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SUPSI

Dipartimento
Ambiente
Costruzioni e
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**Istituto
Sostenibilità
Applicata
Ambiente
Costrutivo**

PILESIM2

Simulation Tool for Heating/Cooling Systems with Energy Piles or multiple Borehole Heat Exchangers

User Manual

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1.	PC and System Requirement

PILESIM2 was tested on a laptop (Pentium 1.7 GHz and 512 MBytes of RAM) with Windows XP Professional. PILESIM2 requires about 10 to 20 MBytes of hard disk space. PILESIM2 is based on PILESIM, the former version of June 1999 which had successfully been tested on a machine with Windows 98 and Windows NT. PILESIM2 is a 32 bits programme and is not working with Windows 3.x. PILESIM2 is a TRANSED application of the TRNSYS package simulation tool made with the TRNSYS version 15.3.

2.	Installation Procedure

All the necessary files are compressed in a single zipped file. To install PILESIM2, you may start the programme Windows Explorer and select the drive and directory where the compressed file is (e. g. select the drive C:\MySavedFiles), provided you have saved the PILESIM2 zipped file in this directory. You may also click on the My Computer icon in order to find the drive and directory where the file is stored. To install PILESIM2, you have to create a directory on your local hard drive. It is recommended to created a new directory, for example C:\PILESIM2, and copy in this directory the PILESIM2.ZIP file. Unzip the file and be sure that the subdirectory structure is maintained. (If you already have TRNSYS on your computer, it is not advised to install PILESIM2 in the same directory. Several of your original TRNSYS files would be overwritten and lost). To remove PILESIM2 from your computer, simply delete the directory in which PILESIM2 was installed.

Two additional utilities are distributed in two separate zipped files. These utilities are 2 Excel files and require the EXCEL programme to be used. They are:

- MakeLoadFile.zip
Zipped excel file "MakeLoadFile.zip". This file is devised to generate hourly profiles for the loading conditions on the basis of the hourly evolutions of the outdoor air temperature and the global solar radiation for a typical year. Unzip this file in the PILEDATA subdirectory.

- Pilesim2-get-output.zip
Zipped excel file "Pilesim2-get-output.xls". This file is devised to visualise the results of a simulation contained in the various output files produced with PILESIM2. Unzip this file in the PILESIM2 directory.

3.   How to Start PILESIM2

With Windows there are different ways of starting PILESIM2. PILESIM2 is started by running the executable file TRNSED.EXE. It is important to run the TRNSED.EXE file from the directory where PILESIM2 is installed. If TRNSYS or another TRANSED application is installed on the computer, another TRNSED.EXE files are present in their respective directory and these executable files must not be run instead of the one in the PILESIM2 directory. The best way to avoid this is to create on the desktop a shortcut to the correct TRNSED.EXE file. To do this, search with Windows Explorer the directory in which PILESIM2 has been installed. Search the executable file TRNSED.EXE. Select the file TRNSED.EXE with the mouse and right click on it. A context sensitive menu appears. Choose "Send to" and select "Desktop" to send the shortcut on the desktop. You can then rename the shortcut to "PILESIM2".

When PILESIM2 is started (i.e. when the programme TRNSED.EXE from the PILESIM2 directory is executed), a dialogue box pops onto the screen to ask you which TRNSED file to open (the file has the extension *.TRD). Choose the file PILESIM.TRD (click on the name) and then open it (click on the Open button).

To check that PILESIM2 is working properly, run the TRNSED file PILESIM.TRD with the default parameter values. To start the calculation, choose TRNSYS / Calculate in the menu. The calculated results are stored in several files (PILESIM.OUT, PILESIM.OPA, PILESIM.PLT and DST.DAT). They should be the same as the output results stored in the directory PILERESU. An original copy of PILESIM.TRD is also stored in this directory.

4.   Limitation of the Technical Support

A "hotline" is provided through e-mail only (use the e-mail address: daniel.pahud@supsi.ch). The "hotline" covers a reduced help service; problems related to the PILESIM2 installation, bad configuration or incompatibility of the personal computer system are not covered by the "hotline". Problems related to the use of the programme TRNSED are also not covered. For each purchased programme, the duration of the work spent for the "hotline" will not exceed 1 hour. If the ISAAC thinks that the help demanded is actually consulting work, or does not correspond to the help described above, the client will be informed and an offer will be proposed (the hourly price is fixed at 150 CHF/hour or 100 EU/hour).

5.   Introduction to Energy Pile Systems

A pile foundation is used when the upper layers of soil are too soft and compressible to support the loads of a superstructure, normally a building. An energy pile is a pile foundation equipped with a channel system, in which a heat carrier fluid can be circulated so as to exchange heat with the surrounding ground. The two main functions of an energy pile are thus to support the loads of a superstructure and to serve as a heat exchanger with the ground. A energy pile system comprises a set of energy piles which are connected together hydraulically, and normally are coupled to a heat pump. Such a system is usually used for heating and/or cooling purposes.

The principal constraint on the system is that the thermal solicitations withstood by the piles must not deteriorate their mechanical properties, i.e., their ability to support the loads of the building. In particular, freezing of the piles must be avoided. In a safely sized energy pile system, the fluid temperature in the piles never drops below 0 °C for a long period of time. This temperature constraint influences the size of the heat pump, which in turn affects the heating potential provided by the energy piles. When geocooling is performed, i.e. when the pile flow circuit is connected to the cold distribution without a cooling machine in between, the cooling potential also depends directly on the temperature level of the fluid in the cooling system. The annual extracted and injected thermal energy through the piles determines the evolution of the ground temperature year after year, which in turn may affect the thermal performances of the system. An accurate assessment of the heating and cooling potential offered by an energy pile system requests a dynamic simulation of the system, which takes into account both short-term and long-term thermal performances. It requires good knowledge of the system's thermal characteristics, the local ground conditions and the use of an accurate system simulation tool.

Simulation tools of energy pile systems have been developed in the Laboratory of Energy Systems (LASEN), at the Swiss Federal Institute of Technology in Lausanne (EPFL) (see Fromentin et al., 1997). Their development has been carried out with the help of measurements from existing systems for comparison and validation purposes. The well-known transient system simulation programme TRNSYS was used. A non-standard simulation model, devised for heat storage in the ground with borehole heat exchangers (Pahud et. al, 1996a), has been adapted for energy piles (Pahud et. al, 1996b).

In the framework of the research project relative to the simulation of an energy pile system at Zürich airport (Hubbuch, 1998), the experience gained in the simulation of such systems was used to create PILESIM2. The development of simulation tools that were validated with measurements from existing systems (Fromentin et al., 1997) forms the basis of PILESIM2. The system's thermal performances, the utilisation potential of energy piles and a variety of system designs can be assessed with PILESIM2. PILESIM2 offers easy use and relatively fast calculations. This programme may also be used for the simulation of ground coupled systems with a relatively large number of borehole heat exchangers. A borehole heat exchanger is a borehole equipped with a pipe system (for example with U-shape pipes) to exchange heat between the heat carrier fluid and the ground.

In chapter 6, "The PILESIM2 Simulation Tool", an overview of the programme is presented. In chapter 7, "Simulation Models Used in PILESIM2", the resolution methods of the main simulation models are described in order to show the main assumptions used by the simulation tool. Chapter

8, "Input Data to PILESIM2", contains explanations on the input parameters and how they are used. In chapter 9, "Output Results from PILESIM2", the quantities calculated by PILESIM2 are described. Explanations to make a Sankey diagrams are also given.

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The data files and programmes sent per e-mail may not be distributed to other users.

6.   The PILESIM2 Simulation Tool

PILESIM2 is version 2 of the PILESIM programme. PILESIM has been developed with TRNSYS (Klein et al. 1998) and then adapted to the TRNSED format. Thanks to the TRNSED application, a stand-alone programme can be created. In addition, the TRNSYS simulation tool is embedded in a user-friendly interface which provides online help and allows a non-specialist TRNSYS user to use the programme.

Relatively to PILESIM, PILESIM2 allows the user to calculate a geocooling potential with a better precision, taking into account the forward or return fluid temperature level in the cooling distribution. Temperature losses in additional heat exchangers is also now taken into account (heat exchanger between the cooling machine condenser and the pile/bore circuit, or between the cooling distribution and the pile/bore circuit). Additional parameters have also been added to better simulate a field of borehole heat exchangers, by taking into account a geothermal temperature gradient in the ground and the internal heat transfer in a borehole heat exchanger.

6.1.   What Does PILESIM2 Simulate ?
In Fig. 6.1, a schematic view of the type of systems simulated by PILESIM2 is shown. Great flexibility has been given to PILESIM2 in order to provide a large variety of systems that can be simulated (see Fig. 6.1).
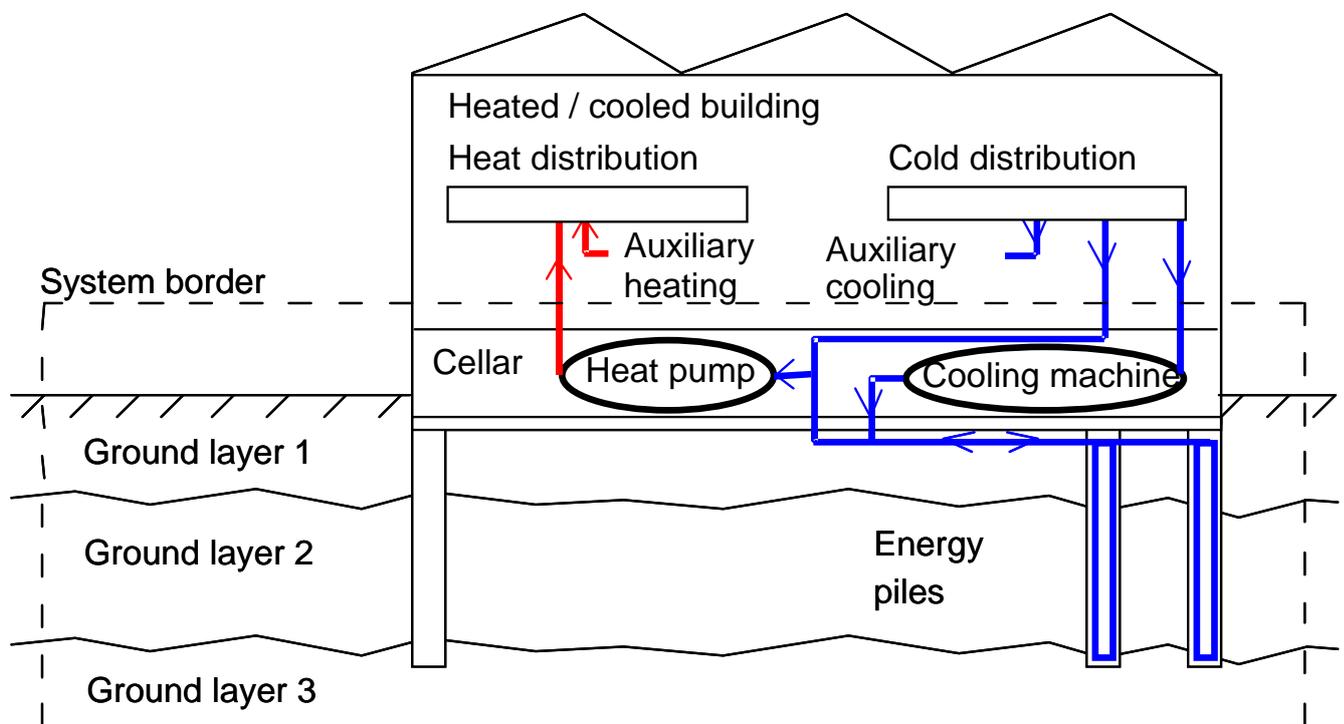

Fig. 6.1   *Schematic view of a energy pile system. The part of the system which is simulated by the PILESIM2 programme is delimited by the pile system border shown with the dashed line.*

The system border shown in Fig. 6.1 indicates the limits of the thermal simulations. The heat transfers are calculated from the ground to the thermal energy distributed in the building (heating and cooling). In particular, the heat transferred by the piles, by the horizontal connecting pipes under the concrete plate of the cellar, through the floor and ceiling of the cellar are assessed. The cellar, assumed to be unheated, has a temperature which depends on the indoor building temperature, the outside air temperature and the ground temperature below the building. The cellar may be given the temperature of the outside air by an appropriate setting of the heat transfer coefficients.

Four different types of system can be simulated:

1. heating only
  a fraction or the totality of the heat demand is covered by a heat pump coupled to the piles. A thermal recharge of the ground can be realised during the summer.

2. heating and geocooling[1]
  a fraction or the totality of the heat demand is covered by a heat pump coupled to the piles. A cooling requirement can be partly or totally covered by geocooling with the piles. No cooling machine connected to the piles is used.

3. heating and cooling with geocooling or a cooling machine
  a fraction or the totality of the heat demand is covered by a heat pump coupled to the piles. The cooling requirement is satisfied in priority by geocooling with the piles. If a greater part of the cooling demand can be realised with the cooling machine[2], the cooling machine is used and takes over geocooling. The thermal loads of the cooling machine are injected in the ground through the piles.

4. heating and cooling with a cooling machine
  a fraction or the totality of the heat demand is covered by a heat pump coupled to the piles. A fraction or the totality of the cooling requirement is also realised by a cooling machine connected to the piles. Geocooling is not performed.

