Measurements and Design Calculations for a Deep Coaxial Borehole Heat Exchanger in Aachen, Germany

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This study aims at evaluating the feasibility of an installation for space heating and cooling the building of the university in the center of the city Aachen, Germany, with a 2500 m deep coaxial borehole heat exchanger (BHE). Direct heating the building in winter requires temperatures of 40°C. In summer, cooling the university building uses a climatic control adsorption unit, which requires a temperature of minimum 55°C. The drilled rocks of the 2500 m deep borehole have extremely low permeabilities and porosities less than 1%. Their thermal conductivity varies between 2.2 W/(m·K) and 8.9 W/(m·K). The high values are related to the quartzite sandstones. The maximum temperature in the borehole is 85°C at 2500 m depth, which corresponds to a mean specific heat flow of 85 mW/m² to 90 mW/m². Results indicate that for a short period, the borehole may deliver the required temperature. But after a 20-year period of operation, temperatures are too low to drive the adsorption unit for cooling. In winter, however, the borehole heat exchanger may still supply the building with sufficient heat, with temperatures varying between 25 and 55°C and a circulation flow rate of 10 m³/h at maximum.

1. Introduction

Before 2004, RWTH-Aachen University planned to install a deep borehole heat exchanger (BHE) to use geothermal energy for heating and cooling of its new “SuperC” student service centre. In summer time the large roof should provide shade, while in winter the sun should irradiate the glass-front, passively heating the building. Solar energy on the roof should generate the electricity for driving the pump of the borehole heat exchanger.

The deep coaxial borehole heat exchanger is a closed system where cold water flows down in the outer pipe, heats up, and rises in the inner pipe. The borehole RWTH-1 of the RWTH-Aachen University reached a depth of 2500 m and was intended to provide the thermal power for heating and cooling as a BHE. The temperature of the outlet inner pipe should have a temperature of at least 55–80°C over a period of 30 to 40 years to drive the climate control adsorption chiller during summer time. In winter the geothermal water will heat directly the building.

The borehole was drilled in spring 2004 before construction of the building (Figure 1). The site is located in the urban center Aachen at a distance of about 500 m from the “Imperial Cathedral,” frequently referred to as the final resting place of Charlemagne, and its vicinity of the famous thermal springs of 60°C.

The borehole penetrates Carboniferous and Devonian rocks Northwest of the Variscan front of the Aachen Overthrust, the large south-east dipping fault separating the Eifel Mountain from the foreland. The rocks are dominated by series of interlayered sandstones, siltstones, and shales. Organic shales and thin coal layers were drilled locally in the upper 1016 m as part of the Carboniferous deltaic cycles. Carbonate bearing rocks only occurred in the underlying...
Upper Devonian series between 1016 m and 1440 m depth. The deeper parts of the borehole are dominated by shale and sandstone series of Lower Devonian age [1].

During drilling, cutting samples from the drill bit (Figure 2) were collected at a depth interval of 1 m. Core samples were available for 3 sections (1391.5 m–1515.7 m, 2128.2 m–2142.8 m, and 2536.8 m–2544.5 m) with a total length of 150 m. Petrophysical and temperature logging followed the drilling operation. Only one out of 81 attempts to sample fluids at selected promising locations was successful. This yielded too little fluid for proper analyses. Accordingly no fluid loss or inflow was observed during drilling.

The most important required information of the rocks to simulate the long-term performance of a deep borehole heat exchanger is the thermal conductivity [2], others being specific heat capacity, porosity, permeability, and density.

This study aims at evaluating the feasibility of such an installation for space heating and cooling. In particular, the clarification of operational and performance characteristics (also in the long term) is attempted.

2. Measurements of the RWTH-1 Borehole

2.1. Laboratory Measurements. For measurements of matrix density and thermal conductivity, 57 cutting samples were selected at a regular interval of 50 m, at depths considered to be interesting due to variations in the geophysical logs.

