Green Energy and Technology

Kun Sang Lee

Underground Thermal Energy Storage

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Contents

Nomenclature

A	Area (m^2)
A_f	Area of the filter (m^2)
A_{fp}	Area of a pore of the applied filter (m^2)
A_p	Area of a pore for which the MFI must be corrected (m^2)
A_s	Amplitude of the temperature wave at the ground surface
a	Radius of duct (m)
B	Formation loss coefficient (day/m^2)
B	Aquifer thickness (m)
B_1	Linear aquifer loss coefficient (day/m^2)
B_2	Linear well loss coefficient (day/m^2)
b	Aquifer thickness (m)
C	Specific heat (J/kg K)
C	Well loss coefficient
C	Nonlinear well loss coefficient (day^P/m^{3P-1})
C	Shape factor
c	Concentration of suspended matter in the infiltration water (kg/m^3)
C_p	Specific heat at constant volume (J/kg K)
C_v	Specific heat at constant pressure (J/kg K)
C_{pl}	Specific heats of the liquid (J/kg K)
C_{ps}	Specific heats of the solid (J/kg K)
d	Diameter (m)
D^*	Coefficient of molecular diffusion (m^2/s)
D_h	Hydraulic diameter (m)
D_l	Laminar equivalent diameter (m)
E	Energy (J)
erfc	Complementary error function
f	Friction factor
g	Acceleration of gravity (m/s^2)
Gr	Grashof number
H	Heat source or sink (W/m^3)

h	Hydraulic head (m)
h	Heat transfer coefficient (W/m^2 K)
K	Hydraulic conductivity (m/s)
K_{eff}	Effective hydraulic conductivity (EHC) (m/s)
K_{ij}	Hydraulic conductivity tensor (m/s)
K_0	Modified Bessel function of the second kind and zero order
k_c	Intrinsic hydraulic conductivity of the filter cake on the borehole wall (m^2)
L	Characteristic length (m)
l	Length (m)
m	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
n	Porosity
Nu	Nusselt number
P	Power
p	Pressure (N/m^2)
Pr	Prandtl number
Q	Source/sink (W/m^3)
Q	Flow rate in m^3/s
q	Heat flux (W/m^2)
R	Source/sink (s^{-1})
R	Thermal resistance (°C/W)
R	Borehole radius (m)
r	Radius (m)
r	Distance in m from the pumped well (m)
Ra	Rayleigh number
Re	Reynolds number
r_w	Wellbore radius (m)
S	Dimensionless storativity
s	Drawdown (m)
S_s	Specific storage (m^{-1})
T	Temperature (°C)
T	Transmissivity of the aquifer (m^2/day)
$T_{a,z}$	Water temperature in the annular region at node z (°C)
T_m	Mean annual ground surface temperature (°C)
t	Time (s)
u	Specific discharge (m/s)
u	Average water velocity in the borehole(m/s)
u_{eq}	Amount of equivalent full load hours per year (h)
v	Average linear ground water velocity (m/s)
v	Infiltration rate on the borehole wall (m/s)
v_b	Infiltration rate on the borehole wall (m/h)
v_i	Average linear groundwater velocity vector (m/s)
v_v	Clogging rate (mw/y)
V	Fluid velocity (m/s)
V	Volume (m^3)

$W(u)$	Well function
w	Frequency of the temperature wave
α	Compressibility of aquifer (1/Pa)
α	Thermal diffusivity (m^2/s)
α	Dispersivity (m)
β	Compressibility of water (1/Pa)
β	Expansion coefficient
ε	Height of the surface roughness (m)
Δh_v	Increment of pressure caused by clogging (m)
ξ	Friction factor of pipe fixtures
λ	Thermal conductivity (W/m K)
μ	Dynamic viscosity(Pa s)
μ_d	Dynamic viscosity (Pa s)
v	Kinematic fluid viscosity (m^2/s)
ρ	Density (kg/m^3)
ρ_w	Density of water (kg/m^3)

Subscripts

i	Inner surface
i	Inner pipe
m	Index
o	Outer surface
o	Outer *p*
w	Well

Chapter 1
Introduction

1.1 Energy Storage

1.1.1 Energy Demand

As fossil fuel resources such as oil, natural gas, and coal are increasingly less available and more expensive, many energy conservation strategies become more feasible. As global warming is also becoming one of the most urgent problems in the world, people need to find a more efficient and economical way to utilize energy: not only in the field of energy production, transmission, distribution, and consumption, but also in the area of energy storage (ES).

Today's industrial civilizations are mainly based upon abundant and reliable supplies of energy. In general, energy demands are not steady. Moreover, some thermal and electrical energy sources, such as solar energy, are not steady in supply. In cases where either supply or demand is highly variable, reliable energy availability has in the past generally required energy production systems to be large enough to supply the peak demand requirements. In all energy production processes, it is economically inefficient to install production and distribution equipment with the capacity to accommodate for the maximum (short term) demand. Furthermore, productivity decreases when production equipment cannot operate at full capacity in periods of reduced demand.

The basic idea behind thermal storage is to provide a buffer to balance fluctuations in supply and demand of energy (Nielsen 2003). Energy demand in the commercial, industrial, and utility sectors fluctuates in cycles of 24 h periods (day and night), intermediate periods (e.g. seven days) and according to seasons (spring, summer, autumn, winter). Therefore, the demand must be matched by various ES systems that operate synergistically.

Capital investments can sometimes be reduced if load management techniques are employed to smooth power demands, or if ES systems are used to permit the use of smaller power generating systems. The smaller systems operate at or near peak capacity, irrespective of the instantaneous demand for power, by storing the

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excess converted energy during reduced demand periods for subsequent use in meeting peak demand requirements. Although some energy is generally lost in the storage process, ES often results in fuel conservation by utilizing more plentiful but less flexible fuels such as coal and uranium in applications now requiring relatively scarcer oil and natural gas.

Therefore, the applications of ES systems have an enormous potential for more effective use of energy equipment and for facilitating large-scale energy substitutions from the economic perspective. Systems for storing energy should therefore reflect the cycles of energy demand, with either short-term, medium-term, or long-term (seasonal) storage capacity.

ES has recently been developed to a point where it can have a significant impact on modern technology. In particular, it is important for the success of any irregular energy source in meeting demand. For example, the need for storage for solar energy applications is clear, especially when solar energy is least available, namely, at night and in winter. With the ES technology, it is possible to overcome the mismatch between the energy production and consumption, lessen the stressed production load of the power plant at peak hours, and reduce consumers' electricity costs by avoiding higher peak hour tariffs.

Moreover, the ES is critically needed to reduce the various shortcomings of renewable energy technologies. Currently, most of the renewable energy sources, especially wind energy and solar energy, are time-based energy sources, whose available energy densities are variable during different hours. ES systems can help us avoid the irregular characteristics of renewable energy resources. The ES technology can be used for storing the excess renewable energy in high production hours, to make up for the possible shortage during low production hours, and to better integrate the energy generator into the local electricity grid.

For example, among the practical problems involved in solar energy systems is the need for an effective means by which the excess heat collected during periods of bright sunshine can be stored, preserved, and later released for utilization during the night or other periods (Dincer 1999). Thermal energy storage (TES) can store solar heat in summer to be used in winter, or during sunny days to be used for cool nights.

TES can also help us in utilizing our natural energy resources such as summer heat or winter cold. These are essentially renewable resources, which have not been fully developed and utilized before. Heat in the summer results from solar radiation, heating the earth's air, soil, and surface water. Storage in summer for winter and/or in winter for summer is the seasonal storage system. These systems contribute significantly to improve the efficiency of energy utilization. Thus the use of fossil fuels and emissions of greenhouse gas or air pollutants such as CO_2, SO_x, and NO_x can be reduced substantially. When natural cold from winter air can be also stored and used for direct summer cooling, the need for electrical energy and expensive refrigerant with ozone depleting gases is reduced.

The main advantage of TES is that heat and cold may be moved in space and time to utilize thermal energy that would otherwise be lost because it was available at the wrong place at the wrong time. Although TES systems themselves do not save energy, ES applications for energy conservation lead to the introduction of more efficient, integrated energy systems. TES therefore makes it possible to more effectively utilize renewable energy sources (solar, geothermal, or ambient) and waste heat/cold recovery for space heating and cooling.

ES is considered an important energy conservation technology and, recently, increasing attention has been paid to its utilization, particularly for heating, ventilating, and air conditioning (HVAC) applications (Dincer 2002; Dincer and Rosen 2007). Economic factors involved in the design and operation of energy conversion systems have brought TES to the forefront. It is often useful to make provisions in an energy conversion system when the supply of and demand for thermal energy do not match. TES appears to be an advantageous option for adjusting the mismatch between the supply and demand of energy, and can contribute significantly to meeting society's needs for more efficient and environment friendly energy use. TES is a crucial component for successful thermal systems. An effective TES incurs minimum thermal energy losses, leading to energy savings, while permitting the highest possible recovery efficiency of the stored thermal energy.

Dincer and Rosen (2011) summarized the significant benefits from use of ES systems as follows:

- reduced energy costs
- reduced energy consumption
- improved indoor air quality
- increased flexibility of operation
- reduced initial and maintenance costs
- reduced equipment size
- more efficient and effective utilization of equipment
- conservation of fossil fuels (by facilitating more efficient energy use and/or fuel substitution)
- reduced pollutant emissions (e.g., CO_2 and chlorofluorocarbons (CFCs))

1.1.2 Energy Storage Methods

Mechanical and hydraulic ES systems usually store energy by converting electricity into energy of compression, elevation, or rotation. Pumped storage is proven, but quite limited in its applicability by site considerations. Compressed-air ES has been tried successfully in Europe, although limited applications appear in the United States. This concept can be applied on a large scale using depleted natural gas fields for the storage reservoir. Alternatively, energy can be stored chemically as hydrogen in exhausted gas fields. Energy of rotation can be stored in flywheels, but advanced designs with high-tensile materials appear to be needed to reduce the price and volume of storage. A substantial energy loss of up to 50 % is generally incurred by mechanical and hydraulic systems in a complete storage cycle because of inefficiencies.

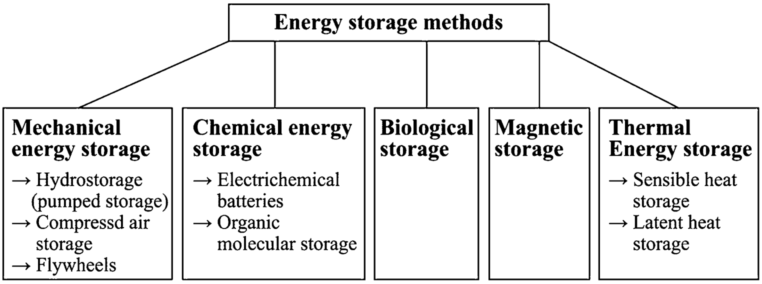

Fig. 1.1 A classification of energy storage methods (from Dincer and Rosen 2011)

Reversible chemical reactions can also be used to store energy. There is a growing interest in storing low-temperature heat in chemical form, but practical systems have not yet emerged. Another idea in the same category is the storage of hydrogen in metal hydrides (lanthanum, for instance).

Electrochemical ES systems have better efficiencies but very high prices. Intensive research is now directed toward improving batteries, particularly by lowering their weight-to-storage capacity ratios, as needed in many vehicle applications. Following after lead-acid battery, sodium-sulfur, and lithium-sulfide alternatives, among others, are being extensively tested. A different type of electrochemical system is the redox flow cell where charging and discharging is achieved through reduction and oxidation reactions occurring in fluids stored in two separate tanks.

Thermal ES systems are varied, and include designed containers, underground aquifers and soils and lakes, bricks and ingots. Some systems using bricks are operating in Europe. In these systems, energy is stored as sensible heat. Alternatively, thermal energy can be stored in the latent heat of melting in such materials as salts or paraffin. Latent storages can reduce the volume of the storage device by as much as 100 times, but after several decades of research many of their practical problems have still not been solved. Finally, electric energy can be stored in superconducting magnetic systems, although the costs of such systems are high.

There are a number of areas in ES technology, as shown in Fig. 1.1 (Dincer and Rosen 2011). Given the cost gap that needs to be spanned and the potential beneficial of ES applications, it is clear that a sustained ES development effort is in order. For solar energy applications, advanced ES systems may not be needed for years and decades. For the near term, many less expensive ES alternatives are available that should allow for the growth of solar energy use.

1.1.3 Energy Storage History

Man has used passively stored energy throughout history. Early examples are people who lived in natural or excavated caverns in rocks and soils. Such dwellings were warm in the winter and cold in the summer because the seasonal temperature variation does not penetrate deeply into the ground. It is also known that the buildings of the native people of Arizona and New Mexico in U.S.A. worked in the same way but on a diurnal basis. In this case the heat of the day did not penetrate the wall until the coldest hour of the night while the cold of the night was cooling the inner wall surface during the warmest period of the day. There are also many examples of ice cellars where ice was stored from the winter for cooling purposes during the summer.

Small-scale short-term storage of hot water and ice was early made in warm water bottles. Another example is electric water heaters in single family houses. Such heaters are motivated by power saving meaning that the heater takes many hours to produce the necessary hot water, while the hot water is used during shorter periods of the day.

One of the earliest types of technical energy stores were large water tanks to reduce the peak power demand. Such stores are now common in District Heating systems and also in solar applications. Storage systems are also needed in solar applications because of the diurnal variation in solar intensity. In this way, the solar energy is available after sunset. The variation in solar intensity also results in the need for weekly and seasonal storage.

The interest in large-scale seasonal TES started with the oil crisis in the early 1970s. At the beginning of seasonal storage research the long-term aim was to store solar heat from the summer to the winter primarily for space heating. Industrial waste heat was another energy source of great potential. This is still true but in recent years cooling has become an increasingly important issue and District Cooling systems are growing in Europe. So far, these systems have utilized passively stored cold but now we see an increasing interest in large-scale seasonal cold storage systems.

1.1.4 Thermal Energy Storage

1.1.4.1 Introduction

Depending on the energy types, ES technology can be divided into two main categories: TES and electrical ES (Cao 2010). Both are also the main energy consumption types in our daily life. In theory, TES can be used to store electrical energy, while the electrical storage can also be used to store thermal energy. The reason that we seldom use the thermal storage technology to store electrical energy or use the electrical storage to store thermal energy is that the transformation between thermal and electrical energy will lead to the loss of a relatively large amount of energy. In this book, we will focus on TES, especially on the underground thermal storage technology.

TES generally involves a temporary storage of high- or low-temperature thermal energy for later use. Examples of TES are storage of solar energy for overnight heating, of summer heat for winter use, of winter ice for space cooling in summer, and of heat or coolness generated electrically during off-peak hours for use during subsequent peak demand hours. Solar energy, unlike energy from fossil fuels, is not available all the time. Cooling loads, which nearly coincide with maximum levels of solar radiation, are often present after sunset. This phenomenon is largely due to the time lag between when objects are heated by solar energy and when they release the heat to the surrounding air. TES can help counterbalance this mismatch of availability and demand.

TES systems have been considered as one of the most crucial energy technologies and recently, increasing attention has been paid to the utilization of this essential technique. Energy may be stored in many ways, but since in much of the economy in many countries, energy is produced and transferred as heat, the potential for TES warrants study in detail.

TES deals with the storage of energy by cooling, heating, melting, solidifying, or vaporizing a material. The thermal energy becomes available when the process is reversed. Storage by causing a material to rise or lower in temperature is called sensible heat storage; its effectiveness depends on the specific heat of the storage material and, if volume is important, on its density. Sensible storage systems commonly use rocks, ground, or water as the storage medium, and the thermal energy is stored by increasing the storage-medium temperature.

Storage by phase change (the transition from solid to liquid or from liquid to vapor with no change in temperature) is a mode of TES known as latent heat storage. Latent heat storage systems store energy in phase change materials (PCMs), with the thermal energy stored when the material changes phase, usually from a solid to a liquid. The specific heat of solidification/fusion or vaporization and the temperature at which the phase change occurs are of design importance. Both sensible and latent TES also may occur in the same storage material. PCMs are either packaged in specialized containers such as tubes, shallow panels, plastic bags, and so on, or contained in conventional building elements (e.g., wall board and ceiling) or encapsulated as self-contained elements.

The oldest form of TES probably involves harvesting ice from lakes and rivers and storing it in well-insulated warehouses for use throughout the year for almost all tasks that mechanical refrigeration satisfies today, including preserving food, cooling drinks, and air-conditioning. The Hungarian parliament building in Budapest is still air-conditioned, with ice harvested from Lake Balaton in the winter.

1.1.4.2 Thermal Energy

Thermal energy quantities differ in temperature. As the temperature of a substance increases, the energy content also increases. The energy required E to heat a volume V of a substance with density ρ from a temperature T_1 to a temperature T_2 is given by

$$E = mC(T_2 - T_1) = \rho VC(T_2 - T_1) \tag{1.1}$$

where m is the material total mass and C is the specific heat of the substance. A given amount of energy may heat the same weight or volume of other substances, and increase the temperature. The specific heat is the amount of heat per unit mass required to raise the temperature by one degree Kelvin. The value of C ranges from about 1 kcal/kg K or 4.186 kJ/kg K for water to 0.0001 kcal/kg K for some materials at very low temperature. The specific heat of water is higher than any other common substance. Water is both cheap and chemically stable. As a result, water plays a very important role in temperature regulation and has excellent properties as a heat storage medium. Rock is another good sensible TES material from the standpoint of cost, but its capacity is only half that of water (Dincer 2002).

The energy exchanged (released or absorbed) by a thermodynamic system that has as its sole effect a change of temperature, is called the sensible heat. Latent heat, which is the amount of energy exchanged that is hidden, meaning it cannot be observed as a change of temperature, is associated with the changes of state or phase change of a material. For example, during a phase change such as the melting of ice, the temperature of the system containing the ice and the liquid is constant until all the ice has melted. The energy required for these changes to convert ice into water, to change water into steam, and to melt paraffin wax is called the heat of fusion at the melting point and the heat of vaporization at the boiling point. The sensible heat for a given temperature change varies from one material to another. The latent heat also varies significantly between different substances for a given type of phase change.

It is relatively straightforward to determine the value of the sensible heat for solids and liquids, but the situation is more complicated for gases. If a gas restricted to a certain volume is heated, both the temperature and the pressure increases. The specific heat observed in this case is called the specific heat at constant volume, C_v. If, instead the volume is allowed to vary and the pressure is fixed, the specific heat at constant pressure, C_p, is obtained. The ratio $\frac{C_p}{C_v}$ and the fraction of the heat produced during compression can be saved, significantly affecting the storage efficiency.

1.1.4.3 Classification

Several TES technologies exist that can be used in combination with on-site energy sources to economically buffer the discrepancy between energy supply and demand. TES is considered to be one of the most important technologies and, recently, increasing attention has been paid to utilizing TES in a variety of thermal engineering applications, ranging from heating to cooling and air conditioning.

Different criteria lead to various categories of TES technologies (Nordell 2000). Based on the temperature level of stored thermal energy, the TES can be divided into “heat storage” and “cool storage” (Hasnain 1998a, b). Based on the time length of stored thermal heat, it can be classified as “short term” and “long term”.

There are basically three types of thermal storage devices being investigated at present by the international research society and some industrial players: that is, “sensible (specific) heat storage”, “latent heat storage (PCMs)”, and “thermo-chemical heat storage” (Sharma et al. 2009). Sensible heat storage, in which the temperature of the storage material varies with the amount of energy stored, and latent heat storage, which makes use of the energy stored when a substance changes from one phase to another by melting (as from ice to water) (Hasnain 1998a).

Sensible heat storage is affected by raising the temperature of the storage medium. Thus, it is desirable for the storage medium to have high specific heat capacity, long-term stability under thermal cycling, compatibility with its containment and, most importantly, low cost. The high specific heat capacity C can have direct impact on the amount of stored thermal energy based on Eq. 1.1. The long-term stability assures the low degradation of the heat storage material after hundreds or thousands of thermal cycling. Good compatibility with its containment is the requirement for both the heat storage material and the containment, and is one of the main factors of the total cost of the storage system. The cost of the sensible heat storage solution mainly depends on the characteristics of the storage material. It is very common to utilize very cheap materials such as water, rocks, pebbles, sands, etc., as the storage medium (Cao 2010).

Sensible heat storage may be classified on the basis of the heat storage media as liquid media storage (like water, oil-based fluids, molten salts, etc.) and solid media storage (like rocks, metals, and others) (Hasnain 1998a). Sensible heat ES has the advantage of being relatively cheap but the energy density is low and there is a gliding discharging temperature. Latent heat storage is a particularly attractive technique, since it provides a high ES density. It has the capacity to store heat as latent heat of fusion at a constant temperature corresponding to the phase transition temperature of the PCMs.

The sorption or thermochemical reactions provide thermal storage capacity. The basic principle is: $AB + heat \leftrightarrow A + B$; using heat a compound AB is broken into components A and B which can be stored separately; bringing A and B together AB is formed and heat is released. The storage capacity is the heat of reaction or free energy of the reaction. Ataer (2006) gives an overview of TES methods as shown in Table 1.1.

As shown in Fig. 1.2, TES technologies can be classified with different criteria, leading to various categories. If the criterion is based on the temperature level of stored thermal energy, the thermal storage solutions can be divided into “heat storage” and “cool storage”. If based on the time length of stored thermal heat, it can be divided into “short term” and “long term”. If based on the state of ES material, it can be divided into “sensible heat storage”, “latent heat storage” and “thermochemical heat storage”.

In Zalba et al. (2003)’s paper, a useful classification was given on the substances used for TES, shown in Fig. 1.3. Cao (2010) also provided a similar schematic (Fig. 1.4) of the categories based on the criterion of state of the ES material.

Table 1.1 Overview of thermal energy storage methods (from Ataer 2006)

Type of thermal energy storage	Functional principle	Phases	Examples
Sensible heat	Temperature change of the medium with highest possible heat capacity	Liquid	Hot water, organic liquids, molten salts, liquid metals
		Solid	Metals, minerals, ceramics
Latent heat	Essentially heat of phase change	Liquid–solid	Nitrides, chlorides, hydroxides, carbonates, fluorides, eutectics
		Solid–solid	Hydroxides
Bond energy	Large amount of chemical energy is absorbed and released due to shifting of equilibrium by changing pressure and temperature	Solid–gas	CaO/H_2O, MgO/H_2O, $FeCl_2/NH_3$
		Gas–gas	CH_4/H_2O
		Liquid–gas	$LiBr/H_2O$, $NaOH/H_2O$, H_2SO_4/H_2O

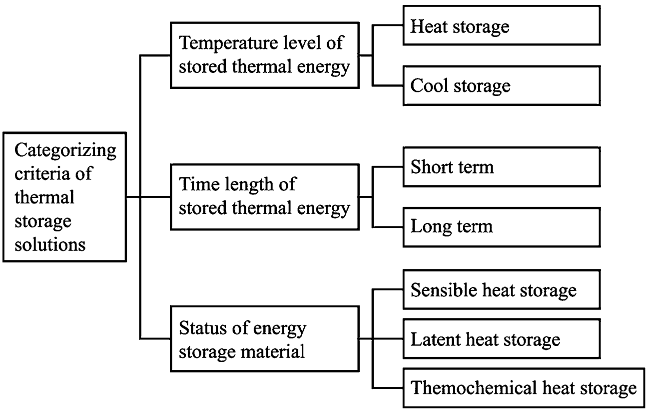

Fig. 1.2 Classification of thermal energy storage solutions (redrawn from Cao 2010)

The selection of a TES is mainly dependent on the storage period required (i.e., diurnal, weekly, or seasonal), economic viability, and operating conditions, etc. Thermal storage for short term (<1 week) is implemented most, such as ice storage and PCMs. In contrast, the application of seasonal storage, a longer term (>3 months) is currently much less common, but growing is in its application worldwide (Gao et al. 2009).

The use of TES in thermal applications can facilitate efficient energy use and energy conservation. Efficient TES systems minimize thermal energy losses and attain high energy recovery during extraction of the stored thermal energy with little degradation in temperature.

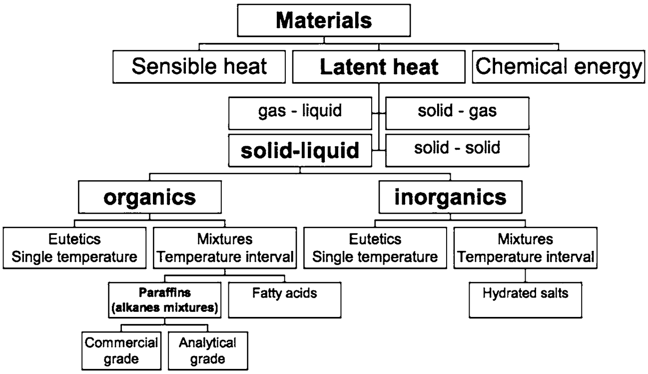

Fig. 1.3 Classification of energy storage materials (from Zalba et al. 2003)

1.1.5 Various Aspects of TES

This section is mainly based on Dincer and Rosen (2001)'s discussion on the various technical, economical, energetic, exergetic, and environmental aspects of TES.

1.1.5.1 Economic Aspects

ES technology is benign to the environment. This is, however, not a good enough reason, as long as the environmental advantages have not been given an economical value. The only valid reason for ES in a market economy (like it or not) is that it is more cost effective to store energy from one time to another, than to produce it later when needed. This implies that the storage energy must be cheaper when injected than the value of energy when it is recovered. This price difference must be big enough to cover the cost of investment, maintenance, operation, and energy losses. Today, there are many economically feasible storage applications.

TES-based systems are usually economically justifiable when the annualized capital and operating costs are less than those for primary generating equipment supplying the same service loads and periods. TES is often installed to reduce initial costs of other plant components and operating costs. Lower initial equipment costs are usually obtained when large durations occur between periods of energy demand. Secondary capital costs may also be lower for TES-based systems. For example, the electrical service equipment size can sometimes be reduced when energy demand is lowered. In comprehensive economic analyses of systems including and not including TES, initial equipment and installation costs must be determined, usually using manufacturer data, or estimated. Operating cost savings and net overall costs should be assessed using life cycle costing or other suitable methods for determining the most beneficial among multiple systems. TES use can enhance the economic competitiveness of both energy suppliers and building owners.

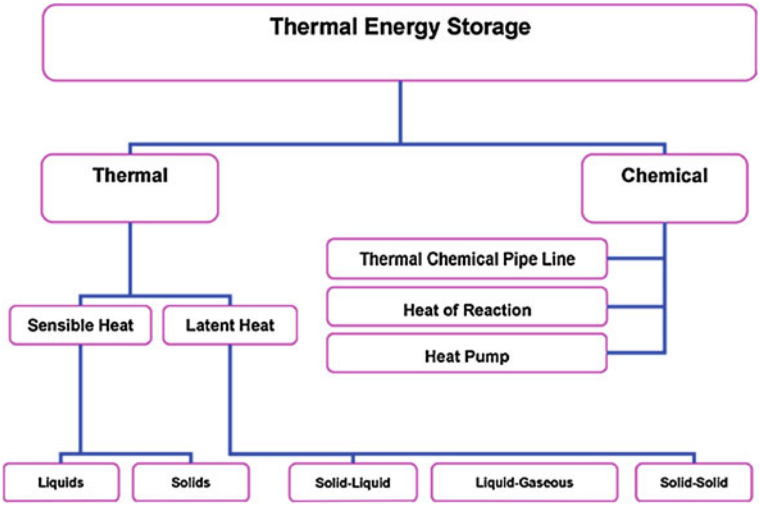

Fig. 1.4 The categories of thermal energy storage technology based on the criterion of the state of the energy storage material (from Cao 2010)

Comprehensive studies are needed to determine details for the selection, implementation, and operation of a TES system since many factors influence these design parameters. Studies should consider all variables which impact the economic benefits of a TES. Sometimes, however, not all factors can be considered. The following significant issues should be clarified and addressed before a TES system is implemented:

- management objectives (short and long term)
- environmental impacts
- energy conservation targets
- economic aims
- financial parameters of the project
- available utility incentives
- the nature of the scenario (e.g., if a new or existing TES system is being considered)
- net heating and/or cooling storage capacity (especially for peak day requirements)
- utility rate schedules and associated energy charges
- TES system options best suited to the specific application
- anticipated operating strategies for each TES option
- space availability (especially for a storage tank)
- the type of TES (e.g., short or long term, full or partial, open or closed)

1.1.5.2 Environmental Aspects

TES systems can contribute significantly to meet society's desires for more environment friendly energy use and reduce environmental impacts, especially in building heating and cooling, space power, and utility applications. By reducing energy use, TES systems provide significant environmental benefits by conserving fossil fuels through increased efficiency and/or fuel substitution, and by reducing emissions of such pollutants as CO_2, SO_2, NO_x and CFCs.

TES can impact air emissions in buildings by reducing quantities of ozone depleting CFC and HCFC refrigerants in chillers and emissions from fuel-fired heating and cooling equipment. TES helps reduce CFC use in two main ways. First, since cooling systems with TES require less chiller capacity than conventional systems; they use fewer or smaller chillers and correspondingly less refrigerant. Second, using TES can offset the reduced cooling capacity that sometimes occurs when existing chillers are converted into more benign refrigerants, making building operators more willing to switch refrigerants.

1.1.5.3 Sustainability Aspects

A reliable supply of energy is generally agreed to be a necessary but not sufficient requirement for development within a civilized society. Furthermore, sustainable development demands a sustainable supply of energy resources. Sustainable development within a society requires a supply of energy resources that, in the long term, is readily and sustainably available at reasonable cost and can be utilized for all required tasks without causing negative societal impacts.

Supplies of such energy resources as fossil fuels and uranium are generally acknowledged to be limited. Other energy sources such as sunlight, wind, and falling water are generally considered renewable and therefore sustainable over the relatively long term. Wastes convertible to useful energy forms and biomass fuels are also usually viewed as sustainable energy sources. Another implication of the sustainability is that sustainable development requires that energy resources be used as efficiently as possible. In this way, society maximizes the benefits it derives from utilizing its energy resources, while minimizing the corresponding negative impacts such as environmental damage. This implication acknowledges that all energy resources are to some degree finite, so that greater efficiency in utilization allows such resources to contribute to make development more sustainable. Even for energy sources that may eventually become inexpensive and widely available, increases in energy efficiency will likely remain sought to reduce the resource requirements for energy and material to create and maintain systems and devices to harvest the energy, and to reduce the associated environmental impacts. TES systems can contribute to increased sustainability as they can help extend supplies of energy resources, improve costs, and reduce environmental and other negative societal impacts.

Sustainability objectives often lead local and national governments to incorporate environmental considerations into energy planning. The need to satisfy basic human needs and aspirations, combined with increasing world population, make successful implementation of sustainable development increasingly needed. Requirements for achieving sustainable development in a society include:

- provision of information about and public awareness of the benefits of sustainability
- investments
- environmental education and training
- appropriate energy and ES strategies
- availability of renewable energy sources and clear technologies
- a reasonable supply of financing
- monitoring and evaluation tools.

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Chapter 2
Underground Thermal Energy Storage

2.1 Introduction

Nature provides storage systems between the seasons because thermal energy is passively stored into the ground and groundwater by the seasonal climate changes. Below a depth of 10–15 m, the ground temperature is not influenced and equals the annual mean air temperature. Therefore, average temperature of the ground is higher than the surface air temperature during the winter and lower during the summer. Consequently, the ground and groundwater are suitable media for heat extraction during the winter and cold extraction during the summer (Nordell et al. 2007). Such extraction systems are often used both for heating during the winter and for cooling during the summer. This means that the extracted heat is recharged during the summer and it becomes a storage system. If the heat demand is less or greater than the cooling demand additional storage might be needed. Systems using natural underground sites for storing thermal energy are called underground thermal energy storage (UTES) systems.

Because large volume is necessary for seasonal purposes, heat storage systems are in most cases in the ground or placed close to the surface. The application of seasonal storage, a longer term (>3 months), is currently much less common, but its application is growing worldwide. UTES is one form of TES and it can keep a longer term and even seasonal thermal energy storage. When large volumes are needed for thermal storage, underground thermal energy storage systems are most commonly used. It has become one of the most frequently used storage technologies in North America and Europe.

UTES systems started to be developed in the 1970s for the purpose of energy conservation by increasing energy efficiency. These systems store thermal energy from natural heat and/or cold in air, soil and water, solar energy, and waste heat from any mechanical process for seasonal purposes. It is possible to use the summer heat for heating in winter and winter cold for cooling in summer with UTES systems. With the use of UTES systems, the consumption of conventional fossil fuels was reduced by enabling the usage of alternative energy sources.

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Replacement of conventional heating systems also resulted in decreasing emissions of CO_2, SO_2, and NO_x emitted from the combustion of fossil fuel. Mechanical cooling devices using ozone-depleting substances such as CFCs can be also reduced. If fully exploited and utilized, UTES systems can play an important role in reducing emissions that lead to global warming and ozone depletion.

2.1.1 Ground Temperature

Measurements have shown that the ground temperature below a certain depth remains relatively constant throughout the year. Temperature fluctuations at the earth's surface influence shallow groundwater temperatures to depths of approximately 10 m. Between depths of 10 and 20 m, that is, maximum depth of annual cyclic variation, groundwater temperatures remain relatively stable at temperatures typically 1–2 °C higher than local mean annual temperatures. Below these depths, groundwater temperatures gradually increase at a rate of roughly 1 °C per 35 m depth toward the earth's interior which is termed the geothermal gradient.

Measurements of ground temperature have a long history. Lavoisier, French physicist and chemist, installed a thermometer in the deep vaults beneath the Paris Observatory in the seventeenth century and proved the constant temperatures at approximately 20 m below street level. Many years later, in 1778, Buffon published observations with that thermometer, and Humboldt noted in 1799 a mean temperature of 12 °C with annual variation of not more than 0.024 °C in the Paris underground. In the nineteenth century, more measurements followed, the most notable are those at the Royal Observatory in Edinburgh, UK. The decrease of seasonal temperature variations with depth and the constant temperatures in the subsurface had been demonstrated (Sanner and Nordell 1998).

The temperature fluctuations at the surface of the ground are moderated as the depth of the ground increases because of the high thermal inertia of the soil. Also, there is a time gap between the temperature fluctuations at the ground surface and in the ground. The observation of relatively constant ground temperature can be explained by these two facts. Therefore, at a sufficient depth, the ground temperature is always higher than that of the outside air in winter and is lower in summer. The temperature variation of the ground at various depths in summer (August) and winter (January) is shown in Fig. 2.1 (Florides and Kalogirou 2007). The graph shows actual ground temperatures as measured in a borehole drilled for this purpose in Nicosia, Cyprus. As can be expected, the temperature is shown to be nearly constant below a depth of 5 m for the year round.

The difference in temperature between the outside air and the ground can be utilized as a preheating in winter and precooling in summer by operating a ground heat exchanger. Also, because of the higher efficiency of a heat pump than conventional natural gas or oil heating systems, a heat pump may be used in winter to extract heat from the relatively warm ground and pump it into the conditioned space.

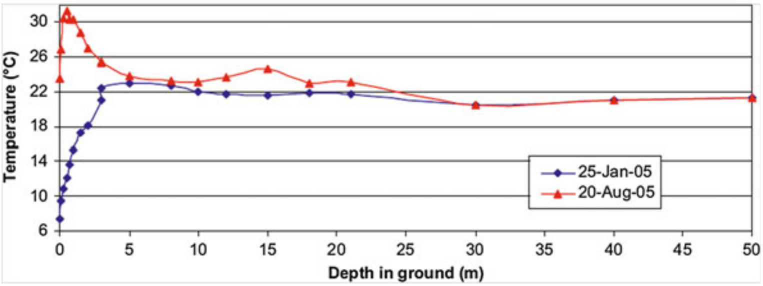

Fig. 2.1 Temperature variations with depth (from Florides and Kalogirou 2007)

In summer, the process may be reversed and the heat pump may extract heat from the conditioned space and send it out to a ground heat exchanger that warms the relatively cool ground.

2.1.2 Historical Development

Technology of underground thermal energy storage has a 40-year history, which began with cold storage in aquifers in China. Outside China, the idea of UTES started with more theoretical work in the early 1970s.

Interest in UTES systems increased rapidly in the 1980s and several pilot and demonstration plants were built, in combination with solar thermal energy, with waste heat or heat pumps. Some of the plants listed were purely experimental, others operated successfully for some years and a few are still in use today. The temperature level ranged from around 0 °C to more than 150 °C in some experiments.

2.1.3 Advantages

The advantages of UTES systems compared to the conventional ones are significant and summarized by Saljnikov et al. (2006) as follows:

- enormous reserves of energy in the nature that could be stored in this manner and later used for various purposes (heating or cooling)
- low operation costs and high long-term profitability (Reduction of electricity costs for operation of cooling machines and plants is nearly 75 %. The period of time during which the additional investment costs become paid off is shorter than five years.)
- protection of the environment (There is no pollution of the environment and the sources are recoverable.)
- possible utilization of the abandoned boreholes that were drilled for different purposes

2.2 Classification

There are several concepts as to how the underground can be used for thermal energy storage depending on geological, hydrogeological, and other site conditions. UTES systems can be classified according to:

- storage temperature (low or high)
- storage purpose (heating, cooling, or combined heating and cooling)
- storage technology (open/aquifer, closed/boreholes, or other techniques such as caverns)
- application (residential, commercial, or industrial)

2.2.1 Storage Temperature

In the low-temperature UTES, storage temperatures range from around 0 °C to a maximum of 40–50 °C. The technology includes thermal energy storage for cooling, combined heating and cooling, and low-temperature heating such as heat source for heat pumps. The boundary between this type of storage and mere ground source heat pumps (GSHP) is vague. Large GSHP installations with a central borehole- or well-field are in fact special types of UTES plants. To be considered a UTES system in this overview, a GSHP system should have a heat dissipation to (or extraction from) the surrounding ground of no more than 25 % of the annual thermal energy turnover. UTES exhibits substantial environmental advantages in reducing emissions of greenhouse and ozone-depleting gases.

Cold storage systems with heat pumps were already described in the IEA Heat Pump Centre Newsletter in 1992. Sanner and Nordell (1998) show the various alternatives of underground cold storage as presented in Fig. 2.2. These systems always substitute chillers which, compared to thermal storage, have a relatively high energy demand to drive compressors or absorption cycles.

When using heat pumps in combination with underground cold storage, three operation modes are possible as seen in Fig. 2.3 (Sanner and Nordell 1998). They use either modes one and two (direct cooling only), mode one and three (cooling with heat pump only), or all three modes (direct cooling in spring and during low demand, cooling by heat pump in summer or during peak demand).

Underground heat storage in the temperature range below 40 °C is usually done to increase the heat-source temperature of heat pumps. Charging sources for the storage include surface water, solar collectors, pipes below paved surfaces, hot air in glassed spaces, low-temperature waste heat, or by other sources.

