GROUND-SOURCED ENERGY WELLS FOR HEATING AND COOLING OF BUILDINGS

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abstract

Energy wells are thermo-active elements for an economical extraction or storage of ground energy, similar to energy piles and other deep foundation elements also used as heat exchangers. Heating and/or cooling of buildings requires a primary and secondary thermo-active circuit, commonly connected by a heat pump. The paper gives several design aspects of energy wells which can be also used for the design of deep energy foundations. Thermal response tests have proved suitable for the in-situ determination of thermal ground properties required for an optimised design. Moreover, different systems of energy wells are discussed, and a comprehensive pilot research project is described.

keywords

energy wells, energy foundations, geothermal geotechnics, geothermal heating/cooling, thermo-active structures, thermal ground properties, field testing

1 INTRODUCTION

The fourth Šuklje Lecture was devoted to geothermal geotechnics as an innovative field of geotechnical engineering (Brandl, 2003). Meanwhile thermo-active ground structures and heat pumps have been used increasingly. In Austria, about 200,000 heat pumps are running presently, and their number increases by more than 5000 per year. Their main purpose was warm water generation first. Since the year 2000 heating (and cooling) of buildings has dominated. It is estimated that these heat pumps save more than 250,000 tons of fuel oil per year.

This corresponds to the Austrian climate strategy of the year 2002 to achieve the Kiyoto targets. The main potential to reduce CO_2 refers to the heating of buildings. Together with other energy consumption (e.g. warm water generation, cooling of buildings), this potential represents about one third of the total sum. Consequently, research has focused on the design of buildings that need minimum energy.

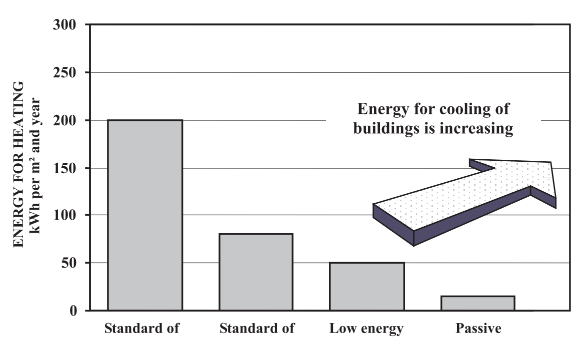


Figure 1. Required energy for the heating of houses in Austria. Improvements since the 1970s.

Fig. 1 illustrates the chronological development of energy saving houses in Europe. The required energy for heating houses has decreased significantly since the nineteen-seventies, but on the other hand the energy for cooling is increasing, mainly due to large glass facades and permanently closed windows of modern architecture. Ultra Low- to Zero-Energy Houses are also called "Passive Houses". The term "Passive House" indicates that such buildings need only minimum or no conventional energy as required for "active" heating or cooling. Such an optimal energy balance can be only achieved in exceptional cases. However, thermo-active ground structures or wells may provide sufficient energy for a cheap and clean heating/cooling of buildings.

The temperature felt by persons in a room consists of the air temperature and the radiation temperature (i.e. the temperature of walls and floors), whereby the ratio between air and surface temperature is essential. Compensating too low wall or floor temperature by higher air temperature is felt uncomfortable (e.g. in temporarily uninhabited cold houses which have to be warmed up). Surface temperatures of 20 to 25°C are optimal corresponding to an air temperature between 16° and 21°C. Low temperature heating systems like wall- and floor heating with a large surface radiation fulfil this requirement, whereby the feed temperature of wall heating should not exceed 40°C and the floor temperature 28°C, respectively. This heating system can be coupled in an ideal way with energy foundations, retaining walls, tunnels, and energy wells.

The dominating ground-sourced elements are energy foundations, but energy tunnels, energy wells, retaining structures etc. are also used. Energy foundations may comprise base slabs, piles barrettes, slurry trench systems (single elements or continuous diaphragm walls), concrete columns, and grouted stone columns. Combinations with near-surface earth collectors and retaining structures are also possible (Fig. 2). Thermo-active ground structures or wells can be used for heating and/or cooling buildings of all sizes, as well as for road pavements, bridge decks, etc.

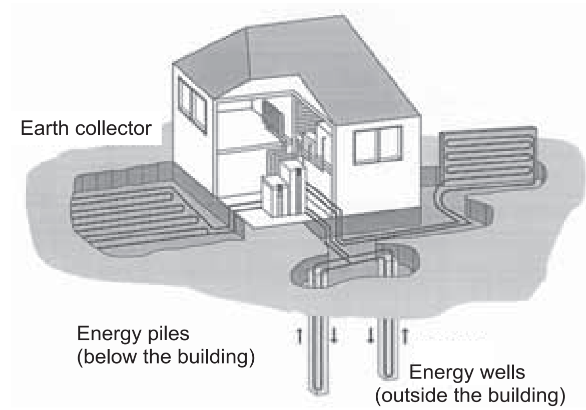


Figure 2. Scheme for heating/cooling a small one-family house with energy foundations and/or energy wells. Also indicated are additional thermo-active ground-source systems.

Energy wells are wells (temporarily) used for groundwater lowering and/or groundwater recharging but simultaneously adapted for energy extraction/storage purposes. The energy systems therefore have a double function, and they work most efficiently if the thermo-active elements are in contact with mobile groundwater in the case of heating or cooling only. However, for seasonal operation (i.e. heating in winter and cooling in summer) rather steady groundwater conditions with a low hydraulic gradient are favourable for seasonal energy extraction and feeding (recharging, storage).

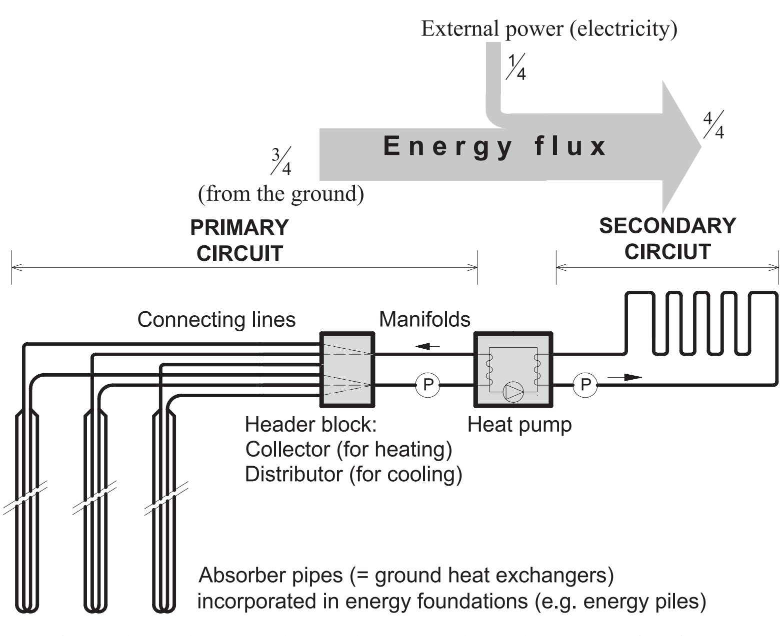


Figure 3. Scheme of a geothermal energy plant with energy piles and an energy flux for COP 4 of the heat pump. COP coefficient of performance defining the heat pump efficiency.

2 THERMO-ACTIVE CIRCUITS FOR ENERGY FOUNDATIONS AND ENERGY WELLS

A thermo-active system consists of the primary circuit below ground and the secondary circuit in the building (Fig. 3).

The primary circuit contains closed pipework in earth-contact concrete elements (piles, barrettes, diaphragm walls, columns, base slabs, and wells) through which a heat carrier fluid is pumped that exchanges energy from the building with the ground. The heat carrier fluid is a heat transfer medium of either water, water with antifreeze (glycol) or a saline solution. Glycol–water mixtures have proved most suitable, containing also additives to prevent corrosion in the header block, valves, the heat pump, etc. Once cast, the pipings within the underground-contact concrete elements are individually joined to a header and manifold block. They are joined by connecting pipes which are normally laid within the blinding beneath the base slab in the case of energy foundations. The secondary circuit is a closed fluid-based building heating or cooling network (secondary pipework) embedded in the floors and walls of the structure or in bridge decks, road structures, platforms etc.

Commonly, primary and secondary circuits are connected via a heat pump that increases the temperature level, typically from 10–15°C to a level between 25°C and 35°C (Fig. 3). All that is required for this process is a low application of electrical energy for raising the originally non-usable heat resources to a higher, usable temperature. The principle of a heat pump is similar to that of a reverse refrigerator (Fig. 10). In the case of the heat pump, however, both the heat absorption in the evaporator and the heat emission in the condenser occur at a higher temperature, whereby the heating and not the cooling effect is utilised.

The coefficient of performance, COP, of a heat pump is a device parameter and is defined by

$$COP = \frac{energy\ output \text{ after heat pump } [kW]}{energy\ input\ \ for\ operation\,[kW]} \qquad (1)$$

The value of COP = 4 means that from one portion of electrical energy and three portions of environmental energy from the ground four portions of usable energy are derived (Fig. 3).

The efficiency of a heat pump is strongly influenced by the difference between extracted and actually used temperature. A high user temperature (inflow temperature to the heating system of the secondary circuit) and a low extraction temperature (due to insufficient return-flow temperature) in the heat exchanger (primary circuit) reduce its efficiency. For economic reasons a value of COP ≥ 4 should be achieved. Therefore, the usable temperature in the secondary circuit should not exceed 35–45°C, and the extraction temperature in the absorber pipes should not fall below 0–5°C. Consequently, this technology tends to be limited to low temperature heating (and cooling).

Commonly, electric heat pumps are used, less frequently heat pumps with internal combustion and occasionally absorption heat pumps. For environmental reasons only refrigerants without ozone reduction potential and with a minimum greenhouse potential are allowed for heat pumps. Therefore halogenated fluorinated hydrocarbons should not be used.

The seasonal performance factor (SPF) of a thermo-active system with a heat pump is the ratio of the usable energy output of the system to the energy input required to obtain it. Therefore SPF includes not only the heat pump but also other energy-consuming elements (e.g. circulation pumps). At present, values of SPF = 3.8–4.3 are achieved with standard electric heat pumps. Special devices with direct vaporisation increase SPF by 10–15%.

$$SPF = \frac{\text{useable } energy\ \ output\ \ of \text{ the energy system } [kWh]}{energy\ \ input\ \ of \text{ the energy system } [kWh]} \qquad (2)$$

Experience has shown that these geothermal cooling/heating systems from energy foundations and other thermo-active ground structures may save up to two-thirds of conventional heating costs. Moreover, they represent an effective contribution to environmental protection by providing clean and self-renewable energy.

If only heating or only cooling is performed, high-permeability ground and groundwater with a high hydraulic gradient are of advantage. However, most economical and environmentally friendly is a seasonal operation with an energy balance throughout the year, hence heating in winter (i.e. heat extraction from the ground) and cooling in summer (i.e. heat sinking/recharging into the ground). In this case low-permeability ground and groundwater with only low hydraulic gradients are favourable.

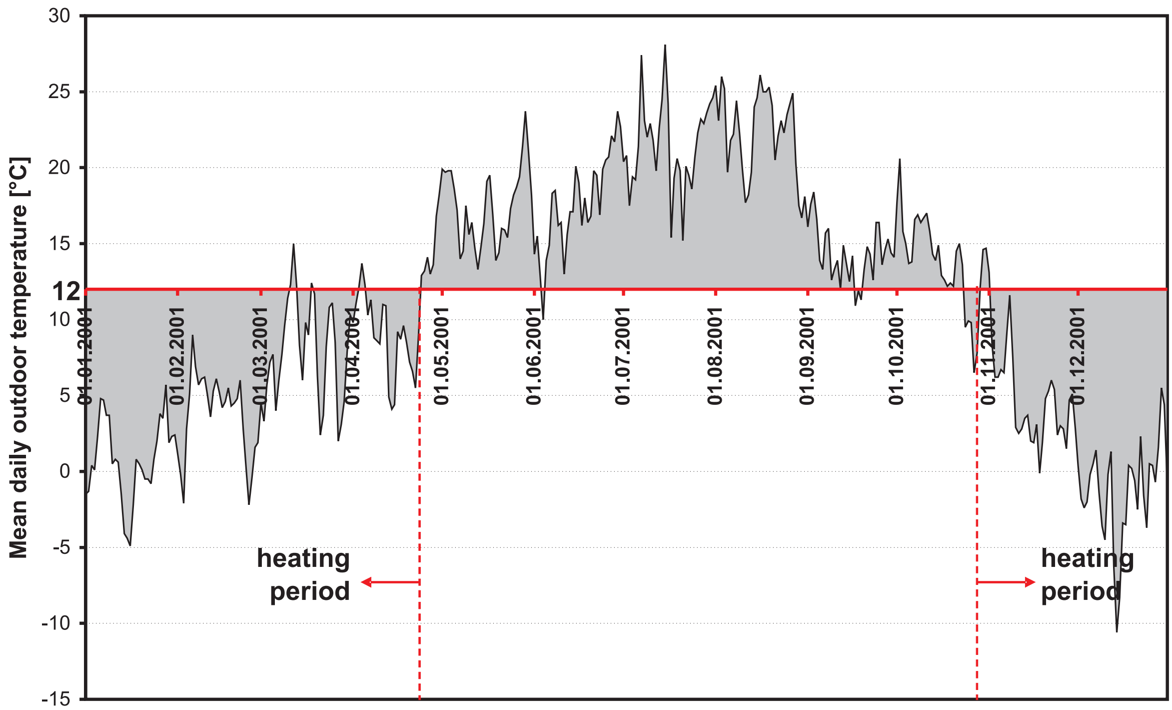


Figure 4. Mean daily outdoor temperatures in Vienna, 2001. If temperature drops below 28C, room heating is usually necessary.

