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A 20'000 m^3 Solar Seasonal Heat Store under an Industrial Building at Meyrin-Geneva - Measurements and Calculations

by O. GUISAN, B. LACHAL, B. MATTHEY, A. MERMOUD and D. PAHUD*)

Summary

The solar system described comprises a seasonal earth heat store located underneath the building, fed by 950 m^2 of flat plate solar collectors. The heat exchanger is made up of 258 fifteen meters deep vertical boreholes, each containing 4 tubes (two polyethylene loops). The distance between the boreholes is 2.3 m. The system is designed to cover 40 % of the thermal demands of the building. The stored heat is recovered by means of a gas heat pump.

The apparatus for measuring the store consists of temperature probes which permit the taking of vertical temperature profiles in different areas of the ground. The power exchange of some boreholes will also be measured.

We solve the problem of the prevision of temperature in the store with an analytical solution of the equation of heat for pure diffusion.

A good correlation is obtained between the measurements and calculations.

Kurzfassung

In dem beschriebenen Solarsystem wird ein saisonaler Erdreich-Wärmespeicher unter einem Gebäude eingesetzt, gespeist von 950 m^2 Platten-Sonnenkollektoren. Der Wärmetauscher ist aus 258 jeweils 15 m tiefen Bohrlöchern aufgebaut, von denen jedes

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4 Rohre enthält (zwei Polyäthylen-Schlangen). Der Abstand der Bohrlöcher zueinander beträgt 2,3 m. Das System ist ausgelegt, 40 % der thermischen Last des Gebäudes abzudecken. Die gespeicherte Wärme wird über eine Gasmotor-Wärmepumpe rückgewonnen.

Die Einrichtung zur Messung des Speichers besteht aus Temperatursonden, die eine Aufnahme von vertikalen Temperaturprofilen in verschiedenen Bereichen des Geländes erlauben. Die ausgetauschte Wärmemenge wird an einigen Bohrlöchern gemessen werden.

Die Aufgabe der Temperaturvorhersage im Speicher ist durch eine analytische Lösung der Gleichung für reine Diffusion gelöst.

Eine gute Übereinstimung zwischen gemessenen und berechneten Werten wurde festgestellt.

Introduction

The whole energy system, as well as the energy management of the building were carefully designed by B. Matthey and C.-A. Roulet (MATTHEY & ROULET, 1987). The whole building and attached systems were built by the owner on entirely private basis, without any financial subsidary from the public authorities.

The Group of Applied Physics of the university of Geneva is in charge of all measurements concerning the energy performances of the building. This work is part of a research activity contracted by the Swiss Federal Energy office. The aim of this study is:

- To separately measure the active solar system, seasonal heat store, gas heat pump, other heating systems and the passive solar gains related to the envelop of the building as well as its energy balance.
- To understand, on a physical basis, the observed performance, to identify and to characterize the significant parameters, to develop and to validate models.

In this paper, we focuse only on the seasonal heat store and its first observed performances and characteristics.

Solar Energy Feeding the Store

Three variables aiming to show the importance of solar energy using the means of thermic captors have been studied, then evaluated. The chosen variable (figure 1) includes:

- 550 m^2 of solar collectors integrated into the roof in the form of sheds.
- 400 m^2 of solar collectors destined for the preparation of hot water for domestic use. When this demand is satisfied, all the collectors participate in the recharging of the underground store.
- A seasonal heat store in the ground of 20'000 m^3, the injection and extraction of the heat are performed by 258 vertical sondes, each 15m deep and 2-3 m apart.
- A gas powered heat pump, having a thermal power of 200 kW, taking its energy either from the underground store, or the solar panels.
- A system of distribution by low temperature floor heating not solely dependent upon the heat provided by the heat pump.
- A system of distribution supplementing the heat in very cold weather by the means of air exchangers or radiators, depending upon the type of room.
- A programmable controler which supervises all the installation.

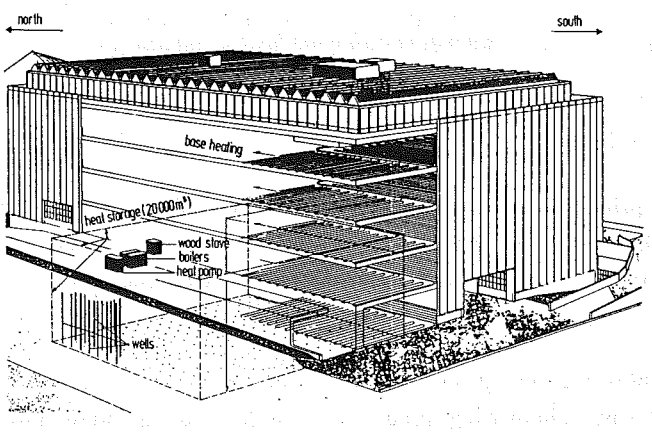

Fig. 1: *Perspective of the building*

The principle functioning of the system is as follows:

During the summer the production of hot water and the recharging of the underground store are assured by the solar collectors. This store should reach 28-32 °C by the end of summer. Starting in autumn, the stored heat is taken by the heat pump, a supplementary boiler assures the supply to cover the extra demand. The heating power for -10 °C is 550 kW. By the end of winter the temperature of the store will reach 4 to 5 °C depending upon the demand. The different sources of energy for the building are given in figure 2.