Matrix density $\rho_m$ of the cuttings (Figure 3) is measured with a helium gas pycnometer (Accupyc by Micromeritics [3]). The device calculates the matrix density from the amount of helium saturating the pores of the dried sample. The density varies from 2640 kg/m$^3$ to 2840 kg/m$^3$ with a mean of 2780 kg/m$^3$. The accuracy of the device is on the order of 1 kg/m$^3$ –0.1 kg/m$^3$. Bulk density could not be measured because only cuttings were available. The cuttings represent only the most stable, that is, massive parts of the drilled host rock.

Density was measured on cores with a multisensor core logger and on some of the cores with helium gas pycnometer. The multisensor core logger uses a gamma radiation source and measures the transmitted gamma radiation intensity. Density is calculated from the absorbed gamma radiation. The process requires careful calibration. Density by helium
gas pycnometer varies between 2391 kg/m$^3$ to 2897 kg/m$^3$ with a mean of 2820 kg/m$^3$. Gamma density varies between 2576 kg/m$^3$ to 3233 kg/m$^3$ with a mean of 2830 kg/m$^3$.

Thermal conductivity of the cuttings (Figure 3) was determined using a TK04 needle probe (built by TeKa Geophysical Instruments) on a cuttings-water mixture. Thermal conductivity of the cuttings varies from 2.2 W/(m·K) to 8.9 W/(m·K) with a mean of 3.8 W/(m·K). The high values can be explained by a high percentage of quartz. Quartz-cemented clean sandstones are frequently observed in the deeper part of the borehole below 1895 m.

Thermal conductivity of the cores was measured using an optical thermal conductivity scanner (TCS), build by Lippmann & Rauen GbR [4]. The thermal conductivity scanner moves a source of defined thermal radiation along the sample and calculates the thermal conductivity of the sample with an error of 3% from the differences of temperatures measured before and after irradiation. The thermal conductivity of the cores varies between 2.3 W/(m·K) to 4.9 W/(m·K) with minimum and maximum values of 2.0 W/(m·K) and 5.9 W/(m·K), respectively. The arithmetic mean is calculated to be 3.02 W/(m·K), the geometric mean to 2.99 W/(m·K). See [5] for detailed descriptions of the measurements.

Further properties measured on the cores with the multisensor core logger are the density, porosity, magnetic susceptibility, sonic velocity, and the natural gamma radiation. Due to the low porosity, no differences have been detected between the properties of saturated and dry core samples.

Porosity $\phi$ of three selected core samples was calculated from the amount of water saturating the sample after evaporation: porosity is almost zero with a mean of 0.012%.

2.2. Borehole Measurements. Different temperature logs are shown in Figure 4. The first temperature measurements of April 2005 show higher temperatures at the upper half of the borehole and lower temperatures at the lower half of the borehole compared to the measurements of June 2006. This is probably caused by the influence of the drilling fluid; it warmed the upper part and cooled the lower part of the borehole during drilling. At the most upper 50 m, a temperature anomaly occurs in both temperature curves. This is unusual, but could be caused by losses of warm drilling water, in the more permeable sediments at the top of the borehole.

No density log was measured because the required radioactive source could not be used in the center of the city Aachen.

Sonic velocity $V_p$, electric resistivity, and gamma logs are shown in Figure 5. The logs are used for the geological interpretation in Section 2.3. The gamma log indicates the content of clay of the rocks. Therefore, this log is used in Section 2.4 to determine (i) the thermal conductivity and (ii) the radiogenic heat generation.

$V_p$-logging data were compared with $V_p$-core data (Figure 6: black line versus blue line of “log/Core $V_p$”). After the correction of a 1.2 m depth shift (caused by their upward travel time) and the use of a sliding window average on the core data (blue line of “log/Core $V_p$”), in situ and laboratory data come to an excellent fit. The data fits best in the carbonate bearing section down to 1440 m and in the deepest part of core section 1. Between 1460 m and 1490 m slight offsets can be observed, which might be attributed to bedding anisotropies. Effects of a $V_p$ lowering by pressure relief are not observed for the RWTH-1 cores.

