11. THREE YEARS MONITORING OF A BOREHOLE THERMAL ENERGY STORE OF A UK OFFICE BUILDING

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Abstract. In the autumn of 2000, the British Engineering Council awarded an Environmental Engineering award to the groundsource heatpump project at Commerce way, Croydon Surrey. This, one of the larger UK groundsource projects, is a speculative built industrial building of about 3,000 m^2 with both offices and warehouse facilities. The building, that is leased by Ascom Hassler Ltd. (a Swiss based IT company), is expected to have an annual cooling load of 100–125 MWh and a heating load of 90–100 MWh. Peak loads under hot summer conditions are anticipated to reach up to 130 kW. During the normal life span of a building (25 years) the surplus of heat rejection would lead to increasing ground temperatures. This results in a less efficient heat pump operation and may even result in insufficient capacity during cooling peak demands. As a solution a hybrid system, incorporating a dry-cooler, was developed. The principal idea is to use the dry-cooler to store cold in the wellfield during early spring, when the required summer peak load cool can be generated very efficiently and cheaply. The operation and efficiency of the wellfield, the installed heat pump system and dry-cooler is controlled and monitored under a Building Management System (BMS). The results of the first three years of operation of the system are presented. Using the monitoring data an evaluation of the original design will be made.

Keywords: heat pump, geo exchange, ground source, borehole heat exchanger, monitoring, croydon

11.1. Introduction

In the Croydon project, one of the larger UK ground source projects to date, the client (AXA Sunlife) opted for a low temperature geothermal energy system as the capital cost were only slightly higher than for traditional HVAC systems (VRV, four pipe fan coils). Using the Building Management System

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several key variables have been monitored, including borehole circulation medium temperatures and ground temperatures. In this paper we present an overview of these monitoring results for the period 2000–2003. Using these measurements an attempt will be made to evaluate the original design.

At the core of any geo-energy system is a heat pump. A heat pump is a machine that can transport heat (thermal energy) from a low to a high temperature level, hence the term "pump". Heat pumps are very attractive as a technology for space conditioning (heating and/or cooling). In fact, in a study conducted in 1993 the US EPA concluded: "GeoExchange systems are the most energy-efficient, environmentally clean, and cost-effective space conditioning systems available". One of the most important benefits of heat pump technology is that the transfer of energy occurs with a very high efficiency. For every kilowatt of electrical energy used to drive the compressor (and secondary side circulation pumps) five or six kilowatts of heat or cool is generated. The efficiency of a heat pump is expressed as it's COP, the ratio between the electrical power consumption and thermal energy generated. Modern heat pumps have typical COP's between 4 and 5 in heating mode and between 3.5 and 4 in cooling mode. This makes a heat pump an economically interesting machine, as the thermal energy taken from the environment comes at no additional cost. Moreover, savings on primary energy and greenhouse gas emissions can be realised. Studies carried out by the IEA for instance have demonstrated that savings of up to 50% of primary energy are possible. With respect to CO_2 reduction the global emissions reduction potential has been estimated at 6% in 1997. In addition to the savings on primary energy consumption and greenhouse gas emissions heat pump technology offers other advantages. The attractiveness of the ground source system lies in the low running cost, low maintenance, emission reductions, small plant room and lack of external plant, absence of sound emissions and of course the marketable sustainable "green image". This potential of ground source is recognised by high-end real estate developers and more progressive architects and consultants.

The heat pump exchanges thermal energy with the building on one side, and with the environment on the other side. In a geo-energy system the environment is the ground (other possibilities are e.g. air or surface water). The ground is particularly suited for low temperature energy exchange: the usual operating temperature bandwidth is between -5 °C and 30 °C (not taking into account high temperature energy stores). The ground can be used either through a closed loop borehole heat exchanger, through direct use of ground water or even through direct expansion systems. Advantages of closed loop borehole heat exchangers are their very long life span (50 years or more) and the fact that they are virtually maintenance free.

The goal of a design of a geothermal heat exchanger is to maintain a specified bandwidth of temperatures in the ground loop heat exchanger at which the heat pump may operate efficiently. The main issue with such a design is that we need to consider both the local process, occurring in and around the borehole, and the global process of the whole ground volume that is thermally influenced and its interaction with the boundaries. Especially for the local process, the earth is usually not capable of transporting the thermal energy rapidly enough to the heat exchanger. This means that the ground temperature around the heat exchanger tends too increase or decrease as long as the heat pump is in operation. For the global process, in a system utilising the ground for both cooling and heating there may either be a balance or imbalance in the total energy. In the first case the ground temperature will tend to show a yearly fluctuation around a mean value, in phase with the energy demand. In the latter case these fluctuations are also present, but the average ground temperature will tend to increase or decrease with time. The interactions with the boundaries include energy exchange due to conduction, groundwater flow, geothermal gradient and interactions at the surface.

