Heat Storage in the Ground

DUCT GROUND HEAT STORAGE MODEL
Manual for Computer Code
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Chapter 1
Duct Ground Heat Storage Model

1.1 Introduction

A duct ground heat storage system is defined as a system where heat is stored directly in the ground. A duct or channel system is used for heat exchange between a heat carrier fluid, which is circulated through the ducts, and the storage region. The heat transfer from the duct system to the surrounding ground takes place by ordinary heat conduction.

We will use the term *ground heat exchanger* for each duct or channel that is used for heat exchange in the ground. The specific arrangement of these ground heat exchangers depends mainly on the geological medium. The properties of rock set it apart from softer media like clay, sand soil, and peat. There are fundamental differences in the design of the ground heat exchanger for these two types of ground.

In solid rock the duct system typically consists of a large number of boreholes, which are uniformly placed in the storage region. Vertical boreholes with diameter of 4-6″ and a spacing of about 4 meters have been used in most of the systems built in Sweden. An alternative arrangement is required for those sites where the ground surface area available for the system is limited. The boreholes are then drilled to form a diverging bundle with increasing duct spacing towards depth.

Each borehole has one or more flow channels in the upward or downward directions for circulation of the heat carrier fluid. The most simple arrangement of the flow channels is to insert a single plastic tube through which the heat carrier fluid is transported down to the bottom of the borehole. The region between the plastic tube and the borehole wall constitutes the channel for upward flow. The fluid is extracted from the top of this channel to the main distribution system. The main advantage of this arrangement, which will be called an *open system*, is that the heat carrier fluid is in direct contact with the surrounding rock in the flow channel outside the plastic tube. This provides for good heat transfer between the heat carrier fluid and the surrounding rock. Unfortunately, the geohydrological and the geochemical conditions at a specific site are often unfavorable for an open system. A common alternative is to provide a *closed system* by inserting one or more U-shaped loops of plastic tubing into the borehole. The base of the loops reaches the bottom of the borehole. The heat transfer from the heat carrier fluid to the surrounding rock takes place via the plastic material and the water or the material that fills the borehole. Thus the heat transfer is not as good as for the open system.

In clay, sandy soil, or peat deposits, the duct system can be obtained by driving down vertical U-shaped loops of thin plastic tubes. For the existing seasonal stores in clay and sandy soil, the spacing between each such ground heat exchanger is typically about 2 meters. This spacing is shorter than that used for boreholes in rock mainly due to the lower thermal conductivity of clay. Ground heat exchangers with two U-shaped loops driven down together may also be used. In shallow deposits, the duct system may be arranged by installing horizontal pipes.

The concept of storing heat in bedrock was first described by the French scientist Brun [*1965, 1967*] in 1965. The first field experiments were initiated around 1976 in France [*Guimbal, 1976*] and in Sweden [*Platell and Wikström, 1981*]. Since then, the conceptual and technical aspects

of heat storage in bedrock have been further developed primarily in Sweden [*Hydén et al; 1983; Andersson et al; 1983; Lundin, 1985; Nordell, 1987*]. There has also been some recent activity in Finland [*Lahtinen, 1983; Puntilla and Saastamoinen, 1983*]. The basic design involves drilling a matrix of boreholes in order to create a heat exchanger within the rock. Conventional well-drilling technology has been used, but further development is required due to the usually big number of boreholes in the store [*Schunnesson, 1983*].

Theoretical studies of large-scale heat storage in clay deposits were first reported in 1977 [*Modin, 1977*]. Field experiments [*Ausseur and Vachaud, 1978; Rosenblad, 1983*] as well as large-scale applications [*Hultmark, 1981*] of this storage technique followed shortly afterwards. During the 80's a few more heat stores have been built in clay [*Olsson, 1983; Chuard et al., 1983*] and in sandy soil [*Wijsman, 1983*]. Seasonal storage in clay for greenhouses has also been investigated [*Areskoug and Wigström, 1980; Nir, 1983*]. The construction methods for heat storage in soft geological media, such as clay and sandy soil, seems to be fairly well established, although the design of the ground heat exchanger may be further improved [*Hellström et al., 1985; Wilén et al., 1985*]. Heat storage in clay deposits is restricted to the low-temperature range due to the possible detrimental effects on the geotechnical properties of clay at high temperatures [*Adolfsson et al., 1983*].

In order to optimize the energy system with a ground heat store, it is necessary to have analytical tools by which the thermal behavior of the store can be assessed. The local thermal processes around a duct have been studied in detail [*Claesson et al., 1985*]. Numerical studies of the natural convection induced by heating a store in sandy soil and the influence of regional flow have been performed [*van Meurs, 1985*]. Simple methods for estimation of the thermal performance are available [*Claesson et al., 1985*]. Detailed simulation models for the store [*Hadorn, 1981; Hellström, 1982; Hadorn and Chuard, 1983; Wijsman and van Meurs, 1985; Eskilson and Claesson, 1988*] or an energy system with a ground heat*International Energy Agency, 1985; Lund and Östman, 1985*] have been developed.

This manual describes a simulation model (DST) for ground heat storage systems. The storage volume has the shape of cylinder with vertical symmetry axis. The ducts are assumed to be uniformly placed within the storage volume. There is convective heat transfer in the ducts and conductive heat transfer in the ground. Insulation sheets may be placed anywhere in the ground outside the storage volume. The temperature in the ground is represented by three parts: A global temperature, a local solution, and a steady-flux part. The global and the local problem are solved with use of the explicit finite difference method (FDM), whereas the steady-flux part is given by an analytical solution. The total temperature at a point is obtained by a superposition of these three parts. This provides for a fast and accurate simulation model for duct ground heat storage.

The DST model simulates a stand-alone heat store. Other components of an energy system are not included in the simulation.

In 1981 the model was chosen by the participants of the International Energy Agency Solar R&D Task VII (Central Solar Heating Plants with Seasonal Storage) to be implemented as a storage module in the MINSUN program. MINSUN is a system simulation program which models a solar energy system containing solar collectors, storage, heat pumps, auxiliary heaters and consumers.

In 1989 the code was translated from FORTRAN to Turbo Pascal 5.0 in order to implement the DST model in a new version of SIMSYS – a simulation model for heating plants with new energy technology. The SIMSYS model can handle different kinds of heat sources; solar collectors, ambient-air convectors, lake water heat pumps, etc.

The Turbo Pascal version of DST consists of two parts: an essential set of procedures that simulates the thermal process in the store and in the surrounding ground; a dispensable shell of procedures that gives the loading conditions, generates output, and displays the results on

the screen in graphics mode. Only the essential procedures are required when the DST model is implemented in a simulation model like SIMSYS.

The DST model has been used extensively both for evaluation of field projects and for dimensioning of heat stores.

1.2 Thermal Processes

The thermal process in the storage region with its duct system is quite complicated. There is a large-scale heat flow between different parts of the store and the surrounding ground. This process interacts strongly with the convective heat transfer in the ground heat exchangers. The global heat flow process in the ground is thus coupled to the local thermal process around each ground heat exchanger. This local thermal process is essentially of the same character throughout the storage region.

1.2.1 Fundamental thermal processes

The thermal analyses require an accurate description of the processes that govern the thermal behavior of the store. The thermal interaction between the often large number of ducts and the heat capacity of the surrounding ground, and the heat transfer properties within the ducts present important problems.

The large-scale heat flow in the storage region determines the heat losses from the store. It has a genuine three-dimensional character that must be accounted for. Typically, the ground consists of horizontal strata of different geological material. The thermal properties may vary accordingly. Thermally insulating material is often placed on the ground surface above the store in order to reduce heat losses. These factors and other large-scale heterogeneities of the thermal properties will influence the global thermal process.

The local process around each duct is very important. It depends to a large extent on the specific arrangements of the flow channels in the ground heat exchanger.

1.2.2 Secondary thermal processes

Other processes that may influence the thermal behavior of the ground heat store are judged to be of secondary importance. Their influence is either small or it may be prevented relatively easily. If the phenomenon is site-specific — it may be a reason to choose another site.

Regional ground water flow may increase the heat losses from a heat store located in a permeable ground layer. A numerical study by van Meurs [*1985*] concerning a porous medium with homogeneous hydraulic properties indicates that the heat store requires a protecting hydraulic screen if the ground water flow exceeds 50 mm/day. Ground water flow in bedrock takes place through fissures and fractured zones within the rock mass. The magnitude of the ground water flow through the storage region depends on the number of fissures, the width of the fissures, the extension of the fractured zones, and the local hydraulic gradients. These factors are very site-specific and a general statement about the influence of on the thermal of the heat store is difficult to make. The experiences from the field projects realized to date show that large storage volumes can be obtained in bedrock where ground water presents minor problems. However, it is obvious that under certain conditions the influence of ground water flow in rock can cause considerable heat losses.

The heating of a water-saturated ground material will induce natural convection due to the temperature-dependent density of water. Buoyancy flow will cause warmer water with lower density to flow upwards. For a ground heat store in a porous medium the natural convection currents will be most pronounced at the vertical boundaries of the store. These currents will

cause warm water to flow out from the upper part of the store and cold water to flow into the lower part. The magnitude of the buoyancy flow depends primarily on the temperature levels of the store and the surrounding ground, the horizontal and vertical permeability of the ground material, and the vertical extension of the store [*Hellström et al., 1988*]. Numerical studies [*van Meurs, 1985*] show that, under normal applications, the thermal performance of the store will be affected if the permeability of the ground exceeds 10^{-12} m^2. However, the presence of interspersed horizontal layers of clay, which are practically impermeable, will reduce the natural convection.

The variation of the boundary conditions at the ground surface during the year can be neglected, except for very shallow ground heat stores. The penetration depth of thermal disturbances due to short-term variations of the conditions in the top-soil layer is very short compared with the depth of the store. A homogeneous infiltration of cold rain water at the ground surface is not important. However, a change of the water content in unsaturated soil layers will influence the thermal properties. It is sufficient to use annual mean values of the ground surface temperature and the thermal properties of the top-soil layer.

Small-scale inhomogeneities in the thermal properties are not significant, except if they occur close to a duct. In that case they will influence the local heat transfer capacity of the ground heat exchanger.

1.3 Local Thermal Process

The basic problem in the analysis of the duct system for ground heat storage is the interaction between the local thermal process around a pipe and the macroscale or global temperature process through the storage and the surrounding ground. A precise description of the local process is necessary in order to obtain the right amount of injected and extracted heat. The heat flow from the pipe to the ground is determined by the fluid temperature, the heat transfer properties, and the temperature in the ground surrounding the pipe. These temperatures, and thereby the heat flow, will vary also along the pipes. The amounts of injected and extracted heat will govern the global thermal process. The local values of the global temperature field are on the other hand necessary for the local problem.

The ground heat exchangers are assumed to be uniformly placed in the storage region. A certain ground region may be assigned to each ground heat exchanger due to symmetry. The cross-sectional area of this ground region is denoted A_p. For the rectangular duct pattern with a duct spacing B and B_1, the cross-sectional area is:

$$A_p = B \cdot B_1 \tag{1.1}$$

For the hexagonal duct pattern, the hexagonal region may be approximated by a cylindrical one, namely:

$$A_p = \frac{\sqrt{3}}{2} B^2 = \pi r_1^2 \tag{1.2}$$

where

$$r_1 = 0.525 \cdot B \tag{1.3}$$

The analysis in this paper shows that the ground heat exchanger has about the same heat transfer capacity for hexagonal and rectangular duct patterns given that the cross-sectional area A_p is the same, and that the duct spacings B and B_1 for the rectangular duct pattern are about equal in length.