2.3. Log Interpretation. For the logging data, the profile is subdivided into three larger units (Figure 5). These correspond to the main stratigraphic units of

(I) lower Carboniferous deltaic cycles,

(II) upper Devonian siltstones, with claystones, carbonatic sandstones and limestones;

(III) rather homogeneous sand- and claystone successions of Lower Devonian age.

In unit (I), which is located between 242 and 1016 m, ten sedimentary cycles of coarsening up sequences were detected. GR-anomalies of up to 200 API can be attributed to thin claystone layers. The anomalies are caused by uranium, which has accumulated over time in sediments enriched with organic material. Coal beds and organic clays are restricted to the upper eight cycles down to a depth of about 900 m (zone 1). The coal-free two cycles between 900 and 1016 m can be correlated with the Walhorn Schichten (zone 2).

The carbonate bearing unit (II) reaches down to 1440 m and can be separated in an upper siltstone dominated section (zone 3), which might be attributed to the Condroz formation and a lower silt and claystone dominated formation (zone 4) belonging to the Upper Famennien shists. In relation to unit (I) potassium is relatively enriched, which indicates micas and/or K-feldspar occurring as rock forming minerals. At the bottom of unit (II), a 6 m thick limestones layer was drilled, which could be dated slightly younger than the *Cheiloceras* Kalk [10], known as a prominent stratigraphic marker in the region. A significant change in the paleo-environment is indicated by the spectral-gamma logs at the base of the *Cheiloceras* Kalk, which marks the boundary
between unit (II) and unit (III). Below this boundary thorium is strongly enriched relative to uranium (zones 5, 6, and 7). This indicates an abrupt change from marine to terrestrial sedimentary environment. After biostratigraphic investigations these underlying terrigenous rocks are formed in the Lower Devonian [10]. This means that rock series, well known from the northern Eifel mountains, such as the Frasnes shists and the limestone units of the Upper to Middle Devonian Massenkalk are completely missed in the borehole. This is also the case for the Carboniferous Kohlenkalk formation, which is missing between unit (I) and unit (II).

Porosity is very low in the drilled paleozoic rocks. Log responses primary reflect variations in rock composition. P-wave velocity varies between 3.5 km/h in coal layers/organic shales and up to 7.0 km/s in limestones. The sand-, siltstones, and shales have a small value range between 4.5 and 5.7 km/s (Figure 7(a)). The \( V_p/V_s \) ratio differs significantly between the carbonatic rocks of unit (II) and the quartz dominated sandstones of unit (III) (Figure 7(b)). In agreement with literature references [11], limestones have high \( V_p/V_s \) ratios of up to 1.9, and the \( V_p/V_s \) ratio of quartz-rich rocks is lower than 1.7.

The resistivity log reaches values of up to 1000 ohmm in carbonates and quartz-cemented sandstones, while organic shales have resistivities lower than 100 ohmm. Cross-plotting \( V_p \) versus resistivity separates carbonates and organic shales from sandstones, silts, and claystones. The most distinct separation of unit (II) is given by the cross-plot of the potassium log K versus \( V_p \) (Figure 7(c)). The distribution of radioactive elements is strongly varying within the drilled rocks. This is especially the case for the shales and siltstones (Figure 7(d)) and is attributed to different clay mineral associations. After [13], Th/K ratios of the rock units (I) and (III) shales give hints to an illite dominance, while the lower ratios in unit (II) are indicative of mica and glauconite.

Core and log data were compared with the petrographic core descriptions [1]. In some cases petrophysical property variation follows the optical subdivision. This is valid for the carbonate bearing rocks and the thin sandstone interlayers. The separation made petrographically for the shales and siltstone cannot be constrained by the petrophysical data. This is because petrographically separation is guided by optical markers, such as colour and bedding changes.

### 2.4. Log-Derived Thermal Properties

It is not possible to measure thermal conductivity directly in the borehole, so an approach to determine thermal conductivity from the existing logs had to be found. The volume content of clay was derived from the contribution of potassium to the entire gamma radiation.