In such a system there is a direct and dynamic coupling between the energy supplier (the ground) and the energy user (the building). Not only are the loads on the ground system determining the thermal response of the ground, the actual power generated will in turn depend on the source temperature. The design therefore needs to specify accurately the total seasonal loads that determine the global response, as well as the peak load demands and duration. These peak loads are superposed on the seasonal response of the system.

For a successful design detailed knowledge of the building loads as well as detailed geological and geo-hydrological knowledge are necessary. Moreover, the actual engineering of the boreholes and ground loop heat exchangers, material choice, etc all has to be considered carefully.

We will not consider the building load design in any detail. For the ground source design the principal input parameters are the seasonal loads and peak loads and duration. Several methods and models exist to calculate the energy requirements of a building (e.g. Ashrae, 1998; Blast, 1986). Main uncertainties are the climatic circumstances and the variations therein and the actual building use during its lifespan.

With respect to heat conduction in the ground the most important parameter is the thermal diffusivity of the ground, the ratio between the ground thermal conductivity and the volumetric heat capacity. Especially the thermal conductivity is difficult to establish with sufficient accuracy (Austin, 2000; van Gelder et al., 1999). Although each soil type has a specific conductivity, the conductivity depends not only on the material itself but also to a large extent on factors such as packing, pore volume and water content. Moreover, the sequence of soil types and presence of ground water or ground water flow in the different formations in the soil profile will affect the overall conductivity and relative contribution to the thermal forcing of the different depth intervals. As the soil conductivity is so important, several methods have been developed to directly measure the overall soil conductivity (Eklöf and Gehlin, 1996; Austin, 1998; Witte et al., 2002).

For the local process especially the borehole resistance is important. The borehole resistance depends mainly on the loop type and material, loop dimensions, circulation fluid properties, temperature of the process, borehole engineering (Hellström, 1991). Furthermore the far field temperature in the ground and geothermal gradient needs to be measured.

11.1.1. THE CROYDON PROJECT

The Croydon building (Figure 68) is a three-story office building located at the Commerce way, Croydon Surrey (UK). Total surface area is about 3,000 m^2, with both offices and warehouse facilities. In the offices 85 Geothermic water-to-air heat pumps have been installed. The warehouse, of approximately 690 m^2 is heated or cooled using a low temperature under floor heating, with to a water-to-water heat pump (26 kW). Total installed heating capacity is 225 kW, maximum cooling capacity installed is 285 kW.

As all Geothermic heat pumps are connected in parallel to the pipe work supplying the source and return water, therefore simultaneous cooling and heating loads are balanced in the building. During periods with a net cooling or net heating demand the ground heat exchanger (Figure 69) supplies the

Figure 68. The Croydon building, Commerce way, Croydon Surrey (UK)