There is no limitation to the depth of piles or wells as far as the installation of energy absorber systems is concerned. The energy potential increases with depth: hence deeper ground-sourced energy systems are advantageous. The economically minimum length of piles, barrettes or diaphragm wall panels is about 6 m. Energy wells should reach deeper, because they have a lower heat transfer capacity than concrete elements.

The production of electric current from energy foundations and other thermo-active ground structures or wells is theoretically possible but not effective. This is similar to biomasses as base materials: they exhibit a high efficiency for heating (85%) but an extremely low efficiency for producing electric current (25%).

3 DESIGN ASPECTS OF ENERGY WELLS AND FOUNDATIONS

Early ecological energy planning for building can often prevent costly refurbishment and renovation in the future. High-quality energy design involves not only heating and cooling (rooms, water) but also lighting, and it requires a multi-objective optimisation.

An optimised energetic-thermal design should also consider the seasonal heat loss from (un-)insulated slab-ongrade floors or basement walls. Far more energy and costs are expended in running an inefficiently laid out building than in constructing an efficient one. A proper design should consider the efficiency of the overall building process, including the sustainability of all elements.

The heat that can be extracted from or fed into/stored in the ground depends on the maximum possible heat flux density in the absorber pipe system. There, the heat transport occurs by forced convection of the fluid (usually an antifreeze – water mixture). In order to optimise the absorber pipe system the following parameters have to be considered:

- Diameter and length of pipes;
- Properties of pipe wall (roughness);
- Heat conductivity, specific heat capacity, density and viscosity of fluid circulating in absorber pipes;
- Flow velocity and flow conditions (laminar-turbulent) within absorber pipes.

Complex ground properties and pile or well groups require numerical modelling of the geothermal heating/cooling system.

Fig. 4 shows the daily mean temperatures in Vienna for the year 2001. Such data are needed to design a heating–cooling system whereby it is assumed that heating typically starts at external temperatures lower than 128°C. This provides the heating period for the unsteady numerical models. Fig. 5 illustrates the simulation of the

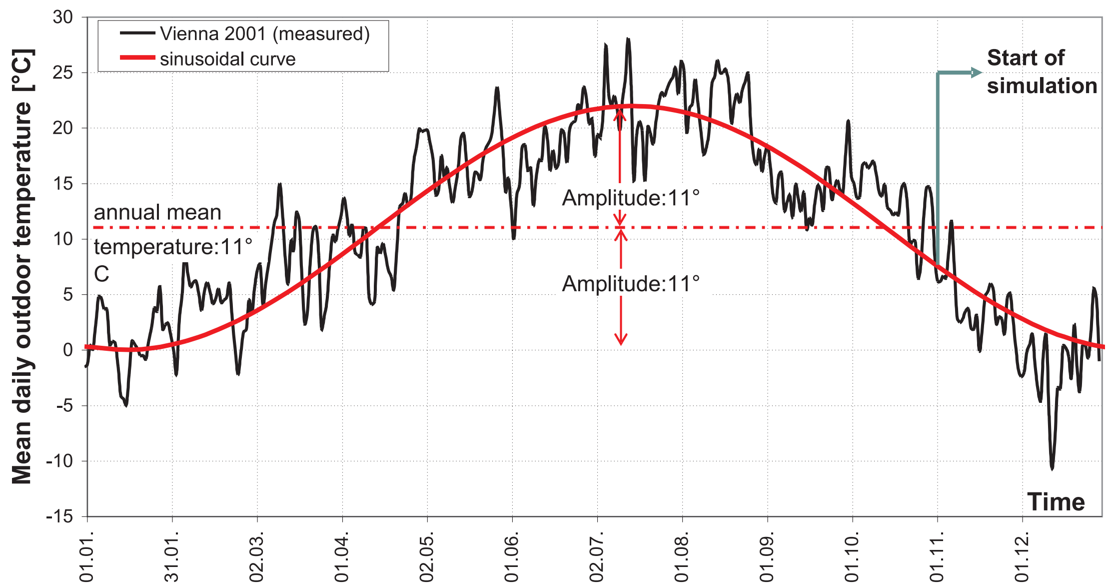


Figure 5. Mean daily outdoor temperatures in Vienna, 2001, with idealised sinusoidal curve for numerical calculations

seasonal course of the air temperature by a sinusoidal curve according to the following equation

$$T_{GS} = T_{m,out} + \Delta T_{out} \cos\left[\frac{2\pi}{P}(t-\varepsilon_t)\right] \qquad (3)$$

where $T_{GS}(t)$ is the ground surface temperature, t is time, $T_{m,out}$ is the average yearly temperature, ΔT_{out} is the temperature amplitude, P is the duration period, and ε_t is the phase displacement.

In the end, the monthly heating and cooling demands have to be compared with the available output, as indicated in Fig. 6. Moreover, the seasonal course of the absorber fluid temperature (heat carrier fluid temperature) should be predicted.

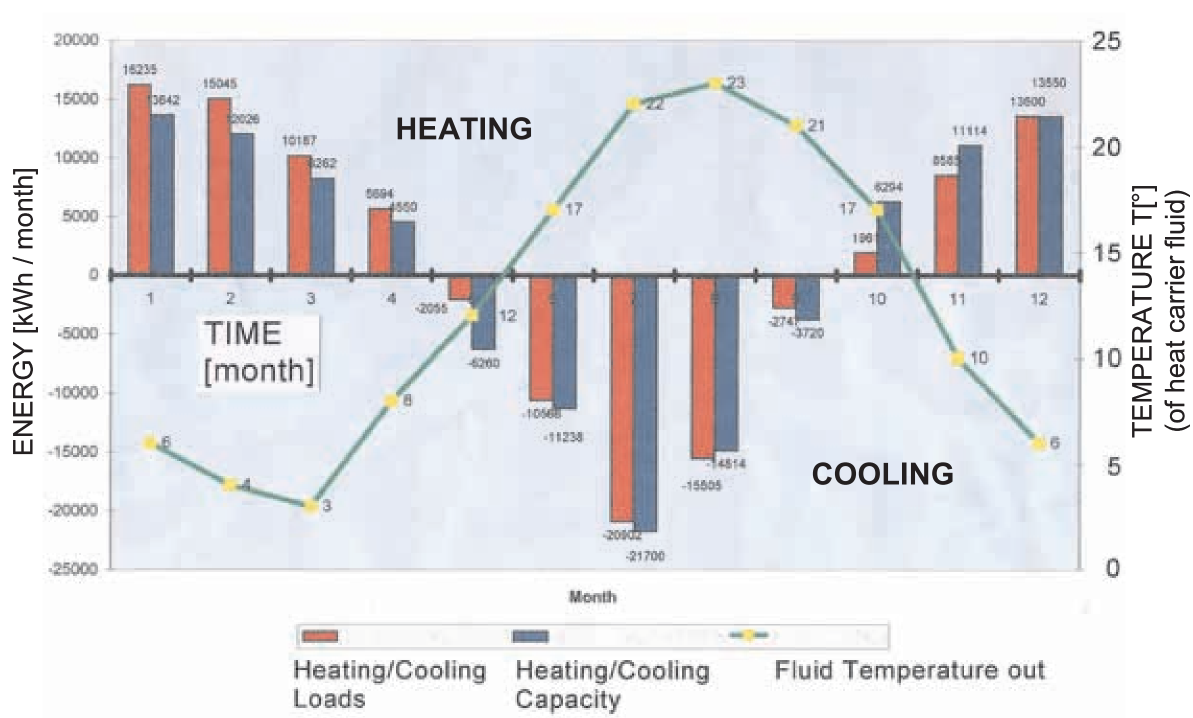


Figure 6. Example of energy demand and output for heating and cooling (annual distribution) of a building founded on energy piles. Temperature of heat carrier fluid is also shown.

Usually, a numerical simulation of the geothermal system is recommended for buildings with a heating and cooling demand of more than 50 kW. This rough value decreases to about 20 kW for buildings where rooms have to be cooled throughout the year. Geometric simplification may lead to significant errors in heat calculation. Therefore three-dimensional analyses should be conducted. The simulation should comprise the expected inflow and outflow temperatures at the energy foundations and the temperature distribution in the ground. Numerical models and computer programs should be reliably calibrated, that is on the basis of long-term measurements and experience from other sites, and on physical plausibility. Otherwise wrong results may be gained, even from well-known suppliers. Experience has shown that the results are very sensitive to even small changes in the finite element mesh. Consequently, the importance of numerical simulations lies rather in parametric studies (to investigate the influence of specific parameters) than in gaining 'exact' quantitative results.

Calculation of the temperature distribution in the ground due to energy foundations or energy wells is increasingly being demanded by local authorities for environmental risk assessment. This refers mainly to possible influences on adjacent ground properties and on the groundwater by the long-term operation of thermo-active deep foundations.

Monitoring of thermo-active ground-sourced systems is essential for an optimized long-term operation, and to enable sophisticated design of future projects. Fig. 7, for example, shows the temperatures along an energy pile (out of a group) that has been used for heating since 1996. The depicted period between 2002 and 2005 illustrates that a reliable interpretation of date and heat exchanger behaviour requires the daily outdoor mean values. Single outdoor temperature measurements parallel to pile (or well) temperature measurements would not be sufficient.

Proper geothermal energy utilisation requires an interdisciplinary design, especially in the case of houses. Geotechnical engineer, architect, building equipment (sanitation) designer and installer, heating engineer and specialised plumber should cooperate as early as possible to create the most economical energy system. However, the tender for construction should clearly specify individual performances on the site. It has proved suitable to entrust the geothermally experienced plumber with all details of the primary and secondary circuits, beginning with the mounting of the absorber pipe systems in the foundation elements.

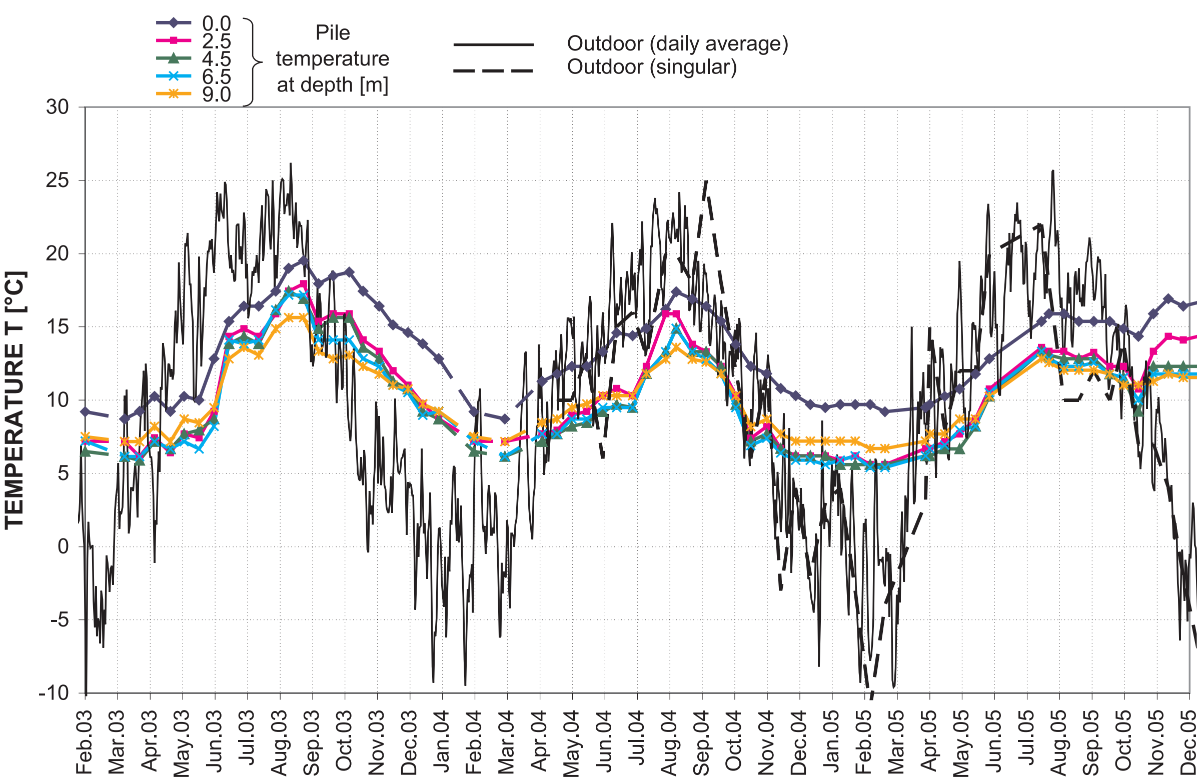


Figure 7. Outdoor temperature near a building with energy piles and temperature within a 'measuring pile'. Strong heatwave in summer 2003; more normal temperature distribution in 2004; cold summer and very warm autumn in 2005.

