Bulletin d'Hydrogéologie No 17 (1999)
Centre d'Hydrogéologie, Université de Neuchâtel
EDITIONS PETER LANG

Underground seasonal heat storage for a solar heating system in Neckarsulm, Germany

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ABSTRACT

In Neckarsulm in the south-west of Germany a new building area with approximately 1300 flats and terraced houses will be realized within the next 5 years. A solar assisted district heating system with underground seasonal heat storage is used for heat supply. A solar contribution of about 50 % to the total heat demand (space heating and domestic hot water) is planned. With this system a duct beat store with temperatures up to 80°C without heat pump is realized for the first time in Germany.

Until now a system with 2.700 m^2 collector area and a duct store with a volume of 20.000 m^3 is built. The store consists of 168 Polybuthene-Double-U-pipes inserted in 30 m deep boreholes in a square pattern of 2 m. The stratigraphy at the location is sedimentary rock, different kinds of claystone in the upper layers and limestone underneath.

First charging experiments were carried out sucessfully for validating a simplified computer model of the duct store. Further measurements will he used for the development of a calculation model which takes into account the combined heat and moisture transport in the ground.

KEYWORDS

Seasonal heat storage, solar heating system, duct storage

System description

Figure 1 shows a map of the building site. The solar collectors are mounted on the roofs of a school, a gymnasium, a seniors people home and a shopping centre. The heating central is located beside the school together with the buffer store. The duct heat store is located in a distance of approximately 150 m in a green area in the centre of the building site. The scheme of the district heating system is shown in figure 2. The duct store is connected directly to the district heating network without a heat-exchanger to avoid temperature drops.

The duct store is charged via the buffer store, which is used to equalize the large power peaks delivered by the solar collectors. The network will be supplied temperature dependent either from the duct or the buffer store. If none of the stores is warm enough an auxiliary gas condensing burner is used.

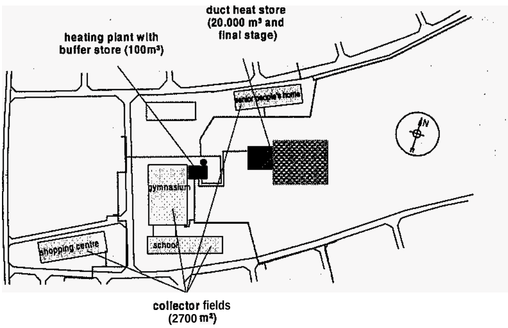

Figure I: Map of the site (status December 1998)

Seasonal heat storage

For seasonal heat storage a duct store is used. The heat is stored directly in the ground. The heat is being transfered to and from the ground via the so called ducts, which consist of heat exchanger pipes installed in vertical boreholes. Figure 3 shows horizontal and vertical cuts through the borehole. The heat exchanger pipes with a dimension of 25 x 2,3 mm are made of polybutene (PB) due to the combined strain of system pressure and temperature. After the installation of the heat exchanger pipes the borehole is refilled with a suspension of bentonite, sand, cement and water. The store is insulated on the top with a 20 cm layer of extruded polystyrole which extends the peripheral boreholes by 4 m in horicontal direction. The refilled ground above the store has a thickness of 2-3 m. One of the main advantages of the duct store is the possibility to extend the store by adding further boreholes in relation to the growth of the building area.