6.2.   Which Types of Parameters Does PILESIM2 Require ?

A energy pile system is defined by 5 main categories of parameters (see chapter 8, Input Data to PILESIM2, for a complete description of the parameters). These categories are:

1. **the ground characteristics**
  they define the thermal properties of the ground layers (up to 3), a possible regional ground water flow in each layer and the initial undisturbed ground temperature;

2. **the energy piles**
  up to 6 different types of energy piles can be defined;

3. **the ground-building interface**
  these parameters are related to the cellar and the horizontal connecting pipes;

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[1] Geocooling is realised by connecting the pile flow circuit to the cold distribution without a cooling machine in between. It is also called direct cooling.
[2] The design power of the cooling machine is fixed before simulation by the user.

4. **the heat pump and cooling machine**
   these parameters define the thermal performances of the heat pump and the cooling machine;

5. **the loading conditions for heating and cooling**
   the loading conditions are read from a file. However, these parameters allow the user to quickly change the annual energy requirements and the temperature levels of the distributed thermal energy.

The loading conditions are given in hourly values. They are determined by the heat and cold demands and their corresponding temperature level. The hourly values are read from a text file. Predefined values are stored in files for several locations and can readily be used for a simulation. These predefined loading conditions were established on the basis of simple models which determine the space heating and space cooling requirements (see chapter 8, Input Data to PILESIM2 for more details). The user also has the possibility to use his own loading conditions with PILESIM2, in order to make them correspond to his particular problem. A temporal evolution of the hourly loading conditions is required for a whole year (see chapter 8, Input Data to PILESIM2, for the creation of an input data file).

6.3.   How May PILESIM2 Be Used ?

PILESIM2 can be used in different ways, depending on the degree of knowledge of a project. At an early stage, a pre-simulation can be performed by using a predefined file for the loading conditions, a constant performance coefficient for the heat pump and a constant efficiency for the cooling machine. Later in the project, more will obviously be known about the building. The pile system's parameters will also be known in greater detail and more accurate loading conditions can be established with the help of other programmes. They can be used to create an input data file for PILESIM2, and a more precise simulation of the pile system can be performed, which may include the temperature-dependent heat pump performance coefficient and cooling machine efficiency.

6.4.   What Does PILESIM2 Calculate ?

The energies transferred between the different components of the systems are calculated on a monthly or a yearly basis. A global heat balance of the system can be made month by month or year by year. Temperature levels, the heat pump performance coefficient and cooling machine efficiency, etc. are also calculated (see chapter 9, Output Results from PILESIM2, for a detailed description of the calculated quantities). In particular, the net auxiliary energy for heating and cooling, the electricity used by the heat pump and the cooling machine are calculated. The influence of long term effects on the results can be assessed for up to 25 years. The temporal evolution of some energy rates and temperatures are printed in a file for the last simulated year (see chapter 9). They can then be plotted thanks to a functionality of TRNSED.

6.5.   How Does PILESIM2 Calculate ?

Once the loading conditions are chosen and all the system parameters fixed, a simulation can be started. The undisturbed ground temperature is chosen for the initial conditions of the ground. The thermal simulation is performed with a time-step set to one hour. At each time-step, the operational

mode of the system is determined, depending on the system type chosen, the current loading conditions and the system component's thermal performances (heat pump, cooling machine, energy piles, etc.). Three basic operational modes are possible (cf. Fig. 6.2).

Operational mode: HEATING
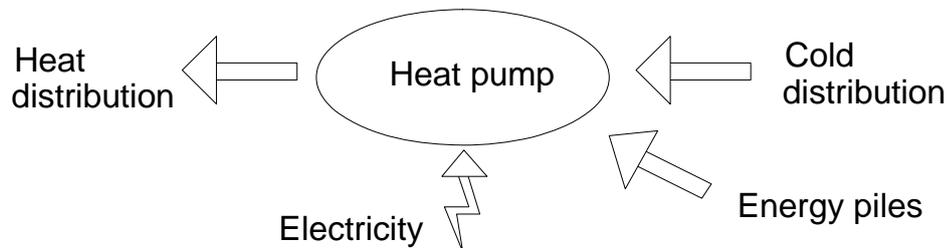
Operational mode: GEOCOOLING
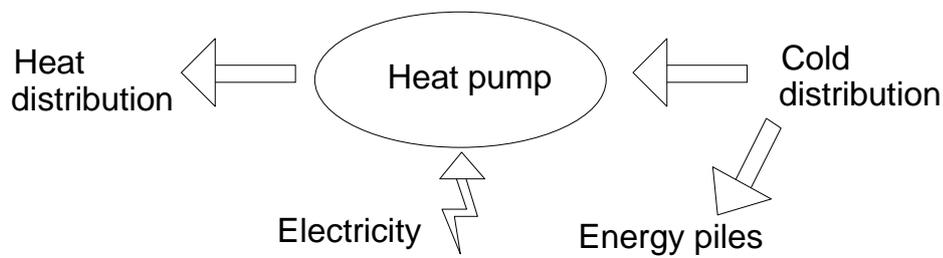
Operational mode: COOLING
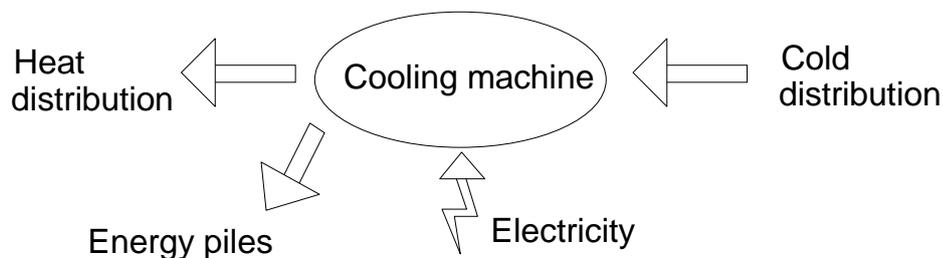
Fig. 6.2   The three drawings illustrate the three basic operational modes of the pile system. The arrows indicate the direction of the (positive) energy fluxes.

Heating and cooling can be simultaneously satisfied with each of these three operational modes. If there is no cooling requirement when heating is needed or vice versa, the three basic operational modes are reduced to three simple situations:

- heating with the heat pump connected to the piles;
- geocooling with the piles connected to the cold distribution;
- cooling with the cooling machine connected to the piles.

The mode that satisfies the greatest part of the heating and cooling demands is chosen. A schematic procedure to determine the operational mode is shown in Fig. 6.3. Note that the "resting mode" corresponds to the periods when the system is not used.
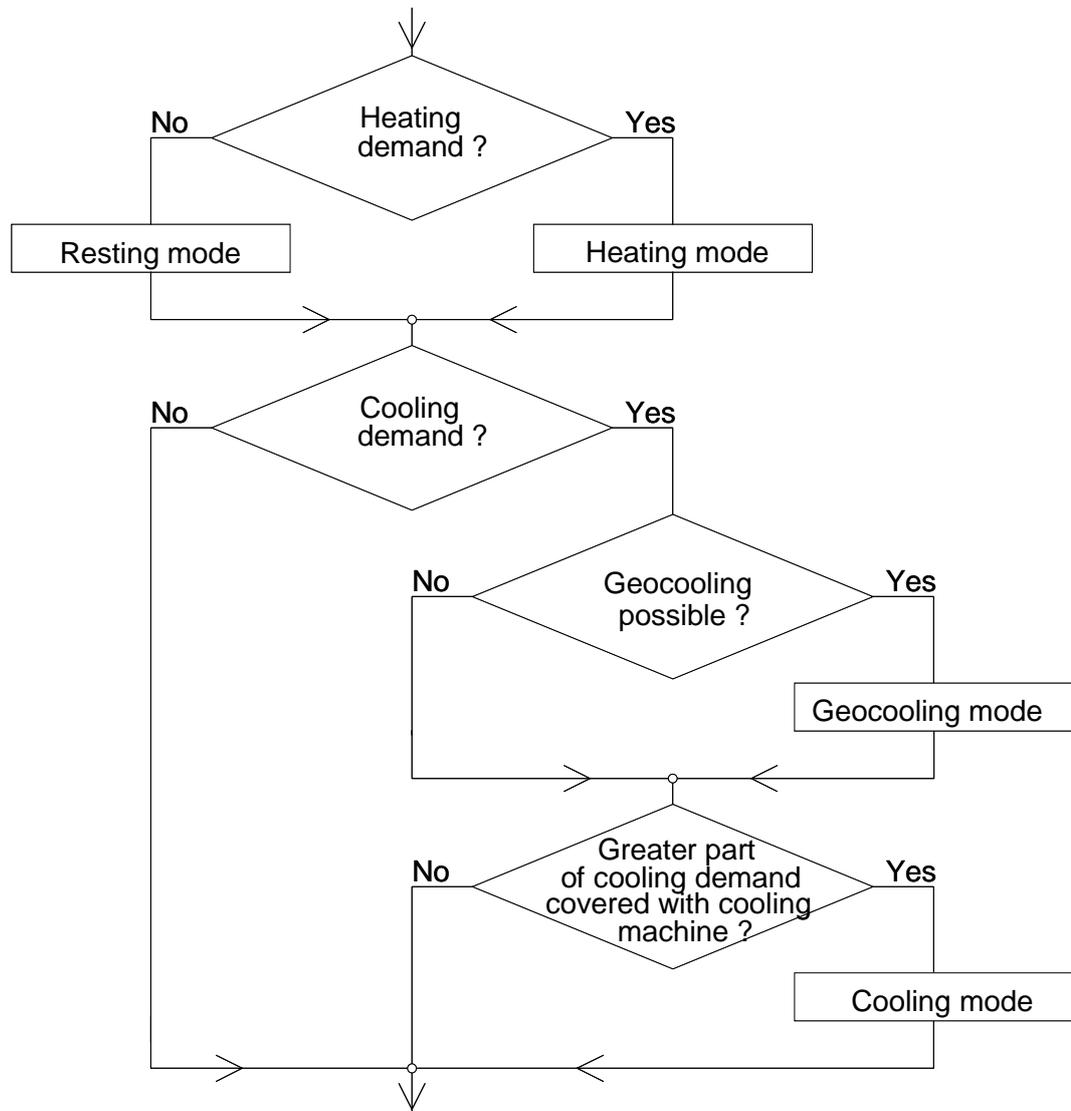
Fig. 6.3   *Schematic presentation of the procedure followed to determine the operational mode.*

The heat pump performance coefficient and the cooling machine efficiency may depend on the temperature levels of the heat carrier fluid in the condenser and evaporator. The performance coefficient determines the heating power, with the help of the design electric power of the heat pump, set to a constant value. The design electric power determines the size of the heat pump and is fixed by the user. If the heating requirement is smaller, the heating power is decreased to match the heating requirement. As a result, the electric power consumed by the heat pump and the heat rate extracted at the evaporator are recalculated with the help of the performance coefficient. The heating power of the heat pump may also be reduced by the temperature constraint associated with the

heat carrier fluid which circulates in the piles. This constraint requires that the fluid temperature in the piles never drops below a user given value, normally fixed at 0 °C. If this is not the case, the heat rate extracted by the heat pump is decreased until the fluid temperature satisfies the criterion. As a result, the heating power delivered by the heat pump is reduced. In consequence, an over-sized heat pump will not yield much more heating energy per year than a correctly sized one. A temperature constraint is also given for the highest allowed fluid temperature in the pile flow circuit. The same kind of considerations apply for the cooling machine.

PILESIM2 assumes an optimal system control: the best operational mode is selected; the heating and cooling powers are adjusted to the heating and cooling demands if necessary, while the temperature constraints on the heat carrier fluid in the piles are satisfied. The influence of frequent starts and stops of the heat pump and cooling machine is not taken into account, although a constant penalty value can be specified by the user on the performance coefficient and efficiency.

The simulation models used for the heat pump (or the cooling machine) and the energy piles are briefly described in chapter 7.

6.6.   Main Assumptions of the PILESIM2 Simulation Tool

As previously mentioned, the system control in PILESIM2 is optimal. Frequent starts and stops of the heat pump and the cooling machine are not taken into account. Other assumptions are related to the specificity of the simulation model used for the energy piles, which is TRNVDSTP (Pahud et al., 1996b). Some characteristics of TRNVDST are given in chapter 7. The main assumptions that can be mentioned in this section are:

- the number of energy piles is relatively large;
- the spatial arrangement of the energy piles is more or less regular;
- the ground area occupied by the energy piles has a shape which is more or less the shape of a circle or a square.
- the energy piles have about the same active length. (The active length of an energy pile is the length along which a radial heat transfer takes place, i.e. heat is transferred from the pile to the ground.)

These assumptions imply that most of the energy piles are surrounded by other energy piles. In other terms, PILESIM2 is not suited to the simulation of a single energy pile or several energy piles arranged in a line. When the shape of the ground area occupied by the energy piles is far from being a circle or a square, or the pile arrangement is highly irregular, the average pile spacing, which is an input parameter to PILESIM2, can be calibrated with another programme. (For example, TRNSBM (Eskilson, 1986; Eskilson, 1987; Pahud et al., 1996c) can be used.)

7. Simulation Models Used in PILESIM2

In this chapter, the heat pump model and the energy pile model are briefly presented.

7.1. The Heat Pump / Cooling Machine Model

The heat pump / cooling machine model is based on the model used in MINSUN (1985). A heat balance of the machine gives (heat losses are supposed to be small):

$$Pel + Qe = Qc \tag{7.1}$$

where:
Pel: electric power used by the machine (kW);
Qe: heat rate extracted at the evaporator (kW);
Qc: heat rate delivered at the condenser (kW).