Let r be the radial distance from the center of a pipe and r_b the (outer) pipe radius. There is a local, radial thermal process around the pipe in the region $r_b \leq r \leq r_1$. The pipe radius

r_b is much smaller then r_1. The heat flux is zero at the outer boundary $r = r_1$, when only the local process is considered.

At the inner pipe radius $r = r_b$ there will be a certain time-varying heat flux. Let us consider the following fundamental case. There is a constant heat injection rate q that starts at $t = 0$. Let T_c be the constant initial temperature in the cylindrical region around the pipe. Figure 1 shows the character of the temperature field of this fundamental case.

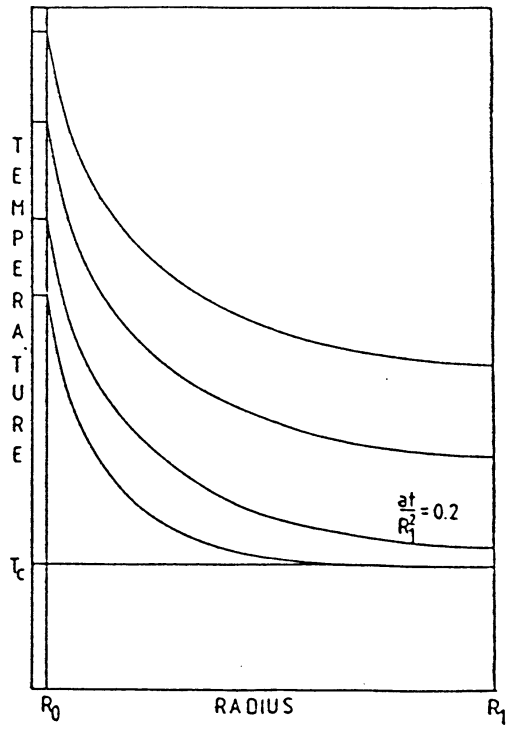


Figure 1. Temperature response to a constant heat injection rate.

The thermal conductivity is λ, the volumetric heat capacity C, and the thermal diffusivity $a = \lambda/C$. The temperature in the fluid is denoted $T_f(t)$. The total thermal resistance, per unit length of the pipe, between the fluid and the ground at $r = r_b$ is denoted R_b.

The influence of the outer boundary $r = r_1$ is negligible during a certain initial period. The process is the same as that of a pipe in an infinite surrounding. The solution of this case is given in [*Carslaw and Jaeger, 1959*]. The influence at the pipe of the outer boundary is felt after a time $at/r_1^2 = 0.2$, and thereafter the solution changes character. The temperature profile becomes constant. The temperature increases linearly as the mean temperature:

$$T_m(t) = \frac{q}{\pi C r_1^2} \cdot t \tag{1.4}$$

The heat flux is at each point constant in time. We are in the important steady-flux regime. Between the fluid temperature $T_f(t)$ and the mean temperature $T_m(t)$ there is the following basic relation:

$$T_f(t) \simeq T_m(t) + \frac{q}{2\pi\lambda}[2\pi\lambda R_b + \ln(\frac{r_1}{r_b}) - \frac{3}{4}] \qquad \frac{at}{r_1^2} > 0.2 \tag{1.5}$$

The heat injection per unit volume is proportional to the difference $T_f - T_m$:

$$\frac{q}{\pi r_1^2} = \frac{\lambda(T_f - T_m)}{\ell^2} \qquad \frac{at}{r_1^2} > 0.2 \tag{1.6}$$

Here ℓ is a characteristic heat transfer length between the fluid in the pipe and the surrounding ground:

$$\ell = r_1 \sqrt{\frac{1}{2}[\ln(\frac{r_1}{r_b}) - \frac{3}{4} + 2\pi\lambda R_b]} \tag{1.7}$$

The relation between the fluid temperature and the injection rate q is given by (1.4-5). The fundamental importance of the steady-flux regime and the heat transfer length is due to the fact that any time-varying injection/extraction $q(t)$ may be considered as a superposition of step-pulses of the considered type.

Consider the following case of granite storage: $r_b = 0.05$ m, $r_1 = 2$ m, and $a = 1.6 \cdot 10^{-5}$ m^2/s. Eq. (1.5) is valid after 6 days. In the analysis of the longtime behaviour on a time-scale of weeks Eqs. (1.4-7) can be used.

The steady-flux regime and the concept of a heat transfer length ℓ is quite useful for duct systems for ground heat storage. The complicated local thermal process is, on an appropriate time-scale, of special character which is determined by a single parameter ℓ. Here, the steady-flux concept is used for the redistribution of heat in the storage volume. A number of radial problems for the local thermal process around the pipes are solved numerically in order to handle time-varying loading conditions.

1.3.1 Superposition

In the present model the temperature at a given point in the storage is a superposition of three parts: A global solution, a steady-flux solution around the nearest pipe, and a local radial solution.

The temperature of the heat carrier fluid at the inlet to the duct system is a function of time $T_{fin}(t)$. The variation of the fluid temperature along the flow path through the ducts is accounted for by use of a heat balance equation. The rate of heat injection/extraction $Q(t)$, or the inlet fluid temperature $T_{fin}(t)$, or a $Q(t)$ that depends on $T_{fin}(t)$ may be specified.

The ground in the storage volume is assumed to have homogeneous thermal properties. Outside the storage volume the ground may consist of different strata and thermal insulations may be put anywhere. The thermal properties of the ground and the arrangement of ducts are assumed to exhibit cylindrical symmetry with respect to a vertical axis through the middle of storage region. The global problem, which does not include the local temperature fields, therefore becomes a function of the radial and the vertical coordinates. The heat flow process in the storage region and the surrounding ground is modeled using a rectangular two-dimensional mesh.

The storage volume is divided into a number of subregions. There is one local solution for each subregion. They also define the flow path of the heat carrier fluid. The injection/extraction of heat gives a distribution of sources and sinks for the global solution, which satisfies

$$C\frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + q_{sf} + q_\ell \tag{1.8}$$

The source term q_{sf} uses the steady-flux solution to account for pulses that vary slowly in time. Here, it is used for the redistribution of heat in each subregion of the storage volume. The source term q_{sf} for a given cell in the mesh is proportional to the difference between the mean temperature of the subregion in question and the temperature in that cell. There is no net energy contribution to the storage by this process.

The short-time effects of the injection/extraction through the ducts are simulated with the local solutions. This solution is assumed to be the same for all pipes within a given subregion. The solution depends only on a radial coordinate and covers the volume from the pipe to the radius r_1 (see (1.1-3)). An energy pulse at a given moment from the pipes to the surrounding

ground is retained in the local problem for a period of time corresponding to $at/r_1^2 = 0.2$. The energy of the pulse is with this time lag added to the global solution as an increase of the temperature with the same amount in the whole subregion, i.e. the source term q_ℓ is a constant within each subregion. The same temperature difference is subtracted from the local solution. The longtime effects are thus shifted over to the global solution.

The short-time variations are covered by the local problems. The slow redistribution of heat during injection/extraction and the interaction between the storage region and the surrounding ground are accounted for by the steady-flux and the global solution.

Chapter 2
Numerical Procedure

2.1 Introduction

The numerical procedure used for simulating the duct storage system was outlined in the previous section. The thermal process is modeled as a superposition of three parts: global, steady-flux, and local problems. These three parts will be discussed independently in this section.

A heat balance for the heat carrier fluid gives the temperature variation along the flow path. This variation is especially important at low fluid flow rates.

2.2 Global problem

The global problem is essentially an ordinary heat conduction problem with two heat source terms in the storage region. It covers the large-scale thermal process, such as the interaction between the storage and the surrounding ground, between different parts within the storage, the influence of the conditions at the ground surface etc. Any details in the temperature field associated with individual ducts are left to the steady-flux and local problem. See sections 2.3 and 2.4.

The simulated volume includes the storage volume and a sufficient part of the surrounding ground. Storage volume, thermal properties, arrangement of ducts, and temperature field are assumed to exhibit cylindrical symmetry with respect to an axis through the center of the storage volume. The thermal properties of the ground are given by the thermal conductivity and the volumetric heat capacity. The present version of the model assumes homogeneous thermal properties within the storage volume. In the surrounding ground they may vary from cell to cell. Insulations may be put anywhere along the surfaces of the storage volume, at the ground surface or in the surrounding ground.

At the ground surface there is a given time-varying temperature. Since the distance from the surface to the storage volume is on the order of meters it is usually enough to use mean values of the ground surface temperature for quite long periods of time. Daily variations are not important. These mean values may be derived from real weather data or supplied as a prescribed function in the program. The inner radial boundary is a symmetry axis, which means that there is no heat flow across this boundary. The outer boundaries of the surrounding ground are chosen so as not to have any significant influence on the thermal process in the storage region. The temperature in the boundary cells should not be significantly influenced by the storage process, which is easy to check. Obviously, the location of the boundaries depends on the size of the storage volume, the thermal properties of the ground, and the duration of the simulated period.

The numerical model uses the explicit finite difference method (FDM). The simulated ground volume is divided into a two-dimensional mesh using a radial coordinate r and a vertical coordinate z. See figure 2.

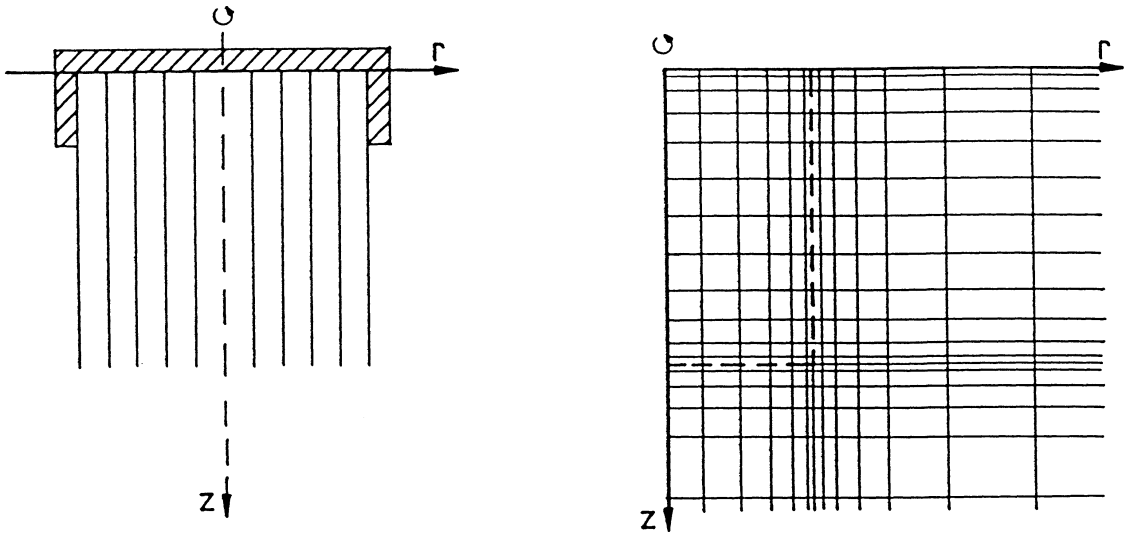


Figure 2. An example of a mesh used for the global problem.

