots the location of temperature sensors)

A soil/sand-water pit heat store has been build at Institute of Thermodynamics and Thermal Engineering (ITW) with a volume of 100 m³ in an entirely insulated pit with a gross volume of 200 m³ (see pictures below). Instead of the excavated soil fine sand (d_m < 1 mm) has been used. In order to prevent elutriation of small particles the soil/sand layers are wrapped in geotextiles (fleece), thus producing water saturated soil/sand packages. The heat transfer in the saturated soil/sand packages is dominated by conduction (A_{HX}/V = 2.8), as convection through the sand/soil package can be neglected.


Figure 3: The construction of the research store, left hand side: filling in the sand layer and on the right hand side wrapping the sand layer in geotextile (fleece) in order to prevent elutriation; on the right hand side of the store the vertical gravel layer can be seen

Further construction methods for a direct charging system for sand/soil pit heat stores by creating water ways can be found in Kiedaisch (2002).

3. SIMULATION OF THE FLOW THROUGH POROUS MEDIA

As in the soil/sand package convection can be neglected, in particular in the case of soil with very small particles (d_m <0.0001 m), the heat must be transferred from the gravel layer into the soil/sand layer by conduction. In addition to the thermal conductivity of the water saturated soil/sand, the heat transfer coefficient between the flow in the gravel channel and the saturated soil/sand package is of importance. In order to investigate the heat transfer mechanisms, measurements at the research store as well as simulations with the commercial CFD-program Fluent have been carried out.
For the calculations the following assumptions have been made: only heat conduction is considered for the heat transfer into the saturated soil/sand package. The gravel layer is modelled as porous medium. For laminar flow in porous media Darcy's law applies:

$$-grad(p) = \frac{\eta}{K} \cdot w \tag{1}$$

with $$w = \frac{\dot{V}}{A \cdot \varepsilon} = \frac{\dot{m}}{A \cdot \varepsilon \cdot \rho} \tag{2}$$

where η is the dynamic viscosity and ρ the density of the fluid. A denotes the cross-sectional area of the porous channel, $\dot{V}$ the volume and $\dot{m}$ the mass flow, respectively. The permeability K can be calculated as a function of the porosity (ε) as follows:

$$K = \frac{d^2 \cdot \varepsilon^2}{A \cdot (1-\varepsilon)^2} \tag{3}$$

According to different authors (Chang 2001, Ergun 1952 and Urbaneck 2003) the empirical factor A in equation (3) can be set to 150. For turbulent flow in porous media (Re > 120) Darcy's law is inadequate. The pressure drop in the flow can be estimated with a quadratic relationship according to Ergun (see Ergun 1952):

$$-grad(p) = \left(\frac{A \cdot \alpha_\varepsilon \cdot \eta}{d^2}\right) \cdot w + \left(\frac{B \cdot \beta_\varepsilon \cdot \rho}{d}\right) \cdot w^2 \tag{4}$$

with $\alpha_\varepsilon = \frac{(1-\varepsilon)^2}{\varepsilon^3}$, $\beta_\varepsilon = \frac{1-\varepsilon}{\varepsilon^3}$ and the empirical values A and B. Fluent provides the following equation for modelling of the flow in porous media:

$$-grad(p) = \left(\frac{\eta}{\alpha}\right) \cdot w + \left(\frac{1}{2} \cdot \rho \cdot C\right) \cdot w^2 \tag{5}$$

The geometry taken into account for the 2D calculation with Fluent is schematically illustrated in figure 4.