The performance coefficient (COP), defined by the ratio Qc/Pel, is calculated with the help of the Carnot efficiency (equ. 7.2).

$$COP = \eta_{tech} \frac{Tc}{Tc - Te} \tag{7.2}$$

where Tc and Te represent the temperature levels of the working fluid in respectively, the condenser and the evaporator of the machine. The technical efficiency, η_{tech}, takes into account irreversible processes and losses in the Carnot cycle. The technical efficiency is determined as for the MINSUN programme (MINSUN, 1985) by the diagram shown in Fig. 7.1.
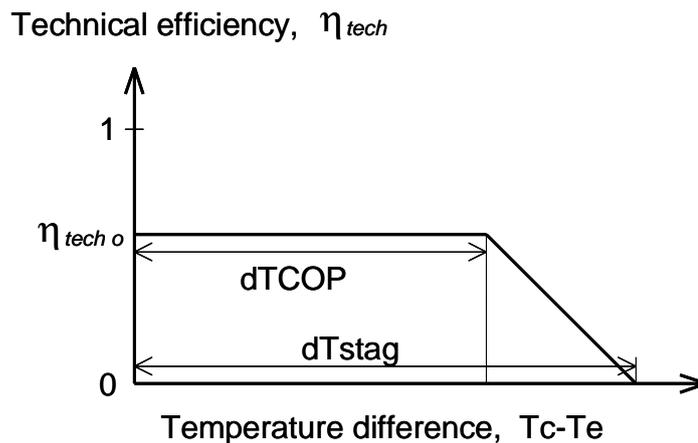

Fig. 7.1   Technical efficiency shape of the heat pump / cooling machine.

The minimum COP value is limited by 1. A maximum value is also given, so that the calculated COP may not have an unrealistic large value.

In the evaporator, the mean temperature of the heat carrier fluid used to extract heat from the cold source (piles, boreholes or else...) is higher than the working fluid temperature. In the condenser it is the other way round, and this leads to a temperature loss in both cases. These temperature losses are calculated by using a simple relation that models a heat exchanger (equ. 7.3 - 7.4).

$$Qc = UAc \ (Tc - Tcf) \tag{7.3}$$

$$Qe = UAe \ (Tef - Te) \tag{7.4}$$

where:

Qc: heat rate delivered at the condenser (kW);
UAc: overall heat transfer coefficient of the condenser (heat exchanger) (kW/K);
Tc: temperature level of the working fluid in the condenser (°C);
Tcf: mean temperature of the heat carrier fluid, determined as the average of the inlet and outlet fluid temperature in the condenser (°C);
Qe: heat rate extracted at the evaporator (kW);
UAe: overall heat transfer coefficient of the evaporator (heat exchanger) (kW/K);
Te: temperature level of the working fluid in the evaporator (°C);
Tef: mean temperature of the heat carrier fluid, determined as the average of the inlet and outlet fluid temperature in the evaporator (°C).

As previously mentioned (see section 7.5), the size of the heat pump and the cooling machine are fixed by their respective design electric power. The design conditions determine their respective heating and cooling power under fixed temperature levels of the heat carrier fluid in the condenser and evaporator. For other conditions, the model described above is used to calculate the corresponding heating and cooling power.

7.2.   The Energy Pile Model

When a pile foundation is used, the upper layers of soil are usually water saturated and ground water movement is quite common. The piles are reasonably thick (from 30 to 150 cm in diameter) and have a relatively short length (common values are between 10 to 30 m). The spacing between the piles varies between 3 to 10 m for most of the cases and is not necessarily regular. When a energy pile system is installed, the length of the horizontal pipes that connect the piles to the main pipe collector is often large in relation to the pile length. Computer programmes devised for the simulation of a duct ground heat storage or multiple heat extraction boreholes can be used to simulate a set of energy piles, if the following effects are taken into account:

- the influence of a regional ground water flow in a ground layer,
- the heat transfer of the connecting pipes between the piles on the ground surface,
- the thermal influence of the building on the ground volume containing the piles,
- the heat capacitive effects of the piles,
- the influence of an irregular arrangement of the piles.

Simulation of a Duct Ground Heat Storage

A duct ground heat storage system is defined as a system where heat or cold is stored directly in the ground. A ground heat exchanger, formed by a duct or pipe system inserted in either boreholes, foundation piles or directly into the ground, is used for heat exchange between a heat carrier fluid, which is circulated through the pipes, and the storage region. The heat transfer from the pipe system to the surrounding ground takes place by ordinary heat conduction.

The duct storage model (Hellström, 1989; Pahud and Hellström, 1996) has been extensively used for the simulation of thermal processes that involve heat storage and/or cold storage in the ground (see for example Pahud, 1996 or Seiwald, 1994). This model (DST) 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 a duct ground heat storage. 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, called TRNVDST, has been implemented by Mazzarella (1993). A more recent version of TRNVDST (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 latest version (Pahud et al., 1996a) offers the possibility of having several ground layers that cross the storage region, each having their own thermal properties.

The TRNVDST model assumes a relatively large number of uniformly placed ground heat exchangers, or energy piles, that are arranged in a ground volume which has the shape of a vertical cylinder. There is convective heat transfer in the pipes and conductive heat transfer in the ground. The thermal process in the ground is treated as a superposition of a global problem and a local problem. The global problem handles the large-scale heat flows in the store and the surrounding ground, whereas the local problem takes into account the heat transfer between the heat carrier fluid and the store. The local problem uses local solutions around the boreholes or energy piles, and a steady-flux part, by which the number of local solutions, and thereby computation time, can be reduced without significant loss of accuracy. The global and the local problems are solved with the use of the explicit finite difference method (FDM), whereas the steady-flux part is given by an analytical solution. The total temperature at one point is obtained by a superposition of these three parts.

The short-time effects of the injection/extraction through the pipes are simulated with the local solutions, which depend only on a radial coordinate and cover a cylindrical volume exclusively ascribed to each borehole (or energy pile). As the model assumes a relatively large number of boreholes, most of them are surrounded by other boreholes. In consequence, a zero heat flux at the outer boundary is prescribed, due to the symmetrical positions of the neighbouring boreholes. A transient period of time is calculated, which would correspond, if no heat flux was transferred by the boreholes during this period of time, to an equilibrium of the local temperature field. The energy transferred by the local problem prior to this period of time is simply transferred to the global problem, by means of a constant temperature correction in the local and global temperature fields. In that way, the local problem keeps only in "memory" the short-term thermal perturbations induced by the boreholes.

The heat transfer from the fluid to the ground in the immediate vicinity of the borehole is calculated with a heat transfer resistance. A steady-state heat balance for the heat carrier fluid gives the temperature variation along the flow path. The local solutions may take into account a radial stratification of the store temperatures (due to a coupling in series of the boreholes), as well as increased resolution in the vertical direction. The local heat transfer resistance from the fluid to the ground (or borehole thermal resistance) may take into account the unfavourable internal heat transfer between the downward and upward flow channels in a borehole.

The three-dimensional heat flow in the ground is simulated using a two-dimensional mesh with a radial and vertical coordinate. A time-varying temperature is given on the ground surface in two different zones. The first zone is located at the top side of the ground volume which contains the boreholes. The corresponding input temperature can be the air temperature of a building's ground floor. The second zone is everywhere else, and the corresponding input temperature is normally the outdoor air temperature.

The last TRNVDST version is chosen for the simulation of systems that use energy piles. In order to have a more appropriate simulation model, the features given below were implemented in TRNVDST. The resulting model is called TRNVDSTP (Pahud et al., 1996b).

- A ground water flow can be 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.

Influence of a 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. A priori, DST is not suitable for such calculations, as the cylindrical geometry is extensively used. Unfortunately, a 3-dimensional DST model could not be developed in the framework of this study.

Approximations 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 to assess their validity.

The first approximation concerns the **global problem**, or the long-term influence of a regional ground water flow. Two methods are implemented in TRNVDSTP. With the method used in PILE-SIM2, the convective loss (or gain) is calculated with the temperature difference between T_{mean}, the average temperature of the ground layer within the storage region, and T_∞, the undisturbed ground water temperature in the ground layer (see equation 7.5). The convective heat loss during a simulation time-step Δt is limited to the maximum possible value, defined by relation (7.6). In that case, the global temperature field within the storage region is replaced by T_∞, the undisturbed ground water temperature.

$$E_{conv} = u \ S \ C_w \ (T_\infty - T_{mean}) \ \Delta t \qquad\qquad (7.5)$$

$$E_{conv\ max} = V \ C_{ground} \ (T_\infty - T_{mean}) \qquad\qquad (7.6)$$

With u: Darcy velocity in the ground layer (m^3_w/m^2s);
d: storage diameter (cylindrical shape) (m);
H: vertical extension of the ground layer inside the storage volume (m);
S: cross area of the storage submitted to the Darcy flow, $S = H \times d$ (m^2);
V: volume of the ground layer inside the storage volume, $V = \pi d^2/4 \times H$ (m^3);
C_w: volumetric heat capacity of ground water (J/m^3K);
C_{ground}: volumetric heat capacity of the ground layer inside the store (J/m^3K);
T_∞: undisturbed ground water temperature in the ground layer (°C);
T_{mean}: mean storage temperature in the ground layer (°C);
Δt: time-step for the calculation of the global temperature field in the ground, calculated to about 1 day for a typical case (s);
E_{conv}: heat quantity transferred by forced convection in the storage layer during the time-step Δt (J).
$E_{conv\,max}$: maximum possible heat quantity transferred by forced convection in the storage layer during the time-step Δt (J).

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

The second approximation concerns the **local problem**, or the short-term influence of a regional ground water flow (influence on the heat transfer around the energy piles). The influence of a regional ground water flow on the heat transferred by the energy piles 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. This latter is assumed to be uniform when far enough from the cylinder. 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_∞ can be expressed in terms of an average Nusselt number (Nield and Bejan, 1992):

$$\overline{Nu}_D = \frac{\overline{q''}}{T_w - T_\infty} \frac{D}{\lambda_m} \tag{7.7}$$

With $\overline{Nu}_D$: 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 (W/m^2)
T_w: surface temperature of the cylinder (°C);
T_∞: temperature of the undisturbed porous medium (°C);
D: diameter of the cylinder (m);
λ_m : effective thermal conductivity of the porous medium (W/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 taking the Darcy flow model as valid:

$$\overline{Nu}_D = 1.015 \ Pe_D^{1/2} \qquad (7.8)$$

$$Pe_D = \frac{u\,D}{\alpha_m} \qquad (7.9)$$

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

       α_m: thermal diffusivity of the porous medium (m²/s), defined by the ratio λ_m/C_w;

The requirement for the validity of (7.8) can be written as:

$$Pe_D^{1/2} >> 1 \quad or \quad \overline{Nu}_D >> 1 \qquad (7.10)$$

As previously mentioned, the local solutions depend only on a radial coordinate and cover a cylindrical ground volume of radius r_1 which is exclusively ascribed to each energy pile. A zero heat flux is prescribed at the outer boundary due to geometrical considerations. Under steady-flux conditions and for pure heat conduction, the heat flux exchanged by an energy pile can be expressed in terms of the ground temperatures at the inner and outer boundaries (see Hellström, 1991):

$$T_w - T_\infty = \frac{q'_{cond}}{2\,\pi\,\lambda_m}\left\{\frac{r_1^2}{r_1^2 - r_o^2}\cdot\left[\ln\left(\frac{r_1}{r_o}\right) - \frac{1}{2} + \frac{r_o^2}{2\,r_1^2}\right]\right\} \qquad (7.11)$$

With r_o: radius of the energy pile, r_o = D/2 (m);

       r_1:   outer radius of the ground cylinder ascribed to the energy pile (m);

       T_w: ground temperature at the energy pile T(r = r_o) (°C);

       T_∞:   ground temperature at the outer radius T(r = r_1) (°C);

       λ_m: effective thermal conductivity of the porous medium (W/mK);

       q'_{cond}: heat transfer rate per unit length transferred by the energy 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 energy pile), is assimilated to the far field temperature T_∞; (the accuracy of this assertion is still to be checked). With this assumption, it is now possible to compare the heat fluxes by noting that:

$$\overline{q'} = \overline{q''}\ \pi\ D \qquad (7.12)$$

Combining (7.7), (7.8), (7.11) and (7.12) gives:

$$\frac{\overline{q'}}{q'_{cond}} = \frac{\overline{Nu}_D}{2}\left\{\frac{r_1^2}{r_1^2 - r_o^2}\cdot\left[\ln\left(\frac{r_1}{r_o}\right) - \frac{1}{2} + \frac{r_o^2}{2\,r_1^2}\right]\right\} \qquad (7.13)$$

The ratio $\dfrac{\overline{q'}}{q'_{cond}}$ 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 for the calculations of the heat transfer rate exchanged by the energy 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 energy piles.

Heat Transfer of the Connecting Pipes on the 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 energy 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 for the calculation of the pipe heat loss or gain 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. An estimation of the pipe loss factor is calculated with the method given by Koschenz and Dorrer (1996):

$$H_{pipe} = \cfrac{L_{pipe}}{S_{interface}\left[R_{pipe} + \cfrac{1}{2\,\pi\,\lambda}\ln\left(\cfrac{S_{interface}}{L_{pipe}\,\pi\,\delta}\right)\right]} \qquad (W/m^2K) \qquad (7.14)$$

With: H_{pipe}: effective heat transfer coefficient between the fluid temperature of the horizontal connecting pipes and the average ground temperature in the plane of the pipes (W/m^2K).