The heat balance for a given cell is quite simple. The net heat flow to the cell changes the temperature so that energy is conserved. The heat flows are estimated by simple difference equations. The indices in the radial and vertical directions are denoted i and j. The radial heat flow between cell $(i-1,j)$ and (i,j) becomes

$$F_r(i,j) = K_r(i,j) \cdot [T(i-1,j) - T(i,j)] \tag{2.1}$$

Where K_r is the heat conductance between cell $(i-1,j)$ and (i,j). A logarithmical expression for the thermal resistance is used when calculating the heat transfer coefficient in the radial direction between two cells. In the vertical direction the flow between cell $(i,j-1)$ and (i,j) is:

$$F_z(i,j) = K_z(i,j) \cdot [T(i,j-1) - T(i,j)] \tag{2.2}$$

For a cell in the storage volume there are two heat source terms to be considered, namely the one that transfer heat from the local problem and the one that redistributes heat within the storage volume due to circulation of the heat carrier fluid. The net contribution from these heat sources to cell (i,j) is denoted $Q_\ell(i,j)$ and $Q_{sf}(i,j)$. When the values of the heat source terms, the temperatures of the nodal points and at the ground surface are known at a given time it is straightforward to calculate the new temperature field. The new temperature for cell i,j becomes:

$$\begin{aligned} T(i,j)_{t+\Delta t} &= T(i,j)_t + [F_r(i,j) - F_r(i+1,j) + F_z(i,j) - F_z(i,j+1) + \\ &\quad + Q_\ell(i,j) + Q_{sf}(i,j)] \cdot \Delta t / C(i,j) \end{aligned} \tag{2.3}$$

Here Δt is the time-step and C the heat capacity of the cell.

2.3 Heat balance for the heat carrier fluid

When the temperature of the heat carrier fluid differs from the temperature of the surrounding ground there will be a transfer of heat between these two parts. The fluid will lose or gain energy, and its temperature will vary along its flow path through the storage volume. The amplitude of the temperature variations depends, among other things, on the fluid flow rate. If transient terms in the fluid are neglected the heat balance equation for the heat carrier fluid may be written:

$$C_f q_{fp} \frac{\partial T}{\partial s} + \alpha_p (T_f - T_a) = 0 \tag{2.4}$$

or

$$C_f q_{fv} \frac{\partial T}{\partial s} + \alpha_v (T_f - T_a) = 0 \tag{2.5}$$

Here, C_f is the volumetric heat capacity of the fluid, q_f is the fluid flow rate, $T_f(s,t)$ is the fluid temperature, α is the heat transfer coefficient between the fluid and the point in the surrounding ground with temperature T_a. The first expression is a heat balance per unit length of pipe (index p) while the second one considers the balance of a unit volume in the storage (index v). The length coordinate along the flow path is s.

A damping factor is defined as

$$\beta = e^{-\frac{\alpha_v V}{C_f Q_f}} = e^{-\frac{\alpha_p L_p}{C_f Q_f}} \tag{2.6}$$

Here, V is the storage volume, Q_f is the total fluid flow rate, and L_p is the total pipe length in the storage volume. The fluid temperature at the outlet from the volume may now be expressed as

$$T_{fout} = \beta \cdot T_{fin} + (1 - \beta) \cdot T_a \tag{2.7}$$

Here T_{fin} is the inlet temperature. We observe that when the fluid flow rate approaches zero the outlet temperature approaches the temperature T_a of the surrounding ground. On the other hand, the outlet temperature equals the inlet temperature as the fluid flow rate goes to infinity.

The total effect injected to the volume is

$$Q = C_f Q_f (T_{fin} - T_{fout}) \tag{2.8}$$

Using the expression (2.7) for the outlet temperature and normalizing to unit volume (2.8) becomes

$$q = \frac{C_f Q_f}{V} \cdot (1 - \beta) \cdot (T_{fin} - T_a) \tag{2.9}$$

These formulas are used to account for the effect of temperature variations along the fluid flow path. It is used both in the local and the steady-flux problem.

2.4 Local problem

The thermal process around the individual ducts due to short-time variations is modeled using a one-dimensional radial mesh. The storage region V is divided into N subregions. The local problem is assumed to be the same around each pipe in a given subregion. There is one local problem for each subregion. See figures 3 and 4.

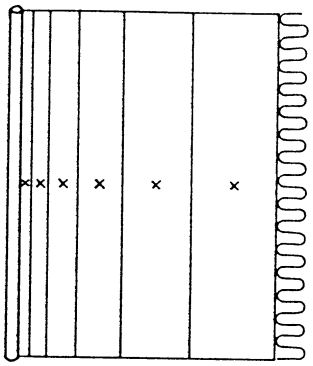


Figure 3. An example of a mesh for the local problem in a subregion.

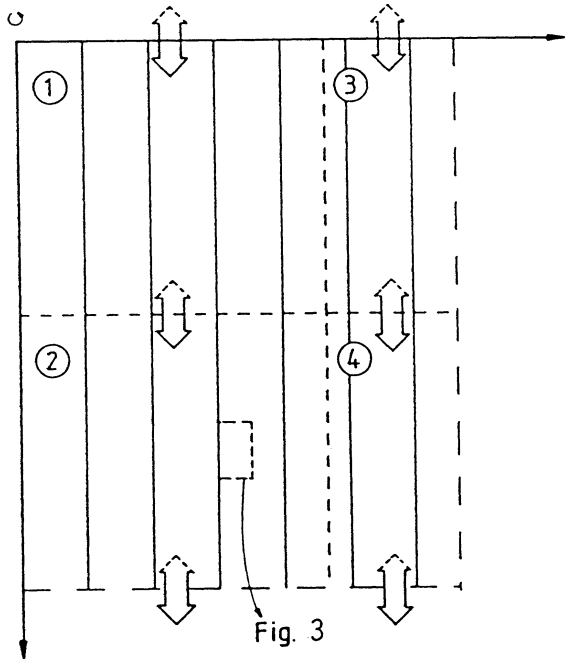


Figure 4. Division of the storage volume into four subregions.

The local temperature T_ℓ satisfies the radial heat conductions equation with a sink:

$$C\,\frac{\partial T_\ell}{\partial t} = \lambda\left(\frac{\partial^2 T_\ell}{\partial r^2} + \frac{1}{r}\frac{\partial T_\ell}{\partial r}\right) - q_\ell \qquad r_b < r \le r_1 \tag{2.10}$$

Here, the thermal conductivity is λ, the volumetric heat capacity is C and q_ℓ is the heat source term used to transfer heat from the local to the global problem. The outer boundary ($r = r_1$) is totally insulated, i.e. there is no heat flow across this boundary.

The subregions are used to define the flow path through the storage volume. The fluid flows through V_1, V_2, $\ldots V_N$ when $Q_f > 0$ and in the opposite direction when $Q_f < 0$. The number of subregions that is needed in order to obtain acceptable accuracy depends on the magnitude of the temperature variations along the flow path through the storage. The accuracy is often acceptable with quite few subregions. However, sometimes it may be necessary to use

many subregions if the flow path is complicated and the fluid flow rate is small. The suitable subdivision of the storage region is checked by varying the number of subregions.

Each subregion normally contains several global cells. The mean global temperature in subregion k is denoted T_g^k. The inlet fluid temperature to this section is T_f^k and at the outlet we have T_f^{k+1}. The average temperature of the local cell ($j = 2$) immediately outside the pipe for all cells in subregion k is:

$$T^k = T_{\ell,j=2}^k + T_g^k \tag{2.11}$$

The fluid inlet/outlet temperatures are related by (see section 2.3)

$$T_f^{k+1} = \beta^k T_f^k + (1 - \beta^k) T^k \tag{2.12}$$

where

$$\beta^k = e^{-\frac{\alpha_p^k L_p^k}{C_f Q_f}} \tag{2.13}$$

Here L_p^k is the total pipe length in section k, and α_p^k is the heat transfer coefficient between the fluid in the pipe and the first cell outside the pipe.

The inlet fluid temperature to the storage region may be a given function of time

$$T_f^1 = T_{fin}(t) \tag{2.14}$$

The inlet temperatures T_f^2, T_f^3, ... to each subregion can be calculated by successively applying (2.12).

Another option in the specification of loading conditions is a prescribed rate of injection or extraction of heat. This has to be converted to an inlet fluid temperature that gives the required effect. A successive use of (2.12) leads to a relation between inlet and outlet fluid temperatures of the type

$$T_{fout} = B \cdot T_{fin} + A \tag{2.15}$$

Here A and B are constants that depend on the damping factors β_k. The constant A also depends on the ground temperatures T^k. The total effect may be written

$$Q = C_f Q_f \left[(1 - B) T_{fin} - A\right] \tag{2.16}$$

The inlet fluid temperature is now given a trial value, which is most conveniently set to zero

$$T_{fin}^0 = 0 \tag{2.17}$$

From (2.16) the corresponding trial effect becomes

$$Q^0 = -C_f Q_f A \tag{2.18}$$

Then by subtracting (2.18) from (2.16) we get

$$Q - Q^0 = C_f Q_f (1 - B) T_{fin} \tag{2.19}$$

Finally the required inlet fluid temperature can be calculated as

$$T_{fin} = \frac{Q - Q^0}{C_f Q_f (1 - B)} \tag{2.20}$$

An additional option for the specification of loading conditions allows for upper and lower limits on the fluid temperature. A desired effect will be used unless the limiting values on the fluid temperature are violated. In that case the loading process will continue with the limiting value as inlet temperature.

The accumulated injection of heat and extraction of heat are computed in the local problem. In the same way the accumulated injection and extraction of thermality are computed. The thermality is treated in [*Claesson, 1979*].

The thermality flow equals the total heat injection/extraction rate times the mean temperature of the fluid in the storage volume. The following expression for the instantaneous value of the thermality injection is used

$$C_f Q_f (T_{fin} - T_{fout})/2 = C_f Q_f (T_{fin}^2 - T_{fout}^2)/2 \tag{2.21}$$

2.5 Heat transfer from local to global problem

The heat source term q_ℓ in the global solution originates from the heat transfer from the fluid to the local problem. Let E_k be the amount of injected heat to a subregion k in the local problem during a global time-step t_g. This heat source term for subregion k is:

$$q_\ell = \frac{E_k}{t_g \, V_k} \tag{2.22}$$

Here V_k is the volume of subregion k. Expressed as a temperature increase in subregion k of the global solution this is:

$$\Delta T_g = \frac{q_\ell \, t_g}{C} = \frac{E_k}{C \, V_k} \tag{2.23}$$

Here C is the volumetric heat capacity in the storage.

The heat transfer due to the source term q_ℓ is effectuated as a mutual temperature change in the local and global temperature fields for each subregion.

2.6 Steady-flux problem

The steady-flux solution which was discussed in section 1.3 gives the temperature field around a pipe for a constant injection/extraction rate. It is used for pulses that vary slowly in time, namely the redistribution of heat within the storage due to the circulation of fluid.