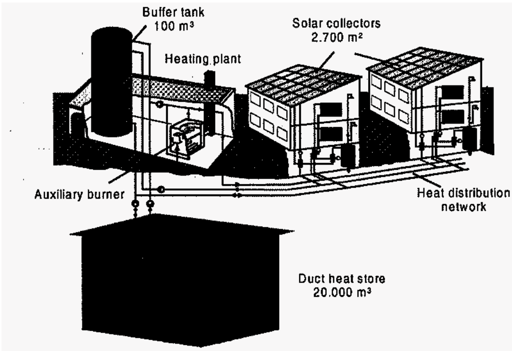

Figure 2: Scheme of the heating system

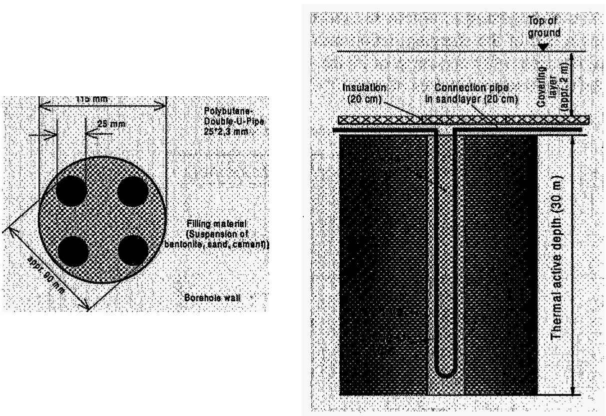

Figure 3: Schematic view of a ground heat exchanger

Hydrogeolocical situation

On site the underground consists of layers of different claystones above the limestone. (see figure 4). The groundwater level is between 10 and 15 m below ground level. While both the Marl layers have a very low hydraulic conductivity ($k_f = 5 \cdot 10^{-8}$ m/s) there is a dolomite layer inbetween which has a considerably higher hydraulic conductivity of $k_f \approx 2 \cdot 10^{-5}$ m/s. The depth of the store was limited to 30 m below ground because of probably high heat losses due to water movement and to avoid difficulties with the water authorities due to sources nearby.

Experimental store and measuring results

A first experimental store with a volume of appr. **4300** m^3 was built in autumn 1997 (lower **left** section in figure 5). The store consisted of 36 double-U-pipes with a depth of 30 m and a borehole distance of 2 m. The borehole diameter was 115 mm. Each 6 boreholes were connected in series. This store was mainly used for charging and discharging experiments. Therefore heat quantities and temperature changes in and outside the store were monitored with about **40** sensors in three additional boreholes (M01-M03, *see* figure 5).

The store was heated up with supply temperatures between 65 and 80°C from mid **of** December 97 until beginning of March 98, starting from an undisturbed ground temperature of 10°C. **At** the **end** of the charging period maximum temperatures of 53°C were reached (measured at borehole M02 in a depth of 20 m). Then a short discharging cycle was camed out, with inlet temperatures between 40 and 50°C.

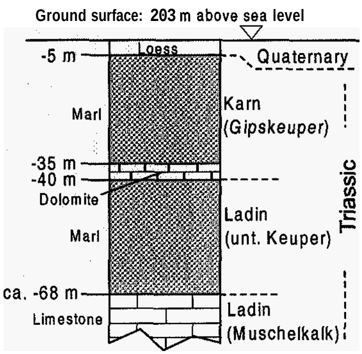

Figure 4: Geological profile at the BTES site

Due to the short charging period (compared to seasonal operation) the store reached only relatively low temperatures. Therefore not much heat could be recovered.

For the validation of the correct layout of the store a comparison between measured and calculated data was carried out. The measured inlet temperature and the mass flow were taken as input data for the storage model **SBM** (Superposition Borehole Model). This model allows a detailed description of the store (position, depth and hydraulic connection **of** the ground heat exchangers), but takes only conduction into account as a heat transfer mechanism. The calculated outlet and ground temperatures were compared to the measured values while varying the thermal parameters **of** the ground and the heat transfer capacity of the ducts.