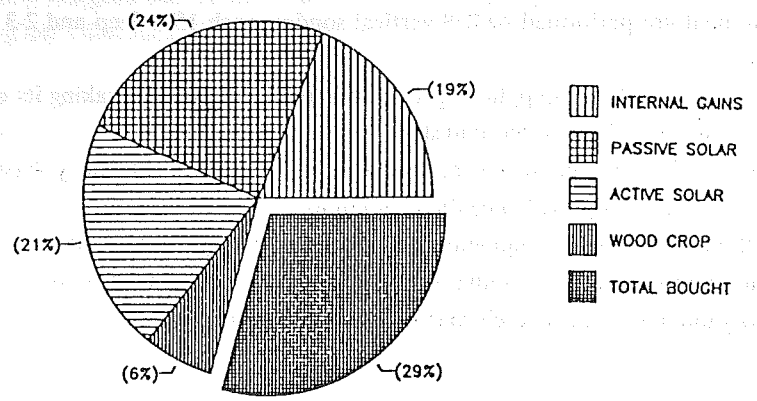

Fig. 2: Parts of the energy sources covering the heat requirement

The Underground Store

In Table 1 the principal characteristics of the underground store are shown. The principal innovation lies in the fact that the store is situated underneath the building itself, this solution being necessary due to the lack of ground available. An insulation at the roof of the store avoids overheating the building at the end of the summer.

An apparatus allowing the injection of water at the head of each of the two U-shaped tubes (each well) is used, improving contact between the ground and the tube.

The vertical tubes feeding the store (i.e.: the wells), are connected so that the radial temperature is vertically stratified from the centre to the border. This means that when

loading, the warm water enters the centre of the store, crosses a series of vertical wells (12-13), and comes out cold at the border of the store. During the discharge period the direction of flow is inverted.

Table 1: Characteristics of the Underground Store Jean Sieber SA at Meyrin, Geneva.

Situation	Under the building
Volume	20'000 m^3
Ground surface	1400 m^2 (40*35)
Nature of the ground	Dry moraine
Number of boreholes	258
Diameter of boreholes	114 mm
Depth of boreholes	15 m
Distance between boreholes	2.30 m
Drilling system	Down hole hammer
Speed of digging	100m/day
Heat exchanger	Two U-shaped tubes
Diameter of tubes	32 mm
Material used for the heat exchanger	Polyethylene
Contact between tube-ground	Fine sand
Total length boreholes	3880 m
Length vertical tubes	15'500 m
Connection	By series of 13 wells
Max. thermal power at injection	200 W/m of borehole
Max. thermal power at extraction	25 W/m
Insulation	5 cm of Foamglass on the store
Max. temperature of store	28-32 °C
Min. temperature of store	4-5 °C
Heat carrying fluid	Network water
Annual energy stocked	400 MWh

Measurements

Measure of Temperature in the Store

We are measuring the temperatures at different accessible places which give a good representation of the thermal stratification of the store.

Figure 3 shows the position of the tubes and represents a probable extension of the isotherms (Pseudo-isotherms have been drawn by joining together the position of each well in its series).

