

**THE DUCT GROUND HEAT STORAGE  
MODEL (DST) FOR TRNSYS USED  
FOR THE SIMULATION OF HEAT  
EXCHANGER PILES.**

**User manual  
December 1996 Version**

**Internal Report**

**Dr D. Pahud  
Dr A. Fromentin  
J.-C. Hadorn**

## **Table of Contents:**

1. Introduction.....	p. 2
2. Several Ground Layers within the Storage Region.....	p. 3
3. Regional Ground Water Flow.....	p. 3
3.1 Long-term Influence of a Regional Ground Water Flow.....	p. 3
3.2 Short-term Influence of a Regional Ground Water Flow.....	p. 5
4. Connecting Pipes on Ground Surface.....	p. 7
5. Parameters, Inputs and Outputs of TRNVDSTP (TRNVDST).....	p. 8
5.1 The Parameter Values.....	p. 8
5.2 The Input Variables.....	p. 13
5.3 The Output Variables.....	p. 14
5.4 Information Flow Diagram.....	p. 15
References.....	p. 15

## 1. Introduction:

The duct storage model DST was developed at Lund Institute of Technology (LTH) in Sweden (Hellström, 1989). It can be used for the simulation of thermal processes that involve heat storage and/or cold storage in the ground. The model assumes a relatively large number of uniformly placed ground heat exchangers for the heat transfer with the ground. A ground heat exchanger is typically formed by a channel system inserted in a borehole. The heat carrier fluid is circulated in the channel system and a conductive heat transfer is assumed between the heat carrier fluid and the ground.

The DST model was chosen in 1981 by the participants of the International Energy Agency, Solar R&D Task VII (Central Solar Heating Plant with Seasonal Storage) for the simulation of duct ground heat storages. A simpler but faster version was implemented by Hellström (1983) in the MINSUN programme (Mazzarella, 1991), a simulation tool for the optimisation of a central solar heating plant with a seasonal storage (CSHPSS). A TRNSYS version based on this faster version has been implemented by Mazzarella (1993). TRNSYS is a widely used, modular and flexible programme, for the simulation of transient thermal processes of an thermal energy system. A more recent version of DST for TRNSYS (Hellström et al., 1996) has combined the easy utilisation of the simple version with the additional features of the more detailed original DST programme (Hellström, 1989). This version also offers the possibility of a detailed computation of the local heat transfer along the flow path within the storage region (see Pahud and Hellström, 1996).

The DST version for TRNSYS is chosen for the simulation of systems that use *heat exchanger piles*. A *heat exchanger pile* is a pile used for the foundation of a superstructure (building or other), and equipped with a channel system for the extraction or injection of heat in the ground. Nevertheless, the type of ground for which *heat exchanger piles* are used often presents a regional ground water flow. Furthermore, the total length of the pipe on the ground surface that connects the *heat exchanger piles* to the rest of the system is often large, due to the relatively large spacing and short depth of the *heat exchanger piles*. These pipes are usually not insulated and may significantly influence the thermal behaviour of the *heat exchanger pile* system. In order to have a more appropriate simulation model, the following features are implemented in the last DST version for TRNSYS which dates from January 1996 (Hellström et al., 1996):

- Several ground layers with different thermal properties can be specified within the storage region.
- A ground water flow is specified for each ground layer. The heat transfer caused by forced convection in the storage region is estimated for each ground layer.
- The heat transferred by the pipe connections on ground surface can be estimated.

The first modification can be regarded as an update of TRNVDST.FOR (TYPE 60), the version of DST for TRNSYS, whereas the last two are specific to the simulation of *heat exchanger piles*. The methods used to assess the influence of a regional ground water flow are not yet validated against detailed calculations or accurate measurements. A new TRNSYS module is thus reserved for them. The resulting module is a TYPE 80 called TRNVDSTP.FOR (P for pile system). These

modifications were performed by Dr. D. Pahud, from the LASEN (Laboratory of Energy Systems) at the EPFL (Swiss Federal Institute of Technology in Lausanne).

Dr. G. Hellström, from the Department of Mathematical Physics at the LTH is acknowledged for letting Dr. D. Pahud adapt the last TRNSYS version of DST for the simulation of *heat exchanger pile* systems. The Swiss Federal Energy Office is also acknowledged for its financial support.

*Neither the authors, nor any employees of the above mentioned institutions, makes any warranty, expressed or implied, or assumes any liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.*

The programme code contained on the distribution diskette may not be distributed to other users.

## **2. Several Ground Layers within the Storage Region:**

In the original DST version, the thermal properties of the ground can vary from layer to layer, but only outside the storage region. Inside, they are uniform and constant; they may differ from those outside. It is now possible to have more than one ground layer within the storage region. In that case, the thermal properties of the ground inside the storage region are set equal to those outside. Furthermore, all the array dimensions are set in an "include file", which makes it easier to check and adjust their dimensions if necessary.