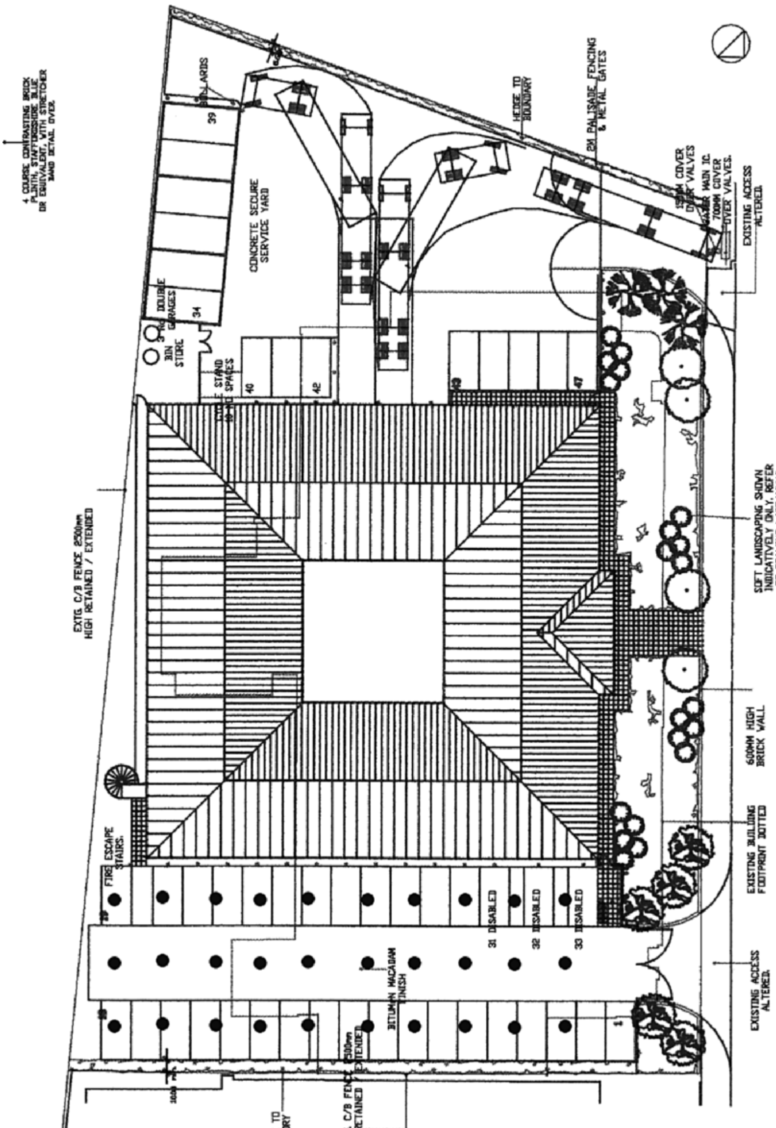

Figure 69. Location map showing the building and parking lot with positions of the installed ground loop heat exchangers and observation wells

additional heat or cool. The ground loop heat exchanger consists of thirty U-loops (40 mm, PE PN16) installed in 100 m deep boreholes, with a distance between the boreholes of about 5 m. Boreholes were fully grouted with a bentonite/cement mixture.

11.1.2. BOREHOLE HEAT EXCHANGER DESIGN

Geology of the site has been described on the basis of three borelogs of the Geological Survey (British Geological Survey, 1997) in the vicinity and on the basis of the borelogs made during the drilling of a test borehole. Main geological sequence is: a surface layer (1.5 m), Thanet Sands (1.5–13 m), Upper Chalk (13–80 m) and Middle Chalk formation (80 m). Groundwater levels are at about −2 m with respect to the surface level. Groundwater flow is in a north to northwesterly direction with an estimated Darcy flow of 20–25 m/year in chalk formations and of between 75 and 100 m/year in Thanet sands.

Critical design parameters are the ground thermal conductivity, far field temperature and energy loads. The thermal ground parameters were measured on-site with an In Situ Thermal Response Test [4]. Results of this test (Figure 70) showed a thermal conductivity of 2.2 W/m K, an average far field temperature of 11.6 °C and a geothermal gradient below 40 m of approximately 0.009 °C/m.

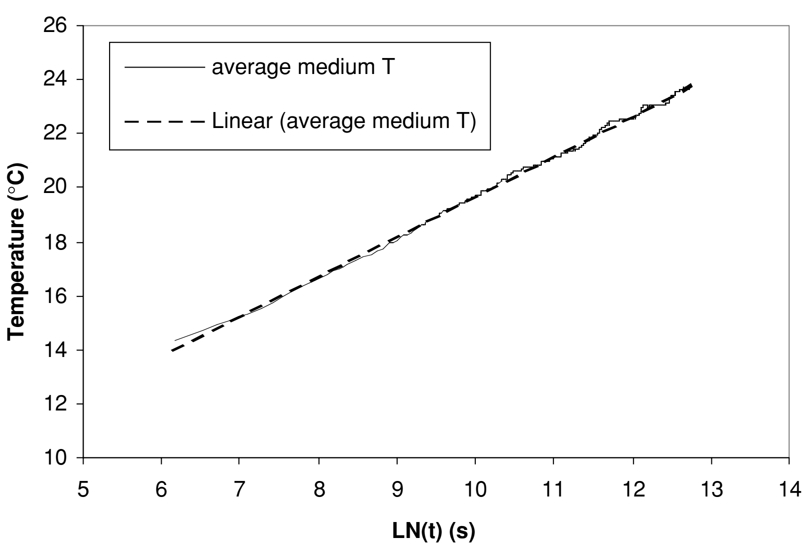

Figure 70. Result (average circulation medium temperature with LN(time)) of the In Situ Thermal Response Test for the Croydon test site