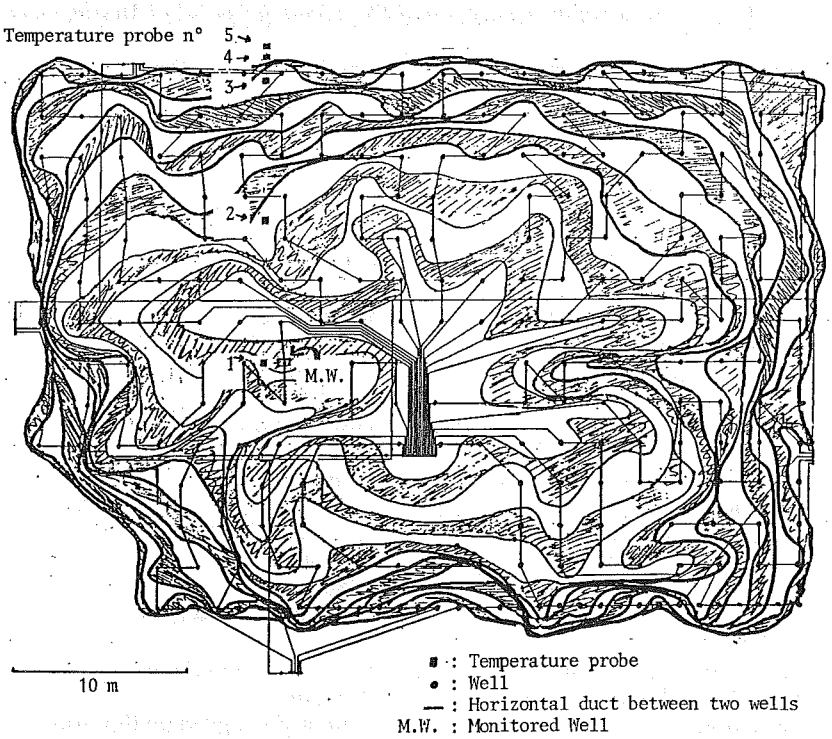

Fig. 3: *Layout of the store showing the duct system and the temperature probes. The curves represent a probable extension of the isothermes due to the in-series-connection of the vertical wells.*

The positions of the 5 temperature probes are also indicated in figure 3. They measure temperature at different depths. The temperature is read inside and at the edge of the store by measuring vertical profiles in the temperature probes which are bored up to a depth of 19 m, thus being 5 m deeper than the base of the wells. Due to technical reasons, the first probe is not deeper than 16,5 m.

- The first probe should represent the temperature at the centre of the store.
- The second probe, the mean temperature of the store.
- The third probe, the temperature at the border of the store, and probes four and five give an idea of the temperature gradient outside the store.

The positions of the probes in relation to the wells are as indicated in figure 4 and are as far as possible from the wells. In this area, the horizontal component of the thermal gradient is nearly zero. Accordingly, a deviation of the probe should not induce an appreciable error on the temperature.

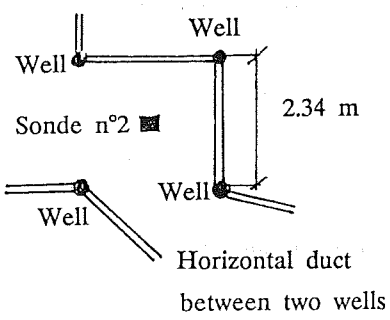

Fig. 4: Position of the probe No. 2 in relation to the wells

Structure of a Temperature Probe

The plastic tube contains the probe (figure 5). It comprises of 10 platinum resistors PT100, fixed on a rigid casing in which are the wires to connect them. They are at the depth of 0.5, 1, 2, 6, 10, 13, 14, 15, 16.5 and 19 m. The temperature is read with the "three-wire measure". The calibration of each PT100 guarantees an absolute error of less than 0.1 °C.

The plastic tube is filled with glycerine in order to prevent thermal convection. Figure 6 shows the stability of the glycerine with temperature in the case of the temperature probes (SAMMEL, 1968).

The platinum resistors are connected to a temperature indicator and are read once a week.

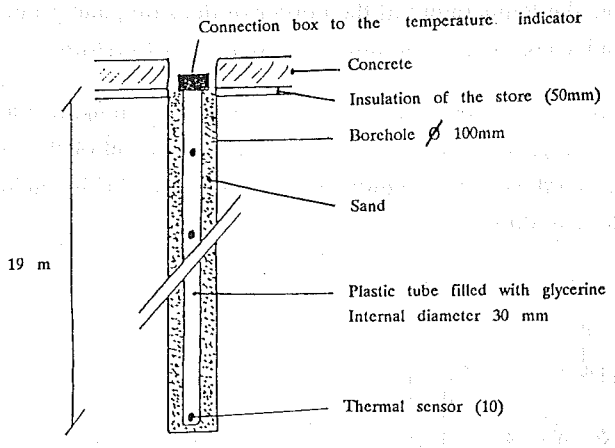

Fig. 5: *Cross section through a temperature probe*

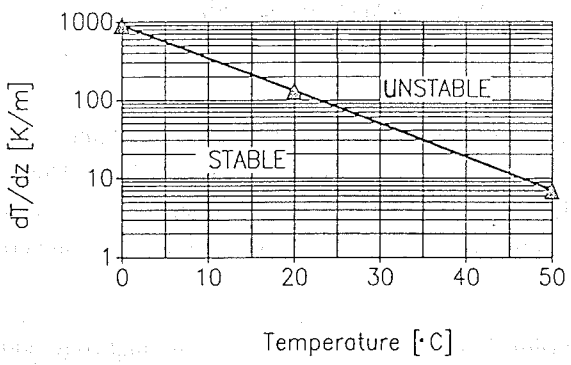

Fig. 6: *Thermal gradient limit in a vertical tube of glycerine, internal diameter 30 mm, Glycerine 99 %, Densitiy 1.26 g/m³ (after SAMMEL, 1968)*

Other Measurements

Measurements of a series of wells:

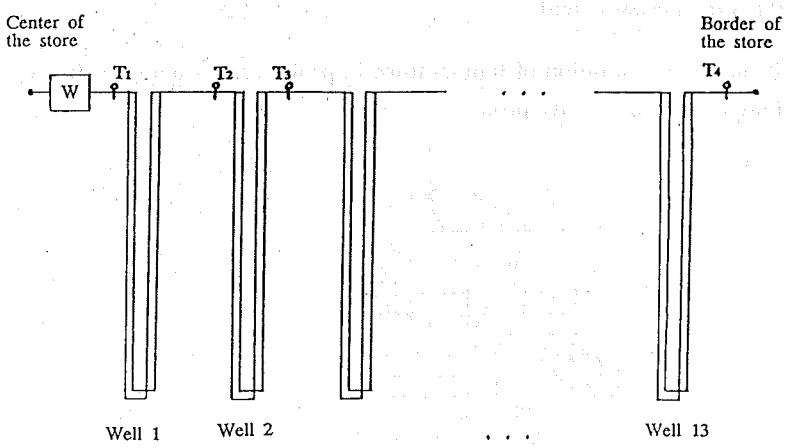

Fig. 7: Situation of the flowmeter (W) and the temperature sensor (T_1, T_2, T_3, T_4) measuring discharge and temperature of the water circulating in a series of wells

The sensors T1 to T4 measure the temperature of the flow of the water passing through the wells (figure 7). The 4 temperatures and the discharge measure permit us to calculate the power exchange in the first and second well, and the series of wells. The position of the second well, the Monitored Well, is shown on figure 3.

These measurements are not yet functioning.

Temperatures on top of the store:

At the centre of the store, there are three PT100 resistors to measure temperatures

- Just below the surface of the concrete
- Between the insulation and the concrete
- Just underneath the insulation

Temperature measured outside the store:

It is planned to install a sixth probe at approximately 5m from the border of the store, outside the building.

First results of the measurements

Figure 8 shows the evolution of temperature in probe 2, and figure 9 shows vertical profile of temperature of the five probes.