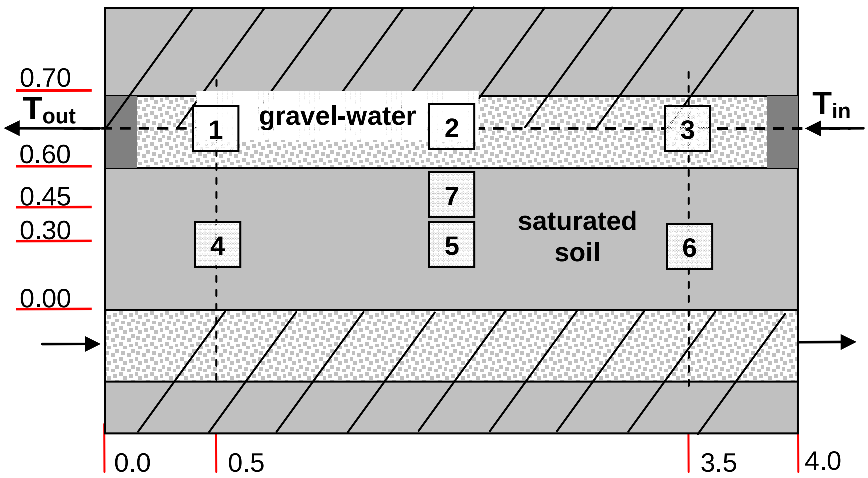

Figure 4: Simplified geometry of the model (in m) used for the calculations.

1-7: location of the temperature sensors.

$A_{HX}/V = 2.8$.

The first 10 cm of the gravel layer (inlet and outlet) are for numerical reasons considered as pure liquid. The hatched area is not included in the simulation for reasons of temporal optimization (symmetry). All parameters and coefficients applied for the simulation are summarised in table 2.

Table 2: Parameters and coefficients used for the calculation (Chang 2001 Giebe 1989, Urbaneck 2004)

			gravel (grain)	sand saturated	sand dry	soil saturated	water (fluid)
mean particle diameter	d_m	m	**0.023**	<0.001	<0.001	<0.0001	-
density	ρ	kg/m³	**2629**	**2000**	1650	2000	**992.2**
specific heat capacity	c_p	kJ/(kg K)	**0.79**	**1.38**	0.4	1.38	**4.177**
thermal conductivity	λ	W/(m K)	**4.8**	**2.4**	1.6	1.8	**0.6306**
dynamic viscosity	η	kg/(m s)	-	-	-	-	**6.5E-04**
permeability	K	1/m²	**1.32E-06**	-	-	-	-
viscous resistance	α	m²	**5.03E-07**	-	-	-	-
inertial resistance	C	1/m	**1719.4**	-	-	-	-

During various simulations the following parameters have been varied: initial temperature ($T_{initial}$), charging temperature (T_{inlet}), flow velocity (w), and thermal conductivity of the water saturated soil/sand package (λ_{Sand}). Figure 5 shows the influence of the flow velocity and of the thermal conductivity on the temperature history of the gravel layer and the sand package:

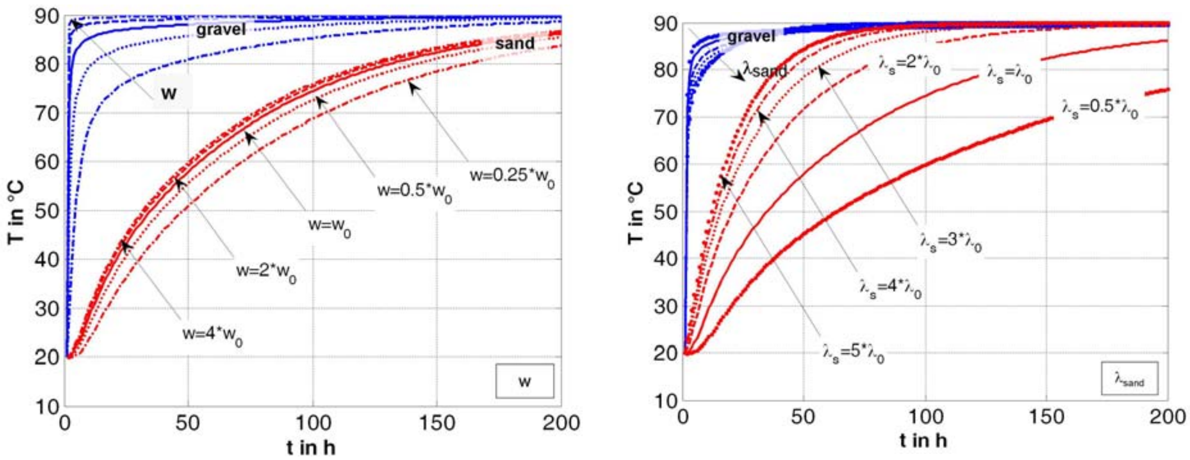

Figure 5: History plot of the mean gravel and sand temperatures; variation of the parameters flow velocity (w_0=2.97 m/s) and thermal conductivity of the sand layer ($\lambda_{sand,0}$=2.4 W/(m K))

Neither the variation of the flow velocity (w) nor the variation of the thermal conductivity of the sand package (λ_{sand}) result in strong changes of the gravel temperature. The variation of the flow velocity also does not lead to major changes in the sand temperature history (figure 5, left hand side). However, significant temperature changes occur when the thermal conductivity of the sand package (figure 5, right hand side) is varied.

4. COMPARISON OF THE MEASUREMENT DATA WITH SIMULATION RESULTS

During a period of several weeks charging and discharging tests have been carried out in the outdoor research store. The charging and discharging pipes, perforated DN100 PP tubes, are placed in the top and bottom gravel layer, respectively. The pipes are connected via buried district heating pipes to the heating station consisting of a connection to the district heating and district cooling system of the university. For additional heating a 170 kW natural gas boiler is installed. The charging and discharging has been carried out with different target temperatures (40, 60, 80 °C) as well as with different flow velocities. In order to verify the parameters the measured results are compared with calculated results. Figure 6 shows a comparison of measured results of a charging period of nearly 150 h with a target temperature of T_{target} = 80 °C and a volume flow of 1.8 m³/h with simulation results, calculated for different values of the thermal conductivity of the sand package. Measured temperatures of the gravel layer are used as input data for the simulation.

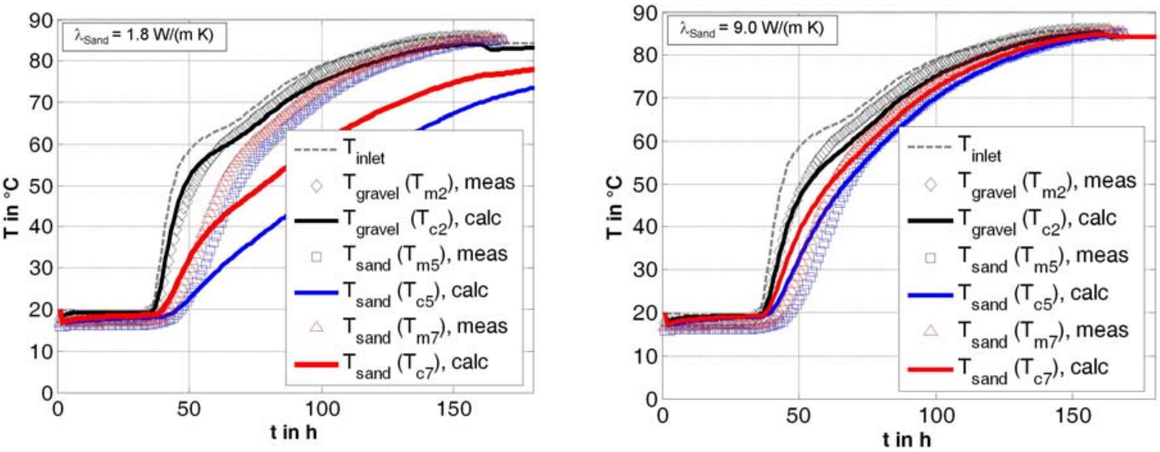

Figure 6: Comparison of the measurement data with the simulation results for different values of the thermal conductivity of the sand layer (λ_{Sand}), good correlation can only be attained by an unrealistic high value of the thermal conductivity

