INTERNATIONAL SUMMER SCHOOL
on Direct Application of Geothermal Energy

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Geothermal District Heating

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Introduction

District heating is widely used around the world. District heating systems were built in northern Europe from the beginning of the 20th century. The oil crises in 1970s had huge impact on the growth of district heating systems and the number increased rapidly there after. The production of heat is often based on burning of fossil fuels, such as gas, coal and oil or refuse and wood, solely or in cogeneration.

Geothermal energy is a common heat source for district heating in countries where geothermal energy is available and heating of buildings are needed. The energy is often reached by drilling down to the hot area and the water used to carry the heat. The use of geothermal energy for district heating has also long history and its use is increasing. Figure 1 shows the world's largest district heating services. The largest geothermal heating service is in Reykjavik, Iceland, and it is only in fifteenth place on this list. The main advantage of using geothermal energy for district heating is the environmental factor and its sustainability if correctly utilised. In this paper the main focus is on geothermal district heating.

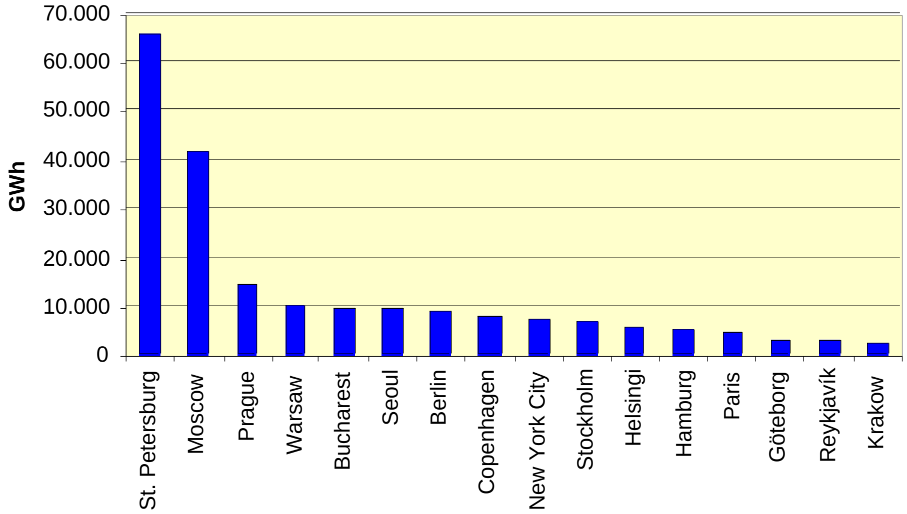

Figure 1. World's largest district heating services.

History of geothermal district heating

The oldest geothermal district heating is most likely in the town Chaides-Aigues in Massif Central in France. The town is in narrow valley in about 750 – 800 m a.s.l. Old manuscripts show that 82°C geothermal water was used to heat houses in the town in the 14th century. The town is located in a steep hill. The water was conveyed along channels in the payvments. A pit was in front of each house and from it to next house. If heat was needed in the house a plug of wood directed the flow from the main channel along channel in the floor of the house.

The first two geothermal wells in the United States were drilled near Boise, Idaho in 1890 and 1891. Both wells were drilled to depths of about 120 m. By the spring of 1891, 35 l/s of 77°C water flowed from the new wells. New houses were being built along Warm Springs Avenue, the road that led to Kelly's Hot Springs. The heating system, which is the oldest district heating system in the United States, began delivering water in 1892. Wooden pipes were used initially but later replaced by new metal pipes. Water temperature proved stable over the years, and two large pumps increased production from 35 l/s to about 52 l/s in 1896. In 1998, the geothermal water is still being used to heat 226 homes and 36 commercial buildings on and near Warm Springs Avenue and part of the downtown Boise area.

In 1928 drilling for hot water started at the thermal springs in Reykjavik, Iceland. Fourteen drill holes were drilled and the result was 14 l/s of about 87 °C water. In 1930 a 3 km long pipeline was built and the first house connected. This was the beginning of district heating in Reykjavik. Shortly a hospital, another schoolhouse, an indoor swimming pool and about 70 private houses were connected to the district heating.

In 1933 about 3% of Reykjavik's population were connected to the Reykjavik District Heating. At that time coal were mainly used for heating and a dark cloud of smoke was commonly seen over Reykjavik. The good success in district heating led to further development. A large geothermal area, located about 17 km east of Reykjavik, was considered to be ideal both relatively close and capable of producing great quantity of geothermal water. By the end of 1943 Reykjavik District Heating could deliver 200 l/s of water at 86°C.

At the end of 1972, 97 % of houses in Reykjavik had geothermal water for heating. Moreover, pipelines were laid to nearby municipalities, which are now supplied with geothermal water by the district heating in Reykjavik. The use of geothermal water in Reykjavik for space heating instead of fossil fuels reduces air pollution.

Today almost all houses in the area are connected to the district heating system. The district heating in Reykjavik serves 56 % of the population of Iceland with geothermal water and is the world's largest municipal geothermal heating service. The installed power is about 750 MW.

Geothermal distict heating

Today geothermal energy is used for district heating in at least 9 capitals of the world, i.e. in Addis Ababa (Ethiopia), Beijing (China), Budapest (Hungary), Bucharest (Romania), Paris (France), Reykjavik (Iceland), Rome (Italy), Sophia (Bulgaria) and Tbilisi Georgia).