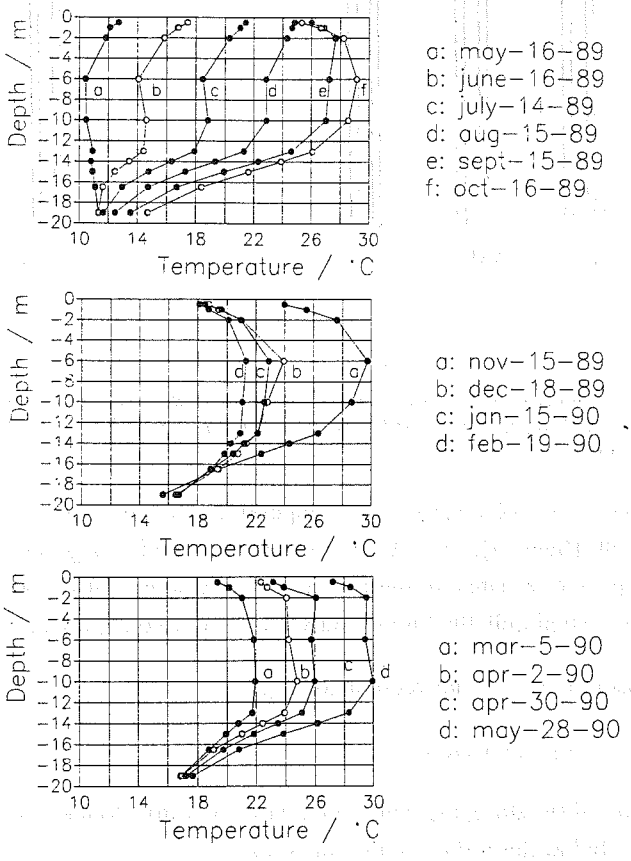

Fig. 8: *Probe No. 2, evolution of temperature*

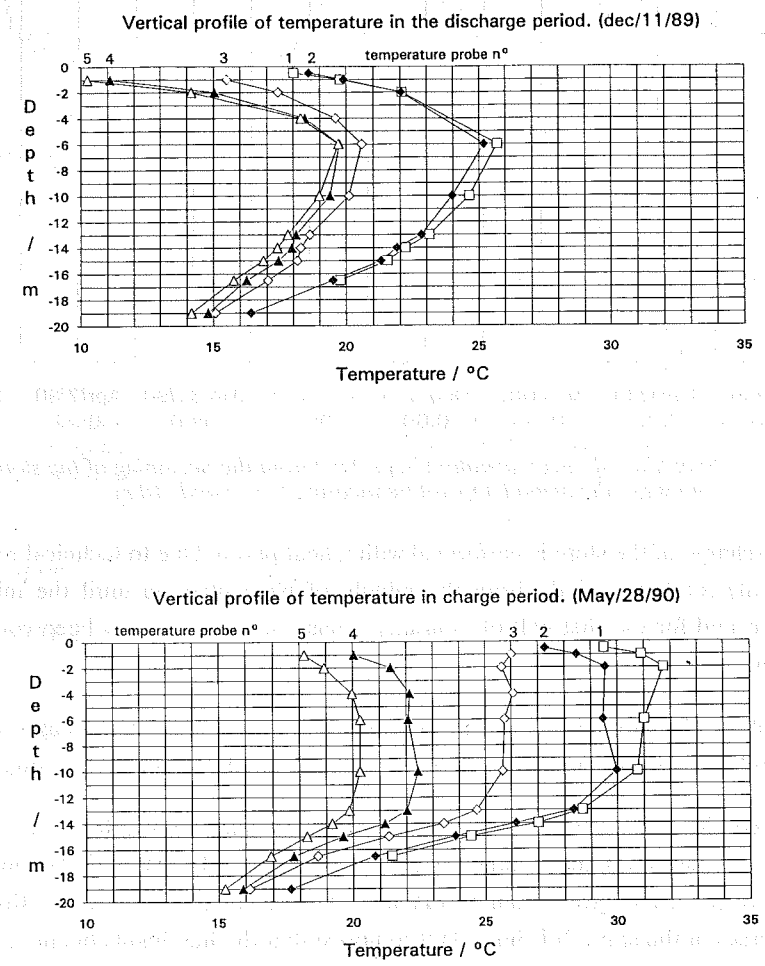

Fig. 9: *Temperature distribution inside (1,2,3) and at the border (4,5) of the store for two given times*

We notice that the horizontal gradient inside the store is the same in both the charge and discharge period. In both cases, there are 5°C between the center and the border of the store. Figure 10 shows the evolution of the temperature in the second probe.

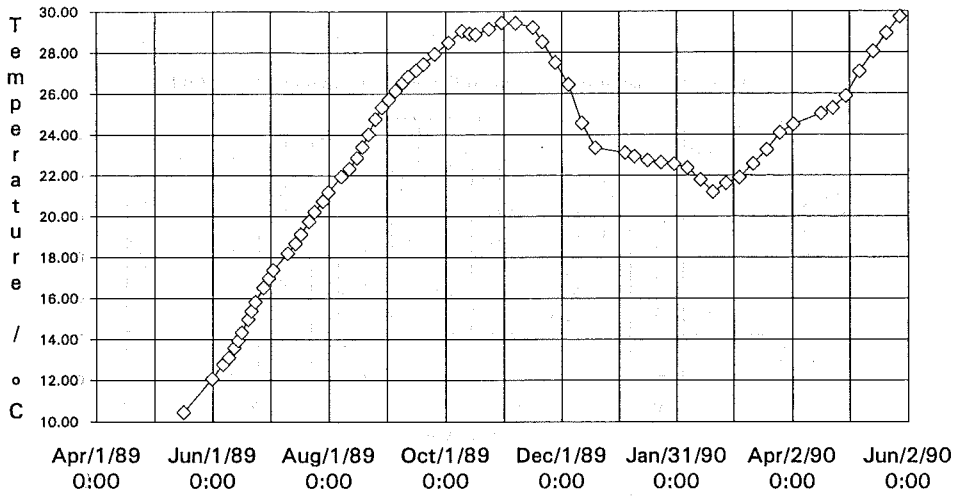

Fig. 10: *Evolution of the temperature in probe 2 from the beginning of the storage. The values are the mean temperature measured at -6 and -10 m*

The discharge of the store is performed with a heat pump. Due to technical reasons it worked only for two periods, from the middle of November up until the middle of December, and for the first half of February. Thus, the store had not been completely discharged.

The values of figure 11 are the mean temperature at -6 and -10m measured in the second probe. They are represented in terms of the thermal balance of the store.

If we consider the size of the store as 20'000m3 and a volumic capacity of 2.7 MJ/m3K (dry moraine), the heating capacity of the store is 15 MWh/K. The inverse of the slope at the origin gives about 14 MWh/K. The distance d is representative of the natural losses of the store. It is important to notice that the line highlights the evolution of time of the measurement points.