High-temperature UTES systems have storage temperatures above 40–50 °C. Typical heat sources for these systems are solar collectors or waste heat. Various system layouts are possible. Heat pumps are either used at the end of the storage unloading period, when temperatures drop, or for achieving higher supply

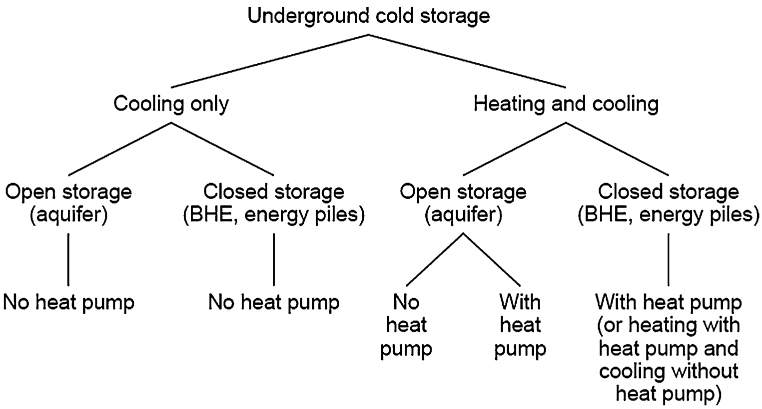

Fig. 2.2 Classification of underground cold storage alternatives (from Sanner and Nordell 1998)

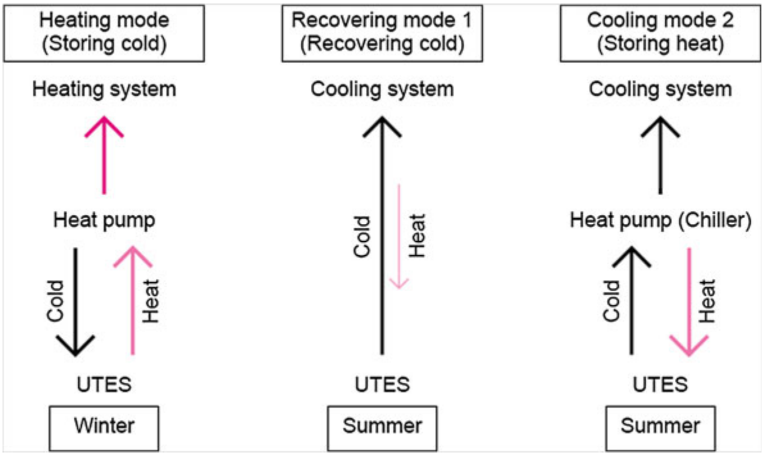

Fig. 2.3 Operational modes of cold storage UTES with heat pumps (from Sanner and Nordell 1998)

temperatures. Hydrochemical, biological, and geotechnical problems increase with increasing temperatures. Experiments showed that UTES with supply temperatures above 100 °C were not successful. Methods for water treatment have been developed for high temperature ATES, but further work is required. The new Annex 12 of the IEA program on Energy Conservation through Energy Storage (IEA ECES) addresses the specific problems of high temperature UTES.

2.2.2 Storage Technology

The basic types of underground thermal energy storage systems under the definition of this book can be divided into two groups (Sanner 2001; Novo et al. 2010):

- Systems where a technical fluid (water in most cases) is pumped through heat exchangers in the ground, also called "closed" systems (BTES).
- Systems where groundwater is pumped out of the ground and injected into the ground by the use of wells, or in underground caverns, also known as "open" systems (ATES, CTES).

Among the UTES systems developed since the 1970s, there are:

- aquifer thermal energy storage (ATES)
- borehole thermal energy storage (BTES)
- cavern thermal energy storage (CTES)
- pit storage
- water tank

Aquifer thermal energy storage uses natural water in a saturated and permeable underground layer called an aquifer as the storage medium. Thermal energy is transferred by extracting groundwater from the aquifer and by reinjecting it at a changed temperature at a separate well nearby. Aquifer thermal energy storage is the least expensive of all natural UTES options.

Borehole thermal energy storage consists of vertical heat exchangers deeply inserted below the soil from 20 to 300 m deep, which ensures the transfer of thermal energy toward and from the ground (clay, sand, rock, etc.). Many projects are about the storage of solar heat in summer for space heating of houses or offices. Ground heat exchangers are also frequently used in combination with heat pumps (geothermal heat pump), where the ground heat exchanger extracts/transfers low temperature heat from/to the soil. The flexibility of this technology at almost any ground conditions has made BTES systems one of the most popular forms of UTES.

Cavern thermal energy storage uses water in large, open, underground caverns in the subsoil to serve as thermal energy storage systems. Caverns used can be natural or man made, including depleted oil or natural gas fields, or abandoned mine tunnels and shafts. These storage technologies are technically feasible, but the actual application is still limited, because extremely specific site conditions are required, which are often not available (Zizzo 2009).

Water tank and pit storage, also called man-made aquifers, are artificial structures built below ground, like buried tanks, or close to the surface to circumvent high excavation cost. They will, then, need to be insulated both on the top and along the walls, at least down to some depth. Hydrogeological conditions at the specific site are not as relevant as in the other concepts. Table 2.1 summarizes some of the characteristics of the main seasonal storage concepts (Schmidt et al. 2003).

Figure 2.4 shows the most common thermal storage systems, namely, ATES, BTES, and CTES (Nordell et al. 2007). The two most promising technologies are

Table 2.1 Comparison of storage concepts (from Schmidt et al. 2003)

Storage concept	Hot water	Gravel water	Duct	Aquifer
Storage medium	Water	Gravel water	Ground material (soil/rock)	Ground material (sand/water or gravel)
Heat capacity (kWh/m^3)	60–80	30–50	15–30	30–40
Storage volume for 1 m^3 water 2–3 m^3	equivalent	1 m^3	1.3–2 m^3	3–5 m^3
Geological requirements	Stable ground conditions Preferably no groundwater 5–15 m deep	Stable ground conditions Preferably no groundwater 5–15 m deep	Drillable ground Groundwater favorable High heat capacity High thermal conductivity Low hydraulic conductivity ($K < 1 \times 10^{-10}$ m/s) Natural groundwater flow <1 m/y 30–100 m deep	Natural aquifer layer with high hydraulic conductivity ($K > 1 \times 10^{-5}$ m/s) Confining layers on top and below No or low natural groundwater flow Suitable water chemistry at high temperatures Aquifer thickness 20–50 m deep

storage in aquifers (ATES) and through borehole heat exchangers (BTES). These concepts have already been introduced as commercial systems on the energy market in several countries. Other options are rarely applied commercially.

Advantages of closed systems are the separation from aquifers and fewer problems related to water chemistry. An advantage of open systems is higher heat transfer capacity of a well compared to a borehole. This makes ATES usually the cheapest option if the subsurface is hydrogeologically and hydrochemically suited.

2.3 Characteristics of Underground Storage Systems

This section is based on the works of EU Commission SAVE Program and Nordic Energy Research (2004) which summarized the characteristics of UTES for ground source cooling in terms of efficiency, availability, applications, temperature, humidity, and load. The concept can be also applied to heating with thermal energy storage.

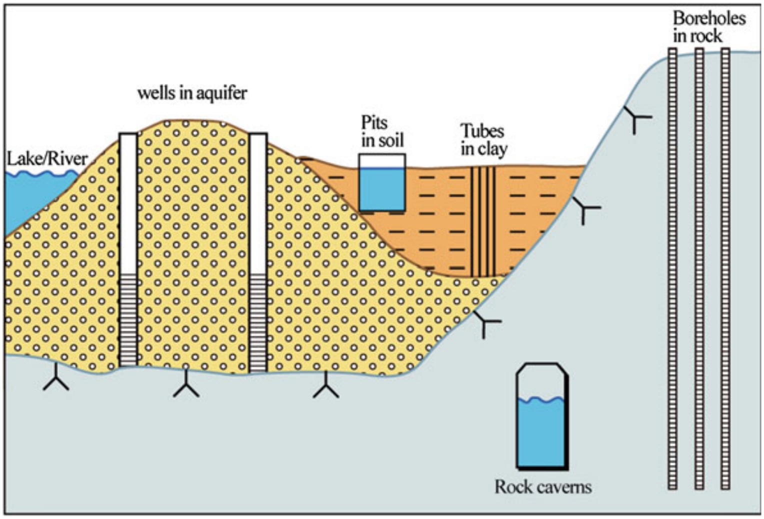

Fig. 2.4 Schematic representation of the most common UTES systems, ATES, BTES, and CTES (redrawn from Nordell et al. 2007)

2.3.1 Efficiency Benefits

Convention cooling machines, which provide comfort and process cooling, are normally driven by electricity with an average seasonal performance factor (SPF), in the range of 2–4. This means that an input of 1 kWh of electricity is needed for every 2–4 kWh of cold.

By storing natural sources of cold seasonally or from night till day, the usage of electricity for production of cold can be markedly reduced. To store, recover, and use these sources for free cooling will drastically increase the performance factor compared to conventional systems. ATES systems will normally work with a SPF of 30–50 when it comes to the cooling part of the system, while BTES has a slightly lower SPF of 20–30. This means that for 1 kWh of electricity, 20–50 kWh of cold is produced.

To have a proper thermal performance, any UTES system has to be of a certain minimum size. If not, the stored cold will be lost in temperature quality due to thermal losses. This may not be a critical factor in the cases when the cooling temperature is at a rather high level and close to the initial ground temperature. Still, any losses will reduce the performance factor. In certain applications, i.e., district cooling, the production temperature is essential and can have a significant impact on the efficiency.

2.3.2 Availability

UTES systems can replace almost any type of conventional cooling and heating in almost any application sector. It is possible to find a system that suits to the geological and hydrogeological conditions at a given site. If one cannot find a suitable aquifer for ATES, it is practically always possible to use boreholes to create a BTES system. Also, pits in the soil or caverns (CTES) may sometimes be considered as an alternative option.

The underground conditions will always be the most important factor in an UTES project. However, there may be other types of conditions that affect the choice of system. For example in the case of ATES, the relevant aquifer may have a priority for drinking water supply and hence will not be approved as storage facility. In some cases, aquifers are too small compared to the expected need for storage, or there are legal or environmental difficulties that limit the availability.

Wells and boreholes used for UTES do not take much space once they have been constructed. In many cases, they may even be hidden under the surface and placed below parking lots, gardens, or buildings. However, during construction, the required space for drilling rigs and side equipment has to be considered.

2.3.3 Potential Applications Sectors

From a global perspective and considering all different types of climate, there are several potential applications for UTES. These applications include

- air conditioning in residential, commercial, and institutional buildings and occasionally industrial buildings
- process cooling in manufacturing industries, food processing, telecom applications, IT facilities, and electric generation with combustion technologies
- cooling for food preservation and quality maintenance
- cooling and heating for growing some agricultural products in greenhouses
- cooling for fish farming in dams

2.3.4 Temperature Levels

The different applications all have different requirements when it comes to the supply temperatures, which vary from +6 up to +15 °C for air conditioning systems. For the other application sectors, the temperature will in most cases be at equal or at a higher level. The temperature difference between flow and return is typically 6 °C.

ATES systems can easily meet any temperature requirement down to 4–5 °C, but operates better at higher temperatures, whereas BTES systems in theory can be used also for temperatures below the freezing point. However, in practice BTES systems are more cost-effective for a supply temperature above 8–10 °C.

2.3.5 Humidity Aspects

Normal requirement for ventilation air is in the range of 40–60 % relative humidity (RH). This means that the air sometime has to be dehumidified in climates with high humidity.

In Scandinavian and North European countries, the humidity is seldom a problem. Hence, air conditioning can take place also with a relatively high cooling supply temperature. That speaks in favor of UTES systems, which normally produce a higher supply temperature at the later stage of the cooling season.

The relative humidity for food preservation of vegetables and fruit should in general be kept above 70 % to prevent drying. In such applications, the UTES concepts have proven to be very useful as they can provide a high supply temperature.

2.3.6 Load Coverage

For comfort air conditioning, the load will mainly be dependent on the building structure, the envelope, and the function of the building. Normally, it is not a problem to meet any load with ATES systems. However, for BTES systems it is often too expensive to design the system to cover cooling peaks. Therefore, it is recommended that systems are designed for the base load and then cut the peaks with a heat pump.

2.4 Advantages and Limitations of Underground Storage Systems

Requirements for energy efficiency of buildings are growing constantly, as the awareness of the environmental effects of energy use is increasing. Heating, cooling, and lighting of buildings cause more than one-third of the world's primary energy use. Thus, the building stock contributes significantly to the energy-related environmental problems. Space heating is by far the largest energy end use of households and offices, but energy use for cooling in households and the tertiary sector is now increasing rapidly and is for this sector alone expected to amount to more than 70,000 GWh in 2020. The technical saving potential of UTES technologies is estimated to be as high as 85 % of the cooling energy, meaning a saving potential of

59,500 GWh per year in whole EU if all cooling systems would be changed into UTES systems. Use of the UTES technologies offers main advantages compared to conventional systems. Naturally, there are also some limitations that should be taken into account, when designing the thermal system. Common advantages and limitations of all UTES technologies for seasonal storage are summarized (EU Commission SAVE Program and Nordic Energy Research 2004).

2.4.1 Advantages

- Energy savings
  Experiences have shown that up to 100 % of the cooling demand can be covered by natural sources combined with use of UTES systems. It corresponds to around 70–85 % saving on electricity used for cooling systems (compared to conventional chillers). Heat pumps (electric or heat driven) can be used together with UTES systems to cover both cooling and heating needs. Then total energy savings would be even higher.
- Environmental impacts
  The saving of electricity will be also beneficial to the environment with fewer emissions of harmful gases to the atmosphere, especially the ones causing global warming, depletion of the ozone layer, and acid rain (preferably CO_2, SO_x, and NO_x).
- Profitabilty
  The economic potential in terms of straight payback time is usually very favorable. The payback period for UTES systems is often less than five years. However, even with a payback period of more than 10 years, life cycle cost assessments show that investments on the UTES are very profitable. Because the systems, especially BTES based, are long lasting, UTES delivers savings for many years. By careful analysis of actual demands, the investment cost may be less than for a traditional (often oversized) cooling plant.
- Esthetics and noise
  The noiseless operation and esthetical superiority of the invisible UTES systems are usually highly appreciated.
- Health aspects
  The risk of Legionella bacteria problems is eliminated as the systems are closed and separated from the distribution system. Thus, they will produce no water aerosols in air, which might appear in traditional systems with cooling towers.

2.4.2 Limitations

There are also a number of limitations and different condition to consider before the decision to construct a UTES system is taken. ATES systems are not as easy to construct as BTES systems, and need more maintenance and preinvestigations.

If the conditions are favorable, payback times are typically short, ranging normally 2–5 years. ATES systems cannot be constructed in all geological conditions, and hence they sometimes require extensive preinvestigations, which have to be taken into account and budgeted from the early design phase. The process of obtaining a permit can be complex and time consuming for the first plant in the region, and many restrictions in relation to protection of groundwater resources and environmental impact assessment may diminish possibilities. Some ATES plants have shown different kinds of operational problems, although most of them can be handled with simple measures. One major identified problem is clogging of wells. In most cases, the clogging processes can be avoided by a proper well and system design and operation.

BTES systems are generally easier to construct and operate, need limited maintenance, and have extraordinary durability. Moreover, BTES systems usually require only simple procedures for authority approvals. Yet, their payback times are relatively long compared to ATES systems, normally 6–10 years. This is due to expensive borehole investments and the fact that BTES systems normally need some other sources to cover the peak load situations.

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Chapter 3
Basic Theory and Ground Properties

Deng (2004) introduced a theoretical background on underground thermal energy systems in his dissertation on standing column wells. The contents in this chapter are mainly based on Deng's (2004) dissertation.

3.1 Basic Physical Mechanism

Above the water table lies the unsaturated zone, where voids or pores between rocks are usually only partially filled with water, the remainder being occupied with air. Water is held in the unsaturated zone by molecular attraction, and it will not flow toward or enter a well. In the saturated zone, which lies below the water table, all the openings in the rocks are full of water that may move through the aquifer to streams, springs, or wells from which water is being withdrawn (see Fig. 3.1).

The energy transport in the ground outside of the well is through a porous media called an aquifer. An "aquifer" is defined as a geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield economical quantities of water to wells and springs. The aquifer can be considered as a porous medium that consists of a solid phase and an interconnected void space totally filled with groundwater.

Transport of groundwater occurs only through the interconnected voids. Heat is transported both in the solid matrix and in the void system, forming a coupled heat transfer process with conduction and advection by moving groundwater. The governing steady-state, one-dimensional equations for heat and fluid flow are given by Fourier's law and Darcy's law, which are identical in the form:

Fourier's law:

$$q = -\lambda \frac{dT}{dx} \tag{3.1}$$

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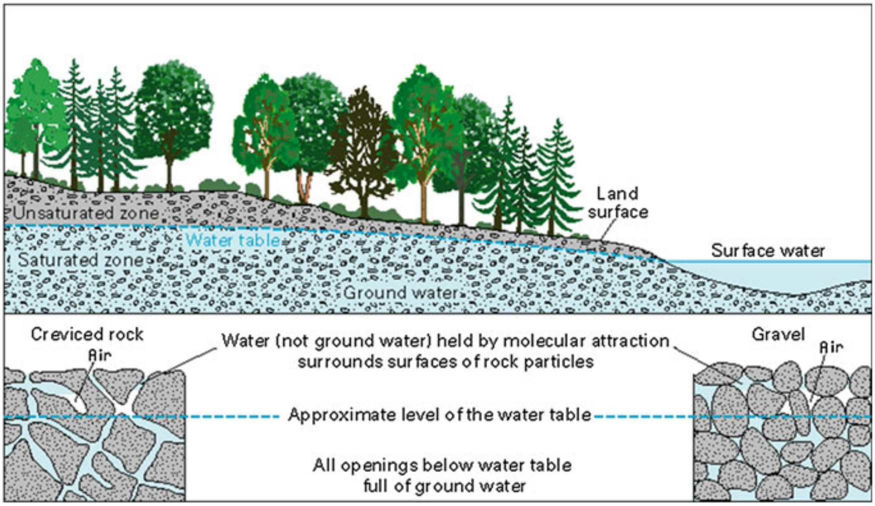

Fig. 3.1 Occurrence of groundwater in rocks (http://capp.water.usgs.gov/GIP/gw_gip/how_occurs.html)

where q is heat flux (W/m^2); λ is the thermal conductivity of the ground (W/m K).

Darcy's law:

$$u = -K\frac{dh}{dx} \tag{3.2}$$

where u is the specific discharge or Darcy flux (volume flow rate per unit of cross-sectional area) (m/s); K is the hydraulic conductivity of ground (m/s); h is the hydraulic head (m).

The specific discharge u is related to average linear groundwater velocity v by:

$$v = \frac{u}{n} \tag{3.3}$$

where n is the porosity, which, for a given cross-section of a porous medium, is the ratio of the pore area to the cross-sectional area.

3.1.1 Hydrological Flow in the Aquifer

The first fundamental law governing groundwater flow is the continuity equation, which expresses the principle of mass conservation (De Smedt 1999). Consider the flow of groundwater through an elementary control volume of porous medium around a point with Cartesian coordinates (x, y, z) as shown in Fig. 3.2.

The principle of mass conservation on the control volume implies that the net result of inflow minus outflow is balanced by the change in storage versus time.

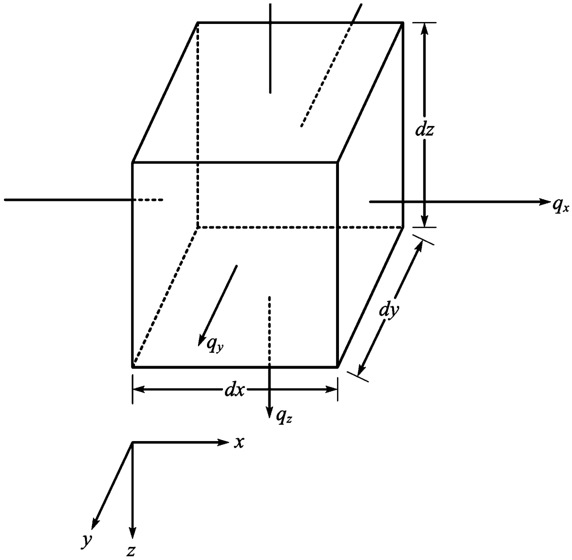

Fig. 3.2 Mass conservation in a reference elementary volume

$$-\left[\frac{\partial(\rho v_x)}{\partial x}+\frac{\partial(\rho v_y)}{\partial y}+\frac{\partial(\rho v_z)}{\partial z}\right]=\frac{\partial(\rho n)}{\partial t} \tag{3.4}$$

The time rate of change of mass stored in the control volume is defined as the time rate of change of fluid mass in storage, expressed as after some manipulation.

$$\frac{\partial(\rho n)}{\partial t}=\rho S_s\frac{\partial h}{\partial t} \tag{3.5}$$

By applying Darcy's law to the law of mass conservation in a control volume, the governing equation defining the hydraulic head distribution in the porous medium can be derived as:

$$S_s\frac{\partial h}{\partial t}=\frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial h}{\partial x_i}\right)+R \tag{3.6}$$

where S_s is the specific storage (m^{-1} [ft^{-1}]). Specific storage is the amount of water per unit volume of a saturated formation that is stored or expelled from storage owing to compressibility of the mineral skeleton and the pore water per unit change in head (Fetter 2001). It is also called the elastic storage coefficient and expressed as:

$$S_s=\rho g(\alpha+n\beta) \tag{3.7}$$

ρ is the density of water (kg/m^3); g is the acceleration of gravity (m/s^2); α is the compressibility of aquifer (1/(N/m^2)); β is the compressibility of water (1/(N/m^2)); K_{ij} is the hydraulic conductivity tensor (m/s); R is the source/sink ([s^{-1}]).

3.1.2 Hydrological Flow in Borehole

The flow in the borehole of UTES systems is often non-Darcy flow where the relationship between the flux and gradient is nonlinear. By introducing the effective hydraulic conductivity (EHC) K_{eff}, we are still able to use Eq. 3.2 to describe the water flow in the borehole just replacing K_{ij} with K_{eff}. It is recommended to use the following formulas:

$$K_{\text{eff}} = \begin{cases} K & \text{Darcy flow in the aquifer} \\ \frac{d^2 \rho_w g}{32\mu} & \text{laminar pipe flow in the borehole} \\ \frac{2gd}{uf} & \text{transitional and turbulent flow in the borehole} \end{cases} \quad (3.8)$$

where d is the diameter (m); μ is the dynamic viscosity (Pa s); u is the average water velocity in the borehole (m/s); f is the friction factor.

3.1.3 Heat Transfer Mechanism

Different mechanisms are used to describe heat transfer in the aquifer (porous medium) and heat transfer in the borehole of UTES systems. Figure 3.3 shows all the heat transfer mechanisms in the standing column well (SCW) system which is the most complicated system.

3.1.3.1 Heat Transfer in the Aquifer

There are several heat transfer processes affecting the heat transferred through an aquifer:

- heat conduction through the fluid phase
- heat conduction through the solid phase
- particle to particle radiation
- heat convection from the fluid phase to the solid phase
- convection through the fluid phase (advection).

Figure 3.4 shows the relationship between the actual thermal conductivity and the four mechanisms that contribute to it. None of the first three processes is affected by fluid flow, and the last two processes are dependent on fluid velocity. At large velocities, the last two processes are dominant.

It is generally assumed that the solid and fluid phases in the aquifer are at the same temperature by thermal equilibrium. Therefore, one can consider the temperature as an average temperature of both phases. An effective thermal conductivity λ_{eff} of porous medium is expressed with classical mixing rule (Lee and Yang 1998):

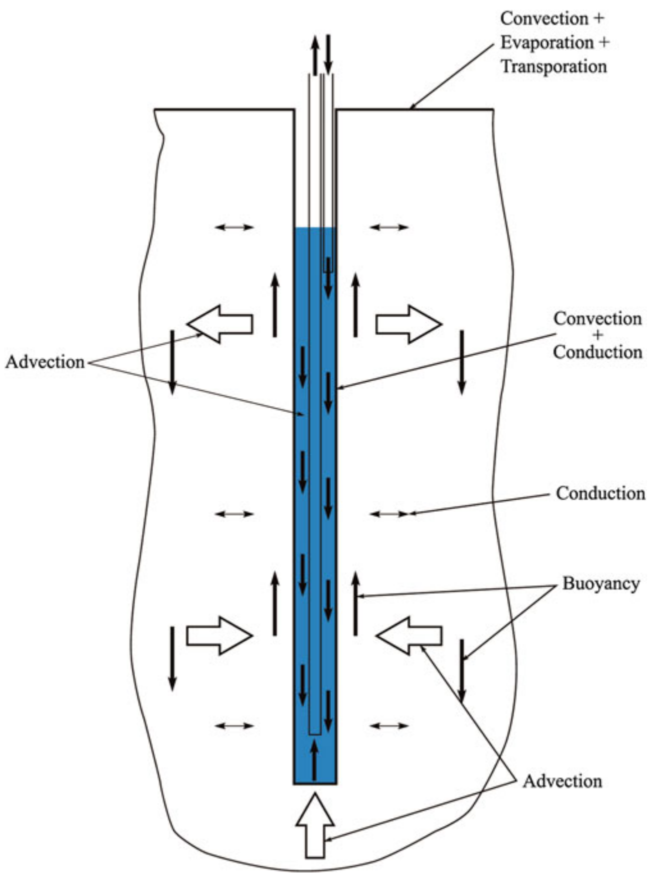

Fig. 3.3 Heat transfer mechanisms in SCW systems (redrawn from Deng 2004)

$$\lambda_{\text{eff}} = n\lambda_l + (1 - n)\lambda_s \tag{3.9}$$

where λ_l is the thermal conductivity of the fluid (W/m K); λ_s is the thermal conductivity of the solid (W/m K). In general, the more porous the medium, the lower the effective thermal conductivity, because water has a lower thermal conductivity than most solids.

The advection–diffusion equation can be used where enthalpy is thermal energy content only. Heat is transported by advection in the liquid phase and by both advection and diffusion in both phases. Dividing by the volume the energy balance equation of the control volume, taking constants out of the derivative and simplifying gives

$$\left(\rho C_p\right)_{cv}\frac{\partial T}{\partial t} + \rho_l C_{pl} V_i \frac{\partial T}{\partial x_i} = k_{\text{eff}}\frac{\partial^2 T}{\partial x_i^2} + Q \tag{3.10}$$

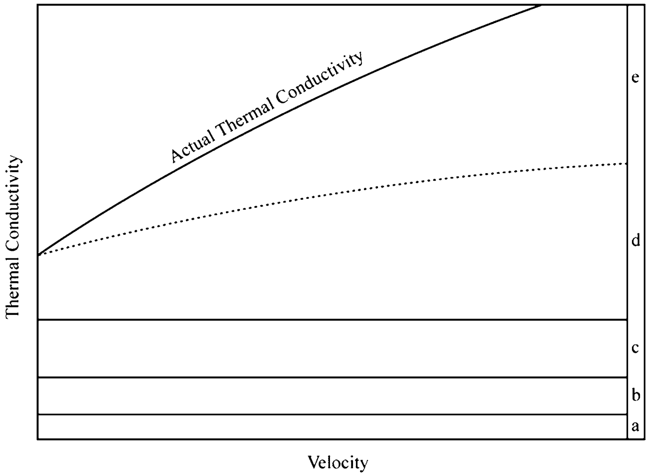

Fig. 3.4 The relationship between the actual thermal conductivity and the mechanisms that contribute to it (redrawn from Deng 2004). (*a*) Heat conduction through the fluid phase, (*b*) heat conduction through the solid phase, (*c*) particle to particle radiation, (*d*) heat convection from the fluid phase to the solid phase, (*e*) convection through the fluid phase (advection)

The effective thermal mass of the control volume, $\left(\rho C_p\right)_{cv}$ is defined by $\left(\rho C_p\right)_{cv} = n\rho_l C_{pl} + (1-n)\rho_s C_{ps}$ where C_{pl} and C_{ps} are the specific heats of the liquid and the solid, respectively.

Thus, after applying the principle of energy conservation to the given control volume, the energy equation for i direction in a density-dependent porous medium is:

$$\left[n\rho_l C_{pl} + (1-n)\rho_s C_{ps}\right]\frac{\partial T}{\partial t} + \rho_l C_{pl} v_i \frac{\partial T}{\partial x_i} = k_{\text{eff}}\frac{\partial^2 T}{\partial x_i^2} + Q \tag{3.11}$$

where v_i is the average linear groundwater velocity vector (m/s), which will be determined from the Darcy's law; ρ is the density (kg/m^3); C_p is the specific heat (J/kg K); Q is the source/sink (W/m^3); and the subscripts: l is water; s is solid (water saturated rock).

The second term of Eq. 3.11 contains only the thermal mass of the liquid because heat is advected only by the liquid phase. The energy Eq. 3.11 and the head Eq. 3.6 are coupled by the fluid velocity. The fluid velocity is obtained from the Darcian groundwater flux as follows and equivalent to Eq. 3.3:

$$v = -\frac{K}{n}\nabla h \tag{3.12}$$

Hence, the solution to the energy equation depends on the velocity data calculated from the Darcy's equation.

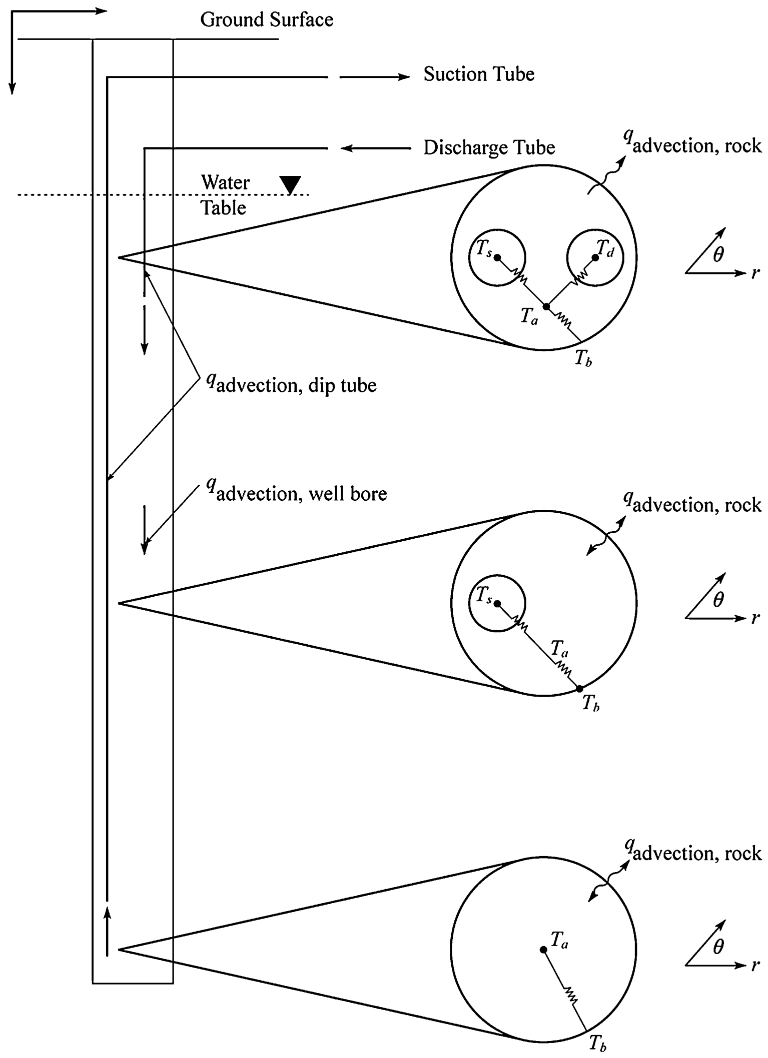

Fig. 3.5 The borehole thermal model (redrawn from Deng 2004)

3.1.3.2 Heat Transfer in the Borehole

Heat transfer in the borehole of SCW systems is characterized in the r direction by convection from the pipe walls and borehole wall, plus advection at the borehole surface, and in the z direction by advection only. The thermal model for the borehole can be described by a series of resistance networks as shown in Fig. 3.5.

An energy balance on the water in the annular region can be formulated in each z plane. The energy balance equation can be written as:

$$\begin{aligned}\frac{d\left(mC_pT_{a,z}\right)}{dt} =& q_{\text{convection; suction tube}} + q_{\text{convection; discharge tube}} + q_{\text{convection; rock}} \\ &+ q_{\text{advection; rock}} + q_{\text{advection; annulus}}\end{aligned} \tag{3.13}$$

Through mathematical manipulations, the left-hand side of Eq. 3.13 can be reduced to:

$$\begin{aligned}\frac{d\left(mC_pT_{a,z}\right)}{dt} &= \frac{dmC_pT_{a,z}}{dt} + \frac{mC_pdT_{a,z}}{dt} = \frac{\dot{m}dtC_pT_{a,z}}{dt} + \frac{mC_pdT_{a,z}}{dt} \\ &= \dot{m}C_pT_{a,z} + mC_p\frac{dT_{a,z}}{dt} = \dot{m}_{gw}C_pT_{a,z} + \dot{m}_{\text{annulus}}C_pT_{a,z} + V\rho C_p\frac{dT_{a,z}}{dt}\end{aligned} \tag{3.14}$$

The right-hand side of Eq. 3.13 can be modified to:

$$\begin{aligned}\text{RHS} =& q_{\text{convection; suction tube}} + q_{\text{convection; discharge tube}} + q_{\text{convection; rock}} \\ &+ \dot{m}_{gw}C_pT_{\text{rock}} + \dot{m}_{\text{annulus}}C_pT_{\text{annulus}}\end{aligned} \tag{3.15}$$

Thus, the energy balance Eq. 3.13 can be rewritten as:

$$\begin{aligned}V\rho C_p\frac{dT_{a,z}}{dt} =& q_{\text{convection; suction tube}} + q_{\text{convection; discharge tube}} + q_{\text{convection; rock}} \\ &+ \dot{m}_{gw}C_p\left(T_{\text{rock}} - T_{a,z}\right) + \dot{m}_{\text{annulus}}C_p\left(T_{\text{annulus}} - T_{a,z}\right)\end{aligned} \tag{3.16}$$

After the new definitions, Eq. 3.16 can be written as:

$$\begin{aligned}V\rho C_p\frac{dT_{a,z}}{dt} =& q_{\text{convection; suction tube}} + q_{\text{convection; discharge tube}} + q_{\text{convection; rock}} \\ &+ q_{\text{advection; rock}} + q_{\text{advection; annulus}}\end{aligned} \tag{3.17}$$

where

$$q_{\text{advection; rock}} = \dot{m}_{gw}C_p\left(T_{\text{rock}} - T_{a,z}\right)$$

$$q_{\text{advection; annulus}} = \dot{m}_{\text{annulus}}C_p\left(T_{\text{annulus}} - T_{a,z}\right)$$

and $T_{a,z}$ is the water temperature in the annular region at node z (°C); V is the volume of water in the annular region (m^3); ρ is the density of water in the annular region (kg/m^3); C_p is the specific heat of water (J/kg K); $\dot{m}_{gw}$ is the mass flow rate of groundwater in/out of the borehole (kg/s); $\dot{m}_{\text{annulus}}$ is the mass flow rate of water in the annulus of the borehole (kg/s).

Similarly, for the water in each of the tubes the energy balance is given by:

$$V\rho C_p\frac{dT_{\text{tube},z}}{dt} = q_{\text{convection; annular region}} + q_{\text{advection; tube}} \tag{3.18}$$

where $T_{\text{tube},z}$ is the water temperature in the tube (discharge tube or suction tube) at node z (°C).

The advection heat transfer rates in Eqs. 3.15 and 3.18 can be given by:

$$q_{\text{advection},n} = \dot{m}C_p\left(T_n - T_{a,z}\right) \tag{3.19}$$

where $\dot{m}$ is the mass flow rate of the water (kg/s); n refers to each of the rock and annular fluid at nodes $z-1$ and $z+1$.

The convection heat transfer rates in Eqs. 3.15 and 3.18 are given by:

$$q_{\text{convection},n} = \frac{1}{R_m}\left(T_m - T_{a,z}\right) \tag{3.20}$$

where R is the thermal resistance (°C/W); m is an index referring to the discharge tube, the suction tube, or the rock.

The thermal resistance in Eq. 3.20 is defined as the following:

$$R_m = \frac{1}{A_{i,m}}\left[\frac{1}{h_{i,m}} + \frac{r_i}{k_{\text{pipe}}}\ln\left(\frac{r_i}{r_o}\right) + \frac{r_i}{r_o}\left(\frac{1}{h_o}\right)\right] \tag{3.21}$$

where A is the area (m^2); r is the radius (m); h is the heat transfer coefficient (W/m^2 K); and subscript: i is the inner surface, o is the outer surface.

The heat transfer coefficient, h, is defined as:

$$h = \frac{\text{Nu}\lambda_{\text{water}}}{D_h} \tag{3.22}$$

where D_h is the hydraulic diameter (m).

3.1.3.3 Convective Heat Transfer in the Borehole

The literature review regarding convective heat transfer correlations in annular spaces suggests that the difference between concentric pipe configurations and eccentric pipe configurations may not be significant. Also, the correlations applicable to eccentric configurations are limited, and most of them are in tabular forms, not explicit correlations. Hence, the correlations will be based on concentric configurations. In the standing column well, to obtain good heat transfer, the annular area in the well is usually smaller than the area inside the dip tube, so the velocity near the wall is high enough to produce turbulent flow. Here, the attention is put on the turbulent flow.

The circular duct correlations for friction factors will be used. For smooth surfaces, the Techo's correlation has least relative error compared to the Prandtl, Kármán, Nikuradse (PKN) empirical formula $\left(\frac{1}{\sqrt{f}} = 1.7372\ln(\text{Re}\sqrt{f} - 0.3946)\right)$.

$$\frac{1}{\sqrt{f}} = 1.7372\ln\frac{\text{Re}}{1.964\ln\text{Re} - 3.8215} \quad \text{for } 10^4 < \text{Re} < 10^7 \tag{3.23}$$

For rough surface, the explicit equation with least relative error compared to the Colebrook-White empirical formula $\left(\frac{1}{\sqrt{f}} = 3.48 - 1.7372\ \ln\left(\frac{\varepsilon}{a} + \frac{9.35}{\mathrm{Re}\sqrt{f}}\right)\right)$ is given:

$$\frac{1}{\sqrt{f}} = 3.48 - 1.7372\ \ln\left(\frac{\varepsilon}{a} + \frac{16.2426}{\mathrm{Re}} \ln A_2\right) \ \text{for all values of Re and } \frac{\varepsilon}{a} \quad (3.24)$$

where f is the Fanning friction factor; Re is the Reynolds number, $\mathrm{Re} = \frac{D_h V}{v}$; V is the fluid velocity (m/s); v is the kinematic fluid viscosity (m^2/s); ε is the height of the surface roughness (m); $A_2 = \frac{\left(\frac{\varepsilon}{a}\right)^{1.1098}}{6.0983} + \left(\frac{7.149}{\mathrm{Re}}\right)^{0.8981}$, a is the radius of duct (m).

In the above formula, the laminar equivalent diameter, D_l, can be substituted for the hydraulic diameter, D_h for more accuracy.

$$\frac{D_l}{D_h} = \frac{1 + r*^2 + \frac{1 - r*^2}{\ln r*}}{(1 - r*)^2} \quad (3.25)$$

where $r* = \frac{r_i}{r_o}$; r_o and r_i are the radius of outer and inner pipes, respectively (m); D_h is the hydraulic diameter which is defined as 4 × area/wet perimeter (here, $D_h = 2(r_o - r_i)$) (m).

The circular duct correlations for Nusselt number could be used for both the inner and outer walls of the pipes in standing column well systems. But the hydraulic diameter ($D_o - D_i$) should be used in those correlations. The correlation by Gnielinski is used for smooth surfaces such as the discharge and suction tube:

$$\mathrm{Nu} = \frac{\frac{f}{2}(\mathrm{Re} - 1000)\,\mathrm{Pr}}{1 + 12.7\left(\frac{f}{2}\right)^{\frac{1}{2}}\left(\mathrm{Pr}^{\frac{2}{3}} - 1\right)} \quad (3.26)$$

For rough surfaces such as the borehole wall, the following correlation may be used because the range of Reynolds number, Re, in this correlation is very wide (i.e., Re > 2,300):

$$\mathrm{Nu} = \frac{\frac{f}{2}(\mathrm{Re} - 1000)\,\mathrm{Pr}}{1 + \left(\frac{f}{2}\right)^{\frac{1}{2}}\left[\left(17.42 - 13.77\,\mathrm{Pr}_t^{0.8}\right)\mathrm{Re}_\varepsilon^{0.2}\,\mathrm{Pr}^{0.5} - 8.48\right]} \quad (3.27)$$

where Pr is the Prandtl number:

$$\Pr_t = \begin{cases} 1.01 - 0.09\,\mathrm{Pr}^{0.36} & \text{for } 1 \le \mathrm{Pr} \le 145 \\ 1.01 - 0.11 \ln \mathrm{Pr} & \text{for } 145 < \mathrm{Pr} \le 1,800 \\ 0.99 - 0.29(\ln \mathrm{Pr})^{\frac{1}{2}} & \text{for } 1,800 < \mathrm{Pr} \le 12,500 \end{cases};$$

Re_ε is the roughness Reynolds number, $\mathrm{Re}_\varepsilon = \frac{\mathrm{Re}\sqrt{\frac{f}{2}}}{\frac{D}{\varepsilon}}$.