The source term q_{sf} for a global cell j is proportional to the difference between the temperature of the cell $T_{g,j}^k$ and the mean temperature T_g^k of the subregion k. Eq. (2.7) is used for the heat balance in the heat carrier fluid. The outlet temperature from subregion k is

$$T_{sf,fout}^k = \sum_j \frac{V_{k,j}}{V_k} \left[\beta_{sf}^k T_{sf,fin}^k + (1 - \beta_{sf}^k)(T_{g,j}^k - T_g^k) \right] = \beta_{sf}^k T_{sf,fin}^k \tag{2.24}$$

Here $V_{k,j}$ is the volume of the global cell j in subregion k. The total fluid temperature is the sum of the fluid temperature used in the steady-flux part T_{sf} and that used in the local problem. The inlet temperature for the steady-flux problem is chosen to be zero ($T_{sf,fin} = 0$). From (2.24) it then follows that the inlet and the outlet temperatures to and from each subregion are zero. The condition of the prescribed inlet temperature is taken care of in the local problem. It should be observed that the net energy contribution to each subregion in the global problem from the steady-flux part is zero.

The heat source term for a global cell in subregion k becomes

$$q_{sf} = \frac{C_f Q_f}{V_k} (1 - \beta_{sf}^k)(T_g^k - T_{g,j}^k) \tag{2.25}$$

Here V_k is the volume of subregion k. The damping factor for the steady-flux part is (2.6):

$$\beta_{sf}^k = e^{-\frac{\alpha_v V_k}{C_f Q_f}} \tag{2.26}$$

where

$$\alpha_v = \frac{\lambda}{\ell^2} \tag{2.27}$$

is the heat transfer coefficient derived in section 1.3.

It should be noted that the steady-flux heat source term depends on the temperature of an individual cell whereas the local heat source q_ℓ term is the same for each subregion.

The steady-flux temperature in the circular region around a pipe is

$$T_{sf} = (T_g^k - T_{g,i,j}^k) \cdot \frac{r_1^2}{2\ell^2} \cdot h\left(\frac{r}{r_1}\right) \tag{2.28}$$

where

$$h\left(\frac{r}{r_1}\right) = \frac{1}{2}\left(\frac{r}{r_1}\right)^2 - \ln\left(\frac{r}{r_1}\right) - \frac{3}{4} \tag{2.29}$$

2.7 Superposition of temperatures

The temperature in the ground is a superposition of three parts: local, global, and steady-flux temperature. The exact locations of the ducts are not known in this model. In order to obtain the superposed temperature one has to specify the radial distance to the nearest pipe. First the global cell (i, j) is given. The appropriate subregion is then automatically calculated in the program. The radial distance from the pipe is obtained by specifying the coordinate j' for the appropriate nodal point in the local mesh. The superposed temperature now becomes

$$T = T_{g,i,j}^k + T_{\ell,j'}^k + T_{sf,j'}^k \tag{2.30}$$

Chapter 3
Description of Computer Code

The DST program is a stand-alone model that is used to simulate ground heat storage where ducts are used for heat exchange between a heat carrier fluid and the surrounding ground. There is no interaction with other components of an energy system.

The Turbo Pascal version of DST consists of two parts: an *essential* set of procedures that simulates the thermal process in the store and in the surrounding ground; a dispensable *shell* of procedures that gives the loading conditions, generates output, and displays the results on the screen in graphics mode.

Only the essential procedures are required when the DST model is implemented in an energy system simulation model like SIMSYS. The essential procedures and important parameters are described in this chapter.

The Turbo Pascal source code is supplied with the program. The code is divided into a number of Turbo Pascal Units.

3.1 Essential procedures

The essential procedures are contained in four Turbo Pascal Units:

DST_GLOB	Declarations of global variables
DST_INIT	Initialization procedures
DST_MAIN	Main simulation procedures
MATH_LIB	Mathematical functions

Each unit will be described below.

3.1.1 Unit DST_GLOB

This unit contains declarations of global parameters. The two-dimensional and one-dimensional fields are described in section 3.2.1 and 3.2.2 respectively. Some important parameters are described in section 3.2.3.

3.1.2 Unit DST_INIT

Procedures marked with a † are local to `initialize_dst`.

`coord1`†
Reads input for generation of the mesh if the long version of input data is used.

`coord2`†
Reads input for generation of the mesh if the long version of input data is used.

get_maximum_timesteps†
Obtains the maximum timesteps for the conductive process in the ground and in the store. Sets the maximum time-steps used in the calculation. Optionally prints these time-steps.

get_options†
Reads options for printing, buffert handling, and graphics output.

ground_coupling_coefficients†
Calculates the coupling coefficients for the conductive process in the ground.

ground_maximum_timestep†
Calculates the maximum timestep for the conductive process in the ground.

ground_2d†
Reads the thermal properties in the ground if the long version of input data is used.

initialize_parameter_values†
Initializes some fields and parameter values.

initialize_dst
Main procedure for initializing the DST program. Reads input data for defining dimensions of store, thermal properties in the storage volume and in the surrounding ground, and initial temperatures.

input_long_version†
Main routine for input of the long version.

input_short_version†
Main routine for input of the short version.

input_store†
Reads data for the storage volume if the long version of input data is used.

input_2d†
Reads the two-dimensional fields if the long version of input data is used.

mesh_generation†
Generates the numerical mesh.

mesher1†
Used to generate a numerical mesh between two storage boundaries based on the thermal properties of the ground.

mesher2†
Used to generate an expanding numerical mesh from a storage boundary based on the thermal properties of the ground.

mesher3†
Used to generate an expanding numerical mesh for the local problem based on the thermal properties of the ground.

print_input_local_problem†
Prints the thermal properties of the local problems.

print_input_summary†
Prints a summary of input data if the short version of input data has been used.

print_volij†
Prints the subregions of the storage volume.

print_2d
Prints two-dimensional fields.

print_2d_input_fields†
Controls the printing of two-dimensional input fields.

stop_if_errors†
Generates a message if input errors have been detected.

store_coupling_coefficients†
Calculates the coupling coefficients for the conductive process in the store.

store_maximum_timestep†
Calculates the maximum timestep for the conductive process in the ground.

thermal_properties†
Assigns thermal properties to the cells in the numerical mesh.

timtosec
Converts special format for time input to seconds (see section 4.4).

3.1.3 Unit DST_MAIN

add_chs_temperature
Calculates new temperatures after redistribution of heat in the storage subregions based on the steady-flux solution.

add_local_temperature
Adds the contributions from the local problems to the global temperature field in the storage region.

air_temperature
This routine supplies a periodic air-temperature if `NAIR=1`.

beta_steady_flux
Calculates flow-rate dependent coefficient for steady-flux solution.

duct_heatflow
Calculates fluid temperature and heat flow from fluid to surrounding ground for each subregion of the storage volume.

global_heatflow
Calculates the heat flows for the global problem.

global_temperature
Calculates new temperatures in the global problem and heat losses from the storage region.

local_process
Calculates fluid temperature and heat flow from fluid to surrounding ground for each subregion of the storage volume.

store_mean_global_temperature
Calculates the mean temperature in the storage region of the global problem.

tmstor
Calculates the mean temperature in the storage region. It includes both the local and global problem.

dst
The main routine of the computer code. The arguments are:

`time`	Actual time at the call (s).
`dtdem`	Simulation time-step (s). The `dst` procedure performs storage simulation for the period period from `time` to `time+dt`.
`lomode`	=0, rest period. =1, given heat injection rate. =2, given heat injection rate with restrictions on fluid temperature. =3, given inlet fluid temperature.
`qdem`	Given heat extraction rate (W). (Used if `lomode`=1 or 2).
`tdem`	Given inlet fluid temperature. (Used if `lomode`=2 or 3).
`qwdem`	Volumetric fluid flow (m^3/s).
`tair`	Ground surface temperature. It is used if `NAIR=0`.
`tin`	Inlet fluid temperature at the end of the call. Output.
`tout`	Outlet fluid temperature at the end of the call. Output.
`tmsto`	Mean temperature in the store at the end of the call. Output.
`dloss`	Heat losses to the surrounding ground during the call (J). Output.

3.1.4 Unit MATH_LIB

This units contains functions that calculate the minimum and maximum value of two parameters. The parameters may be of the Turbo Pascal data types integer, single, or double. There is also a function that calculates x^y for the single type.

3.2 Fields and parameters

3.2.1 Two-dimensional fields

The cell indices in the horizontal and the vertical direction of the cell structure in the global problem are `i` and `j` respectively. The cell index in the radial direction of the local problem is

denoted ir. There may be several local problems. The different local problems are identified by the index iloc.

arear[i,j]	The area of the partition between the cells [i-1,j] and [i,j]
areaz[i,j]	The area of the partition between the cells [i,j-1] and [i,j].
cin[i,j]	The volumetric heat capacity (J/m^3,K) in cell [i,j] during input. After initiation it is redefined as the inverted total heat capacity (K/J) in cell [i,j].
fr[i,j]	The total heat flow between the cells [i-1,j] and [i,j] (W).
frr[iloc,ir]	The heat flow between the cells [i-1] and [i] in the local problem iloc.
fz[i,j]	The total flow between the cells [i,j-1] and [i,j] (W).
gfr[i,j]	The coupling coefficient which relates the temperature difference between the cells [i-1,j] and [i,j] to the heat flow. fr[i,j]=gfr[i,j]*(t[i-1,j]-t[i,j]).
gfz[i,j]	The coupling coefficient which relates the temperature difference between the cells [i,j-1] and [i,j] to the heat flow fz[i,j].
gvohs[i,j]	Used to define the storage region in the global problem during input. After initialization it is redefined as a coupling coefficient for the steady-flux part of the solution.
invol[i,j]	Non-zero values indicate a cell in the storage volume. The value is used to identify a subregion and to define the flow path of the heat carrier fluid through the storage volume.
risor[i,j]	The thermal resistance (m^{2}K/W) between the cells [i-1,j] and [i,j].
risoz[i,j]	The thermal resistance (m^{2}K/W) between the cells [i,j-1] and [i,j].
rlam[i,j]	The thermal conductivity (W/mK) in cell [i,j] during input. After initialization it is redefined and used when printing global heat flows.
t[i,j]	The temperature in cell [i,j].
tr[iloc,ir]	The temperature in cell [ir] of the local problem iloc.
tsf[i,j]	The amplitude of the steady-flux sloultion in cell [i,j].

3.2.2 One-dimensional fields

beta[iloc]	Used in the local problem when calculating the temperature change in the heat carrier fluid along the flow path.
cinr[ir]	Inverted total heat capacity (K/J) in cell [i] in the local problem.
dtemp[iloc]	Temperature change in a subregion of the global problem originating from injection/extraction to the local problem.
gfrr[ir]	The coupling coefficient which relates the temperature difference between the storage cells ir-1 and ir to the heat flow frr[iloc,ir]. frr[iloc,ir]=gfrr[ir]*(tr[iloc,ir-1]-tr[iloc,ir]).
plstl[iloc]	The total duct length in a subregion.
r[i]	The horizontal coordinate of the partition between the cells [i-1,j] and [i,j] in the global problem.
rm[i]	The horizontal coordinate of the midpoint of cell [i,j] in the global problem.
rmr[ir]	The horizontal coordinate of the midpoint of cell [ir] in the local problem.
rr[i]	The horizontal coordinate of the partition between the cells [ir-1] and [ir] in the local problem.
sfbeta[iloc]	A parameter used to account for the effect of the fluid flow rate for the steady-flux solution.
tgm[iloc]	Mean temperature in a subregion of the global solution.
tsfh[ir]	Dimensionless temperature given by the steady-flux solution. The amplitudes are given by tsf[i,j].
voloc[iloc]	Fraction of the storage volume that a subregion occupies.
z[j]	The vertical coordinate of the partition between the cells [i,j-1] and [i,j] (m).
zm[j]	The vertical coordinate of the midpoint of cell [i,j] (m).