## **3. Regional Ground Water Flow:**

An accurate simulation of the influence of the ground water flow can not be realised with a calculation procedure that assumes a cylindrical geometry around the boreholes and the store, as a regional ground water flow will shift the temperature field in the direction of its displacement. Apriori, DST is not suited for such calculations, as the cylindrical geometry is extensively used. Nevertheless, a 3-dimensional DST model can not be developed in the framework of this study.

The two approximations described below are implemented in the two-dimensional version of DST. A more accurate model, developed for a typical situation, should be used to highlight the limitations of such approximations. However they have not yet been checked for an assessment of their validity.

### **3.1 Long-term Influence of a Regional Ground Water Flow:**

A rough estimate of the heat transferred by forced convection in each storage ground layer is calculated with one of the following two methods. The first method is to be chosen in priority, whereas the second one allows the user to artificially impose a large ground water flow, so that the temperatures in the storage region are maintained to the temperature values of the undisturbed ground. The local temperature fields,

which determine the temperature profiles around each borehole due to heat injection or heat extraction, are calculated for pure heat conduction. They are not directly affected by these two methods. Only the global temperature field, responsible for the storage heat losses and heat redistribution within the storage region, is affected by these methods. They should give an estimation of the long-term influence of a regional ground water flow on the heat balance of a ground heat storage.

With the first method, the convective loss (or gain) is calculated with the temperature difference between the temperature of the two cells on both sides of the storage boundary at the vertical border (see relation (3.1)). The simulation time-step  $\Delta t$  for the calculation of the global temperature field may be constrained by this method, as the displacement of the thermal front during this time-step must be smaller than the radial extension of these two cells.

$$E_{\text{conv}} = u S C_w (T_{\text{mean out}} - T_{\text{mean in}}) \Delta t \quad (3.1)$$

With  $u$ : Darcy velocity in the layer ( $\text{m}^3/\text{m}^2\text{s}$ );  
 $S$ : cross area of the storage submitted to the Darcy flow,  $S=H \cdot D$  ( $\text{m}^2$ );  
 $D$ : storage diameter (cylindrical shape) (m);  
 $H$ : vertical extension of the ground layer inside the storage volume (m);  
 $C_w$ : volumetric heat capacity of ground water ( $\text{J}/\text{m}^3\text{K}$ );  
 $T_{\text{mean out}}$ : average temperature along  $H$  of the cells just outside the vertical storage boundary ( $^{\circ}\text{C}$ );  
 $T_{\text{mean in}}$ : average temperature along  $H$  of the cells just inside the vertical storage boundary ( $^{\circ}\text{C}$ );  
 $\Delta t$ : time-step for the calculation of the global temperature field in the ground, calculated to about 1 day for a typical case (s);  
 $E_{\text{conv}}$ : heat quantity transferred by forced convection in the storage layer during the time-step  $\Delta t$  (J).

The velocity of the thermal front is given by relation (3.2).

$$V_{\text{thermal}} = C_w/C_{\text{ground}} \cdot u \quad (3.2)$$

With  $V_{\text{thermal}}$ : velocity of the thermal front (m/s);  
 $C_{\text{ground}}$ : volumetric heat capacity of the ground layer ( $\text{J}/\text{m}^3\text{K}$ );

The second method uses the relation (3.3). The convective loss is calculated with the temperature difference between  $T_{\text{mean}}$ , the average temperature of the ground layer within the storage region, and  $T_{\infty}$ , the undisturbed ground water temperature in the ground layer. The convective heat loss during a simulation time-step  $\Delta t$  is limited to the maximum possible value, defined by relation (3.4). In that case, the global temperature field within the storage region is replaced by  $T_{\infty}$ , the undisturbed ground water temperature.

$$E_{\text{conv}} = u S C_w (T_{\infty} - T_{\text{mean}}) \Delta t \quad (3.3)$$

$$E_{\text{conv max}} = V C_{\text{ground}} (T_{\infty} - T_{\text{mean}}) \quad (3.4)$$

With  $V$ : volume of the ground layer inside the storage volume ( $\text{m}^3$ );  
 $C_{\text{ground}}$ : average volumetric heat capacity of the ground layer inside the store ( $\text{J}/\text{m}^3\text{K}$ );  
 $T_{\infty}$ : undisturbed ground water temperature in the ground layer ( $^{\circ}\text{C}$ );  
 $T_{\text{mean}}$ : mean storage temperature in the ground layer ( $^{\circ}\text{C}$ );  
 $\Delta t$ : time-step for the calculation of the global temperature field in the ground, calculated to about 1 day for a typical case (s);  
 $E_{\text{conv max}}$ : maximum possible heat quantity transferred by forced convection in the storage layer during the time-step  $\Delta t$  (J).

The heat quantity transferred  $E_{\text{conv}}$  is then equally distributed as a temperature correction on each cell of the ground layer within the storage volume. If  $E_{\text{conv}}$  is greater than  $E_{\text{conv max}}$ , then the temperatures are set to  $T_{\infty}$ , the undisturbed ground water temperature.

The Darcy velocity in each ground layer is an additional parameter required for the model. The Darcy velocity is set to zero if there is no regional ground water flow. A ground water flow specified outside the storage volume is not taken into account in the calculations. Another additional parameter specifies whether the convective heat losses are calculated or not, and which one of the two methods is chosen when calculated.