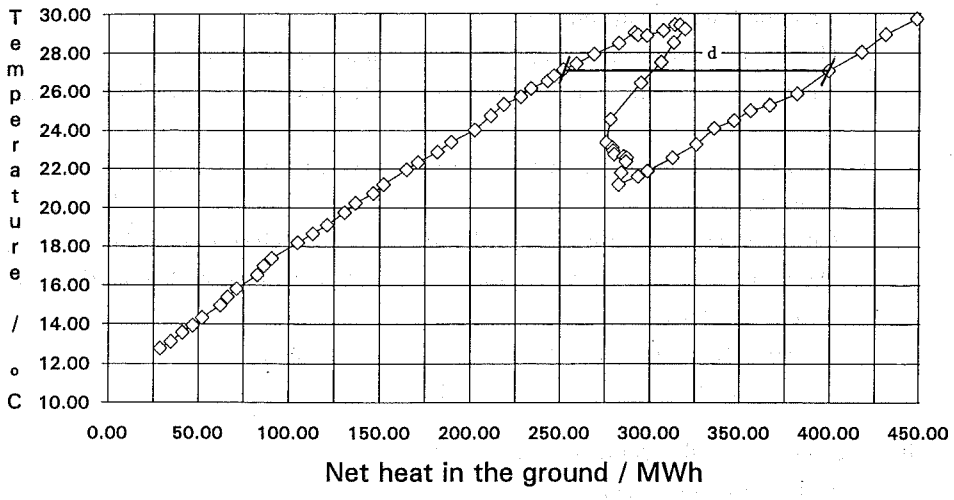

Fig. 11: *Mean temperature at level -6 and -10 m in probe 2 in function of the thermal balance of the store. Injected and extracted heat is measured by mean of two heatmeters*

Calculations

Definition of the Problem:

The first idea is to study the local process, i.e.: the conduction of heat around the wells. In order to lead the calculations of temperature as far as possible without using a numerical method, we have to modelise the store to simplify as much as possible.

The store is divided into vertical and equal cells, so that each cell contains exactly one well (figure 12).

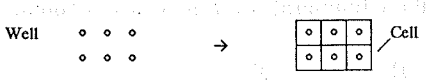

Fig. 12: *Scheme of cells in the store*

Keeping in mind solely the local process, the effects of the top and bottom of a well are said to be negligible.

Next we have the following hypotheses:

- The flux around a well is supposed to be radial (r dependance).
- The flux is constant along a well. This assumes a flow of water which is sufficiently fast in the well.
- The flux on the border of a cell is zero. This is true for the cells at the centre of the store.
- The section of a cell is circular with a radius R_{eff} which conserves the section.
- The ground which is contained in a cell is homogenous. It is characterised by the two qualities:
  - constant thermal conductivity: λ W/m·WK
  - themal diffusivity: k m^2/s

Thus in summary a cell is defined with:

- R_o, radius of a well.
- R_{eff}, radius of the cell.
- the characteristics of the ground λ and k.

The equations:

Definition: $\vec{j}$: flux (W/m^2) j_o: flux at R_o (on a well)(W/m^2)
T: temperature (K) T_o: temperature at R_o (on a well)(K)

We have $\vec{j} = \vec{j}(r,t)$ r is the radius: $R_o \leq r \leq R_{eff}$
$T = T(r,t)$ t is the time: $t \geq 0$

The equation of the heat is resolved with:

·at R_o : $T(R_o,t) = T_o(t)$
Prescribed temperature which is dependent upon time

·at R_{eff} : $\frac{\partial}{\partial r} T(r,t)\Big|_{r=R_{eff}} = 0$

Initially, we have $T(r,t=0) = f(r)$ with $R_o \leq r \leq R_{eff}$
f(r):initial temperature function.

The solutions are: PAHUD (1989).

$$T(r,t)=\begin{cases} T_o(t) & \text{if } r = R_o \\ \frac{\pi^2}{2}\cdot\sum_{n=1}^{\infty}\alpha_n^2\cdot e^{-k\alpha_n^2 t}\cdot A_n(r)\cdot I_n - k\pi\cdot\sum_{n=1}^{\infty}\alpha_n^2\cdot A_n(r)\cdot\int_0^t T_o(\lambda)\cdot e^{-k\alpha_n^2(t-\lambda)}\cdot d\lambda & \text{if } R_o < r \le R_{eff} \end{cases}$$

$$j_o(t) = \frac{\pi\lambda}{R_o}\cdot\sum_{n=1}^{\infty}\alpha_n^2\cdot e^{-k\alpha_n^2 t}\cdot B_n\cdot I_n - \frac{2k\lambda}{R_o}\cdot\sum_{n=1}^{\infty}\alpha_n^2\cdot B_n\cdot\int_0^t T_o(\lambda)\cdot e^{-k\alpha_n^2(t-\lambda)}\cdot d\lambda$$

With:

- α_n, n^{th} positive root of
  $$J_o(\alpha\cdot R_o)\cdot Y_1(\alpha\cdot R_{eff}) - Y_o(\alpha\cdot R_o)\cdot J_1(\alpha\cdot R_{eff}) = 0$$
- $$B_n = \frac{J_1^2(R_{eff}\cdot\alpha_n)}{J_o^2(R_o\cdot\alpha_n) - J_1^2(R_{eff}\cdot\alpha_n)}$$
- $$A_n(r) = B_n\cdot\left(J_o(r\cdot\alpha_n)\cdot Y_o(R_o\cdot\alpha_n) - Y_o(r\cdot\alpha_n)\cdot J_1(R_o\cdot\alpha_n)\right)$$
- $$I_n = \int_{R_o}^{R_{eff}} r'\cdot f(r')\cdot\left(J_o(\alpha_n\cdot r')\cdot Y_o(\alpha_n\cdot R_o) - Y_o(\alpha_n\cdot r')\cdot J_o(\alpha_n\cdot R_o)\right)\cdot dr'$$

J_o, Y_o, J_1 and Y_1 are Bessels functions.