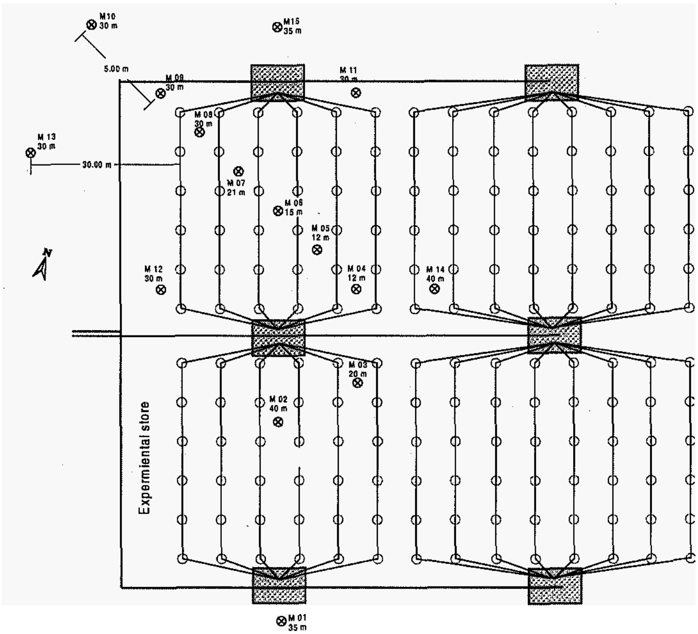

Figure 5: Plan of the duct store (status December 1998) with the location of the boreholes for temperatures (M01-M15) and moisture measurement (M04-M12)

Figure 6 shows the result of the identification process for the whole experimental period. The store inlet temperature (and hence the measured and calculated outlet temperature) shows significant daily fluctuations, which were induced from the imperfect control of the network supply temperature. In addition temperature curves from three sensors in the ground (M01 and M02 at 20 m depth, M03 at 10 m) are shown, in dark the measured and in light the calculated values.

The thermal parameters of the ground determined by the identification process are 2 W/mK for the heat conductivity and 3 MJ/m^{3}K for the volumetric heat capacity. These values are about 10% higher then the assumed values from the prestudies. Simulations with the identitied values showed that this larger values are negligable on the overall performance of the system. The higher heat capacity is positive because of a higher storage capacity of the store in comparison to the assumed value. On one hand the higher heat conductivity leads to higher heat losses of the store, on the other hand the heat transfer capacity of the store is enhanced. This results in lower return temperatures to the solar collectors and therefore in higher solar gains, which egalize the increased losses of the store.

The heat transfer capacity of the ducts was found not as good as estimated. Reasons for that are a closer distance between the U-pipes than planned *(65* mm shank spacing) and a lower thermal conductivity of the refilling material. This effect however decreases the performance of the overall system. Above all the discharging of the store is reduced due to the network return temperature. Simulations showed that the heat transfer capacity of the ducts can he improved significantly by enlarging both the borehole diameter from 115 to 150 mm and the pipe shank spacing from *65* to 100 mm. Therefore the extension of the store from 4.300 m^3 to 20.000 m^3 with additional 132 boreholes was made with this duct geometry.

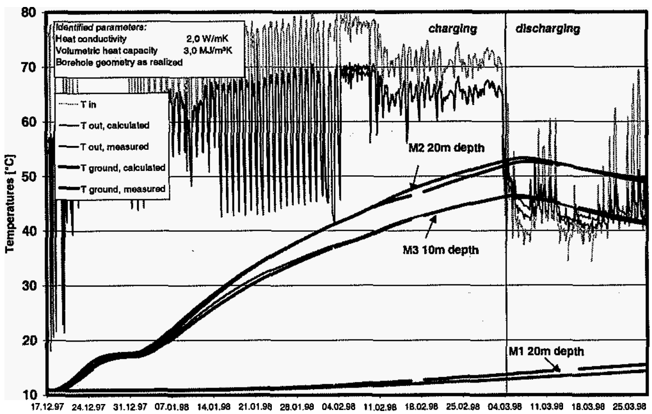

Figure 6: Comparison of measured vers. calculated temperatures in the experimental store

Extension of the store and further monitoring programme

The store was extended during the second half of 1998 by adding 6 rows with 6 boreholes each in northern direction and further 8 rows with 12 boreholes each in eastern direction. This results in an axis symetrical design of the store with a central hot pipe and two cold pipes at the north and south side (see figure 5). System operation started in January 1999.

Besides the monitoring of the overall system (especially the interaction between the collectors and the store during charging and the effect of the network return temperatures on discharging), special attention will he paid on the combined heat and mass transfer inside the store .

Theoretical model of the heat and moisture interaction

High temperature energy input (70 - 90 "C) into the ground produces noticeable temperature gradients and simultaneous moisture flow in the vicinity of the ground heat exchangers. The thermal energy flow is mainly by conduction over a complex system of solid soil particles and partly by convection due to liquid moisture, air and vapour movement.