3.2.3 Some other variables

`chatm`	The end time of the current loading period.
`chatmo`	The time when the current loading period started.
`cpst`	Total heat capacity (J/K) of the fluid in the pipes.
`crtot`	Total heat capacity (J/K) in the region outside the pipe in the local problem.
`cst`	Total heat capacity (J/K) in the local problem including the fluid in the pipe.
`cw`	Volumetric heat capacity of the heat carrier fluid.
`d1`	Heat transfer length ℓ (m) discussed in the theory section.
`dt`	Time-step used in the global problem.
`dtdem`	Time-step to the next print time or end of loading period. This time-step is given to the DST subroutine from the main program.
`dtmax`	Maximum time-step that ensures numerical stability of the solution for the global problem.
`dtokay`	Maximum allowed time-step for the global problem. Given as input.
`dtr`	Time-step used in the local problem.
`dtrmax`	Maximum time-step that ensures numerical stability of the solution for the local problem.
`ebot`	Accumulated heat loss through the bottom of the storage volume (J).
`endtm`	The time when the simulation ends (s).
`eneg`	Extracted amount of heat (J).
`eplus`	Injected amount of heat (J).
`eside`	Accumulated heat loss through the side of the storage volume (J).
`etaq`	Energy efficiency defined as `eneg/eplus`. It is calculated when `lomode<0`.
`etat`	Temperature efficiency.
`etop`	Accumulated heat loss through the top of the storage volume (J).
`gvohst`	The quantity $\lambda V/\ell^2$ discussed in section 1.3.
`ibloss`	Heat loss balance is made if `ibloss`=1.
`imax`	The number of cells (including one for boundary nodes) in the radial direction of the ground cell structure.
`imaxr`	Number of cells (including the pipe) in the local problem.
`jmax`	The number of cells (including one for boundary nodes) in the vertical direction of the ground cell structure.
`jtz`	`j`-value for the top row inside the storage volume in the ground cell structure.
`jbz`	`j`-value for the bottom row inside the storage volume in the ground cell structure.
`lomode`	Loading mode (see section 4.1 or 4.2).
`plst`	Total duct length in the storage.
`qdem`	Total heat injection rate that the main program demands to be injected into the storage region. It will be injected if no restrictions on fluid temperature are violated.
`qdem1`	Actual total heat injection rate that is supplied to the storage region. It may differ from `qdem` if `lomode` equals 2 (or 3).
`qwdem`	Volumetric fluid flow rate (m^3/s).
`qwgm`	Mean fluid flow rate during a global time step.
`r0`	Radius of the circualr duct.
`r1`	Outer radius of the region used for the local problem.
`rlamr`	Thermal conductivity (W/mK) for the local problem.
`rmpipe`	Thermal resistance (m^2K/W) between the fluid and the ground immediately outside the pipe.
`stoptm`	The end time of the loading period or the time when the simulation ends, whichever comes first (s).
`strttm`	The time when the simulation starts (J).
`tair`	Ground surface temperature.
`tdem`	Inlet fluid temperature when `lomode`=3. When `lomode`=2 the fluid temperature cannot exceed/subceed TDEM during injection/extraction.
`therm`	Net thermality in the system. `therm=thplus-thneg`.

`thneg`	Thermality of the extracted heat. `thneg` divided by `eneg`, gives the mean extraction temperature.
`thplus`	Thermality of the injected heat. `thplus` divided by `eplus` gives the mean injection temperature.
`time`	The current time at the call of routine `dst` (s).
`timglo`	Time counter within each global time-step. It is reset to zero when a global heat balance is made.
`tin`	Inlet fluid temperature.
`tmstor`	Average temperature in the storage volume.
`tout`	Outlet fluid temperature.
`tpipe`	Temperature of the fluid in the duct.
`tpiper`	Difference between the fluid temperature `tpipe` and the mean storage temperature `tstave` in the global problem. It is used as the fluid temperature in the local problem.
`tstave`	Average value of the temperature in the storage region of the global problem. This and the average temperature in the local problem gives the mean temperature `tmstor` in the storage.
`t0`	Reference temperature for the thermality calculation.
`volst`	Total volume of the storage region.

3.3 Shell procedures

DST

This is the main program of the DST shell. It gives an example on how to call the essential procedures of `dst`.

Unit DST_DECL

This unit contains declarations of global variables used by the shell routines.

Units DST_EGA1 and DST_EGA2

The code for the graphics output is contained in these units. The initialization of the graphics screen is handled by `dst_ega1`.

Unit DST_OUT

Procedures for printing output from the DST model.

Unit DST_RUN

This unit contains most of procedures used by the shell program. Opens input and output files. Reads loading conditions.

Chapter 4
Description of Input

The simulation model permits a rather a detailed description of the storage volume, the thermal properties in the ground, and the initial temperatures. See section 4.1. However, this requires some input data to the model that may be superfluous in many cases, e.g. when a quick estimate of the thermal performance of a certain storage configuration is needed. An option of using a less detailed description has been provided for the case of a cylindrical underground storage volume. The numerical mesh is generated automatically based on a physical description of the storage volume and the thermal properties in the surrounding ground. The input data to the model then become much simpler. See section 4.2.

Special procedures are used for input of one- and two-dimensional fields. These routines are described in section 4.3. Time data may be given in various ways. See section 4.4.

4.1 Long version with detailed description of the store

1. LQST
=1, input questions printed.
=0, otherwise.

2. LPRT
=1, input data printed.
=0, otherwise.

3. LFPRT
=2, one- and two-dimensional fields, time-step information, and summary of new loading conditions are printed.
=1, only time-step information and summary of new loading conditions are printed.
=0, otherwise.

4a. IGRAPH
=1, results will be presented in graphic mode (requires EGA).
=0, no graphics used.

4b. ICYEND (skip this card if IGRAPH=0)
=1, stop output when a cycle is completed.
=0, otherwise.

4c. TMIN, TMAX (skip this card if IGRAPH=0)
Specifies the temperature interval (minimum and maximum integer value) to be displayed in the graphic output. The program will choose a suitable temperature scale that encloses this interval.

4d. DTGRAPH (skip this card if IGRAPH=0)
Maximum sampling time interval for drawing the curves.

5. MAUT
=0, long version with detailed description of the store chosen.

Data for global problem

6. IMAX, JMAX
The radial and vertical dimensions of the mesh. Note that the cells with index I=1 or J=1 designate boundary nodes used only for the boundary conditions. The cells with index I=2 or J=2 are the first cells in the simulated volume. The boundary nodes at the outer boundaries (at IMAX and JMAX) are automatically added in the program. However, the field dimensions must include these extra nodes, i.e. the dimensions should not subceed (IMAX+1, JMAX+1).

7. DTOKAY
User specified maximum time-step (s).

8. R(I)
Cell structure in horizontal direction. Read in procedure `coord1` (see below).

9. Z(J)
Cell structure in vertical direction. Read in procedure `coord1`.

10. RLAM(I,J), CIN(J)
Thermal conductivity (W/mK) and volumetric heat capacity (J/m^3K). Read by procedure `ground_2d` (see below).

11. RISOR(I,J)
Thermal insulations between cells (I-1,J) and (I,J) (m^2K/W). Read by procedure `input_2d`.

12. RISOZ(I,J)
Thermal insulations between cells (I,J-1) and (I,J) (m^2K/W). Read by procedure `input_2d`.

13. T(I,J)
Initial temperatures in the ground. Read by procedure `input_2d`.

14. TAIRM, TAIRA, TAIRP1, TAIRPH
Specifies the ground surface temperature function: mean value (°C), amplitude (°C), period (s), and phase time (s).

15. INVOL(I,J)
Defines storage volume and flow path. Read by subroutine `input_2d`. The subregions should have a consecutive numbering starting with 1. The flow will follow the subregions in rising order if the fluid flow rate is positive. If the fluid flow rate is negative, the flow direction is reversed.

16a. IBLOSS
=1, accumulated heat loss through a given cylindrical boundary surface is calculated.
=0, otherwise.

16b. ISIDE, JTOP, JBOT (skip this card if IBLOSS=0)
Defines the boundaries through which the accumulated heat losses are calculated:
ISIDE = radial cell immediately inside the vertical boundary,
JTOP = the uppermost vertical cell in the cylindrical volume,
JBOT = the bottom vertical cell in the cylindrical volume.

Data for local problem

17. IMAXR
The number of cells used in the local problem. Note that the first cell outside the pipe has index I=2.

18. CW, RMPIPE
Volumetric heat capacity of fluid (J/m^3K), thermal resistance (K/(W/m)) between fluid and soil/rock.

19. T0
Reference temperature for the thermality calculation.

20. RR(I)
Cell structure for local problem. Read by subroutine `coord2`.

21a. NSPEC
Number of special output points.

21b. IGSPEC, JGSPEC, ILSPEC
Coordinate `i` and `j` for the global cell, and coordinate `ir` for the local cell. One card for each point.

22. STRTTM, ENDTM
Start-time and end-time of simulation.

23. PRETIM(I), PRNTDT(I)
First print-time and printing interval for the following printouts (one card for each type).

a. `*dst1*` Ground surface temperature, average temperature in the storage volume, fluid temperature at outlet and inlet, demand fluid temperature, accumulated injected and extracted energy, heat injection rate, demand heat injection rate, loading mode, volumetric fluid flow rate, special point output, and accumulated heat loss. The two last items are optional.

b. `*dst2*` Global temperature field.

c. `*dst3*` Local temperature fields, steady-flux function and amplitudes.

Data for loading conditions

24. LOMODE, CHATM, TDEM, QDEM, QWDEM
Data for the next loading period, which will continue until time CHATM. At this time a new card is read. The program expects data until end time (ENDTM) is reached.

TDEM = Inlet fluid temperature.
QDEM = Heat injection rate (W).
QWDEM = Fluid flow rate (m^3/s).

LOMODE=0. Rest period. The values of TDEM, QDEM, QWDEM are not used.
LOMODE=1. Given heat injection rate with no restriction on fluid temperature. A negative value is used for heat extraction. TDEM is not used.
LOMODE=2. Given heat injection rate with restrictions on fluid temperature. TDEM may not be exceeded during injection or subceeded during extraction of heat. If the demand heat injection rate requires a temperature violating the limiting value TDEM the heat injection will continue with the inlet fluid temperature TDEM.
LOMODE=3. Given inlet temperature. QDEM is not used.
LOMODE>10. Indicates that there will be cyclical loading conditions until time CHATM. There are LOMODE-10 periods per cycle. On the card with LOMODE>10 the values of TDEM, QDEM, and QWDEM will not be used. This card is followed by LOMODE-10 cards giving the loading conditions for each period during the cycle. On these cards the duration of the period is given by CHATM.
LOMODE<0. The procedure `print_cycle_summary` will be called immediately. A summary of storage conditions since the previous call of this procedure (or since the start of simulation) will written to the output file. The program then continues with the positive value of LOMODE.