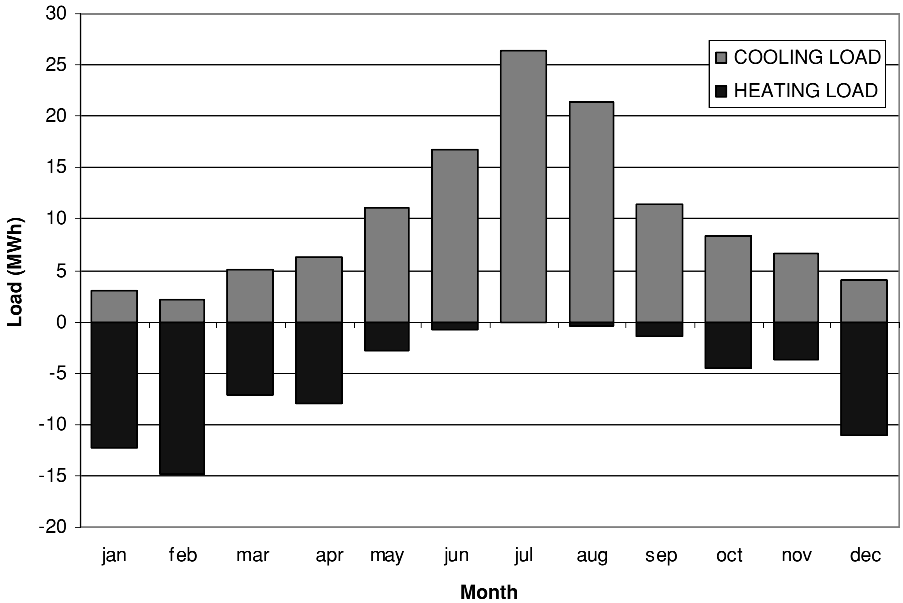

Figure 71. Design loads building (net loads to the ground), monthly heating and cooling loads

Building loads were calculated by EDSL (Environmental Design Solutions, Milton Keynes, UK) using a three-dimensional dynamic model. Total yearly loads have been calculated as 100 MWh/year (average summer) up to 120 MWh/year (warm summer) cooling and about 95 MWh/year heating. Taking into account the average efficiency of the heat pumps, this translates to a load on the ground of 65 MWh heating and between 120 and 145 MWh cooling. Seasonal distribution of the average loads is depicted in Figure 71.

Evident from Figure 4 is that even in winter appreciable cooling occurs and that only in July no heating demand is present. The total net load on the ground during an average year is 55 MWh annual heat rejection.

Average monthly fluid temperatures (Figure 72) in the ground loop heat exchanger were modelled using Earth Energy Designer (EED, Eskilson et al., 2000) and GhlePro (Spitler, 2000). Clearly average temperatures in the ground tend to increase, from about 13.5 °C in the first year to about 17 °C in the twenty-fifth year. The installed Geothermic heat pumps can operate efficiently within a temperature bandwidth of 0–30 °C, and design temperatures were selected accordingly. The limiting design temperature is the temperature during cooling peak loads, with a 30 °C limit.

Superposing a 136 kW cooling peak load on the modelled average medium temperatures a 7 h peak load can be accommodated in year 5, in year 10 only 5 h and in year 25 just 2 h can be accommodated.

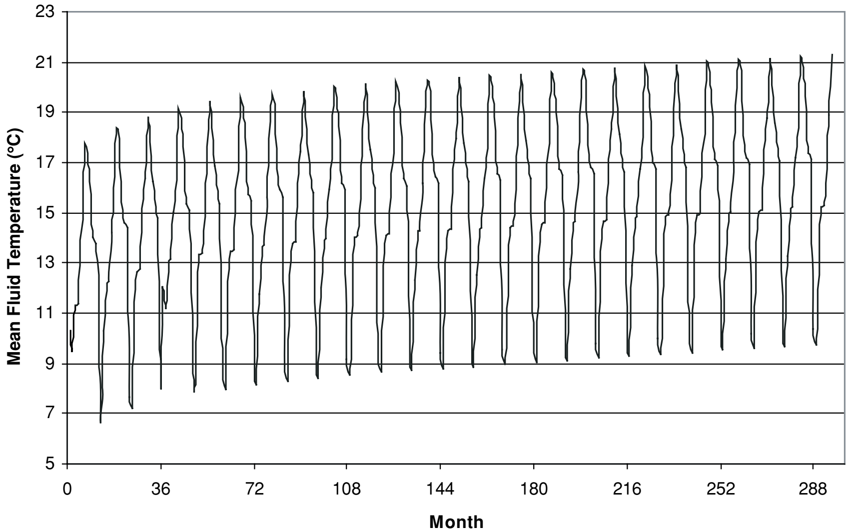

Figure 72. Average modelled monthly fluid temperatures in the ground loop heat exchanger, for 25 years

Instead of increasing the size of the ground loop-heat exchanger a dry cooler was incorporated in the system. Depending on the operating temperatures (source and sink) a dry cooler can very efficiently reject heat. The principal idea is therefore to use the dry cooler to store cold in the ground during times when this can be done at high efficiency (spring and at night). Such a hybrid system allows more flexibility in building use (adding or removing heat pumps), and makes an active management of the ground temperatures possible. Also, a dry cooler is a relatively cost-effective way of rejecting heat.