### 3.2 Short-term Influence of a Regional Ground Water Flow:

A rough influence of the regional ground water flow on the heat transferred by the boreholes can be estimated with the help of the Nusselt number associated with a cylinder imbedded in a porous medium and submitted to a regional ground water flow. The cylinder is perpendicular to the flow, which is assumed to be uniform. The surface temperature of the cylinder is prescribed and constant.

The steady-state heat transfer rate between the surface of the cylinder at temperature  $T_w$  and the saturated porous medium at far-field temperature  $T_{\infty}$  can be expressed in terms of an average Nusselt number (Nield and Bejan, 1992):

$$\overline{\text{Nu}}_D = \frac{\overline{q''}}{T_w - T_{\infty}} \frac{D}{\lambda_m} \quad (3.5)$$

With  $\overline{\text{Nu}}_D$ : average value of the Nusselt number over the cylinder surface, based on the diameter of the cylinder  $D$  (-);  
 $\overline{q''}$ : average heat transfer rate per unit area on the cylinder surface ( $\text{W}/\text{m}^2$ );  
 $T_w$ : surface temperature of the cylinder ( $^{\circ}\text{C}$ );  
 $T_{\infty}$ : temperature of the undisturbed porous medium ( $^{\circ}\text{C}$ );  
 $D$ : diameter of the cylinder (m);  
 $\lambda_m$ : thermal conductivity of the porous medium ( $\text{W}/\text{mK}$ );

When the boundary layer is distinct (thin), i. e., when the boundary layer thickness is smaller than the cylinder radius, the average value of the Nusselt number can be calculated (Nield and Bejan, 1992), by assuming the Darcy flow model valid:

$$\overline{Nu}_D = 1.015 Pe_D^{1/2} \quad (3.6)$$

$$Pe_D = \frac{u D}{\alpha_m} \quad (3.7)$$

With  $Pe_D$ : Péclet number based on the cylinder diameter  $D$  (-);

$\alpha_m$ : thermal diffusivity of the porous medium ( $m^2/s$ );

The requirement for the validity of (3.6) can be written as:

$$Pe_D^{1/2} \gg 1 \quad \text{or} \quad \overline{Nu}_D \gg 1 \quad (3.8)$$

In the DST model, the short-time effects of the injection/extraction through the ducts are simulated with the local solutions, which depend only on a radial coordinate and cover a cylindrical volume of radius  $r_1$  exclusively ascribed to each duct (or *heat exchanger pile*). As the model assumes a relatively large number of ducts, most of them are surrounded by other ducts. In consequence, a zero heat-flux at the outer boundary is prescribed, due to the symmetrical positions of the neighbouring ducts. Under steady-flux conditions and for pure heat conduction, the heat flux exchanged by the *heat exchanger pile* can be expressed in terms of the ground temperatures at the inner and outer boundaries (see Hellström, 1991):

$$T_w - T_\infty = \frac{q'_{cond}}{2 \pi \lambda_m} \left\{ \frac{r_1^2}{r_1^2 - r_o^2} \cdot \left[ \ln\left(\frac{r_1}{r_o}\right) - \frac{1}{2} + \frac{r_o^2}{2 r_1^2} \right] \right\} \quad (3.9)$$

With  $r_o$ : radius of the *heat exchanger pile*,  $r_o = D/2$  (m);

$r_1$ : outer radius of the ground cylinder ascribed to the *heat exchanger pile* (m);

$T_w$ : ground temperature at the *heat exchanger pile*  $T(r = r_o)$  ( $^{\circ}C$ );

$T_\infty$ : ground temperature at the outer radius  $T(r = r_1)$  ( $^{\circ}C$ );

$\lambda_m$ : thermal conductivity of the porous medium (W/mK);

$q'_{cond}$ : heat transfer rate per unit length transferred by the *heat exchanger pile* (W/m)

In order to be able to compare the heat fluxes transferred by forced convection and pure conduction, the ground temperature at the outer boundary (at the radius  $r_1$  from a *heat exchanger pile*), is assimilated to the far field temperature  $T_\infty$ ; (this is certainly the most questionable assertion). With this assumption, it is now possible to compare the heat fluxes by noting that:

$$\overline{q}' = \overline{q}'' \pi D \quad (3.10)$$

Combining (3.5), (3.6), (3.9) and (3.10) gives:

$$\frac{\bar{q}'}{q'_{\text{cond}}} = \frac{\overline{\text{Nu}}_D}{2} \left\{ \frac{r_1^2}{r_1^2 - r_o^2} \cdot \left[ \ln\left(\frac{r_1}{r_o}\right) - \frac{1}{2} + \frac{r_o^2}{2 r_1^2} \right] \right\} \quad (3.11)$$

The ratio  $\frac{\bar{q}'}{q'_{\text{cond}}}$  indicates by how much the actual heat transfer rate differs from that resulting from heat conduction only. This ratio is used as a correction factor to the calculations of the heat transfer rate exchanged by the *heat exchanger piles*, but only if it is greater than 1. The same correction factor is assumed for the calculations of the transient heat transfers around the *heat exchanger piles*.