The borehole wall of standing column well systems is always rougher than the surface of a plastic or steel pipe. The roughness depends on the local geological conditions and drilling methods. Increased roughness increases the borehole wall's surface area and promotes local turbulent flow at the rough wall of borehole, which augments heat transfer. But at the same time, it also increases the friction factor. The following correlation for heat transfer in rough pipes was suggested:

$$\frac{\mathrm{Nu}}{\mathrm{Nu}_{\mathrm{smooth}}} = \left(\frac{f}{f_{\mathrm{smooth}}}\right)^n \quad \text{for} \quad \frac{f}{f_{\mathrm{smooth}}} \le 4 \tag{3.28}$$

where n = 0.68 Pr $^{0.215}$.

For $\frac{f}{f_{\mathrm{smooth}}} > 4$, it was also found that Nusselt number no longer increased with the increasing roughness. This was attributed to the fact that when roughness becomes very large $\left(\frac{f}{f_{\mathrm{smooth}}} > 4\right)$, the heat transfer resistance has become essentially a conduction resistance at the surface between the roughness elements.

Free convection is the motion that results from the density difference within a fluid. The density differences in heat transfer result from temperature gradients. Free convection may occur at the bottom of the borehole or when the pump is off. The correlation for the vertical cylinder may be used as an approximation of the problem.

$$\mathrm{Nu} = \left\{0.825 + \frac{0.387\mathrm{Ra}^{\frac{1}{6}}}{\left[1 + \left(\frac{0.492}{\mathrm{Pr}}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right\}^2 \tag{3.29}$$

where Rayleigh number $\mathrm{Ra} = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha}$; L is the characteristic length of the cylinder (m), this is the height of the borehole; β is the expansion coefficient; α is the thermal diffusivity (m^2/s). Equation 3.29 has a condition to be satisfied, which is usually satisfied for our case.

$$\frac{D}{L} \ge \frac{35}{\mathrm{Gr}_L^{\frac{1}{4}}} \tag{3.30}$$

where Grash of number $\mathrm{Gr}_L = \frac{gL^3\beta\Delta t}{\nu^2}$.

3.2 Hydrogeological Conditions

The EU Commission SAVE Programme and Nordic Energy Research (2004) summarized the hydrogeological conditions for underground thermal energy storage systems.

3.2.1 Aquifer Systems

The aquifer's hydraulic conductivity (K) is a measure of the ability of the porous geologic media to transmit water. It is of first-order significance in design and evaluation of aquifer thermal energy storage systems, and is dependent on the size and shape of the pores. Hydraulic conductivity varies over a wide range of over 13 orders of magnitude. Hydraulic conductivity multiplied by aquifer thickness (b) equals aquifer transmissivity (T), which is a measure of the rate at which water moves through a unit width of the aquifer under a unit hydraulic gradient. A high hydraulic conductivity (and transmissivity) is desired to produce the largest volume of water from a well with the least drawdown of groundwater level. However, low hydraulic conductivity is desirable for decreased regional groundwater velocity and prevention of excessive tilting of the thermocline from viscosity/buoyancy effects in high-temperature ATES systems. Isotropic aquifer media having the same hydraulic conductivity in all directions are desirable to obtain maximum water supply from a well with minimum drawdown. But, conversely, anisotropic conditions with vertical hydraulic conductivity being much less than horizontal hydraulic conductivity are desirable for high-temperature ATES systems to resist tilting of the thermocline.

If total volume (V_T) of the rock is divided into the volumes of solid and voids (V_v), porosity (n) of geologic media is defined as $n = \frac{V_v}{V_T}$. With regard to the storage and movement of water in a porous medium, effective porosity considering only the system of interconnected interstices is important. The porosity of the aquifer matrix is an important consideration in ATES systems because it determines the amount of heated or chilled water that can be stored per unit volume of the aquifer. Porosity also is important because it is one factor that controls the average linear velocity of groundwater flow. Average linear velocity of groundwater in a porous medium is proportional to the hydraulic conductivity and gradient by Darcy's law and inversely proportional to the porosity as indicated in Eq. 3.12.

Areal aquifer boundaries and thickness determine the volume available for storage of heat or chill. Aquifer volume generally is much greater than the required storage volume, but boundary location may be of interest if the proposed ATES storage site is near zones of recharge or discharge, or on the periphery of a groundwater system.

Thermal characteristics of the aquifer are important in determining the heat capacity of the system and heat transfer out of the storage volume. Thermal conductivity is the quantity of heat conducted in unit time across an element of surface under a given thermal gradient. Porous geologic materials, saturated with water, do not vary widely in thermal conductivity values. Basically, earth materials are good insulators under ATES conditions, and differences in their thermal conductivities are relatively small. Thus, thermal conductivity is of second-order importance in hydrogeologic characterization. Thermal capacity (specific heat) of a material is the quantity of heat required to produce a unit change of temperature

Table 3.1 Typical hydraulic conductivity values (from EU Commission SAVE Programme and Nordic Energy Research 2004)

Type	Hydraulic conductivity (m/sec)
Course gravel	$100–10^{-1}$
Fine gravel	$10^{-1}–10^{-3}$
Course sand	$10^{-3}–10^{-4}$
Medium sand	$10^{-3}–10^{-5}$
Fine sand	$10^{-4}–10^{-6}$

in a unit mass of media. Variation in thermal capacity of earth materials, as with thermal conductivity, is small.

For ATES applications, an aquifer close to the object or process to be heated or cooled is required. However, for district cooling systems, the aquifer may also be located elsewhere in the area of the distribution net. In general, the aquifer porosity will govern the volume needed.

The requirements of the aquifer properties depend on the size of the storage project, i.e., the flow rate that has to be handled and the amount of energy that will be stored. The flow rate that, as a function of time, can be extracted and reinjected from and into the aquifer, will be related to the aquifer transmissivity. In theory, there is no transmissivity limit. However, in practice the limit for primary porosity aquifers is determined by the possibilities of constructing functional wells. This limit can be defined as a situation where the dominating grain size is less than 0.06 mm and corresponds to a transmissivity less than 10^{-5} m^2/s. The latter figure may also be relevant for the fractured aquifer type, but in that case without any well design restrictions (Table 3.1).

The site-specific geological and hydrogeological conditions can be surveyed by means of test drillings and pumping tests. Typical hydraulic conductivity values for different dominating grain sizes in natural sediments are:

The large variation within each grain size group depends mainly on sorting, stratification, roundness of grains, and degree of packing.

Other properties and conditions to be considered are:

- stratigraphy (sequence of layers)
- grain size distribution (mainly primary porosity aquifers)
- structures and fracture distribution (mainly fractured aquifers)
- aquifer depth and geometry, hydraulic boundaries included
- storage coefficient (hydraulic storage capacity)
- leakage factor (vertical hydraulic influence)
- degree of consolidation (hardness)
- thermal gradient (temperature increase with depth)
- static head (groundwater level)
- natural groundwater flow and direction of flow
- water chemistry.

Table 3.2 Typical thermal conductivity values (from EU Commission SAVE Programme and Nordic Energy Research 2004)

Type or rock	Thermal conductivity (W/m K)
Quartzite	4.0–6.0
Light granites	3.5–4.0
Light gneisses	3.0–3.5
Dark granites	2.5–3.0
Limestones	2.5–3.0
Sandstones	2.5–4.0
Shales	2.0–3.0

3.2.2 Borehole Systems

Borehole thermal energy storage (BTES) system with drilled boreholes can be applied in any type of geology. However, the geological and hydrogeological conditions will influence the construction of boreholes as well as the storage efficiency.

The most important underground parameters to be considered are the thermal conductivity and the thermal capacity.

- The thermal conductivity is related to the mineral composition and the porosity of the underground strata. Normally, the conductivity ranges between 2 and 5 W/m K. The lowest values are to be found in clayey unconsolidated formations with a high porosity, and even lower in organic sediments. In theory, these types of sediments can be used, but in practice they are rejected for economic reasons.
- The thermal capacity is in general related to the content of water in the strata, which in turn is directly depending on the groundwater level and the porosity. A high porosity above the groundwater level will result in a low thermal conductivity. This means that a low groundwater table combined with high porosity is a worst-case situation that should be avoided.

Furthermore, the efficiency of a BTES system at a given site may be influenced by a natural groundwater flow. In the case that the stored energy is partly or completely transported away from the BTES site, the groundwater flow shall be regarded as a hydrogeological boundary condition.

The site-specific thermal properties of the underground can be detected by test drilling and the performance of a thermal response test (TRT). Typical thermal conductivity values for some different rocks are given in Table 3.2

Variations within each group of rocks are mainly due to water content in fractures and primary porosity, structure, mineral content, and size of crystals. The thermal conductivity in soils will normally be in the range of 2.0–2.5 W/m K.

3.3 Determination of Hydrogeological Properties

Successful design and operation of a UTES system depend on three elements: (1) the presence of a suitable aquifer for ground-water supply and energy storage; (2) the availability of a source of free or low-cost thermal energy; and (3) a temporal mismatch between thermal energy availability and thermal energy use.

Element 1 is usually the most difficult component of an ATES system to assess quantitatively. In their paper, Hall and Raymond (1992) presented a practical and economic method for characterizing hydrogeologic systems for ATES applications. The method combines conventional hydrologic testing with single-well geochemical tracer tests.

Aquifer characterization is important to the engineering design of an ATES installation; that is, the aquifer must be considered as one important component of the ATES heating or cooling plant. However, unlike the pumps, heat exchangers, and other mechanical components of the system, the aquifer cannot be changed to meet design specifications. Thus, to some degree, the ATES plant must be designed to accommodate the aquifer.

For example, the capacity of the aquifer to accept or yield water limits the flow rate that can be used in an ATES plant. Also, the effective porosity of the aquifer affects the volume of aquifer required to store a given volume of heated or chilled water. These affect the size of an ATES well field. The direction and rate of groundwater flow similarly affects the size, shape, and operation of the well field.

3.3.1 *Step-Drawdown Tests*

Boonstra (1999a) and American Society for Testing and Materials (1999) provided a summary on the drawdown in a pumped well and drawdown test. The drawdown in a pumped well consists of two components: the aquifer losses and the well losses. Aquifer losses are the head losses that occur in the aquifer where the flow is laminar. They are time dependent and vary linearly with the well discharge. The drawdown s_1 corresponding to this linear aquifer loss can be expressed as

$$s_1 = B_{1(r_w,t)}Q \tag{3.31}$$

where B_1 is the linear aquifer loss coefficient in day/m^2. This coefficient can be calculated from the well flow equations. For confined aquifers for example, it can be expressed as

$$B_{1(r_w,t)} = \frac{W(u)}{4\pi T} \tag{3.32}$$

where $u = \frac{r_w^2 S}{4Tt}$. From the results of aquifer-test analyses, the values for transmissivity T and storativity S can be used to calculate B_1 values as function of r_w and t.

Well losses are divided into linear and nonlinear head losses. Linear well losses are caused by damaging the aquifer during drilling and completion of the well. They comprise head losses due to the compaction of the aquifer material during drilling; head losses due to plugging of the aquifer with drilling mud, which reduces the permeability near the bore hole; head losses in the gravel pack; and head losses in the screen. The drawdown corresponding to this linear well loss can be expressed as

$$s_2 = B_2 Q \qquad (3.33)$$

where B_2 is the linear well loss coefficient in day/m^2.

Among the nonlinear well losses are the friction losses that occur inside the well screen and in the suction pipe where the flow is turbulent, and head losses that occur in the zone adjacent to the well where the flow is usually also turbulent. All these losses responsible for the drawdown inside the well are much greater than one would expect on theoretical grounds. The drawdown s_3 corresponding to this nonlinear well loss can be expressed as

$$s_3 = CQ^P \qquad (3.34)$$

where C is the nonlinear well loss coefficient in day^P/m^{3P-1}, and P is an exponent. The general equation describing the drawdown in a pumped well as function of aquifer/well losses and discharge rate thus reads as

$$s_w = (B_1 + B_2)Q + CQ^P = BQ + CQ^P \qquad (3.35)$$

where $s_w = s_1 + s_2 + s_3$. The value of P can vary between 1.5 and 3.5 and may be even higher in fractured rock aquifers. The value of $P = 2$ is, however, widely accepted. Values of the three parameters B, C, and P in Eq. 3.35 can be found from the analysis of so-called step-drawdown tests.

A step-drawdown test is a single-well test in which the well is pumped at a low constant-discharge rate until the drawdown within the well stabilizes. The pumping rate is then increased to a higher constant discharge rate and the well is pumped until the drawdown stabilizes once more. This process is repeated through at least three steps, which should all be of equal duration, say, a few hours each (Fig. 3.6).

In step-drawdown analyses, use is made of so-called diagnostic plots. Values of $\frac{s_w}{Q}$ versus Q are therefore plotted on arithmetic paper, where s_w represents the drawdown at the end of each step. Various configurations of diagnostic plots are then possible:

- The points fall on a horizontal line. This implies that $\frac{s_w}{Q} = B$. Equation 3.35 reduces to

$$s_w = BQ \qquad (3.36)$$

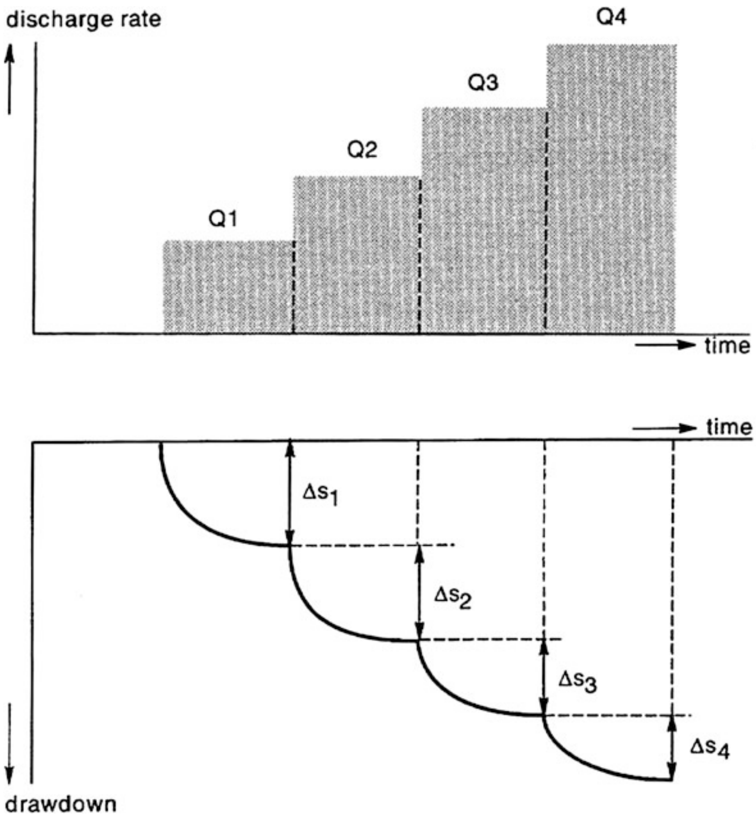

Fig. 3.6 Principles of a step-drawdown test (from Boonstra 1999a)

Hence, there are no nonlinear well losses. This situation is only encountered with very low pumping rates. The well will act differently if the pumping rates are increased.

- The points fall on a straight line under a slope. This means that $\frac{s_w}{Q} = B + CQ$. Equation 3.35 then reduces to

$$s_w = BQ + CQ^2 \tag{3.37}$$

Equation 3.37 is known as the Jacob's equation. Based on this equation, Jacob (1947) developed an analysis method to calculate the values of B and C.

- The points fall on a curved line, i.e., $P \neq 2$ in Eq. 3.35. When a concave curve can be drawn through the points, it implies that $P > 2$ and for a convex curve that $P < 2$. For these cases, an analysis method was developed to calculate the values of B, C, and P. Both analysis methods may be applied to confined, unconfined, and leaky aquifers.

3.3.2 Well Flow Equations

As summarized by Boonstra (1999b), the well flow equations presented were developed under the following common assumptions and conditions: (1) the aquifer has a seemingly infinite areal extent; (2) the aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by the test; (3) prior to pumping, the hydraulic head is horizontal (or nearly so) over the area that will be influenced by the test; (4) the pumped well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow; (5) the aquifer is pumped at a constant-discharge rate; (6) the water removed from storage is discharged instantaneously with decline of head; and (7) the diameter of the pumped well is small, i.e., the storage inside the well can be neglected.

Theis was the first to develop an equation for unsteady-state flow which introduced the time factor and the storativity. He noted that when a fully penetrating well pumps an extensive confined aquifer at a constant rate, the influence of the discharge extends outward with time. The rate of decline of head, multiplied by the storativity and summed over the area of influence, equals the discharge. The Theis equation, which was derived from the analogy between the flow of groundwater and the conduction of heat, is written as

$$s(r,t) = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-y}}{y}dy = \frac{Q}{4\pi T}W(u) \tag{3.38}$$

with

$$u = \frac{r^2 S}{4Tt}$$

where $s(r,t)$ is the drawdown in m measured in a well, Q is the constant well discharge in m^3/day, T is the transmissivity of the aquifer in m^2/day, $W(u)$ is the dimensionless Theis well function, r is the distance in m from the pumped well, S is the dimensionless storativity of the aquifer, and t is the time in days since pumping started. In Fig. 3.7, the Theis well function $W(u)$ is plotted versus $\frac{1}{u}$ on semi-log paper. This figure shows that, for large values of $\frac{1}{u}$, the Theis well function exhibits a straight-line segment. The Jacob method is based on this phenomenon. For the straight-line segment, Eq. 3.39 can be approximated by

$$s(r,t) = \frac{2.3Q}{4\pi T}\log\frac{2.25Tt}{r^2 S} \tag{3.39}$$

In most handbooks on this subject, the condition to use Eq. 3.39 is taken as $\frac{1}{u} > 100$. This limiting condition can often be relaxed to $\frac{1}{u} > 10$.

When a confined aquifer is pumped, the cone of depression will continuously deepen and expand. Even at late pumping times, the water levels in the piezometers will never stabilize to a real steady state. Although the water levels continue to drop, the cone of depression will eventually deepen uniformly over the area

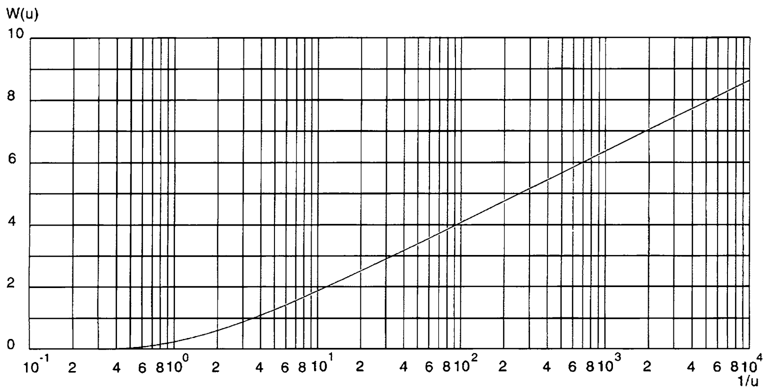

Fig. 3.7 Theis well function $W(u)$ versus $\frac{1}{u}$ for fully penetrating wells in confined aquifers (from Boonstra 1999b)

influenced by the pumping. At that stage, the hydraulic gradient has become constant and this phenomenon is called a pseudosteady state. For this situation, the so-called Thiem–Dupuit equation was developed using two or more piezometers, which can be written as

$$s(r_1, t) - s(r_2, t) = \frac{2.3Q}{2\pi T} \log \frac{r_2}{r_1} \tag{3.40}$$

Equation 3.40 can also be derived by applying Eq. 3.39 to two piezometers at distances r_1 and r_2 at large times.

The physical properties of a confined aquifer can be found by developing the time-drawdown relationship based on Eq. 3.40. If the pumping time is long enough, a plot of the drawdowns observed at a particular distance r from the pumped well versus the logarithm of time t, will appear as a straight line. If the slope of the straight-line segment is expressed as the drawdown difference ($\Delta s = s_1 - s_2$) per log cycle of time $\left(\log \frac{t_2}{t_1} = 1\right)$, rearranging Eq. 3.40 gives

$$T = \frac{2.3Q}{4\pi \Delta s} \tag{3.41}$$

If this line is extended until it intercepts the time-axis where $s = 0$, the interception point has the coordinates $s = 0$ and $t = t_o$. Substituting these values into Eq. 3.40, after rearrangement, gives

$$S = \frac{2.25Tt_o}{r^2} \tag{3.42}$$

Figure 3.8 shows an example of the time-drawdown plot on semi-log paper. The data plot exhibits a straight line in the time range from 20 to 360 min.

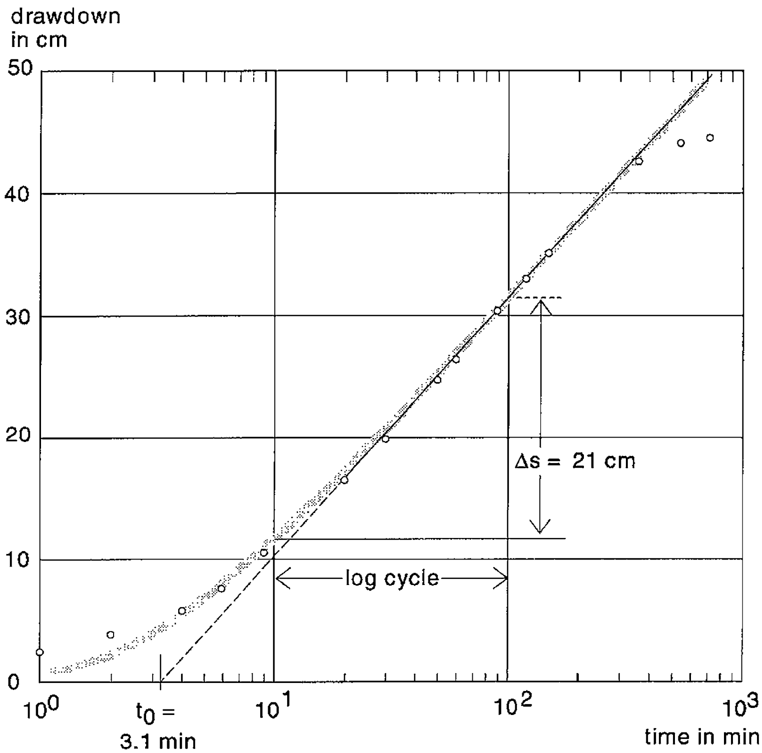

Fig. 3.8 Time-drawdown plot of field data of an aquifer test in a confined aquifer (from Boonstra 1999b)

Through these points a best-fitting straight line was drawn; its slope Δs is 21 cm = 0.21 m per log cycle of time.

With single-well tests, basically the same procedures can be applied as with aquifer tests. The r value now represents the effective radius of the single well. This is difficult to determine under field conditions; as a "best" estimate, the outer radius of the well screen is often used.

A complicating factor is the phenomenon that, due to nonlinear well losses, the water levels inside the well can be considerably lower than those directly outside the well screen. This implies that drawdown data from the pumped well can, in general, only be used for the analysis when corrected for these nonlinear well losses using the results of so-called step-drawdown tests.

A combination of pressure derivatives, straight-line solutions, and type-curve matching techniques was applied to the corrected data to estimate values of transmissivity, storage coefficient, and specific yield.

3.3.3 Anisotropy Test

The ratio of horizontal to vertical permeability is a parameter that strongly affects the degree of tilting of the thermal front for a mass of hot water injected into a confined aquifer. Substantial tilting of the thermocline provides a larger surface area for conductive heat loss to the upper confining layer and admits cold water near the bottom of the aquifer during recovery pumping. Both phenomena contribute to poor energy recovery. Parr et al. (1983) presented a summary on the anisotropy test.

Weeks (1969) presented three methods whereby drawdown data in partially penetrating observation wells or piezometers near a partially penetrating well pumped at constant rate can be analyzed to determine the permeability ratio. Weeks' Method 2 will be considered for piezometers or observation wells screened over no more than about 20 % of the aquifer thickness. The method is based on Hantush's drawdown equation.

$$
\begin{aligned}
s &= \frac{Q}{4\pi T}[W(u)+f] \\
&= \frac{Q}{4\pi T}\left\{W(u)+\frac{4b}{\pi(z_w-d)}\sum_{n=1}^{\infty}\frac{1}{n}K_0\left[\frac{n\pi r}{b}\sqrt{\frac{K_z}{K_r}}\right]\left(\sin\frac{n\pi z_w}{b}-\sin\frac{n\pi d}{b}\right)\cos\frac{n\pi z}{b}\right\}
\end{aligned}
\tag{3.43}
$$

where

s drawdown, m
Q pumping rate, m^3/day
T transmissibility in m^2/day
$W(u)$ well function
r distance from pumped well to piezometer in m
S storage coefficient; T time in days
K_0 modified Bessel function of the second kind and zero order
K_z vertical hydraulic conductivity in m/day
K_r horizontal hydraulic conductivity in m/day.

The dimension z is measured from the middle of the screen for observation wells. Equation 3.43 applies for $t > \frac{bS}{2K_z}$. The term f in Eq. 3.43 accounts for the deviation in drawdown observed in a partially penetrating piezometer in an anisotropic aquifer from that predicted for a fully penetrating observation well at the same location. The deviation is, therefore, given by

$$
\delta s = \frac{Q}{4\pi T}f \tag{3.44}
$$

where δs is in meters.

Two or more partially screened piezometers are required to perform the method. The procedure is paraphrased as follows:

- Step 1. Determine values of T for each piezometer from the time-drawdown plots using the modified nonequilibrium method.
- Step 2. For a selected time, plot drawdown versus r for each of the wells on semilog paper with r on the logarithmic scale. Also draw a line of slope $\delta s = \frac{2.3Q}{2\pi T}$ beneath the data points if δs is negative (or above if δs is positive).
- Step 3. Determine trial values of δs for each well by subtracting observed drawdown from the corresponding straight-line drawdown.
- Step 4. Determine f for each well from Eq. 3.44 using the trial δs-values obtained in Step 3 and make a semilog plot of f versus $\frac{r}{b}$ with f on the arithmetic scale.
- Step 5. Prepare a type curve on semilog paper of f from Eq. 3.43 versus $\frac{r}{b}\sqrt{\frac{K_z}{K_r}} = \frac{r_c}{b}$ with f on the arithmetic scale.
- Step 6. Match the data plot with the type curve and select a match point.
- Step 7. Determine the $\frac{r}{b}$ and $\frac{r_c}{b}$ coordinates for the match point, then calculate the permeability ratio from

$$\frac{K_z}{K_r} = \left[\frac{\left(\frac{r}{b}\right)}{\left(\frac{r_c}{b}\right)}\right]^2 \tag{3.45}$$

- Step 8. Correct the trial f values computed in Step 4 by adding algebraically the value obtained by subtracting the data curve value of f from the type-curve value of f for the match point.
- Step 9. Determine a calculated storage coefficient, S_c, for each well from the time-drawdown plots, assuming the wells are fully penetrating.
- Step 10. Determine the true storage coefficient for each well by using the corrected f values from Step 8 and the calculated storage coefficients from Step 9 in the equation

$$S = S_c \exp(f) \tag{3.46}$$

3.3.4 Dispersivity Testing

Hydrodynamic dispersion occurs because of mechanical mixing during fluid advection and because of molecular diffusion due to the thermal–kinetic energy. The hydrodynamic dispersion coefficient is an important parameter which can affect the efficiency of a thermal energy storage system. In general, the smaller the dispersivity, the sharper the interface between hot and cold water. Minimal mixing of injected and native waters maximizes the recovery temperature.

In order to provide a useful measure of the dispersion coefficient, a conservative tracer test is performed during the injection. The resulting concentration in the storage aquifer was recorded in a tracer observation well located apart from the injection well. The one-dimensional form of the advection–dispersion equation for nonreactive dissolved constituents in saturated, homogeneous media under uniform flow is:

$$D_l \frac{\partial^2 C}{\partial x^2} - v\frac{\partial C}{\partial x} = \frac{\partial C}{\partial t} \tag{3.47}$$

where D_l is the coefficient of hydrodynamic dispersion and C is solute concentration. The coefficient of hydrodynamic dispersion can be expressed as

$$D_l = \alpha v + D* \tag{3.48}$$

where α is dispersivity and D^* is the coefficient of molecular diffusion.

The procedure is based on an approximate solution to the radial flow dispersion equation given by

$$\frac{C}{C_o} = 0.5\mathrm{erfc}(u) \tag{3.49}$$

where

erfc = complementary error function

$$u = \frac{\frac{r^2}{2} - At}{\sqrt{\frac{4\alpha r^3}{3}}}$$

r radius from injection well
α = dispersivity

$$A = \frac{Q}{2\pi bn}$$

Q injection rate.

Through manipulation of 3.49, $\mathrm{erf}(u) = 1 - 2\left(\frac{C}{C_o}\right)$, or $\mathrm{erf}^{-1}\left[1 - 2\left(\frac{C}{C_o}\right)\right] = u$ Hence,

$$\sqrt{\alpha}\mathrm{erf}^{-1}\left[1 - 2\left(\frac{C}{C_o}\right)\right] = \frac{\frac{r^2}{2} - At}{\sqrt{\frac{4\alpha r^3}{3}}} \tag{3.50}$$

Thus, a plot of $\mathrm{erf}^{-1}\left[1 - 2\left(\frac{C}{C_o}\right)\right]$ versus $\frac{\frac{r^2}{2}-At}{\sqrt{\frac{4\alpha r^3}{3}}}$ is a straight line with a slope equal to $\sqrt{\alpha}$.

3.4 Determination of Thermal Properties

The major thermodynamic quantities which must be measured or at least estimated are the thermal conductivity and heat capacity of the aquifer and confining layers. These quantities are subject to much less natural variation than the hydraulic properties which were discussed previously. Therefore, they can normally be estimated or measured in the laboratory using core samples obtained during construction of the various exploratory and/or test wells.

The specific heats of many common dry rock materials are in the relatively narrow range of 0.19–0.22 kcal/kg/°C. Using values for pure materials obtainable from standard tables, one can estimate the effective heat capacity of a water saturated porous medium on a volumetric basis using the equation

$$C_{va} = n\rho_w C_w + (1-n)\rho_s C_s \tag{3.51}$$

where C_{va} aquifer volumetric heat capacity; ρ_w, ρ_s densities of water and solid respectively; C_w, C_s specific heat of water and solid respectively; and n porosity. A porosity in the range of 20–60 % would yield an effective heat capacity between about 600 and 800 kcal/m^3/°C.

The knowledge of underground thermal properties is a prerequisite for proper design of borehole heat exchangers (BHE). The most important property is the thermal conductivity of the ground. This parameter is site specific and cannot be influenced by engineering. The thermal contact from the borehole wall to the fluid inside the pipes, however, is controlled by borehole diameter, pipe size and configuration, pipe material, and the filling inside the annulus. These items are subject to efforts in order to reduce the thermal resistance between borehole wall and fluid, usually summarized in the parameter "borehole thermal resistance".

Since the mid 1990s, a method has been developed and refined to measure the underground thermal properties on-site, and mobile equipment for these measurements has been built in several countries. The TRT, also sometimes called geothermal response test (GRT), is a suitable method to determine the effective thermal conductivity of the underground and the borehole thermal resistance or the thermal conductivity of the borehole filling, respectively (Sanner et al. 2005). From the test, a temperature curve is obtained which can be evaluated by different methods. The resulting thermal conductivity is a value for the total heat transport in the underground, noted as a thermal conductivity. Other effects like convective heat transport (in permeable layers with groundwater) and further disturbances are automatically included, so it may be more correct to speak of an "effective" thermal conductivity λ_{eff}.

3.4.1 Development of Thermal Response Test

The theoretical basis for the TRT was laid over several decades. In the 1990s, the first practical applications were made, e.g., for the investigation of borehole heat storage in Linköping. In 1995, a mobile test equipment was developed at Luleå Technical University to measure the ground thermal properties for BHE between some 10 m to over 100 m depth. A similar development was going on independently since 1996 at Oklahoma State University in the U.S.A. The first TRT in Germany was performed in summer 1999 (Sanner et al. 2005).

A somewhat different test rig was developed and tested in the Netherlands. This rig uses a heat pump instead of electric resistance heaters, in order to be able to also decrease the temperature inside the BHE. This method, however, has intrinsic problems because of the dynamic behavior of the heat pump and the need for a heat source/sink, and should only be used where testing with extracting heat has to be done explicitly. Besides the Dutch test rig, there are at least two other heat pump systems, one in Germany and one in Sweden.

There are test rigs operational today in the following countries:

- Canada
- Chile (experimental)
- China
- Germany (4)
- Netherlands
- Norway
- South Korea
- Sweden (several)
- Switzerland
- Turkey
- United Kingdom
- U.S.A. (several)

3.4.2 Operation of the Test

The general layout of a TRT is shown in Fig. 3.9. For good results, it is crucial to set up the system correctly and to minimize external influences. This is done easier with heating the ground (electric resistance heaters) than with cooling (heat pumps). However, even with resistance heating, the fluctuations of voltage in the grid may result in fluctuations of the thermal power injected into the ground.

Other sources of deviation include climatic influences, affecting mainly the connecting pipes between test rig and BHE, the interior temperatures of the test rig, and sometimes the upper part of the BHE in the ground. Heavy insulation is required to protect the connecting pipes, and sometimes even air-conditioning for

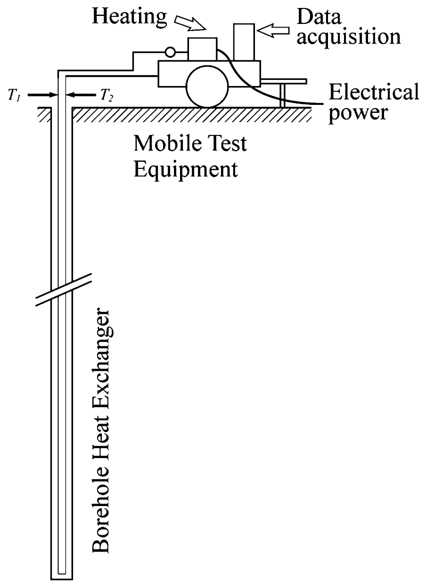

Fig. 3.9 Test setup for a Thermal Response Test (redrawn from Sanner et al. 2005)

the test rig is necessary, as was done in U.S.A. With open or poorly grouted BHE, also rainwater intrusion may cause temperature changes. A longer test duration allows for statistical correction of power fluctuations and climatic influence, and results in more trustworthy evaluation. Typical test curves with strong and with low climatic influence are shown in Fig. 3.10.

With the increasing commercial use of TRT, the desire for a shorter test duration became apparent, in particular in the U.S.A. A recommendation for a minimum of 50 h was given, which is compatible with the IEA recommendations, but there is also skepticism. A test time of about 12 h is desired, which also would allow not to have the test rig out on the site overnight, In general, there are physical limits for the shortening of the measuring period, because a somewhat stable heat flow has to be achieved in the ground. In the first few hours, the temperature development is mainly controlled by the borehole filling and not by the surrounding soil or rock. A time of 48 h is considered by the authors as the minimum test period.

In the evaluations made of German tests, the minimum duration criterion proved helpful:

$$t_b = \frac{5r^2}{\alpha} \tag{3.52}$$

with

t_b lower time limit of data to be used
r borehole radius
α thermal diffusivity with estimated values $\left(\alpha = \frac{\lambda}{\rho C_p}\right)$

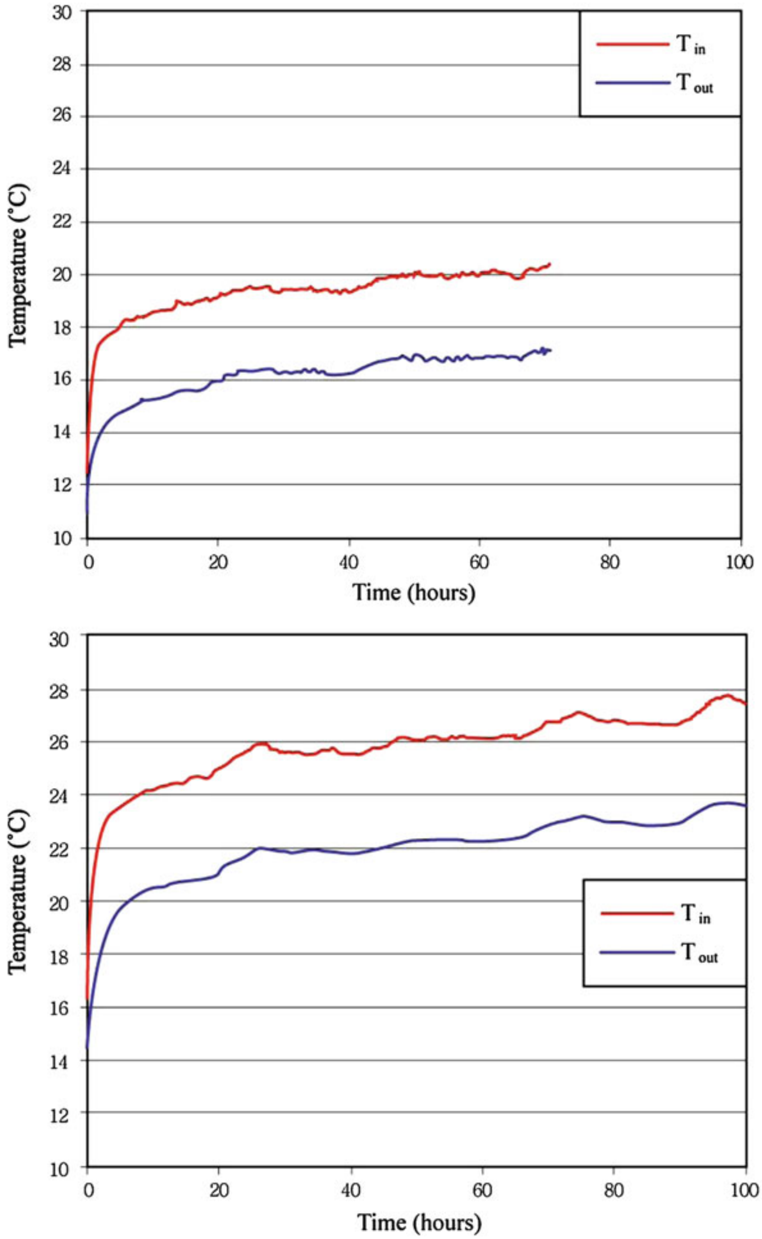

Fig. 3.10 Measured temperature curves with low (*above*) and strong (*below*) climatic influence (redrawn from Sanner et al. 2005)

However, an optical cross-checking is recommended because the measured data may deviate from the theoretical assumptions. It is also worthwhile to calculate the minimum duration criterion again with the thermal conductivity resulting from the first evaluation, to start a kind of iteration.

3.4.3 Test Evaluation

The main methods for determining thermal conductivity of ground from the data measured during TRT are (Saljnikov et al. 2006):

- slope determination technique;
- two-variable parameter fitting method;
- Geothermal Properties Measurements (GPMs) method— i.e., by utilizing the GPM software.