4.2 Short version with automatic mesh generation

The following assumptions are made. The storage volume has the shape of a cylinder with the symmetry axis in the vertical direction. The thermal properties in the ground are specified for the storage volume and a number of horizontal layers. There are two ways to insulate the store. The first alternative allows for insulation of the upper surface of the storage volume and an arbitrary fraction of the vertical side of the store. The second alternative assumes a horizontal thermal insulation sheet at the same level as the upper surface of the store. The initial temperature is given by a ground surface temperature with a linear vertical temperature gradient.

The numerical mesh is generated automatically. It is adjusted according to the thermal properties in the ground, daily changes in loading conditions and duration of the simulated time period. A finer grid spacing is used where large temperature gradients are expected. The thermal properties in the surrounding ground are given for a number of horizontal strata. There is only one subregion in this case. The local problem is then the same around each duct. The ducts in the store are all coupled in parallel.

Data for global problem

1. LQST
=1, input questions printed.
=0, otherwise.

2. LPRT
=1, input data printed.
=0, otherwise.

3. LFPRT
=2, one- and two-dimensional fields, time-step information, and summary of new loading conditions are printed.
=1, only time-step information and summary of new loading conditions are printed.
=0, otherwise.

4a. IGRAPH
=1, results will be presented in graphic mode (requires EGA).
=0, no graphics used.

4b. ICYEND (skip this card if IGRAPH=0)
=1, stop output when a cycle is completed.
=0, otherwise.

4c. TMIN, TMAX (skip this card if IGRAPH=0)
Specifies the temperature interval (minimum and maximum integer value) to be displayed in the graphic output. The program will choose a suitable temperature scale that encloses this interval.

4d. DTGRAPH (skip this card if IGRAPH=0)
Maximum sampling time interval for drawing the curves.

5. MAUT
=1, short version with detailed description of the store chosen.

6. VOLUME
Volume of storage region (m^3.

7. DEEP
Distance between ground surface and lower surface of storage volume.

8. DISPIP
Spacing between ducts in a hexagonal duct pattern (m). See section 1.3.

9. R0
Outer radius of duct (m).

10. THISO
Thickness of covering thermal insulation (m).

11. RISLAM
Thermal conductivity of insulation (W/mK).

12. ISO
=0, no thermal insulation.
=1, insulation on upper surface and side of storage volume. An upper fraction FRISO of the side is covered.
=2, insulation on upper surface of the storage. This horizontal insulation extends a certain distance outside the side of the storage. This distance is a fraction FRISO of the height of the storage volume.

13. FRISO
Fraction of the height of the storage volume. See card 12 for details.

14. DEPTH
Distance between ground surface and upper surface of storage volume (m).

15. RLAMR, CR
Thermal conductivity (W/mK) and volumetric heat capacity (J/m^3K) in the storage volume.

16. CW
Volumetric heat capacity (J/m^3,K) of heat carrier fluid.

17. RMPIPE
The total thermal resistance (K/(W/m)) between the bulk fluid in a duct and the ground immediately outside the flow channel. For a pipe in the ground, this thermal resistance is composed of three components; the heat transfer resistance between the bulk fluid in the pipe and the channel wall, the thermal resistance of the pipe wall, and a contact thermal resistance between the outer pipe wall and the surrounding ground. For the case of an unlined borehole in rock there is only the heat transfer resistance between the bulk fluid and the rock wall.

18. TIMO3
Duration of the simulated time period (years). This parameter is only used for the generation of the numerical mesh.

19. TSTART
Initial ground surface temperature (°C).

20. TGRAD
Temperature gradient used together with TSTART to define initial ground temperature (°C/m).

21a. ILAY
Number of layers in the ground with different thermal properties. ILAY must be larger than zero.

21b. RLAM(I), CL(I), THL(I)
Thermal conductivity in a layer (W/mK), volumetric heat capacity in a layer (J/m^3K), and thickness of a layer (m).
All three values given on one card. Repeated for each layer. Note that the deepest layer must extend below the region included in the numerical mesh.

22. TAIRM, TAIRA, TAIRP1, TAIRPH
Specifies the ground surface temperature function: mean value (°C), amplitude (°C), period (s), and phase time (s).

23. T0
Reference temperature for the thermality calculation.

24. STRTTM, ENDTM
Start-time and end-time of simulation.

25. PRETIM(I), PRNTDT(I)
First print-time and printing interval for the following printouts (one card for each type).

a. `*dst1*` Ground surface temperature, average temperature in the storage volume, fluid temperature at outlet and inlet, demand fluid temperature, accumulated injected and extracted energy, heat injection rate, demand heat injection rate, loading mode, volumetric fluid flow rate, special point output, and accumulated heat loss. The two last items are optional.

b. `*dst2*` Global temperature field.

c. `*dst3*` Local temperature fields, steady-flux function and amplitudes.

Data for loading conditions

26. LOMODE, CHATM, TDEM, QDEM, QWDEM
Data for the next loading period, which will continue until time CHATM. At this time a new card is read. The program expects data until end time (ENDTM) is reached.

TDEM = Inlet fluid temperature.
QDEM = Heat injection rate (W).
QWDEM = Fluid flow rate (m^3/s).

LOMODE=0. Rest period. The values of TDEM, QDEM, QWDEM are not used.
LOMODE=1. Given heat injection rate with no restriction on fluid temperature. A negative value is used for heat extraction. TDEM is not used.
LOMODE=2. Given heat injection rate with restrictions on fluid temperature. TDEM may not be exceeded during injection or subceeded during extraction of heat. If the demand heat injection rate requires a temperature violating the limiting value TDEM the heat injection will continue with the inlet fluid temperature TDEM.
LOMODE=3. Given inlet temperature. QDEM is not used.
LOMODE>10. Indicates that there will be cyclical loading conditions until time CHATM. There are LOMODE-10 periods per cycle. On the card with LOMODE>10 the values of TDEM, QDEM, and QWDEM will not be used. This card is followed by LOMODE-10 cards giving the loading conditions for each period during the cycle. On these cards the duration of the period is given by CHATM.
LOMODE<0. The procedure `print_cycle_summary` will be called immediately. A summary of storage conditions since the previous call of this procedure (or since the start of simulation) will written to the output file. The program then continues with the positive value of LOMODE.

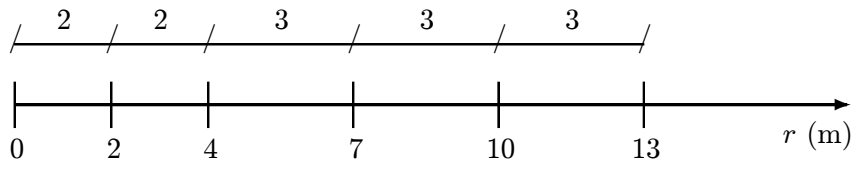
4.3 Input procedures

4.3.1 Procedure coord1

This procedure is used for the generation of the mesh. The first card gives the location of the inner boundary. For the radial part this corresponds to the value of the inner radius R(2) and for the vertical part it is the upper boundary Z(2). The cells with index I=1 and J=1 are used for boundary conditions. The cell widths in the radial and the vertical directions are given. Since the location of the inner (first) partitions are specified the cell structure is completely determined. The cell I,J has an inner radial boundary at R(I) and an outer boundary at R(I+1). The nodal point for the temperature calculation is the middle of the cell, namely

$$RM(I) = (R(I) + R(I+1))/2 \tag{4.1}$$

Example



This simple one-dimensional radial mesh consists of 2 cells with a width of 2.0 meters and 3 cells with a width of 3.0 meters. The inner boundary is at 0.0 meter. The cards read by procedure `coord1` are:

a. 0.0
b. 2
c. 2 2.0 3 3.0

The number on card b is the number of pairs on cards c (as indicated above).

4.3.2 Procedure input_2d

This procedure reads values for the cells in a two-dimensional mesh. A general value for all cells is given on the first card. The value given to the parameter ITYP specifies if more data is

required and the preferred form of input. The options are:

ITYP = 1 — Nothing more than the general value is required.

ITYP = 5 — A value is given to a block of cells as determined by the values of I_{min}, J_{min}, I_{max}, J_{max}. See example below. Any number of blocks may be speci- fied. The sequence of cards is:
b. ITYP=5
c. Number of blocks
d. I_{min}, J_{min}, I_{max}, J_{max}, value. One card for each block.

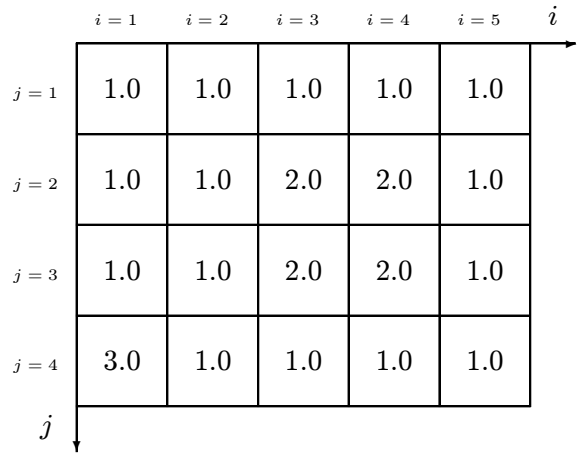
ITYP = 7 — A value is given to a single cell. This could of course be done by the block input but this is somewhat faster. The sequence of cards is:
b. ITYP=7
c. Number of single cells
d. I, J, value. One card for each cell.

ITYP = 35 — Both types of input as described for ITYP=5 and ITYP=7 are used. The sequence of cards is now:

b. ITYP=35
c. Number of blocks
d. I_{min}, J_{min}, I_{max}, J_{max}, value. One card for each block.
e. Number of single cells
f. I, J, value. One card for each cell.

As an example of input using the procedure `input_2d` we have the following simple problem.

Example



The general value is 1.0. There is a block of cells with a value 2.0 and a single cell with the value 3.0. The required input would be:

a. 1.0

b. 35
c. 1
d. 3 2 4 3 2.0
e. 1
f. 1 4 3.0

4.3.3 Procedure ground_2d

This procedure is used for specifying the thermal properties in the ground. It only differs from `input_2d` in that two values are given instead of one. These values are thermal conductivity and volumetric heat capacity. See `input_2d` for details. The input of "value" is now replaced by "thermal conductivity, volumetric heat capacity".

4.4 Input of time data

The basic unit for all time values used in the program is seconds. On input of time data, the number of seconds should be given in the required Turbo Pascal floating-point format. However, a special format for time data may be used in order to simplify the input. The time value must then start with the letter T and be immediately followed by a sequence of contiguous pairs with a number and one of the following letters:

Y	Year (365 days, 31536000 seconds).
Q	Year/12 (30.417 days, 2628000 seconds.)
D	Days (86400 seconds).
H	Hours (3600 seconds).
M	Minutes (60 seconds).
S	Seconds.

Examples

T1Y12D	1 year and 12 days.
T25D4H2M	25 days, 4 hours, and 2 minutes.
T3Q500S	3/12 year and 500 seconds.