11.2. Monitoring Results

A number of variables have been monitored with a relatively high frequency from September 2000 until July 2003 (20 min interval). In this paper we will focus on the borehole heat exchanger temperatures, thermal loads on the ground and ambient temperatures. Using the borehole flow and return temperatures the load on the ground at each time step was calculated using the known fluid properties and (fixed) pumping rate. The building was commissioned in September 2000. The monitoring data from September 2000 up to July 2003 is now available. In July 2003 the tenant suspended UK operations in response to market developments. As the lease still runs and no new tenant is using

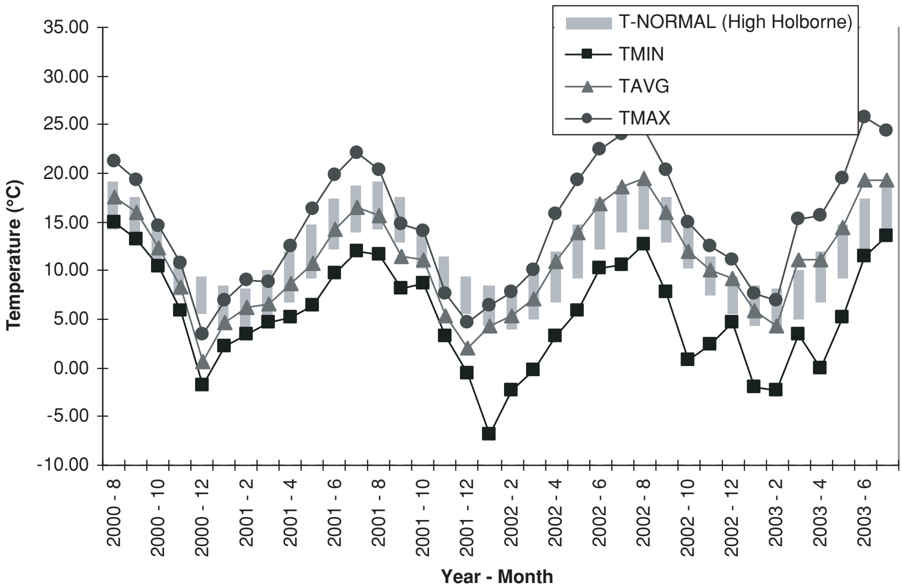

Figure 73. Average monthly day-minimum, day-maximum and day-average temperatures at Croydon and average typical temperature range of the climate station High Holborne London Weather Centre—(design temperatures)

the building, no new data is being gathered at the moment as all systems are on standby. During the operational period the dry cooler has not been used, energy demands presented therefore only refer to the building.

The main questions we would like to address are:

1. How well do the actual measured building loads compare with the design building loads, taking into account possible differences in climate.
2. How well does the borehole heat exchanger design match with the measured temperatures, and what impact do the measured loads have on the design?

Ambient temperatures (Figure 73) measured at Croydon are by and large comparable to the design temperatures at High Holborn. It can be noted that the winters of 2000 and 2001 have been somewhat colder than normal, while summers (and especially maximum temperatures reached) have been quite a bit warmer in 2002 and 2003. The difference between minimum and maximum temperatures is much larger, as in the monitored data the temperatures are not averaged over a period of more years.

Daily ambient and borehole temperatures monitored at the Croydon facility (Figure 74) also show a clear trend. Design limits of the borehole heat exchanger of 0 °C during heating and 30 °C during cooling have not been exceeded, but average winter temperatures have increased during the season