L_{pipe}: total length of the pipes (m).

$S_{interface}$: surface of the plane containing the horizontal pipes (m^2).

δ: pipe diameter (m).

R_{pipe}: thermal resistance between the fluid and the outer border of the pipe (K/(W/m)).

λ: thermal conductivity of the ground containing the pipes (W/mK).

Equation (7.14) is accurate if the thickness d of the ground layer which contains the pipes (see DMESH below) is greater than the average pipe spacing $l = S_{interface}/L_{pipe}$. A uniform placement of the pipes in the surface $S_{interface}$ is assumed. In practice, this is not the case, and the effective heat transfer coefficient H_{pipe} represents a maximum value. The total pipe length should be decreased, but the reduction depends on the pipe arrangement and cannot easily be estimated. By default, half the total pipe length is assumed to be reasonable.

The TRNVDSTP module has two additional inputs to collect the heat transfer rates exchanged by the connecting pipes. Two additional outputs return 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 specifies a value smaller than twice the smallest mesh:

$$\text{If DLAY1} > 2 \cdot \text{DMIN then DMESH} = \text{DMIN} \qquad (7.15a)$$
$$\text{If DMIN} < \text{DLAY1} < 2 \cdot \text{DMIN then DMESH} = \text{DLAY1} / 2 \qquad (7.15b)$$
$$\text{If DLAY1} \leq \text{DMIN then DMESH} = \text{DLAY1} \qquad (7.15c)$$

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 TRNVDSTP. In PILESIM2, DLAY1 is set to 0.3 m and is in most cases smaller than DMIN. In other terms, the vertical extension of the uppermost mesh layer of the store, where the horizontal connecting pipes lie, is normally equal to 0.3 m (DMESH).

Thermal Influence of the Building
As previously mentioned, a time-varying temperature is given to TRNVDSTP on the ground surface in two different zones. The first zone is located on the top side of the ground volume which contains the energy piles. The second zone is everywhere else, and the corresponding input temperature is the outdoor air temperature. The temperature of the first zone corresponds to the building ground floor or ground space which is assumed to be un-heated. This temperature is calculated on the basis of a heat balance which takes into account the heat gains or heat losses from the ground, the outdoor air and the heated/cooled part of the building (supposed to have a constant temperature during the year).

Heat Capacitive Effects of the Piles
The heat capacity of the piles is composed of the fluid contained in the pipes and the material forming the piles (concrete, etc.). The heat capacitive effects of the fluid are simulated by coupling a pipe component in series to TRNVDSTP. The fluid volume of the pipe component corresponds to the fluid volume contained in the piles. When the piles are at rest, the fluid contained in the pipe component is circulated in the piles, so that the fluid temperature follows the pile temperature. A zero heat transfer coefficient is ascribed to the pipe component, as only the heat capacitive effects are to be simulated. A plug flow model is used in this standard pipe component of the TRNSYS library.

The heat capacitive effects of the pile material have thermal behaviour which differs from that of the heat carrier fluid. Due to the heat transfer by conduction around the pipes, only a fraction of the pile material is actually playing a role in the heat capacitive effects. It is to be remembered that these effects are not taken into account in TRNVDSTP. In this model, steady state conditions are assumed in the pile, and the heat transfer from the fluid to the ground is calculated with the help of thermal resistances. In PILESIM2, it is possible to specify a fraction of the pile material which will take part in the heat capacitive effects. This effective heat capacity is simulated by reducing the pile diameter, so that the additional heat capacity obtained with a greater simulated ground volume equals the effective heat capacity of the pile material. The thermal resistance of the additional

ground annulus simulated is deducted from the pile thermal resistance. This latter characterises the heat transfer between the fluid and the ground at the pile wall. In that way the heat transferred under steady state conditions is the same with or without a reduction of the pile diameter. However, the effective heat capacity of a pile remains to be assessed. Calibrations with measured thermal performances have shown that half of the pile heat capacity provides a reasonable value (for pile diameter of 30 - 50cm).

Influence of an Irregular Arrangement of the Piles

The influence of an irregular arrangement of the piles can not be taken into account with PILE-SIM2. As previously mentioned, a uniform arrangement of the piles in a cylindrical volume is assumed. Such an influence can be assessed with the Superposition Borehole Model (Eskilson, 1986). This model is devised for the simulation of multiple heat extraction boreholes (or energy piles). A TRNSYS version (TRNSBM) has been adapted by Pahud et al., 1996c. The position, the active length and the tilting of each pile is specified in the programme. The heat transfer in the ground is assumed to occur by pure heat conduction. The three-dimensional temperature field in the ground is reconstructed by a superposition technique. TRNSBM does not have all the capabilities of TRNVDSTP and is too time consuming to run with many energy piles. Nevertheless, it can be used to "calibrate" TRNVDSTP for a particular spatial arrangement of the piles. Providing that the parameters of both models are equivalent, and, in particular, that the number and total length of energy piles are the same in both programmes, the volume (or the average spacing of the energy piles) is varied in TRNVDSTP, so that the calculated thermal response is as close as possible to that obtained with TRNSBM.

8.   Input Data to PILESIM2

The input data to PILESIM2 concern all the information that can be varied by the user. In particular, the input data define the type of system to be simulated, the size and characteristics of the different parts of the system and the driving conditions which will condition the operation of the system. In this chapter, each parameter required to PILESIM2 is described and explained.

Once the data are defined as desired, it is recommended to save the data before a simulation is started. The input data are saved in the file PILESIM.TRD. It is done in the *File / Save* menu of the TRNSED programme. A simulation is started in the menu *TRNSYS / Calculate*. A series of simulations can also be defined and then simulated. The user is advised to read the help provided with the TRNSED programme. It is found in the menu *Help / TRNSED Help,* and then look for the topic *Parametrics Menu*).

An Excel file called "Pilesim2-get-output.xls" has been devised to help visualise the results of a PILESIM2 simulation. It conditions the values of the three parameters "*Length of simulation*", "*Time interval for output results*" and "*Print hourly values for last year*" (see below).

8.1.   Simulation Parameters
The two entries related to these parameters define the month of the year when the simulation starts and the duration of the simulation period.

Month for simulation start: the simulation starts the first day of the chosen month.

Length of simulation: duration of the simulation period. The maximum duration is limited to 25 years if the simulation starts in January. If the simulation starts another month, the maximum duration is shorter, as the maximum of 25 years is counted from January of the first operational year. Recommendation for the use of the Excel file "Pilesim2-get-output.xls": set the length of a simulation to 20 years.

8.2.   Output Results
These two parameters condition the writing of the output results.

Time interval for output results: quantities can be calculated on a monthly basis or a yearly basis. They are integrated heat rates or average values. See chapter 5 for a complete description of the output results. Recommendation for the use of the Excel file "Pilesim2-get-output.xls": set the time interval for output results to monthly results.

Print hourly values for last year: this parameter determines if the hourly values of some selected quantities are written or not for the last operational year (see chapter 5 for more details). Recommendation for the use of the Excel file "Pilesim2-get-output.xls": answer "yes" to the question "print hourly values for last year?".

8.3.   Weather Data and Loading Conditions

The weather data and the loading conditions are read in a file. The data files are grouped in the PILEDATA directory. The input file to be chosen has the extension .PIL. This is a listing file containing the key word FILES on the first line, followed by the path name of the data file (with the extension .TXT), repeated 25 times on the next lines.

For example, data contained in the USERDATA.TXT file require the creation of a USERDATA.PIL file in the PILEDATA directory. The USERDATA.PIL file is a text file that contains:

FILES
piledata\userdata.txt
piledata\userdata.txt
...
piledata\userdata.txt

The data file, with the extension .TXT, contains the hourly values of the outdoor air temperature and the loading conditions, determined by the heat and cold demand and their associated temperature level. The first line must correspond to the first hour of the year. Each line must contain, in the order given below, the following quantities separated by a space or a tab character:

- the outdoor air temperature (°C);
- the total heat demand (kW);
- the temperature level of the distributed heat or the forward fluid temperature for heating (°C);
- the total cold demand (kW);
- the temperature level of the distributed cooling energy or the forward fluid temperature for cooling (°C).

There are actually two possible ways of writing the heat rates, called "user hourly data" and "normalised hourly data":

User hourly data:
With this option, the hourly values of the heat and cold demands are written in kW with positive values. This provides more flexibility for the user, who has the possibility to build his own input data and use, for example, detailed loading conditions obtained with another programme. He would only need to arrange the data with a spreadsheet programme according to the above description (a listing file *.PIL is also needed).

Normalised hourly data:
The normalised heat rates are written with a negative sign. The hourly values of the heat demand are divided by the annual energy demand for heating and expressed in 1/h (or kW/kWh). These numbers are then multiplied by 10'000. The same procedure is used for the cold demand. In this way, the user gives annual values for the heat and cold demand, and the normalised hourly values transform the annual energies into hourly thermal powers, according to the models that were used to prepare the normalised data.

The following files were prepared with normalised data and available to PILESIM2:

NormBase.pil : input data file for the area of Basel, Switzerland;
NormBern.pil : input data file for the area of Bern, Switzerland;
NormChur.pil : input data file for the area of Chur, Switzerland;
NormGene.pil : input data file for the area of Genève, Switzerland;
NormLaus.pil : input data file for the area of Lausanne, Switzerland;
NormLuga.pil : input data file for the area of Lugano, Switzerland;
NormNeuc.pil : input data file for the area of Neuchatel, Switzerland;
NormSion.pil : input data file for the area of Sion, Switzerland;
NormVadu.pil : input data file for the area of Vaduz, Liechtenstein;
NormZuri.pil : input data file for the area of Zurich, Switzerland;

In these files, the heating and cooling requirements are calculated as follows:

HEATING:
Heating is calculated for space heating requirements only. Heating is needed only when the average outside air temperature during the previous 24 hours is lower than 12°C. The heating requirement is proportional to the difference between a reference temperature and the outside air temperature. The reference temperature is fixed to 16°C. The forward fluid temperature for heating is set to 50°C when the outside air temperature is -10°C or less. For higher air temperatures, the forward fluid temperature follows a linear decrease with increasing air temperature, down to 20 °C for an air temperature of 20°C.

COOLING:
Cooling is calculated for space cooling requirements only. Cooling is needed only when the outside air temperature is greater than 20°C. The cooling requirement is proportional to the difference between the outside air temperature and a reference temperature. The reference temperature is fixed at 16°C. The forward fluid temperature for cooling is constant and set to 16°C.

8.4.   System Type
Four types of system can be selected:

Heating combined with a possible forced recharge of the ground: the heat demand is partly or completely covered by one or more heat pumps coupled to the energy piles/boreholes. No cooling demand is satisfied by the pile/bore system. A thermal recharge of the ground can be realised every year during 1000 consecutive hours. The recharge period starts July 1. The annual energy of the thermal recharge is an input parameter (see below the parameter description for *Annual energy demand for cooling*).

Heating combined with geocooling: the heat demand is partly or completely covered by one or more heat pumps coupled to the energy piles/boreholes. If there is a cooling demand, only geocooling on the piles/bores is performed. No cooling machine connected to the piles/bores is used.

Heating combined with geocooling or a cooling machine: the heat demand is partly or completely covered by one or more heat pumps coupled to the energy piles/boreholes. If there is a cooling demand, geocooling with the piles/bores is tried in priority. If a greater part of the cooling demand can be met with the cooling machine, the cooling machine takes over geocooling. The thermal loads of the cooling machine are injected in the ground through the piles/bores.

Heating combined with a cooling machine: the heat demand is partly or completely covered by one or more heat pumps coupled to the energy piles/boreholes. If there is a cooling demand, it will be partly or completely covered by one (or more) cooling machine(s) coupled to the energy piles/boreholes.

8.5.   Annual Energies and Temperature Levels

Annual energy demand for heating: annual heat demand of the system, given with a positive value. This value is only used with normalised input loading conditions. It is otherwise ignored. The heating demand can be scaled with the next parameter (Scaling factor for heating demand).

This parameter is labelled: **QhYEAR**

NB: Normalised loading conditions are written with negative values in the input data file. The heat demand values are written in the second column of the input data file. Data files whose names start with "NORM" were prepared with normalised loading conditions.

Scaling factor for heating demand [ScaleH]: the heat demand is scaled with this factor. A default value of 1 must be set if no scaling is desired. A scaling factor of 2 makes the hourly values of the heat demand two times larger. The scaling factor is used for both normalised and no-normalised data.

This parameter is labelled: **ScaleH**

Annual energy demand for cooling: annual cold demand of the system, given with a positive value. This value is only used with normalised input loading conditions or when a forced thermal recharge of the ground is realised. It is otherwise ignored. The cooling demand or the forced recharge of the ground are scaled with the next parameter (*Scaling factor for cooling demand*).

This parameter is labelled: **QcYEAR**

NB: Normalised loading conditions are written with negative values in the input data file. The cold demand values are written in the fourth column of the input data file. Data files whose names start with "NORM" were prepared with normalised loading conditions.

Scaling factor for cooling demand [ScaleC]: the cooling demand is scaled with this factor. A default value of 1 must be set if no scaling is desired. A scaling factor of 2 makes the hourly values of the cold demand two times larger. This scaling factor is used for both normalised and non-normalised data. It is also used when a forced thermal recharge of the ground is realised.