3.4.3.1 Slope Determination Technique

This method is simple and accurate. It relies upon the solution of the LSM (Line Source Model) problem. It is using the expression for the temperature field of the working fluid as the function of time (t) and borehole radius (R) around a line heat source of constant power (P) which can be assumed to be equal to the power of the BHE:

$$T_f = \frac{P}{4\pi\lambda L}\left[\ln\frac{4\alpha t}{R^2} - \gamma\right] + \frac{PR_b}{L} + T_o \tag{3.53}$$

Expression 3.53 is a formula of the form:

$$T_f = k\ln(t) + m \tag{3.54}$$

where $k = \ln\frac{P}{4\pi\lambda L}$Therefore, thermal conductivity (λ) is determined based upon slope (k) of linear dependence T_f on $\ln(t)$, therefrom the title of the method.

3.4.3.2 Two-Variable Parameter Fitting Method

The need for a more interval-independent evaluation technique led to fit the data using a fitting function in Eq. 3.54 with thermal conductivity and borehole thermal resistance left as the two-variable parameters.

3.4.3.3 Geothermal Properties Measurement

The GPM is a program developed at the Oak Ridge National Laboratory to determine thermal properties from the short-term field test data. The program uses a parameter-estimation-based method—combined with a 1-D numerical model. It relies on the cylinder source model considering two pipes of the U-loop as a single cylinder.

3.4.4 Limitations of Thermal Response Test

A limitation to TRT is the amount of groundwater flow. Because the thermal conductivity obtained includes convection effects, the estimated thermal conductivity becomes masked with high groundwater flow and the values cannot be used for design of BHE plants. The groundwater flow considered here is not the simple velocity (the time a water particle travels from one point to another, e.g. in m/s), but the Darcy-velocity, which is a measure for the amount of water flowing through a given cross-section in a certain time ($m^3/m^2/s$, resulting also in m/s). The Darcy-velocity thus depends on the porosity and the velocity.

A useful method to check for excessive groundwater flow in the standard line-source evaluation is the step-wise evaluation with a common starting point and increasing length of data-series. The resulting thermal conductivity for each time-span can be calculated and plotted over time. Usually in the first part of such a curve the thermal conductivity swings up and down, converging to a steady value and a horizontal curve in the case of a prefect test. If this curve continues to rise (i.e. the more heat is carried away the longer the test lasts), a high groundwater flow exists and the test results may be useless (Fig. 3.11).

This method also shows if other external factors (weather, unstable power for heating, etc.) are disturbing the measurement.

An even more problematic kind of groundwater influence is groundwater flow upwards or downwards in the borehole annulus. This occurs in open boreholes (Sweden), but also in poorly grouted BHE or in those backfilled with sand. In combination with confined aquifers or other vertical pressure differences this leads to tests which cannot be evaluated at all.

3.5 Construction Costs

The largest economic burden of UTES systems occurs at the time of installation. Zizzo (2009) summarized construction cost of UTES in his thesis. Building these systems, with the required ground condition studies and drilling, accounts for the vast majority of the costs. Since these studies must be undertaken regardless of system size, it has been found that larger systems are more economical since a

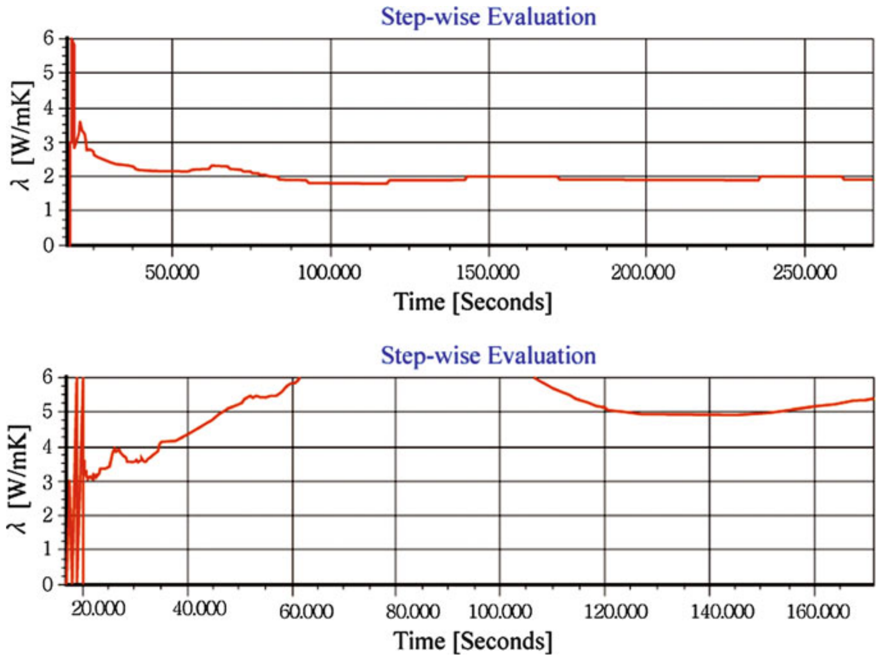

Fig. 3.11 Step-wise evaluation showing perfect convergence (*above*) and test with high groundwater flow (*below*) and unreasonably high thermal conductivity value (redrawn from Sanner et al. 2005)

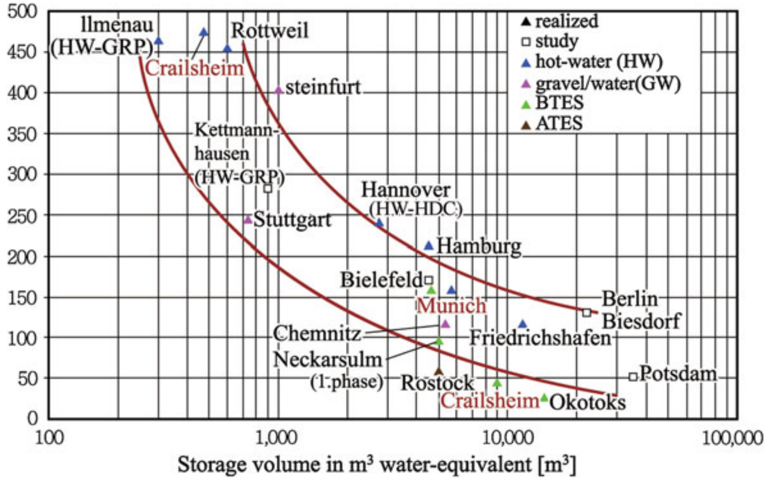

Fig. 3.12 Decreasing marginal cost of UTES systems (from Zizzo 2009)

Table 3.3 Solar heated BTES cost comparison with alternate systems (from Zizzo 2009)

System	Construction costs (millions $ CAD)	Annual costs (millions $ CAD)
Solar heated BTES	1.377	0.161
Small-scale DE	0.878	0.179
GSHP for each building	0.945	0.149

greater output is achieved for marginally increased capital expenditures. Figure 3.12 illustrates that as system size increases, the investment per unit output decreases.

Nordell and Hellström (2000) performed a detailed energy simulation for a solar heated BTES system. The system was designed to serve 90 building units of 100 m^2 each using a 3,000 m^2 roof-mounted solar collection system and a 99 borehole BTES system of 65 m depth for a storage volume of 60,000 m^3. It was estimated that 60 % of the total heat demand would be met by the system. The construction cost, including heat exchanger installations in buildings (which can range from $1,000 to $10,000), and annual operation expenses were then compared with two conventional alternate systems—a small-scale, biomass pellet and oil DE system, and a GSHP system for each building. A summary of his findings can be seen in Table 3.3, showing that the DE system has the lowest construction cost, but also the highest annual cost. The solar heated BTES has the highest initial cost, but has an annual cost only 8 % higher than the least expensive annual option of GSHP (annual DE costs are 20 % above GSHP). This example illustrates that although UTES systems do cost more than some alternatives, they provide long-term stability of energy pricing into the future and should be considered for future projects.

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Chapter 4
Aquifer Thermal Energy Storage

4.1 Definition

In general, groundwater temperatures remain relatively stable at temperatures typically 1–2 °C higher than local mean annual temperatures between depths of 10–20 m. Below these depths, groundwater temperatures gradually increase at a rate of geothermal gradient. As a result, in areas where a supply of groundwater is readily available from an aquifer, a reliable source of low temperature geothermal energy exists.

Open-loop geothermal systems use this resource by extracting groundwater from an aquifer using a water well, and passing it across a heat exchanger to allow transfer of energy for direct use in the HVAC system of a building, typically in combination with a heat pump. The majority of open-loop systems subsequently dispose of the used groundwater either by discharging to a surface water body or reinjecting into the aquifer. These types of open-loop systems, known as pump-and-release or pump-and-dump systems, are relatively simple to implement. For commercial or institutional applications, they offer energy efficiencies comparable to closed-loop systems at substantially reduced capital costs (Bridger and Allen 2005).

In the open-loop systems, energy is typically transferred to and from the building's heating and cooling system via a heat exchanger. Conversely, closed-loop systems exchange energy directly in the ground using ground heat exchanges, which are commonly installed in adapted trenches at relatively shallow depth or in vertical boreholes. Other variations allow for the transfer of energy through heat exchanger pipe work installed in foundation structures (Dickinson et al. 2009).

It is useful to understand a difference between higher and lower enthalpy systems. Higher enthalpy systems take advantage of higher temperature geothermal resource generated from a heat flux originating from decaying radioactive isotopes of uranium, potassium, and thorium in the deeper formation of the earth's crust. Lower enthalpy systems utilize the net solar energy absorbed and stored in the subsurface. In the lower enthalpy systems, the groundwater temperature near

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the surface is inherently associated to the surface temperatures throughout the year. There are seasonal fluctuations in temperatures within a few meters below ground surface. This effect is reduced with greater depth, so the prevailing temperature gradient relating to the thermal flux.

Open-loop systems are a particular type of low temperature geothermal system. A particular type of open-loop system using aquifers for energy storage, is referred as aquifer thermal energy storage (ATES) systems. Aquifer thermal energy storage is an approach used to enhance the efficiency in comparison with other ground energy system. ATES installation actively store cooled and heated groundwater in the ground from respective heating and cooling mode cycles (Dickinson et al. 2009).

Goundwater is used to transfer the thermal energy into and out of an aquifer in ATES systems. ATES systems utilize aquifers for the storage of low-grade thermal energy such as solar heat or waste heat during off-peak periods. The low-grade energy is used to heat or chill water which is injected into an aquifer for storage. Later, the water is withdrawn for space heating or cooling during a period of high demand.

Water wells are used for the connection to the aquifer. However, these wells are normally designed with double functions, both as production and infiltration wells, as shown in Fig. 4.1 (Andersson 2007). The energy is partly stored in the groundwater itself but partly also in the grains (or rocks mass) forming the aquifer. The storage process in the rocks mass takes place when the groundwater is passing the grains and will lead to the development of a thermal front with different temperatures. This front will move in a radial direction from the well during charging of the store and then turn back during discharging.

Practically all systems are designed for low temperature applications where both heat and cold are seasonally stored. However, the systems are sometimes also applied for short-term storage.

ATES open-loop systems can offer increased energy efficiency and long-term cost savings over pump and dump systems and closed-loop systems by using an aquifer as a seasonal storage reservoir for waste or excess thermal energy generated in off-peak seasons or periods of low demand such as solar energy in summer months or cold air in winter months. ATES systems are operated by transferring heat or cold mass to or from groundwater through a heat exchanger. The groundwater that is injected back into the aquifer is heated or chilled. The reinjected groundwater may hold a temperature higher or lower than the undisturbed ground temperature, depending on the thermal properties of the ground and flow characteristics of the aquifer. During periods of high heating or cooling demand, water is pumped from the aquifer and used as an energy source or sink.

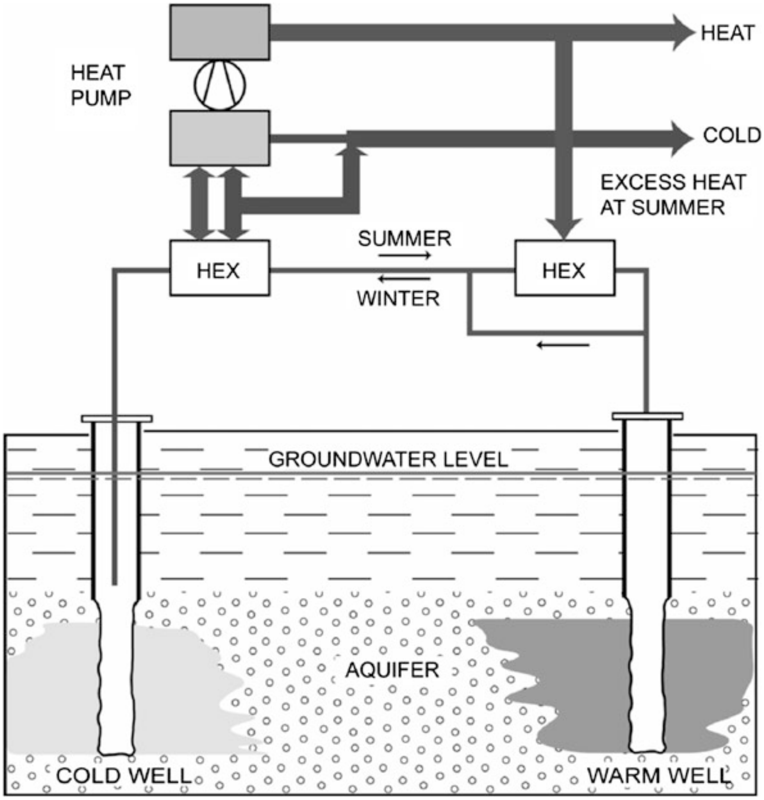

Fig. 4.1 Principal ATES configuration (from Andersson 2007)

4.2 Types of ATES

4.2.1 Operation

Two groups of wells which are hydraulically coupled and separated by a suitable distance are used for ATES purpose (Paksoy et al. 2000). There are two basic principles for aquifer thermal storage: cyclic regime (bidirectional) and continuous regime as illustrated in Fig. 4.2 (Nielsen 2003). A plant can also be made with groups of wells instead of just two single wells.

With a cyclic regime, cold and heat can be stored below/above the natural ground temperature, whereas the continuous regime can only be used where the load can be met with temperatures close to natural (existing) ground temperatures. The storage part is therefore an enhanced recovery of natural ground temperatures. Some pros and cons of the two regimes are:

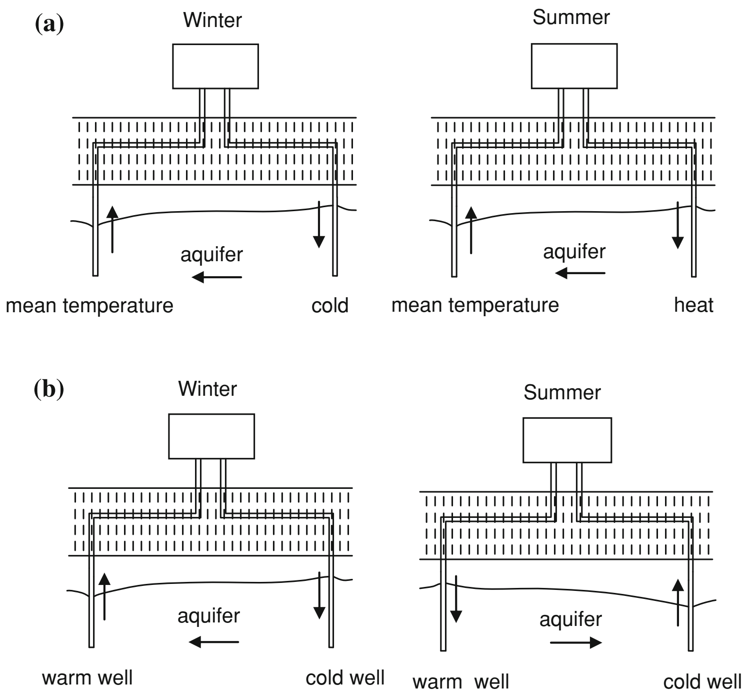

Fig. 4.2 Basic operational regimes for aquifer thermal energy storage (**a**) continuous regime, (**b**) cyclic regime (from Nielsen 2003)

- Cyclic flow will create a definite cold and heat reservoir around each well or group of wells. Cold can be stored around one of the well groups heat can be stored and around the other. Groundwater is pumped from one of the well groups, and then heated or cooled within the building before being injected back into the aquifer in the other well group. The groundwater circuit is closed in the sense that the water is produced from a number of warm wells and then injected through the cold wells at the same flow rate and without being exposed to air. It is possible to maintain a ground volume above or below the natural ground temperature all the time. One disadvantage is a more complicated well design and control system with each well being able to both produce and inject groundwater.
- Continuous flow is simpler with regard to system design and well control, and only one well or group of well need to be equipped with pumps. The disadvantage is the limited temperature range.

4.2.2 Form of Energy

On the basis of the form of energy being stored, three main types of ATES systems can be defined. These are chilled water storage systems (or cold storage), heat storage systems, and integrated heat and cold storage systems.

Cold storage involves the injection, storage, and recovery of chilled (or cold) water at temperatures between 6 and 12 °C in a suitable storage aquifer for storage periods from several hours to several months. One or more wells are used depending on energy requirements and the properties of the aquifer.

Applications of cold storage include primarily air conditioning and equipment cooling in institutional and commercial buildings, and industrial process cooling. These systems are best applied when a demand for cooling exists for significant portion of the year. Presently, many cold storage systems operate in Europe and North America, particularly in The Netherlands. The storage efficiency of a cold storage system is equivalent to the amount of energy injected into an aquifer (e.g., energy injected to the aquifer while cooling a building) divided by the amount of energy taken from an aquifer (e.g., energy rejected from the aquifer using a fluid cooler to passively refrigerate the aquifer during cold spells). It should be calculated over an entire charge/discharge cycle where the aquifer reaches the same bulk temperature at the end of each cycle, which is ideal for environmental sustainability considerations. It can reach 70–100 % for most long-term cold storage projects. The cold storage efficiency decreases as the heat transfer from the surroundings to the storage aquifer increases.

Heat storage involves the injection, storage, and recovery of heated water in a suitable storage aquifer. Heat storage systems can be classified on the basis of low to moderate temperature heat (10–40 °C) or high temperature heat (40–150 °C). The components, well configurations, and storage periods of heat storage ATES systems are similar to cold storage systems. Applications of aquifer heat storage exist in space heating, industrial heating, heating for agricultural purposes (e.g., greenhouses), and roadway de-icing and snow-melting. Because convective heat losses (buoyancy effects) are greater for heat storage than for cold storage, the storage efficiency is typically less than that of cold storage and ranges from 50 to 80 %.

To counter the effects of higher heat losses due to convection currents, the storage wells for high temperature heat storage are preferably drilled to greater depths. This minimizes heat losses by using the overburden formation above the storage aquifer as an insulator between the warm aquifer and the cooler ambient air, and by choosing a storage medium that is surrounded by warmer materials due to the geothermal gradient, thereby reducing losses.

Integrated or combined heat and cold ATES systems may offer an improved efficiency over cold- or heat-only storage systems, particularly in large-scale applications. These systems are most commonly used in combination with a heat pump to provide heating and cooling in commercial or institutional buildings.

The components of combined systems are virtually the same as for cold or warm mass storage alone. However, the design of above-ground and below-ground components of integrated systems is more complicated. For underground components, the positioning of the wells become more important as the aquifer is used as a heat source or sink. Specifically, storage of warm and cold mass results in the development of thermal plumes around the wells and there is increased risk of heat transfer between them.

From an economic perspective, integrated ATES systems for combined space heating/cooling applications using a heat pump, with no other sources of waste heat or chilled water, may be more sensitive to costs associated with aquifer characterization and other design costs compared to ATES systems with higher grade waste heat sources. In smaller applications, it will be challenging to rely on a relatively small increase in heat pump coefficient of performance (COP) to generate sufficiently attractive returns on the incremental capital investment. The increased complexity of the system, in addition to the effort for aquifer characterization, may add significant cost to the project. In the cooling mode application of an integrated ATES system, an opportunity may exist for direct cooling (without the use of a heat pump) where direct cooling might otherwise not be possible. In this case, substantial energy savings could result.

COP is the classic parameter that has been used to describe the performance of a heat pump. A simple definition of the coefficient of performance adequate for our purposes is The COP is a dimensionless parameter on which upper bounds can be found using the laws of thermodynamics. It is common in the U.S. air-conditioning industry to report the cooling performance in terms of what is called the "energy efficiency ratio" or EER. The EER is not a dimensionless parameter, as the energy input rate is in watts and the output thermal effect is in Btu/h. The EER can be readily determined by multiplying the COP by 3.413. While COPs will vary, depending on the quality of the heat pump unit and its operating conditions, in the heating mode, COPs in the range of 3–4.5 can be expected for GSHPs. In the cooling mode, performance will generally be lower; a net COP of 2–3.5 can be expected when the heat load within the conditioned space that is generated by the fans, compressors, and parasitics is subtracted from the gross cooling effect. When comparing GSHP system performance to conventional system performance the designer must be careful to also include all the parasitic losses of the conventional systems if a legitimate comparison is to be achieved (Phetteplace 2007).

4.3 Aquifer and Groundwater

4.3.1 Aquifer

To be able to construct an ATES systems a suitable aquifer has to at hand at or close to the site where the ATES user is located. As explained in Chap. 2, "aquifer" is defined as a geologic formation that contains sufficient saturated permeable material to yield economical quantities of water to wells and springs. An aquifer is in practice defined to be a geological formation from which groundwater can be pumped by using water wells.

Groundwater refers to subsurface water found beneath the water table in the void spaces of unconsolidated (i.e., sands and gravels) and consolidated (i.e., sandstone and volcanic rocks) geologic formations. A groundwater aquifer exists in geologic formations which are sufficiently permeable to store and yield large quantities of groundwater.

By definition groundwater can be found almost anywhere. The groundwater table is defined as the level under which all pores or fractures are water saturated. Above the water table lies the unsaturated zone, where voids between rocks are mostly filled with air. Some water is held in the unsaturated zone by molecular attraction, and it will not flow toward or enter a well. In the saturated zone, which lies below the water table, all the openings in the rocks are full of water that may move through the aquifer to streams, springs, or wells from which water is being withdrawn.

There are two major types of aquifers. If the groundwater stands in direct contact with the atmosphere, the aquifer is regarded as unconfined. If, on the other hand a permeable formation below the groundwater table is covered by a less permeable layer, the aquifer is regarded as confined.

The confined type of aquifer has a hydraulic pressure (static head) that is on a higher level than the top of the aquifer. This artesian pressure can sometimes reach above the surface level resulting in self-flowing wells or artesian wells. In nature, the groundwater is a part of the hydrological cycle. Hence, groundwater is naturally recharged and drained. Sometimes the draining is shown up as springs, but more common it flows out to a lake or a river.

4.3.2 Aquifer Properties

To determine the suitability of an aquifer for thermal energy storage, a characterization of the aquifer must be performed. Aquifer characterization for an ATES project usually involves a detailed assessment of the aquifer in terms of its geology, physical properties, flow characteristics, and water chemistry. These characteristics are similar to those assessed for most environmental investigations or water supply studies.

Any ATES application will require a good knowledge on the properties of the aquifer being the target to use (Andersson 2007). The most important properties for ATES application include geometry (surface area and thickness), stratigraphy (different layers of strata), static head (groundwater or pressure level), groundwater table gradient (natural flow direction), hydraulic conductivity (permeability), transmissivity (hydraulic conductivity × thickness), storage coefficient (yield as a function of volume), leakage factor (vertical leakage to the aquifer), and boundary conditions (surrounding limits, positive or negative). The first four items are studied by using topographical, geological and hydrogeological maps and descriptions, data from existing wells and older site investigations. The latter ones may contain geophysical data as well as pumping tests and so forth. Any information on groundwater chemistry is of importance as well as information of the natural groundwater temperature (Bridger and Allen 2005)

4.3.2.1 Geology and Aquifer Thickness

The physical makeup of the sediments or rocks and depth, aerial extent, and thickness of permeable and impermeable geological units both at a regional scale and locally at the proposed ATES site, are important factors in determining the nature and distribution of aquifers in the subsurface. The majority of thermal storage projects use unconsolidated aquifers as storage media. However, unfractured and highly fractured bedrock aquifers also can be used for thermal energy storage. In these aquifers, the mapping of structural features, such as fractures and faults that strongly influence fluid flow, will be also important.

4.3.2.2 Hydraulic Properties and Groundwater Flow

The effective porosity and the hydraulic properties such as hydraulic conductivity and specific storage are important to the design and evaluation of ATES systems. The effective porosity refers to the system of interconnected void space in the porous aquifer media. It is important in determining the amount of heated or chilled water that can be stored per unit volume of the aquifer.

The hydraulic conductivity is a measure of the ability of the porous medium to transmit water. High hydraulic conductivities are required for large flow rates of water to be withdrawn or injected from or to the aquifer with the least change to the hydraulic and temperature gradients around the production wells. Specific storage is a measure of the water storage capacity of an aquifer and is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head. These properties, along with the hydraulic gradient, control the velocity, and direction of groundwater flow or the flow regime in an aquifer.

4.3.2.3 Thermal Properties and Ground Temperature Field

The physical processes of conduction and convection govern the transport and storage of heat in an aquifer. Conductive heat transport refers to the movement of heat along a thermal gradient. Convective heat transport refers to the movement of heat by flowing groundwater. In an ATES system, conductive heat transport occurs due to the temperature gradients induced by warmer or cooler storage water coming into contact with the surrounding aquifer water. The conduction of heat in the aquifer is governed by the thermal properties of aquifer such as the volumetric heat capacity and the effective thermal conductivity. Heat capacity indicates the amount of temperature change that occurs when the aquifer media absorbs or loses a specific amount of energy and thermal conductivity represents the ability of the aquifer media to transmit heat. Since water has a higher heat capacity but lower thermal conductivity than rock, the storage of thermal energy in aquifers is best suited to a high porosity formation to minimize conductive energy losses and increase the efficiency of the thermal store.

Convective heat transport results from groundwater flow driven by hydraulic head and temperature differentials, which exist both locally in the vicinity of the well field as a result of pumping/injection of groundwater and regionally within the aquifer. Convective heat transport has both advective and dispersive components.

Advection describes the movement of thermal energy directly due to the average linear flow of groundwater through the porous medium. Thermal dispersion refers to the microscopic dispersal or spreading of thermal energy in three dimensions beyond the regions it normally would occupy as a result of advection alone. Dispersion can be regarded as a zone of mixing, which travels in advance of the thermal energy front defined by advection. In addition, free convection also occurs when groundwater movement is driven by density variations due to temperature gradients. In high temperature ATES systems, the effects of free convection will become important, as the thermal energy will rise due to a lowered density of the heated water. In lower temperature ATES systems, including heat storage and cold storage, the density differences between the stored water and the ambient groundwater will be small enough so that free convection is limited.

Regional groundwater flow is an important consideration in the design of ATES systems as higher groundwater flow regimes can lead to advection or down-gradient ‘drift’ of stored energy beyond potential recovery regions. In the presence of a steep regional gradient in hydraulic head, which would correspond to faster groundwater flows, a lower permeability aquifer is required to minimize convective losses (dispersion reduces the thermal intensity of the recovered plume). In addition, small-scale vertical and horizontal variations in hydraulic conductivity or heterogeneity in the aquifer that result from changes in geology are important, as these will affect the dispersion of the thermal plume.

4.3.2.4 Groundwater Chemistry

The chemistry of aquifers often represents a significant problem in the design of ATES systems. The primary problems related to groundwater chemistry include (1) the scaling of heat exchangers and clogging of wells resulting from the precipitation of minerals such as calcium carbonate and iron or manganese oxides, (2) the corrosion of piping and heat exchangers by ambient and heated groundwater, (3) biofouling of the well intake area; and (4) the clogging of the aquifer as a result of precipitation of minerals within the aquifer or the transport of precipitates into the aquifer.

These problems are avoidable if consideration of the potential for geochemistry problems is considered in advance of the system design phase. Many design strategies and water treatment technologies have been used to mitigate these problems.

4.3.3 Aquifer Characterization

Aquifer characterization for an ATES project typically involves phases of desktop review, drilling, hydraulic testing, and modeling, although the level of complexity of these characterization steps can vary considerably depending on how much information is known about the local geology/hydrogeology and how large the ATES system will be.

A simple review can be performed as a preliminary data gathering or prefeasibility study step to determine whether an ATES system is feasible. If the area is well developed and much is known already about the hydrogeology of the area, then geological/hydrogeological investigative costs can be kept to a minimum. In unexplored areas, more effort may be needed.

In a prefeasibility study, information regarding the site geology and groundwater potential often can be obtained from various sources such as existing nearby water wells, previous hydrogeological investigations, aerial photographs, topographic and geologic maps. If there is a suitable aquifer being capable of yielding the amount of water required for the project, one need to determine the number of wells needed to meet the demand, bearing in mind peak demand, average demand, and the fact that injection wells are often less efficient at receiving water. Ultimately, a well (or wells) will have to be hydraulically tested to ensure that they are capable of producing and receiving water. The spacing of the wells only can be estimated by a hydrogeologist in a preliminary sense. A decision then can be made concerning space availability, piping costs, etc.

If the prefeasibility study suggests that ATES is feasible, then a preliminary test well should be drilled to confirm the information collected to that point. It is not recommended that an expensive production size well be drilled initially, particularly if large diameter wells are needed. A test well can later be over-drilled to a production diameter. Logging of borehole cuttings/sediments should be undertaken to verify the geology, and identify permeable zones and target aquifers. In unconsolidated aquifers, grain size analyses should be performed on these sediments to select an appropriate slot size for a well screen. Sampling and analysis of groundwater should be carried out to assess groundwater chemistry.

To determine the hydraulic properties of the aquifer, and to assess the response of the aquifer to pumping and injection during operation of the ATES system, hydraulic testing of the aquifer should follow test drilling. Constant discharge pumping tests, step-injection tests, step-drawdown tests, and tracer tests are examples of tests performed for ATES aquifer characterization, although not all of these need to be done. Thermal conductivity can be calculated using values for known minerals and porosity, measured in a laboratory using either a needle probe (sediments) or divided bar apparatus (rock core or chips), or measured in situ using a formation thermal conductivity testing unit.

For borehole thermal energy storage (BTES) systems, in situ measurements of thermal conductivity should be conducted because these systems rely solely on conductive heat transport. In cases where thermal conductivity is high, the length of the loop can be shortened leading to lower costs for installation of the system. For ATES systems, thermal conductivity can be estimated because heat conduction is not significant. Therefore, the additional expense to perform an in situ thermal conductivity test would not have as significant a payback as for a closed-loop borehole system. The volumetric heat capacity typically is calculated.

For larger systems, borehole geophysical logging is very useful for identifying geologic units and permeable zones, particularly fractures in the bedrock, and to determine the temperature-depth profile in the aquifer. A monitoring well network, installed around the production wells and in background areas, can be used to determine the hydraulic gradient and direction of groundwater flow at the site. Later, they can be used to monitor the movement of the thermal front during operation of the system. Maps showing temperature isotherms, lines of equal temperature, of the thermal plume subsequently can be produced.

The geologic and hydraulic data collected from desktop studies, site investigations, and aquifer testing subsequently can be input into simulation models that can predict the movement of the thermal plume and calculate the heat balance of the thermal energy store. These thermo-hydraulic codes provide either analytical or numerical solutions to heat transport and storage problems posed by ATES systems. Complex three-dimensional models, combining groundwater and heat flow within the aquifer and heat conduction to surrounding layers, can be used to calculate the temperature of the water recovered from the store.

4.3.4 Groundwater Chemistry

The chemical composition of the groundwater is of extreme importance when it comes to the design of any ATES system. It may be related to the potential risks for functional problems with wells and other components in the system.

The most common technical problem is clogging of wells. Clogging is defined as an increased flow resistance for water to enter the well (or be disposed through the well). The clogging process normally gets more evident with time and will result in a lower well capacity. Clogging can easily be traced and dealt with in an early stage by monitoring flow rates and drawdown as shown in Fig. 4.3 (Andersson 2007).

The figure illustration shows occurrence of clogging by plotting data from an observation well (OW) and compare that to the production well (PW). In this case, the production well shows a decreased specific capacity while the observation well shows a steady level versus time. This observation reveals that the resistance for water to enter the production well is increasing. The increased resistance will

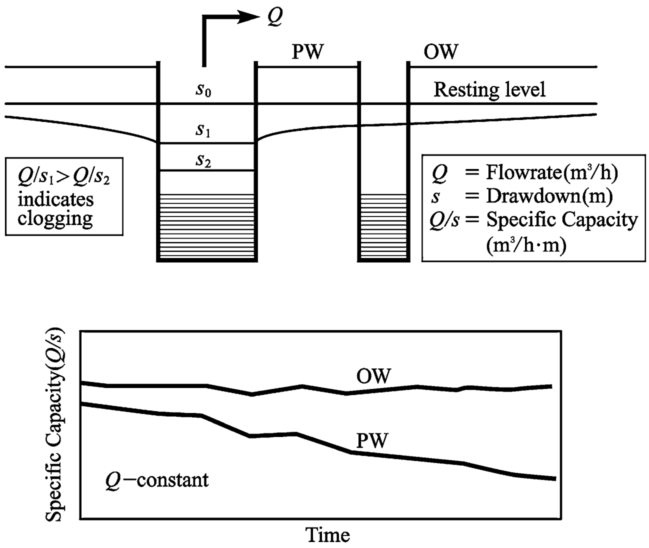

Fig. 4.3 Detection of clogging by using a monitoring program in an early stage (from Andersson 2007)

lower the drawdown inside the well, while the groundwater table outside the well is kept constant. This will increase the hydraulic gradient between the well and the aquifer and hence maintain a constant flow rate.

"False clogging" sometimes occurs. Such events are either explained by a general lowering of the groundwater table or by failure of the submersible pumps cutting down the flow rate. However, by monitoring both the production wells and the aquifer in observation wells or pipes such events can be excluded as a result of clogging.

4.4 Problems of Aquifer Thermal Energy Storages

4.4.1 Clogging

Scaling is precipitation within the above-ground portion of an ATES system and clogging of wells, gravel pack, adjacent aquifer represents reduced aquifer permeability caused by precipitation within the aquifer. Both are caused by chemical precipitates and has been frequently encountered in existing ATES systems, especially the precipitation of carbonates in the systems operating above 85 °C and Fe and Mn oxides in low temperature (<40 °C) systems (Jenne et al. 1992).

The precipitation of Fe and Mn oxides is caused by a change in water chemistry. Precipitation of Fe III oxides can be induced by increasing either the redox potential (Eh) or the pH. As illustrated in the Fe stability field diagram shown in Fig. 4.4, if either the Eh or pH of slightly reduced water (point A in the diagram) is increased, precipitation of Fe oxides is likely. Not shown on this figure is the effect of Fe concentration; as Fe concentration increases, its oxide will precipitate at progressively lower Eh and pH values. In practice, there are at least three processes involved to create the Eh and pH changes. Those are (1) oxygen is added from some source and the Eh value is increased (displacement from *A* to *B* in Fig. 4.4); (2) waters differing in their Eh status are mixed upon entering the well causing either an increase or decrease in Eh and possibly pH (*A* to *B* or *B* to *A*); or (3) carbon dioxide escapes from the water, increasing the pH-value (*A* to *C*). The latter process is also believed to be one of the main factors causing the precipitation of carbonates in a well with little or no scaling in the heat exchanger. Where there are significant Fe concentrations, Fe carbonate rather than Ca carbonate may precipitate. The Fe carbonate precipitate is not readily solubilized by acid treatment of the well.

Shallow, unconfined aquifers generally have levels of Fe and Mn that are likely to yield oxyhydroxide precipitates if air is allowed to enter the ATES system. An air leak in the ATES system caused Fe and Mn scaling of the well screen.

However, none of the processes causing Fe oxide precipitation need occur during injection if the system is airtight, and the aquifer is selected or the hydrology is controlled to eliminate the mixing of dissimilar waters near the well. For these reasons, the likelihood of Fe oxide clogging during injection is low in a properly designed system. If for any reason an airtight system is not feasible, any one of a number of iron removal methods may be used.

Clogging by biofilm or microbial slime is a well-known phenomenon in the water-well industry. The most frequent biologically caused well clogging is that associated with iron bacteria, especially the ones belonging to the Gallionella family. However, in a highly reduced environment, clogging can also be associated with sulfur bacteria. In ATES applications, clogging by iron bacteria slime will is a potential risk mainly in low-temperature systems (less than 25 °C) and in waters with an iron content of at least 1 mg/L. Other conditions that favor major bacterial growth are Eh values between 200 and 400 mV and pH values between 5.5 and 7.5.

Gas clogging may occur as a result of the exsolution of gases present in excess of the amount that would be present at equilibrium with air at atmospheric pressure.

Swelling and dispersion of clays contained within the aquifer sediment occurs when the Na saturation exceeds an amount determined by the ionic strength (i.e., conductivity) of the water. Clay swelling and dispersion are unlikely to pose a problem in consolidated or silica-cemented aquifers even when the water is passed through a Na ion exchanger repetitively. Clay swelling and/or dispersion has been avoided by treating the minimum fraction of the water necessary to prevent carbonate scaling; no scaling is observed at a calcite saturation indices of 0.6–0.7.

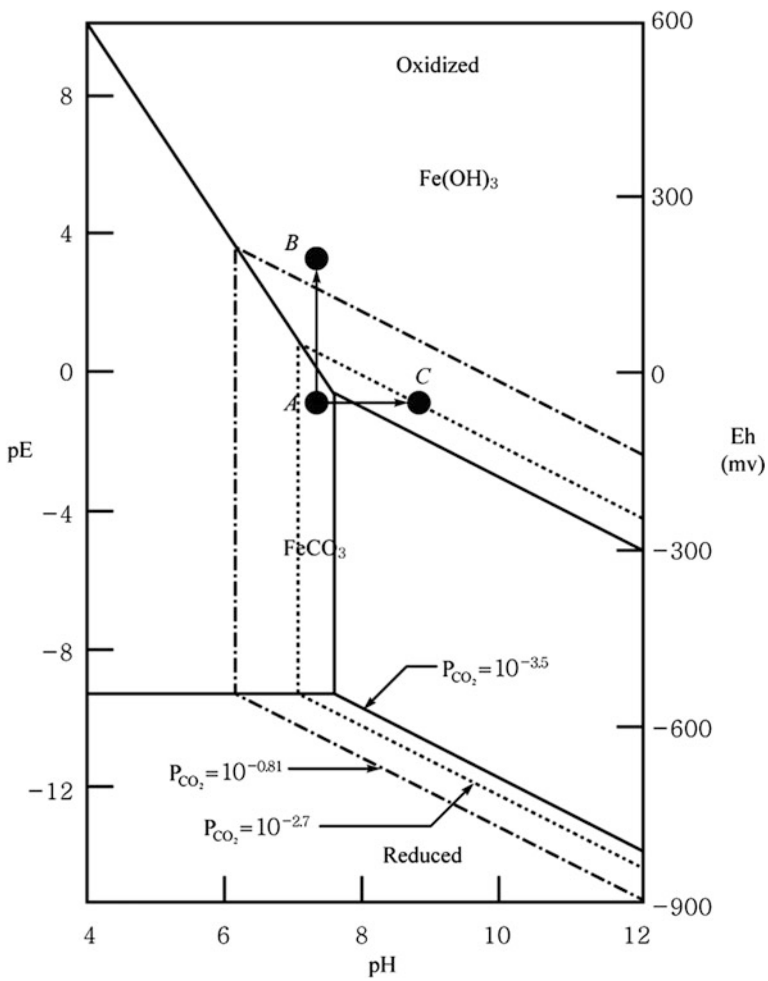

Fig. 4.4 A portion of the Eh (or pE) versus pH stability field for iron illustrating the likely precipitation of ferric hydroxide and/or ferrous carbonate (siderite) as result of a change in Eh or pH ($a_{Fe} = 10^{-4}$ M, temperature = 25 °C; redrawn from Jenne et al. 1992)

The amount of suspended sediment may have been increased by the use of foreign water (i.e., local surface water) into the aquifer and/or the inadequacy of the gravel pack.