As described in the previous section, the borehole was divided into 7 zones (see Section 2.3).
Figure 6: Petrophysical core data (right) and on the left borehole log data (left) for the RWTH-1 borehole; (i) on the right, dots indicate the core measurements and the black lines are sliding window average of the core measurements; (ii) on the left, the black lines are borehole logs and the blue line shows the sliding window average of the core measurements. Colors indicate rock type according to the petrographic core description [1, 7–10].
Figure 7: Cross-plots of logging parameter separated for seven depth intervals. Green colours indicate the carbonatic unit (II), which is differing in the log properties from the siliciclastic sediments of unit (I) and unit (III) (brown and orange colours).

Due to the paleoenvironment and postsedimentary processes, the relation between the natural gamma activity and the relative clay volume differs between these zones. This segmentation enabled deriving a continuous thermal conductivity profile over the entire depth of the borehole by using the natural gamma log for each individual zone and calibrating it with the thermal conductivities measured on the cores and cuttings [5].

Compressional wave velocity and potassium contribution to natural gamma radiation were used to identify 7 zones of individual definitions of 100% clay. Assuming clay as the only source of relevant potassium radiation, 0% clay was allocated
Figure 8: Thermal conductivity TC AM (arithmetic mean) and TC GM (Geometric mean) and heat generation A derived from volume fraction based on total (GR) and spectra (K, U, Th); colors indicate different zones of the borehole.
to the lowest overall value. Identifying a thermal conductivity \( \lambda_1 \) on the scale of clay with the clay content and a thermal conductivity \( \lambda_2 \) on the scale of quartz with the rest of the rock yields a thermal conductivity \( \lambda_{\log} \) for the logging point. The log has a vertical resolution of 0.076 m and the values were smoothed over an interval of 2 m. To calculate thermal conductivity, the arithmetic (AM) and the geometric (GM) means were used:

\[
\lambda_{AM} = \lambda_1 V_{\text{clay}} + \lambda_2 (1 - V_{\text{clay}}),
\]

\[
\lambda_{GM} = \lambda_1^{V_{\text{clay}}} \lambda_2^{(1-V_{\text{clay}})}.
\]

For each previously identified zone, individual thermal conductivities were assigned to the contents in clay and the remaining rock. For each value measured on a sample, the corresponding log value was identified. The calculated \( \lambda_{\log} \) were matched to the measured ones by varying \( \lambda_1 \) and \( \lambda_2 \) [5]. This resulted in thermal conductivity logs (Figure 8).

(i) “TC AM” is based on the arithmetic mean of \( \lambda_{\log} \) calibrated by minimizing the variance between \( \lambda_{\log} \) and the measured values.

(ii) “TC GM” is based on the geometric mean of \( \lambda_{\log} \) calibrated by minimizing the minimum square deviation between \( \lambda_{\log} \) and the measured values.

Furthermore, a continuous heat production profile over the entire hole borehole depth was derived from the sonic log [14, 15] and from the spectral gamma log [16]. The results are shown in Figure 8.

3. Numerical Cylindrical Model

The Finite Difference (FD) numeric simulation tool SHEMAT (Simulator for HEat and MAss Transport) [17] was used to examine the effects of various operating and design parameters on the outlet temperature and the thermal power of the borehole heat exchanger.

Due to the fact that the permeabilities are very low and no natural groundwater flow was detected, a cylindrically symmetric model could be used. Because of the symmetry, only a 2D grid is required (Figure 9). Constant material properties zones are specified for each grid block. The different geological property zones are indicated on the right side after [1]. The different properties zones of the borehole heat exchanger are based on the geometry of the borehole heat exchanger shown on the left side of Figure 9. The borehole heat exchanger has four casings of different lengths. The total 2D grid model comprises a cylinder with a radius of 99.5 m and a depth of 2973.5 m. The geologic zones are assumed to be horizontal because of the small inclination of the layers relative to the borehole of about 10°.

Fluids and heat flows are calculated across the interfaces separating the blocks (staggered grid approach).