4 IN-SITU MEASUREMENT OF THERMAL GROUND PROPERTIES

In order to optimise the design of energy foundations or energy wells the thermal ground properties have to be considered. The most important parameter is the thermal conductivity λ. For the preliminary design of complex energy foundations, or for the detailed design of standard geothermal systems, it can be taken with sufficient accuracy from diagrams considering water content, saturation density and texture of the soil. However, for sophisticated design in-situ measurements are recommended, for instance the thermal response test. Its theory can be also applied to energy foundations and energy wells, thus providing a feedback referring to design assumptions and data collections for future projects.

A defined energy is applied to a vertical heat exchanger, and the inflow and returnflow temperatures of the heat carrier fluid are registered. Therefore, the measurements involve the entire length of the ground heat exchanger, thus providing an effective value for the thermal conductivity considering borehole refilling (or pile properties), heterogeneous ground conditions and groundwater situation. In addition, the thermal borehole resistance R_b is determined which is another parameter for designing earth-contact thermo-active elements.

Heat transfer from/to a vertical heat exchanger causes a temperature change in the surrounding soil. The temperature field as a function of time and radius around a borehole can be described as a line heat source with constant heat storage/extraction (Hellström, 1991):

$$\Delta T(r_b,t) = \frac{\bar{q}}{4\pi\lambda_{eff}} \int_{r/2\sqrt{at}}^{\infty} \frac{e^{-\bar{\beta}^2}}{\bar{\beta}} d\bar{\beta} \qquad (4)$$

where

$\Delta T(r_b, t)$	=	temperature increase [K]
$\bar{q}$	=	heat storage rate per unit borehole length [W/m]
λ_{eff}	=	effective thermal conductivity
L_b	=	effective borehole length [m]
t	=	time after storage/extraction of heat has started [s]
a	=	thermal diffusivity ($\lambda/\rho c$ where c is the heat capacity)
r	=	radial distance from the centre line of the borehole [m]
r_b	=	borehole radius [m]
$\bar{\beta}$	=	eintegrating variable [-]

For the thermal response test, Eq. (4) can be approximated for the temperature field around a borehole. The theory is based on Gehlin (1998) as follows:

$$\Delta T(r_b,t) = \frac{\bar{q}}{4\pi\lambda_{eff}} \left(\ln\frac{4at}{r_b^2} - \bar{\gamma} \right) \text{ provided that } t > \frac{5r_b^2}{a} \qquad (5)$$

where γ is Euler's number (0.5772…)

The above derivation assumes

- Constant temperature along the borehole which is not exactly the case in practice. However, the axial temperature gradient is small in relation to the radial quotient; thus, the approach provides only negligible deviation.
- Infinite length of the borehole. In practice, the borehole length is considerably larger than the borehole radius. Therefore, for short periods of time (as in the case of response tests) the borehole end effects can be ignored (Gehlin, 1998).

Another important factor for the design of heat exchanger systems is the thermal resistance between the heat carrier fluid and the borehole wall. It dictates the temperature difference between the fluid temperature (T_m) and the borehole wall (T_b) for a certain heat flux $\bar{q}$

$$T_m - T_b = R_b \bar{q} \qquad (6)$$

The thermal borehole resistance R_b depends on the arrangement of the absorber pipes and on the material involved, i.e. pipe plastic and surrounding borehole fill material or concrete (in the case of energy piles). R_b causes temperature losses that affect the heat transfer. The equation for the temperature field considering the thermal borehole resistance can be written

$$\Delta T(r_b,t) = \bar{q}\left[R_b + \frac{1}{4\pi\lambda_{eff}} \left(\ln\frac{4at}{r_b^2} - \bar{\gamma} \right) \right] \qquad (7)$$

Further transformation of equation 7 leads to equation 8 that approximates the transient process around a vertical heat exchanger (Fig. 8):

$$T_m = \frac{\dot{Q}}{4\pi\lambda_{eff} L_b} \ln(t) + \left[\frac{\dot{Q}}{L_b} \left(\frac{1}{4\pi\lambda_{eff}} \left(\ln\left(\frac{4a}{r_b^2}\right) - \bar{\gamma} \right) - R_b \right) + T_0 \right] \qquad (8)$$

where

$T_m = \dfrac{T_{\text{inflow}} - T_{returnflow}}{2}$ [°C] is the mean heat carrier fluid temperature

$\dot{Q}$ = constant heat power [W], stored or extracted [W]

T_0 = undisturbed initial temperature of the ground [°C]

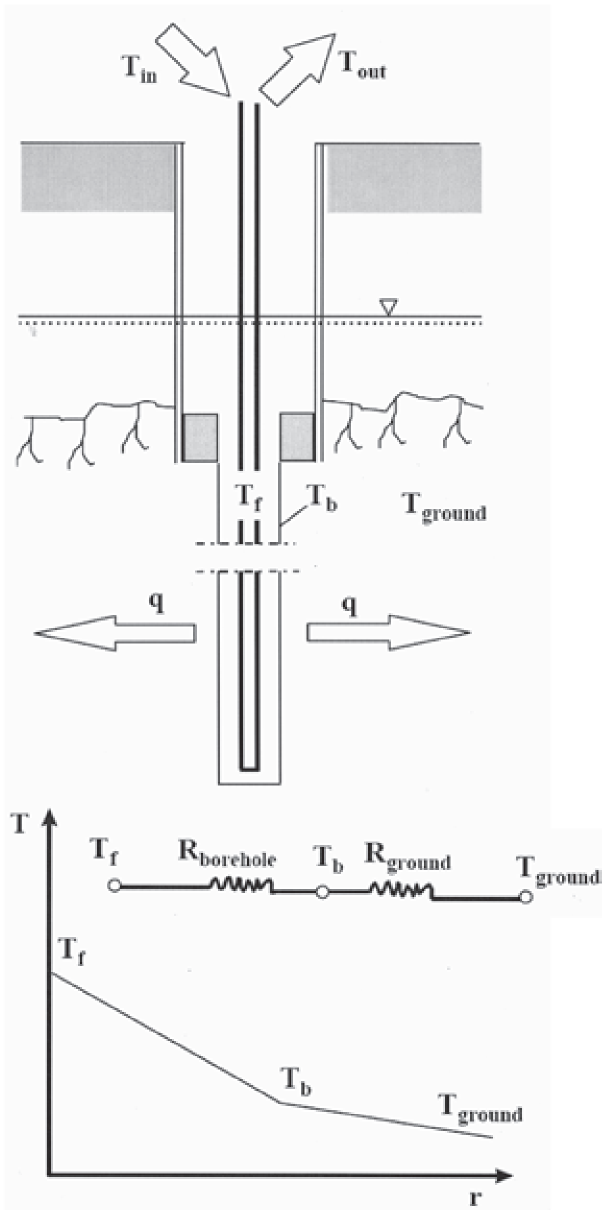


Figure 8. Temperature loss due to the thermal resistance of absorber and fill-material in a borehole (Gehlin).

Equation 8 can be simplified to a linear relation between T_m and ln(t):

$$T_m = k \ln(t) + m \qquad (9)$$

with

$$k = \frac{\dot{Q}}{4\pi\lambda_{eff} L_b} \qquad (10)$$

and

$$m = \frac{\dot{Q}}{L_b}\left(\frac{1}{4\pi\lambda_{eff}}\left(\ln\left(\frac{4a}{r_b^2}\right) - \overline{\gamma}\right) - R_b\right) + T_0 \qquad (11)$$

By plotting the mean fluid temperature versus the dimensionless time parameter $\tau = \ln(T)$ the inclination k of the graph is obtained, hence leading to the thermal conductivity λ from equation 10. This finally provides the thermal resistance R_b between the heat carrier fluid and the borehole wall

$$R_b = \frac{L_b}{\dot{Q}}(T_m - T_0) - \frac{1}{4\pi\lambda_{eff}}\left(\ln(t) + \ln\left(\frac{4a}{r_b^2}\right) - \overline{\gamma}\right) \qquad (12)$$

in [K/(W/m)]

The higher the thermal borehole resistance, the higher is the temperature step between the heat carrier fluid and the surrounding ground, hence the temperature loss. This is also the case for energy piles or energy diaphragm walls.

5 ENERGY WELLS – AN OVERVIEW

There are three different groups of geothermal wells that serve for environmentally friendly heating/cooling at low cost:

(a) Exploiting hot water from the ground by boreholes reaching to a depth up to about 2000 m;
(b) Conventional ground heat exchanger boreholes drilled up to about 300 m depth;
(c) Wells that are anyway required for temporary groundwater lowering serve simultaneously as a heat extraction/storage system;
(d) Near-surface open systems.

Drilling deep geothermal boreholes for (a) and (b) requires specialized equipment, considerable chill and experience. Such systems only serve for heat exchanging. Energy wells of group (c), however, represent a two-purpose system, hence a technology containing geotechnical and geothermal engineering: Many construction sites require wells for groundwater lowering. Sometimes discharge wells are coupled with recharge wells in order to minimize ground settlement. These temporary measures can be also used for heating and cooling adjacent buildings. This may be performed temporarily during the construction period but also permanently after ceasing groundwater lowering. Experience has revealed that the public acceptance of metros, railways and roads by neighbouring people increases if they are provided by cheap, renewable energy from such energy wells or other geothermal systems.

Thermo-active foundations, tunnels etc., hence earth-contact structural elements and related energy wells exhibit closed circuits. In contrast, open systems use water from an aquifer which is pressed through a heat exchanger or heat pump. These are simpler but hardly used in Austria because of operational problems such as clogging or bio-fouling in the wells and heat exchangers. Clogging may occur by precipitation of dissolved minerals caused by temperature changes and precipitation of iron-manganese hydroxides. It increases with temperature variations in the aquifer and with air entering the wells or pipework. The latter can be avoided by operating the system with a slight overpressure. Furthermore, such wells need submersible pumps that can be lifted for maintenance.

In order to gain sufficient energy from open systems a great number of wells may be needed, thus extracting a high quantity of groundwater. The groundwater-based cooling and heating system of the Technical University of Eindhoven, for instance, circulates about 3,000 m^3/h from 48 wells (Holdsworth, 2003). In several countries this may cause legal problems, because a considerable quantity of water is extracted from an aquifer and recharged at a different temperature. Moreover, groundwater extraction may cause settlement of adjacent buildings, unless it is properly coupled with the groundwater recharging scheme. TU Eindhofen has solved this problem by placing the wells in "mirrored" clusters, so that when one set is extracting water the others inject. In the first phase of this scheme (with 32 wells) more than 20 MW of energy were delivered, leading to estimated annual savings of 2,600 MWh of electricity and 1.2 Mm^3 of natural gas, as well as reducing annual carbon dioxide emissions by 2,800 t.

6 PILOT RESEARCH PROJECT

6.1 FIELD TESTS

Fig. 9 shows the scheme of a large-scale test with energy wells for heating and cooling. Simultaneously, these wells were used for a long-term groundwater lowering along a new railway line under construction. Hence, the tests could run from 2001 to 2003.

The following investigations were carried out for research purposes and to optimise an adjacent energy tunnel in cut and cover:

- In-situ determination of thermal soil parameters (thermal conductivity, specific heat capacity);
- Maximum amount of extractable heat and energy influx, and storage capacity;
- Long-term behaviour and temperature conditions;
- Influence of groundwater flow.

