Design and application of low grade, geothermal energy systems.

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Utilisation of low grade thermal energy from the ground is becoming an increasingly popular option for providing high efficiency and environmentally sustainable air-conditioning systems.

It involves both refrigeration and non-refrigeration based systems using soil or underground aquifers, known as Underground Thermal Energy Storage (UTES) systems. They provide heat sink or source for air-conditioning or other industrial processes.

The paper discusses currently available technology utilising the low grade thermal energy resources of the ground. Some examples of the application and design aspects of UTES technology are also presented.

1. Introduction.

In the recent debates on the greenhouse gases emission targets and energy sustainability in general, we can hear much about energy sources. It appears that the flip side of the coin remain unnoticed, namely energy sinks. There are energy sources and energy sinks which make any energy system efficient or inefficient. It is generally meaningless to talk about energy efficiency in thermal energy systems without taking into account both energy sources and energy sinks.

Installing a high efficiency split air-conditioning system, driven by cheap brown coal fired electricity, with an unshaded condenser unit facing north-west is perhaps as equally energy inefficient as using electric resistance heater.

In the following presentation we would like to give a few examples of an air-conditioning technology which uses the renewable energy resources of the soil and underground aquifers as a heat sink as well as a thermal energy storage.

We will briefly discuss applications of this technology in various sectors and also present some of the realised projects. Some of the storage systems described in this paper are becoming increasingly popular in Europe, some with a negative pay-back period. Although climatic conditions in Australia can differ dramatically from those in Europe, the thermodynamic principles of those system warrant further study to assess the applicability of underground storage systems in our country.

2. Thermodynamic background of a UTES system.

Soil, due to its large thermal capacity and thermal inertia can serve as a heat source or sink for a heat pump, offering relatively constant operating conditions. The same observation applies to underground aquifers.

The soil temperature at the depth of 1.6-2.0 m fluctuates around the yearly average air temperature at a given location [1]. The amplitude of the fluctuation depends on the geographic location and also on the soil thermal properties. With increasing depth the fluctuation becomes less pronounced, and, for practical purposes, we can assume the soil, or water, temperature to be constant. This offers a lower and stable heat sink temperature in cooling mode operation and a higher and stable heat source temperature in heating mode operation. The major consequence of this fact for any UTES system is lower energy consumption as compared with a standard air-coupled air-conditioning system.

Due to its large thermal inertia, the soil temperature at depths greater than 1.6m is usually lower than the ambient air temperature in Summer (and higher than the ambient air temperature in Winter). It also does not immediately reflect short time scale ambient temperature variations. As a result, the power consumption of an air-conditioning plant is decoupled from the ambient conditions as far as the heat sink (condenser) operation is concerned. In a typical air-conditioning plant with an air cooled condenser the energy consumption of the plant closely reflects ambient conditions. The energy consumption increases not only due to an increased air-conditioning load, but also due to a higher heat sink (condensing) temperature. The heat sink temperature is usually much higher than the ambient air temperature due to direct solar radiation. This can be demonstrated analytically [2]. The schematic representation of the problem is presented on Fig.1.

Let us consider a hypothetical situation where a house is to be heated and cooled by either an Air-Source Heat Pump (ASHP) or a Ground Coupled Heat Pump (GCHP) system. Cooling (heating) load is assumed to be the same in both cases. The soil temperature is assumed to be constant and equal to the yearly average air temperature at a given location. The ambient air temperature variation is assumed to have a sinusoidal characteristic with a given maximum and the daily amplitude.

We can calculate the power input required for both systems. It can be demonstrated that, in most situations, a GCHP requires less energy than ASHP for the same cooling load.

It has to be noted however, that the power input depends, not only on the geographical location of the site, but also on the local soil conditions. Generally, the greater the seasonal temperature variation the better GCHP performs as compared with a standard air-coupled air conditioning.

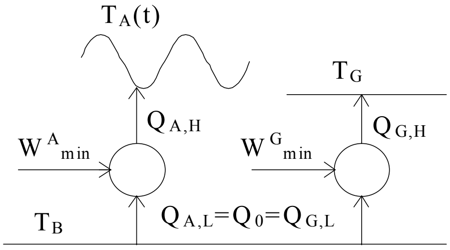


Fig.1 Schematic for the comparison of an air-source heat pump and GCHP.