In the programme, an additional parameter is defined to specify whether this effect is calculated or not.

#### 4. Connecting Pipes on Ground Surface

The heat transferred by the connecting pipes can be simulated by using two “pipe” modules in TRNSYS, one for the fluid flowing to the *heat exchanger piles* and one for the returning fluid. During a simulation time-step, the “pipe” modules lose or gain heat relative to a given temperature, set to the average ground temperature on top of the store. The resulting transferred heat is then injected on top of the storage, as a temperature correction to the temperatures of the meshes in the uppermost mesh layer of the store. The new ground temperature on top of the store will be the next temperature input to the “pipe” modules and so on. Other modules can be used, as long as an input temperature is used to calculate the heat transfer rate exchanged by the pipes, which is then returned as an output variable.

The TRNVDSTP module has two additional inputs to collect the heat transfer rates exchanged by the connecting pipes. Two additional outputs returns the average ground temperature on top of the store and the total heat rate exchanged by the connecting pipes.

The average ground temperature on top of the store is determined with the mesh temperatures of the uppermost mesh layer of the store. The vertical extension of this mesh layer (DMESH) is determined by the extension of the smallest mesh (DMIN) used for the computation of the global process. It may be influenced by the vertical extension of the first ground layer in the store (DLAY1), if the user specify a value smaller than twice the smallest mesh:

$$\text{If } \text{DLAY1} > 2 \cdot \text{DMIN} \text{ then } \text{DMESH} = \text{DMIN} \quad (3.12a)$$

$$\text{If } \text{DMIN} < \text{DLAY1} < 2 \cdot \text{DMIN} \text{ then } \text{DMESH} = \text{DLAY1} / 2 \quad (3.12b)$$

$$\text{If } \text{DLAY1} \leq \text{DMIN} \text{ then } \text{DMESH} = \text{DLAY1} \quad (3.12c)$$

The value of DMESH is written in DST.DAT, an output file that gives a summary of the input parameters and automatic settings performed by the programme.



## 5. Parameters, Inputs and Outputs of TRNVDSTP (TRNVDST):

The parameters, inputs, outputs and changes that are specific to TRNVDSTP, the TRNSYS version of TRNVDST adapted for the simulation of *heat exchanger piles*, are written in *italics*, and correspond to the December 1996 version. The description below applies to TRNVDST as well (the version which dates from October 1996), if the information given in *italics* is disregarded. (The date of each version is indicated at the beginning of the source file code or in the information file DST.DAT which can be written when the programme is executed). Additional information about the theory and a more accurate description of the programme can be found in Hellström, (1989), Hellström, (1991) and Pahud and Hellström, (1996).

### 5.1 The Parameter Values:

#### PARAMETER VALUES DESCRIPTION

1. **V** - Volume of storage region [m<sup>3</sup>]
2. **H** - Storage height or length of one borehole [m]
3. **DPH** - Distance between the ground surface and the upper side of the storage volume [m]
4. **Nb** - Number of boreholes [-]
5. **Ro** - Outer radius of each borehole [m]  
- NB: if the borehole thermal resistance is extrapolated from the values read in a file, the radius given here (Ro) must correspond to the radius that was assumed or used for the calculations or determinations of the borehole thermal resistance values.
6. **NSerie** - Number of boreholes connected in series (<MAXRLO; MAXRLO is defined in TRNVDST.INC) [-]
7. **NRLoc** - Number of radial subregions for the computation of the local process (NRLoc ≤ NSerie) [-]
8. **NZLoc** - Number of vertical subregions for the computation of the local process (NZLoc·NRLoc ≤ IDIMLO; IDIMLO is defined in TRNVDST.INC) [-]
9. **k<sub>s</sub>** - Thermal conductivity of the storage material [kJ/h m K]. If **k<sub>s</sub>** is set to a negative value, the ground properties (**k<sub>s</sub>** and **C<sub>s</sub>**) are set as those of the corresponding ground layer outside the storage volume; they may differ from layer to layer within the storage. The ground layer properties are defined below. (*This value is not used in TRNVDSTP, as in the programme, it is already set to a negative value*)
10. **C<sub>s</sub>** - Volumetric heat capacity of the storage material [kJ/m<sup>3</sup>K]. This value is not used if **k<sub>s</sub>** is set to a negative value. (*This value is not used in TRNVDSTP*)

11. **R<sub>p</sub>**      **IF R<sub>p</sub>≥0: R<sub>p</sub>:**
- thermal resistance between the fluid in the pipes and the ground at the borehole wall per unit of borehole length (fluid-to-ground thermal resistance) [K/(kJ/h·m)]  
(x [K/(W/m)] = x / 3.6 [K/(kJ/h·m)])
- IF -11≤R<sub>p</sub><0:-R<sub>p</sub>:**
- number of U-pipes in each borehole (1 to 10); -11: coaxial pipes [-]. R<sub>p</sub> is calculated with the help of the 9 following parameters. R<sub>p</sub> is kept constant during the simulation.
- IF R<sub>p</sub>≤-12:** Flow- and temperature-dependent borehole thermal resistance. (-R<sub>p</sub>) is the logical unit through which the flow- and temperature-dependent R<sub>p</sub> values are provided. The file name should be assigned to this logical unit with an ASSIGN statement in the TRNSYS deck.