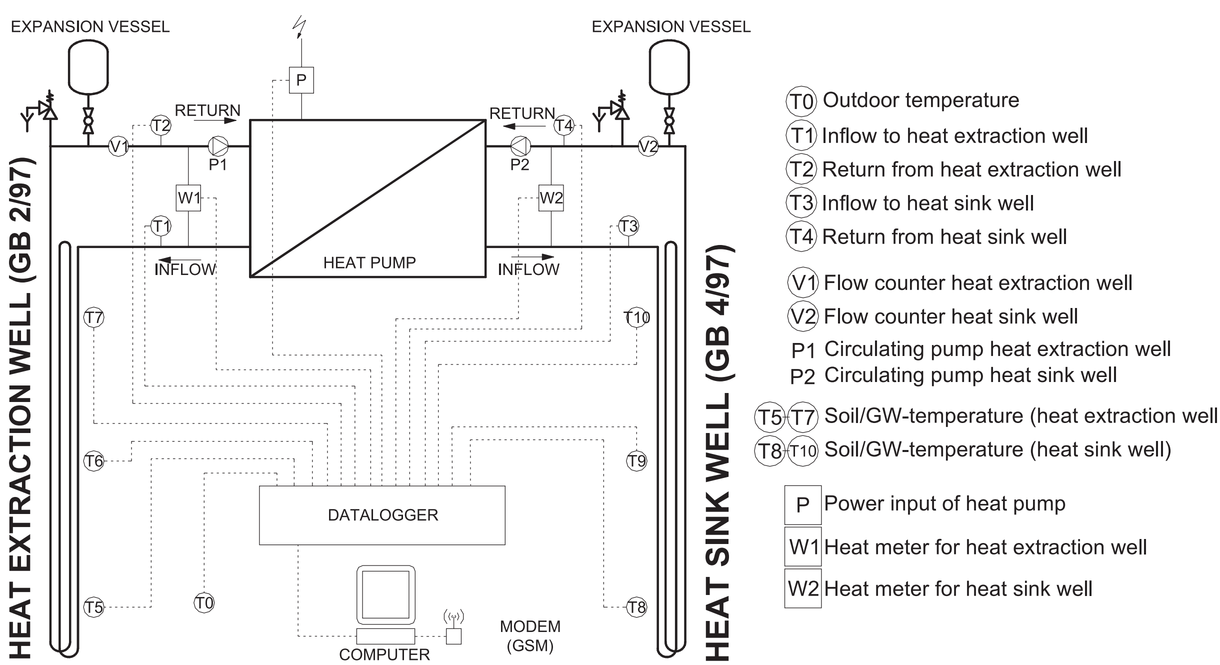


Figure 9. Scheme of testing plant "Energy well H" with GB 2/97 as heat extraction well and GB 4/97 as heat sink well.

Figure 10. Installation of absorber pipes into the filter pipe of a well used for groundwater lowering during a cut and cover tunnel construction.

Figure 11. Detail of Fig. 10 showing the U-shaped toe zone of absorber pipes.

During the tests several parameters were changed to investigate their influence, i.e. capacity of the circulating and heat pump, circuit temperatures, operation scheme (permanent, intermediate), ground temperature regeneration period between energy extraction, and storage. Moreover, the measurement should serve to compare numerical calculations with semi-analytical calculations.

The 45 m deep test wells were installed in 50 m deep boreholes of 600 mm diameter. The subsoil consisted of manmade fills (down to 4.7 m) underlain by heterogeneous tertiary sediments: silty clay, sand, sandy silt, gravel and wide-grained silty-sandy gravel, locally with sandstone and boulders. Below 23.0 m stiff cohesive layers with interlayers of sand and clay dominate.

The hydraulic conductivity was extremely scattered: locally from $k = 10^{-3}$ to 10^{-10} m/s with an overall value of about $k = 10^{-6}$ m/s. Due to the layered ground profile the horizontal permeability exceeded the vertical one, hence $k_h = 10\ k_v$ to $50\ k_v$.

Seepage water occurred between 9.5 to 13.4 m depth, the closed groundwater table lay at 20-23 m depth (seasonal amplitude), and in 36 m depth artesian groundwater was found.

Both boreholes were fitted with U-pipe heat exchangers consisting of HDPE-pipes of 25 mm outer diameter and located within the filter tube of the wells (Figs. 10 and 11). In order to achieve an optimal heat exchange between absorber and surrounding soil the spacing is typically filled with a cement-bentonite suspension for common energy wells. However, in this case only sand and gravel was used because the wells should be used again, at least temporarily, for groundwater extraction, too. Moreover, the influence of different contact-media should be investigated. In well GB 2/97 (Fig. 9) sand was filled between the tube and the filter, in well GB 4/97 the heat transfer into the absorber pipes should mainly occur by the contact with ground water.

Thermal energy was taken from the heat source GB 2/97 (discharge well), transported to a heat pump where the energy was raised to a higher temperature level, and then transferred back to the ground by the heat sink GB 4/97 (recharge well) - Fig. 9.

The following data were measured:

- Outdoor temperature [°C];
- Temperature of inflow and outflow [°C] of primary and secondary circuit;
- Temperature in both wells at different depths from 2.8 m to 45.6 m [°C];
- Volume flux in primary and secondary circuit [m³/h];
- Cumulative heat volume in primary and secondary circuit [kWh];
- Electric performance of all electric equipment (heat pump, circulating pump, data-logger) [W].

The data-logger was connected to all measuring devices, registered in 20" and calculated / stored in 10^3-intervalls. Instead of clean water a water-glycol mixture circulated in the absorber pipes thus influencing the measured heat quantity. This was taken into account by a reduction factor of 0.85.

Fig. 12 shows the temperature fluctuation in the absorber system after the start of operation on 28.03.2001. In the heat source (GB 2/97) the temperature

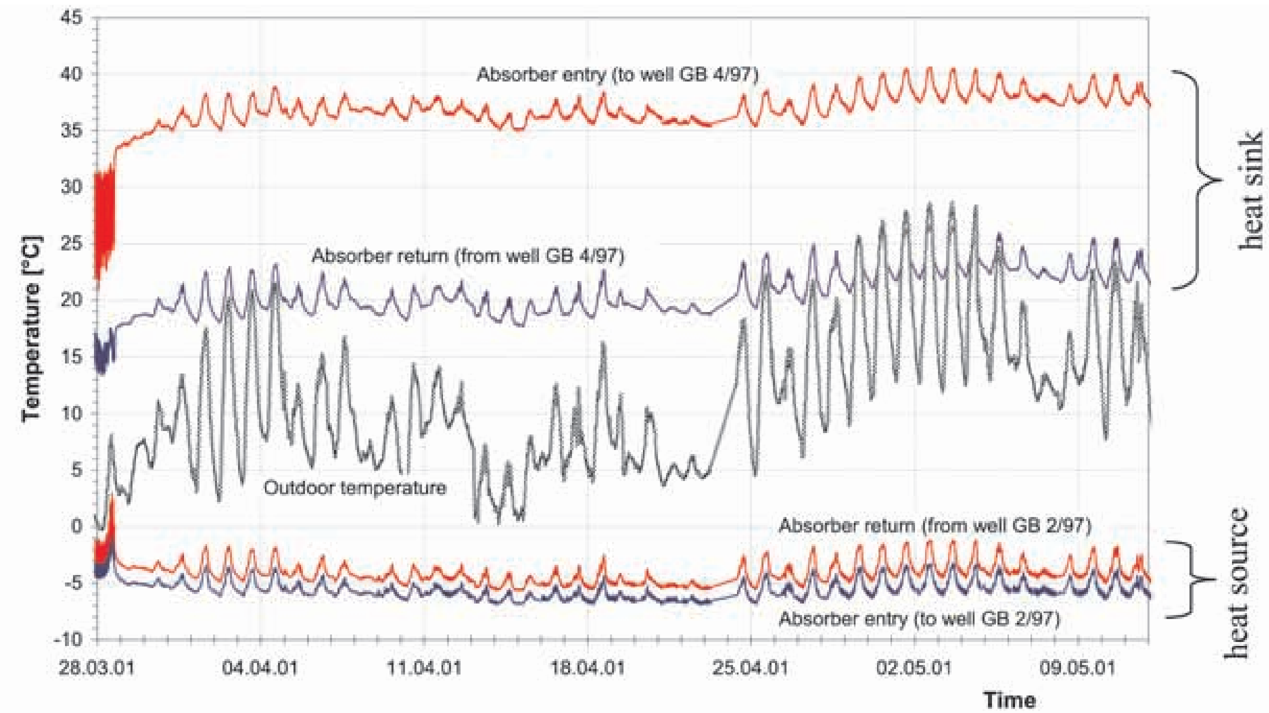


Figure 12. Operating temperatures in absorber system of energy well.

difference of the heat carrier fluid between absorber inflow and outflow was about ΔT=1.5°C, whereby the temperature level was very low and fluctuated at about T=-5°C. This was caused by a high-performance circulating pump, which had too much power in relation to the relatively short absorber pipes in the well. But the over-capacity of the pump had been chosen deliberately to investigate the effects of an over-design.

Fig. 13 shows measured temperatures from February to June 2001. At the beginning of this period an intermediate operation was executed, whereby the heat pump was turned on and off within minutes. With such an operation only the temperature at the top of the heat sink is influenced. Temperatures of the heat source fluctuate in a range of about 1°C and interact strongly with the outdoor temperature.

At the end of March the operation scheme was changed form intermediate to continuous operation. The temperature set value of the secondary circuit was set to 55°C, so that the heat pump never turned off automatically. Fig. 13 shows that the lowest temperature of the heat carrier fluid was T=-7°C in the mid of April and the highest temperature in the secondary circuit was T=41°C in the mid of May. All temperature curves exhibit daily fluctuations, which indicate the influence of outdoor temperature. The temperature level is nearly constant during the whole period. Fig. 14 illustrates that about 60 kWh energy could be extracted from the ground with one well within 24 hours. This energy was raised to a higher temperature level by the heat pump, so that an energy of about 110 kWh/24h was transferred back to ground.

In order to test various operation procedures the schema of Fig. 9 was changed to that of Figs. 15 and 16 in December 2001. The former energy storage well (sink well) was transformed into an energy extraction well, thus increasing the primary circuit. The heat gained by this energy system was increased by a heat pump to a higher temperature level and then sent to a heating radiator. After the radiator was exhausted a continuous operation had been started. A comparison of Fig 13 and Fig. 17 shows that the temperature level of the primary circuit is much higher after the system modification. Fig. 17 shows big temperature fluctuation of the heat carrier medium in the secondary circuit. This is caused by the radiator, which transfers the heat directly to the air.

The heat output of the secondary circuit (radiator) was lower and the extracted heat (primary circuit) was just a little bit higher than before the system had been modified (see Fig. 14 and Fig. 18). Due to smaller circulating pumps the demand of external energy was lower than before the system modification. About 62 kWh energy within 24 hours could be extracted from the ground with both wells, and the radiator finally had an output of about 93 kWh/24h.

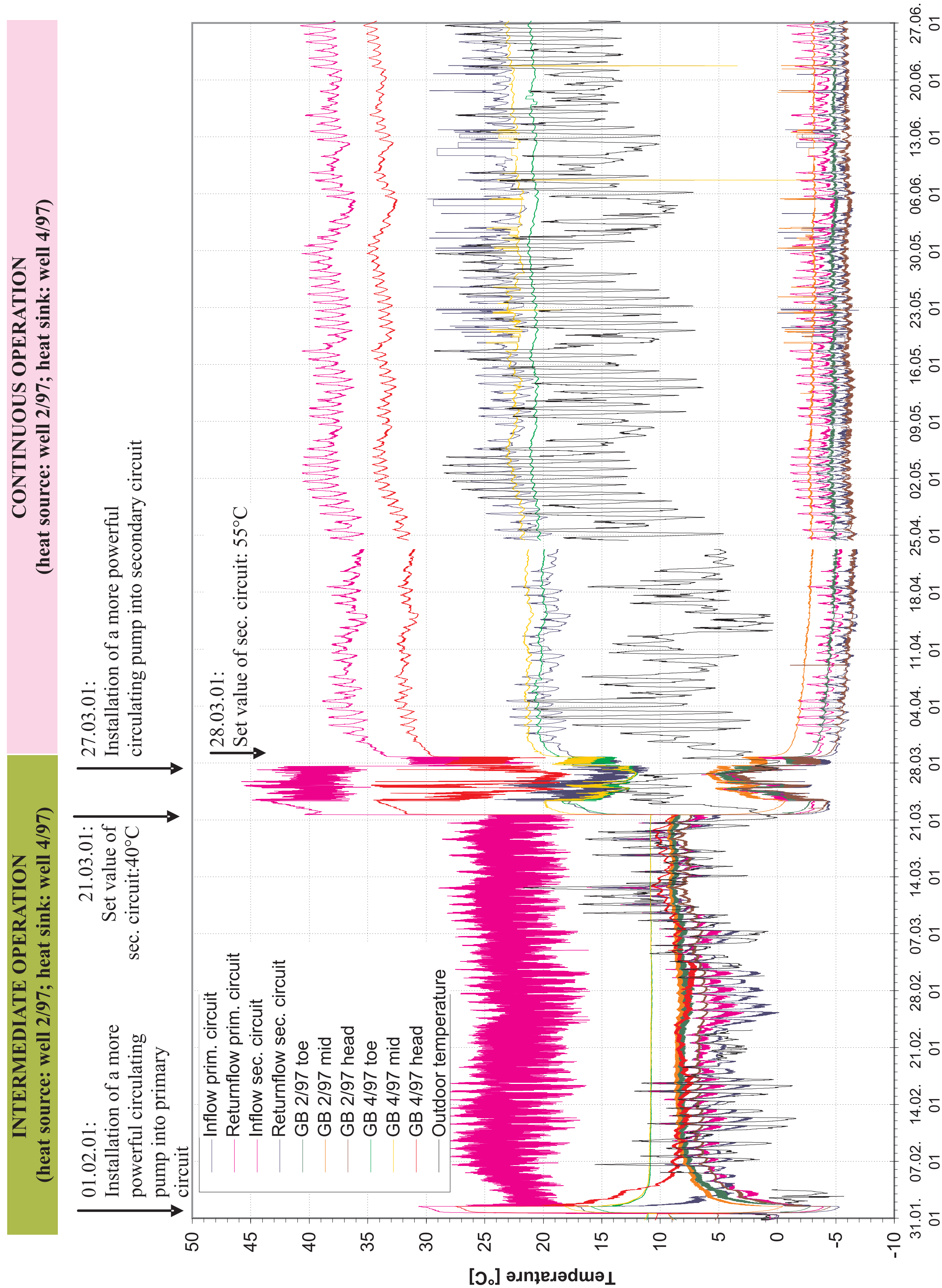


Figure 13. Measured temperatures from February to June 2001 (before system modification).