3. Classification of Underground Thermal Energy Storage (UTES) systems.

Before going into a more detailed discussion, let us briefly discuss some basic concepts and the nomenclature.

Any system utilising renewable energy resources of the soil or underground aquifers is in fact a storage system. Due to its nature, it is a seasonal sensible heat storage. What makes it very attractive is its vast thermal capacity, limited only by our technical means to retrieve this energy, and its temperature.

The thermal energy can be retrieved either by means of a heat pump system, in which case it is called a Ground Coupled Heat Pump (GCHP) system, or by circulating heat transfer liquid through an array of Ground Heat Exchangers (GHE), which is also called a Ducted Thermal Energy Storage (DTES), or in the case of an aquifer storage by means of directly circulating underground water, which is called an Aquifer Thermal Energy Storage (ATES).

4. Types of UTES systems.

4.1. Ducted Thermal Energy Storage.

This is the most common type of a UTES system. The main part of the system is a Ground Heat Exchanger usually made of high density polyethylene pipes buried in the soil. In GCHP applications, GHE substitutes a cooling tower or an air cooled condensing unit. There are two basic configurations of GHE; horizontal and vertical.

In the horizontal configuration pipes are placed in trenches at the depth of 1.6-2.0 m, usually four pipes per trench, one over the other with the vertical spacing of about 0.3 m, see Fig.2. Each trench with GHE pipes constitutes a loop, the length of which depends on the local soil and climatic conditions. It is usually necessary to install a number of GHE loops connected in parallel, in order to cope with a given air-conditioning load.

In the vertical configuration U-shaped pipes are placed in wells, about 100 mm in diameter, and backfilled with a grouting material of high thermal conductivity which also provides good contact with pipes. Each well constitutes a loop. The GHE vertical loops are installed in an array, see Fig.3 . The loops' length and spacing depends on the condenser load and the local soil and climatic conditions.

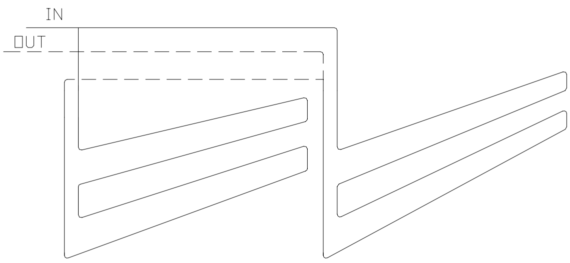


Fig.2 Horizontal type GHE.

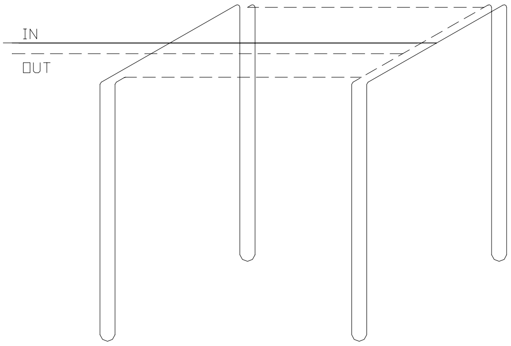


Fig.3 Vertical type GHE.

4.2 Aquifer Thermal Energy Storage.

An Aquifer Thermal Energy Storage uses water confined in water bearing geological formations (sand, sandstone) for heat/cool storage purposes. The water temperature in an aquifer depends on its depth and the local climatic conditions. Generally the water temperature varies between 10-20 °C. The groundwater can be subjected to some natural or artificial pressure difference causing it to flow. This can be a mixed blessing as far as the aquifers use is concerned. If the prime objective is to store thermal energy then the water flow will cause undesirable energy losses. On the other hand, if an aquifer is primarily used as a natural heat sink or source then the water flow is advantageous by allowing for its continuous recharging. The major advantage of ATES, apart from the temperature, is its storage capacity and the fact that it is a natural structure.

As in the case of DTES, thermal energy accumulated in an aquifer can be accessed directly by simply circulating the underground water through a heat exchanger coupling the air-conditioning installation with the aquifer.

If the temperature levels do not allow for direct use, a heat pump system can be used for coupling an aquifer with the air-conditioning or other industrial installation, see Fig.4 and Fig.5.