Research makes clear that clogging of recharge wells (ATES and ASR) by suspended solids is very common and, despite advances in infiltration well technology, remains a key determinant of infiltration well performance. The clogging potential of suspended solids in water is not just a function of concentration, but also of particle size and composition. Since 2000 in the Netherlands the MFI is used to estimate the clogging potential of water that has to be infiltrated using recharge wells (Buik and Snijders 2006). The MFI gives no detailed information about each individual particle, instead it gives a direct value of the clogging potential of the water. In 2000, a quantitative relation between clogging rate and MFI was developed. In the years between 2000 and 2005, the relation was used to design over 250 ATES systems. During these years the relation has proven itself as reliable and as a useful tool to predict clogging rates of recharge wells satisfactory, especially considering the uncertainties in measured parameters like MFI and permeability. Further an easy, cheap (fast) and reliable apparatus was developed to measure the MFI of the water that has to be infiltrated.

Clogging caused by both straining and physical–chemical filtration can be described by the following equation:

$$\Delta h_v = \left(\frac{1}{\rho_w g}\right)\left(\frac{c\mu_d}{K_c}\right)v^2 t \tag{4.1}$$

where Δh_v = increment of pressure caused by clogging (m_w); ρ_w = density of the infiltrated water (kg/m^3); g = gravity acceleration (m/s^2); c = concentration of suspended matter in the infiltration water (kg/m^3); μ_d = dynamic viscosity (Ns/m^2); K_c = intrinsic hydraulic conductivity of the filter cake on the borehole wall (m^2); v = infiltration rate on the borehole wall (m/s); t = infiltration time (s).

One of the best parameters to predict the clogging potential of infiltration water, is the MFI. The MFI is a variation of the Silting Index (SI) and Silt Density Index (SDI). Both indices were developed to characterize the fouling potential of reverse osmosis feed water on RO membranes. The SI and the SDI have week theoretical foundations and do not vary linearly with the concentration of colloidal and suspended solids in water. The MFI, on the other hand, has a strong theoretical foundation and exhibits a linear correlation with the concentration of colloidal and suspended solids in water.

The MFI is equal to the slope of the line that describes the inverse of the flow rate versus the amount of water that passes a membrane filter with 0.45 μm pores under a constant pressure drop for standard conditions and can be described with Eq. (4.2):

$$\mathrm{MFI} = \frac{\mu_d}{2pA_f^2}\frac{c}{K_c} \tag{4.2}$$

where MFI = membrane filter index (s/l^2); p = pressure loss (N/m^2); A_f = area of the filter (m^2).

If an MFI of 1 s/l^2 is directly translated [with Eqs. (4.1 and 4.2)] into a clogging rate for an infiltration well under standard conditions ($A_f = 1.38 \times 10^{-3}$ m^2 for a standard membrane filter; $p = 2 \times 10^5$ Pa; $\mu_d = 1.3 \times 10^{-3}$ Ns/m^2 and $v = 1$ m/h on the borehole wall, a 'common' value for infiltration wells), the calculated clogging rate of more than 2,000 m/y is not compatible with measured clogging rates of around 0.1 m/y in the field. This demonstrates that a clogging rate derived using a filter with a pore size of 0.45 μm cannot be translated directly into a clogging rate for an infiltration well. The calculated clogging rates were found to be more compatible to clogging rates for water flood wells in oil fields. The difference was attributed to the fact that the pore size of the receiving formation in an oil field is closer to that of the MFI-membrane than the pore size in groundwater environments.

The MFI measured with a standard membrane filter can now be translated into an MFI that is valid for other pore sizes.

$$\mathrm{MFI_{cor}} = \mathrm{MFI_{mea}} \frac{A_{fp}}{A_p} \tag{4.3}$$

where $\mathrm{MFI_{cor}}$ = corrected MFI; $\mathrm{MFI_{mea}}$ = measured MFI; A_{fp} = area of a pore of the applied filter; A_p = area of a pore for which the MFI must be corrected.

To calculate the ratio between the pore size of the aquifer and the pore size of the filter, it is necessary to estimate the pore size of the aquifer. The effective pore size is about a sixth of the median grain size of the sand (D_{50}).

In an aquifer with a D_{50} of 300 μm the effective pore size is then about 50 μm. A measured MFI of 1 s/l^2 (pore size 0.45 μm) will give a corrected MFI of 8.1×10^{-5} s/l^2 (Eq. 4.3). The calculated clogging rate (for an MFI of 1 s/l^2 and v = 1 m/h) is now about 0.20 m/y, which is a realistic value.

Equations (4.1, 4.2 and 4.3) can be combined and rewritten as:

$$\frac{\Delta h}{t} = \frac{2\mathrm{MFI_{mea}} p A_f^2}{\rho_w g} \frac{t}{t_o} \frac{\mu}{\mu_o} \frac{A_{fp}}{A_p} v^2 \tag{4.4}$$

The ratios $\frac{t}{t_o}$ and $\frac{\mu}{\mu_o}$ are added to make corrections for the amount of equivalent full load hours per year ($t_o = 8,760\,\mathrm{h}$) and temperature influences (μ_o = viscosity at 10 °C), and the ratio $\frac{A_{fp}}{A_p}$ is added to translate a measured MFI to an MFI for the aquifer.

For practical use the D_{50} is translated into hydraulic conductivity K;

$$K = 150\left(D_{50} 10^3\right)^{1.65} \tag{4.5}$$

with D_{50} in m and K in m/d. Equation 4.5 can be rewritten as:

$$D_{50} = 10^{-3} \left(\frac{K}{150}\right)^{0.6} \tag{4.6}$$

If the standard circumstances for the MFI measurement are substituted in 4.5, the equation can be simplified and rewritten to (t is replaced by u_{eq} and $\frac{\Delta h_v}{t}$ is replaced by v_v i.e. the clogging rate):

$$v_v = 2 \times 10^{-6}\, \mathrm{MFI_{mea}} u_{\mathrm{eq}} \frac{v_b^2}{\left(\frac{K}{150}\right)^{1.2}} \tag{4.7}$$

where u_{eq} = amount of equivalent full load hours per year (h) (m^3 infiltrated per year divided by max. flow rate in (m^3/h)); v_v = clogging rate (mw/y); v_b = infiltration rate on the borehole wall (m/h).

The water that is infiltrated will not be distributed equally over the height of the aquifer but it is divided over the well screen in relation to the hydraulic conductivity of the aquifer. This means that layers with a high hydraulic conductivity are receiving more water than layers with a low hydraulic conductivity. The infiltration rate in layers with a high hydraulic conductivity is therefore higher than in layers with a low hydraulic conductivity, and because the clogging rate is quadratically related to the infiltration rate (and linear to the MFI), these layers with a high hydraulic conductivity will clog faster than layers with a low hydraulic conductivity.

4.4.2 Corrosion

Both chemical and electrochemical corrosions may occur in ATES systems. Chemical corrosion is induced by constituents, such as CO_2, O_2, H_2S, dissolved sulfide, chloride, and sulfate. Corrosion was also experienced when a pipe connection was not sufficiently tight and allowed a small amount of air to diffuse through the threaded joint and react with reduced groundwater. Electrochemical corrosion appears to be more frequent than chemical corrosion. Electrochemical corrosion is caused mainly by joining metals with different electrochemical potentials but electrochemical corrosion also occurs on monometallic components that have been stressed, e.g., welded joints, cut surfaces, or damaged coatings. Further, it seems that electrochemical corrosion causes loss of material only on parts of well screens and casings. Usually it occurs in water that is slightly acidic and with total dissolved solids greater than about 1,000 mg/L.

Protection against corrosion is in most cases dependent upon the choice of materials for each specific system. For instance, different steel alloys may cope with expected corrosion, as well as plastic materials, ceramics, or corrosion-resistant coatings. A world-wide method for galvanic corrosion protection of wells is to use a cathodic protection system, normally accomplished by connecting a sacrificial anode to the well casing.

4.4.3 Other Problems

Some of the problems and future issues with ATES may include:

- Interference between wells, especially between group of "warm" wells and group of "cold" wells. Detailed investigation, calculation, and simulation should be conducted to establish the optimal well density, interval, and interactions before the practical implementation. Some of simulation programs can be used to predict the spread of thermal fonts under different well plannings.

- Better combination of heat pump and ATES. It is better to find the optimal ways to combine heat pumps and ATES, because different combination methods will influence the design value of warm/cold well temperature and heating/cooling effect of the whole system. Furthermore, it is very useful and significant to investigate the compatibility between ATES, heat pumps, and the whole distribution system. Their individual viable and vulnerable features need to be checked when the other components fail. For example, for the ATES heating system in Rostock introduced in (Bauer et al. 2010), the failure of heat pumps lead directly to the poor performance of ATES after 2006. If this problem can be solved, ATES will be more desirable.
- Currently, very few researches are focusing on the environmental impact of ATES to the surrounding aquifer and soil layers, such as (1) influences of the increased or decreased temperatures around the warm or cold wells on the local biological communities, (2) influences of the varied temperatures on the chemistry composition and properties of the local aquifer water, and (3) influences of the varied temperatures and the well operations on the geological structures of the local soils. All these questions are lacking enough investigations, simulations, research and references.

4.5 Construction of ATES

Construction of ATES is summarized by AEE Institute for Sustainable Technologies (2006). Aquifers are below-ground widely distributed and water filled permeable formations with high hydraulic conductivity, such as sand, gravel, sandstone, or limestone layers. If there are impervious layers above and below and no or only limited natural groundwater flow, they can be used for thermal energy storage. In this case, two wells or groups of wells are drilled into the aquifer formation and served for extraction or injection of groundwater. As seen in Fig. 4.5, cold groundwater is extracted from the cold well during charging periods, heated up by the heat source (e.g. solar or waste heat), and injected into the warm well. In discharging-periods the flow direction is reversed. Warm water is extracted from the warm well, cooled down by the heat sink, and injected into the cold well. Because of the different flow direction during each flow period, both wells are equipped with pumps, production, and injection pipes.

Because the storage volume of an ATES cannot be thermally insulated against the surroundings, heat storage at high temperatures (above 50 °C) is normally only efficient for large storage volumes (more than 20,000 m^3) with a favorable surface to volume ratio. However, for low temperature or cooling applications also smaller storages can be feasible.

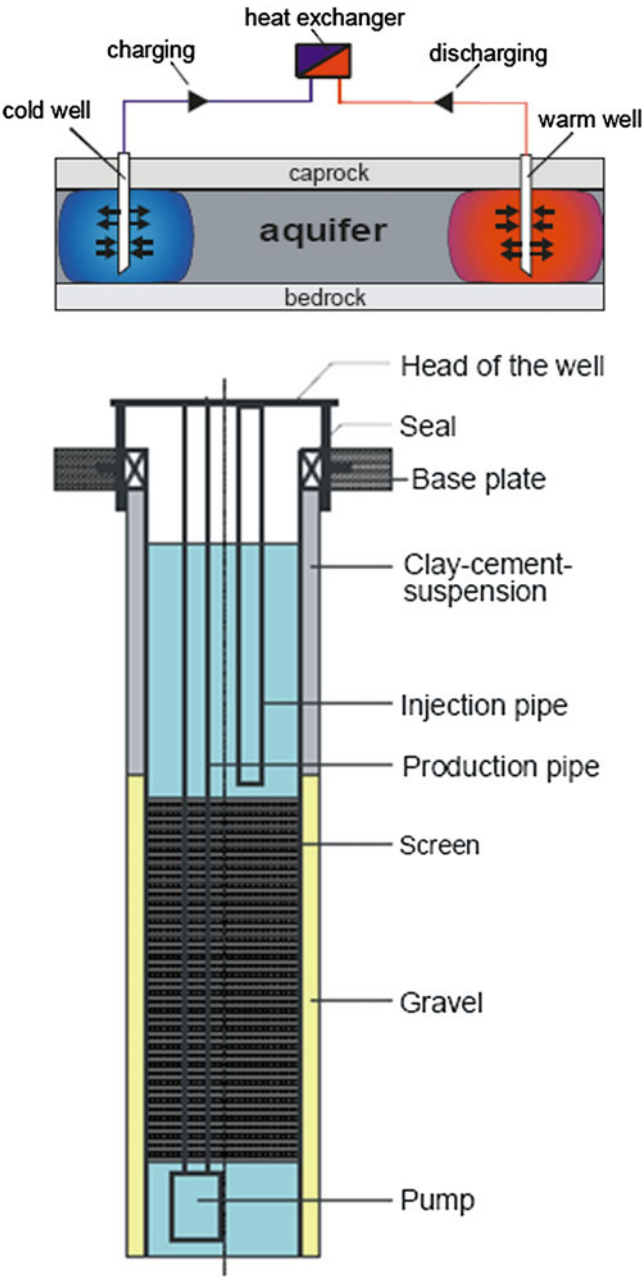

Fig. 4.5 Schematics of an Aquifer thermal energy storage (ATES) and layout of a well for charging and discharging (from AEE Institute for Sustainable Technologies 2006)

ATES systems are not as easy to realize as BTES systems, and need more maintenance and pre-investigations, but if the conditions are favorable, payback times are typically short (EU Commission SAVE Programme and Nordic Energy Research 2004). ATES systems cannot be constructed in all geological conditions, and hence they sometimes require extensive pre-investigations, which have to be taken into account and budgeted already from the early design phase. The process of obtaining a permit for installation can be complex and time-consuming for the first plant in the region. Many restrictions in relation to protection of groundwater resources and environmental impact assessment may reduce possibilities. Some ATES plants have shown various kinds of operational problems, most of which can be controlled with simple measures. One major identified problem is clogging of wells. In most cases, the clogging processes can be avoided by a proper design of well and total system.

An ATES system has a high demand on ground conditions at the construction site. A suitable hydrogeology is a prerequisite. The ground properties have a strong effect on feasibility, design, and operation of an ATES system (number and location of wells, production rate, thermal losses, etc.). The hydraulic conductivity K of the aquifer layer is the most important parameter. For a water exchange between aquifer layer and production/injection well, values of $K > 10^{-5}$ m/s are necessary.

According to AEE Institute for Sustainable Technologies (2006), it is not possible to give exact criteria for the feasibility of an ATES system. It depends strongly on the total system concept. The requirements on the aquifer properties from the system side depend on the size of the storage project, which is related to the flow rate that has to be handled and volume of energy that will be stored.

In general the aquifer porosity will govern the volume needed. This will normally be much less for an aquifer with a primary porosity than for an aquifer that mainly consists of fractured rock. The flow rate, that means the volume of water that can be extracted and reinjected from and into the aquifer as a function of time, will be related to the aquifer transmissivity (the hydraulic conductivity times the aquifer thickness). Although there is no transmissivity limit in theory, the limit for primary porosity aquifers is determined by the possibilities to construct functional wells in practice. This limit can be defined as a situation where the dominating grain size is less than 0.06 mm and corresponds to a transmissivity less than 10^{-5} m^2/s. The latter figure may also be relevant for the fractured aquifer type, but in that case without any well-designed restrictions.

Other properties and conditions that have to be considered are:

- stratigraphy (sequence of layers)
- grain size distribution (mainly for primary porosity aquifers)
- structures and fracture distribution (mainly for fractured aquifers)
- aquifer depth and geometry including hydraulic boundaries
- storage coefficient (hydraulic storage capacity)
- leakage factor (vertical hydraulic influence)
- degree of consolidation (hardness)

Table 4.1 Site-specific prerequisites for ATES systems (from EU Commission SAVE Programme and Nordic Energy Research 2004)

Parameter	Small project ($25\ m^3/h$)	Big project ($500\ m^3/h$)
Thickness of confining layer	$d > 5$ m	$d > 20$ m
Thickness of aquifer	$D > 10$ m	$D = 50–100$ m
Transmissivity	$T > 5 \times 10^{-4}\ m^2/s$	$T = 1 \times 10^{-2}$ to $3 \times 10^{-2}\ m^2/s$
Natural groundwater flow	$v < 3$ cm/d	$v < 11$ cm/d
Danger of ground depression	Not relevant	Prefer deep aquifer

- thermal gradient (temperature increases with depth)
- static head (groundwater level)
- natural groundwater flow and direction of flow
- water chemistry

Table 4.1 gives recommendations for values of hydrogeological parameters for small and big ATES systems for the Netherlands. Table 4.2 shows typical general values for ATES systems which are also valid as a general reference for Germany and central Europe.

The suitability of the ground conditions at a specific site has to be evaluated during pre-design step by a geological investigation. In a first step, a ground profile for the interesting range of depths is adequate. If a suitable ground layer is assumed based on this information the hydrogeological parameters like hydraulic conductivity and natural groundwater gradient should be identified by pumping tests.

4.5.1 Design Steps and Permit Procedure

Any ATES realization is a quite complex procedure and has to follow a certain pattern to be properly developed. Typical designing steps are suggested by Andersson (2007).

- prefeasibility studies (to describe the principal issues)
- feasibility study (to identify the technical and economical feasibilities and environmental impact compared to one or several reference systems)
- the first permit applications (local authorities)
- definition of hydrogeological conditions by complementary site investigations and measurements of loads and temperatures, etc.
- evaluation of results and modeling (used for technical, legal, and environmental purposes)
- final design (used for tender documents)
- final permit application (for court procedures)

Table 4.2 Typical values of ATES system for heat storage application (from EU Commission SAVE Programme and Nordic Energy Research 2004)

Flow pumped per well (m^3/h)	10–100	Capacity per well at 25 m^3/h and ΔT = 30 K (kW)	870
Flow re-infiltration per well (m^3/h)	10–75	Min./max. re-infiltration temperature (°C)	3/80
Borehole diameter (mm)	200–600	Transmissivity of aquifer (m^2/s)	10^{-3} to 10^{-4}
Borehole depth (m)	10–300	Typical total cost of ATES storage (€/kW)	100–200

The technical issues are general, but the permit procedure may be different from country to country. However, in most countries the use of groundwater for energy purposes will be restricted and will be an issue for application according to different kind of acts.

4.5.2 Elements of System Design

The basic elements of an ATES system are the source of thermal energy, the delivery system, the aquifer store, and the thermal loads. Paksoy et al. (2009) provided an extensive summary on the each element.

Thermal Loads. The most common application of ATES is cooling buildings. Most large buildings are cooling load dominated even in more northern climates. With very well-designed (green) buildings becoming more common, the reduced heating demand is more substantial than the reduced cooling demand due to interior gains, making the imbalance even greater.

Another common application is heating of buildings. If both heating and cooling are required, systems can be designed for optimal efficiency. The most common applications within the building sector are buildings with long hours of operation, such as hospitals, academic buildings, shopping malls, hotels, multiple family housing, and office buildings which have a high level of utilization. Less common applications are greenhouses and industrial heating and cooling. While small buildings and single family housing might benefit, the problem is that storage volume may be too low resulting in too high a loss factor of seasonal stored energy. In practice, at least a thermal demand of 200 kWt ($\sim$50 tons) is the smallest that can be matched with seasonal thermal storage. More recently thermal utilities which provide thermal energy to small buildings as part of a small district heating/cooling system are expanding the use of seasonal thermal storage.

Thermal Cold Source. The most common thermal source is cold outside air in winter. It is collected by a cooling tower, dry cooler, and/or heat exchanger from fresh air intake on a building. Also common is waste cold water from a heat pump (while generating heat). Less common is cold water from a harbor, ocean, estuary, river, or lake. If chilled water is being stored, for most applications it is optimum to store as cold as possible for direct use. In practice, the minimum is ~5 °C (41 °F). Any lower temperature might result in freezing water.

Thermal Heat Source. The source of heat is most commonly waste heat from heat pumps which are being used to cool in summer months. Less common is waste heat from cogenerators or industrial processes. Another heat source is solar thermal collected in the summer months. Direct application is not as easily achieved since high temperatures are required by the delivery system. In these cases, additional traditional sources are required to boast the temperature such as boilers and heat pumps.

Delivery System. The most effective and efficient HVAC system for ATES is one which separately handles latent and sensible loads during the cooling season. Fresh air intakes for most climates produce a substantial latent cooling load. To effectively reduce the wet bulb temperature of incoming outside air the coolant needs to be below 12 °C. To realize the required wet bulb temperature and utilize the stored thermal energy effectively, a larger heat exchanger than normally applied in the air handling unit is required with a counterflow configuration. A second HEX can utilize the warm water for reheating when needed. This typically results in a discharge temperature of aquifer water at 18 °C.

In any event an air-to-air heat recovery system with both latent and sensible heat recovery reduces the fresh air thermal demand and is typically included in the ATES delivery system design. The sensible heat and cooling demand is often delivered by a radiant system or fan coil. Radiant ceilings are becoming more popular in these cases. In this case, that the ATES system serves both for heating and cooling, the HVAC system often includes heat pumps. In this case, the cooling load is often delivered directly with the heat pump for short peak periods when the ATES system cannot provide the full load.

ATES store. The entire system including the ATES store needs to supply not only the thermal energy for the year but also the peak thermal power. The later criterion cannot always be cost justified. An optimum ATES system can supply the vast majority of thermal energy demand utilizing the ATES store when designed to serve as a thermal base load thermal plant.

The most important aspect of the design of wells is to ensure that surrounding properties are not adversely affected by the ATES store. A careful configuration of wells is required to ensure that the hydraulic head does not extend substantially onto adjacent properties. (e.g., change of hydraulic head not more than 30 cm at the property boundary.) Another requirement is that the temperature change would not reduce the possibility of a neighboring property owner utilizing ATES. (e.g., temperature change not larger than 0.5 °C at the boundary.) Finally, it is critical that there is not a thermal breakthrough between warm (hot) and cold stores over the long-time operation. To achieve these conditions requires a very sophisticated and careful modeling.

The simplest system for ATES cold seasonal thermal storage utilizes a cooling tower (or dry cooler) during the winter months to charge cold wells. The cold aquifer store is then used to directly cool a building or buildings in the summer.

Such a system requires a peaking chiller to supply cold when the ATES system is not adequate.

Optimum Systems. An example of an optimum system is one that delivers heat during the winter at the same time generating cold water as a byproduct. Thus no extra energy is utilized to generate this chilled water.

In the winter, the water source heat pump utilizes 18 °C water stored in the summer operating at a relative high efficiency, delivering the base load heating for the building. In addition, when the outside temperature is below 0 °C, warm ATES water is utilized to preheat incoming fresh air and at the same time the cold water from an eventual dry cooler is stored in the ATES cold wells. When the heating demand cannot be fully supplied by the heat pump then a gas boiler comes on. The amount of gas energy is typically less than 10 % of total energy demand while about 50 % of peak thermal demand. The dry cooler is utilized to make additional cold water when air temperature is below 2 °C.

In the summer operation, the base load cooling is supplied directly by the ATES cold wells to both the building including the fresh air intake. When the cooling load cannot be met by the ATES cold wells the heat pump comes on. Again the ATES cold wells supply the vast majority of the cooling load.

The system is designed to optimize, financially, by trading off peak load from the ATES system with traditional sources for short periods of time-reducing up-front investment with conventional peakers.

4.5.3 Field Investigations

One essential part in developing an ATES project is to perform site investigations. The more knowledge that is obtained of the underground properties, the better basis for design is achieved.

The site investigations will most commonly cover the following procedure:

- geological mapping
- geophysical investigations
- test drillings
- pumping tests

The test drillings will define the stratigraphical units in the area while the geophysics and geological mapping are used for extrapolation of the layers and for definition of geometry.

Test drillings may be a part of the final system and can be looked upon as an early investment in system. However, more commonly they are drilled in a small dimension and do not fit into the final system after design. In these cases, they still can serve as observation wells.

For shallow aquifers in the overburden it is common to drive slim steel pipes that are perforated in the lower meter or so. This method has proven to be an excellent way of taking samples for the design of screened production wells.

Based on the results a conceptual model is created and the hydraulic properties of the aquifer and its surrounding layers are derived from the pumping test. The final outcome will be a geological model that is more or less accurate and that can be used for the final design using simulation models.

To be able to make model simulations, the loads of heat and cold have to be known. For this reason, it is common to perform measurements on how the loads are varied at different outdoor temperatures.

Such investigations that also covers supply and return temperatures in the distribution systems are often done prior to or in parallel with the underground site investigations. The results are key factors as basis for design in order to calculate flow rates and size of the ATES storage.

4.5.4 Model Simulations

Simulations are used for several reasons, but preferably to study how different flow rates and different number and distances between the wells are functioning. The results will then guide the decision where to place the wells and with what flow rate they should be operated.

The outcomes of such simulations are of two kinds, namely

- the hydraulic impact shown as cones of depression and uplift around the wells
- configuration of the thermal front around the wells

4.6 History and Current Status

4.6.1 Belgium

Desmedt and Hoes (2007) and Desmedt et al. (2006) summarized the status of ATES in Belgium. ATES was introduced on the Belgian market since 1995. Since 1998, many companies showed interest in the technology, but this is not translated into a steady increase of realized projects. This is mainly caused by the hydrogeological circumstances. In Belgium, the North-eastern part of the country has very good technical and economical potentials for ATES applications. However, the most interesting economical and industrial areas are located outside this region. A thick clay layer covers the Western part of Belgium; the southern part mainly exists of Silurian schist and Devonian rock. At this time, 15 large ATES-systems (>300 kW) are operational and most installations are monitored.

A number of ATES projects are monitored within the framework of a subsidy program for the stimulation of innovative energy technologies, called

“Energy Demonstration Program”. For ATES system the monitoring is three years in order to have representative results for steady-state performance. Enterprises can get financial support (35 % of the extra investment of the innovative investment in comparison to a traditional installation).

The implementation of the ATES technology in Belgium went unarguable together with some unavoidable growing pains. Some of these problems were caused by the unusual combination of technologies and working parties. Especially the knowledge of hydrogeological and technical issues of ATES applications is not well understood or not existing with engineering companies. Drilling companies get involved in the process of HVAC installation. Most critical are the connection points between the traditional and innovative installation part, defined as the boundary zone between the underground and aboveground installation. As typical example, the communication between the control systems of HVAC and ATES system can be mentioned. Other common problems are the treating of the wells from time to time by the owner of the installation, the energy balance in the ground (cold storage), control problems, etc.

4.6.2 Norway

Accroding to Midttømme et al. (2008, 2009), there are about ten large Aquifer Thermal Energy Storage (ATES) installations. In 1987, the first known ATES system in Norway was established in Seljord. A 10 m-deep well was drilled for heating and cooling of Seljord lysfabrikk. The largest UTES system in Norway is at Oslo’s Gardermoen international airport. This ATES system has been in operation since the airport opened in 1998 and comprises an 8 MW heat pump array, coupled to 18 wells of 45 m depth, 9 for extraction of groundwater, and 9 for re-injection. The wells are sunk into the Øvre Romerike glaciofluvial sand and gravel aquifer. This system covers the total cooling needs of the airport, of which 25 % (2.8 GWh/y) is free cooling via direct heat exchange with cold groundwater, and 75 % (8.5 GWh/y) is active cooling via the use of the heat pumps. The annual heating provision is typically 11 GWh. There have been some problems with clogging of the groundwater loop, and the groundwater wells and heat exchangers require cleaning every few years. Because of a lack of knowledge of ATES systems in Norway, Dutch consultancies were hired to design the ATES system and GSHP installations. The total cost of the system was 17 million NOK and the payback time, compared to traditional heating and cooling systems, is estimated to be less than 4 years.

Oslo Centre for Interdisciplinary Environmental and Social Research, a component of the Oslo Innovation Centre in Oslo, is a 13,500 m^2 office building with laboratories. An ATES system, extracting groundwater from the underlying limestone and shale rock, provides both heating and cooling to the building. A closed-loop BTES system was originally intended for the site, but extremely difficult ground conditions were encountered during initial drilling: namely, zones of remarkably high groundwater flow associated with a Permian syenite dyke structure several meters thick. It became clear that it would be both more feasible and cheaper to drill a small number of groundwater wells (using the dyke as an aquifer) than a large number of closed-loop boreholes. Thus, a total of nine wells were drilled. These wells are typically located in extraction-injection pairs, one well drilled to 100 m depth and the second to 100–200 m depth. Using this arrangement, it is possible to access enough groundwater and rock volume to cover the seasonal cooling and heating demands of the building.

4.6.3 Sweden

The ATES systems being used in Sweden can be divided into four basic configurations (Andersson et al. 2003). In the simplest system (A), groundwater is directly used for preheating of ventilation air during the winter and for cooling during the summer season. In this case, heat and cold from ambient air is seasonally stored in the aquifer at a temperature level of approximately +5 °C (winter) and +15 °C (summer). More commonly used is the heat pump supported system (B) that works the same way as system A. However, the production of heat is much larger and the temperature change is somewhat greater. System C represents an early type of ATES applications where surface water is used as a source of energy for the heat pump. This heat, at a temperature of 15–20 °C, is stored during the summer and used during the heating season. The fourth system (D) is similar, but in this case cold from the winter is stored to be used for district cooling.

Of these systems, heat pump supported combined heating and cooling applications (system B) are dominating (65 %). However, in recent years, there is a growing interest for storage of natural cold (system D), which is used for district cooling applications or for industrial cooling. In Table 4.1 the recent statistics of ATES utilization are presented. It is seen that the technology is preferably used for commercial and institutional buildings from small-scale applications to large-scale utilization in district heating and cooling. In the industry sector only a couple of systems are applied for manufacturing industries. The rest represents cooling of telecommunication installations.

The currently designed total storage capacities are in the order of 40 MW for heating and 70 MW for cooling. A rough calculation on the yearly energy turnover, based on designed values, indicates a storage heat utilization of 120 GWh while the utilization of cold is about 80 GWh (Nordell et al. 2007).

Still, high temperature ATES projects are lacking in Sweden. However, recent feasibility studies of two large-scale applications have yielded promising results. In both cases these projects are related to storage of waste heat.

A survey within Annex 13 of IEA ECES IA revealed that 40 % of the plants have had or have operational problems or failures. The major part of these has been solved by fairly simple measures. However, approximately 15 % have continued difficulties with well capacities. The dominating reason is clogging of the wells mainly caused by iron precipitation. These wells have to be treated from time to time. Other common problems are corrosion and malfunctioning control systems. In general, these types of problems are now clearly identified and understood, and are therefore less common in newer plants. The research in Sweden has been focused on geodata collection by test drilling as one important part for proper well and system design. The objective with this work, which was carried out at the Lund Institute of Technology, was to create guidelines for site investigations related to ATES design. These guidelines are part of a more extensive work with UTES guidelines that takes place within Annex 13 of IEA ECES IA. These covers all aspects of design, construction, and maintenance of UTES wells and boreholes and will be published during the autumn 2003.

From 1999, a new legislation (The New Act of Environment) was applied. This Act has complicated the ATES permit procedures in Sweden and it has become an obstacle for some potential ATES projects. However, the environmental benefits in terms of energy conservation and economics will probably still favor a further growth of ATES projects in Sweden, especially for large-scale systems.

4.6.4 Germany

Lottner and Mangold (2000), Schmidt et al. (2003, 2004), and Sanner et al. (2005) reported the status of ATES in Germany. In Germany, two aquifer heat stores are in operation in Rostock-Brinckmanshöhe and in Berlin.

In the solar assisted district heating plant of the new housing project in Rostock-Brinckmanshöhe, an aquifer is used as a low temperature seasonal store. Due to the small size of the plant, the shallow 30 m deep aquifer has to be operated in a temperature range between 10 and 50 °C. Model calculations for the design of the plant showed that a maximal fraction of the stored solar heat can be recovered by a 100 kW heat pump. The aquifer is charged with solar heat from a 1,000 m^2 solar collector roof. A long-term monitoring program has been started in early 2000.

The district heating and cooling scheme of the renovated Reichstag building and of the connected neighboring large office buildings of the Parliament include a shallow and a deep aquifer, where a cold store in a depth of about 60 m and a heat store in a depth of about 300 m. The deep aquifer is charged in summer with surplus heat of 70 °C from the combined heat and power plants. These plants are operated dependent on the electricity demand of the connected buildings. According to the design calculations, about 60 % of the stored heat can be recovered during the heating period from the aquifer in the temperature range between 55 and 70 °C and can supplement the absorption heat pump system. The groundwater of the shallow aquifer is used at ambient temperature for the air conditioning of the buildings. An extensive long-term monitoring program will examine the technical and economic feasibility of the concept.

4.6.5 The Netherlands

In the Netherlands, Aquifer Thermal Energy Storage started to be implemented in the early 1980s (Snijders 2005). In first instance, the objective was to store solar energy for space heating in winter. R&D activities and the first demonstration projects were financed within the framework of the National Research Programme on Solar Energy (National Onderzoek Programma Zonne-energie).

In the first project, (commissioned in 1983) vertical soil heat exchangers were used (BTES application). Given the good experience with aquifer storage in later projects and the fact that in the Netherlands aquifers can be found almost everywhere, in particular the application of ATES has been further developed in the Netherlands. Although, ATES systems can be applied almost everywhere in the Netherlands, geographical proximity between projects and agglomeration is emerging in four provinces: North and South Holland, North Brabant and Gelderland contain over 75 % of all projects.

In 2005, the number of registered ATES projects was 537. In almost every major city a number of ATES projects are in operation. The aim of most ATES projects is to store cold in winter for cooling in summer. In general, cooling is direct, that is to say without using a chiller. In most projects, the cooling capacity supplied from storage lies between 500 and 2000 kWt. This means that by applying cold storage these projects economize on a large chiller.

The heat released during cooling is stored in the aquifer also. If possible, the heat is used for heating during the winter season. This combination is called "Cold storage and low temperature heat storage". The largest ATES project in operation is for supplying cooling and low temperature heat to the buildings and laboratories on the campus of Eindhoven University. Both the cooling and heating capacity of the store are 20,000 kWt (5,700 tons and 68 MBtu/h respectively).

Until 2000, most ATES applications were for individual buildings like offices and hospitals. However, since about 2000 ATES also started to be applied as a central (collective) system for a number of buildings, mixed developments, and housing projects. At present several utility companies are offering their clients to supply heating and cooling with ATES-based district heating and cooling systems, whereby the system is owned and managed by the utility.

Currently, the expectation is that the number of systems constructed each year can grow from about 100–1000 (Coenen et al. 2009). So in 2008, the Dutch government formed a new actor, an ATES taskforce. This task force was asked to make an inventory of the main barriers for implementing ATES systems. One problem is the increasing geographical proximity in the underground in the Netherlands of other infrastructural systems (cables, pipes, sewers systems, tunnels, storage systems, etc.). Another problem is the lack of a clear regulatory framework for the use of the underground and the groundwater. Moreover, it is not clear how the government should deal with conflicting interests of different users of the underground and groundwater. Because of this, the ATES network expresses confusion and uncertainty about what is permitted and what not. Another barrier is the already mentioned potential interference of systems.

4.6.6 Canada

ATES has been or is currently being implemented in a number of large-scale building projects in Canada (Allen et al. 2000). Existing large installations include, for example, the Carleton University campus in Ottawa, the Sussex Hospital in New Brunswick, and the Scarborough Centre near Toronto. Many of these have been operating since the late 1980s.

The Carleton University project draws its water from fractured limestone aquifers at a temperature of about 9 °C. The project was originally designed for implementation in four phases. Phase 1 (consisting of five wells) opened in February 1990, and was constructed using standard heat-pump technology in combination with aquifer thermal energy storage. The system was designed to provide heating and cooling for approximately 40 % of the campus buildings. The high cost of energy associated by using the heat pumps prompted the university to re-assess the original design. In 1992–1993, a retrofit was undertaken in one building such that it could be directly cooled during the summer months and pre-heated in the winter by a heat exchanger, without the use of heat pumps.

This new design (without heat pumps) formed the basis for an expansion to the system. Additional wells for Phase 2 were drilled during 1994 and were to have been incorporated with the existing five well system. Unfortunately, the system has never been implemented or tested because of non-technical administrative problems. Nevertheless, two wells continue to provide heating and cooling to one building.

New ATES installations are being designed for buildings operated by Environment Canada in Ottawa and by Agriculture Canada in Agassiz, British Columbia. The Environment Canada system consists of a multiple well field, and groundwater is extracted from a fractured sandstone aquifer at an ambient temperature of about 9 °C. To date, the wells have been drilled and hydraulic testing and modeling has been undertaken. Work on the building retrofit is expected to take place this year. At Agriculture Canada's laboratory facility, five wells have been drilled. Four of the wells will be used for ATES, and the fifth well will act as a dump well to dispose of a small amount of excess cold water generated in the building during the winter heating.

Research on ATES in Canada is limited; however, Canadian Scientists have been active participants in several Annexes on Energy Conservation through Energy Storage under the auspices of the International Energy Agency. The most recent Annex (13) is aimed at identifying state of the art techniques for the design construction and maintenance of underground thermal energy storage wells and boreholes.

There are four early ATES systems installed in Canada (Wong et al. 2006). Good amount of information has been published from these studies and this pioneering work in ATES technology led the way in the development of ATES application in Canada. Through these early projects, the technical community has identified many challenges and also provided many learning opportunities in advancing the technology introduction.

The earlier ATES projects included the Scarborough Canada Centre which began in 1986 and studied the application of ATES for office building cooling. Later heat pumps were added to increase peak cooling and also provide some heating. Another important project was the Sussex Health Centre. This project was first commissioned in 1994. It was designed for cooling with limited heating. The Carleton University system has been in operation since 1990. The system was designed for cooling and heating and operated with heat pump in the low temperature range. In 2002, the ATES system at the Pacific Agriculture Research Centre was implemented for cooling and heating using heat pump. These installations helped the scientific and engineering community in getting a better understanding on how the ATES systems work in the low temperature range. The main challenges encountered were in cooling and heating load balance.

4.6.7 Denmark

As far as known, no BTES projects will be operational in Denmark by that time. The majority of the groundwater cooling projects provide direct cooling to industrial applications. In general, the warm groundwater is reinjected into the aquifer without thermal balancing.

Recently, there is a growing interest in the application of ATES for the heating and cooling of buildings (Hendriks et al. 2008). The first project of this kind was operational by the end of 2007. The major reason for this increasing interest is the introduction of the European Energy Performance Directive for Buildings. Lack of awareness is considered to be the major bottleneck to the application of UTES technologies in Denmark.

4.6.8 United Kingdom

There is only one known ATES system installed to date in the UK. The system is for a residential development in West London and has a storage capacity of 250 kW. The system was installed in 2006. By the end of 2007, there were a number of larger scale (>500 kW) ATES and BTES systems under development, and the level of interest in UTES application is increasing. This is to a large extent attributable to recent sustainability requirements for larger scale new developments and retrofits.

UTES technology is only just starting to enter into the UK market and thus is regarded as a “new” technology. The availability of suitable aquifers varies significantly in the UK and therefore certain areas are suitable for ATES systems and others areas are more favorable to closed-loop BTES systems. London, the South East, Birmingham, Liverpool, and East Anglia are examples of areas where ATES systems are viable.

In the UK, the Environment Agency (EA) is the government body which regulates the groundwater industry. Any larger scale open-loop ground source heating and/or cooling system has to go through the EA permitting procedure. The EA is becoming increasingly worried about net heating or cooling effects on the ground of GSHP’s and is therefore in favor of ground coupled systems like ATES and BTES, creating a thermal balance annually.

4.6.9 China

According to Morofsky (1994), Gao et al. (2006), applications of ATES in large-scale projects started in the 1960s, mostly in China. There were three interrelated problems in Shanghai that led to the development of aquifer thermal energy storage—ground subsidence, groundwater pollution, and the lack of summer cooling in factories. Restrictions on groundwater extraction aimed to solve subsidence and pollution. However, large-scale year round injection made the groundwater temperature unsuitable for cooling.

In 1965, cold water injection during winter started for summer cooling and has continued since giving 30 years of experience. Heated water is also injected for winter heating. Experience with heat storage is also extensive with the water volume injected being about 30 % of the cold storage volume.