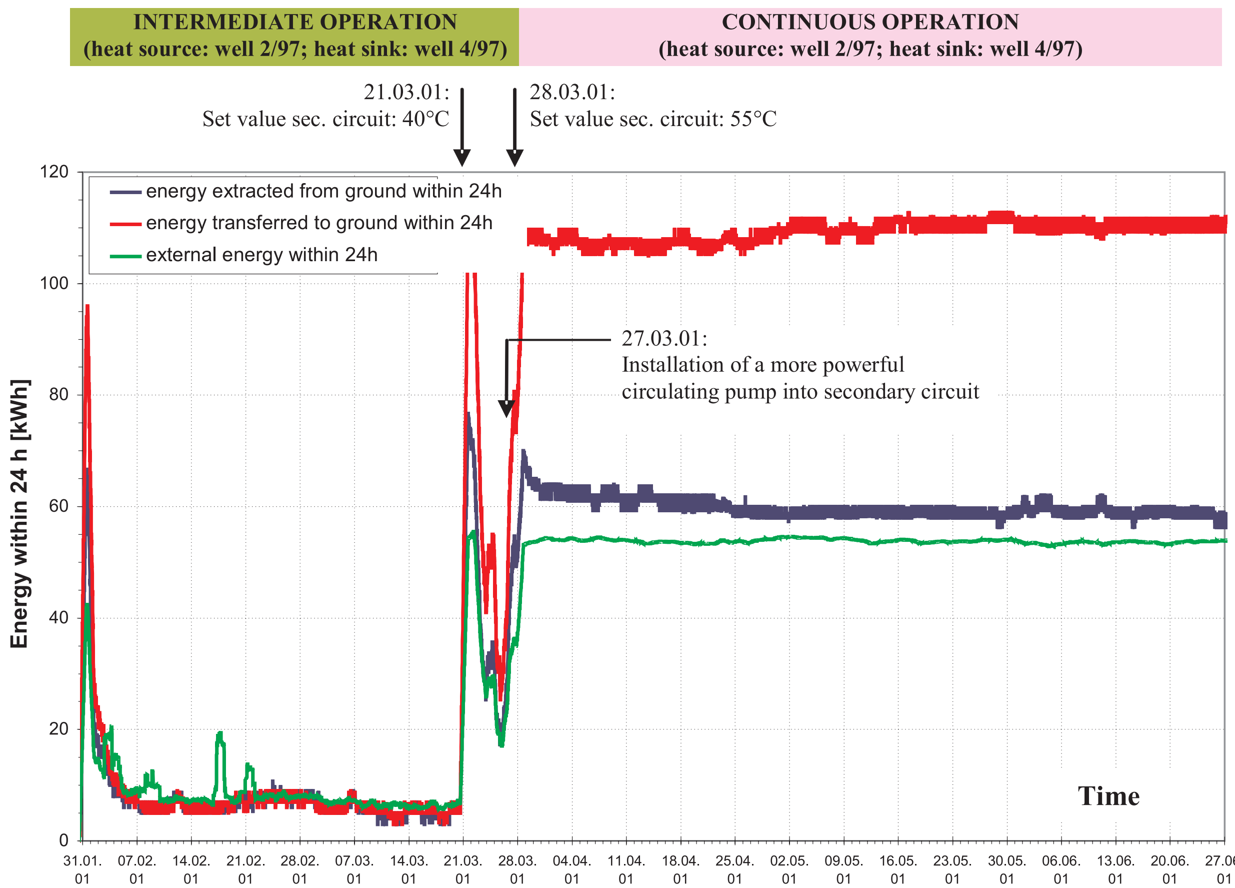


Figure 14. Measured energy within 24h from February to June 2001 (before system modification).

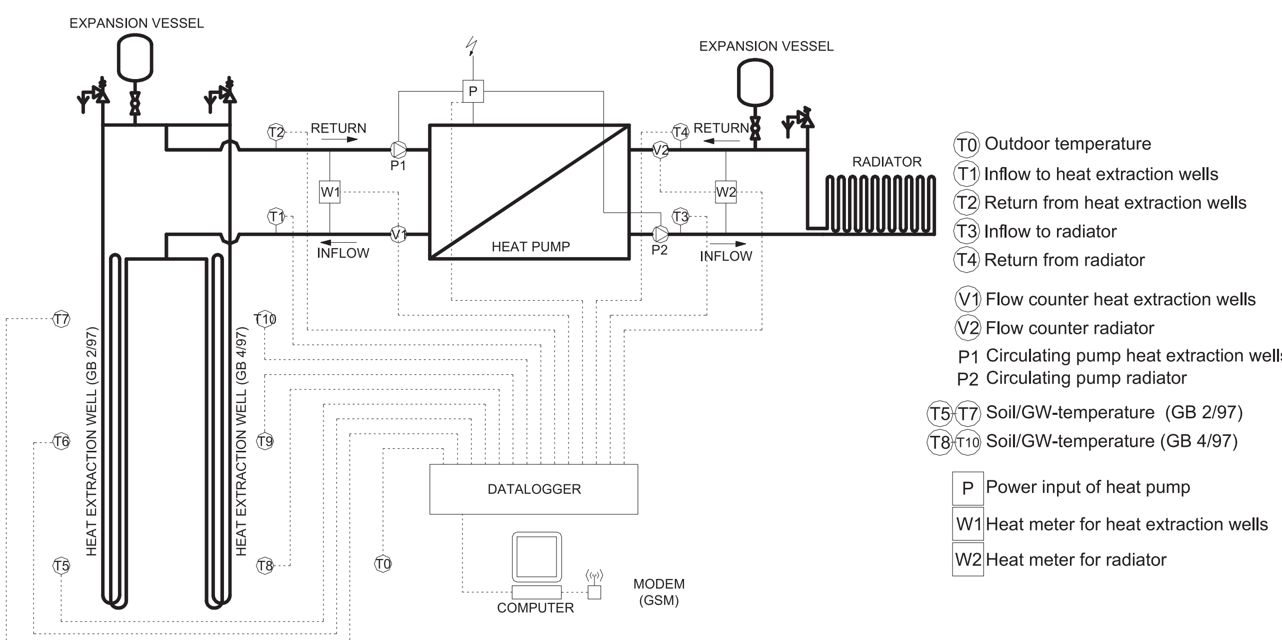


Figure 15. System modification of testing plant “Energy well H” with both GB2/97 and GB 4/97 as heat extraction wells. A second radiator serves as new heat sink that transfers heat to the outdoor air.

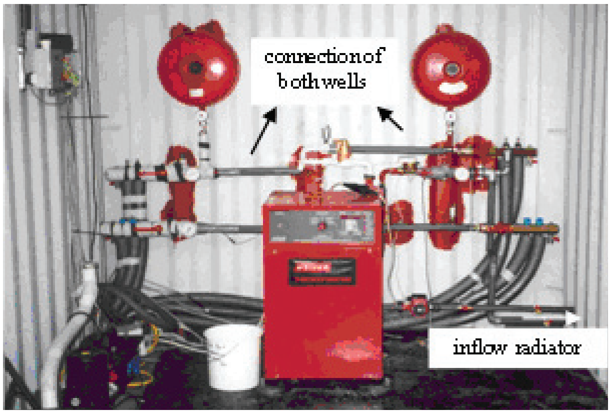


Figure 16. The testing plant "Energy well H" in a container on the construction site; details of Fig. 15.

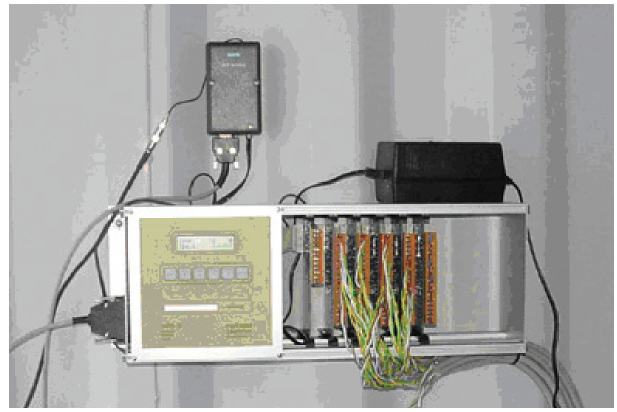


Figure 16a. Data-logger with GSM-module; detail of Figs. 15 and 16.

Fig. 19 shows that in this period the seasonal performance factor was in the range of about β = 2.4, whereby the performance factor of the *Carnot*-process was calculated to ε_{Carnot} = 6.6. This low performance factor confirmed that heat pumps of a too high coefficient of performance should be avoided.

At the end of April 2002 the system was modified again in order to investigate heat extraction from the energy well GB 4/97 only. Therefore the circuits to the well GB 2/97 were closed. Fig. 17 illustrates the regeneration process of this well after a long continuous operation period.

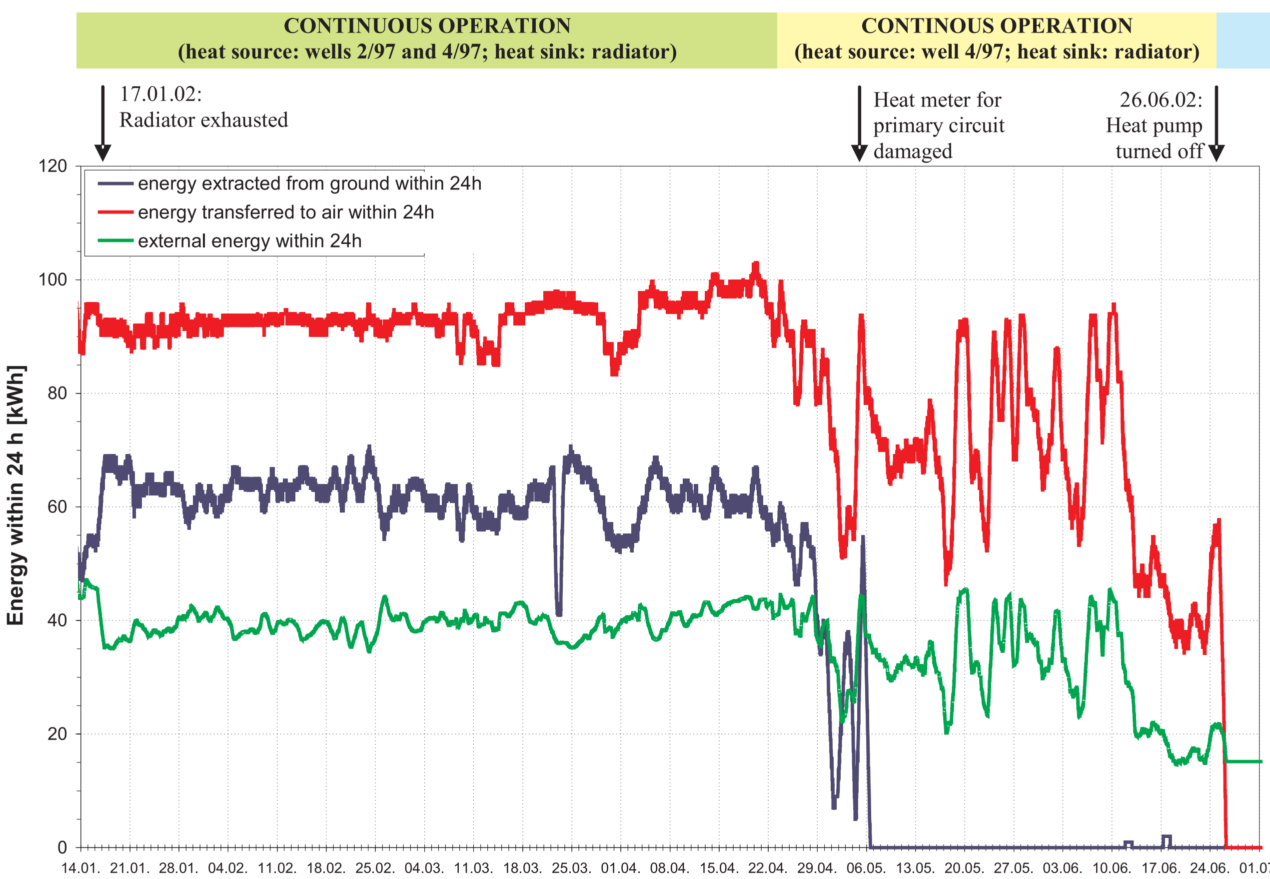


Figure 18. Measured energy within 24h from February to June 2002 (after system modification).