The cooling effect of a single borehole heat exchanger has been shown to affect only a volume of about 10 m radius around the borehole [2]; therefore the radial extension is more than sufficient. A minimum cell size of 5 mm was used in every zone of special interest, (i.e., inlet, outlet, and the casing) due to the required high accuracy at these locations. Grid size of the transition zones from the borehole to the surrounding rocks is increasing size by a factor of 1.5 resulting in a maximum cell size of 25 m for the remaining cells. The number of cells amounts to \( 91 \times 201 = 18291 \) cells. Each calculation step required more or less 1 second. Figure 9 shows the model in comparison to the geologic profile. The lithological column was simplified to units of 25 m (maximum cell size). The radii and depths of the casing as well as the changes in lithology are well represented.

3.1. Model Parameters. Rock permeability in the model was set to zero because of the extremely low porosities and the lag of water inflow during fluid sampling. The flow field in the inner pipe and between the inner and the outer pipes is completely defined by a fixed volume flow rate. Thus, no permeability is required for its calculation.

Since no layers with high specific heat capacity are present, an average value of the specific heat capacity of; 2.2 MJ/(m\(^3\)·K) ± 20% was used for the surrounding rocks (Figure 9) in the simulations [18, 19]. The three outer pipe steel casings (Figure 9: (5)) have a specific heat capacity of 3.51 MJ/(m\(^3\)·K). The specific heat capacity values of the cementation are 1.4 MJ/(m\(^3\)·K) for the insulating cementation till a depth of 1025 m, 1.58 MJ/(m\(^3\)·K) for the heat conducting.
cement from a depth of 1025 m till the final borehole depth, and 1.65 MJ/(m$^3$K) for the normal cement.

Thermal conductivity of the model cells varies with depth according to the averaged thermal conductivity of determined log (see Figure 8). The inner pipe, dividing the cold water flowing down from the hot water flowing up, needs to be insulated and has a realistic thermal conductivity of 0.1 W/(mK) if not mentioned otherwise. The outer pipe has a thermal conductivity for steel of 50 W/(mK) (Figure 9). The values of the cementation were given by Karat: 0.52 W/(mK) for the insulating cementation, 2.02 W/(mK) for the heat conducting one, and 1.21 W/(mK) for the normal one. Based on the logging data of the cementation, a perfect backfilling could be assumed [5].

As shown in Figure 8, the heat generation $A$ is smaller than 3 $\mu$W/m$^3$ and an average only of about 0.5 $\mu$W/m$^3$ and is therefore neglected in the model.

Based on measurements [20] a constant surface temperature of 10.35°C is used as the upper boundary condition of the model.

A constant specific heat flow is set as bottom boundary condition. It was varied until the steady-state bottom borehole temperature of the model reached the measured bottom borehole temperature of about 79°C. Later temperature log showed a bottom borehole temperature of about 85°C, which is not used in the simulations. This results in a specific heat flow of 85 mW/m$^2$–90 mW/m$^2$.

The temperature of the injected water in the model was set to 40°C, according to the expected design parameters of the climate control system.

A specific heat flow of 85 mW/m$^2$–90 mW/m$^2$ is far more than the German average of 69 mW/m$^2$ [21] and still exceeds the 72 mW/m$^2$ measured at the nearby borehole Konzen [22]. On the other hand, values of 110 mW/m$^2$ at a depth of 1312 m and above 90 mW/m$^2$ between 1791 m–2201 m were determined for the boreholes Peer and Soumagne [23]. While the borehole RWTH-1 is located about 500 m to the north of the Aachen thrust fault and East from the normal fault, Konzen lies 15 km to the south-east and to the south of the Aachen thrust fault, peer is 52 km to the north-west and to the north of the Aachen thrust fault, and Soumagne is 20 km to the south-west of the thrust fault.

A large 3D model of the Aachener region (40 km $\times$ 40 km) [24] shows that areas with thick Westphalian coal bearing layers are indicated by low specific heat flow (0.06 mW/m$^2$). At the borders of these low conductivity layers, there is a lateral heat flow corresponding to a lateral variation in temperature gradient. This effect becomes smaller with distance from the boundary of the coal layers. Furthermore, the hanging walls of the fault systems show increased specific heat flow due to uplift and erosion, while the foot walls show decreased specific heat flow due to downwarping and sedimentation. This results in horizontal heat flow at the normal faults or the overthrust faults. RWTH-1 is situated close to the crossing of both, the overthrust and the normal fault. At the other side of these faults, low conductive Westfalian coal bearing layers are absent or very thin, so this could cause a "local" higher specific heat flow at the RWTH-1.