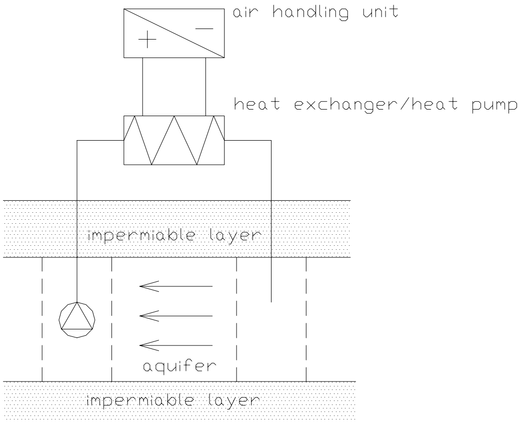


Fig.4 Flow through ATES system.

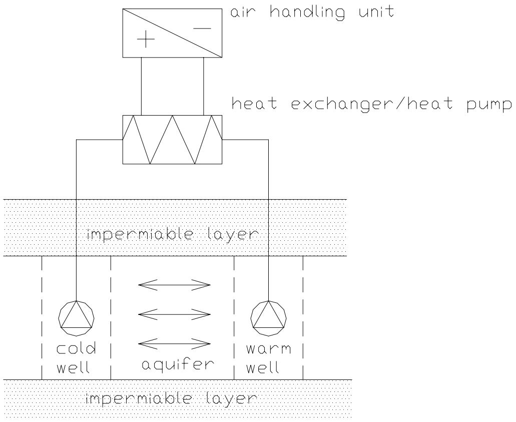


Fig.5 Double well ATES system, low/high temperature storage.

5. Design considerations of UTES systems.

Design of UTES systems can be very complex and might require expertise from various disciplines such as chemistry, geology, biology not to mention heat and mass transfer.

It is impossible in this paper to present, in a systematic way, the design process of UTES systems. Nonetheless, in this section we will point out some of the most important aspects of the design procedure.

5.1. Ducted Thermal Energy Storage.

As was mentioned before, the GHE substitutes for a cooling tower or air cooled condensing unit in the air-conditioning plant. The major difference between those two systems is the fact that we have very little or no control over the heat dissipation rate in the soil after the GHE is installed. It is thus crucial that due care is taken at the design stage of a GHE field and that the pipe lengths and spacing are adequate for the design heat extraction or rejection rates.

Pipe lengths and spacing, in either the vertical or horizontal configuration, depend on the soil physical properties, such as the thermal conductivity, density and specific heat. Those three parameters determine the rate of heat dissipation in the soil, described by the soil thermal diffusivity. The higher the soil thermal diffusivity the faster heat is dissipated in the soil, which results in a smaller size GHE. Generally speaking, heavy soils with a high initial moisture content dissipate heat faster than light and dry soils.

Another very important aspect of a GHE design, specially for the vertical configuration, is the heat accumulation in the soil activated by a GHE operation. As a result, the GHE field temperature increases over a time period thus reducing its capacity. This transient state can continue for up to 10 to 15 years. This process has also to be taken into account at the design stage. This is normally done using a design and simulation software.

A properly designed GHE allows for a highly energy efficient operation of an air-conditioning system. From experience to date, a ground coupled air-conditioning system uses up to 30-40% less energy to run compared with a conventional air conditioning [3].

5.2. Aquifer Thermal Energy Storage.

Similarly to DTES, an underground aquifer can be used as a heat sink or source for an air-conditioning or other industrial plant.

The thermal capacity of the storage depends on the aquifer's volume and flow pattern of the water. Those factors are established by hydrogeological tests and computer modelling which take into account heat and water flow.

Sealing-off of ATES requires special attention in order to avoid problems associated with the precipitation of Fe and Mn oxides. There is also a possibility of chemical and electrochemical corrosion which is induced by the presence of CO_2, O_2, H_2S and other chemical compounds. The corrosion problems can be avoided by a proper chemical analysis of the aquifer and an appropriate selection of the construction materials.

In order to avoid scaling of heat exchangers and wells, which may occur as a result of precipitation of carbonates, an appropriate water treatment should be applied. There is a number of water treatment techniques available which do not have any negative impact on the environment [4].