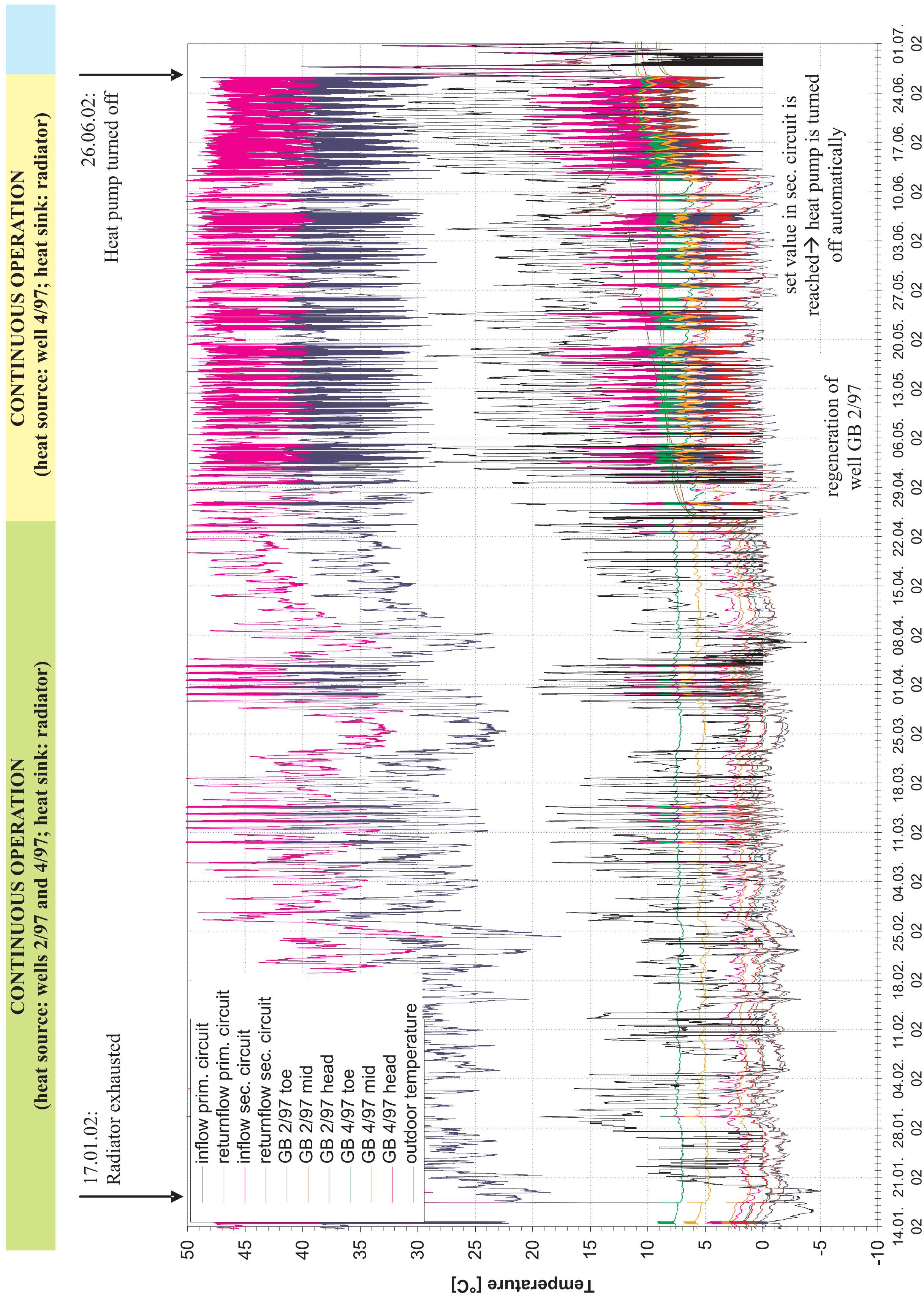


Figure 17. Measured temperatures from February to June 2002 (after system modification).

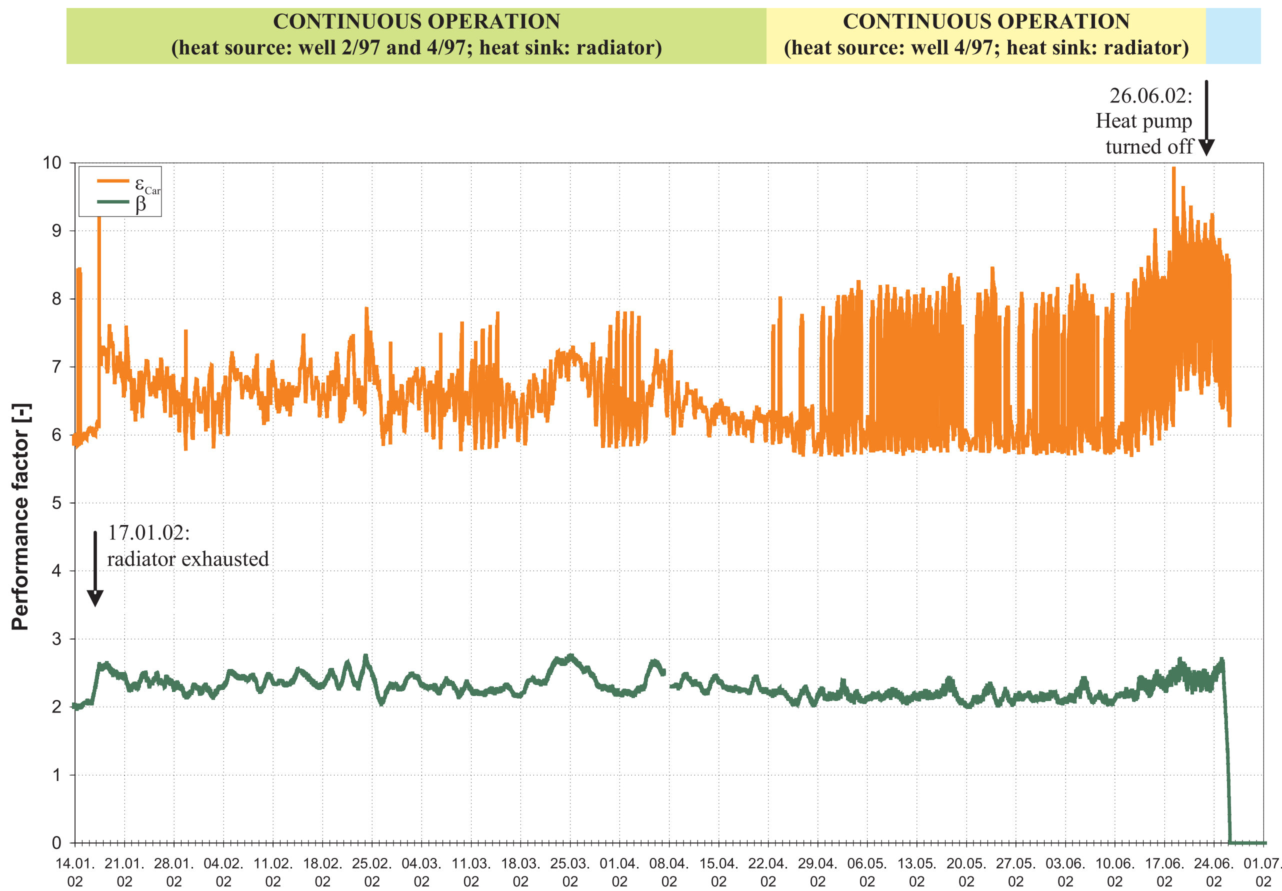


Figure 19. Measured performance factor from February to June 2002 (after system modification).

6.2 NUMERICAL SIMULATIONS COMPARED TO ANALYTICAL SOLUTIONS

An energy well is a vertical heat absorber of finite length embedded in a half-infinite soil body and it is a suitable model to prove all basic cases of heat conduction. For numerical simulations it is assumed that the temperature of the soil surface (half-infinite body) oscillates with a sinus function to simulate the annual temperature change. The temperature at the borders of the borehole is assumed to be periodically constant in order to calculate the maximum possible heat transfer (extraction and input, respectively).

A typical simulated temperature distribution is demonstrated in Fig. 20 representing the temperature field after five months of heat extraction. Different flux velocities of energy depending on the geometry and thermal soil parameters are indicated by the isotherms.

The accuracy of the numerical finite element model depends on numerous parameters, such as the refinement of the mesh and the polynomial order of the used elements. The basic cases 1 (semi-infinite body), 2

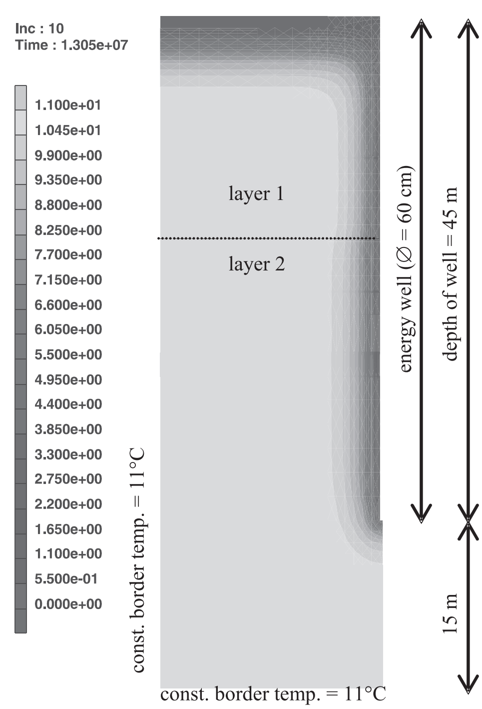


Figure 20. Temperature distribution around an energy well after 5 months of heat extraction.

(infinite body with cylindrical gap) and 3 (infinite body with spherical gap) in Table 1 can be used to simulate appropriately most of the commonly used absorber elements. With regard to the energy wells all basic cases interact: Case 1 refers to the ground surface, case 2 to the shaft interface of the well, and case 3 describes the spherical situation in the bottom of the well. Comparative calculations have shown that there are only minimal differences between the numerical and the analytical solutions as indicated in Fig. 21 for the example of Fig. 20. The corresponding parameters are given in Table 2. One of the results is that the soil temperature is influenced only to a depth of 7m at the maximum despite a simulated extreme energy flux in the wells.

Energy balances were also investigated with the numerical model. The simulation provided the power of extraction and the power of influx during a two-year simulation period for the 45 m deep test well. From Fig. 22 it can be seen that during the second heating period more energy could be extracted from the ground due to the energy influx in summer. These calculations can be also compared with measurements. Both calculations and measurements have resulted in a long-term extraction power of about 1.8 kW per well.