From figure 6 it can be seen that the temperature increases quickly after the initiation of the charging flow. The saturated sand/soil layer is heated up slower than the gravel layer, but the heat is transported into the saturated soil/sand layer. Comparing the measured data with the calculated results shows that the heat in the sand/soil package is not only transported by conduction (as it would be in the case of soil with $d_{m,soil} << d_{m,sand}$) but also by convection. Only if an unrealistically high value of the thermal conductivity of the sand/soil layer (λ_{Sand} = 9.0 W/(m K)) is used in the simulation, good agreement between measured data and calculation results may be achieved. In the case of soil instead of sand the amount of heat stored during the charging period would not be sufficient with $\lambda_{soil,max}$ < 3.5 W/(m K) and $\lambda_{soil,av} \cong$ 2.4 W/(m K), respectively.

In order to simulate the behaviour under realistic boundary conditions, cyclic supply temperatures (measured data of the supply temperature of a solar system in Stuttgart Vaihingen, Germany, see Schenke 2006) and realistic flow rates are used as input for the

simulation. The results of a three day simulation with measured input data are plotted in figure 7.
The temperature of the gravel layer increases at the beginning of the charging period (8:00 h) with a maximum charging temperature of 90 °C from 20 °C to about 80 °C within 8 hours.
After the charging cycle is stopped further heat is conducted from the gravel layer into the soil/sand layer. Thereby the temperature of the soil/sand package increases to nearly 35 °C until the beginning of the next charging period. Simultaneously, the gravel layer cools down to about 45 °C. As a consequence the return flow temperature increases from 20 °C to 45 °C within 24 h. In the same period the soil/sand package heats up from 20 °C to 35 °C. The behaviour at the following days is similar. The temperature difference between the gravel and the soil/sand package remains at about 10 K after each charging cycle.

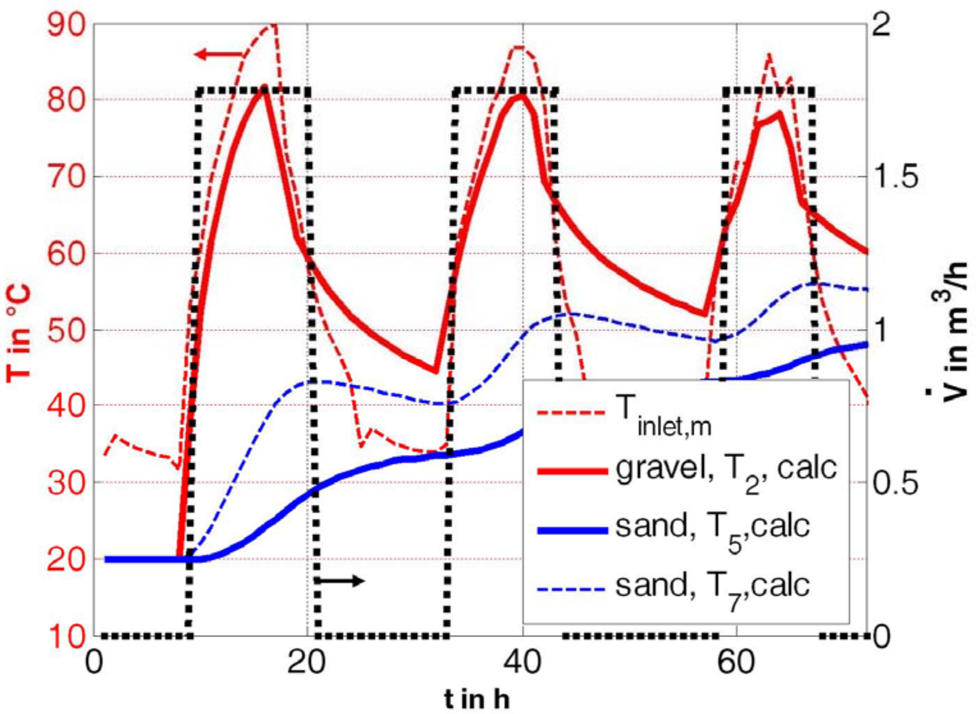

Figure 7: Results of a simulation of a charging with cyclic charging temperatures (measured data of a solar system, Schenke 2006), d_{sand}=0.6 m, λ_{sand}= 2.4 W/(m K), c_p=1 800 J/(kg K), location of the temperature sensors according to figure 4