k=0

only if -11≤R<sub>p</sub><0-----

12. **R<sub>po</sub>**      - Pipe outer radius [m] (if coaxial, inner pipe outer radius)
13. **R<sub>pi</sub>**      - Pipe inner radius [m] (if coaxial, inner pipe inner radius)
14. **D**         - U-pipe centre-to-centre half distance [m]; (if coaxial pipes, outer pipe inner radius; the outer radius is the borehole radius)
15. **λ<sub>bh</sub>**      - Thermal conductivity of borehole filling material [kJ/h·m·K]
16. **λ<sub>p</sub>**        - Thermal conductivity of pipe material [kJ/h·m·K]
17. **λ<sub>gap</sub>**      - Equivalent thermal conductivity of gap between the pipes and the filling material [kJ/h·m·K]
18. **Gap**       - Gap thickness (assumed existing on only half of the heat transfer surface) [m]
19. **V<sub>ref</sub>**      - Reference fluid flow rate per borehole (water) for the calculation of the fluid-to-ground thermal resistance (borehole thermal resistance) [kg/h]
20. **T<sub>ref</sub>**      - Reference fluid temperature (water) for the calculation of the fluid-to-ground thermal resistance [°C]

k=9

-----

12+k. <b>Ra</b>	<p><b>IF Ra &lt; 0:</b> the heat transfers between the upward and downward fluid in the borehole are taken into account. (The concept of effective fluid-to-ground thermal resistance is used).</p> <p><b>Ra &gt; 0:</b> the effective fluid-to-ground thermal resistance is calculated for the case of COAXIAL PIPES</p> <p><b>Ra &lt; 0:</b> the effective fluid-to-ground thermal resistance is calculated for the case of a U-PIPE installation.</p> <p><b>IF Rp ≥ 0:</b> <b>abs(Ra)</b> is thermal resistance between the upward and downward fluid in the pipes (per unit of borehole length) [K/(kJ/hm)]</p> <p><b>IF -11 ≤ Rp &lt; 0:</b> <b>Ra</b> is calculated with the help of the 9 preceding parameters. <b>Ra</b> is kept constant during the simulation. Nevertheless, the sign of the parameter <b>Ra</b> determines the case calculated (U-pipe or not), and should be set to agree with the borehole installation.</p> <p><b>IF Rp ≤ -12:</b> <b>Ra</b> is flow- and temperature-dependent. (-Rp) is the logical unit through which the <b>Ra</b> values are provided.</p> <p><b>IF Ra = 0:</b> the heat transfers between the upward and downward fluid in the borehole are NOT taken into account.</p>
13+k. <b>cf</b>	- Specific thermal capacity of the heat carrier fluid [kJ/kg·K]
14+k. <b>rf</b>	- Mass density of the fluid [kg/m <sup>3</sup> ]
15+k. <b>ISO</b>	- = 0 no thermal insulation [-] = 1 insulation on upper surface and side of the storage volume. An upper fraction <b>FRISO</b> of the side is covered [-] = 2 insulation only on upper surface, which extends a certain distance beyond the boundary of the storage. This distance is a fraction <b>FRISO</b> of the height of the storage [-]
16+k. <b>FRISO</b>	- Fraction of the height of the storage volume [-]
17+k. <b>TH<sub>ins</sub></b>	- Thickness of insulation [m]
18+k. <b>k<sub>ins</sub></b>	- Thermal conductivity of insulation material [kJ/h·m·K]
19+k. <b>SY</b>	- Number of simulation years. The numerical mesh extension depends on (increases with) this number [-]
20+k. <b>T<sub>max</sub></b>	- Max. temperature allowed to the storage [°C]
21+k. <b>T<sub>gs</sub></b>	- Initial temperature of the undisturbed ground surface [°C]
22+k. <b>DT<sub>g</sub></b>	- Initial thermal gradient in the undisturbed ground [K/m]
23+k. <b>IPRE</b>	- Number of preheating cycles (0 no pre-heating). During preheating sinusoidal yearly variation of the average storage temperature is used to heat up the surrounding ground.
24+k. <b>T<sub>max,ph</sub></b>	- Max. uniform storage temperature during preheating cycles [°C]
25+k. <b>T<sub>min,ph</sub></b>	- Min. uniform storage temperature during preheating cycles [°C]