By 1984, there were 492 cold storage wells in Shanghai accepting 29 million cubic meters of water annually. Of these wells, 90 % were used for both injection and extraction. These cold storage wells supplied textile mills, chemical works, and other industrial plants, but also commercial buildings such as the Shanghai Exhibition Hall where there are five injection wells and 1 extraction well. Most of these cold storage wells are 10–12 inches in diameter. The total annual cooling energy stored in Shanghai is about 1,100 TJ. Hot water storage of waste heat is practiced with injection temperatures as high as 400 °C. Recovery temperatures in winter can be as high as 38 °C.

Recently Applications of ATES are fewer and fewer. The bottleneck of ATES is recharging which is the key point of groundwater resource sustainable utilization. Low temperature ATES and heat pump technology should be combined to improve efficiency and extend development space.

4.6.10 Turkey

According to Paksoy et al. (2000, 2004) and Paksoy and Evliya (2009), R&D activities on the underground thermal energy storage in Turkey started with participation in IEA ECES Annex 8. UTES potential study carried out in Annex 8 revealed that there is significant potential for applications in buildings (residential, commercial, and service), industry and agriculture (greenhouses) sectors. First feasibility study on aquifer thermal energy storage using nearby Seyhan Lake was realized for the new annex of Çukurova University Hospital. 3,250 MWh of electricity for cooling and 1,000 tons of oil for heating were estimated to be saved annually with a calculated payback time of less than two years. In a joint study, carried out with Lulea University of Technology winter air as a cold source for borehole thermal energy storage was investigated. The ground temperature was decreased to 20–15 °C at the end of 3 months of cold storage in 2002–2003.

These activities were followed by a commercial ATES application in a supermarket in Mersin with a heating load of 74 kW and cooling load of 195 kW. This project has been in operation since 2001 with about 60 % annual energy savings. Heating and cooling potential of greenhouses in the Mediterranean climatic zone—using ATES systems was investigated in a 360 m^2 greenhouse for growing tomatoes. "Zero" fossil fuel was consumed for the heating in winter and cooling was a bonus in spring time. The yield of tomatoes was increased by 40 % with a 68 % energy savings. The calculated payback time is two years for this project.

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Chapter 5
Borehole Thermal Energy Storage

5.1 Definition

If it is impossible to exploit a suitable aquifer for energy storage, a borehole thermal energy storage system (BTES) can be considered. Vertical ground heat exchangers (GHE), also called borehole heat exchangers (BHE) are widely used when there is a need to install sufficient heat exchange capacity under a confined surface area such as where the Earth is rocky close to the surface, or minimum disruption of the landscape is desired. This is possible because the temperature below a certain depth remains relatively constant over the year. In a standard borehole, which in typical applications is 20–300 m deep, plastic pipes made of polyethylene or polypropylene are installed. The space between the pipe and the hole is filled with an appropriate material to ensure good contact between the pipe and the undisturbed ground and reduce the thermal resistance (Florides and Kalogirou 2007). Figure 5.1 shows a side view of borehole thermal energy storage tube.

Vertical loops are generally more expensive to install, but require less piping than horizontal loops because the Earth deeper down is cooler in summer and warmer in winter, compared to the ambient air temperature.

With borehole storage, vertical borehole heat exchangers are inserted into the underground, which ensure the transfer of thermal energy toward and from the ground (clay, sand, rock, etc.). Many projects are about the storage of solar heat in summer for space heating of houses or offices. Ground heat exchangers are also frequently used in combination with heat pumps ("geothermal heat pump"), where the ground heat exchanger extracts low-temperature heat from the soil (International Energy Agency 2006).

BTES makes use of long boreholes that are dug into the ground. Thermal energy is transferred to the underground by means of conductive flow from a number of closely spaced boreholes. The boreholes can be equipped with different kinds of borehole heat exchangers, making the boreholes act as a large heat exchanger between the system and the ground. Each borehole contains a U-tube which links together with a central piping system at the surface. Sometimes more

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DOI: 10.1007/978-1-4471-4273-7_5,

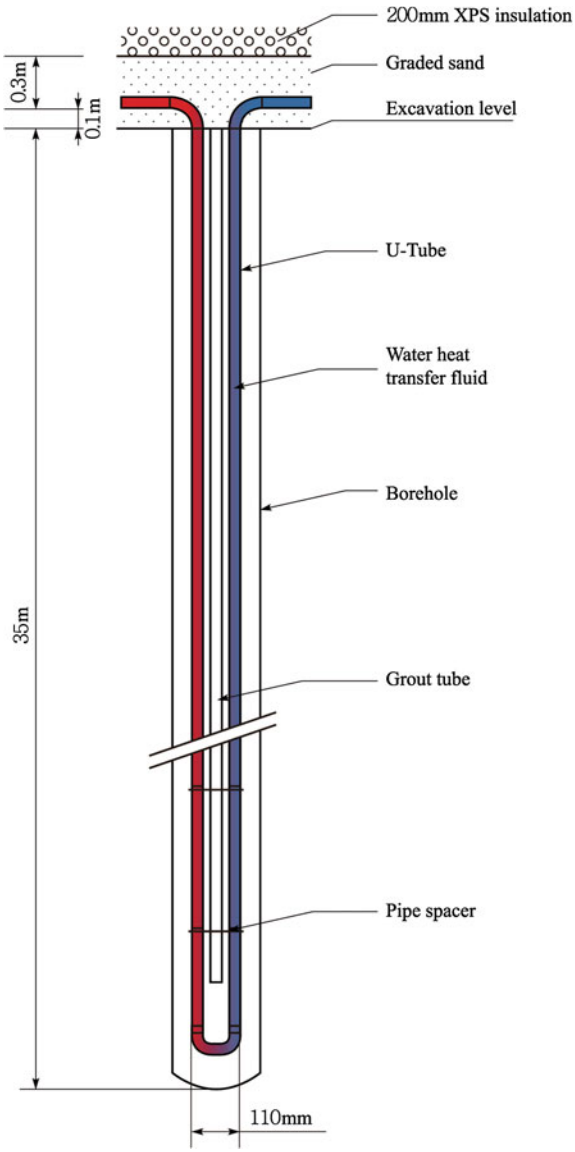

Fig. 5.1 Side view of single borehole thermal energy storage (BTES) tube (http://www.dlsc.ca/borehole.htm)

effective heat exchange systems are used, e.g., double U-tube systems. This technology can be applied to almost any ground condition from clay to bedrock. Heat or cold is delivered or extracted from the underground by circulating a fluid in a closed loop through the boreholes. The fluid usually consists of water, which is mixed with glycol or alcohol to allow the system to work below the freezing point, if so required. Fluid is pumped through the U-tubes, flowing down then back up each borehole. In the summer, the heat is transferred from the heat carrier fluid to

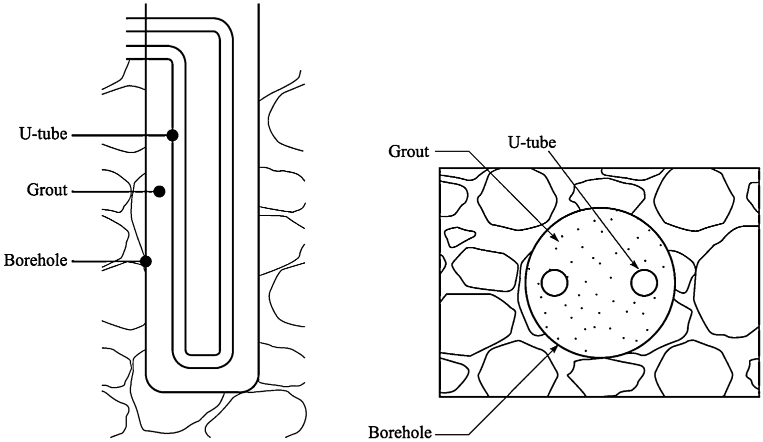

Fig. 5.2 Schematic diagram of a single U-tube borehole heat exchanger (redrawn from He 2007)

the ground by conduction. Over the course of a season, the borehole field is continually heated. When the winter arrives, the flow is reversed. Heat is extracted from the underground and delivered to the building (Zizzo 2009).

BTES systems consist of several borehole heat exchangers. Applications where thermal energy is injected or extracted through the borehole with the use of heat pumps are commonly referred to as ground-coupled heat pump systems (GCHP), or ground-source heat pump (GSHP) systems. Feasible applications also include ground heat exchangers, where heat pumps are not used, e.g., dissipative systems for direct cooling, or high-temperature thermal storage for low-temperature applications (Gehlin 2002).

Due to the significant cost associated with drilling multiple deep boreholes, BTES is the most expensive option among the natural UTES applications (Wong et al. 2006). While double U-tubes are common in central Europe, most BTES systems today use single U-tubes. Systems in northern Europe are usually saturated with groundwater up to a few meters below the ground surface. In other areas of the world including North America, it is common to fill the boreholes with a backfill material such as bentonite, concrete, quartz sand, or grouts. To provide good thermal contact with the surrounding soil, the borehole is then filled with a high thermal conductivity grouting material. The heat transfer capacity of the system depends on the material properties of the tubes, grout, and surrounding soil as well as the arrangement and flow characteristics of the field (Zizzo 2009).

The flexibility of this technology to almost any ground conditions has made BTES systems one of the most popular forms of UTES. A BHE is usually a borehole drilled to a depth of 20–300 m with a diameter of 10–15 cm. A single or double U-tube is inserted inside the borehole so that a heat carrier fluid can circulate and exchange heat with the surrounding ground (He 2007). Figure 5.2 shows the schematic diagram of BHE with a single U-tube.

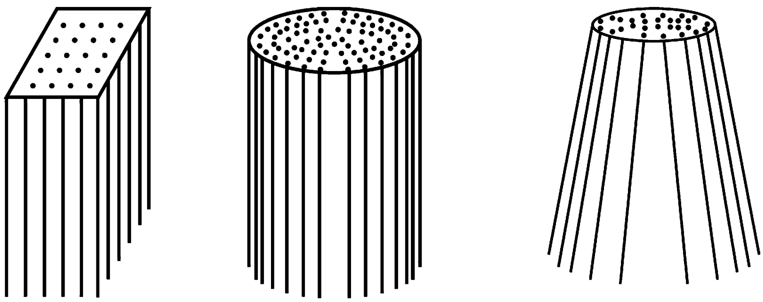

Fig. 5.3 Examples of different drilling patterns that may be used in a BTES facility (redrawn from Nielsen 2003)

A BTES system consists of an array of boreholes resembling standard drilled wells. The holes can be drilled either in a quadratic or a hexagonal pattern, and they are usually vertical. A hexagonal pattern is better with regard to energy transmission and heat losses in the rock mass, but a square pattern is simpler to drill and connection between boreholes is easier. The distance between the boreholes will among other factors depend on the thermal properties of the rock. Distances of 6–8 m are quite common in Scandinavian rock types (Nielsen 2003)

The holes can be connected in serial configuration, in parallel, or in a combination serial/parallel depending on the planned thermal loading and unloading of the facility. The shape of the storage facility, seen at the surface, can be adapted to the shape of the available land area as illustrated in Fig. 5.3.

From a depth of some 10 m, the underground has an ambient temperature that is practically constant throughout the year and normally related to the mean annual air temperature. At further depths, the temperature will increase with the geothermal gradient, normally with 1–3 °C per 100 m. In some BTES applications, the ambient ground temperature can be directly used for free natural cooling purposes. Such systems are regarded as passive in the sense that they are naturally recharged. However, in most cases cold has to be actively stored in the soil and rock mass to provide the temperature that is demanded. These actively recharged systems are regarded as true BTES applications.

In the true BTES systems, natural or artificial cold is stored during the winter by extracting heat from the underground, practically always by operating a heat pump. During the summer, the chilled rock will deliver free cooling and slowly be heated up again. In some cases, the heat pump is used as a chiller to cover peak load demands. Figure 5.4 explains BTES operations for cooling and heating (http://underground-energy.com/BTES.html).

In the cold season, the heat stored in the outside of the array is used for heating. Water from the store at around 15–20 °C is passed through a heat pump, which in turn provides water around 40–50 °C for use in building heating.

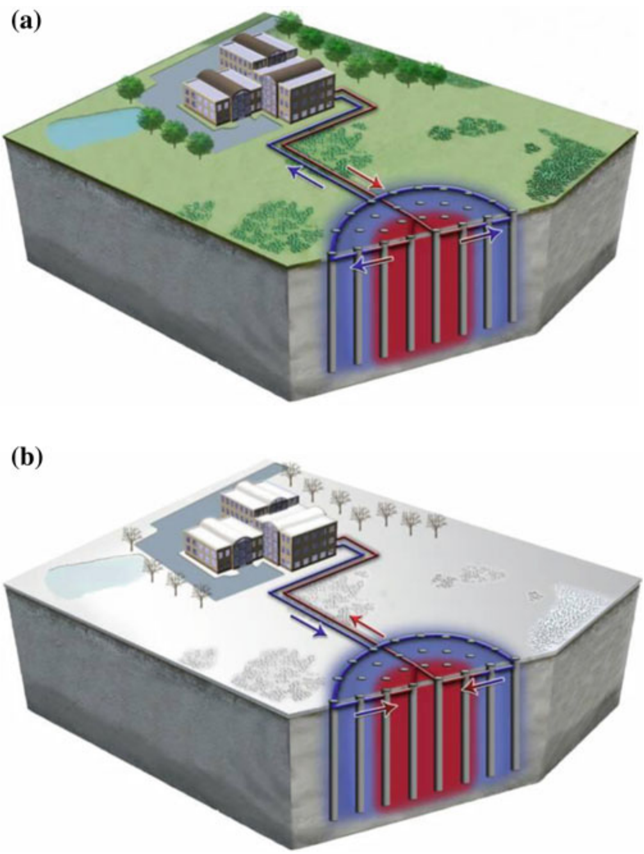

Fig. 5.4 BTES operations for cooling and heating (http://underground-energy.com/BTES.html). **a** summer operation–cooling, **b** winter operation–heating

While the groundwater passes through the heat pump it cools to around 7–10 °C. The cooled water is return to the center of the underground array. Thus, charging the store with cold energy for use in summer.

During the warm season, water from the cold store at around 7–10 °C is passed through a heat exchanger providing direct cooling water to the building. The heat pump is available automatically as support in periods of peak demand. The store circuit water will pick up energy from the building and thus be raised in temperature to around 18–20 °C (or higher for fresh air load). This water, the temperature of which is higher than the natural groundwater temperature, will be run to the outside of the array and charge the store with warm energy.

The performance factor of heat pump supported BTES systems will normally be in the range 4–5, depending on the amount of cold produced in the system. The cold production (free cooling) in itself is normally around 20–30. The payback time for these kinds of systems ranges between 5 and 10 years, depending on size and other circumstances (EU Commission SAVE Programme and Nordic Energy Research 2004). This is significantly higher than that for ATES, but on the other hand, the operational risks are much lower.

In recent years, a third kind of system, known as "the American", has been introduced in Europe. In this system, both the condenser (cooling mode) and the evaporator (heating mode) of the heat pump are connected to the boreholes. Hence, the heat pump serves as both a heater and a chiller. During cold production, the waste heat is stored in the underground, and during heat production waste cold is stored. These systems are preferably designed for the cooling load, and the advantage is that they do not need any peak load coverage. The heat rejection from the condenser during cooling can be performed at higher temperatures (25–32 °C) in the ground loop than during free natural cooling (10–15 °C). This requires less borehole length per installed cooling capacity than free cooling systems, but at the same time, the heat pump is larger (for the same application), and the performance factor is somewhat lower (since the cooling is performed with the heat pump).

The BHE is the most common practice used for GHE installations because it requires a relatively small land area for installation. Moreover, the ground temperature and thermal properties are more constant in the deep ground, thus resulting in a higher heat transfer rate for the BHE. The heat transfer process of the BHE is very complicated, and the heat transfer rate of the BHE depends on a number of factors including the ground thermal properties, moisture content, regional groundwater flow, the installation and the arrangement of the heat exchanger including the grout material, the U-tube configuration, and the spacing and the depth of the boreholes. In order to properly and accurately design or evaluate the systems, modeling the BHE is the first and the most important step. By making various simplifications and assumptions, different methods have been developed to model the BHE.

BTES can achieve coefficient of performance (COP) values from 4 to about 8, compared to COP values of around 3.5 for a conventional GSHP geothermal installation (http://underground-energy.com/BTES.html). The capital cost of a large BTES system can be significant, as a large number of geothermal boreholes will need to be drilled compared to just a few thermal wells for an ATES system. However, the installation cost should be similar to conventional GSHP systems, and the higher COP values will result in a lower total life cycle-cost than a conventional GSHP system. Both closed-loop geothermal systems will have a lower life-cycle cost than a conventional fossil-fuel fired HVAC system. Because BTES is a closed-loop geothermal technology, there should be little difficulty in obtaining permits. Typically, the most common constraint is on the available land area in which to construct the GHX array.

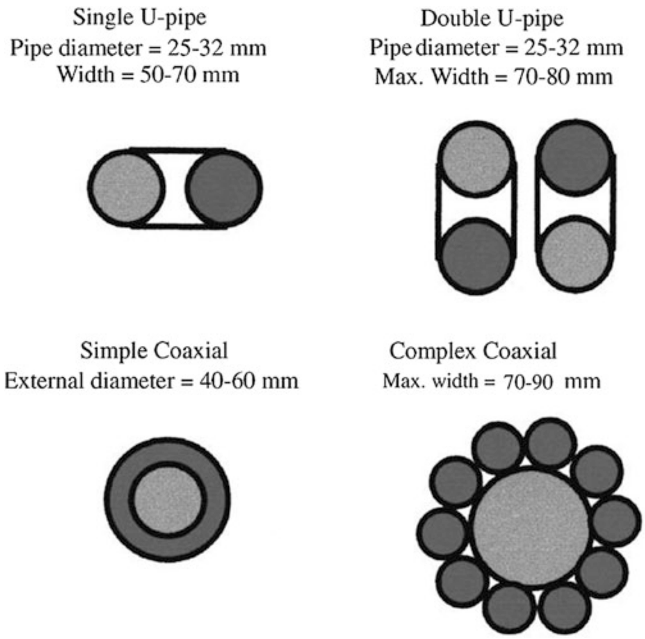

Fig. 5.5 Common vertical ground heat exchanger designs (from Florides and Kalogirou 2007)

5.1.1 The Collector

Vertical ground heat exchangers are classified based on their cross-sectional geometry and how the heat exchange from the flow channels takes place. Several types of borehole heat exchangers were tested and are widely used (Florides and Kalogirou 2007). These are classified in two basic categories as shown in Fig. 5.5:

- U-pipes, consisting of a pair of straight pipes, connected with a U-turn at the bottom. Because of the low cost of the pipe material, two or even three of such U-pipes are usually installed in one hole. In the U-pipe type BHE, both the downward and the upward flow channel contribute to the heat exchange with the surrounding ground. U-pipe type BHE exists with two or more channels. Most common is the single U-pipe BHE, but double U-pipe BHE has become increasingly popular, with increasing drilling depths, due to its lower thermal resistance and head loss.
- Concentric or coaxial pipes, joint either in a very simple way with one straight pipe inside a bigger diameter pipe or joint in complex configurations. The characteristics of the coaxial (also called tube-in-tube) type BHE is that heat exchange occurs from either the upstream or downstream flow channel (the flow direction may also be different during injection or extraction of heat). The inner pipe is often thermally insulated in order to avoid thermal short circuiting between the upward and downward flow channel. Coaxial BHEs may be designed with or without liner or outer tube, i.e., as a closed or open flow circuit.

5.1.2 Borehole Filling

A vertical borehole may require that some kind of backfilling material is used to fill the space between the flow channels and the borehole wall. The filling material provides a good thermal contact with the surrounding ground due to low thermal conductivity of natural filling material or low groundwater level. Another important issue is to limit vertical water movement along the borehole to avoid migration of polluted water, drainage of soil layers near the ground surface, and disturbance of the hydraulic characteristics of artesian formations. There is no regulation.

Special grouts are used to provide a low permeability. It is important that these grouts have the capability to bond against both borehole wall and pipes. The mixtures must be workable and pumpable during installation with little shrinkage during settling. If shrinkage occurs, this may cause a pathway for fluid migration. Common grouts, such as bentonite, usually have low thermal conductivity. Special grouts have been developed to enhance the thermal conductivity.

Laboratory tests to investigate thermal resistance and thermal conductivity of grouts have been reported by various authors and the results provide a good overview of experience on grouted boreholes and various grouts (Florides and Kalogirou 2007).

In Sweden and Norway, it is most common to leave the boreholes ungrouted, i.e., the boreholes are filled with groundwater. Boreholes are commonly drilled in hard rock with the groundwater table a few meters below ground surface. Stagnant water has low thermal conductivity, however thermal gradients that will necessarily occur in BHEs cause natural convection, thus enhancing the heat transfer between the heat exchanger and the surrounding ground.

5.2 Applications

Borehole systems (BTES) are the most generally applicable UTES. In such systems, bedrock is used as the storage medium. The boreholes that penetrate the storage volume are heat exchangers of the system, through which a heat carrier is pumped. A pipe system is installed in the borehole to enable the circulation of a heat carrier. When thermal energy is injected the temperature of the storage medium is increased.

Nordell (2000) summarized the various applications of the BTES system.

- Small-scale systems:
  - Single borehole for cooling (with and without recharge)
  - Single borehole for heating with heat pump (with and without recharge)
  - Single borehole for heating with heat pump and direct cooling

- Large-scale systems:
  - System of Boreholes for heat extraction with heat pump
  - System of Boreholes for heat extraction with heat pump and recharge of extracted energy
- Borehole Storage Systems
  - Seasonal loading of thermal energy (heat or cold) for later extraction
  - Seasonal loading of thermal energy for the purpose of cooling or heating of the ground

BTES systems are most suitable for base load operation, both when loading and unloading the store. It is mainly for seasonal storage. The theory of BTES was summarized by Hellström (1991).

Many hundreds of thousands of BTES systems have been constructed around the world. The Geothermal Heat Pump Consortium (GHPC) estimates that 400,000 BTES systems would annually be built in US within a few years. Most of them are borehole systems of one or a few boreholes. There are however an increasing number of large-scale systems i.e., more than 10–20 boreholes.

5.3 Market Opportunities and Barriers

The problems often encountered with BHE design include inadequate address of flow, pressure drop, and control parameters, leaks associated with corrosion of fittings, poor workmanship, as well as the selection of pipe materials and of the circulated heat transfer fluid (Sanner et al. 2003). All of the above require the expertise of an engineer and contractor qualified in the installation of ground-source heat pumps, which represents a significant barrier to their market penetration. In countries with higher sales of geothermal heat pumps such as Sweden, Switzerland, and Germany, technical guidelines, contractor certifications, and quality awards, etc., are beginning to be set into force to protect the industry and the consumers against poor quality and insufficient longevity of geothermal heat pump systems.

5.4 Analysis of Ground Thermal Behavior

Heat flow, which is a measure of the amount of thermal energy coming out of the Earth, is calculated by multiplying the geothermal gradient by the thermal conductivity of the ground. Each rock type has a different thermal conductivity, which is a measure of the ability of a material to conduct heat. Quartz-rich rock like sandstone, has a high thermal conductivity, which indicates that heat readily passes through them. Rocks that are rich in clay or organic material, like shale and coal, have low thermal conductivity, meaning that heat passes slower through these layers. If the heat flow is constant throughout a drill hole (i.e., water is not flowing up or down the hole), then it is obvious that low-conductivity shale layers will have a higher geothermal gradient compared to high-conductivity sandstone layers (Florides and Kalogirou 2007).

Proper design of borehole heat exchangers (BHE) for commercial and institutional buildings utilizing ground-source heat pump systems requires a good estimate of the thermal conductivity of the ground in order to avoid significantly oversizing or undersizing the ground heat exchanger (Gehlin and Spitler 2003). A good estimate of the thermal conductivity is also needed when designing a BTES system. The ground thermal properties may be measured in situ at a specific location using thermal response test.

In a thermal response test, a constant heat injection or extraction is imposed on a test borehole. The resulting temperature response can be used to determine the ground thermal conductivity, and to test the performance of boreholes. The first mobile measurement devices for thermal response testing were independently constructed in Sweden and the USA, in 1995.

Different mathematical models—analytical and numerical—are used for the evaluation of response test temperature data (Yang et al. 2010). The different models require somewhat different sets of input data.

5.4.1 Heat conduction Outside Borehole

A number of simulation models for the heat transfer outside the borehole have been recently reported, most of which were based on either analytical methodologies or numerical methods. A few models were developed based on the incorporation of the analytical and numerical solutions.

He (2007) and Yang et al. (2010) classified and summarized basic approaches used to simulate BHEs. One is the analytical method, like the line-source model (Ingersoll et al. 1954) and the cylindrical model (Carslaw and Jaeger 1959), another one being the response factor method such as Eskilson's model (Eskilson 1987), Hellträm's model (Hellström 1991) and Yavuzturk's model (Yavuzturk 1999), The third one is the numerical method, for example Gu's model (Gu and O'Neal 1998) and Zeng's model (Zeng et al. 2003).

5.4.1.1 Line-Source Model

The earliest approach to calculate the thermal transport around a heat exchange pipe in the ground is the Kelvin line-source theory assuming the infinite line source. In the Kelvin's line-source theory, the ground is regarded as an infinite medium with an initial uniform temperature.

The borehole is assumed as an infinite line source. The heat transfer in the direction of the borehole axis, including the heat flux across the ground surface and down the bottom of the borehole, is neglected. The heat conduction process in the ground can be, therefore, simplified as one-dimensional one.

Ingersoll et al. (1954) developed the line-source model, assuming the borehole as a line source which is infinitely long and the heat flow is all normal to the line source with a constant flux. This is the basic model used to calculate the heat transfer between the line source and the ground, and a lot of other models developed by further researchers are basically based on the line-source model. If the line source starts at zero time and the medium is at an initially uniform temperature, the expression given by Ingersoll for the temperature at any time *t* at any point can be written as:

$$T - T_o = \frac{Q'}{2\pi k}\int_X^{\infty}\frac{e^{-\beta^2}}{\beta}d\beta \equiv \frac{Q'}{2\pi k}I(X) \tag{5.1}$$

where $\beta = \frac{r}{2\sqrt{\alpha(t-t')}} X = \frac{r}{2\sqrt{\alpha t}}$

By applying this line-source model, Ingersoll et al. (1954) studied the system of ground heat exchangers with heat pumps, and it was reported that in general, the agreement of the theory and experiment was acceptable.

Although it is characterized by the simplicity and less computation time, this model can only be applied to small pipes within a narrow range of a few hours to months because of the assumption of the infinite line source. It was estimated that the application of Kelvin's line source may cause a noticeable error when as $\frac{\alpha t}{r_b^2} < 20$.

This approach has been widely utilized in some analytical design methods that are currently used to analyze the heat transfer of GHEs. A number of improvements for this approach have been proposed to account for some complicated factors so that the accuracy can be comparable to that of the numerical methods.

However, in the line-source model, the borehole was treated as an infinite line source. The borehole geometry, thermal properties, and the mass and other properties of the fluid had not been accounted for. The outlet temperature of the fluid can only be obtained with the same approximation that is used by Eskilson (1987) and Yavuzturk (1999). Moreover, since the line-source model is a one-dimensional model, it does not directly provide a method for predicting the interference between the boreholes. The assumption that the borehole is infinitely long ignores the end effects, which will cause some error in the long term. Lastly, the line-source model has low accuracy at short (e.g. hourly) time steps.

5.4.1.2 Cylinder Source Model

Based on the Eskilson (1987)'s model, an analytical solution to the finite line source has been developed by considering the influences of the finite length of the borehole and the ground surface as a boundary. The following assumptions are taken in the analytical model in order to derive an analytical solution.

- The ground is regarded as a homogeneous semi-infinite medium with constant thermophysical properties.
- The boundary of the medium, i.e., the ground surface, keeps a constant temperature (T_o), same as its initial one throughout the time period concerned.
- The radial dimension of the borehole is neglected so that it may be approximated as a line-source stretching from the boundary to a certain depth, H.
- As a basic case of study, the heating rate per length of the source, q_l, is constant since the starting instant, $t = 0$

Carslaw and Jaeger (1959) solved the problem on the infinite circular cylinder by the Laplace transformation method. Assuming a constant flux Q' along the borehole r_o and the borehole is infinite long, the governing equation for one-dimensional heat transfer problem in the cylindrical coordinate can be expressed as:

$$\frac{\partial^2\theta}{\partial r^2} + \frac{1}{r}\frac{\partial\theta}{\partial r} - \frac{1}{\alpha}\frac{\partial\theta}{\partial t} = 0 \quad r_o < r < \infty \tag{5.2}$$

while the boundary conditions and initial condition can be expressed as:

$$-2\pi r_o k\frac{\partial\theta}{\partial r} = Q' \quad r = r_o, \quad t > 0 \tag{5.3}$$

$$\frac{\partial\theta}{\partial r} = 0 \quad r = 0 \tag{5.4}$$

$$\theta = 0 \quad r > r_o, \, t = 0 \tag{5.5}$$

where $\theta = T - T_o$

Taking the Laplace transform and the inverse Laplace transform, the solution is

$$\theta(r,t) = \frac{2Q'}{\pi k}\int\left(1 - e^{-\alpha u^2 t}\right)\frac{J_0(u,r)Y_1(u\alpha) - Y_0(ur)J_1(u\alpha)}{u^2\left[J_1^2(u\alpha) + Y_1^2(u\alpha)\right]}du \tag{5.6}$$

where J_0, J_1, Y_0, Y_1 are the zero and the first order of Bessel functions, respectively.

The solution of the temperature excess was given by Zeng et al. (2003):

$$\theta = \frac{q_l}{4k\pi}\int_0^H\left\{\frac{\operatorname{erfc}\left[\frac{\sqrt{r^2+(z-h)^2}}{2\sqrt{\alpha\tau}}\right]}{\sqrt{r^2+(z-h)^2}} - \frac{\operatorname{erfc}\left[\frac{\sqrt{r^2+(z+h)^2}}{2\sqrt{\alpha\tau}}\right]}{\sqrt{r^2+(z+h)^2}}\right\}dh \tag{5.7}$$

It can be seen from Eq. 5.7 that the temperature on the borehole wall, where $r = r_o$, varies with time and borehole depth. The temperature at the middle of the borehole depth ($z = 0.5H$) is usually chosen as its representative temperature. An alternative is the integral mean temperature along the borehole depth, which may be determined by numerical integration of Eq. 5.7. For the convenience of applications, the former is usually accepted as the representative temperature in the design and analysis program. It is obvious that the integral of Eq. 5.7 can be computed much faster than the numerical solution of the same heat conduction problem in the semi-infinite domain with long duration. The methodology has been complied in the later design and simulation software developed by other researchers.

Comparing the cylinder source model with the line-source model, it can be observed that during the unsteady-state heat transfer process, the results by the line-source model were delayed. It was because the line-source model assumed the heat flux was on the central line of the borehole ($r = 0$), while the cylinder source model assumed the heat flux was on the borehole surface ($r = r_o$), which was closer to the actual heat transfer process.

However, similar to the case of the line-source model, the cylinder source model ignored the heat transfer inside the borehole, for example the heat transfer between the fluid and the U-tube, the U-tube and the grout, and the grout and the borehole. Thus, only with the same assumption used by Eskilson (1987) and Yavuzturk (1999), the model can be used to obtain the fluid temperature, which is the critical factor in the evaluation of system performance. Moreover, due to the assumption of the infinite length of the cylinder, it has the same limitations as the line-source model.

5.4.1.3 Eskilson's Model

Eskilson's model was developed to analyze the ground heat exchanger response, i.e., the relation between heat extraction rate and temperature of the fluid circulating inside the U-tube (Eskilson 1987). It was totally neglected in both the line-source model and the cylinder source model. First, the thermal process of a single borehole was analyzed using an analytical method. Then the thermal interaction between boreholes was investigated, and the thermal resistance was modified by dimensionless time response factors, called g-functions. A numerical model for any configuration of boreholes was developed, and the superposition method was used to solve for the thermal influence of multiple boreholes, while the heat transfer process along the borehole was determined by an analytical solution. Several assumptions and simplifications were used in Eskilson's model; (1) The annual mean air temperature T_o was considered to be the ground surface temperature. (2) The ground was assumed to be homogeneous. (3) The uppermost part of the borehole was treated as thermally insulated. (4) The borehole temperature T_b was assumed to be constant along the borehole depth.

Accounting for the assumptions above, the thermal process of a single borehole can be expressed by the heat conduction equation, and the mathematical equation in cylindrical coordinates can be expressed as:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \tag{5.8}$$

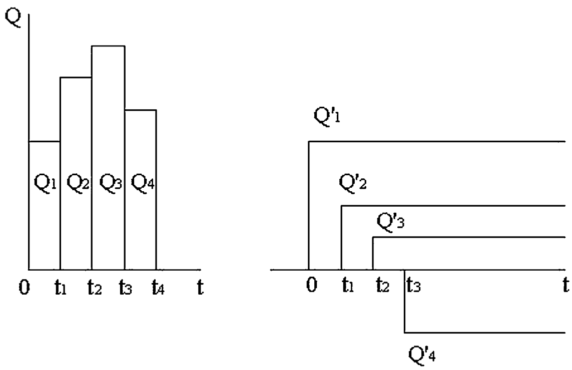

Fig. 5.6 Schematic diagram of heat step functions and step pulses (from He 2007)

The boundary conditions at the ground surface and the initial condition were given as follows:

$$T(r,0,t) = T_o$$
$$T(r,z,0) = T_o$$
$$T(r,\infty,t) = T_o$$
$$\frac{\partial T}{\partial r}(0,z,t) = 0$$

And the boundary condition of the borehole temperature was assumed to be constant over the borehole length H:

$$T(r_b,z,t) = T_b(t) \quad D<z<D+H \tag{5.9}$$

By considering the heat extraction or dissipation as a step function $Q(t)$, the temperature response of any heat input can be calculated using a basic step pulse, and the solution can be obtained by superimposing the responses in time as a series of step pulses. Figure 5.6 shows the schematic diagram of the step function and the step pluses. Converting the temperature responds to a series of dimensionless temperature response factors, called g-functions, it was possible to calculate the temperature change at the borehole in response to a single heat step pulse. Superimposing the responds of any heat extraction or dissipation, the borehole temperature can be determined.

$$T_b(t) = T_o + \sum_{i=1}^{n} \frac{Q_i - Q_{i-1}}{2\pi k} g\left(\frac{t_n - t_{i-1}}{t_s}, \frac{r_b}{H}\right) \tag{5.10}$$

The finite line-source model was used to approximate the g-functions for different borehole configurations, and each finite source solution was calculated numerically with finite difference method. The basic time-scale for the borehole process was introduced as $\frac{5r_b^2}{\alpha}$ and the heat transfer rate below this time-scale was considered with a very low accuracy. The typical time-scale used in Swedish applications was of the order of 2 h (Eskilson 1987), while Yavuzturk (1999) reported it was 3–6 h for a typical borehole. Eskilson (1987) had reported the different *g*-functions for 226 cases in his studies, and the guidelines for optimizing the configuration were given.

5.4.1.4 Hellström's model

Hellström (1991) developed the duct storage (DST) model to investigate the thermal response of the ground heat exchanger, i.e., the relation between the heat transfer rate and the temperature of the fluid circulating inside the U-tube. There were two basic assumptions for the thermal analyses; (1) Only heat conduction took place in the ground. (2) The ground was homogenous or the subregion of the ground was homogenous. Hellström divided the heat transfer process into three subprocesses: (1) the thermal process between heat carrier fluid and the ground immediately outside the heat exchanger, (2) the heat exchanger interacting with the surrounding ground in a local thermal process, and (3) the global process involving the storage volume and the surrounding ground. A single fluid-to-ground thermal resistance was employed to calculate the heat transfer from the fluid to the ground. The temperature difference between the fluid and the ground was determined by an analytical solution, while the local and the global process were solved by using the finite difference method. In the local process, the heat injection rate was approximated by a step-wise constant value, and by superposition, it was regarded as a series of simple heat injection steps. Due to symmetry, the heat flux through boundaries of the local region around a ground heat exchanger was considered to be zero, and the temperature in this region increased linearly with time. The global process dealt with three fundamental components: a transient heat loss through the storage boundaries during the initial years, a steady-state value of heat loss being gradually approached, and also a superimposed periodic variation during the storage cycle. For computational accuracy and efficiency, the DST model was implemented as a component of TRNSYS, a well-known transient system simulation program.

5.4.1.5 Gu's Model

In order to incorporate the thermal interference between the two pipe legs of the U-tube into the analytical solution of the cylindrical source model, Gu and O'Neal (1998) developed an expression for the equivalent diameter of a vertical U-tube heat exchanger. For a steady-state operation, the two legs of a U-tube were considered as two constant cylindrical heat sources. One of the legs was assumed to be concentric with the grout and the thermal influence from the other leg was estimated using the principle of superposition, since the heat conduction equations were linear. Based on the concept of equivalent external thermal resistance (ETR), an expression for the equivalent diameter can be achieved. Figure 5.7 shows the diagram of the equivalent diameter of a single U-tube.

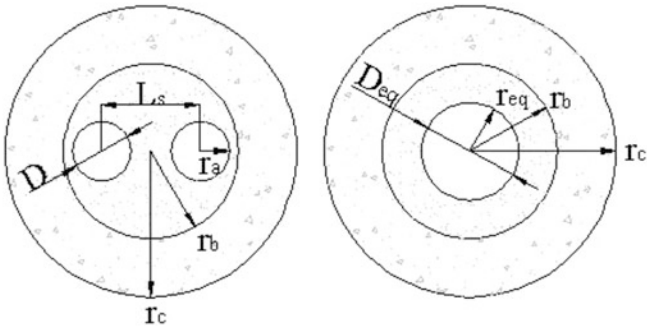

Fig. 5.7 Diagram of equivalent diameter of a single U-tube (from He 2007)

First, assuming the first leg to be concentric with the grout and the far-field boundaries, the average surface temperature rise of the first leg due to its own heat rejection can be calculated when applying the one-dimensional equation of heat flow through multiple cylinders:

$$\Delta T_{11} = \frac{Q_1'}{2\pi}\left[\frac{\ln\left(\frac{r_b}{r_c}\right)}{k_B} + \frac{\ln\left(\frac{r_c}{r_b}\right)}{k_g}\right] \tag{5.11}$$

Next, assuming the second leg to be concentric with the grout and the far-field boundaries, the average temperature rise at the first leg caused by the heat rejection from the second leg can be determined as:

$$\Delta T_{21} = \frac{Q_2'}{2\pi}\left[\frac{\ln\left(\frac{r_b}{L_s}\right)}{k_B} + \frac{\ln\left(\frac{r_c}{r_b}\right)}{k_g}\right] \tag{5.12}$$

So, the total temperature rise at the first leg can be obtained by adding ΔT_{21} to ΔT_{11}:

$$\Delta T_1 = \frac{1}{2\pi}\left[\left(Q_1' + Q_2'\right)\frac{\ln\left(\frac{r_c}{r_b}\right)}{k_g} + Q_1'\frac{\ln\left(\frac{r_b}{r_c}\right)}{k_B} + Q_2'\frac{\ln\left(\frac{r_b}{L_s}\right)}{k_B}\right] \tag{5.13}$$

In the same way, the total temperature rise at the second leg can be written as:

$$\Delta T_2 = \frac{1}{2\pi}\left[\left(Q_1' + Q_2'\right)\frac{\ln\left(\frac{r_c}{r_b}\right)}{k_g} + Q_2'\frac{\ln\left(\frac{r_b}{r_c}\right)}{k_B} + Q_1'\frac{\ln\left(\frac{r_b}{L_s}\right)}{k_B}\right] \tag{5.14}$$

Thus, the average temperature difference between both legs and the far-field boundary would be:

$$\Delta\bar{T} = \frac{\Delta T_1 + \Delta T_2}{2} = \frac{Q'_1 + Q'_2}{2\pi}\left[\frac{\ln\left(\frac{r_b}{\sqrt{r_a L_s}}\right)}{k_B} + \frac{\ln\left(\frac{r_c}{r_b}\right)}{k_B}\right] \tag{5.15}$$

The ETR value of the U-tube can then be obtained by dividing Eq. 5.15 by the total heat transfer rate, $Q'_1 + Q'_2$:

$$(\mathrm{ETR})_{\mathrm{total}} = \frac{1}{2\pi}\left[\frac{\ln\left(\frac{r_b}{\sqrt{r_a L_s}}\right)}{k_B} + \frac{\ln\left(\frac{r_c}{r_b}\right)}{k_B}\right] \tag{5.16}$$

For a pipe with the equivalent diameter, the ETR can be written as:

$$(\mathrm{ETR})_{\mathrm{eq}} = \frac{1}{2\pi}\left[\frac{\ln\left(\frac{r_b}{\sqrt{r_{eq}}}\right)}{k_B} + \frac{\ln\left(\frac{r_c}{r_b}\right)}{k_B}\right] \tag{5.17}$$

By comparing Eqs. 5.16 and 5.17, the following expression for the equivalent diameter can be obtained:

$$D_{eq} = 2r_{eq} = 2\sqrt{r_a L_s} = \sqrt{2DL_s} \quad D \le L_s \le r_b \tag{5.18}$$

Gu investigated the errors of applying the equivalent diameter to transient heat conduction by comparing the results obtained to the solutions of cylindrical source model. As expected, the errors were largest during the start-up of a transient process, but they dropped to below 5 % after 1 h. Moreover, a conformal mapping technique was employed to develop a more accurate representation of ETR. The results using the conformal mapping technique and the simple analytical expression were compared, and it turned out that the differences between the ETRs calculated with the two methods were within 5 % for a wide range of grout radii and thermal conductivities, the leg spacing, and the surrounding soil radii.