This parameter is labelled: **ScaleC**

Outdoor air temperature for heating design: this temperature parameter is the minimum outdoor air temperature for which the heating system is designed for.
If the next parameter (design forward fluid temperature for heating) is lower than 20 °C, the forward fluid temperature for heating is read from the input data file and this parameter is ignored.

This parameter is labelled: **TexMin**

Design forward fluid temperature for heating [TfoHea]: maximum fluid temperature for heating. The forward fluid temperature for heating is set to this value if the outdoor air temperature is below the outdoor air temperature for heating design (previous parameter). For higher air temperatures, the forward fluid temperature follows a linear decrease with increasing air temperature, down to 20 °C for an air temperature of 20°C. With normalised loading conditions, the heating is stopped if the air temperature exceeds 12 °C.

If this parameter is set to a value lower than 20 °C, the forward fluid temperature for heating is read from the input data file and this parameter is ignored.

This parameter is labelled: **TfoHea**

Design forward fluid temperature for cooling [TfoCol]: design forward fluid temperature for cooling. This value is assumed to be constant all through the year.
If this parameter is set to a value lower than 0 °C, the forward fluid temperature for cooling is read from the input data file and this parameter is ignored.

This parameter is labelled: **TfoCol**

Design forward-return temperature difference in cooling distribution [dTGeocool]: design temperature difference between return and forward fluid temperature in the cooling distribution. This temperature difference is supposed to be constant. As a consequence for the geocooling mode, it results a smaller fluid flow rate in the pile/bore flow circuit when the cooling demand is smaller.

This parameter is labelled: **dTGeocool**

Relevant temperature level for geocooling operation: the relevant temperature level for geocooling operation can be determined by the forward fluid temperature to the cooling distribution or the return one. These two possible choice are selected with:

Forward fluid temperature to cooling distribution: geocooling energy is produced to the required temperature level, and this even if the cooling demand is not completely met. In that case, an auxiliary cooling production has to be used. The geocooling and auxiliary cooling productions are performed in parallel or at the same temperature level.

Return fluid temperature from cooling distribution: geocooling is performed with the highest possible temperature level. If the cooling demand is not completely covered by geocooling, geocooling is achieving a pre-cooling. An auxiliary cooling production has to be used to lower the temperature level of the cooling energy to the required one. The geocooling and auxiliary cooling productions are performed in series and at two different temperature levels.

8.6.   Temperature Limitations

Minimum allowed temperature of the heat carrier fluid in the piles/boreholes [TfMin]: minimum tolerated fluid temperature in the bores/piles hydraulic circuit. This value may limit the heat rate that is extracted from the ground, as the simulated inlet fluid temperature in the piles will never be lower than this value. This constraint limits the size of the heat pump.
It is recommended not to set this value below 0°C (when energy piles are used).

This parameter is labelled: **TfMin**

Maximum allowed temperature of the heat carrier fluid in the piles/boreholes [TfMax]: maximum tolerated fluid temperature in the bores/piles hydraulic circuit. This value may limit the heat rate that is injected into the ground, as the simulated fluid temperature in the piles will never be greater than this value. This constraint limits the size of the cooling machine.

This parameter is labelled: **TfMax**

8.7.   Heat Pump and Cooling Machine

Design electric power of the heat pump [Pel]: the design (or nominal) electric power is the electric power consumed by the heat pump (PAC) at full load. It is assumed that the temperature levels in the condenser and evaporator do not influence the design electric power.

This parameter is labelled: **Pel**

Design performance coefficient [COPo]: the design performance coefficient is the performance coefficient of the heat pump when the inlet fluid temperature in the evaporator and the outlet fluid temperature from the condenser are at their design values; (see the next parameters TeIn, the design inlet fluid temperature in evaporator, and TcOut, the design outlet fluid temperature from condenser). The design performance coefficient is expressed by relation (8.1):

$$COPo = Qco / Pel \hspace{6cm} (8.1)$$

Qco: design heating power delivered by the heat pump.
Pel: design electric power of the heat pump

This parameter is labelled: **COPo**

Constant COP and efficiency during simulation: this parameter determines if the performance coefficient (COP) of the heat pump and the efficiency of the cooling machine are kept constant at their design value or free to vary according to the fluid temperatures in the condenser and evaporator. The two possible answer are:

No: the COP and efficiency are free to vary according to the operating conditions;
Yes: the COP and efficiency are kept constant and set to their respective design values (COPo and EffCOM).

If a penalty is chosen by the user, the COP and efficiency are decreased by the penalty value (see below the parameter COPpen, the penalty on the COP (PAC and cooling machine)).

This parameter is labelled: **ICTCOP**

Design inlet fluid temperature in evaporator: design inlet fluid temperature in the evaporator that leads to the design performance coefficient (COPo) of the heat pump.

This parameter is labelled: **TeIn**

Design outlet fluid temperature from condenser: design outlet fluid temperature from the condenser that leads to the design performance coefficient (COPo) of the heat pump.

This parameter is labelled: **TcOut**

Temperature difference for COP reduction: parameter dTCOP for the heat pump and cooling machine model (see Fig. 7.1 of chapter 7, the heat pump model). This parameter is ignored if the COP and efficiency are not allowed to vary (parameter ICTCOP set to YES).

This parameter is labelled: **dTCOP**

Temperature difference for COP stagnation: parameter dTstag for the heat pump and cooling machine model (see Fig. 7.1 of chapter 7, the heat pump model). This parameter is ignored if the COP and efficiency are not allowed to vary (parameter ICTCOP set to YES).

This parameter is labelled: **dTstag**

Maximum possible COP (PAC and cooling machine): maximum value that the performance coefficient of the heat pump (COP) may have. This maximum value is also used with the cooling machine (if present). In that case, the maximum efficiency is limited to (COPmax - 1).

This parameter is labelled: **COPmax**

Penalty on the COP (PAC and cooling machine): penalty on the performance coefficient. This value is subtracted from the calculated or constant value, so that transient effects, bad control of the heat pump or something else, can be artificially taken into account. The same penalty value is used on the cooling machine efficiency (if a cooling machine is present). Typical values are comprised between 0 and 0.5.

This parameter is labelled: **COPpen**

Design electric power of the cooling machine [PelCOM]: the design electric power is the electric power consumed by the cooling machine at full load. It is assumed that the temperature levels in the condenser and evaporator do not influence the design electric power. This parameter is ignored if no cooling machine is used in the system.

If a cooling machine is used, there are two possibilities:
- the heat pump is used in reverse mode as a cooling machine. In this case, the design electric power of the cooling machine should be set as equal to that of the heat pump. It can automatically be done by setting this parameter to a negative value.

- a separate cooling machine is used. This parameter is simply the design electric power consumed by the cooling machine.

NB: in a real system, a heat exchanger is likely to be present between the cooling machine condenser and the pile/bore flow circuit. It induces an additional temperature loss between the two flow circuits and penalises the efficiency of the cooling mode. This temperature loss is taken into account with the parameter LossTCool in the following "Counterflow Heat Exchangers" section.

This parameter is labelled: **PelCOM**

Design efficiency of cooling machine [EffCOM]: this parameter defines the design efficiency of the cooling machine. A negative value means that the design parameters used for the heat pump are also used for the cooling machine.
The design efficiency is the efficiency of the cooling machine when the inlet fluid temperature in the evaporator and the outlet fluid temperature from the condenser are at their design values; (see the next parameters TeinCo, the design inlet fluid temperature in evaporator, and TcutCo, the design outlet fluid temperature from condenser). The design efficiency is expressed by relation (8.2):

$$EffCOM = Qevo / PelCOM \qquad (8.2)$$

Qevo: design cooling power provided by the cooling machine;
PelCOM: design electric power of the cooling machine.

This parameter is ignored if no cooling machine is used in the system.

This parameter is labelled: **EffCOM**

Design inlet fluid temperature in evaporator: design inlet fluid temperature in the evaporator that leads to the design efficiency (EffCOM) of the cooling machine.
This parameter is ignored if no cooling machine is used in the system. It is also ignored if EffCOM (see previous parameter) is set to a negative value, or the COP and efficiency are fixed at their design value (constant) during a simulation.

This parameter is labelled: **TeinCo**

Design outlet fluid temperature from condenser: design outlet fluid temperature from the condenser that leads to the design efficiency (EffCOM) of the cooling machine.
This parameter is ignored if no cooling machine is used in the system. It is also ignored if EffCOM (see the second previous parameter) is set to a negative value, or the COP and efficiency are fixed at their design value (constant) during a simulation.

This parameter is labelled: **TcutCo**

Design inlet-outlet temperature difference in evaporator (PAC and cooling machine): design temperature drop between the inlet and outlet fluid that crosses the heat pump evaporator. Together with the heat power extracted under design conditions, this temperature drop determines

the flow rate through the evaporator. This flow rate is also the total flow rate in the flow circuit of the energy piles.

The temperature drop is also used for the cooling machine evaporator (if any).

The flow rate used for the simulation is written in the output parameter file with the extension ".OPA" (parameter label: FlowRate).

This flow rate is used when the PAC is operating. It is called the heating flow rate. If a cooling machine is included in the system, a cooling flow rate is determined on the basis of dTcond, the design inlet-outlet temperature difference in the condenser (see the 2nd following parameter). When the operating mode is geocooling, the flow rate through the pile flow circuit is variable and depends on the forward-return temperature difference in the cooling distribution (dTGeocool) and the instant cooling power demand.

The design inlet-outlet temperature difference in evaporator is labelled: **dTevap**

Design inlet-outlet temperature difference in condenser (PAC and cooling machine): design temperature drop between the inlet and outlet fluid that crosses the heat pump condenser. This temperature drop is also used for the cooling machine condenser (if any). Together with the heat power injected by the cooling machine under design conditions, it determines the flow rate through the condenser. This flow rate is called cooling flow rate; it is also the total flow rate in the flow circuit of the energy piles when the cooling machine is operating.

This parameter is labelled: **dTcond**

8.8. Counterflow Heat Exchangers

Design temperature loss in cooling heat exchanger [LossTCool]: design temperature loss in the cooling heat exchanger. The cooling heat exchanger, if present, separates the cooling machine condenser flow circuit from the pile/bore flow circuit. A zero value has to be entered if no heat exchanger is present.

This parameter is labelled: **LossTCool**

Design temperature loss in geocooling heat exchanger [LossTGeo]: design temperature loss in the geocooling heat exchanger. The geocooling heat exchanger, if present, separates the cooling distribution flow circuit from the pile/bore flow circuit. A zero value has to be entered if no heat exchanger is present.

This parameter is labelled: **LossTGeo**

8.9. Interface Ground-Building

Room air temperature in the building [TairH]: the room air temperature is prescribed in the building and assumed to be constant during the year. A non heated cellar separates the heated rooms from the ground below the building.

This parameter is labelled: **TairH**

Height of the cellar between rooms and ground [Hfloor]: height of the cellar that lies between the ground and the heated rooms. This parameter is used to estimated the air volume of the cellar for air change losses.

This parameter is labelled: **Hfloor**

Air change rate in the cellar [AchRat]: this air change rate determine the heat losses or gains with the outdoor air. For the sake of simplicity, the losses from the cellar to the exterior (outdoor air) are only computed by ventilation losses. Thus the specific heat losses from the cellar to the exterior (Uce) are established with formula 8.3.

$$Uce \ (kJ/hK) \ = \ Cellar\_floor\_area \ (m^2) \ x \ Cellar\_height \ (m) \ x \ 1.2 \ (kJ/m^3K)$$
$$x \ Cellar\_air\_change \ rate \ (1/h) \tag{8.3}$$

$$Uce \ (W/K) \ = \ Uce \ (kJ/hK) \ x \ 1000 \ (J/kJ) \ / \ 3600 \ (s/h) \tag{8.4}$$

The Cellar_air_change_rate is AchRat (label of this parameter), the Cellar_height is Hfloor (label of the previous parameter) and the Cellar_floor_area, supposed to be delimited by the area occupied by the energy piles or boreholes, is calculated with relation 8.5.

$$Cellar\_floor\_area \ = \ BPILE \ x \ BPILE \ x \ PileNumber \tag{8.5}$$

BPILE is the average spacing between the piles (see below **Average spacing between the piles**);

PileNumber is the total number of energy piles or boreholes.

- If the top of the bore/pile field is in contact with the outside air temperature, set the two parameters AchRat and UCelBu to:
AchRat = 10^{25} [1/h]
UCelBu = 0 [W/m^{2}K] (next parameter)

- If the heated zone (with a room air temperature fixed to TairH) is in direct contact with the bore/pile field (no cellar), set the two parameters AchRat and UCelBu to:
AchRat = 0 [1/h]
UCelBu = 10^{25} [W/m^{2}K] (next parameter)

The air change rate in the cellar is labelled: **AchRat**

Global room-cellar heat transfer coefficient [UCelBu]: the global room-cellar heat transfer coefficient determines the total heat transfer coefficient (transmission and ventilation) between the heated rooms and the cellar. The corresponding specific losses Ucm are obtained with formula 8.6.

$$Ucm \ (W/K) \ = \ Cellar\_floor\_area \ (m^2) \ x \ UCelBu \ (W/m^2K) \quad\quad (8.6)$$

See formula 8.5 for the calculation of Cellar_floor_area.