Chapter 5
Using the Program

5.1 Introduction

The code has been written for the Turbo Pascal 5.0 compiler. The compiled version of the code supplied on the disk does *not* require a math coprocessor (80x87) in order to execute. However, execution times will be reduced by a factor of 3 if a math coprocessor is present. An enhanced graphics adapter (EGA) will be required only if the graphics option is specified. The input data to the model are described in chapter 4. Two sample cases are given in chapter 6. The input and output files for the sample cases are included on the disk.

5.2 Files on the disk

Contents of the root directory:

DST.EXE	Executable code
EGAVGA.BGI	Turbo Pascal graphics driver for EGA. Only required if the graphics option is used.
SANS.CHR	Turbo Pascal font file. Only required if the graphics option is used.
SOURCE `<DIR>`	Subdirectory that contains Turbo Pascal source files
SAMPLES `<DIR>` OUTPUT `<DIR>`	Subdirectory that contains the sample output files

Contents of the directory SAMPLES:

SAMPLE1.DAT	Input data for sample case no.1 (See section 6.2.1)
SAMPLE2.DAT	Input data for sample case no.2 (See section 6.2.2)

Contents of the directory OUTPUT:

SAMPLE1.OUT	Output data for sample case no.1
SAMPLE2.OUT	Output data for sample case no.2

5.3 Starting the program

To run the program DST, make the drive and directory where the program resides the default drive, and type:

`DST` *input-file-name output-file-name*

The input file name and the output file name are optional command line parameters.

If the command line has only one parameter it is assumed to be the input file name. The user will be prompted for the name of the output file.

If there are no command line parameters, the user will be prompted for the names of the input data file and the output file.

If the name of the output file is omitted in response to the prompt, the output is directed to the screen.

When the program has read the input data without detecting any formal errors, it will display the following message on the screen:

```
Duct Storage Model - Input data OK
```

5.4 Screen output without graphics

The elapsed simulation time is displayed using the following abbreviations:

y	years (365 days, 31536000 seconds)
d	days (86400 seconds)
h	hours (3600 seconds)
s	seconds

Example

```
1y 57d 2h 0s
```

The user may request a summary of storage conditions to be printed on the output file at certain times (see section 4.1 or 4.2). When such a summary has been printed, a message of the following type will appear on the screen:

```
Duct Storage Model - Completed cycle No.  1
```

5.5 Screen output with graphics

The graphics option uses two pages for output. It will not work properly on computers with old enhanced graphics adapters (EGA) that do not support multiple video pages. When the simulation begins it will display the first page, as described below, which is the active page during the simulation.

5.5.1 First page

The left part of the screen displays the ground temperatures as a function of depth through the center of the store. The storage region is indicated by red dots. The depth scale in chosen automatically by the program, whereas the temperature scale is given as an input (see section 4.1 or 4.2).

The right part displays inlet fluid temperature, outlet fluid temperature, and mean storage temperature as a function of time. The time scale is fixed and shows 365 days. The curves are updated at the maximum time interval given as input.

The simulation may be interrupted by pressing any key. The second page (see below) can then be accessed by pressing the `F1` function key. If the option of retaining old storage temperature profiles has been used (see section 4.1 or 4.2), the `F2` function key can be used to erase these old profiles and to show only the current profile. Continue execution by pressing the `ENTER` key or quit the program by pressing the `ESC` key.

5.5.2 Second page

The second page is accessed by interrupting the program (see above) and then pressing the `F1` function key. A summary of current loading conditions is displayed in text mode. It contains the following items:

- Energy balance
  - Injection (MWh)
  - Extraction (MWh)
- Storage heat losses (MWh)
  - Total, top, side, and bottom
- Recovery factor (Extracted energy divided by injected energy)
- Inlet temperature
- Outlet temperature
- Mean storage temperature
- Fluid flow rate (m^3/s)
- Load mode (see section 4.1 or 4.2)
- Heat injection rate (W)
- Mean fluid temperature
- Driving temperature, i.e. difference between mean fluid temperature and mean storage temperature.
- Heat transfer capacity (kW/K). Ratio between heat injection rate and driving temperature.
- Volumetric heat transfer capacity (kW/m^3K).

Return to the first page by pressing the `F1` function key. The execution may be continued by pressing the `ENTER` key.

5.6 File output

As explained in the description of input data, section 4.1 and 4.2, different sets of output data from the model may be obtained a regular time intervals.

The following abbreviated variable names occur in the output list:

`Temp.in`	Inlet temperature
`Temp.out`	Outlet temperature
`Temp.air`	Ground surface temperature
`Vol.flow`	Volumetric flow rate (m^3/s)
`Lomode`	Load mode (see section 4.1 or 4.2; data for loading conditions
`Tmstor`	Average temperature in the storage volume
`Temp.dem`	Given inlet temperature or limiting value on inlet temperature (see section 4.1 or 4.2)

`Q.dem`	Requested heat injection rate (see sectionm 4.1 or 4.2)
`Q`	Momentary heat injection rate
`Inj.energy`	Injected amount of energy
`Ext.energy`	Extracted amount of energy

5.6.1 Time-step information

The time-step for the global process and the maximum time-step for the local process in the store are given. The time-scale for local transients is the time after which neighboring ducts will influence the solution around a given duct. See section 1.3 for further details.

```
*dst*
Timescale for local transients   985587.7
Timestep for global process      109509.7
Max timestep for local process    15485.0
*dst*
```

5.6.2 New loading condition

When the program reads a record with new loading conditions from the input data file, it will print a summary of the conditions to the output file if LFPRT≠0 (see section 4.1 or 4.2).

```
*dst+* From time  0.00000E+0000 s  until  1.31400E+0007 s
*dst+* Load mode 3 Temp    30.00
*dst+* Heat inj. rate  0.000E+0000 Vol.flow  2.00000E-0002
```

5.6.3 Momentary loading conditions

```
*dst** Results time=    0y 150d  0h    0s
*dst1* Temp.in =       30.00 C  Temp.out=    27.59 C
*dst1* Tmstor  =       22.23 C  Temp.air=     6.40 C
*dst1* Lomode  = 3
*dst1* Temp.dem=       30.00 C     Q.dem=  0.000E+0000 W
*dst1* Vol.flow= 2.000E-0002 m3/s  Q    =  2.024E+0005 W
*dst1* Inj.energy= 4.538E+0012 Ext.energy= 0.000E+0000 J
*dst1* Accumulated heat loss through: top= 4.322E+0010 J
*dst1*       side= 9.576E+0011 J   bottom= 7.936E+0010 J
```

5.6.4 Global temperature field

The ground temperature within the store is a superposition of three parts: global, local, and steady-flux temperature. The ground temperature outside the store is given by the global temperature.

The global temperatures are given for each cell of the numerical mesh. The midpoint of the cell is given as a function of depth (`z-dist`) from the ground surface and radial distance (`r-dist`) from the symmetry axis.

```
*dst2* Global temperature field (C)
                    radial distance (m)
   depth        0.00         2.86         8.59        13.05        15.44
-------------------------------------------------------------------------------
    0.00    6.000E+0000  6.401E+0000  6.401E+0000  6.401E+0000  6.401E+0000
    0.40    6.004E+0000  2.045E+0001  2.023E+0001  1.923E+0001  1.777E+0001
    1.20    6.012E+0000  2.145E+0001  2.121E+0001  2.012E+0001  1.847E+0001
    2.40    6.024E+0000  2.261E+0001  2.234E+0001  2.111E+0001  1.912E+0001
    4.80    6.048E+0000  2.387E+0001  2.356E+0001  2.212E+0001  1.984E+0001
    9.59    6.096E+0000  2.457E+0001  2.423E+0001  2.268E+0001  2.037E+0001
   19.18    6.192E+0000  2.470E+0001  2.436E+0001  2.280E+0001  2.051E+0001
   37.79    6.378E+0000  2.475E+0001  2.440E+0001  2.286E+0001  2.058E+0001
   62.21    6.622E+0000  2.480E+0001  2.446E+0001  2.293E+0001  2.068E+0001
   80.82    6.808E+0000  2.483E+0001  2.450E+0001  2.298E+0001  2.075E+0001
   90.41    6.904E+0000  2.462E+0001  2.430E+0001  2.282E+0001  2.062E+0001
   95.20    6.952E+0000  2.338E+0001  2.310E+0001  2.177E+0001  1.973E+0001
   97.60    6.976E+0000  2.144E+0001  2.118E+0001  2.001E+0001  1.823E+0001
   98.80    6.988E+0000  1.982E+0001  1.958E+0001  1.850E+0001  1.690E+0001
   99.60    6.996E+0000  1.845E+0001  1.821E+0001  1.719E+0001  1.572E+0001
  100.40    7.004E+0000  1.672E+0001  1.649E+0001  1.551E+0001  1.417E+0001
  101.20    7.012E+0000  1.517E+0001  1.496E+0001  1.406E+0001  1.287E+0001
  102.40    7.024E+0000  1.315E+0001  1.296E+0001  1.219E+0001  1.127E+0001
  104.80    7.048E+0000  1.019E+0001  1.007E+0001  9.605E+0000  9.119E+0000
  109.59    7.096E+0000  7.683E+0000  7.654E+0000  7.557E+0000  7.467E+0000
  116.78    7.168E+0000  7.218E+0000  7.216E+0000  7.207E+0000  7.199E+0000
  170.77    7.708E+0000  7.706E+0000  7.706E+0000  7.706E+0000  7.706E+0000
  220.77    8.208E+0000  8.208E+0000  8.208E+0000  8.208E+0000  8.208E+0000
-------------------------------------------------------------------------------
```

5.6.5 Local temperature field

The ground temperature within the store is a superposition of three parts: global, local, and steady-flux temperature. The global temperature field is discussed in the previous section. The local temperature field is given for each subregion (see section 2.4). The steady-flux temperature is obtained by multiplying the steady-flux amplitude with the value of the steady-flux solution at the desired radius (see eqs. 2.28-29).

```
*dst3* Local temperature field
*dst3* The temperature around a pipe is given by :
*dst3* T(global)+TR(local)+TSF(amplitude)*TSFH
*** Storage section   1
Radius:   0.17    0.39    0.66    1.03    1.46    1.89
Temp  :   2.38    1.33    0.70    0.20   -0.09   -0.22


*dst3* Steady flux solution - function h (TSFH)
Radius:   0.17    0.39    0.66    1.03    1.46    1.89
Temp  :   1.78    0.95    0.46    0.08   -0.14   -0.24
```

```
*dst3* Steady flux solution - TSF(amplitudes)
                    radial distance (m)
   depth        0.00         2.86         8.59        13.05        15.44
--------------------------------------------------------------------------------
    0.00    0.000E+0000  0.000E+0000  0.000E+0000  0.000E+0000  0.000E+0000
    0.40    0.000E+0000  3.371E-0001  3.798E-0001  5.769E-0001  8.658E-0001
    1.20    0.000E+0000  1.341E-0001  1.804E-0001  3.958E-0001  7.207E-0001
    2.40    0.000E+0000 -9.453E-0002 -4.301E-0002  2.002E-0001  5.929E-0001
    4.80    0.000E+0000 -3.426E-0001 -2.825E-0001  1.822E-0003  4.532E-0001
    9.59    0.000E+0000 -4.803E-0001 -4.136E-0001 -1.086E-0001  3.484E-0001
   19.18    0.000E+0000 -5.059E-0001 -4.382E-0001 -1.321E-0001  3.218E-0001
   37.79    0.000E+0000 -5.147E-0001 -4.475E-0001 -1.438E-0001  3.065E-0001
   62.21    0.000E+0000 -5.253E-0001 -4.588E-0001 -1.583E-0001  2.873E-0001
   80.82    0.000E+0000 -5.318E-0001 -4.659E-0001 -1.680E-0001  2.739E-0001
   90.41    0.000E+0000 -4.914E-0001 -4.275E-0001 -1.368E-0001  2.983E-0001
   95.20    0.000E+0000 -2.470E-0001 -1.904E-0001  7.148E-0002  4.749E-0001
   97.60    0.000E+0000  1.377E-0001  1.880E-0001  4.178E-0001  7.709E-0001
   98.80    0.000E+0000  4.583E-0001  5.055E-0001  7.175E-0001  1.034E+0000
   99.60    0.000E+0000  7.304E-0001  7.760E-0001  9.769E-0001  1.267E+0000
--------------------------------------------------------------------------------
```

As an example we will use the values given in this section to calculate the temperature at a point located at a depth of 2.5 m and at a radial distance of 5 m from the symmetry axis of the storage volume. This point is located within the cell I=2 and J=4. We may now obtain the global temperature and the steady-flux amplitude for this cell. Let us assume that the point is located at a radial distance of 0.66 m from the center of the circular duct. In this case there is only one subregion specified for the storage volume. The local temperature for this subregion and the value of the steady-flux function is given below.