Table 1. Basic cases for heat conduction in soil

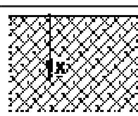
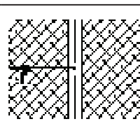
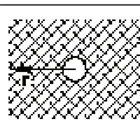
Basic case	Sketch	Differential Equation
1 Semi-infinite body		$\frac{\partial^2}{\partial x^2}\vartheta(x,t)=\frac{1}{a}\frac{\partial}{\partial t}\vartheta(x,t)$
2 Infinite body with cylindrical gap		$\frac{\partial^2}{\partial r^2}\vartheta(r,t)+\frac{1}{r}\frac{\partial}{\partial r}\vartheta(r,t)=\frac{1}{a}\frac{\partial}{\partial t}\vartheta(r,t)$
3 Infinite body with spherical gap		$\frac{\partial^2}{\partial r^2}\vartheta(r,t)+\frac{2}{r}\frac{\partial}{\partial r}\vartheta(r,t)=\frac{1}{a}\frac{\partial}{\partial t}\vartheta(r,t)$

Table 2. Exemplary parameters for calculating the basic cases of Table 1

Property	Value
Thermal conductivity λ	2.5 W/(M.K)
Density ρ	2,700 kg/m^3
Specific heat capacity c	800 J/(kg.K)
Temperature conductivity a	1.1574x10^{-6} m^2/s
Radius of cylindrical and spherical gap	0.3 m
Sudden temperature rise ϑ_S	25 K
Observed period t	a half year = 182.5 days

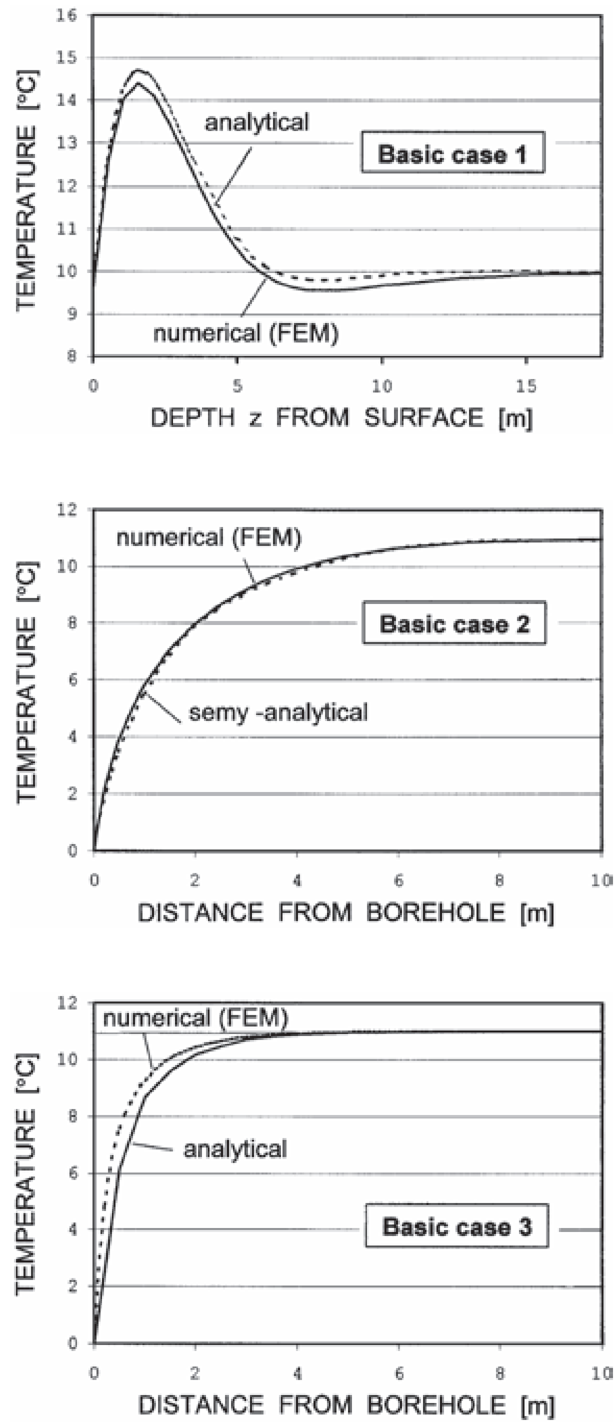


Figure 21. Temperature distribution at a certain time calculated with the FE-model (continuous line) and the analytical solution (dashed line) for basic cases 1, 2 and 3.

To sum up, parametric studies and comparative calculations have shown that both methods, numerical and analytical solutions, are suitable for thermal calculations. Complicated cases, however, can be only solved numerically.

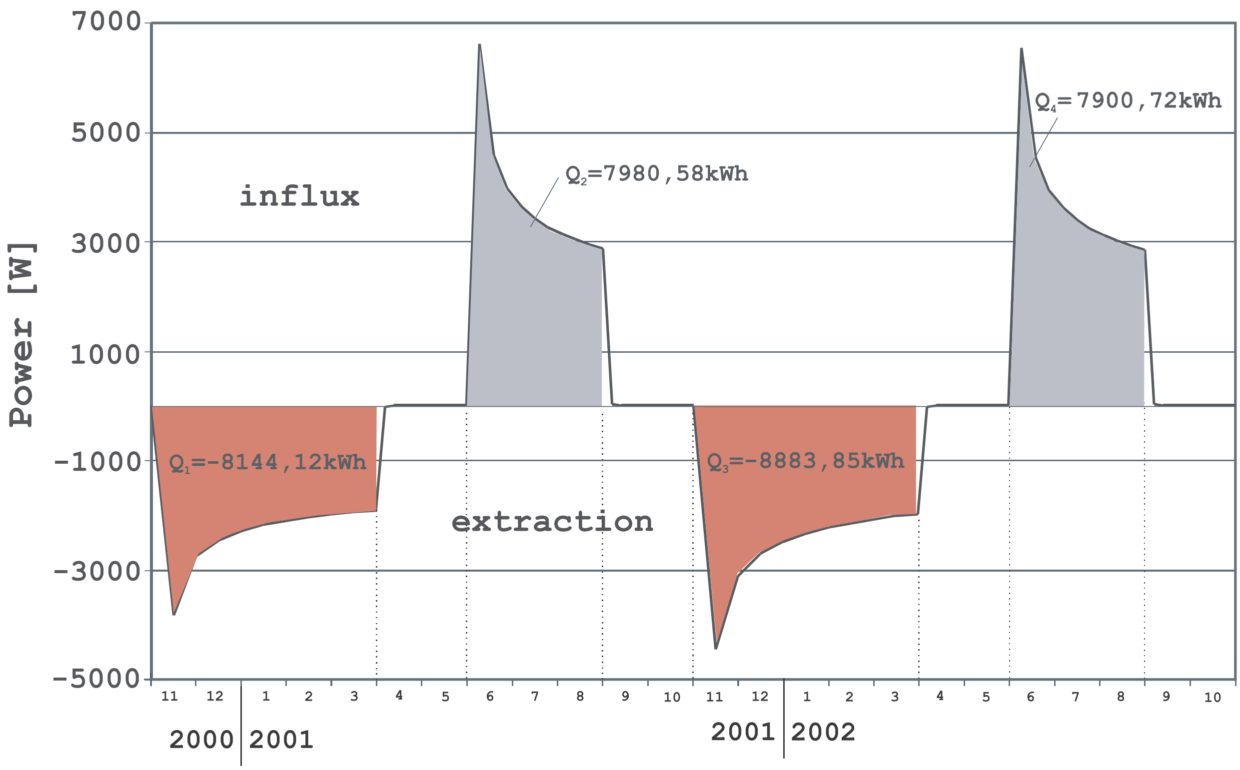


Figure 22. Results from FEM calculations for an energy well (example of Fig. 20).
The covered areas represent the extracted energy (-) and the input energy (+) over a period of two years.

6.3 OPTIMISED OPERATION

Fig. 17 demonstrates that an intermediate operation with short intervals produces significantly less energy than a permanent, continuous operation of the energy system. Furthermore, it could be confirmed that the performance factor of the plant drops with increasing temperature difference between primary and secondary circuit, especially if the performance of the heat pump is not adapted to the temperature difference. A too high capacity causes a too strong cooling of the heat transfer fluid.

The Carnot-process represents the ideal heat pump process and has theoretically the highest thermal efficiency of all circulating processes between two given temperatures. Its coefficient of performance is

$$COP_{Carnot} = \frac{T_{cond}}{T_{cond} - T_{evap}} \qquad (13)$$

where T_{cond} = temperature at condenser [K]

T_{evap} = temperature at evaporator [K]

When calculating COP_{Carnot} it should be considered that the evaporative temperature is by 3 to 5K lower than the outflow temperature of the heat source from the evaporator, and that the liquefaction temperature is at least 3K higher than the outflow temperature of the useable heat carrier from the liquefier. Consequently, the modified coefficient of performance of the Carnot-process becomes

$$COP_{Carnot} = \frac{T_{cond} + 3K}{(T_{cond} + 3K) - (T_{evap} - 5K)} \qquad (14)$$

Calculations based on the measured temperatures provided performance coefficients of $\varepsilon_{Carnot} \geq 6$. However, the real heat pump process usually achieves only about 55% of the performance coefficient of the Carnot-process due to significant compression losses, losses from friction etc.

This intensive heat extraction caused freezing in the discharge well, which should be usually avoided. Freezing increases the lateral pressure on the absorber pipes and may cause bulging. The measurements disclosed an increase in pressure caused by a constriction (necking) of the pipe. Such phenomena have been mainly observed in rather dense granular soils whereas in soft cohesive soil lateral soil displacement prevails. Freezing, therefore, strongly stresses the PE-pipes, reduces gradually their cross section and may eventually cause a full drop out of a ground heat exchanger or heat exchanger borehole. Consequently, pressure and temperature are the main parameters influencing serviceability and life-time of HDPE absorber pipes in energy wells. Contrary to that, absorber pipes embedded in concrete (energy piles etc.) keep nearly "unlimited" function.

6.4 BACK CALCULATION OF THERMAL PARAMETERS

The in-situ determination of thermal soil parameters illustrates the strong influence of freezing, which should be investigated in the research programme because improper operation (excessive heat extraction) may occur in practice. The back-calculation is based on the following project data:

- Length of bore hole: L_b = 45 m;
- Type and material of heat exchanger: double U-tube absorber (HDPE);
- Radius of borehole: r_b = 30 cm;
- Measurements from the beginning of April 2001 (continuous operation of the test well) to determine the effective thermal conductivity. The period from start of pre-operation until April 2001 comprises 2081 hours (see Fig. 23).

The mean temperature of the heat carrier fluid is:

$$T_m = \frac{T_{\text{inflow}} + T_{returnflow}}{2} \qquad (15)$$

A reliable interpretation of the measured data requires a time-temperature regression line after a certain period of operation (tmin). This is obtained from a "minimum-time" criterion using the following soil parameters:

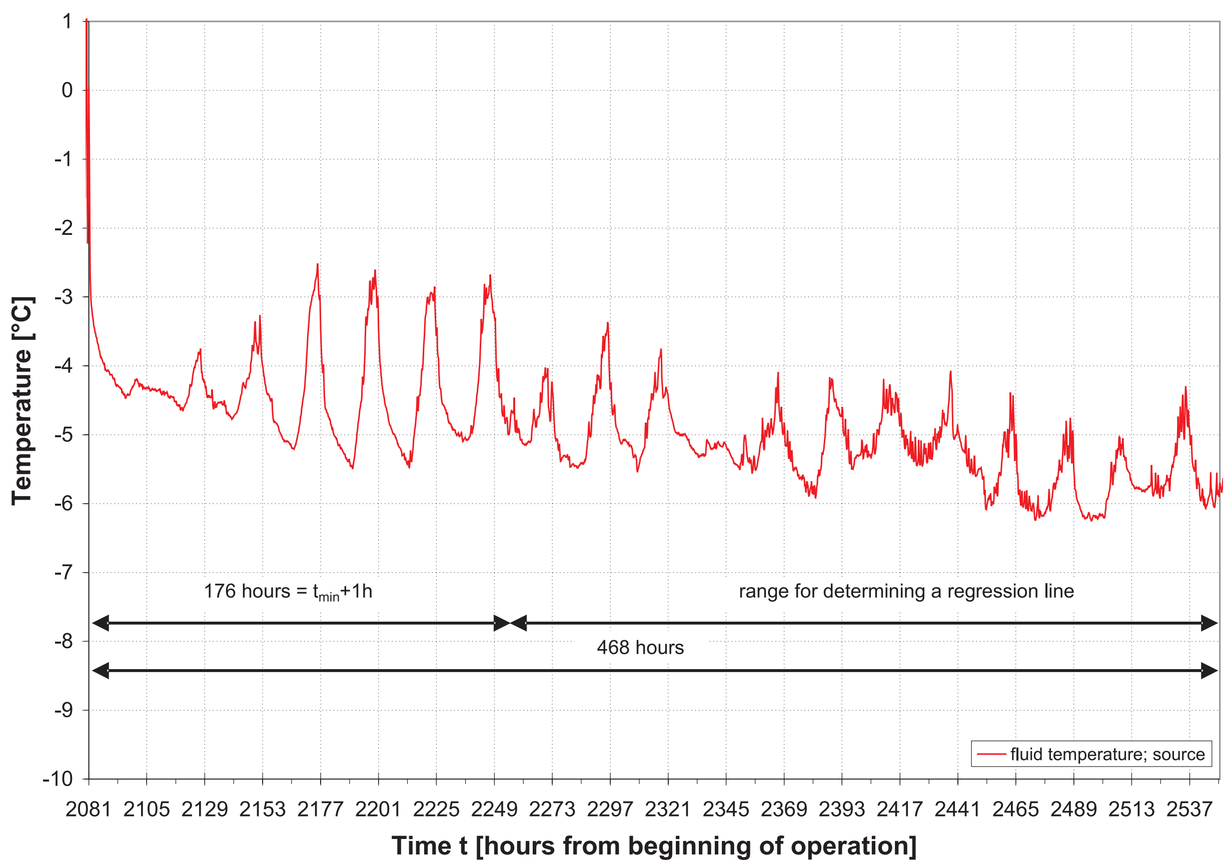


Figure 23. Mean heat carrier fluid temperature of the heat source. The temperature oscillation is caused by the outdoor temperatures. Also shown is the time range for determining a relevant regression line (see Fig. 24).