- If the top of the bore/pile field is in contact with the outside air temperature, set the two parameters AchRat and UCelBu to:
AchRat = 10^{25} [1/h] (previous parameter)
UCelBu = 0 [W/m^{2}K]

- If the heated zone (with a room air temperature fixed to TairH) is in direct contact with the bore/pile field (no cellar), set the two parameters AchRat and UCelBu to:
AchRat = 0 [1/h] (previous parameter)
UCelBu = 10^{25} [W/m^{2}K]

The global room-cellar heat transfer coefficient is labelled:			**UCelBu**

Insulation thickness between ground and cellar [Hinsul]: the insulation thickness between the ground and the cellar determines the thickness of the insulation layer that lies between the cellar and the ground. A thermal conductivity of 0.05 W/mK is assumed for the insulation material. The horizontal pipes that connect the heat exchanger piles to the pipe collectors are supposed to lie below the insulation layer. A different thermal conductivity for the insulation material (for example "New_lambda_insulation" W/mK) can be taken into account by using formula 8.7.

$$Hinsul \ = \ Hinsul\_actual \ x \ 0.05 \ (W/mK) \ / \ New\_lambda\_insulation \quad (W/mK) \quad (8.7)$$

Where Hinsul_actual is the actual thickness of the insulation layer.

The insulation thickness between ground and cellar is labelled:			**Hinsul**

Concrete thickness between ground and cellar [Hmagco]: the concrete thickness between the ground and the cellar determines the thickness of the concrete plate that lies between the cellar and the ground. A thermal conductivity of 1.3 W/mK is assumed for this concrete. The horizontal pipes that connect the heat exchanger piles to the pipe collectors are supposed to lie below the concrete plate. A different thermal conductivity for the concrete (for example "New_lambda_concrete" W/mK) can be taken into account by using formula 8.8.

$$Hmagco \ = \ Hmagco\_actual \ x \ 1.3 \ (W/mK) \ / \ New\_lambda\_concrete \quad (W/mK) \quad (8.8)$$

Where Hmagco_actual is the actual thickness of the concrete plate.

The concrete thickness between ground and cellar is labelled:			**Hmagco**

Length of the horizontal pipes on ground [LCOEPF]: the length of the horizontal pipes on ground is the effective pipe length that connects the heat exchanger piles to the pipe collectors. This parameter is used for the determination of the heat transfer that occurs between the fluid in these pipes and the ground in the plane of the pipes. The pipes are supposed to lie below the concrete plate and the insulation layer if any. The calculation assumes a uniform density of horizontal pipes in the interface ground - cellar. In reality this is not the case and a rough approximation is to set this parameter to half of the total horizontal pipe length.
This heat transfer coefficient is calculated with an approximation developed by Koschenz and Dorer (1996). See formulas 8.9 and 8.10.

$$\text{ECARCO (m)} = \text{Cellar\_floor\_area (m}^2) / \text{LCOEPF (m)} \tag{8.9}$$

ECARCO is the average distance between the horizontal pipes on ground and the Cellar_floor_area is defined by formula 8.5. LCOEPF is the label for the length of the horizontal pipes on ground. The heat transfer coefficient from the fluid in the pipes to the ground in the plane of the pipes, UPipeCo, is given by two thermal resistances in series (see relation 8.10).

$$\text{UPipeCo (W/m}^2\text{K)} = \cfrac{1}{\text{ECARCO}\left(\text{Rfluid\_pipe} + \cfrac{1}{2\,\pi\,\lambda\text{g}}\ln\left(\cfrac{\text{ECARCO}}{\pi\,\phi o\_\text{pipe}}\right)\right)} \tag{8.10}$$

Rfluid_pipe (K/(W/m)) is the thermal resistance between the fluid and the outer side of the pipe wall. This resistance is arbitrarily fixed to 0.272 K/(W/m). The second term in the parenthesis of relation 8.10 is the thermal resistance from the outer pipe wall to the average temperature of the ground in the plane of the pipes. The thermal conductivity of the ground in the pipe plane, is denoted λg, is fixed to 1.3 W/mK. The outer diameter of the pipe is ϕo_pipe and fixed to 32mm.

The length of the horizontal pipes on ground is labelled: **LCOEPF**

8.10. Energy Piles or Borehole Heat Exchangers

Up to 6 different pile/bore types can be specified. A pile/bore type is defined by its diameter, thermal resistance and average active pile/bore length. Average values are calculated from these quantities, as only one pile/bore type is simulated.

Diameter of pile/borehole type *i* (*i* = 1 **[dp1]**, 2, 3, 4, 5 or 6). This parameter determines the diameter of pile/bore type *i*. The average pile/bore diameter is calculated so that the total volume of piles/bores is preserved (see relation 8.11). It is written in the output parameter file with the extension ".OPA" (parameter label: AvePilDiam).

$$\text{AvePilDiam} = 2\left(\cfrac{\sum\limits_{i=1}^{6}(\text{dp}i/2)^2\,\text{H}i\,\text{N}i}{\sum\limits_{i=1}^{6}\text{H}i\,\text{N}i}\right)^{\frac{1}{2}} \tag{8.11}$$

dp*i* is the pile/bore diameter of type *i*, H*i* the pile/bore active length and N*i* the pile/bore number (see below).

The diameter of pile/bore type *i* is labelled: **dp*i*** (dp1, dp2, dp3, dp4 dp5 or dp6)

Number of piles/boreholes for type *i* (*i* = 1 **[N1]**, 2, 3, 4, 5 or 6). This parameter determines the number of piles/bores of type *i*. The total number of energy piles or boreholes is the sum of each pile/bore type number (see 8.12) and is written in the output parameter file with the extension ".OPA" (parameter label: PileNumber).

$$\text{PileNumber} = \sum_{i=1}^{6} \text{N}i \tag{8.12}$$

The number of piles/bores for type *i* is labelled: **N*i*** (N1, N2, N3, N4, N5 or N6)

Average active length of piles/boreholes type *i* (*i* = 1 **[H1]**, 2, 3, 4, 5 or 6). This parameter determines the average active pile length of pile type *i*. The active length of a pile is defined by the pile length for which a radial heat transfer with the ground may occur. In other terms, it is the length of the pile that is equipped with pipes. The pile active length is smaller than the total pile length. An average active pile length is calculated for ALL the heat exchanger piles (see formula 8.13). It defines the vertical extension of the ground volume that contains the simulated piles. It is written in the output parameter file with the extension ".OPA" (parameter label: AvePLength).

$$\text{AvePLength} = \frac{\sum_{i=1}^{6} \text{N}i \, \text{H}i}{\sum_{i=1}^{6} \text{N}i} \tag{8.13}$$

The average active length of piles type *i* is labelled: **H*i*** (H1, H2, H3, H4, H5 or H6)

Thermal resistance Rb of pile/borehole type *i* (*i* = 1 **[Rb1]**, 2, 3, 4, 5 or 6). This parameter determines the thermal resistance of pile/bore type *i*. The thermal resistance of a pile/borehole determines the temperature difference between the fluid and the ground in the immediate vicinity of the pile/borehole under a given heat transfer rate. For example, a thermal resistance value of 0.1 K/(W/m) will induce a temperature difference of 5 K between the fluid temperature and the ground temperature at the pile/bore border, when a heat transfer rate of 50 W/m takes place in steady flux conditions in the pile/bore. For more information on pile thermal resistances, see Fromentin et al., 1997. For borehole thermal resistances, the use of the programme EED (Earth Energy Designer) is recommended (Hellström and Sanner, 1994). In EED, a tool for the calculation of borehole thermal resistances with single, double, triple U-pipe or coaxial pipes is integrated. Other pipe configurations in a borehole or a pile can be treated with the programme MPC (Bennet et al., 1987). Some thermal resistance values are given below.

Energy pile thermal resistances:

0.15 K/(W/m)	hollow prefabricated pile with a double U-pipe, pile diameter: 30 to 50 cm;
0.10 - 0.11 K/(W/m)	pre-cast or cast in place pile, double U-pipe fixed on the metallic reinforcement. Pile diameter: 30 to 150 cm;
0.07 - 0.08 K/(W/m)	pre-cast or cast in place pile, triple U-pipe fixed on the metallic reinforcement. Pile diameter: 30 to 150 cm;
0.06 K/(W/m)	pre-cast or cast in place pile, quadruple U-pipe fixed on the metallic reinforcement. Pile diameter: 30 to 150 cm;

Borehole thermal resistances:
A typical value of 0.1 K/(W/m) is representative for a double U-pipe in a borehole of diameter 10 to 15 cm.

An average pile/bore thermal resistance is calculated for ALL the energy piles/boreholes with the help of formula 8.14. The average pile/bore thermal resistance is calculated relatively to the average pile diameter (AvePilDiam). It is written in the output parameter file with the extension ".OPA" (parameter label: AveRbPile).

$$\sum_{i=1}^{6} \mathrm{H}i\,\mathrm{N}i\,\frac{1}{\mathrm{AveRbPile}} = \sum_{i=1}^{6} \left\{ \mathrm{H}i\,\mathrm{N}i\,\frac{1}{\left(\mathrm{Rb}i + \dfrac{1}{2\,\pi\,\lambda\,\mathrm{avegr}}\ln\left(\dfrac{\mathrm{AvePilDiam}}{\mathrm{dp}i}\right) \right)} \right\} \qquad (8.14)$$

λavegr is the average ground thermal conductivity. This value takes into account the thermal conductivity of each ground layer which is crossed by the average active pile/bore length (AvePLength). It also takes into account the influence of a regional ground water flow by using the correction factor applied on the thermal conductivity (see section 7.2).

The thermal resistance of pile/bore type *i* is labelled: **Rb*i*** (Rb1, Rb2, Rb3, Rb4, Rb5 or Rb6)

Internal thermal resistance Ra of pile/borehole type *i* (*i* = 1 **[Ra1]**, 2, 3, 4, 5 or 6). This parameter determines the internal thermal resistance of the piles/boreholes. The internal thermal resistance of a pile/bore determines the internal heat transfers within the pile/bore.

A typical value is comprised between 0.1 - 0.4 K/(W/m) for a double U-pipe in a borehole heat exchanger.

The internal resistance of pile/bore type *i* is labelled: **Ra*i*** (Ra1, Ra2, Ra3, Ra4, Ra5 or Ra6)

Average spacing between the piles/boreholes [BPILE]: this parameter specifies the effective average spacing of ALL the piles/boreholes in the TWO spatial directions of the ground area that contains the piles/boreholes. This parameter determines the ground volume (GrndVolume) that is ascribed to the piles/boreholes with relation 8.15.

$$\mathrm{GrndVolume} = (\mathrm{BPILE})^2 \times \mathrm{PileNumber} \times \mathrm{AvePLength} \qquad (8.15)$$

See equations 8.12 and 8.13 for the total number of energy piles/boreholes (PileNumber) and the average active pile/bore length (AvePLength). The average spacing between the piles/bores is called BPILE. The ground volume used for the simulation is written in the output parameter file with the extension ".OPA" (parameter label: GrndVolume).

The best pile/bore arrangement for increased thermal performances is obtained with a regular spacing between the piles/boreholes. If the shape of the area occupied by the piles/bores is close to a square, then the average spacing is easy to calculate.
A method to establish this parameter is to draw a line around the ground area that is occupied by the piles/boreholes. A "half average spacing" is maintained between the line and the

piles/bores in the periphery. The area drawn by this line is then divided by the total number of energy piles/boreholes, and the average spacing is obtained by taking the square root of this number.

If the energy piles/boreholes are not uniformly placed within this area, it will result in a smaller average spacing. However, the effective average spacing remains greater than the smallest spacing between two energy piles/boreholes.

If the shape of the area that contains the piles/bores is close to a rectangle which is character-ised by a large difference between its width and its length, then the average spacing will tend to be greater. As an example, about 200 heat exchanger piles uniformly placed in a rectangular shape of 500m x 30m were simulated. The calibration described below resulted in an increase of the average spacing from 9.3 to 10.1 m, thus less than 10%.

A more accurate method is to calibrate the model used in PILESIM2 with a model that takes into account the exact position of the piles/bores. It can be done with TRNSBM, the Superposition Borehole Model. Contact the PILESIM2 author for more information.

The average spacing between the piles is labelled: **BPILE**

Number of piles/boreholes coupled in series [NSERIE]. This parameter determines the number of piles/bores that are connected in series. As the simulation model simulates a cylinder, a ra-dial interconnection of the piles/bores is taken into account.

This parameter is labelled: **NSERIE**

Pipe configuration in pile/borehole. The two possible pipe configuration in the pile/bore are:
U-pipe configuration: the pipe installation in the pile/bore is formed by one or more U-pipes placed close to the circumference of the pile/borehole.
Coaxial pipe installation: the pipe installation in the pile/bore is formed by a coaxial pipe.

Pipe number in a cross section of a pile/borehole: average number of pipes in a pile/bore cross section. This number is used to estimate the total volume of fluid that is contained in the energy piles/boreholes. This parameter is only used to take into account the heat capacitive effects of the heat carrier fluid in the piles/bores. The total volume of heat carrier fluid contained in the piles is calculated with relation 8.16.

$$\text{Fluid\_volume} = \text{NTUB} \times \pi \times (\text{Inner\_pipe\_radius})^2 \times \text{PileNumber} \times \text{AvePLength} \tag{8.16}$$

NTUB is the pipe number in a pile/bore cross section; Inner_pipe_radius is defined with the next input parameter (pipe number in a cross section of a pile); PileNumber and AvePLength are re-spectively the total number and the average active length of the energy piles/boreholes. If Fluid_volume, the volume of heat carrier fluid in the piles/bores, is known, then relation 8.16 can be used to calculate the average number of pipes in a pile/bore cross section.