3.2. Simulations and Results. Here we describe and discuss the simulations and resulting production temperature $T_{\text{out}}$ of the borehole heat exchanger and the time interval for which production temperatures greater than 55°C are available for the climate control unit.

Time step size has a great effect on the duration of a simulation and its accuracy. Greater time steps underestimate fast changes in temperature; therefore, simulations of cycled operations require short-time steps for sufficient accuracy. This results in extremely large computing times (weeks).

3.2.1. Effects of the Thermal Conductivity of the Inner Pipe. The thermal conductivity of the inner pipe $\lambda_{\text{pipe}}$ has a significant influence on the production temperature $T_{\text{out}}$ and the associated thermal power $P_T$. In general, the importance of the insulation increases as the volume flow rate decreases. This effect is due to the longer time available for heat transfer from the water in the inner to the outer pipe.

As shown in Figure 10, with a flow rate of 4 m$^3$/h, a decrease from 0.005 W/(mK) to 0.0001 W/(mK) insulation results in an increase in the maximum production temperature $T_{\text{out}}$ of less than 2 K; that is, 0.005 W/(mK) is the next to optimum value. On the other hand, an increase to 0.05 W/(mK) reduces the time $t_{(T_{\text{lim}}<55^\circ\text{C})}$ in which $T_{\text{out}}$ is greater than the required temperature 55°C. According to [25], GRP-pipes usually have a conductivity of 0.36 W/(mK). At Weggis (Switzerland), a double-walled steel pipe with a maintained vacuum of 0.02 MPa is in use. Its minimum thermal conductivity $\lambda_{\text{pipe}}$ is quoted to be 0.09 W/(mK) [26]. Simple state-of-the-art GRP-pipes have a thermal conductivity on the order of 0.36 W/(mK). On the other hand, even with the best available insulation with a thermal conductivity $\lambda_{\text{pipe}}$ of about 0.1 W/(mK); therefore, temperature losses of 19%–31% occur. Therefore, as shown in Figure 10, only insulation less than 0.1 W/(mK) is sufficient to maintain the required temperature for the climatic control unit. As shown in Figure 10, in case of a realistic insulation of 0.1 W/(mK), the production temperature falls below the required minimum of 55 already after a continuous operation time of 1/2 day.

3.2.2. Effects of the Volume Flow Rate. The water in the borehole heat exchanger may circulate with different flow rates $F$ (m$^3$/h). The residence times of the water in the inner pipe and the corresponding total circulation times are 1.0 and 11.7 h for a flow rate of 10 m$^3$/h and 1.9 and 23.4 h for a flow rate of 5 m$^3$/h. Flow rates $F$ are directly related to the thermal power $P_T$ of the borehole heat exchanger by

$$P_T = c_{\text{pw}} \rho_w F_w (T_{\text{out}} - T_{\text{in}})$$

with $c_{\text{pw}}$ being the heat capacity of the water, $\rho_w$ the density of the water, and $T_{\text{out}}$ and $T_{\text{in}}$ the inlet and outlet temperature of the borehole heat exchanger, respectively. To see the effect on the outlet temperature, several volume flow rates were simulated for a continuous operation: 1 m$^3$/h, 4 m$^3$/h, 6 m$^3$/h, and 10 m$^3$/h. For this an insulation of 0.01 W/(mK) is assumed which is even 1/10 better than the present realistic thermal conductivity of the inner pipe.
As shown in Figure 11, even with this insulation of 1/10 of the present best insulation, the production temperature falls below the required minimum of 55°C if flow rates increase. After 5 days of continuous operation, the corresponding temperatures and thermal powers are about 52°C, 57°C, 60.5°C, and 61°C and 120 kW, 110 kW, 90 kW, and 20 kW, respectively.