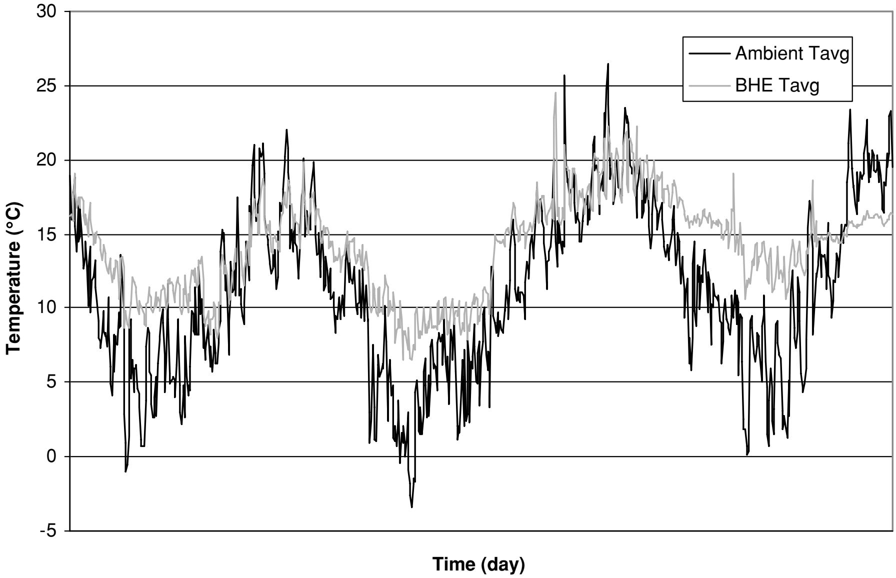

Figure 74. Average daily ambient and borehole heat exchanger temperatures at Croydon (period 2001–2003)

2002–2003 with respect to previously recorded values. Minimum heat pump source temperature (ground loop heat exchanger return temperature) recorded throughout the period is 4.2 °C, maximum heat pump source temperature was 26.8 °C. The loads that have been recorded are shown in Figure 75. Clearly the net cooling loads to the ground greatly exceed the heating loads. During the monitoring period total heat extraction was 140 MWh (200 MWh design), total heat injection was 441 MWh (368 MWH design). Heating loads are 30% lower than anticipated while cooling loads are 20% higher. The original imbalance factor (cooling/heating) was 1.84, in reality the imbalance is 3.15.

A direct comparison of the measured and design monthly loads is depicted in Figure 76. Here also, the trend of heating loads being smaller than anticipated while cooling loads are higher than anticipated is very clear. One of the main reasons for the difference in loads is the fact that occupancy level (number of people per m^2) was higher than anticipated.

The question of how well the borehole heat exchanger system holds up under these conditions is an interesting one. We compare the measured temperatures in the borehole heat exchanger system with the predicted temperatures using the design and measured loads. The program Earth Energy Designer (EED) was used to calculate temperatures for the first year, the analysis of the complete monitoring period was done using TRNSYS with the DST (Hellström, 1989) model. Figure 77 shows the simulated temperatures using the design and measured building heating and cooling loads.

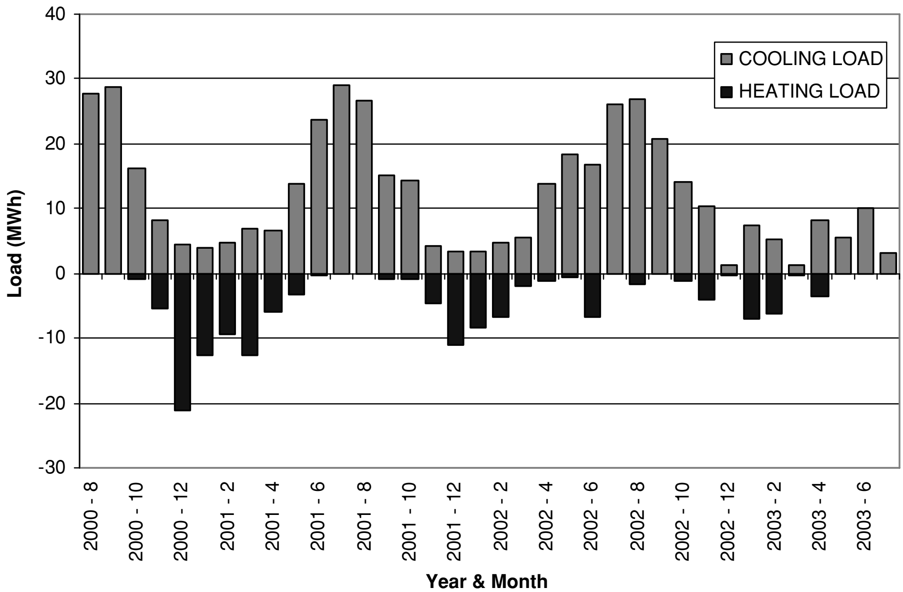

Figure 75. Monthly heating and cooling loads (measured loads to the ground) at Croydon (period 2001–2003)