The pipe number in a cross section of a pile/bore is labelled: **NTUB**

Inner diameter of one pipe: this parameter represents the average inner diameter of the pipes in the energy piles/bores. It is only used to estimate the total volume of fluid that is contained in the energy piles/boreholes with relation 8.16. The total volume of fluid is only used to take into account the heat capacitive effects of the heat carrier fluid in the piles/bores.

The inner diameter of one pipe is labelled: **DIAMI**

Fraction of pile/borehole concrete/filling thermal capacity: this parameter defines the fraction of the pile concrete/bore filling material in the active zone of a pile/bore which contributes to heat capacitive effects. The active zone of a pile/bore is the part that is equipped with plastic pipes for the heat transfer with the ground, i.e. the heat exchanger. A typical value of 50% was found to satisfactorily match measured data of a pile system (pile diameter of 30 to 40 cm). A large value may produce an error which aborts the programme when run. An error message is written in the listing file (PILESIM.LST). Do not forget to read a possible error message near the end of this file if you can not run your case.

If borehole heat exchangers are simulated, the heat capacitive effects are small and a fraction of 0 can be set.

The heat capacitive effects of the pile concrete are calculated with an effective pile diameter and an effective pile thermal resistance (see equation 8.17 and 8.18). They are written in the output parameter file with the extension ".OPA" (the parameter labels are respectively: Eff-PilDiam and EffRbPil).

$$EffPilDiam = AvePilDiam \left(1 - FrCapa \left(Cconcr/AveGrndCap\right)\right)^{\frac{1}{2}} \qquad (8.17)$$

AvePilDiam is the average pile diameter (see equation 8.11); FrCapa is the fraction of pile thermal capacity taken into account; Cconcr is the volumetric heat capacity of the pile concrete (Cconcr is set to 2'592 kJ/m^{3}K); AveGrndCap is the average volumetric heat capacity of the ground in the zone crossed by the average active pile length.

$$EffRbPil = AveRbPil - \frac{1}{2 \pi \lambda \text{avegr}} \ln\left(\frac{AvePilDiam}{EffPilDiam}\right) \qquad (8.18)$$

AveRbPil is the average pile thermal resistance and λavegr is the average ground thermal conductivity (see equation 8.14). AvePilDiam and EffPilDiam are respectively the average pile diameter and the effective average pile diameter (see equations 8.11 and 8.17).

The fraction of pile concrete thermal capacity is labelled: **FrCapa**

8.11. Ground Characteristics

Up to 3 different horizontal ground layers can be specified. A ground layer is defined by its thickness, the thermal conductivity and volumetric heat capacity of the ground and the Darcy velocity of the water contained in the ground layer.

Initial ground temperature [TGRDIN]: this parameter specifies the initial temperature of the ground before the construction of the building. This temperature should be set to the annual average value of the ground near the surface. A rough estimation is to use the mean annual air temperature at the surface.

The initial ground temperature is labelled: **TGRDIN**

Mean temperature gradient in the undisturbed ground [dTGRND]: geothermal temperature gradient present at the project location. Assumed to be constant, it defines the temperature increase in the ground with depth.

The geothermal temperature gradient is labelled: **dTGRND**

Thermal conductivity of ground layer *i* [LGi] (*i* = 1, 2 and 3): this parameter sets the thermal conductivity of ground layer *i*. For water saturated soils that requires the use of foundation piles, a typical value of 2 W/mK can be assumed. More information on ground thermal conductivity can be found for example in Fromentin et al., 1997 or Hellström and Sanner, 1994.

The thermal conductivity of ground layer *i* is labelled: **LG*i*** (LG1, LG2 and LG3)

Volumetric thermal capacity of layer *i* [CGi] (*i* = 1, 2 and 3): this parameter sets the volumetric thermal capacity of ground layer *i*. For water saturated soils that requires the use of foundation piles, typical values lie between 2 and 3 MJ/m^{3}K. More information on ground volumetric thermal capacity can be found for example in Fromentin et al., 1997 or Hellström and Sanner, 1994.

The volumetric heat capacity of ground layer *i* is labelled: **CG*i*** (CG1, CG2 and CG3)

Thickness of ground layer *i* (*i* = 1, 2 and 3): this parameter sets the thickness of ground layer *i*. The first ground layer must be larger than 0.3m, which is the layer 0, in which lie the horizontal pipes that connect the heat exchanger pile to the heat pump. The thickness ground layer 3, which is the lowest ground layer, is supposed to extend downward as far as necessary by the thermal calculations.
The thickness of ground layer *i* is labelled: **HG*i*** (HG1, HG2 and HG3)

Darcy velocity of ground water in layer *i* [DAi] (*i* = 1, 2 and 3): this parameter sets the Darcy velocity of the ground water in the ground layer *i*. This parameter determines the forced convection in the ground layer *i* due to a horizontal regional ground water flow. A zero value means no forced convection. The Darcy velocity (in m/s) can be obtained by the product of the ground layer permeability (in m/s) times the horizontal hydraulic gradient of the regional ground water flow (in m/m). More information on ground permeability can be found for example in Fromentin et al., 1997.

The Darcy velocity of ground water in layer *i* is labelled: **DA*i*** (DA1, DA2 and DA3)

NB: only a direct thermal interaction with the piles/bores is computed. In other terms, if the ground layer *i* lies below the bottom of the piles/bores, the effect of a regional ground water flow will not be computed. If only the upper part of ground layer *i* is crossed by the energy piles/boreholes, the effect will be computed in the upper part only. The thermal influence will be then propagated upwards and downwards by pure heat conduction.

NB: the full influence of a ground water flow is only calculated if the following two parameters switches are "ON".

Simulate forced convection on global process: this parameter determines if the global effect of the forced convection is taken into account (see below).

YES: global effect of forced convection taken into account;
NO: global effect of forced convection not taken into account.

This parameter is labelled: **FGLOB**

Simulate forced convection on local process: this parameter determines if the local effect of the forced convection is taken into account (see below).

YES: local effect of forced convection taken into account;
NO: local effect of forced convection not taken into account.

This parameter is labelled: **FLOCAL**

The effect of forced convection is treated as the superposition of two effects:
the global process:
a heat balance of the heat transfer by forced convection is performed on the boundary of the ground volume that is ascribed to the energy piles/boreholes. The heat quantity transferred by forced convection to or from the ground volume is treated as a global temperature change of the ground temperature in the volume. The global process takes into account long term effects, which, in particular, determine the magnitude of a natural thermal recharge of the ground by a regional ground water flow.

the local process:
for the case of pure heat conduction, a temperature gradient takes place around the energy piles/boreholes when they are used to transfer heat with the ground. As a result, the heat transfer is limited by the presence of a local temperature difference between the piles/bores and the mean ground temperature. If ground water flows across the piles/bores, the temperature field will be shifted. For a sufficiently large flow, the local temperature difference will be decreased and the heat transfer between the piles/bores and the ground improved. The local process takes into account the improvement of this heat transfer.

9.	Output Results from PILESIM2

The output data from PILESIM2 are written in five different files. Two files contain the input information given to PILESIM2 and possible error messages, and three files contains the calculated quantities by PILESIM2. Assuming that the file containing the input data is called PILESIM.TRD, the following files are written:

PILESIM.LST   (listing file, contains run time error message if any)
DST.DAT   (input data related to TRNVDSTP)
PILESIM.OPA   (output data, calculated parameters used by the programme)
PILESIM.OUT   (output data, integrated quantities)
PILESIM.PLT   (output data, evolution of selected variables)

After a simulation, the file PILESIM.LST can be viewed in the *Windows* menu of the TRNSED programme, and the files PILESIM.OPA and PILESIM.OUT in the *Windows / Output* menu. A plot can be made with the file PILESIM.PLT and viewed in the *Plot* menu. The file DST.DAT can be viewed in the *File / Open* menu. The file name DST.DAT has to be entered in the *File name* field of the dialogue box which popped on the screen. (An error message will then appear, as DST.DAT is supposed to be a TRNSED file. However, it is still possible to view the file).

The PILESIM2 output files can be easily processed and analysed with the "Pilesim2-get-output.xls" excel file.

9.1.   The Listing File PILESIM.LST
This is the listing file written by TRNSYS. All the information contained in PILESIM.TRD is written in the listing file, together with some information related to the simulation itself (simulation duration, total number of call for each component, warning message if any, etc.). It should be noted that if an error makes a simulation to abort, the corresponding error message is written at the end of the listing file. It is recommended to read this file every time a simulation is terminated with an error.

9.2.   The File DST.DAT
This file is written by the TRNVDSTP component which simulates the energy piles or the borehole heat exchangers. It contains all the parameter used by this component, together with information on the fields used for the simulation of the heat transport in the ground.

9.3.   The Parameter File PILESIM.OPA
This file contains some of the mean parameter values which are calculated and used for the simulation. They are:

PileNumber   [-] : total number of energy piles/boreholes (cf. equation 8.12).

AvePLength   [m] : average active pile length of the energy piles/boreholes (cf. equation 8.13).

GrndVolume   [m^3]: ground volume ascribed to the energy piles/boreholes (cf. equation 8.15).

AvePilDiam   [m] : average pile/borehole diameter (cf. equation 8.11).

EffPilDiam   [m] : effective pile/borehole diameter for heat capacitive effects (cf. equation 8.17).

AveRbPile [K/(W/m)]: average pile/borehole thermal resistance (cf. equation 8.14).

EffRbPile [K/(W/m)]: effective pile/borehole thermal resistance for heat capacitive effects (cf. equation 8.18).

FlowRate [kg/h]: total flow rate through the pile/bore circuit when heating (i.e. when the heat pump is on. See the description of parameter "design inlet-outlet temperature difference in evaporator", in section 8.6).

AveEfGrndL [W/mK]: effective mean thermal conductivity in the ground volume GrndVolume (the effective value includes the effect of forced convection on the local problem, see comment for equation 8.14).

AveGrndCap [kJ/m^{3}K]: mean volumetric heat capacity in the ground volume GrndVolume (see comment for equation 8.17).

9.4.   The Output File PILESIM.OUT

This file contains integrated or average quantities during long period of time (month or year), as well as the maximum or minimum values of some selected quantities. The labels of each calculated quantity are explained below.

MaxHeatDem [kW]: maximum hourly heat demand of the system during the month or the year.

MaxExtPile [kW]: maximum hourly heat power extracted from the piles/bores during the month or the year.

MaxColdDem [kW]: maximum hourly cold demand of the system during the month or the year.

MaxInjPile [kW]: maximum hourly heat power injected through the piles/bores during the month or the year.

TinPileMin [degree C]: minimum inlet fluid temperature in the piles/bores during the month or the year.

TinPileMax [degree C]: maximum inlet fluid temperature in the piles/bores during the month or the year.

QHeat [kWh]: total energy demand for heating.

QHeatCov [kWh]: heating energy covered by the heat pump.

Auxiliary heating energy:

QHeatAux = QHeat – QHeatCov

QCold [kWh]: total energy demand for cooling.

QColdCov [kWh]: cooling energy covered by the pile/bore system (geocooling and cooling machine).

Auxiliary cooling energy:

QColdAux = QCold – QColdCov

QElecTot [kWh]: total electric energy used by the pile/bore system; (heat pump, cooling machine but without circulation pumps).

Electric energy used by the heat pump:

QelPAC = QHeatCov/COP

Electric energy used by the cooling machine:

QelCoolM = QElecTot – QelPAC

QHeatPil [kWh]: heating energy covered by the heat pump coupled to the piles/boreholes. The rest, QHeatCov-QHeatPil, is covered by the heat pump coupled to the cold energy demand.

QFreeCool [kWh]: cooling energy that is provided by geocooling with the piles/boreholes. The rest, QColdCov-QFreeCool, is provided by the heat pump (extracted energy at the evaporator when there is a simultaneous demand for heating and cooling, i.e. see below QHextCold), and the cooling machine (if any). The energy extracted from the cold demand by the cooling machine is:

QCoolMach = QColdCov – QFreeCool – QHextCold

COP [-]: average performance coefficient of the heat pump. It is defined as the ratio of the delivered heating energy by the electric energy used by the heat pump:

COP = QHeatCov/QelPAC

COPglobal [-]: mean performance coefficient including the cooling machine:

COPglobal = (QHeatCov + QHCoolMach)/QElecTot

Where QHCoolMach is the waste heat energy dissipated in the ground by the cooling machine:

QHCoolMach = QHinjGrnd – QFreeCool

EffCoolM [-]: average efficiency of the cooling machine:

EffCoolM = QCoolMach/QelCoolM

QCoolMach = QColdCov – QFreeCool – QHextCold

QelCoolM = QElecTot – QHeatCov/COP

QHextCold [kWh]: energy extracted from the cold demand by the heat pump for heating purposes.

QHextGrnd [kWh]: energy extracted from the ground by the heat pump.

QHinjGrnd [kWh]: energy injected into the ground (geocooling and cooling machine). The energy injected into the ground by the cooling machine is:

QHCoolMach = QHinjGrnd – QFreeCool

GrndRatio [-]: ratio energy injected in the ground over energy extracted from the ground:

GrndRation = QHinjGrnd/QHextGrnd

FracHeat [-]: fraction of the total heat demand covered by the heat pump:

FracHeat = QHeatCov/QHeat

Qext/mPil [kWh/m]: energy extracted from the ground per energy pile/bore meter.

FracCold [-]: fraction of the total cold demand covered by the pile/bores system (pile/bores and cooling machine):

FracCold = QColdCov/QCold

Qinj/mPil [kWh/m]: energy injected into the ground per energy pile/bore meter.