- 26+k.  $\phi$  - Phase delay in preheating sinusoidal temperature curve [days]  

$$T_{storage} = \frac{T_{max,ph} + T_{min,ph}}{2} + \frac{T_{max,ph} - T_{min,ph}}{2} \sin(\omega(t + \Phi))$$
N.B.:  $T_{storage}(t=0)$  is taken as initial condition after the ground preheating.
- 27+k.  $T_{ma}$  - Yearly average air temperature [°C]. (For preheating calculation only)
- 28+k.  $T_{aa}$  - Yearly amplitude of the air temperature [°C]. (For preheating calculation only)
- 29+k.  $\phi_{air}$  - Phase delay in sinusoidal air temperature curve [days]  

$$T_{air} = T_{ma} + T_{aa} \sin(\omega(t + \Phi_{air}))$$
- 30+k. **IFCGLO** - *Flag for the calculation of the effect of forced convection on the global process (long-term influence). (0: no calculation; 1: method 1, recommended; 2: method 2, used together with "large" Darcy velocities, so that the ground temperatures in the corresponding ground layers are close to the undisturbed temperature)*
- 31+k. **IFCLOC** - *Flag for the calculation of the effect of forced convection on the local process (short-term influence). (0: no calculation; 1: calculation)*
- 32 (30) +k.  $N_I$  - Number of ground layers (maximum NLAY, NLAY is defined in TRNVDST.INC) [-]  
for  $i = 1$  to  $N_I$ ;  $J=4$  for TRNVDSTP; ( $J=3$  for TRNVDST)
- 33 (31) +k+(i-1)·J.  $k_g$  Thermal conductivity of i-th layer [kJ/h m K]
- 34 (32) +k+(i-1)·J.  $c_g$  Volumetric heat capacity of i-th layer [kJ/m<sup>3</sup>K]
- 35 (33) +k+(i-1)·J.  $TH_g$  Thickness of i-th layer [m]
- 36 +k+(i-1)·J. **Darcy** *Darcy velocity in the i-th layer [m<sup>3</sup><sub>water</sub>/m<sup>2</sup>s]*
- 37 (34) +k+(N<sub>I</sub>-1)·J. **IPRT** = 1 print input data, mesh coordinates and initial temperature fields. (=0 no print) [-]
- 38 (35) +k+(N<sub>I</sub>-1)·J. **OPRT** = 1 print detailed results according the following parameters [-]
- 39 (36) +k+(N<sub>I</sub>-1)·J. **LUW** Output logical unit for **IPRT** and/or **OPRT** special printing [-]
- 40 (37) +k+(N<sub>I</sub>-1)·J. **IP1** = 1 print **Tair**, **Tav.stor.**, **Tin**, **Tout** and exchanged thermal power during the last time-step, accumulated injected energy and accumulated extracted energy until the current time, mass flow rate during the last time-step. If **NSPEC** greater than zero, the temperature in **NSPEC** storage locations will be printed out. If **IBLOSS** equals 1, the accumulated heat losses through the storage boundaries will be printed out [-]
- 41 (38) +k+(N<sub>I</sub>-1)·J. **DT1** Time interval between **IP1** printing [h]
- 42 (39) +k+(N<sub>I</sub>-1)·J. **IP2** = 1 print global temperature field [-]
- 43 (40) +k+(N<sub>I</sub>-1)·J. **DT2** Time interval between **IP2** printing [h]
- 44 (41) +k+(N<sub>I</sub>-1)·J. **IP3** = 1 print heat flow fields [-]
- 45 (42) +k+(N<sub>I</sub>-1)·J. **DT3** Time interval between **IP3** printing [h]
- 46 (43) +k+(N<sub>I</sub>-1)·J. **IP4** = 1 print local temperature field [-]

47 (44)  $+k+(N_1-1) \cdot J$ . **DT4** Time interval between **IP4** printing [h]  
 48 (45)  $+k+(N_1-1) \cdot J$ . **IBLOSS** = 1 print losses through storage boundaries [-]  
 49 (46)  $+k+(N_1-1) \cdot J$ . **NSPEC** N° of storage locations of which the temperature has to be printed out (maximum **MAXSPE**; **MAXSPE** is defined in **TRNVDST.INC**) [-]

for  $i = 1$  to **NSPEC**

50 (47)  $+k+(N_1-1) \cdot J+(i-1) \cdot 3$ . **IR** Node number in radial direction (global field) [-]

51 (48)  $+k+(N_1-1) \cdot J+(i-1) \cdot 3$ . **IZ** Node number in vertical direction (global field) [-]

52 (49)  $+k+(N_1-1) \cdot J+(i-1) \cdot 3$ . **IL** Node number in local field [-]