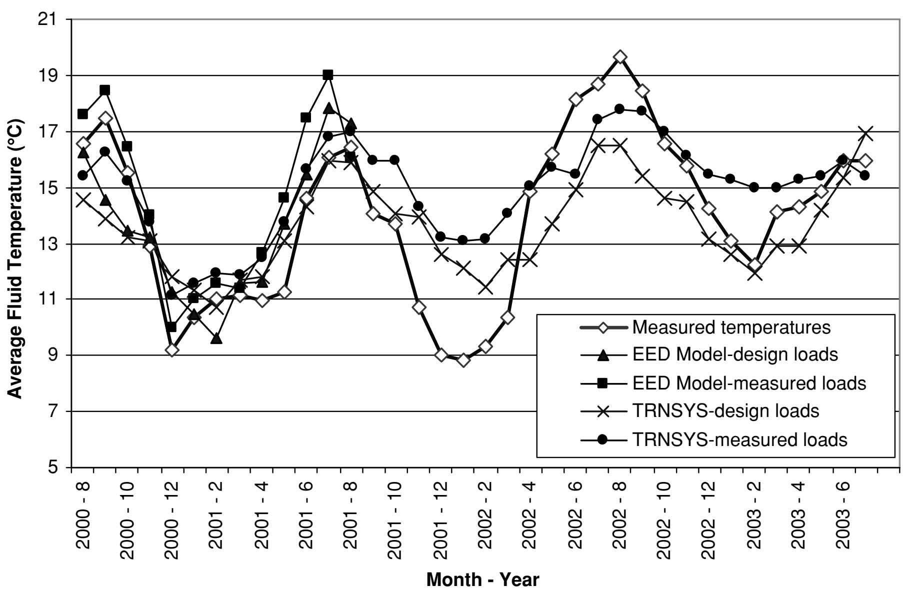

Figure 76. Comparison between design and measured monthly loads (period 2001–2003)

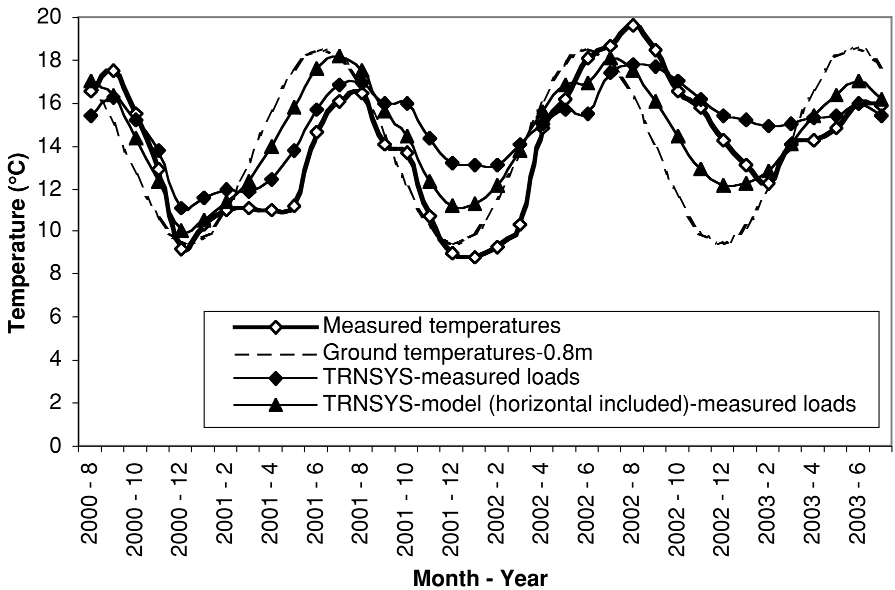

Figure 77. Comparison of measured and modelled borehole heat exchanger temperatures (period 2001–2003)

Some interesting observations can be made from these graphs. First of all, the measured temperatures and the calculated temperatures for the first year are all in fair agreement. EED tends to overestimate temperatures during cooling when using the measured loads. The TRNSYS model, that has been used to predict temperatures for the complete monitoring series, predicts the increasing average store temperature relatively well. The measured fluid temperatures however, show a larger temperature amplitude than the model calculations. Also, fluid temperatures in the 2001–2002 winter season are much lower than expected considering the measured loads.

As the larger temperature amplitude seems to be a temperature effect (and not a thermal load effect, which would mean larger temperature differences as well), and the low temperatures in the 2001–2002 winter season correlate with the low ambient temperatures during this period, it is thought that the horizontal connecting pipes may experience a larger than expected seasonal temperature effect. In the Croydon Borehole Heat Exchanger well field a total of about 1,200 m of horizontal pipework has been laid, beneath a black asphalt surface. We extended the TRNSYS model to include the effects of the horizontal pipes, using the average ambient temperature and average temperature amplitude to calculate the ground temperature at the depth of the horizontal pipes (±0.8 m below surface). The results are show in Figure 78.