TmInbuild [degree C]: air temperature in the heated (or cooled) rooms.

TmCellar [degree C]: air temperature in the cellar.

TmSurfFlo [degree C]: surface temperature of the cellar floor.

TmGrndTop [degree C]: mean temperature of the 30 cm thick ground layer that contains the horizontal connection pipes.

TmGround [degree C]: mean temperature of the ground volume that is ascribed to the energy piles/bores.

QBuiToCel [kWh]: thermal energy transferred from the heated (or cooled) rooms to the cellar. A negative value means thermal energy transferred from the cellar to the ground.

QCelToOut [kWh]: thermal energy transferred from the cellar to outside. A negative value means thermal energy transferred from outside to the cellar.

QCelToGrd [kWh]: thermal energy transferred from the cellar to the ground. A negative value means thermal energy transferred from the ground to the cellar.

QTotExtGd [kWh]: total energy extracted from the ground by the pile/bore system. Only the hourly values of the extracted energy from the piles/bores are summed.

QHoPipExt [kWh]: energy extracted from the ground by the horizontal connection pipes. The hourly heat transfer values are summed only when heat is extracted from these pipes.

QDSTtoGrd [kWh]: thermal energy injected in the ground through the piles/bores alone (without the horizontal connection pipes). A negative value means extracted energy.

QPIPtoGrd [kWh]: thermal energy injected in the ground through the horizontal connection pipes. A negative value means extracted energy.

QlossOut [kWh]: total heat losses from the ground volume ascribed to the energy piles/bores. A negative value is a heat gain.

QEDSTin [kWh]: variation of the internal energy of the ground in the volume ascribed to the piles/bores. A positive value means stored energy, i. e., a global increase of the ground temperatures. A negative value means a cooling of the ground temperatures.

ERRDS% [%]: error on the heat balance performed on the ground volume ascribed to the piles/bores (for calculation control).

ErrorExt% [%]: error on the energy extracted from the ground (for calculation control).

ErrorInj% [%]: error on the energy injected into the ground (for calculation control).

QlossTout [kWh]: heat losses through the top side of the ground volume ascribed to the energy piles/bores. A negative value is a heat gain.

QlossSout [kWh]: heat losses through the vertical sides of the ground volume ascribed to the energy piles/bores. A negative value is a heat gain.

QlossBout [kWh]: heat losses through the bottom side of the ground volume ascribed to the energy piles/bores. A negative value is a heat gain.

9.5. The Plot File PILESIM.PLT

This file contains the time evolution of some temperatures and heat rates for the last year of the simulation period. Hourly values of these quantities are written in this file only if the input parameter "*Print hourly values for last year*" is set to "*Yes*". Their labels are explained below.

TempInPile   [degree C]: inlet fluid temperature in the pile/bore flow circuit.

TempOutPil   [degree C]: outlet fluid temperature from the pile/bore flow circuit.

HeatDemand   [kW]: heat demand of the building.

HeatSatisf   [kW]: heat demand covered by the heat pump.

ColdDemand   [kW]: cold demand of the building.

ColdSatisf   [kW]: cold demand covered by the pile/bore system (geocooling or cooling machine).

9.6. Heat Balance of the System

The quantities contained in the file PILESIM.OUT allows the user to establish an overall heat balance of the system. A diagram of the energy fluxes is shown in Fig. 9.1.
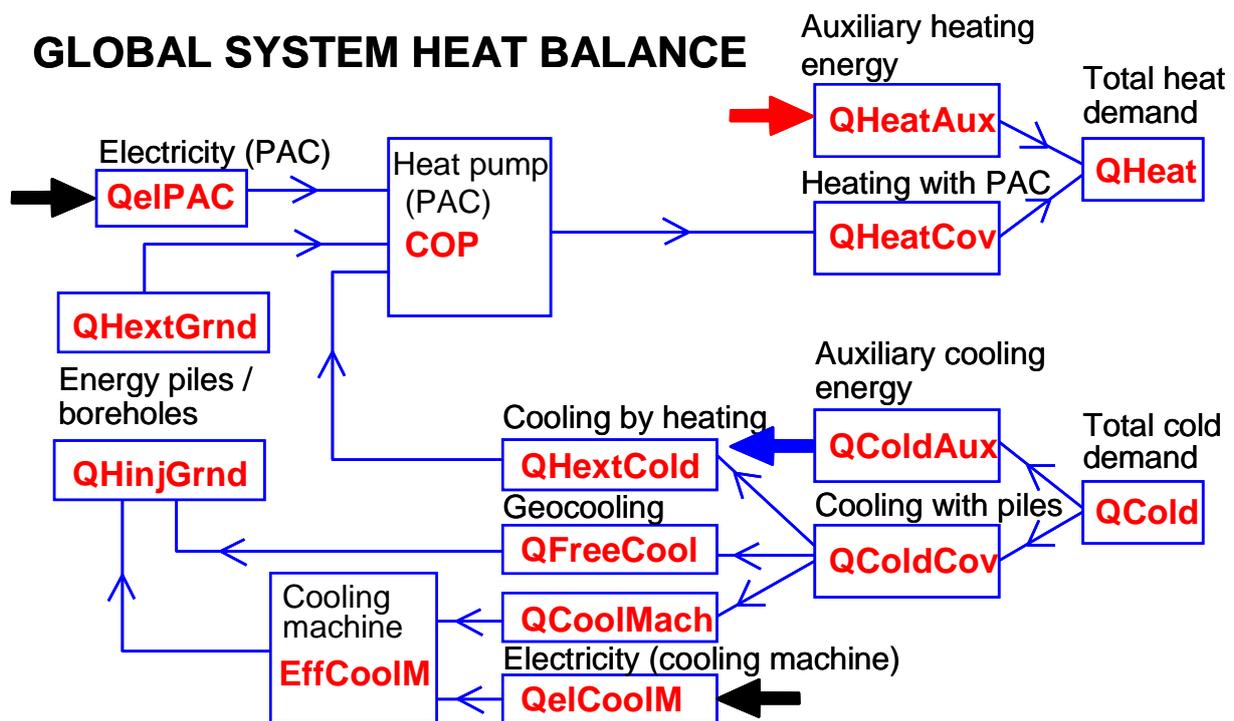

Fig. 9.1   *Energy fluxes diagram of the system.*

The quantities used for the Sankey diagram of Fig. 9.1 are read or deducted from the PILE-SIM.OUT file. They are:

QHeat　　　　[kWh]: total energy demand for heating (in PILESIM.OUT).

QHeatAux　　[kWh]: heating energy covered by auxiliary energy.

　　　　　　　　QHeatAux = QHeat – QHeatCov

QHeatCov　　[kWh]: heating energy covered by the heat pump (in PILESIM.OUT).

COP　　　　　[-]: average performance coefficient of the heat pump (in PILESIM.OUT).

QelPAC　　　[kWh]: electric energy used by the heat pump.

　　　　　　　　QelPAC = QHeatCov/COP

QHextGrnd　[kWh]: energy extracted from the ground by the heat pump (in PILESIM.OUT).

QHinjGrnd　　[kWh]: energy injected into the ground by geocooling and the cooling machine (in PILESIM.OUT).

EffCoolM　　[-]: average efficiency of the cooling machine (in PILESIM.OUT).

QHextCold　[kWh]: energy extracted from the cold demand by the heat pump for heating purposes (in PILESIM.OUT).

QFreeCool　[kWh]: cooling energy that is provided by geocooling with the piles/bores (in PILESIM.OUT).

QCoolMach　[kWh]: energy extracted from the cooling demand by the cooling machine.

　　　　　　　　QCoolMach = QColdCov – QfreeCool – QHextCold

QelCoolM　　[kWh]: electric energy used by the cooling machine.

　　　　　　　　QelCoolM = QElecTot – QHeatCov/COP

QColdAux　　[kWh]: cooling energy covered by auxiliary energy.

　　　　　　　　QColdAux = QCold – QColdCov

QColdCov　　[kWh]: cooling energy covered by the pile/bore system (geocooling and cooling machine); (in PILESIM.OUT).

QCold　　　　[kWh]: total energy demand for cooling (in PILESIM.OUT).

9.7. Heat Balance of the Energy Piles

The quantities contained in the file PILESIM.OUT allows the user to establish a heat balance of the energy piles/borehole heat exchangers. An energy fluxes diagram relative to the energy piles/borehole heat exchangers is shown in Fig. 9.2.
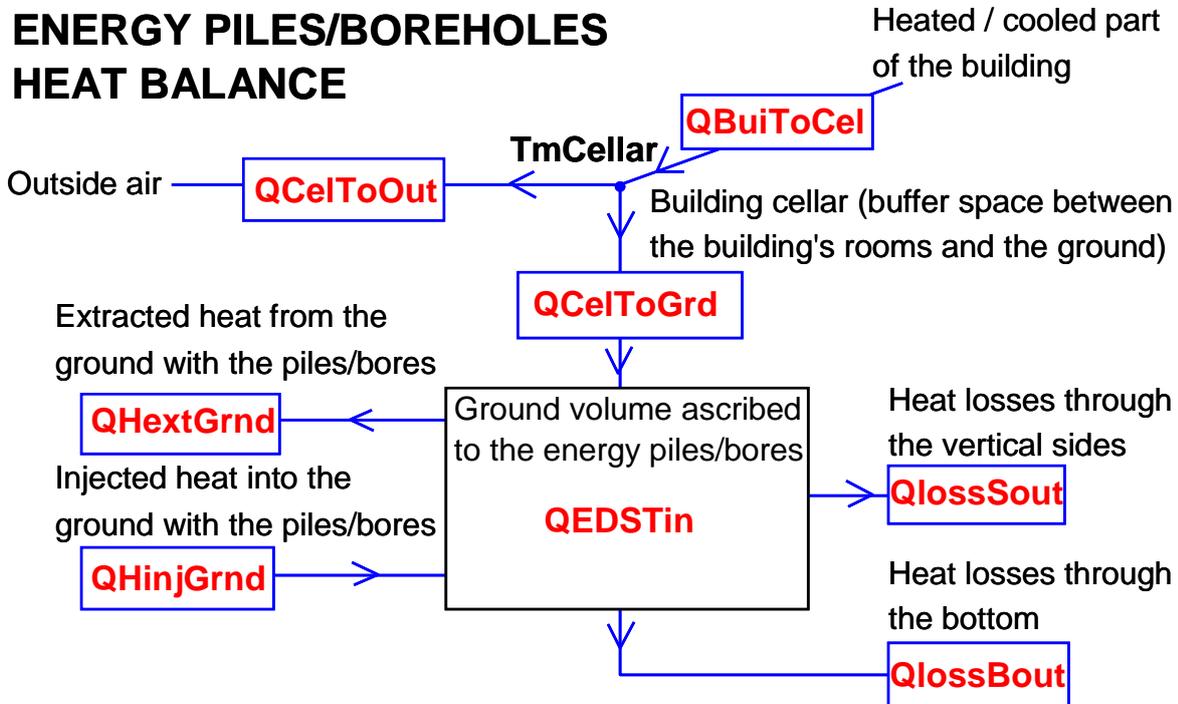

Fig. 9.2   Energy fluxes diagram of the energy piles/borehole heat exchangers.

The definitions of the labels shown in Fig. 9.2 are given in section 9.4 and the corresponding energy quantities are found in the PILESIM.OUT file. The cellar is considered as a non-heated zone. Its temperature **TmCellar** (calculated and written in the PILESIM.OUT file) depends on the heat gain or losses from the building, the ground and the outside air. A steady flux heat balance of the heat fluxes through the cellar allows the calculation of its temperature (see equation 9.1).

$$TmCellar = \frac{(ToutsideAir \times Uce + TmInbuild \times Ucm + TmGrndTop \times Ucg)}{(Uce + Ucm + Ucg)} \qquad (9.1)$$

ToutsideAir is the temperature of the air outside the building, **TmInbuild** is the indoor air temperature of the heated and cooled part of the building above the cellar and **TmGrndTop** is the mean temperature of the 30 cm thick ground layer that contains the horizontal connection pipes.
Uce is the specific heat losses between the cellar and the exterior (see equation 8.4).
Ucm is the specific heat losses between the heated/cooled part of the building and the cellar (see equation 8.6).
Ucg is the specific heat losses between the cellar and the top part of the ground. It is calculated with 4 thermal resistances in series (see equation 9.2).

$$Ucg = Cellar\_floor\_area \times \frac{1}{\dfrac{DLAY1/2}{\lambda\,topGrnd} + \dfrac{Hinsul}{\lambda\,insul} + \dfrac{Hmagco}{\lambda\,magco} + \dfrac{1}{AcgSur}} \qquad (9.2)$$

The 4 thermal resistances at the denominator are, from left to right:

- thermal resistance of half of the ground layer that contains the horizontal connection pipes. **DLAY1** is set to 0.3 m and λ**topGrnd** to 1.3 W/mK.
- thermal resistance of the insulation layer between the ground and the cellar. **Hinsul** is the insulation layer thickness (input parameter) and λ**insul** the insulation thermal conductivity (set to 0.05 W/mK).
- thermal resistance of the concrete plate between the ground and the cellar. **Hmagco** is the concrete plate thickness (input parameter) and λ**magco** the concrete thermal conductivity (set to 1.3 W/mK).
- thermal resistance between the surface of the floor and the air of the cellar. **AcgSur** is fixed to 6 W/m²K.

The **Cellar_Floor_Area** is the top side area of the ground volume ascribed to the energy piles/borehole heat exchangers (see equation 8.5).

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