3.2.3. Effect of the Heat Capacity of the Inner Pipe. To estimate the influence of the specific heat capacity of the inner pipe, values of specific heat capacity $c_p$ of "window glass," "district heating network pipe," "glass-fibre reinforced plastic," and others were used in the simulations. Aside from unrealistic values, $T_{\text{max}}$ and $t_{(T>55^\circ C)}$ are not affected by these variations.

Most simulations were run for the value of the district heating network pipe Kusiflex [27].

3.2.4. Effect of Operational Cycles. The simulations described previously showed, that in continuous operation the deep borehole heat exchanger will not deliver the temperatures required by the adsorption chiller. Cycled operations with daily periods of heat extraction and recovery were simulated to maximize the outlet temperature (Figures 12 and 13). At a volume flow rate of 3 m$^3$/h, a period of 6 h of heat extraction alternates with a period of 18 h of recovery. Shorter periods of extraction proved ineffective, because at least 1 h is needed to remove the cooled water from the inner...
A low volume flow rate was chosen to maintain high productive temperatures for a long period. High flow rates in contrast would cool the rocks too fast. Furthermore, it was demonstrated that even within the best available insulated pipe, temperature drops during shut-in. In continuous and cyclic operation production temperature, and thermal power are about 49°C and 34°C till 51°C and 29 kW and −20 kW till 35 kW, respectively (negative values are due to the production of cool water after restart following shut-in).

Figure 12 shows the production outlet temperature and the associated thermal power after 20 years of operation for cyclic and a continuous flow rate of 3 m³/h for a 4-day time interval.

Figure 13 shows a long term simulation over a time period from 10 year to 20 years with a volume flow rate of 3 m³/h both for a continues operation and a daily operation cycle consisting of 6 h pumping followed by 18 h of recovery. Only the maximum temperatures and minimum temperatures of the cyclic operation are shown. It shows that even after 20 years of operation, the deep borehole heat exchanger did not stop loosing efficiency.

In the first years, the decrease in thermal power and production temperature is greatest, then it stays stable even after 20 years of operating time. The temperature of the water is sufficient for direct heating in winter. An important consideration is the constant input temperature of 40°C. The temperature difference of the maximum temperatures between the cyclic and noncyclic operation is 2°C. An increasing amount of time is needed until the inner pipe starts discharging hot water. The different volume flowrates simulated for a cycled operation consisting of 6 h pumping followed by 18 h of recovery with a realistic thermal conductivity of the inner pipe of \( \lambda_{\text{pipe}} = 0.1 \, \text{W/(m·K)} \). The curves of the cycle in Figures 12 and 13 show that the required minimum temperature of 55°C is never achieved.

3.2.5. Simulation of Climate Control System Planned for the SuperC Building Real. The above discussion makes it clear that it is impossible given the currently available insulations of inner piping to reach the temperature of 55°C required for the climate control unit (the adsorption unit). And even in case of future better insulation possibilities, the flow rates are restricted to reach the required temperature.

Next to the adsorption chiller, two compression chillers are planned with 130 kW thermal power capacity each. The adsorption chiller operates with coefficient of performance (COP) of 0.38–0.63 for lower temperatures of, respectively,
55°C–85°C [12]. So, to cool the building with 1 kW, the adsorption chiller should use more or less $1/0.38 = 3$ kW of geothermal power and would result in 4 kW additional heat to the environment, an additional contribution to global warming. So even with future innovations of insulation possibilities, one could question the fact whether this is a sustainable way of cooling.

Anyway, according to the state building regulations, the required max cooling power needs to be dimensioned for temperature of 28°C. In Aachen, temperatures will exceed this temperature for 37 hours a year. Also cooling is required for climatic temperatures above 20°C, which corresponds to 580 hours a year in Aachen [12]. In case the adsorption cooling unit fails, only 50% of the total cooling power can operate, which corresponds to a cooling deficit for 190 hours a year.