We see that to calculate T(r,t) or $j_o(t)$, we need to know $T_o(t)$. However, we want to use the second equation to calculate $T_o(t)$ knowing $j_o(t)$.

This is the procedure that has been used for the following calculations.

Calculations and Comparisons between Measurements:

A program has been developed to calculate the temperature in a cell knowing the flux on the well.

We have in INPUT:
- dimensions of a cell: R_o and R_{eff}.
- characteristics of the ground: λ and k.
- the initial temperature: f(r).
- the flux at the border of the well.

In our case the flux is determined with daily measures of the energy stored during a recharge time T_{load} of 12 hours per day. Taking an equal flux on each well, we have to know the total exchange surface of the wells.

Then with
- Q_{stor}: heat stored during a day.
- N_{well}: total number of wells.
- L_{well}: length of a well.
- S_{tot}: total exchange surface of the wells.
- T_{load}: time during which heat is injected.

The flux takes the form for one day:

$j_o(t) = Q_{stor} / S_{tot} \cdot T_{load}$ $\quad 0 < t \leq T_{load}$

$jo(t) = 0$ $\quad T_{load} < t \leq 24\ h$

where $S_{tot} = 2\pi \cdot N_{well} \cdot R_o \cdot L_{well}$.

For the first calculations, we have:

$R_o = 0.075$ m $\quad R_{eff} = 1.3$ m

$\lambda = 2.4$ W/m·K $\quad k = 0.9 \cdot 10^{-6}$ m^2/s (dry moraine)

f(r) = 10.5 °C $\quad R_o \leq r \leq R_{eff}$

At the beginning of the charge period, the ground is supposed to have a constant temperature. The 10.5 °C were measured with the second probe.

$N_{well} = 260$ and $L_{well} = 14$ m.

Figure 13 shows the evolution of temperature calculated at $r = R_{eff}$ and the points are the mean temperature at -6 and -10 m measured in the second probe.

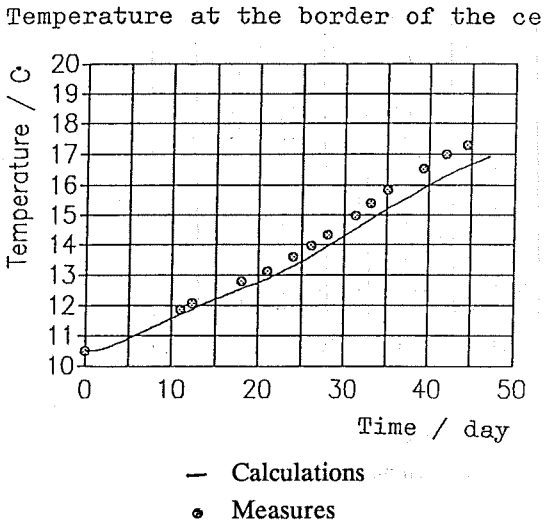

Fig. 13: *Comparison between calculations and measurements.*
Evolution from May 19, 1989 up until July 4, 1989
Measures: *Mean temperature of level -6 and -10 m in probe 2*
Calculations: *Temperature calculated at r = R_{eff}*
Parameter: Thermal diffusivity $k = 0.9 \cdot 10^{-6}$ m^2/s

It is not sure that the second probe is representative of the mean temperature of the store, but if we recalculate with $k = 10^{-6}$ m^2/s instead of $0.9 \cdot 10^{-6}$ m^2/s, we obtain figure 14.

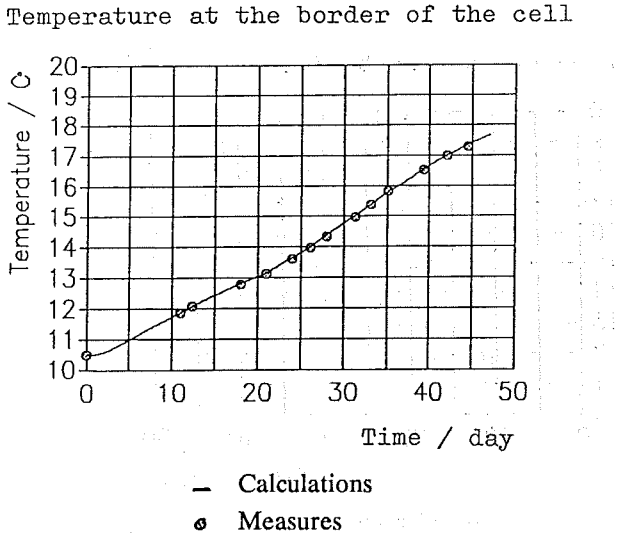

Fig. 14: *Comparison between calculations and measurements.*
Evolution from May 19, 1989 up until July 4, 1989
Measures: *Mean temperature of level -6 and -10 m in probe 2*
Calculations: *Temperature calculated at* $r = R_{eff}$
Parameter: Thermal diffusivity $k = 10^{-6}\ m^2/s$