6. Applications of UTES systems.

6.1. Commercial air-conditioning.

There are many examples of successful UTES installation both in Europe, North America and also in Australia. DTES systems are mainly used in the USA, where they are known as Geothermal Heat Pump systems [5]. DTES systems have also been installed in Australia and proved to be a viable alternative to conventional air-conditioning systems. In northern Europe and Canada both types of UTES have been successfully installed.

Since DTES systems, or GCHP, are relatively well known we would like to concentrate on three examples of ATES systems from the Netherlands, Sweden and Canada. All three installation are based on the schematic presented on Fig.5.

6.1.1. Jaarbeurs, Utrecht, The Netherlands [4].

The Royal Netherlands Industries hall "De Prins van Oranje". The dimensions of the hall are 185x85x10m and can accommodate up to 25,000 people. It is the largest event hall in the Benelux countries.

The maximum cooling load is 2.46 MW with the cooling demand of 400 MWh. There are five wells, two cold and three warm wells, at depths ranging from 15-45m. The well diameter is 0.8 m. The maximum summer water flow rate is 400 m3/h and 210 m^3/h in winter. The natural ground water temperature is 12.4 °C. The cold water storage is 7 °C and the warm water storage temperature is 14 °C. The system operates without a Heat Pump. The electrical energy consumption saving is of the order of 60%, with the energy cost saving of about 80% due to a lower capacity rate.

6.1.2. Sussex Health Centre, Canada [4].

The Sussex Health Centre consists of three buildings, a nursing home (3,000 m^2 floor area), a hospital (7,500 m^2 floor area, 60 beds) and a Medical Centre (1,300 m^2 floor area).

Total energy consumption for the Hospital is about 3,500 MWh of which 800 MWh is used for air preheat and which will be taken care of by the ATES system. Annual life cycle cost saving of approximately $86,000 are anticipated, due to an energy consumption reduction of 1,100 MWh and electrical demand saving of 450 kW. Final temperatures of cool and warm well fields are projected to be 6 °C and 14 °C, respectively.

6.1.3. SAS Frosundavik Office, Sweden [4].

The head office of Scandinavian Airlines System, SAS, was completed in January 1988. The office building, with an area of 64,000 m^2 is heated and cooled by an energy system, which uses an underlying aquifer as an energy storage for both short time and seasonal energy storage.

The total heating load, including hot water, is of the order of 3 MW and the total cooling load is of the order of 2 MW.

There are altogether five wells, three 25 m deep and two 10 m deep. The total volume of the aquifer is about 1.5×10^6 m^3. Heat is produced by extraction of warm water (approximately 15 °C) from two wells. The chilled water, 5-8 °C, is injected into the cold wells during periods with heat production.

Experience from the first six years of operation indicates that the annual heat production is about 3.5 GWh and the production of cooling energy is about 2.8 GWh. Annual electrical energy consumption is of the order of 1.17 GWh, which gives a system COP of 5.4.

6.2. Agricultural air-conditioning.

6.2.1. Greenhouse climate control.

Greenhouses differ from conventional buildings in two major ways:

1. Greenhouses are heated by the internal absorption of solar radiation that has been transmitted through the transparent glazing material, as distinct from the heating of conventional buildings which takes place by the absorption of solar radiation by walls and roof that are largely opaque, with the heat being transmitted inwards by convection and thermal radiation from these heated surfaces.
2. The glazing material of greenhouses has negligible thermal mass and thermal resistance, unlike conventional buildings in which the walls, roofs, and components in the structure have considerable thermal mass and generally have considerable thermal resistance as well, in order to enhance comfort and reduce cooling and heating requirements.

These characteristics of greenhouses arises from the need to maximise the entry of solar radiation for enhanced plant growth, and the need to provide an increase in air temperature above that outside. This latter attribute results in enhanced plant growth, the growing of plants out of season and the growing of plants that would not normally survive in the local climate. The unwanted result, however, is that greenhouses often become overheated during sunny weather, and they require large amounts of heating energy in order to maintain the desired temperature on cold nights.

Further, because of low thermal mass, greenhouses are subject to wide variations in heating and cooling loads in response to rapid changes in the outside climate, such as intermittent cloud.