In this section, we concentrate only on the heating part of the energy requirement of the building. According to the plans [12], the total coefficient of heat transmission ($U$-value) through the building is 7.9285 kW/K [12]. With this $U$-value it is possible to calculate the maximum heating power required to maintain a room temperature of 18.3°C at an outside temperature of –12°C.

The heaters in the building are laid out to accept a large temperature range; using normal radiators (70°C–35°C), floor heating (32°C–30°C), and concrete core activation (28°C–25°C). This large temperature range makes it possible to store...
high amounts of thermal heat into the building and reduce the building output water temperature to 25°C.

Air temperatures recorded at the Europlanetarium Genk (60 km from Aachen) in 2005, every 30 minutes, were used to simulate the required power with time for the SuperC building (Figure 14(1)). The required power (Figure 14(4)) and the building output water temperature (25°C) of the building are used as input parameters for the simulation of the borehole heat exchanger. Figure 14(2) shows the required flow rate result of a half-year simulation. The flow rate of the borehole heat exchanger is changing every 30 min to reach the required power. It is clear that the outlet temperature (Figure 14(3)) is slowly decreasing with time, but the required thermal power (Figure 14(4)) is satisfied. There are some peaks in the simulated thermal power compared to the required thermal power, because of the delay time of the corrected flow rate, which was set to 30 min. In the real situation this could be set to shorter periods.

4. Comparison of Borehole Heat Exchangers with Thermal Springs and Open Geothermal Doublets

Comparing the local RWTH-1 borehole heat exchanger with the regional geothermal natural springs, provide a good comparison of the order of magnitude of thermal power. The thermal springs (Aachen and Burtscheid) have a total flow rate of 175 m³/h at 60°C. Assuming a cooling of from 60 to 25°C, using \( c_{pw} = 4200 \text{ J/(kg·K)} \), the heat capacity of the water, and \( \rho_w = 1000 \text{ kg/m}^3 \), the density of the water, the total thermal power is 7146 kW. Table 1 gives an overview of the thermal power of the natural springs and the RWTH-1 borehole heat exchanger. It is clear that using the thermal power of the natural springs with 7146 kW, which is currently sparsely used, would be more costly efficient than drilling an additional borehole with a borehole heat exchanger.

The thermal power of the Geothermal Aachener springs is comparable with the thermal power of open geothermal doublets at 2500 m depth in good reservoirs, where flow rates of more than 100 m³/h at 60°C can be achieved [28, 29].

However, the rocks of the Maas-Eifel region have very low permeabilities, so besides using the natural geothermal springs, borehole heat exchangers could be another (expensive) sustainable option for direct heating.

5. Final Result

In 2008, the SuperC building (Figure 15) was officially opened, using residential heating, but still with the intention of using the borehole for geothermal heating in the future. At that time there were still problems in finding the appropriate material for the inner pipe. Finally, in 2011, the RWTH-Aachen decided that the operation of the borehole heat exchanger was economically not feasible because of high additional costs of the insulated inner pipe.

6. Conclusion

To heat and cool the SuperC building of the RWTH-Aachen University in the center of the city Aachen, Germany, direct heating the building in winter requires temperatures of 40°C. In summer, cooling the university building uses a climatic control adsorption unit which requires a temperature of minimum 55°C. Measurements and design calculations for a 2500 m deep coaxial borehole heat exchanger (CBHE) with a maximum temperature in the borehole of 85°C at 2500 m depth reveal a conflict between the maximum required temperature with respect to the climate control adsorption unit and the maximum thermal power. Numerical calculation results indicate that for a short period, in cyclic operation mode, the borehole may deliver at the same time the required temperature of 55°C and a thermal power of 120 kW, with an inlet temperature of 40°C and a flow rate of 3 m³/h. However, after a 20-year period of operation, temperatures are too low to drive the adsorption unit for cooling. During wintertime, the borehole heat exchanger may supply the building with sufficient heat, with temperatures varying between 25 and 55°C and a circulation flow rate of 10 m³/h at maximum. The calculation stresses the importance of the insulation of the inner pipe. This results in a very expensive inner pipe, which makes the total operation of the deep borehole heat exchanger at the RWTH-Aachen economically not feasible.

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