- Thermal conductivity: $\lambda_S = 4.0$ W/m K
- Density: $\sigma_S = 2800$ kg/m³
- Specific heat capacity: $c_S = 1200$ J/kg K

$\Big\}\ \sigma_S c_S = 3.36$ MJ/m³ K

The thermal diffusivity a_S is obtained from:

$$a_S = \frac{\lambda_S}{\rho_S c_S} = \frac{4.0}{3360000} = 1.19 \cdot 10^{-6}\ \text{m}^2/\text{s} \qquad (16)$$

The "minimum-time" criterion results in:

$$t_{\min} > \frac{5r_b^2}{a_S} = \frac{5 \cdot 0.15^2}{1.19 \cdot 10^{-6}} = 630000s = 175 \text{ hours} \qquad (17)$$

The regression line is derived from a time-temperature series of the daily mean temperature, whereby the temperature data starting one hour after the "minimum-time" (i.e. 176h) are used. On the abscissa the dimensionless time parameter $\tau = \ln(t)$ is drawn in a linear scale. As shown in Fig. 24, the inclination of the regression line results in $k = -1.02$, and the intersection with the ordinate is at $m = 0.62$. The intersection point with the ordinate lies in the zero point of the diagram and is therefore not shown in Fig. 24.

Calculating the effective thermal conductivity $\lambda_{S,eff}$ needs the extracted amount of heat. According to the measurements a total heat volume of $\dot{Q} = 2605$ W was extracted from the soil, leading to:

$$\lambda_{S,eff} = \frac{\dot{Q}}{4\pi k L_b} = \frac{-2605}{4 \cdot \pi \cdot -1.02 \cdot 45} = 4.52 \text{ W/(m K)} \qquad (18)$$

This high effective thermal conductivity (for comparison: concrete has a thermal conductivity of $\lambda_{concrete} = 2.1$ W/(m K)) was caused by the site-specific conditions and temperatures. Measurements disclosed that the temperature of the heat carrier fluid was about -5°C (and lower) for a long time. Because of this deep temperature the groundwater close to the heat exchanger started to freeze. Finally, a continuous groundwater flow created a big ice block around the absorber pipes. Later measurements, which were taken after heat extraction in order to investigate the thermal regeneration capacity of the ground, proved this.

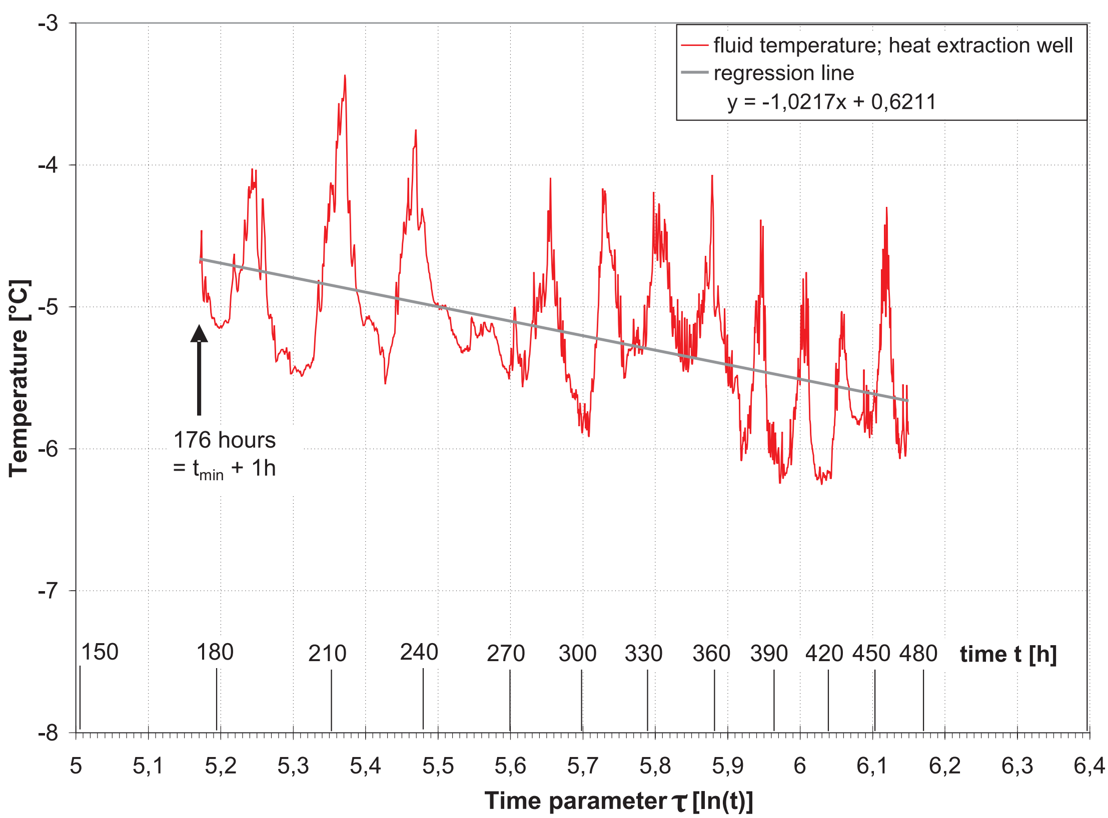


Figure 24. Mean temperature of the heat carrier fluid from the 176th hour until 486th hour after starting the test (Note: ln(176)=5.17 and ln(468)=6.15).

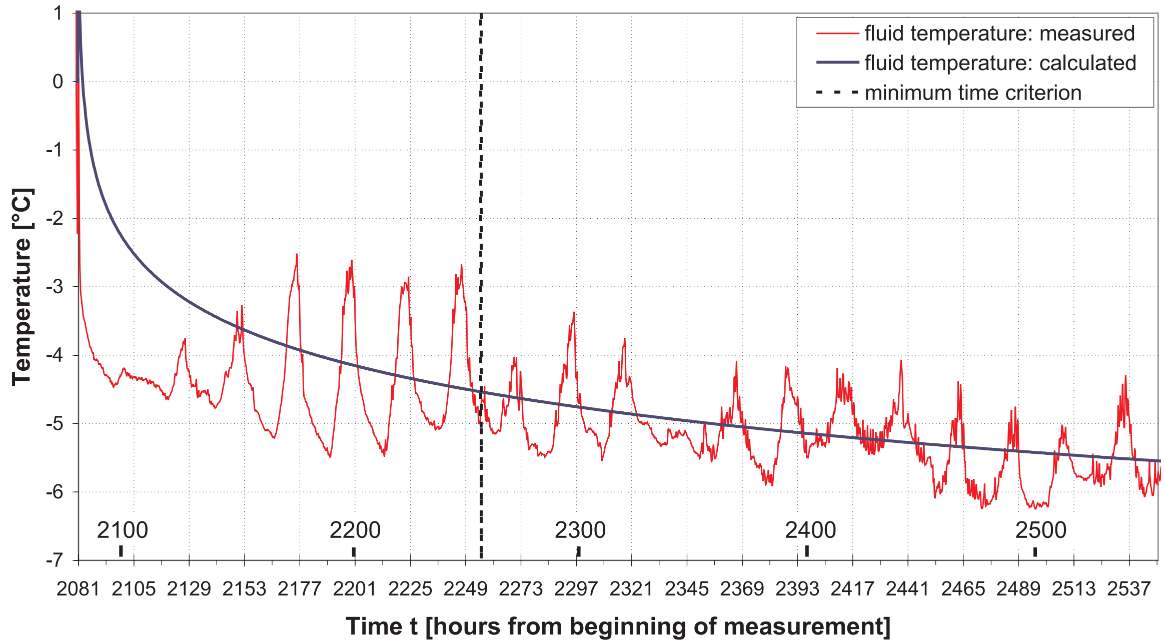


Figure 25. Measured and calculated (with R_b=0.19 K/(W/m)) mean temperature of the heat carrier fluid for the testing plant "Energy Well".

During freezing of water energy is extracted until the water becomes ice. This so called latent heat is the significant reason for the calculated high effective thermal conductivity: thermal conductivity of water λ_{water} = 0.56 W/(m K) and thermal conductivity of ice λ_{ice} = 2.23 W/(m K). In addition to that a groundwater flow results in a high effective thermal conductivity because of a continuous heat supply by convection.

The temperature loss from the borehole wall to the heat carrier fluid is described by the thermal borehole resistance which typically lies about R_b = 0.1 K/(W/m). It can be determined by a variation of t and T_m using equation (12) with the following parameters:

- Undisturbed temperature of the soil: T_s = T_0 = 11°C;
- Thermal conductivity: $\lambda_{S,eff}$4.5 = W/m K;
- Thermal diffusivity: a_S = 1.34 * 10^{-6} m²/s.

The thermal borehole resistance at the testing plant varied between 0.179 to 0.202 with an average value of R_b = 0.19 K/(W/m). This high value was due to the improperly excessive heat extraction that lead to freezing. Eq. (12) shows that this parameter depends on the mean temperature of the heat carrier fluid, which for its part fluctuates in relation to the outdoor temperature.

With the determined effective thermal conductivity and thermal borehole resistance the time-mean fluid temperature curve can be back-calculated analytically. In Fig. 25 both the calculated and measured values are shown.

Field tests and numerical simulations confirmed that there is a clear analogy between energy wells and hydraulic wells. The rate of pumping corresponds to heat extraction: The groundwater drawdown curve is analogous to the temperature change in the ground depending on the distance from the well, time, ground properties and on the pumping rate or extracted heat respectively.

Moreover, it could be found that energy extraction and sink wells should have a distance of at least 15 m. For 10 kW of usable energy about 1.5 to 1.8 m³/h of groundwater is required.

7 PROMOTION OF GEOTHERMAL ENERGY UTILISATUON

Early ecological energy planning for buildings can prevent in many cases costly refurbishment and renovation in the future. High-quality energy design involves not only heating and cooling (rooms, water) but also lighting.

Geothermal geotechnics offers a promising alternative to conventional heating/cooling systems, providing solutions to the challenges of today's energy policies. The targets for renewable energy and for energy buildings can be generally reached only by political measures.

- High taxes on fossil fuels are the most important prerequisite for energy saving and promotion of renewable energy sources.
- In order to promote the installation of thermo-active systems or other heating/cooling systems based on renewable energy, the economic incentives for private investors, house owners, companies, and also for public administrators to invest in renewable energy systems should be improved in many countries. Strong support by European Union policy is necessary.
- Legislation.
- Public grants.

Since January 2004 each person who wants to build a family house in Austria has received financial support by the local government only if they present an energy performance certificate with a low energy number. This number describes the energy consumption (provided by heating energy minus heating losses) and is expressed in kWh/m² and year.

Promotion by public funds is granted only if this energy number is smaller than 50 kWh/m² for each floor. At values less than 40, 30, 25, 20 and 15 kWh/m² the grant increases step by step.

However, if a building is heated/cooled by means of clean, renewable energy, for example by geothermal systems, the allowable limit value for energy consumption may be increased. The target of multidisciplinary innovation should approach heat-and-light systems combined with groundsourced or solar residual heating/cooling.

Thermo-active structures (including energy foundations and energy wells) are therefore very helpful in reaching this low energy number. Their installation is widely supported by politicians and media. Consequently, about 500 buildings with energy foundations or retaining/basement walls already exist in Austria. This philosophy is fully supported by Directive 2002/91/EC of the European Parliament and of the Council on the energy performance of buildings, which will come into force in the European Community on 4 January 2006 at the latest. Thus an energy performance certificate has to be presented if a building with more than 500 m² is sold or rented.

8 CONCLUSIONS

Global energy consumption is increasing tremendously. The "World Energy Outlook 2005" estimates that in 2030 about 16.5 billion oil units will be needed annually if the present energy strategies do not change globally. World supplies of fossil fuels are rapidly being depleted. Consequently, multidisciplinary efforts are needed to develop innovative building practices using renewable energy, including new energy storage technologies. Near-surface geothermal and deep geothermal energy, solar photovoltaic and solar thermal energy, and wind energy are promising alternatives (like conventional hydropower energy). Optimum economical efficiency and environmental protection are gained in most cases by an 'energy mix' from different sources. Local climate and ground properties, technological level, the specific use of a building, seasonal fluctuations, environmental conditions and actual energy prices are the main influencing parameters.

Integral planning and balancing of buildings means considering the technical, economic, aesthetic and ecological aspects. An integral design, therefore, is always a sustainable design too, and it requires multi-objective optimisation. Balancing refers to materials, energy, emissions, waste water, waste/rubbish and its disposal or recycling, costs (investment, maintenance, demolition), and life cycle.

Both thermo-active ground structures (energy foundations, retaining walls, tunnels) and energy wells are the geotechnical contribution to renewable energy production. A significant advantage of such systems is that they are installed within elements that are already needed for statical/structural or geotechnical reasons. Hence no additional structural or hydraulic measures are required. Foundations, walls (below and above ground) and tunnel linings can be used directly for the installation of absorber pipes for heat exchange. Wells for groundwater lowering may also be simultaneously used for heat extraction/storage, thus becoming energy wells. This innovation is a key improvement over the conventional geothermal methods such as (deep) borehole heat exchangers or near-surface earth collector systems. At a certain depth, ground temperature remains widely constant throughout the year (e.g. 10–15°C below 10–15 m in most European regions), and a heat exchanger allows it to be used as a heat source in winter and for cooling in summer.

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