The heat is transferred from the gravel layer into the soil/sand package but the ratio of the height of the soil/sand package to the gravel layer must be reduced from 60:10 to 30:10 in order to allow the storage of the total heat load in the soil/sand layer within 24 hours. A reduction of 50 % of the height of the soil/sand package minimises the economical benefit compared to a pure gravel-water heat store.

5. Conclusions

It could be demonstrated that the concept of a soil/sand-water heat store with a direct charging system is technically feasible. However, the process of heat storage over a charging period of 24 h is possible only in the case of saturated sand with a relatively high effective thermal conductivity (a superposition of heat conduction and convection). In the case of saturated soil as heat storage material no convection would take place and thus the height of the soil packages has to be reduced further. The proof of the economical benefit in comparison to a pure gravel-water heat store is object of further work.

ACKNOWLEDGEMENTS

This project is supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit), FKZ 0329607E. The authors gratefully acknowledge this support and carry the full responsibility for the content of this paper.

REFERENCES

Chang, W. (2001). Experimentelle Untersuchung zur freien Konvektion an Rohren in einer Kies/Wasser-Schüttung, Dissertation, Universität Stuttgart, in german.

Fluent®: www.fluent.de.

Ergun., S. (1952). Fluid Flow through Packed Columns, Chem. Eng. Prog., 48(2):89-94,.

Giebe, R. (1989). Ein Kies/Wasser-Wärmespeicher in Praxis und Theorie, Dissertation, Universität Stuttgart, in german.

Hadorn, J.-C. (1985). The Vaulruz Project. Experimental Results, Proc. Enerstock, Toronto.

Hausladen G., Pertler, H. (1998). LFU Augsburg – Solare Langzeitwärmespeicherung mittels Großkollektoranlage mit Kies-Wasser-Speicher, Proc. DGS, 11. internationales Sonnenforum, Köln, in german.

Heller, A. (2000). Development of Seasonal Storage in Denmark: Status of Storage Programme 1997-2000, Proc. Terrastock 2000, Stuttgart.

Kiedaisch, J. (2002). Entwicklung einer Wasserwegsamkeit durch Geokunststoffe oder Kies für einer Erdreich/Wasser-Wärmespeicher, Diplomarbeit, Universität Stuttgart, in german.

Nußbicker, J. (2003). Solar assisted district heating system with duct heat store in Neckarsulm-Amorbach (Germany), Proc. ISES Solar World Congress 2003, Göteborg, Schweden, 14.-19.06.

Ochs F., et al. (2005). Außenlaborversuche zur Entwicklung kostengünstiger Erdbecken-Wärmespeicher für Solarwärme, Proc. OTTI, 15. Symposium „Thermische Solarenergie“, Kloster Banz, Bad Staffelstein, in german.

Pfeil, M., Koch, H. (1999). Saisonaler Kies/Wasser-Wärmespeicher der 3. Generation für die Solarsiedlung Steinfurt Borghorst, Proc. OTTI, 10. Symposium „Thermische Solarenergie“, Kloster Banz, Bad Staffelstein, in german.

Schenke A., et al. (2006). Optimierung großer Solarer Kombianalagen in Theorie und Praxis, Proc. OTTI, 16. Symposium „Thermische Solarenergie“, Kloster Banz, Bad Staffelstein, in german.

Urbaneck, T (2003). Berechnung des thermischen Verhaltens von Kies-Wasser-Speichern, Dissertation, TU Chemnitz, in german.