Global temperature	22.61
Local temperature	0.70
Steady-flux temperature -0.09453·0.46	-0.04
Ground temperature	23.27

5.6.6 Summary of cycle loading conditions

If the loading mode, LOMODE, is set to a negative value, then the procedure `print_cycle_summary` will be called immediately. A summary of the storage conditions since the last call to this procedure will printed. The counters are then reset to zero. (The first summary concerns the time period from the start of the simulation.)

```
*dst4*  Time    1y   0d  0h    0s
*dst4*                Summary of cycle   1
*dst4*                ====================
*dst4*
*dst4* Time                               31536000.000000 s
*dst4* Injection
*dst4*      energy                         3.300E+0012 J
*dst4*                                        916.7600 MWh
*dst4*      average injection temperature       28.44 C
*dst4* Extraction
*dst4*      energy                         1.183E+0012 J
*dst4*                                        328.5018 MWh
*dst4*      average extraction temperature       8.54 C
*dst4* Efficiencies
*dst4*      energy efficiency                   0.358
*dst4*      temperature efficiency              0.113
*dst4*         with reference temperature        6.00 C
*dst4* Inlet fluid temperature
*dst4*      minimum value                        4.91 C
*dst4*      maximum value                       30.00 C
*dst4* Outlet fluid temperature
*dst4*      minimum value                        5.99 C
*dst4*      maximum value                       27.87 C
*dst4* Mean storage temperature
*dst4*      minimum value                        6.50 C
*dst4*      maximum value                       18.14 C
*dst4*      Start of cycle                       6.50 C
*dst4*      End of cycle                        10.80 C
*dst4* heat losses from storage volume
*dst4*      top                  5.8%          18.7867 MWh
*dst4*      side                87.6%         285.2787 MWh
*dst4*      bottom               6.6%          21.6381 MWh
*dst4*      total              100.0%         325.7035 MWh
*dst4*
```

Chapter 6
Examples

6.1 Input data for detailed version. Sample case no.1

This example is taken from the heat store constructed in Luleå in 1982-1983. The heat store consists of 115,000 m^3 of granite perforated by 120 vertical boreholes to a depth of 65 meters. The borehole diameter is 0.152 meter. The boreholes a drilled within a rectangular ground surface area with the side lengths of 36 and 44 meters. The bedrock is covered by a 2 to 6 meters thick soil layer. The heat carrier fluid is circulated through the store in 24 flow paths that are coupled in parallel. Each flow path consists of five boreholes.

The DST model assumes that the storage volume has the shape of a cylinder. Five concentric subregions of equal volume are used in order simulate the flow paths of five boreholes coupled in series (See card 8 and 15). The loading data given are the measured monthly average values for the first four annual cycles. A cycle summary is printed after each injection and extraction period.

The input data file for sample case no.1 is listed below. The card numbers on the left are not part of the input data file. The numbers refer to description of input data in section 4.1.

```
Card   Data
no.
1      1
2      1
3      2
4a     1
4b     0
4c     0 80
4d     T1D
5      0
6      18 21
7      T12H
8a     0.0
8b     17
8c     1 6.0  1 5.05 1 2.95 1 1.62 1 1.88 1 1.63 1 1.57 1 1.39
8c     1 1.41 1 1.20 1 1.20 1 1.60 1 2.50 1 5.0  1 10.0 1 20.0 1 100.0
9a     0.0
9b     14
9c     2 1.75 1 1.5  1 2.5  1 3.5 1 5.0 4 10.0 1 4.0 2 2.0 2 1.0 1 2.0
9c     1 4.0  1 10.0 1 20.0 1 100.0
10a    3.4 2.2E+6
10b    5
10c    1
10d    2 2 18 3 0.75 3.5E6
11a    0.0
11b    1
```

```
12a    0.0
12b    1
13a    3.7
13b    1
14     3.7 0.0 T1Y T0S
15a    0.0
15b    5
15c    5
15d     2  4  3  15  1.0
15d     4  4  5  15  2.0
15d     6  4  7  15  3.0
15d     8  4  9  15  4.0
15d    10  4 11  15  5.0
16a    1
16b    12 4 15
17     7
18     4.184E+6 0.05
19     3.7
20a    0.0756
20b    6
20c    1 0.0744 1 0.1 1 0.2 1 0.4 1 0.6 1 0.81
21a    2
21b    2 9 2
21b    2 9 5
22     T0S   T1433D
23a    T30D   T30D
23b    T1432D T100Y
23c    T1432D T100Y
24      3 T28D   49.4   0.0 0.0146  1046.6
24      3 T59D   61.8   0.0 0.0126   841.6
24      3 T89D   66.9   0.0 0.0105   694.7
24      3 T120D  69.1   0.0 0.0123  1171.8
24      3 T150D  67.8   0.0 0.0105   774.4
24      3 T181D  67.5   0.0 0.0121   638.9
24      3 T212D  68.6   0.0 0.0114   559.4
24     -3 T241D  42.5  47.2 -0.0044  -106.5
24      3 T272D  32.9  41.5 -0.0062  -222.6
24      3 T302D  31.6  38.5 -0.0069  -205.4
24      3 T333D  31.9  36.6 -0.0049   -98.5
24      3 T340D  29.8  32.5 -0.0029   -37.5
24     -3 T363D  56.9  43.6 0.0101   699.9
24      3 T394D  56.1  46.1 0.0115   490.7
24      3 T425D  57.8  48.7 0.0084   385.3
24      3 T455D  66.7  56.3 0.0151   679.2
24      3 T486D  68.6  59.8 0.0140   576.8
24      3 T492D  63.6  54.6 0.0129   562.9
24     -3 T516D  40.7  49.0 -0.0084  -298.5
24      3 T547D  37.3  44.3 -0.0087  -258.2
24      3 T578D  32.6  41.1 -0.0054  -192.3
24      3 T606D  27.6  37.2 -0.0056  -231.8
```

```
24      3 T637D  28.3  35.5 -0.0064  -192.9
24      3 T667D  27.6  33.2 -0.0061  -147.0
24      3 T687D  26.0  30.6 -0.0062  -117.7
24     -3 T698D  55.1  40.6 0.0118   812.0
24      3 T728D  65.5  50.3 0.0124   831.0
24      3 T759D  41.9  37.1 0.0045   154.3
24      3 T790D  65.0  50.2 0.0116   751.3
24      3 T820D  68.2  55.8 0.0127   666.2
24      3 T851D  70.1  60.9 0.0127   538.7
24      3 T878D  69.6  61.3 0.0094   437.5
24     -3 T881D  41.2  46.4 -0.0054  -164.3
24      3 T912D  39.8  45.2 -0.0100  -262.6
24      3 T943D  38.9  46.5 -0.0069  -241.3
24      3 T971D  36.4  43.9 -0.0064  -216.2
24      3 T1002D 33.6  41.1 -0.0072  -237.5
24      3 T1032D 31.6  38.3 -0.0064  -190.8
24      3 T1063D 31.1  36.9 -0.0042  -106.5
24      3 T1078D 30.7  34.8 -0.0033   -60.6
24     -3 T1093D 62.9  47.0 0.0122   853.8
24      3 T1124D 68.2  54.6 0.0124   733.6
24      3 T1155D 68.4  58.0 0.0131   593.3
24      3 T1185D 68.2  57.8 0.0121   526.0
24      3 T1200D 68.3  60.1 0.0126   471.1
24     -3 T1216D 40.6  48.6 -0.0104  -388.9
24      3 T1246D 37.1  47.5 -0.0091  -297.0
24      3 T1277D 38.4  44.4 -0.0085  -225.0
24      3 T1308D 36.8  42.7 -0.0056  -141.6
24      3 T1336D 28.4  34.4 -0.0058  -163.9
24      3 T1367D 25.7  29.5 -0.0095   -82.5
24      3 T1397D 31.0  36.6 -0.0073  -178.8
24      3 T1428D 30.1  34.9 -0.0055  -117.5
24     -3 T1432D 25.5  28.9 -0.0022   -39.6
24      3 T2000D 25.5  28.9 -0.0022   -39.6
```

Comments:

4d The graphics output is updated every day. Longer time intervals will make the curves look less smooth, but it will require a shorter execution time.

The output data file SAMPLE1.OUT is stored in the subdirectory OUTPUT on the disk.

6.2 Input data for short version. Sample case no.2

The input data file for sample case no.2 is listed below. The card numbers on the left are not part of the input data file. The numbers refer to description of input data in section 4.2.

```
Card   Data
no.
1      1
2      1
3      2
4a     1
4b     1
4c     5 50
4d     T10D
5      1
6      100000.0
7      100.0
8      4.0
9      0.0575
10     0.1
11     0.04
12     1
13     0.02
14     0.0
15     3.5 2.2E6
16     4.2E6
17     0.1
18     1.0
19     6.0
20     0.01
21a    1
21b    3.5 2.2E6 1000.0
22     6.0 10.0 T1Y T0S
23     6.0
24     T0S  T1Y1D
25a    T0D  T10D
25b    T6Q  T100Y
25c    T6Q  T100Y
26      3 T5Q 30.0      0.0 0.020
26      0 T6Q  0.0      0.0 0.0
26      2 T11Q 4.0 -90000.0 0.020
26      0 T1Y  0.0      0.0 0.0
26     -3 T20Y 30.0    0.0 0.020
```

Comments:

4d The graphics output is updated every ten days. Shorter time intervals will make the curves look smoother, but it will require a longer execution time.

21b The total thickness of the layers must be larger than the depth of the numerical mesh. A practical approach is to set the thickness of bottom layer to 1000 m.

The output data file SAMPLE2.OUT is stored in the subdirectory OUTPUT on the disk.

Chapter 7
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