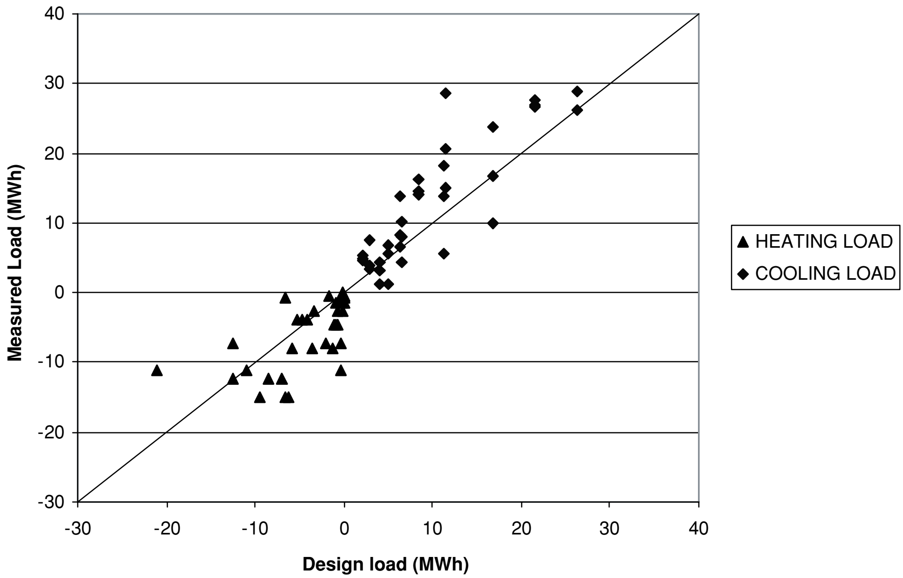

Figure 78. Comparison between TRNSYS model with and without horizontal connecting pipes, measured and modelled borehole heat exchanger temperatures (period 2001–2003). Also shown is the undisturbed ground temperature at depth of horizontal pipes

From this figure it is clear that a much better fit is obtained. The fluid temperatures during the summer season 2001 and in the winter season 2001–2002 are still too high. This can be explained by taking into account that the real ambient temperatures during those years have not been used in the model, only average atmospheric temperatures. Fit in the winter season 2002–2003 is excellent.

11.3. Conclusions

The borehole heat exchanger at Commerce Way (Croydon, UK) has, during its 36 month of operation, rejected 440 MWh of heat into the ground and extracted 140 MWh. In spite of the large difference between anticipated and actual cooling and heating loads, cooling loads being 20% higher while heating loads were 30% lower, the design temperature limits have not been exceeded. The average store temperature appears to be increasing due to the imbalance in heating and cooling loads. This was anticipated during the design, and a dry-cooler was incorporated to reject excess heat in the winter/early spring period when conditions are favorable. It had been expected to start operation of the dry cooling in 2004/2005. However, due to changes in the market the activities of the tenant at the Croydon office were suspended, at present the offices remain closed and no heat is rejected or extracted. Unfortunately, further monitoring of data had to be suspended as well.

A first comparison between measured and modelled temperatures has been made, using standard software such as EED and TRNSYS. During the first year of operation measured and modelled temperatures agree fairly well. After the first seasonal cycle results are less comparable, the measured fluid temperatures showing a much wider amplitude. Including a model of the horizontal connecting pipes in the model greatly improved the fit. Given the type of surface (asphalt), the influence of the seasonal temperature changes in the shallow ground may be much bigger than anticipated. Normally the influence of horizontal pipes is not considered to be very great, as the conductivity in the usually dry zone where the pipes are buried limits the downward migration of the temperature pulse at the surface. However, the thermal properties of the surface as well as the shallow ground will influence the temperature amplitude experienced there. In these cases (e.g. horizontal pipes under asphalt) additional insulation may be required. Although the energy exchanged is not affected, the coefficient of performance will be affected as the heat pumps will operate less economically with the higher temperatures in summer, or lower temperatures in winter.

In this paper we have presented a general overview of the monitoring data. The dataset provides more detail, both in several additional systems components that have been monitored as well as in the frequency of logging. In the future a more detailed statistical analysis of the high-resolution dataset (20 minutes logging interval) will provide more insight in the behaviour of the system during daily cycles.

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