Conventional refrigerated air-conditioning and heat pump systems are not normally economic for greenhouses, except for some specialised applications such as tissue culture, nutrient heating and cooling in hydroponic systems and precise temperature control for the production of very high value crops. However, the availability of UTES systems, with their very high COP and their ability to readily accommodate rapidly changing loads, can make them economically viable for any production greenhouses.

6.2.2. Crop drying.

The various crop drying industries would benefit from UTES technology as an alternative to systems currently in use. These systems rely either on direct burning of fossil fuels, electricity (sometimes using conventional heat pump technology) or on solar technologies that are sometimes either very expensive on the one hand, or too crude and inefficient on the other.

Vine fruits (raisins, sultanas and currants) are normally dried either on the vine or on relatively crude and inexpensive drying racks in the open. During times of unfavourable weather during the drying period (rain and/or high humidity) there is a very high risk of spoilage or, at least a severe downgrading of the quality and price of the marketable product. The availability of a reliable and cost effective systems, such as UTES systems, would eliminate spoilage during drying.

Other fruit crops, including peaches, apricots, apples and figs, which are dried in a variety of ways and at various temperatures, would also benefit. The technology could, of course, be extended to drying non-horticultural products such as grains, timber, leather and fibreglass.

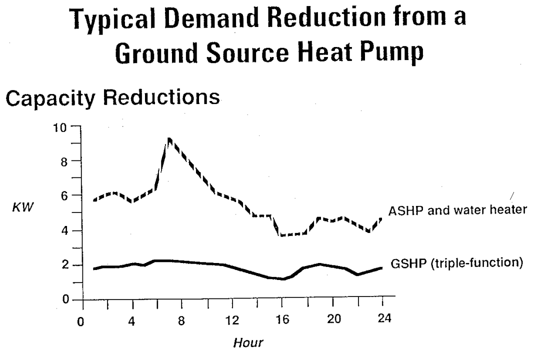
7. Conclusions.

As was mentioned in the second section, ground coupling of a heat pump offers better thermodynamic operating conditions, as compared with an air-coupled heat pump system. If the energy efficiency is an important factor, then a GCHP system generally outperforms a conventional air-source heat pump systems.

The US Environmental Protection Agency conducted a study comparing various aspects of operation of different space conditioning equipment ie. GCHPs, ASHPs, Gas-Fired Heat Pumps (GFHP) and standard air-conditioning equipment. In the conclusions of the study we can find that:

- GCHP have the highest Seasonal Performance Factor (SPF) for both heating and cooling
- both GCHP and GFHP have the lowest annual operating cost
- GCHP can reduce energy consumption and, correspondingly emissions, by 23-44% compared with ASHP and by 63-72% compared with electric resistance / standard air-conditioning equipment.

The other benefit of using GCHP, apart from a reduced energy consumption, is the demand leveling characteristic, a very attractive feature from the utilities point of view, see Fig.6.



Source: National Rural Electric Cooperative Association, "Closed Loop/Ground-Source Heat Pump Systems: Installation Guide", NRECA, Research Project 86-1, p. 19

Fig.6 Demand reduction from a GCHP system.

There are however some limitation regarding the economics of GCHP systems. The major limitation results from the installation cost of the GHE, and, indirectly from the geographical position of a given site. The factors that will limit the applicability of the GCHP system will result from the local soil conditions, availability of the available ground area and the soil temperatures at practical soil depths for the installation of a GHE.

Thousands of GCHP installations in the US [5] and Europe, especially in Scandinavia, confirm the highly competitive nature of those installations and their environmental benefits, stemming from their high energy efficiency and use of the renewable energy resources of the soil.

It seems that the relatively small number of GCHP installations in Australia results from a lack of a practical knowledge of those systems in the HVAC community, as well as at the energy policy making level.

ATES systems may offer a more economically viable alternative to DTES or GCHP, specially in the urban environment, where the available ground area is rather limited. The major obstacle may come from local regulations concerning the use of the underground aquifers. However, in countries like the Netherlands and Belgium, ATES systems are becoming even more attractive after increases in charges for the discharge of underground water, used for cooling purposes in industrial and commercial applications, to the drainage system or rivers. In those countries ATES systems are exempted from the ground water levy [6].

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