**Note:**

- 1) Parameter numbering: the second number in brackets corresponds to the numbering in **TRNVDST**, whereas the first one applies for **TRNVDSTP**.
- 2) Parameters from 40 (37)  $+k+(N_1-1) \cdot J$  have to be specified only if **IPRT** or **OPRT** are greater than zero.
- 3) If  $-11 \leq \mathbf{Rp} < 0$ , i.e. automatic calculation of thermal resistance between the heat carrier fluid and the ground surrounding the borehole has been specified, the resulting value can be found into the **DST.DAT** file, if **IPRT** = 1 has been specified. **DST.DAT** also contains a summary of the parameters defining the store and provides the user with useful information about intermediate calculated quantities, meshes, time-steps, subregions and more.
- 4) **NSerie** is used to determine the flow rate per borehole and to constrain the radial mesh so that **NSerie** radial divisions of equal volume are possible in the store.
- 5) The highest accuracy is obtained when the number of radial subregions, **NRLoc**, is set equal to **Nserie**. In that case, there is one radial division of the storage volume per radial subregion. In counterpart, the calculation time may significantly be increased. When less radial subregions are specified, there are different ways of regrouping the radial divisions into the radial subregions. For a given number of radial subregions, it has been found that better accuracy is obtained when each radial subregion contains the same number of radial divisions. In consequence, the **NSerie** radial divisions of the storage volume are distributed as evenly as possible in the **NRLoc** specified radial subregions.
- 6) The vertical mesh is not constrained by **NZLoc**. According to test results (see point 5)), the vertical subregions regroup vertical meshes in such a way that the vertical extension of each subregion is set as evenly as possible. The maximum number of vertical subregions is limited by the maximum number of vertical meshes within the storage volume. In that case, the highest accuracy is obtained.
- 7) When more than one ground layer is defined within the storage volume, the vertical mesh is generated for each of the layers that cross the storage, i. e., the mesh matches these layer boundaries and is defined there with the finest mesh resolution. The **NZLoc** vertical subregions are distributed as equally as possible in each ground layer within the storage volume. The procedure described in point 6) is then executed for each ground layer. The minimum number of vertical subregions is determined by the number of ground layers that cross the storage volume. **NZLoc** is increased if necessary.

- 8) *A pre-heating of the store is performed without forced convection. Ground water flow specified outside the storage volume is not taken into account in the calculations.*
- 9) *Insulation on the side of the store has no influence on forced convection: the ground water flow is not affected on the storage sides.*

## 5.2 The Input Variables:

### INPUT VARIABLES DESCRIPTION

- |    |                         |   |  |
|----|-------------------------|---|--|
| 1. | <b>T<sub>in</sub></b>   | - | Inlet fluid temperature [°C]   |
| 2. | <b>m'</b>               | - | Mass flow rate [kg/h]  |
| 3. | <b>T<sub>airh</sub></b> | - | Air temperature on top of the store (i.e. house, etc.) [°C]  |
| 4. | <b>T<sub>air</sub></b>  | - | Air temperature elsewhere (anywhere on ground surface except on top of the store) [°C]   |
| 5. | <b>Circul</b>           | - | Switch to set the circulation of the fluid in the ground heat exchanger [-]<br><b>IF Circul&gt;0:</b> the fluid circulates from subregion 1 to subregion NLoc=NRLoc·NZLoc.<br><b>IF Circul≤0:</b> the fluid circulates from subregion NLoc to subregion 1.<br>If NRLoc=NZLoc=1, the switch can be set to any constant value. |
| 6. | <b>Q<sub>pip1</sub></b> | - | Heat rate exchanged by connecting pipes 1 on top of the store [kJ/h]   |
| 7. | <b>Q<sub>pip2</sub></b> | - | Heat rate exchanged by connecting pipes 2 on top of the store [kJ/h]<br><i>Q<sub>pip1</sub> or 2 &gt;0: heat rate injected on top of the store;</i><br><i>Q<sub>pip1</sub> or 2 &lt;0: heat rate extracted from the top of the store.</i>  |

**Note:** If NLoc=NRLoc·NZLoc>1, the first subregion is set at the centre of the store (if NRLoc>1) and at the bottom (if NZLoc>1). The last subregion (NLoc) is set at the border and the top of the store. In order to provide a radial stratification of the ground temperatures in the store, the fluid should circulate from the centre to the border during a heat injection period (Circul>0) and from the border to the centre during a heat extraction period (Circul≤0).

### 5.3 The Output Variables:

#### OUTPUT VARIABLES DESCRIPTION

1.	<b>T<sub>out</sub></b>	-	Outlet fluid temperature [°C]
2.	<b>m'</b>	-	Mass flow rate [kg/h]
3.	<b>T<sub>av.st.</sub></b>	-	Average storage temperature [°C]
4.	<b>Q'</b>	-	Average exchanged heat rate [kJ/h]
5.	<b>Q<sub>loss,t</sub></b>	-	Heat losses through the top boundary of the storage [kJ/h]
6.	<b>Q<sub>loss,s</sub></b>	-	Heat losses through the side boundary of the storage [kJ/h]
7.	<b>Q<sub>loss,b</sub></b>	-	Heat losses through the bottom boundary of the storage [kJ/h]
8.	<b>QDST</b>	-	Storage internal energy variation during the last time-step [kJ/h]
9.	<b>Q<sub>pip.top.</sub></b>	-	<i>Heat rate transferred by the connecting pipes on top of the store [kJ/h]</i>
10.	<b>T<sub>av.top.</sub></b>	-	<i>Average soil temperature on top of the store; (temperature average of the uppermost mesh layer in the storage volume) [°C]</i>
11. (9.)	<b>T<sub>av.bh.</sub></b>	-	Average soil temperature near the boreholes (average value on the whole storage) [°C]
12. (10.)	<b>T<sub>bh,1</sub></b>	-	Average soil temperature near the boreholes in radial subregion 1 (centre)
If NRLoc≥2:			
13. (11.)	<b>T<sub>bh,NRLoc</sub></b>		Average soil temperature near the boreholes in radial subregion NRLoc (border)
If NRLoc≥3:			
14. (12.)	<b>T<sub>bh,NRLoc-1</sub></b>		Average soil temperature near the boreholes in radial subregion NRLoc-1
If NRLoc≥4:			
15. (13.)	<b>T<sub>bh,NRLoc-2</sub></b>		Average soil temperature near the boreholes in radial subregion NRLoc-2
etc.			