5.4.1.6 Yavuzturk's Model

By extending Eskilson's long time-step model, Yavuzturk (1999) developed the short time-step model by approximating the *g*-functions suitable for shorter time steps. A numerical model was used to compute short time-step average borehole temperatures by a two-dimensional finite difference method using cylindrical coordinates. A simplified representation of the numerical domain implemented to simulate the heat transfer in and around a ground heat exchanger borehole is provided in Fig. 5.8.

To handle the short time-step thermal responses, the short time-step *g*-function needs to allow for the thermal resistance effects inside the boreholes. The following relationships were used for the grout R_g, U-tube pipes R_p and the convection resistance R_c per unit borehole length:

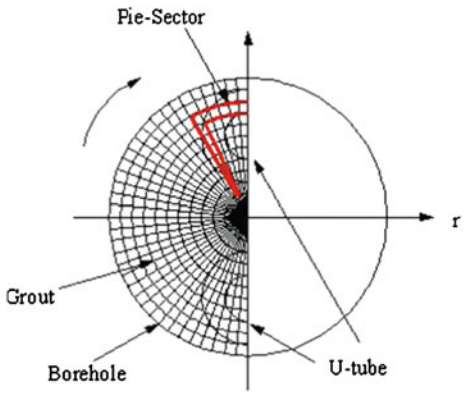

Fig. 5.8 Simplified representation of the borehole region on the numerical model domain using the pie-sector approximation (from He 2007)

$$R_g = \frac{1}{k_g \beta_0 \left(\frac{D_b}{D_p}\right) \beta_1} \tag{5.19}$$

$$R_c = \frac{1}{2pD_{\mathrm{in}} h_{\mathrm{in}}} \tag{5.20}$$

$$R_p = \frac{\ln\left(\frac{D_{\mathrm{out}}}{D_{\mathrm{in}}}\right)}{4\pi k_p} \tag{5.21}$$

$$R_{\mathrm{total}} = R_g + R_c + R_p \tag{5.22}$$

The convection coefficient is determined using the Dittus-Boelter correlation:

$$h_{\mathrm{in}} \cong \frac{0.023 \mathrm{Re}^{0.8} \, \mathrm{Pr}^n \, k_f}{2r_{\mathrm{in}}} \tag{5.23}$$

The total borehole resistance for each time step is multiplied by the heat transfer rate per unit length of borehole for that time step to calculate the temperature rise adjustment. This temperature rise due to the total borehole resistance needs to be subtracted from the temperature value obtained from the numerical model to determine the actual temperature rise for that time step. Consequently, Eq. 5.10 is recast to solve for the g-function with a single step pulse and modified to account for the borehole thermal resistance:

$$g\left(\frac{t_i}{t_s}, \frac{r_b}{H}\right) = \frac{2\pi k \left[T_b - (R_{\mathrm{total}} Q) - T_g\right]}{Q} \tag{5.24}$$

Comparing the results of this numerical model with the analytical cylindrical source model, Yavuzturk found that some error was introduced by assuming the thermal resistances inside the boreholes were in steady-state conditions, but this error diminished rapidly with time. Two applications of the model were reported by Yavuzturk (1999). One was to obtain the thermal response of the ground heat exchanger on shorter time scales in order to design and simulate the ground-source heat pump system, and the other was to model the short time response under in situ conductivity test conditions to estimate the ground and grout thermal conductivity.

5.4.1.7 Zeng's Model

Zeng et al. (2003) developed a quasi-three-dimensional model to determine the thermal influence inside the borehole. He formulated the borehole heat transfer process on a solid analytical basis, while taking into account the fluid temperature variation along the borehole depth and its axial convection. However, the conductive heat flow in the grout and ground in the axial direction was still neglected. Several assumptions were made to develop the model: (1) The heat capacity of the materials inside the borehole and the heat conduction in the axial direction were considered to be negligible. (2) The borehole temperature T_b was regarded as constant along its depth. (3) The ground and the grout were homogeneous. (4) The thermal properties were independent of temperature.

The fluid temperature profiles along the borehole depth can be expressed as a set of coupled linear differential energy equilibrium equations. When combined with certain configuration conditions, these differential equations can be solved by means of Laplace transforms. Taking the inverse Laplace transform, the fluid temperature profile along the borehole depth can be analytically solved and the thermal resistance inside the borehole can be determined accurately. Zeng et al. (2003) investigated the cases of different borehole configurations, i.e., single U-tube borehole, double U-tubes borehole, and the different U-tubes connection inside the double U-tubes borehole, for example, in series or in parallel. Based on these analytical expressions of the thermal resistance, the performance of the ground heat exchanger could be compared between single U-tube and double U-tubes boreholes, and the double U-tubes boreholes with different connection arrangements. By applying this model, Zeng et al. (2003) compared the different heat transfer performance between single U-tube and double U-tubes, and it turned out that the double U-tubes in parallel configuration provided a better thermal performance.

Diao (2004) continued to explore the application of the quasi-three-dimensional model by estimating the impact of groundwater flow on the performance of ground heat exchangers. An analytical transient solution was obtained for a line heat source in an infinite medium by means of the Green function analysis. In the cylindrical coordinates, the mathematical equation of the temperature variation due to the groundwater flow can be expressed as:

$$\theta(r,\varphi,\tau) = \frac{q_l}{4\pi k}\exp\left(\frac{Ur}{2\alpha}\cos\varphi\right)\int\frac{1}{\eta}\left(-\frac{1}{\eta}-\frac{U^2r^2\eta}{16\alpha^2}\right)d\eta \quad (5.25)$$

By applying the solution of Eq. 5.25, Diao (2004) stated that the impact of moderate groundwater flow on ground heat exchangers may be prominent, and more efforts should be made in understanding the implications of hydrogeology.

5.4.2 Heat Transfer Inside Borehole

The thermal resistance inside the borehole is primarily determined by the thermal properties of the grouting materials and the arrangement of flow channels of the borehole. It has a significant impact on the GHE performance. The main objective of analysis on the heat transfer inside borehole is to determine the entering and leaving temperatures of the circulating fluid in the borehole according to the borehole wall temperature, its heat flow and the thermal resistance. A few models with varying degrees of complexity have been established to describe the heat transfer inside the GHE boreholes. The models are summarized by Yang et al. (2010).

5.4.2.1 One-Dimensional Model

A simplified one-dimensional model for GHE design considers the U-tube as a single “equivalent” pipe. In this model, both the thermal capacitance of the borehole and the axial heat flow in the grout and pipe walls are negligible as the borehole dimensional scale is much smaller compared with the infinite ground outside the borehole. Thus, the heat transfer in this region is approximated as a steady-state one-dimensional process. The simplified one-dimensional model was appropriate and convenient for most engineering practices except for the analysis to deal with dynamic responses within a few hours. However, this oversimplified model seems inadequate and unsatisfactory because it is incapable of evaluating the impact of the thermal “short circuiting” between the U-tube legs on the performance of the GHEs.

5.4.2.2 Two-Dimensional Model

Hellström (1991) derived the analytical two-dimensional solutions of the thermal resistances among pipes in the cross-section perpendicular to the borehole axis, which is superior to empirical expressions and one-dimensional model. In the two-dimensional, the temperature of the fluid in the U-tubes is expressed as a superposition of the two separate temperature responses caused by the heat fluxes per unit length, q_1 and q_2 from the two pipes of the U-tube, as shown in Fig. 5.9. If the temperature on the borehole wall, T_b, which is also considered as uniform along the borehole depth, is taken as a reference of the temperature excess, the fluid temperatures in the U-tubes can be obtained from the following Eqs:

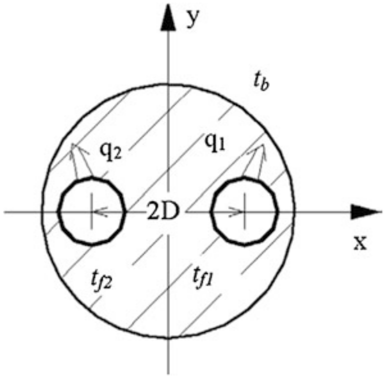

Fig. 5.9 Configuration of a U-tube in a borehole

$$\begin{aligned} T_{f1} - T_b &= R_{11}q_1 + R_{12}q_2 \\ T_{f2} - T_b &= R_{12}q_1 + R_{22}q_2 \end{aligned} \tag{5.26}$$

where R_{11} and R_{22} are the thermal resistances between the circulating fluid in each pipe and the borehole wall, and R_{12} is the resistance between the two pipes. A linear transformation of Eq. 5.26 leads to:

$$\begin{aligned} q_1 &= \frac{T_{f1} - T_b}{R_1^\Delta} + \frac{T_{f1} - T_{f2}}{R_{12}^\Delta} \\ q_2 &= \frac{T_{f2} - T_b}{R_2^\Delta} + \frac{T_{f2} - T_{f1}}{R_{12}^\Delta} \end{aligned} \tag{5.27}$$

where $R_1^\Delta = \frac{R_{11}R_{22} - R_{12}^2}{R_{22} - R_{12}}$, $R_2^\Delta = \frac{R_{11}R_{22} - R_{12}^2}{R_{11} - R_{12}}$, and $\mathrm{R}_{12}^\Delta = \frac{\mathrm{R}_{11}\mathrm{R}_{22} - \mathrm{R}_{12}^2}{\mathrm{R}_{12}}$. For the instance of the symmetric disposal of the U-tube inside the borehole (i.e. $R_{11} = R_{22}$), these resistances can be deduced as:

$$R_1^\Delta = R_2^\Delta = R_{11} + R_{12} \tag{5.28}$$

$$R_{12}^\Delta = \frac{R_{11}^2 - R_{12}^2}{R_{12}}$$

The steady-state heat conduction problem in the cross-section of a borehole was analyzed in detail with the line-source and multiple approximations by Hellström (1991).

It is noted that there is no distinction between the entering and exiting pipes since this model does not take into account the heat transmission on the axial flow of the circulating fluid. In this case, Eskilson (1987) assumed $T_{f1} = T_{f2} = T_f$ and $q_1 = q_2 = \frac{q_l}{2}$ to simplify the problem. Therefore, the thermal resistance between the fluid and borehole wall can be determined by:

$$R_{b2} = \frac{R_{11} + R_{12}}{2} \tag{5.29}$$

With these assumptions, the temperatures of the fluid entering and exiting the GHE can be calculated. Being superior to the model of an equivalent pipe, this two-dimensional model presented quantitative expressions of the thermal resistance in the cross-section, and provided a basis for discussing the impact of the U-tube disposal on the heat conduction. However, the temperatures of the fluid circulating through different legs of the U-tubes are, in fact, different. As a result, the thermal interference or thermal "short circuiting" between the U-tube legs is inevitable, which degrades the effective heat transfer in the GHEs. With the assumption of identical temperature of all the pipes, it is impossible for the two-dimensional model to reveal the impact of this thermal interference on the GHE performance.

5.4.2.3 Quasi-Three-Dimensional Model

On the basis of the two-dimensional model aforementioned, a quasi-three-dimensional model was proposed by Zeng et al. (2003). The model takes account of the fluid temperature variation along the borehole depth. Being minor in the order, the conductive heat flow in the grout in axial direction, however, is still neglected so as to keep the model concise and analytically manageable. The energy equilibrium equations can be written for upflow and downflow of the circulating fluid:

$$\begin{aligned} -Mc\frac{dT_{f1}}{dz} &= \frac{T_{f1} - T_b}{R_1^\Delta} + \frac{T_{f1} - T_{f2}}{R_{12}^\Delta} \\ Mc\frac{dT_{f2}}{dz} &= \frac{T_{f2} - T_b}{R_2^\Delta} + \frac{T_{f2} - T_{f1}}{R_{12}^\Delta} \ldots (0 \le z \le H) \end{aligned} \tag{5.30}$$

Two conditions are necessary to complete the solution:

$$\begin{aligned} z = 0,\ T_{f1} &= T_f' \\ z = H,\ T_{f1} &= T_{f2} \end{aligned} \tag{5.31}$$

The general solution to this problem is derived by Laplace transformation, which is slightly complicated in form. For the instance of the symmetric placement of the U-tube inside the borehole, the temperature profiles in the two pipes were illustrated by Diao et al. (2004). For the purpose of practical applications an alternative parameter $\varepsilon = \frac{T_f' - T_f''}{T_f'' - T_b}$ is derived from the temperature profiles, which is named as the heat transfer efficiency of the borehole. It should be noticed that T_f' and T_f'' and are the entering/exiting fluid temperatures to/from the U-tube. From the derived temperature profile, a more accurate heat conduction resistance between the fluid inside the U-tube and the borehole wall can be calculated by

$$R_{b3} = \frac{H}{Mc}\left(\frac{1}{\varepsilon} - \frac{1}{2}\right) \tag{5.32}$$

The authors validated that the quasi-three-dimensional model was more accurate than the other current models and recommended it for the design and thermal analysis of the GHEs.

5.5 Current Status

The first field experiments for a BTES system occurred in 1976 in France, and the first large-scale system was brought online in 1982 near Luleå, Sweden. The largest BTES field in the world was built in 1995, consists of 400 boreholes with a depth of 135 m, and is located at Richard Stockton State College, Pomona, New Jersey, USA.

5.5.1 Sweden

Sweden is one of the leading countries in using the BTES for heating and cooling. Heat pumps are usually part of such systems that supplies about 20 % (20 TWh) of all space heating in Sweden (Nordell et al. 2007). There are about 300,000 heating systems in operation for single-family houses, with an increase of 35–40,000 systems, annually. During the last decade more than 1,000 larger systems have also been constructed. These are usually for both heating and cooling though there are large plants for heating only or cooling only. This energy efficient technology is environmentally benign since extracted heat is renewable energy that is passively stored from ground surface. These systems are most efficient if low-temperature heat distribution systems are used.

Heating systems by using the ground for heat extraction have been increasingly popular during the last decades. Typical payoff times are 10–15 years but the rising energy cost improves the economy considerably. Another fact is that the value of the house increases at least with the investment. For larger systems >1,000–3,000 MWh the economy is considerably better with typical payoff times of 2–6 years.

Large-scale BTES are mainly used for seasonal heat storage. Typical heat sources are industrial waste heat or solar heat. The most favorable system is high-temperature storage for low-temperature applications, where no heat pump or additional heating is required. The solar system in Anneberg, Stockholm, is a good example of how solar heat is stored and used for space heating. In this case, about 1,000 MWh is stored from the summer and used for heating of 60 single-family houses during the winter. Stored heat is used at a temperature of 32 °C, for heating of tap water and space heating through the low-temperature floor heat distribution system.

Storage temperatures up to about 80–90 °C are used in BTES though low-temperature systems are most common. Occurring heat losses from such systems depends on the bedrock properties, temperature, geometry, and volume. The first high-temperature BTES (82 °C), with a volume of 120,000 m^3, was constructed in Luleå, Sweden. Its heat loss was about 40 %. In larger (few hundred thousand m^3) heat temperature BTES systems the annual loss is about 10–15 %.

5.5.2 Canada

Two systems have recently been developed in Canada. The first being North America's second largest field, built in 2004 at the University of Ontario Institute of Technology. The field consists of 370 boreholes with a depth of 200 m, arranged in a 14 by 27 grid with 4.5 m spacing (Wong et al. 2006). Now, the thermal storage system is a critical component of the university's heating and cooling system, and helps to keep the cost down and the efficiency up. In addition, the thermal storage system is used for research and to educate students in TES. Researchers and students have the rich opportunity of on-site research and education in one of North America's biggest geothermal fields (Gao et al. 2009).

The second Canadian example is the 52-house Solar Community, in Okotoks Alberta. This project uses both a BTES field and two above-groundwater thermal storage tanks. The solar BTES residential development is located in a new development called the Drake Landing community. The new subdivision to be heated by an integrated solar and BTES system consists of 52 single-family homes each with floor space in the range of 1,400–1,600 square foot. Systems relying on thermal resources having significant short-term variations such as solar thermal usually combine the larger seasonal storage system with a smaller water-filled buffer tank to increase short-term response. The borehole field consists of 144 boreholes, each 35 m deep with 150 mm diameter, with 2.25 m spacing. The system contains 24 parallel circuits, each having six boreholes in series. This system saves more than 110 GJ of energy, and five tons of GHGs per home annually, and has a solar fraction (percentage of energy use that is met by solar gains) of nearly 90 % (Wong et al. 2006). These examples show that BTES systems are feasible for a large range of project types and settings.

5.5.3 Belgium

BTES applications are an alternative solution for regions where ATES applications cannot be applied due to the absence of an aquifer and are normally used in small-scale applications in the commercial sector such as hospitals, office buildings, etc., for cooling and heating. According to Desmedt et al. (2006), there is large interest in BTES applications in recent years. VITO carried out several feasibility studies in the health and commercial building sector on ground-source heat pumps (GSHP) in combination with vertical borehole heat exchangers (BHEs). A number of these feasibility studies have resulted in concrete projects. The easy way of installing and operating the BTES in conjunction with ATES applications has an important impact on this evolution. BTES applications are most suitable for seasonable thermal storage such as solar heat, heat from cogeneration units during summer period, etc., and are a proved technology to work without any leaks or collapses. One other advantage of these applications is that the system can be used for direct or natural cooling during summer period (without the need for a classical mechanical chiller consuming a lot of electricity), on one condition that the air handing units (AHUs) are suitable and designed for the higher temperature levels (e.g. 14/18 °C instead of 6/12 °C for cooling purposes). This natural cooling can be delivered at a high COP (coefficient of performance) and by regenerating the ground this delivers an improved heat pump operation in winter period. Under normal conditions, small-scale BTES applications for combined heating and cooling commonly will be paid back within 7–10 years.

During winter the high-temperature heat (radiators) is produced by gas-fired boilers and the low-temperature heat (AHUs, floor heating) by the heat pump. If the heat from the heat pump is insufficient the gas-fired boilers can support them. The heat pump is designed for a part of the low-temperature heat demand because the BHE's cannot deliver the whole needed evaporator heat. The number of BHE's is determined on an economic optimum.

During summer period (only cooling) the BHE's deliver direct or natural cooling at a temperature level of 14/18 °C. If the cooling demand is higher than the limit of the BHEs, the reversible heat pump and/or the classical chiller can deliver the extra cooling.

Most of the BTES applications are situated in hospitals and office buildings where of course ATES was not possible for the location. The typical heating and cooling capacity is 25–650 kW using 10–250 boreholes 30–150 m in depth. Typical layers consist mainly of sand or sand and clay.

When designing BHEs with GSHPs the knowledge of ground thermal properties (thermal conductivity, borehole thermal resistance, undisturbed soil temperature, specific heat capacity, etc.) are important for correct functioning of the system. Due to the higher investments costs, oversizing of BHEs and GSHPs pays a higher penalty than in conventional applications. Obtaining accurate values for thermal ground properties requires detailed survey on site by a thermal response test. Parameters that can have an influence on the result are the building load, borehole spacing, borehole fill material, and the on-site characteristics. In the last year, there was a growing interest in thermal response tests. In situ testing has recently become a standard measurement for larger BTES applications.

However, the data obtained from a thermal response test is useless data for engineering companies. The reason why BTES application are nowadays not common practice is the lack of technical knowledge from engineering companies, no financial incentives for the technology, extra investments costs, no believe in the proven BTES technology, etc. Most of the engineering companies and building owners find that the integration of BHEs and GSHPs can be simplified by some rules of thumb as they are used for calculating the heating and cooling demand of buildings. The opposite is true. When designing new buildings the owner appoints an engineering company that must know every innovative technique that is available in the sector. This is impossible for small engineering companies due to lack of personnel. The building sector in Belgium has to search for advice by energy consulting companies when designing new buildings. This needs a change in mentality which can not be solved in a few years and needs the cooperation of several actors in the building sector.

5.5.4 Germany

Mangold (2007), Mangold and Schmidt (2009), and Nuβbicker-Lux et al. (2009) reported the history and current status of BTES in Germany. Since 1997 a pilot borehole thermal energy storage is in realization in Neckarsulm. In the first step, the feasibility of the storage concept was proven with the installation of a 5,000 m^3 research storage at the site of the plant. The ducts are double-U-pipes made of polybutene with a depth of 30 m. The design data of the model calculations have been validated by the experimental results of the monitoring program. In 1999, the storage was enlarged to a storage volume of 20,000 m^3. In 2002, the next phase of the solar assisted district heating project was started: the borehole storage was enlarged to 63,300 m^3 storage volume reaching half of the finally planned volume. The BTES is directly connected to the heat distribution network and charged by the solar collectors by means of two 100 m^3 buffer tanks. The two buffer tanks are used for short-term heat storage to balance peaks in heat delivery from the solar collectors. The buildings are connected to the district heating system via a 3-pipe heat distribution network. The heat distribution network is supplied either by the buffer tanks or the BTES, depending on the temperature level. A condensing gas boiler supplies additional heat to provide the required temperature level.

Next generation borehole thermal energy storage was built in Crailsheim in 2008. The storage consists of 80 boreholes with a depth of 55 m in a first construction phase. The storage volume (37,500 m^3) is a cylinder with the boreholes situated in a 3 $\times$ 3 m square pattern. The ground heat exchangers are double-U-pipes made from cross-linked polyethylene (PEX). The storage volume will be doubled when the second part of the connected residential area is going to be built in some years.

The hydro-geological investigation showed an intermittent water movement in the upper part (5 m) of the storage volume. For this reason, the boreholes were drilled with a bigger diameter in this part. After installation of the ground heat exchangers the lower part was filled with a thermally enhanced grouting material (thermal conductivity 2.0 W/mK), whereas the upper part was filled with a thermally reduced grouting material to reduce the heat transfer into this layer and thereby the thermal losses due to the water movement in this region. The horizontal piping on top of the storage is embedded into an insulation layer of foam glass gravel. On top of the insulation layer a protecting foil (water-tight but open for vapor diffusion) and a drainage layer (gravel) are installed below a 2 m layer of soil.

5.5.5 Switzerland

In Switzerland, geothermal heat pump systems have found a high level of popularity for space heating purposes and deliver in total an annual geothermal energy of ~ 1 TWh (Signorelli 2004). Actual statistical evaluations show that in Switzerland >50 % of geothermal energy is produced by borehole heat exchangers (BHEs).

Since BHE heating systems mainly use the temperature field below a depth of 20 m, which is not influenced by atmospheric conditions or seasonal variability, they always achieve a high efficiency even when the ambient air temperature is low. For BHE-coupled heat pumps COP values are generally higher than 4. This fact has contributed to the high popularity of BHE systems in Switzerland. Since 1980 over 30,000 buildings have been heated by BHE systems, corresponding to 4,700 km of drilled BHEs. Most BHE systems are located in the Alpine Foreland, the most densely populated area. In terms of areal density (BHE/km^2), Switzerland is the world leader in this ecologically friendly technology.

5.5.6 Norway

Today, the most frequently used energy storage technology for heat and cold is Underground Thermal Energy Storage (UTES) systems combined with Ground-Source Heat Pumps (GSHP). The Norwegian geology favors Borehole Thermal Energy Storage (BTES) applications and at present time the number of BTES installations is about 90 (Midttømme et al. 2009).

An example of a standard BTES has recently been completed at Falstadsenteret, a 2,850 m^2 historical museum in Levanger. The heating and cooling system comprises a 130 kW heat pump and thirteen 180 m deep Borehole Heat Exchangers (BHE). The total cost of the GSHP and BTES is 170,000 Euro, and the payback time compared to conventional heating and cooling systems is estimated to be 12 years. Some of the largest BTES systems in Europe are located in Norway as indicated in Table 5.1.

A BTES system comprising 228 boreholes of 200 m depth was drilled during winter 2007, and will provide heat and cold to the new Akershus University Hospital (Ahus). The building has a total floor area of 137,000 m^2, and an annual heating and cooling demand of 26 GWh and 8 GWh, respectively. One of the goals

Table 5.1 Large capacity BTES systems in Norway (from Midttømme et al. 2009)

Project	No. of BHE	Depth BHE	GSHP capacity (MW)	Year of construction
Akershus University Hospital, Lørenskog	228	200	8	2007
Nydalen business park, Oslo	180	200	6	2004
Ullevål stadion, Oslo	120	150	4	2009
Post terminal building, Lørenskog	90	200	4	2010
IKEA, Slependen, Asker	86	200	1.2	2009
Ericsson, Asker	56	200	0.8	2001
Alnafossen office building, Oslo	52	150	1.5	2004

for the energy systems was that renewable energy sources should provide a minimum of 40 % of the supplied energy for heating and cooling.

The BTES became operational in May 2007, but the second phase of drilling is planned in 2009/2010 to provide an extension of the BTES scheme making a total of 350 boreholes. The boreholes are drilled in dioritic rocks with 5-40 m clay cover. The thick clay cover increases the drilling cost. A combined ammonia chiller and heat pump system is installed. The total cost of the BTES and the GSHP system is 19.5 million USD.

It was originally planned to drill the boreholes close to the hospital, but seismic geophysical surveys and test drilling showed a high density of the clay filled fracture zones. This observation suggested that full-scale drilling would be difficult and expensive. The proposed BTES borehole array was therefore relocated to a field about 300 m from the hospital. Today, the borehole heads are completely underground, and the farmer is using the field to grow crops.

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Chapter 6
Cavern Thermal Energy Storage Systems

6.1 Introduction

Cavern thermal energy storage (CTES) belongs to the seasonal sensible liquid storage in various forms of underground cavities (EU Commission SAVE Programme and Nordic Energy Research 2004). Potential structures for CTES include abandoned mines, tunnels or rock caverns, natural karst structures, and artificially constructed caverns in rock or deep pits in soil. For artificial caverns, CTES needs construction of large underground water reservoirs to serve as the thermal energy system. Enormous investment for the construction limits the practical application of the cavern storage method, which is seldom used nowadays.

When warm/hot water is first filled into the cavern, the heat losses to the surrounding rock mass will be substantial. However, during the first year or two after charging, the cavern develops a relatively stable thermal halo around itself with decreasing temperature away from the warm/hot center. There will still be a loss of heat, but dry rock is generally a poor heat conductor. The heat loss should be less than 10 % during one operational cycle under favorable conditions. A crucial factor is groundwater transport through the rock masses in the area, the less the better.

The advantage of rock cavern heat storage includes very high injection and extraction powers (just a matter of pump capacity), while the disadvantage is its high construction cost. There are some examples of how old rock caverns, previously used for oil storage, have been converted for high temperature water storage (Nordell et al. 2007).

In the rock CTES, energy is stored as hot water in an underground cavern. In such a system with a large volume of water it is of great importance to maintain a stratified temperature profile in the cavern. During injection hot water is injected at the top of the store while colder water is extracted from the bottom.

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6.2 Analysis

Rehbinder and Reichelt (1984) considered the quasi-steady solution of the heat conduction equation for this geometry with periodic temperature variations. The analysis is based upon a number of simplifications and assumptions. They also assumed that the convection of heat with the groundwater can be neglected. The density and heat capacity of the rock are constants and the heat conduction coefficient is isotropic and constant. The cavern is a torus with cylindrical symmetry. The cavern is assumed to be located well below the ground, implying that the presence of a free ground surface can be neglected. The first assumptions, dealing with the rock properties, are reasonable; for economic reasons the cavern has been located in very good quality rock. The shape of the cavern is not perfectly symmetrical but the deviation is small. The last assumption, that the ground surface has no influence, is the most questionable since the distance between the top and bottom of the cavern is equal to the distance between the top of the cavern and the ground surface.

Consider a region exterior to a torus Ω symmetric with respect to the z-axis, with the boundary $\partial\Omega$. Let the inner radius of $\partial\Omega$ be the characteristic length of the problem (Fig. 6.1). At $\partial\Omega$ the temperature T is prescribed $T_o\Phi(r,t)$ where the constant T_o is the characteristic temperature of the problem, and $\Phi(r,t)$ is a given function of $[0,\infty)\times\partial\Omega$. The temperature is assumed to vanish at infinity. The initial temperature is zero. The region consists of a rock whose heat conduction is λ, heat capacity C, and density ρ. These parameters can be combined giving the diffusivity $\alpha = \frac{\lambda}{\rho C}$. Thus with cylindrical coordinates:

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right) \text{ in } \Omega \tag{6.1}$$

$$T(r,z,t) = T_o\Phi(t,r) \text{ on } \partial\Omega\ t \geq 0$$
$$T(r,z,t) = 0 \quad r^2 + z^2 \to \infty \quad t > 0$$
$$T(r,z,t) = 0 \text{ in } \Omega\ t < 0$$

The solution can be expressed with the T-matrix representation used in scattering theory. To solve the limiting problem $\varphi(t,r) = \exp(i\omega t)$ when $t \to 0$, the following variables are introduced.

$$u = \frac{Te^{-i\omega t}}{T_o} \tag{6.2}$$

$$\xi = \frac{r}{a}$$
$$\zeta = \frac{z}{a}$$
$$\tau = \frac{\alpha t}{a^2}$$

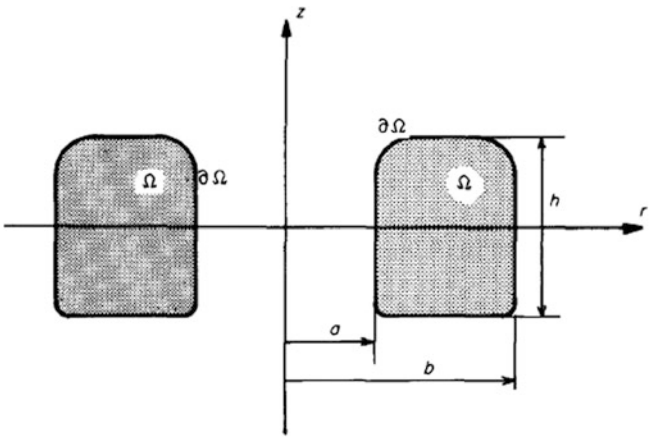

Fig. 6.1 The torus region

$$\hat{b} = \frac{b}{a}$$
$$\hat{h} = \frac{h}{a}$$
$$\hat{\omega} = \frac{\omega a^2}{\alpha}$$
$$k = e^{\frac{3\pi i}{4}} \hat{\omega}^{\frac{1}{2}}$$

The heat conduction problem above is then reduced to a boundary value problem for the Helmholtz equation. The parameters a, b, and h can be varied to study their effect on u. Helmholtz problem in cylindrical coordinates is:

$$\frac{\partial^2 u}{\partial \xi^2} + \frac{1}{\xi}\frac{\partial u}{\partial \xi} + \frac{\partial^2 u}{\partial \zeta^2} + k^2 u = 0 \; in \; \Omega \tag{6.3}$$

$$u = 1 \; on \; \partial\Omega$$

$$\lim_{R \to \infty} R\left(\frac{\partial u}{\partial R} - iku\right) = 0 \; R = \sqrt{\xi^2 + \zeta^2}$$

Rehbinder and Reichelt (1984) sought the solution in the form of a linear combination of particular solutions, which satisfy Eq. 6.3. By using cylindrically symmetric particular solutions, it can be shown that the cylindrically symmetric three-dimensional problem on an infinite domain is reduced to a one-dimensional approximation problem on a curve of finite length.

If $\hat{h} \gg 1$, the solution of Eq. 6.3 in the vicinity of $\zeta = 0$ is equal to the solutions for pure radial flow. These solutions can be found in Carslaw and Jaeger (1959)'s textbook.

$$u = \frac{K_0(k\xi)}{K_0\left(k\hat{b}\right)} \quad \xi \geq \hat{b} \; |k| > 0$$

$$u = \frac{I_0(k\xi)}{I_0(k)} \quad \xi \leq 1$$

The modified Bessel functions K_v, and I_v, for a complex argument are most conveniently expressed with the modulii M_v, and N_v, and phases θ_v and φ_v, of Kelvin's functions. Then, the solutions can be in simple form:

$$u(\xi) = \frac{N_0\left(\xi\sqrt{\hat{\omega}}\right)}{N_0\left(\hat{b}\sqrt{\hat{\omega}}\right)} e^{i\left[\phi_0\left(\xi\sqrt{\hat{\omega}}\right) - \phi_0\left(\hat{b}\sqrt{\hat{\omega}}\right)\right]} \quad \xi \geq \hat{b}$$

$$u(\xi) = \frac{M_0\left(\xi\sqrt{\hat{\omega}}\right)}{M_0\left(\hat{b}\sqrt{\hat{\omega}}\right)} e^{i\left[\phi_0\left(\xi\sqrt{\hat{\omega}}\right) - \phi_0\left(\hat{b}\sqrt{\hat{\omega}}\right)\right]} \quad \xi \leq 1$$

6.3 Current Status

Two CTES systems were built in Sweden, Avesta with a volume of 15,000 m^3 and Lyckebo with a storage volume of 115,000 m^3. The Avesta CTES was built in 1981 for short-term storage of heat produced at an incineration plant. The Lyckebo store, which is partly heated by solar energy, has been in operation since 1983. The storage volume of 115,000 m^3 had a maximum water temperature of 90 °C and 5,500 MWh of heat was stored between the seasons (Nordell et al. 2007). There were a few more CTES systems built but in these cases the caverns used were not initially constructed for CTES. There are examples of shut down mines and oil storage caverns that have been reconstructed for hot water storage.

For the time being, there are no CTES applications for storage of cold in caverns. However, storage of snow (or ice) in pits is a promising storage concept. One such demonstration project has been realized in Sundsvall, Sweden. Here, a snow pit supplies some 2 MW of comfort cooling to a hospital, as shown in Fig. 6.2 (EU Commission SAVE Programme and Nordic Energy Research 2004).

The snow melted by heat transfer from the surroundings is called natural melting, and it depends on climate, area of the storage, and insulation. In the Sundsvall case, the pit is only a couple of meters deep, and to prevent the natural melting, the snow layer is insulated with wood chips. In this case, the predicted natural melt is about 20–25 % of the 30,000 m^3 snow pile. Cold can be extracted either by putting pipes under the snow pile and circulating a heat carrier, or by circulating the melted water itself. In Sundsvall, the melt water circulation solution is used.

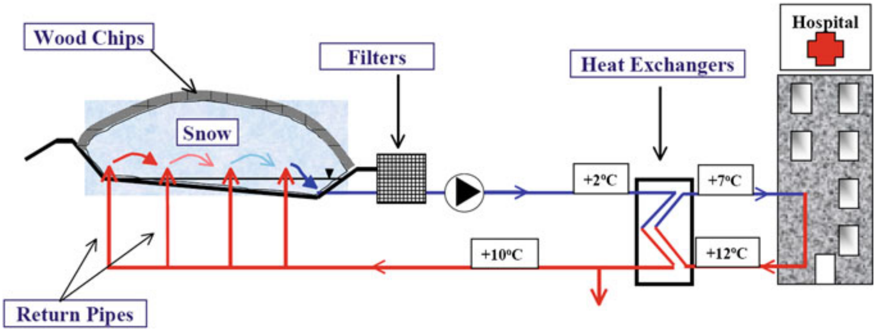

Fig. 6.2 The principal configuration of the Sundvall snow storage (from EU Commission SAVE Programme and Nordic Energy Research 2004)

Snow can be made with snow guns or collected from streets and squares during winter. Snow collected from cities is normally polluted. With the snow pit technique, the melt water can be cleaned from pollutions, which is the case in Sundsvall.

In case there is a lack of natural snow for storage, snow guns can be used to produce artificial snow very efficiently at a low cost. Water, electricity, and cold ambient air are then needed. The temperature has to be below −2 °C and the water close to the freezing point to make snow in an efficient way. The COP for making artificial snow varies between 50 and 500, depending on water and outdoor temperature, humidity, wind, and equipment.

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Chapter 7
Standing Column Well

7.1 Definition

A number of ground systems cannot be categorized either as open or as closed. Such a system is the standing column well (SCW) shown in Fig. 7.1, where water is pumped from the bottom of the well to the heat pump (Florides and Kalogirou 2007). The exiting water is percolated through gravel in the annulus of the well in order to absorb heat. Standing wells are typically 15 cm in diameter and may be as deep as 500 m.

In his chapter, Deng (2004) provided an excellent review on SCW and this chapter is mainly based on his work. SCW systems are also referred to in the literature as “turbulent wells”, “energy wells”, “concentric wells”, “recirculating wells”, “geo-wells”, “thermal wells”, and “closed-loop, open-pipe systems”.

The use of SCW was first suggested by local Maine well drillers and hydrogeologists. In fact, the concept of SCW systems is about as old as the groundwater heat pump systems, but is recently receiving much more attention because of their lower installation cost, lower operating cost, and improved overall performance in the regions with suitable geological conditions.

Compared to other ground heat source heat pump systems, shorter boreholes and more stable water temperatures make the SCW system an attractive commercial and industrial design approach. Now, there are approximately 1,000 SCW installations in the United States. Most of them are located in the Northeast and Pacific Northwest in addition to parts of Canada in heating-dominated residential and light commercial applications. These regions have lower mean ground temperature and higher heating loads than other areas, so now most SCW design is focused on heat extraction.

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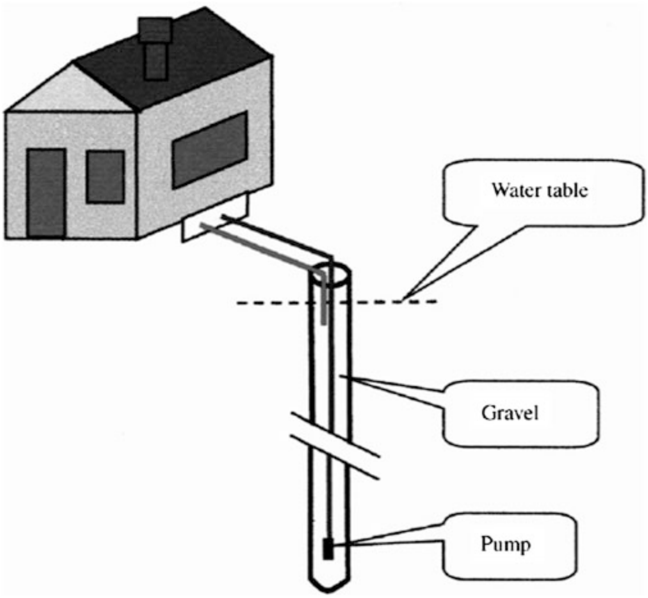

Fig. 7.1 Standing column well (from Florides and Kalogirou 2007)

7.2 Operation

The SCW system can be considered as a cross between closed-loop earth-coupled system and open-loop groundwater source system. During much of the year, they are operated by recirculating water between the well and the heat pump. However, during peak temperature periods, they can “bleed” some water from the system to induce groundwater flow. The SCW systems adopted various numbers of wells depending on system capacity. Usually, only one well is required. Larger projects may have several wells in parallel.