It shows that:

- the solutions obtained and calculated are correct and constitute a good tool for further investigation.
- the mechanisms of heat transport in the ground are dominated by conduction.

Perspective

Considering the whole store is another problem. How is it possible to link the local process to the whole store ?

As it is shown in figure 15, we see that the natural heat loss makes the calculations differ from the measurements.

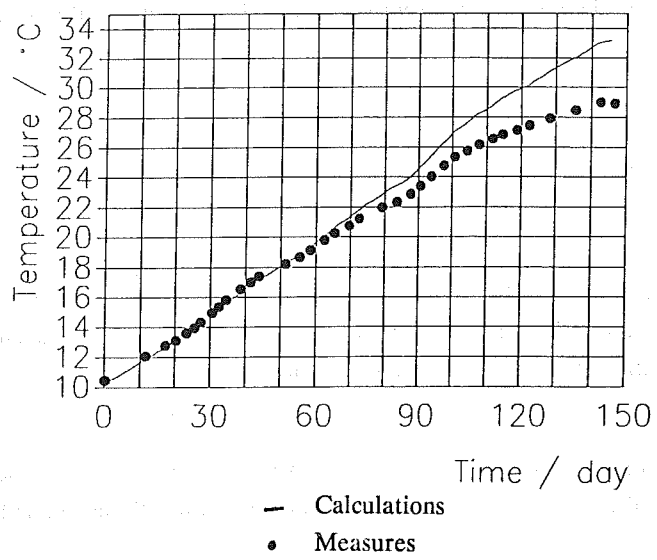

Fig. 15: *Comparison between calculations and measurements.*
Evolution from May 19, 1989 up until October 11, 1989
Measures: *Mean temperature of level -6 and -10 m in probe 2*
Calculations: *Temperature calculated at* $r = R_{eff}$

The horizontal gradient in the centre of the store, typically 0.1-0.5 °C/m, should not be responsible for this difference.

If we have a general look at the store, it will diffuse through its faces. As a result, the flux exchanged will be larger at the border than in the centre. And the mean flux j_o, as defined in the local process, will be overestimated. These considerations lead to the double well model.

The Double Well Model:

The next step is to calculate the flux which passes through the border of the store. The idea is to calculate the temperature of the store with the same procedure as before for a given period. Then we calculate the amount of heat Q which passes through the border of the store during this period.This amount of heat Q will be a correction to the input heat of the next period.

There are essentially two different areas:

a) The top, which is covered with insulation and concrete.

b) The rest of the border which is in direct contact with the ground.

a) The top:

The amount of heat which crosses the top may be evaluated knowing the thermal resistance of concrete, the insulation and the inside temperatures.

b) The rest:

We have seen that a cell is defined with a well of radius R_o which is enclosed within a cylinder of radius R_{eff}. We want to consider the whole store as a well. The radius R_{stor} of this well is obtained from the horizontal section of the store S_{stor}:

$$\pi \cdot R_{stor}^2 = S_{stor}$$

The radius of the cell R_{eff} has to be large enough so that the temperature of the ground at this distance is not affected by the store. We will call this radius R_{cell}.

Then we may calculate the flux at R_{stor} if we know the temperature at this radius. In the case where the temperature of the store is not stratified horizontally, this temperature is given by $T(r=R_{eff},t)$. $T(r=R_{eff},t)$ is calculated with the local process.

If we calculate the flux over a given period, we may obtain the amount of heat which corresponds if we know D_{stor}, the effective depth of the store. In the first approach we may take it so that the surface of the store in the ground is equal to $2 \cdot \pi \cdot R_{stor} \cdot D_{stor}$.

If we ignore the effect of the top, we have the double well model in its simpler form.

Thermal Resistance of the Well:

We hope to attribute a thermal resistance per unit length to the well. If so, we have a complete description of the store.

Conclusion

The first results show that the active solar system and the seasonal heat store behave the way they were designed for.

The thermal behaviour of individual boreholes is satisfactorily described by an analytical model based on a cylindrical geometry and on a very limited number of parameters as well as involving heat conduction only. In the next phase we intent to extrapolate such a model (Double Well Model) in order to describe the thermal behaviour of the entire store.

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