**Note:**

- 1) Output numbering: the second number in brackets corresponds to the numbering in TRNVDST, whereas the first one applies to TRNVDSTP.
- 2) The maximum number of outputs is limited to 20. The soil temperature near the boreholes in radial subregion *i* is an average value along the height of the store during the TRNSYS simulation time-step.

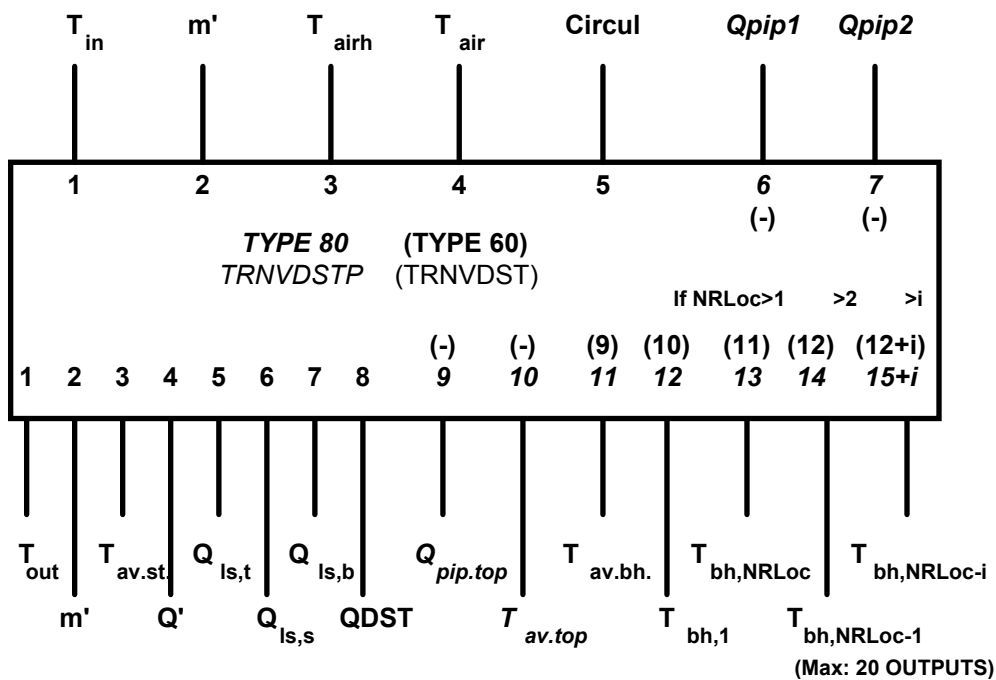
### 5.4 Information Flow Diagram:

**INPUTS:** 7 TRNV DSTP; 5 (TRNV DST)

**OUTPUTS:** 11+NRLoc, maximum 20; 9+NRloc, maximum 20

**PARAMETERS:** from 38; from 35

(The maximum number of parameters is set to 112; change the value in the source code and recompile if more are needed).



### References:

- Hellström G. (1983) Heat Storage Subroutines in Minsun. Duct Storage Systems. Department of Mathematical Physics, University of Lund, Sweden.
- Hellström G. (1989) Duct Ground Heat Storage Model, Manual for Computer Code. Department of Mathematical Physics, University of Lund, Sweden.
- Hellström G. (1991) Ground Heat Storage. Thermal Analyses of Duct Storage Systems. Theory. Thesis, Department of Mathematical Physics, University of Lund, Sweden.
- Hellström G., Mazzarella L. and Pahud D. (1996) Duct Ground Heat Storage Model. Lund - DST. TRNSYS 13.1 Version January 1996. Department of Mathematical Physics, University of Lund, Sweden.
- Mazzarella L. (1991) MINSUN 6.0 - NEWMIN 2.0. A Revised IEA Computer Program for Performance Simulation of Energy Systems with Seasonal Thermal Energy Storage. Proceedings Thermastock' 91, pp. 3.5-1 - 3.5-7, Scheveningen, The Netherlands.



- Mazzarella L. (1993) Duct Thermal Storage Model. Lund-DST. TRNSYS 13.1 Version 1993. ITW, Universität Stuttgart, Germany, Dipartimento di Energetica, Politecnico di Milano, Italy.
- Nield D. A. and Bejan A. (1992) Convection in Porous Media, Springer-Verlag, New-York.
- Pahud D. and Hellström G. (1996) The New Duct Ground Heat Model for TRNSYS. In Proceedings of Eurotherm Seminar N° 49, A.A. van Steenhoven and W.G.J. van Helden (eds), pp. 127 - 136