In SCW systems, water is recirculated between the well and the building (heat pump). Deep bores are drilled in hard rock, creating a standing column of water from the static water level down to the bottom of the bore. Water is recirculated from one end of the column to the heat pump, and back to the other end of the column (Fig. 7.2).

During peak heat rejection or extraction periods, if the well-water temperature drops too low or climbs too high, SCW systems can bleed part of the water rather than returning it all to the well. This causes water to flow to the column from the surrounding formation to make up the flow. This cools the column and surrounding ground during heat rejection in the summer, and heats the column and surrounding ground during heat extraction in the winter. This flow thus restores the well-water temperature to the normal operating range and improves the system performance. The bleed water can be diverted to a storm sewer, used for domestic water

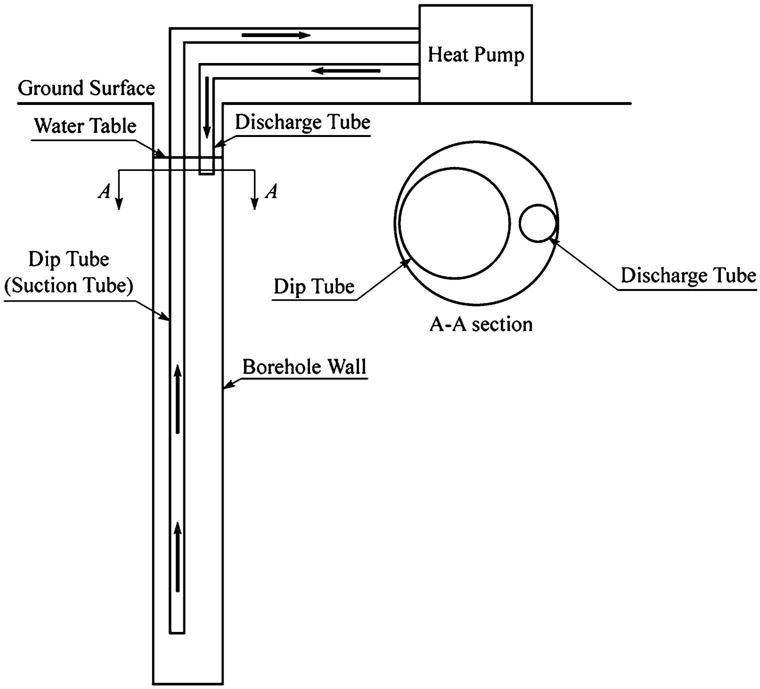

Fig. 7.2 A schematic drawing showing the borehole arrangement (redrawn from Deng 2004)

consumption, or otherwise disposed. Sometimes, SCW systems serve to provide household domestic water, which cause the system to naturally bleed the whole year.

7.3 Applications

SCW systems are used in geologic regions with abundant groundwater. This system can provide the necessary water flows as well as shorter heat transfer lengths (depths) and the ability to return water to the same aquifers. The combination of relatively shallow water table and a deep well (sometimes greater than 300 m) means that the well has a large water volume, about 1,800 L per 100 m for a 152.4 mm nominal diameter well. Based on experience, 50–60 feet of water column is needed per ton of building load (4.3–5.2 m/kW). Commercial systems larger than 350 kW (100 tons) have successfully used multiple SCWs.

The application of SCW systems is limited to geologic areas with good groundwater quality like other groundwater heat pump systems. This enables the groundwater to be directly circulated through the heat pump. Applications may also exist in areas with poorer water quality. In such situations, it is common practice to use an intermediate heat exchanger between the well and the heat pump in order to avoid fouling the heat pump heat exchangers.

It is suggested that the designer of SCW systems should (1) work with an experienced local hydrologist and (2) avoid any areas with salt bed or other formation that could be dissolved. Also, any water well including SCWs must be constructed, developed, and operated according to state and local regulations for water wells. It is imperative that designers and installers of SCW systems be aware of the regulations in their locations.

SCW systems have some advantages shared with all the other forms of ground source heat pump systems:

- Economy

When properly designed, a geothermal heat pump system is one of the lowest cost ways of providing heating/cooling because of high equipment efficiency, annual storage/reuse of energy, and availability. However, geothermal heat pump systems have comparatively high capital costs. A geothermal system often has lower life cycle costs than conventional systems due to its reduced energy and maintenance costs. Because there is no outdoor equipment in the geothermal systems, corrosion, weathering, and vandalism are not normal problems.

- Environmental benefits

The need for electricity (pumps) introduces the only credible source of possible environmental concern for a geothermal system. The geothermal system itself produces zero local pollution. This system causes less carbon dioxide emission and other pollutants than its conventional alternatives, thus reducing global warming and other environmental impacts.

- Reduced requirement for mechanical room floor place
- Quiet operation
- Potential for reducing the peak electrical demand

Standing column well systems share the same advantages, in terms of energy efficiency, environmental benefits, low maintenance, etc., with other forms of geothermal heat pump systems. At the same time, the heat exchange rate in a SCW is enhanced by direct contact and by the pumping action, which promotes groundwater flow to and from the borehole. Consequently, heat transfer with the surrounding rock takes place by advection in addition to conduction. If a SCW is considered as a cylinder, the surface area for heat exchange of a 152.4 mm borehole with 304 m long is about 145 m^2, which allows substantial heat exchange. Putting another way, SCW systems have substantially heat exchange rate and the fact that such systems are open loop means that the fluid flowing through the heat pump system is closer to the mean ground temperature compared to systems with closed-loop U-tube heat exchangers.

SCW systems have a lower initial cost because the borehole depths are in the 50–60 feet per ton compared to closed loops at 150 or more feet per ton. Thus, the borehole in SCW systems could be one-half the depth of closed-loop earth-coupled methods. To date, the typical drill rigs in the regions where SCW system are mainly located (Northeast and Pacific Northwest), can be able to reach 560 m and the deepest SCWs are in the range of 460 m. The depth of this cost-effective geothermal coupled method can be extended with the development of rigs.

7.4 Current Status

7.4.1 United States

A survey of installations and details of some projects are given by Orio et al. (2007). They have collected data from 34 wells at 21 locations. They are believed to be representative of current installation practice and geographic distribution. These installations all have heating-dominated loads. Heat extraction has accordingly been the main focus of these well designs. Bleeding of the well to induce flow of groundwater at more moderate temperatures into the well is a key feature of the well and system designs.

There are approximately 1,000 SCW installations in the United States. Most of them are located in the Northeast and Pacific Northwest in addition to parts of Canada for residential and light commercial applications. These regions have lower mean ground temperatures and higher heating loads than other areas. Consequently, the SCW design has been focused on heat extraction capacity. Also there are some installations out of North America.

Construction differences existing in the reported SCWs relate in part to the depth of the well rather than any other influencing parameter. Shallower wells with depths less than 150 m tend to be dominated by placement of the pump near the bottom of the well with the return located near the top. Deeper wells with depth greater than 150 m mostly use dip tubes constructed of 100 mm diameter PVC pipe to the bottom of the well. The pump and return pipe ends are located near the top of the well, taking into account drawdown depths at bleed flow rates of from 2 to 25 % of total heat pump flow depending on the application.

The location and hydraulic properties of the different groundwater regions of North America have been presented. The regions where SCW installations have been identified are all in the Northeast of North America. Each of these regions has igneous or metamorphic rock where relatively high well capacities and good water quality are available.

The Haverhill public library is located in Haverhill, Massachusetts. There are four SCWs to provide a heat sink/source for water-to-water heat pumps (initially two SCWs in 1994 but expansion of the library resulted in two additional SCWs after 1996). Each of the SCW wells is 457 m deep. Water is drawn from the bottom of the well, run through the heat pump and discharged at the top of the well.

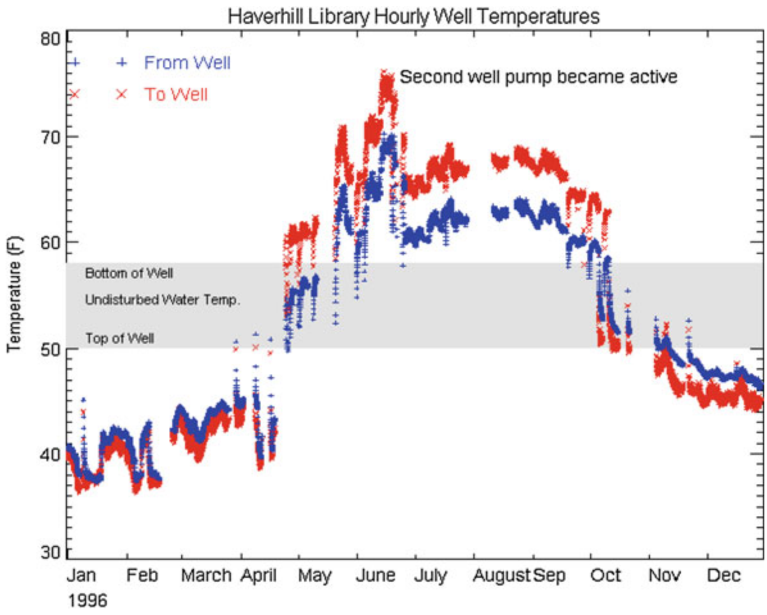

Fig. 7.3 Standing column well-water temperature trends in Haverhill public library (http://www.cdhenergy.com/ghp/haverhill/haverhill_main.htm)

Whenever the well-water temperature drops below 4.44 °C, a bleed cycle initiates. This automatic bleed diverts approximately 10 % of the flow from returning to the wells. A bleed cycle typically lasts for 30 min. It acts to limit the lower well temperatures by drawing in new warmer groundwater from far field. There is no bleed for high temperatures.

As Fig. 7.3 shows the well-water temperature remained above 2.78 °C and generally operated in the lower 40s °F during heating mode. The peak loop temperature reached 21.1 °C in June. However system operation changed after June 25th when the second well pump became active and the maximum well temperature remained below 18.9 °C thereafter. There was also less variation in the temperature after June 25 in both heating and cooling mode.

7.4.2 China

From March 2001 to present, Ever Source Science & Technology Development Co. Ltd. in Beijing, China, has been applying the concept of the SCW in about 200 projects, with the name "single well for supply and return" (Deng 2004). The schematic drawing of the single well is shown in Fig. 7.4. A heat exchanger is located at the well mouth, where the well water and recycle water circulated in separate loops. Therefore, the groundwater from the well is neither consumed nor

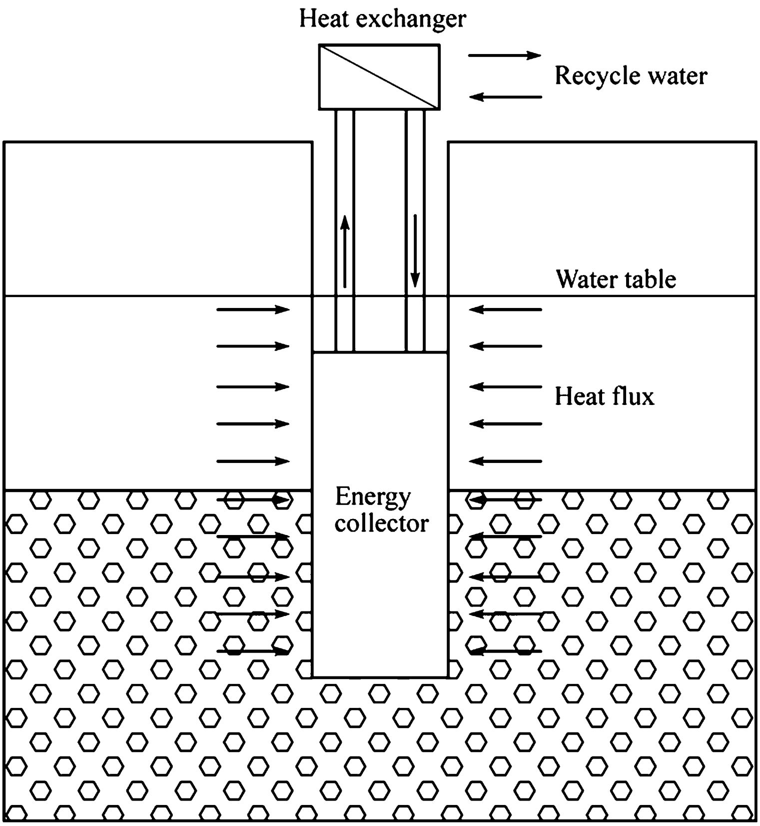

Fig. 7.4 The schematic drawing of "single well for supply and return" (redrawn from Deng 2004)

polluted. According to their experience, this single well system can solve problems such as moving sands, pollution of groundwater, and collapse, which are all related to multi-well systems. More detailed technical information about this system is not available.

From December 12, 2003 to March 17, 2004, Ever Source Science & Technology Development Co. Ltd. measured the energy consumption of 11 different type of buildings in Beijing. These buildings use SCWs as a heat source for heating in winter. This investigation shows that energy consumptions of 7 buildings among the 11 buildings are lower than that of the conventional heating system with a coal boiler. All 11 buildings have lower energy consumptions than other conventional oil/gas/electrical boiler heating system.

7.4.3 Korea

According to Lee (2009), 31 SCW systems were reported in Korea. Most of the groundwater wells (74.2 %) in the SCW system were installed at depths of 300–500 m with a mean of 391 m. It is considered that deeper wells in Korea are necessary due to the installation of SCW systems in public and education buildings that have larger system capacities.

The SCW systems adopted various numbers of wells depending on system capacity. The number of groundwater wells ranged between 1 and 12 with a mean of 4.4 wells for each system. Similarly, with SCW systems in North America, well diameters were generally 150 mm in bedrock with 200 mm steel casing from the ground surface to the interface between upper soil and lower bedrock.

The installation cost of SCW systems depends mainly on system capacity. For the period of 2003–2006, the installation costs of SCW system (1055 kW) was $1,164,000. Meanwhile, the installation cost per unit capacity gradually decreased with years. The decease in the cost appears to be derived from the progress of installation technology, and award competition in the market between geothermal companies. In 2008, the authority (Korea Energy Management Corporation) revised the recommended unit costs to $3,552/usRT for SCW systems.

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Chapter 8
Modeling

8.1 General Aspects of Modeling

Performance of TES is influenced by various factors such as location, construction type, size, geometry, storage medium, and used materials. Furthermore, TES are integrated in heating and cooling systems with a great variety of system configurations and control and operation strategies. Boundary conditions also influence the energetic and exergetic efficiency of TES. Hence, for a realistic comparison system simulations are required, which include all sensitive parameters (Ochs et al. 2009).

The comparison of different (seasonal) TES is difficult. Comparing different types of TES (ATES, BTES, tank, pit) without consideration of the entire energy system (including production, distribution and load) may lead to wrong conclusions. The following parameters have to be considered.

- The volume and geometry of the TES, the design of the composite wall (concrete, insulation, and liner), the distribution of insulation (cover, side wall, and bottom), the insulation thickness and type may differ. The geometry (e.g. cuboid, cylinder, or cone) influences both the surface-to-volume-ratio which determines the thermal losses and the height-to-diameter ratio which influences the quality of thermal stratification.
- The location may affect performance. For example, thermal losses depend on the ambient and soil temperature and on soil properties, in particular the thermal conductivity and the volumetric heat capacity. At locations with groundwater, with or without regional groundwater flow, thermal losses are higher.
- The operational conditions such as the (average and maximum/minimum) operation temperatures, the return flow temperature of the heating net, or the number of charging cycles may differ with each system.

All these constructional and operational characteristics as well as the boundary conditions influence the energetic and exergetic efficiency of (seasonal) TES.

K. S. Lee, *Underground Thermal Energy Storage*, Green Energy and Technology,
DOI: 10.1007/978-1-4471-4273-7_8,

Hence, system simulations, which include all sensitive parameters, are required for a realistic comparison of different TES. Obviously, quality of system simulations depends on the quality of applied models for the individual components such as solar collector, heat pump, or TES.

Basically, TES models can be distinguished into detailed models using computational fluid dynamics (CFD) and coarse models. Detailed or CFD models enable the exact representation of the real geometry in a discretized fashion using finite-difference method (FDM), finite-element method (FEM), or finite-volume method (FVM). All transport phenomena occurring in reality can be considered. CFD models require the solution of partial differential equations (PDE) for all the physical values such as temperature, pressure, and velocity. It is possible to integrate CFD models, which predict the thermo-hydraulic behavior in a detailed way, into system simulation tools. However, the computational effort is enormous. A further disadvantage of CFD models is that every change of the geometry requires new mesh generation which is time consuming and tedious.

Coarse models apply simplifying assumptions with respect to geometry, material properties, and boundary conditions. Depending on the problem, the computational effort can be significantly reduced compared to CFD simulations. Generally, in coarse structure models flow is considered as one-dimensional (1D) flow. The decision for detailed or coarse models depends on the objective of the investigation. In system simulations, it may be sufficient that the energy balance is fulfilled in the majority of cases.

8.2 Theoretical Background

The proper simulation of UTES requires a precise understanding and corresponding treatment of the relevant heat transfer and flow processes in the ground under transient conditions. The local thermal processes in and around the UTES combined with varying temperature along the UTES present particular complications. One specific problem is the successful modeling of the interaction of the advective heat flow in the pipes with the conductive thermal processes in the ground. Groundwater flow further complicates the thermal processes and advective heat transport must be considered.

This chapter is a general introduction to the physical background of thermal modeling and mainly based on Signorelli (2004) and Yang et al. (2010)s' work. The description of the physical processes is based on a model assuming two different units: solids and fluids. First, the principles of groundwater hydraulics and hydraulics in pipes are described, then, a description of heat transport in a porous medium and pipe systems is discussed.

Table 8.1 Typical hydraulic properties of rocks (from EU Commission SAVE Programme and Nordic Energy Research 2004)

	Medium hydraulic conductivity [ms^{-1}]	Porosity
Gravel	10^{-3}–10^{-1}	0.25–0.40
Silt	10^{-9}–10^{-5}	0.35–0.50
Limestone	10^{-9}–10^{-6}	0–0.20
Sandstone	10^{-10}–10^{-6}	0.05–0.30
Fractured igneous and metamorphic rock	10^{-8}–10^{-4}	0.05–0.30
Unfractured igneous and metamorphic rock	10^{-13}–10^{-10}	0–0.05

8.2.1 Groundwater Hydraulics

In groundwater hydrology, the groundwater flow is generally described by Darcy's law. The groundwater velocity is determined by the pressure difference along a flow path which is either density driven (convection) or forced by gravity such as by the relief of the groundwater table (advection). As already presented in Chap. 3, the average Darcy velocity, u, can be expressed by

$$u = -K\nabla h \tag{8.1}$$

The constant of proportionality in 8.1 is known as the hydraulic conductivity, K is related to permeability as follows:

$$K = \frac{k\rho_f g}{\mu_f} \tag{8.2}$$

k is the permeability and μ_f the fluid dynamic viscosity.

The hydraulic conductivity value is a combination of solid and fluid related values. It can strongly vary for the same type of rocks depending on the porosity. It is generally high for gravel and low for unfractured rocks as shown in Table 8.1. Due to the temperature dependence of density and viscosity, the hydraulic conductivity is also temperature dependent. In the temperature range relevant for UTES operation, the temperature dependence of density can be ignored. However, the viscosity is strongly temperature dependent. The value decreases by $\sim$ 15% when the groundwater temperature drops from 10 to 5°C. Depending on the application, the temperature dependence must be considered.

8.2.2 Hydraulics in Pipes

When a fluid flows through a pipe, pressure drops due to friction at the borehole wall and at the walls of the horizontal conduits. In BHE applications, the knowledge of the resulting pressure loss is necessary for sizing the circulation pump. Thereby, the volumetric flow rate is predetermined by the size of the heat pump, which is defined by the energy demand of the individual building. The volumetric flow rate itself defines then the flow velocity v_{pipe} in the pipe. Considering 1D flow in the pipe, the pressure loss, Δp, along the BHE length, l, in a pipe of diameter, d_{pipe}, is defined by:

$$\Delta p = \frac{fl}{d_{\text{pipe}}}\frac{\rho v_{\text{pipe}}^2}{2} + \sum_{i=1}^{n} \xi_i \frac{\rho v_{\text{pipe}}^2}{2} \tag{8.3}$$

f is the borehole friction factor, ξ the friction factor of pipe fixtures ($\xi = 1$ for the pipe turn point fixtures at the bottom; a list of ξ for various pipe fixtures can be found in the literature) and i is the number of pipe fixtures.

Depending on laminar or turbulent flow regimes different formulations of the borehole friction factor, f, are applicable. The flow regime in pipes is described by the dimensionless Reynolds Number, Re:

$$\text{Re} = \frac{v_{\text{pipe}} d_{\text{pipe}}}{\nu_f} = \frac{v_{\text{pipe}} d_{\text{pipe}} \rho_f}{\mu_f} \tag{8.4}$$

ν_f is the fluid kinematic viscosity and can be calculated from the fluid dynamic viscosity, μ_f, and the fluid density, ρ_f. Generally,

- $\text{Re} < 2{,}300$ laminar flow
- $2{,}300 < \text{Re} < 10^4$ transient between laminar and turbulent flow
- $\text{Re} > 10^4$ fully developed turbulent flow

In practice, flow regimes with $\text{Re} > 2{,}300$ are often treated as turbulent.

For laminar flow, f increases linearly with the flow velocity and is given by:

$$f = \frac{64}{\text{Re}} = \frac{64 \nu_f}{v_{\text{pipe}} d_{\text{pipe}}} \tag{8.5}$$

For turbulent flow, the Blasius approximation is often used and f is defined as:

$$f = \frac{0.3164}{\text{Re}^{\frac{1}{4}}} = 0.3164 \left(\frac{\nu_f}{v_{\text{pipe}} d_{\text{pipe}}} \right)^{\frac{1}{4}} \tag{8.6}$$

For both flow regimes, f is dependent on the viscosity of the heat carrier fluid. As well known, the viscosity is temperature dependent. The same applies for f here.

Much of the frictional pressure loss is due to the dependence of fluid flow on the pipe diameter of the pipe. Clearly, when reducing the pipe diameter by half, the flow velocity is squared for fixed flow rate. Due to the quadratic dependency of pressure loss on flow velocity in Eq. 8.3, this will lead to a 4th order change in pressure loss. In installing less expensive, smaller pipes the pressure loss will increase which requires stronger circulation pumps and thus, may lead to inefficient BHE systems.

8.2.3 Heat Transfer

Heat is mainly transported by three mechanisms:

- Conduction

Conductive heat transfer occurs due to an energy transmission of molecular vibration. The heat is conducted through a medium in which there is a spatial variation in temperature. Heat conduction is the dominant thermal process in solid rocks. The basic relation for conductive heat transport is Fourier's law. It states that the conductive heat flow, q_{con}, at a point is proportional to the temperature gradient, ∇T, at that point:

$$q_{\text{con}} = -\lambda \nabla T \tag{8.7}$$

λ is the thermal conductivity.

- Advection

Advective heat transport is associated with the motion of a fluid. Although the thermal conductivity of water is low (0.6 W/m·K compared to an average value of 2.5 W/m·K for sedimentary rocks), groundwater flow can transport a large amount of thermal energy by advection through pores and fractures due to its high heat capacity. Therefore, advective heat transport can have a significant impact on BHE performance. Groundwater movement is mainly due to differences in pressure. The specific thermal power q_{adv} which is provided by advective mechanisms can be calculated as follows:

$$q_{\text{adv}} = \rho_f C_f v_f \nabla T \tag{8.8}$$

C_f is specific fluid heat capacity.

- Heat transfer

If two bodies of different temperature are in contact, heat is transferred from the warm body to the cold one. This mechanism is called heat transfer. The heat flow, q_{trans}, is proportional to the temperature difference of the two bodies:

$$q_{\text{trans}} = h(T_1 - T_2) \tag{8.9}$$

h is the heat transfer coefficient and T_is are the temperatures of the two bodies.

8.2.3.1 Heat Transport in the Ground

In principle, the subsurface can be treated as two different systems: a fluid and a solid phase. The fluid phase is defined as the groundwater in pores and fractures and the solid phase represents the rock matrix. We get energy balance equation for the fluid phase, *f*:

Table 8.2 Typical thermal properties of rocks and fluids (EU Commission SAVE Programme and Nordic Energy Research 2004)

Medium		Thermal conductivity [W/m K]	Heat capacity [MJ/m^3 K]
Rocks	Gravel (saturated)	0.30–0.50 (1.8)	1.4–1.6 (2.4)
	Silt	0.30–2.30	1.5–2.8
	Limestone	1.90–3.90	2.1–2.5
	Sandstone	1.20–5.10	1.5–2.8
	Fractured igneous and metamorphic rock	2.50–4.70	2.2
	Unfractured igneous and metamorphic rock	2.50–4.70	2.2
Heat carrier fluid	Water	0.6	4.18
	Water–ethylenglycol mixture (20 %)	0.51	4.05

$$\rho_f C_f \frac{\partial T_f}{\partial t} = -\rho_f C_f v_f \nabla T_f + \nabla \cdot \left(\lambda_f \nabla T_f\right) + h\frac{A}{V}\left(T_s - T_f\right) \tag{8.10}$$

and for the solid phase, *s*:

$$\rho_s C_s \frac{\partial T_s}{\partial t} = \nabla \cdot (\lambda_s \nabla T_s) + h\frac{A}{V}\left(T_f - T_s\right) \tag{8.11}$$

t is the time, and A/V describes the heat transfer area A in a reference volume V. In a water saturated formation, one can assume that the water temperature is equal to the rock temperature and the heat transfer term can be neglected. Thus, Eqs. 8.10 and 8.11 can be reformulated as one single equation by implementing average material parameters:

$$\bar{\rho}\bar{C}\frac{\partial T}{\partial t} = -\rho_f C_f n v_f \nabla \cdot \left(\bar{\lambda}\nabla T\right) \tag{8.12}$$

The parameters with overbars contain values from both phases. The average volumetric heat capacity value is calculated as the arithmetic mean of the two phases in a body:

$$\bar{\rho}\bar{C} = (1-n)\rho_s C_s + n\rho_f C_f \tag{8.13}$$

The calculation of the thermal conductivity is more complex. Generally, the geometric mean is assumed:

$$\bar{\lambda} = \lambda_s^{1-n}\lambda_f^n \tag{8.14}$$

However, often an arithmetic formulation is used corresponding to Eq. 8.14. The thermal conductivity decreases with increasing temperature. In the temperature range relevant for the UTES operation, no significant temperature dependence occurs. Table 8.2 summarizes thermal properties of the soils and rocks.

The ratio between thermal conductivity and heat capacity can be described by the thermal diffusivity, α:

$$\alpha = \frac{\bar{\lambda}}{\bar{\rho}\bar{C}} \tag{8.15}$$

The heat advection in porous media is only provided by the fluid phase. Since the advective part is weighted by porosity, the convective thermal front progresses with the Darcy velocity. The ratio between the convective and the conductive transport is given by the Peclet Number:

$$\mathrm{Pe} = \frac{\rho_f C_f v_f L}{\bar{\lambda}} \tag{8.16}$$

L is the characteristic length (e.g. flow path).

8.2.3.2 Heat Transport in Pipes

Inside the pipe, the axial heat conduction is insignificant compared with the advection of heat by the fluid due to the low thermal conductivity of the heat carrier fluids. There is only 1D heat flow inside the pipe and heat transport can be simplified by:

$$\rho_f C_f \frac{\partial T_f}{\partial t} \cong -\rho_f C_f v_f \nabla T_f \tag{8.17}$$

During operation, the heat from the BHE surroundings is transferred into the circulation fluid by heat transport through the pipe wall. At the pipe wall, two independent thermal regimes are in contact, and the temperature for the fluid and solid phase cannot be assumed as identical. Therefore, a heat transfer coefficient between the wall heat flux and the excess fluid becomes necessary. The heat transport through the pipe wall is defined as:

$$\rho_{\mathrm{pipe}} C_{\mathrm{pipe}} \frac{\partial T_{\mathrm{pipe}}}{\partial t} = \nabla \cdot \left(\lambda_{\mathrm{pipe}} \nabla T_{\mathrm{pipe}}\right) + h\frac{A}{V}\left(T_f - T_{\mathrm{pipe}}\right) \tag{8.18}$$

Only heat conduction in the radial direction has to be considered which can be simplified by a radial 1D process. If lateral temperature changes in the pipe fluid can be neglected (i.e. perfect lateral heat transport inside the pipe), then the heat transfer is limited to the pipe wall. The heat transfer coefficient at the interface, h, is found from the 1D Fourier equation:

$$q = h\left(T_{\mathrm{pipe}} - T_f\right) \tag{8.19}$$

The fluid mechanics literature commonly introduces a dimensionless measure of the heat transfer coefficient known as the Nusselt Number, Nu, the ratio of total to conductive heat transport:

$$\mathrm{Nu} = \frac{h d_{\mathrm{pipe}}}{\lambda_f} = \frac{h\left(T_{\mathrm{pipe}} - T_f\right)}{\frac{\lambda_f\left(T_{\mathrm{pipe}} - T_f\right)}{d}} = \frac{q_{\mathrm{total}}}{q_{\mathrm{cond}}} \tag{8.20}$$

Depending on laminar or turbulent flow regimes, different formulations of the Nusselt Number are applicable. For laminar flow, the Nusselt Number can be calculated from the Prandtl Number, Pr, the Reynolds Number, Re, the dynamic viscosity of the fluid, μ_f, and the dynamic viscosity at the wall temperature, μ_w, formulated as the Sider–Tate equation:

$$\mathrm{Nu} = 1.86\left(\frac{d_{\mathrm{pipe}}\mathrm{Re}\,\mathrm{Pr}}{l}\right)^{\frac{1}{3}}\left(\frac{\mu_f}{\mu_w}\right)^{0.14} \tag{8.21}$$

l is the pipe length.

In the temperature range relevant for BHE operation, the dynamic viscosity does not vary strongly for the wall temperature and the fluid temperature. The last term in Eq. 8.21 is close to 1 even for a temperature difference of 10 K. A different correlation must be used for turbulent flow. An equation of the Dittus-Boelter form is often used:

$$\mathrm{Nu} = 0.023\mathrm{Re}^{\frac{4}{5}}\,\mathrm{Pr}^{m} \tag{8.22}$$

The exponent of the Prandtl Number slightly varies depending on which correlation is used. For the Dittus-Boelter equation it is:

- $m = 0.4$ if $T_{\mathrm{pipe}} > T_{\mathrm{fluid}}$ (Fluid is heated)
- $m = 0.3$ if $T_{\mathrm{pipe}} < T_{\mathrm{fluid}}$ (Fluid is cooled)

The Prandtl Number is a material constant and defined as the ratio of the kinematic viscosity, v, and the thermal diffusivity, α:

$$\mathrm{Pr} = \frac{v_f}{\alpha} = \frac{v_f}{\frac{\lambda_f}{\rho_f C_f}} = \frac{\rho_f \mu_f}{\lambda_f} \tag{8.23}$$

Basically, there are three approaches used to simulate BHEs. One is the analytical method, like the line source model and the cylindrical model, another one being the response factor method, e.g., Eskilson's model, Helltröm's model, and Yavuzturk's model. The third one is the numerical method, for example Gu's model and Zeng's model (He 2007).

8.3 Numerical Models

A large number of computer models dealing with UTES have been developed during last decades. The suitability of models dealing with ATES and BTES applications range from predesign to detailed design as summarized in Table 8.3 (EU Commission SAVE Programme and Nordic Energy Research 2004).

Table 8.3 Examples of ATES and BTES models (from EU Commission SAVE Programme and Nordic Energy Research 2004)

	ATES models	BTES models
Simple (Pre-design)	SPREADSTO-1	SMARTSTORE
↑	CONFLOW	TECOCLAY
	AST	EED
	TWOW	DST
	PIA12	SBM
	HB-MULTIFIELD	COSOND
	MODFLOW	TRADIKON-3D
	TRNAST	TRNSYS-DST
	TRADIKON-3D	TRNSYS-EWS
	TOUGH2	TRNSYS-SBM
	THETA	
	HST2D/HST3D	
↓	PHREEQM-2D	
	SHEMAT	
Advanced (Detailed-design)	FEFLOW	

Groundwater flow and thermal energy transport in the porous media have been studied in some detail in the discipline of hydrogeology. Numerical research into groundwater and heat transport has been continuing for more than a decade in North American and Europe. Numerous commercially available and public domain numerical software codes exist. Of these, focus will be given to the simulation modeling both mass and heat transport in groundwater. Table 8.4 lists some numerical models for groundwater flow and energy or solute transport in groundwater (Deng 2004). These models can all be used to simulate an ATES system. Models THETA and SUTRA are selected for a more detailed review.

In assessing the effect of groundwater flow on UTES performance, numerical software code is selected for the study based on his selection criterion:

- the type of boundary conditions handled by the code
- the solution scheme employed by the code
- verification of the code
- cost

8.3.1 Numerical Model THETA

THETA was developed at Helsinki University of Technology. It can be used to accurately simulate the three-dimensional coupled transport of fluid and energy in porous media. Simulations have been performed to evaluate the effect of groundwater on the performance of a ground heat extraction system using vertical wells.

Table 8.4 Numerical models for groundwater (from Deng 2004)

Model	Creator	Descriptions
AQUA3D	Vatnaskil Consulting Engineers, Reykjavik, Iceland	Three-dimensional, finite-element method; developed mainly for simulation of mass transport problems, but can be adapted to model heat transport without density-dependent groundwater flow.
HST3D	United States Geological Survey (USGS)	Three-dimensional, finite-difference method; capable of simulating mass and heat transport in variable-density groundwater flow system.
FEFLOW	WASY Institute for Water Resources Planning and Systems Research, Ltd., Berlin, Germany	Three-dimensional, finite-element method; capable of simulating both mass and heat transport in density-dependent groundwater flow systems.
SUTRA (Saturated-Unsaturated Transport)	Clifford L. Voss	Two-dimensional hybrid finite-element and finite-difference method; simulated fluid movement and the transport of either energy or dissolved substances in the subsurface environment.
THETA 3.0	Kangas and Lund	Three-dimensional, finite-difference method; coupled transport of fluid and energy in porous media.

THETA used the porous medium approximation to study the groundwater flow. The specific discharge vector (**u**) is given by Darcy equation:

$$\mathbf{u} = -\frac{\mathbf{k}}{\mu}(\nabla p - \rho g) \tag{8.24}$$

$$\mathbf{k} = \frac{\mathbf{K}\mu}{\rho g}$$

where **k** is the tensor form of intrinsic permeability (m^2 or Darcy). k is a function of the size of the openings through which the fluid moves. It depends only on the geological properties of the ground. $k = Cd^2$); C is the shape factor and d is the diameter of the effective grain, they are properties of the porous media (Fetter 2001); **K** is the hydraulic conductivity of rock (m/s) (It depends not only on the geological properties of the ground, but also on the thermal properties of the flowing medium); p is the pressure (N/m^2); g is the acceleration of gravity (m/s^2); μ is the dynamic viscosity of water ($N{\cdot}s/m^2$).

In addition, it was assumed that, locally, the groundwater and the surrounding ground are in the thermal equilibrium to derive the transferred energy equation in groundwater from the principle of conservation of energy. The resulting energy equation with an incompressible fluid is:

$$(\rho C)_s \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) - (\rho C)_f \mathbf{u} \nabla T + H \tag{8.25}$$

where ρC is the volumetric heat capacity (J/m^3·K); λ is the thermal conductivity (W/m·K); **u** is the specific discharge (volume flow rate per unit of cross-sectional area) (m/s); H is the heat source or sink (W/m^3); and subscripts: f is fluid (water); s is fluid saturated soil. The above two governing equations are discretized in THETA using the explicit FDM and solved numerically.

The results from the THETA simulations suggest that an increase in groundwater flow will result in improved system performance, which results from the energy transfer by groundwater; groundwater constantly replenishes the recoverable energy at the site of extraction. The presence of groundwater flow significantly increases the amount of recoverable energy. Similarly, standing column well systems, especially with groundwater bleed, make use of the energy stored in the aquifer.

The THETA aquifer simulation model has been incorporated into a computer simulation model AQSYST for simulating energy systems employing ATES. THETA simulates the thermo-hydraulic flow in the aquifer when either injecting water to the well or extracting water from the well. It cannot model simultaneous injection and extraction to/from a single well. The performance of standing column well systems is characterized by circulating, injecting, and extracting water to and from an aquifer at the same time. Therefore, THETA cannot be applied directly to the standing column well system.

8.3.2 Numerical Model SUTRA

SUTRA (Saturated–Unsaturated Transport) is a computer program developed by Voss (1984). This numerical model simulates fluid movement and the transport of either energy or dissolved substances in the subsurface environment (aquifer). A two-dimensional hybrid finite-element and FDM is used to approximate the governing equations. SUTRA can solve the two interdependent processes:

1. fluid density-dependent saturated or unsaturated groundwater flow and either
2a. transport of a solute in the groundwater or
2b. transport of thermal energy in the groundwater and solid matrix of the aquifer

SUTRA was primarily intended to simulate two-dimensional flow, and either solute or energy transport in a saturated variable-density system. To simulate the groundwater in unconfined aquifers affected by a periodic boundary condition, Ashtiani et al. (1999) modified the SUTRA model in three aspects:

- the basic flow equation is changed from a pressure-based form to a mixed form
- an automatic under-relaxation method is applied for adjustment of pressure after each iteration to handle the nonlinearity of the unsaturated zone equations;
- the model has been adjusted to handle a seepage-face boundary condition.

The validation tests of this two-dimensional numerical model for density-dependent groundwater flow in unconfined aquifers against experimental data were successful.

Like THETA, SUTRA cannot model simultaneous heat/mass injection and extraction to/from a single well. So, SUTRA cannot be applied directly to the standing column well system, either.

8.3.3 Other Numerical Models

A few other models address energy transfer in the aquifer. Hellström developed a model that simulates the thermal process in the aquifer and in the surrounding ground under certain simplifying assumptions concerning the groundwater flow (Breger et al. 1996). The basic assumption of the model is that the groundwater flow is essentially radial in the thermally active region around the well. There are other assumptions that must be fulfilled:

- negligible regional groundwater flow;
- negligible buoyancy flow caused by varying water temperature in the aquifer;
- negligible influence of viscosity differences between different flow paths.

Convective heat transport and three-dimensional heat conduction are accounted for in this model. The combined diffusive and convective heat flow processes in the aquifer and the surrounding layers are solved using the explicit difference method (FDM).

Molson and Frind (1992) simulated the thermal energy storage in an unconfined aquifer with a three-dimensional finite-element numerical model. In their model, the authors coupled the density-dependent groundwater flow and thermal energy transport. A symmetric matrix time integration scheme with the Galerkin FEM is employed.

Chevalier and Banton (1999) applied the random walk method to model energy transfer in porous media. The method is based on the concept that cumulative results of repeated trials with an arbitrary probability distribution tend to a Gaussian distribution. They compared their random results with the analytical solution and the numerical finite-difference solution. The results are similar in both cases.

Because the above three models cannot model simultaneous heat/mass injection and extraction to/from a single well, so they cannot be applied directly to the standing column well system.

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