PHILIP & DE VRIES (1957) developed the theory of thermally driven soil moisture which has never been verified for high temperatures. This approach considers the effect of soil temperature on vapour pressure and surface tension i.e. on the driving forces of vapour diffusion and liquid moisture flow. Based on this theory (NEISS 1982, WAGNER 1991, HELLSTRÖM 1991) a computer model was developed to simulate heat and soil moisture interactions in high temperature ground heat storages.

The model consists of two parabolic differential equations with temperature and volumetric moisture content as variables (VAN GENUCHTEN 1980).

Moisture transport: Equation (1) considers liquid moisture and vapour movement due to a thermal and a moisture gradient. The energy transport equation (2) is based on Fourier's Law and takes into account the latent heat transport by evaporation and condensation of water within the porous medium.

As a general analytical solution of these differential equations is impossible, a numerical approximation by the finite-differences-method (FDM) was used.

Moisture transport : $$\rho_L \frac{\partial \theta_L}{\partial t} = \nabla\left[(D_{TL} + D_{TV})\nabla T\right] + \nabla\left[(D_{\theta L} + D_{\theta V})\nabla \theta_L\right] + \rho_L \frac{\partial k_u}{\partial z} \qquad (1)$$

Energy transport: $$C\frac{\partial T}{\partial t} = \nabla(\lambda \nabla T) + \nabla(H_L * D_{\theta V} * \nabla \theta_L) \qquad (2)$$

ρ	density [kg/m^3]		t	time [s]
θ	volumetric part [m^3/m^3]		z	depth [m]
D_{TL}	thermal water diffusion [kg/msK]		λ	thermal conductivity [W/mK]
D_{TV}	thermal vapour diffusion [kg/msK]		C	volumetric heat capacity [J/m^3K]
$D_{\theta L}$	water diffusion due to moisture gradient [kg/msK]		k_u	unsaturated hydraulic conductivity [m/s]
$D_{\theta V}$	vapour diffusion due to moisture gradient [kg/msK]		H_L	spec. evaporation enthalpy of water [J/kg]
T	temperature [°C, K]	index	L	liquid water
			V	vapour

As already mentioned, dry-out effects in the vicinity of the ground heat exchangers may occur which have to be considered by an additional contact resistance between the tube and the ground.

Measuring equipment

In order to analyse this effect after a set of laboratory tests the north-westem-sectionof the duct store in Neckarsulm will be monitored for at least two years. The model as well as the laboratory experiments show that for high permeable underground like sand significant dry-out will occur whereas clay (kaolin) of low permeability does not show this effect.

During the construction of the storage a set of steel tubes was installed in the north-west quarter of the borehole field from the centre to the comer (figure 5). The circles give the position of the boreholes with heat exchangers. Each circle with a cross represents the location of a measuring tube for determination of the moisture of the underground with a neutron probe. At the same spot temperatures at different depths are measured.

The initial temperatures and moisture contents of the ground measured in January 1999 at location M10 are shown in table 1.

Table 1: Initial temperatures and moisture content at location M10 (January 1999)

depth [m]	0.0	1.0	3.0	6.0	9.0	15.0	21.0	24.0	27.0	29.0	30.0
temperature [°C]	10.5	10.6	11.5	10.8	10.9	11.0	11.1	11.3	11.3	11.4	11.3
moisture [%vol.]	31.5	39.0	35.5	44.0	35.7	21.5	19.3	26.5	35.5	24.0	17.9

Future outlook

At the final stage the total heat demand of the building area will amount to approximately 10.500 MWh/a and the available collector area to 15.000 m^2. According to present simulations a storage volume of about 150.000 m^3 will **be** necessary to achieve a solar fraction of 50%.

If **the** ongoing project leads to sucessful results it is planned to extend the duct store stepwise according to the growth of the building area and herewith rising collector area. The extension will take place in eastern direction while using the maximum available space of **45** m in N-S-direction. The heat recovery factor of the store will reach **75** to 80 % depending on the depth of the store, **i.e.** on the surface/volume-ratio. A quasi-steady-state operation will be reached after approximately 5 years.

Acknowledgements

The construction **of** the project and the scientific work has been financed by the German Federal Research Ministry (BMBF), the country Baden Württemberg and the City **of** Neckarsulm. The authors gratefully acknowledge this support.

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