The purpose of district heating system is to supply adequate heat for its consumers. The consumer uses the heat to maintain indoor temperature at a reasonable constant level and to obtain domestic hot tap water. A district heating system has to be able to maintain adequate indoor temperature in all the buildings during cold spells. The design of the system has therefore to take into account the worst cold periods during the lifetime of the system. Good weather data is therefore essential for the design.

The economics of district heating have to be evaluated. The main cost factors of district heating system operation are:

- Capital cost
- Pumping cost
- Maintenance
- Heat and water loss in the system

There are different economical aspects concerning fixed and direct cost in a geothermal and a fossil fuel fired district-heating systems. In the fossil fuel fired systems the cost of energy is high compared to the capital cost, whereas the reverse is true in the geothermal systems. The economy of geothermal systems is more related to the maximum power of the system. The analysis of the system performance at high load conditions is critical for the geothermal systems for two main reasons (Valdimarsson, 1993).

- The geothermal system have to carry the burden of the investment in drilling, which is high compared to the investment in boiler stations.
- The energy cost of the operation of a geothermal system is mainly the pumping cost, assuming that the geothermal system is not limited.

During summer the heating demand is low but the system has to be able to supply sufficient water for hot domestic tap water.

It is clear that different parameters have to be taken into account when planning a geothermal district heating service. Different simulation models have been applied to describe the dependent behaviour of the system. The models have different time scale as seen in figure 2.

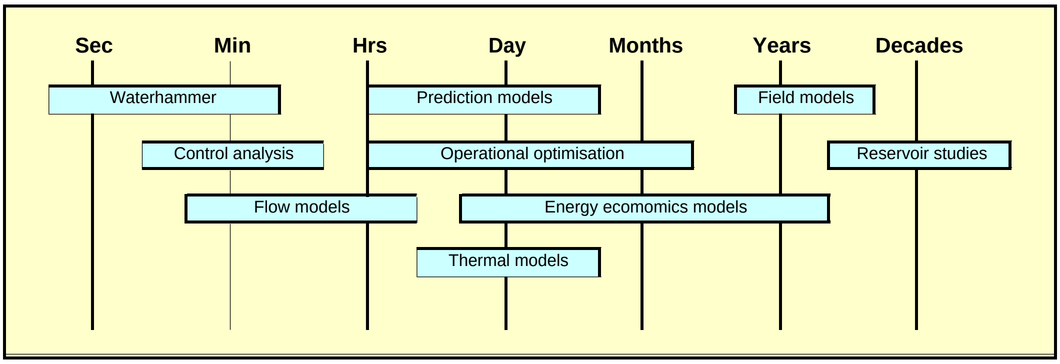

Figure 2. Time scale of district heating simulations (after Valdimarsson, 1993).

The short time models are similar for all district-heating services of cause taking into account different temperature of the water, which led to different flow models and design. The field models and specially the reservoir model is characteristic for the geothermal district heating systems.

Weather data

The weather data is the main signifycant input in district heating simulation models along with consumer behaviour. The primary interest is the outdoor temperature but other factors are treated as well. The operation of district heating is mainly influenced by the outdoor temperature and wind speed.

An example of outdoor temperature duration curve is shown in figure 3 showing heating demand.

The monthly average energy demand is different from one place to another. In colder climate heating is needed all the year around where in other places heating is limited to the winter months and can be turned off entirely during the summer months. On the other hand need for domestic hot tap water is all the time. Figure 4 shows average energy use for district heating in Reykjavik, Iceland.

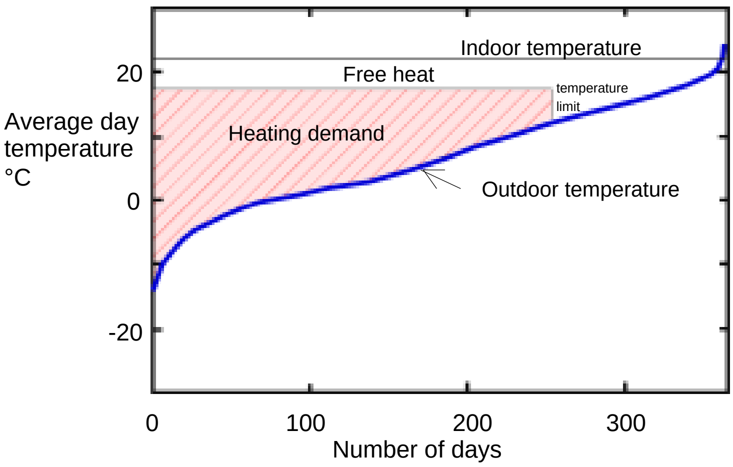

Figure 3. Heating demand defined from outdoor and indoor temperature.

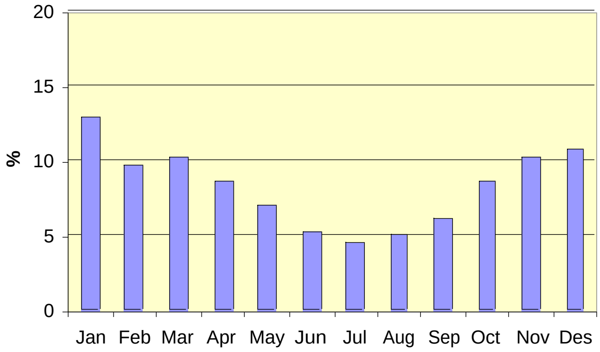

Figure 4. Heating demand in Reykjavik, Iceland

Reservoir studies

Geothermal exploitation involves energy extraction from highly complex underground systems. The generating capacity of geothermal systems is often poorly known and they often respond unexpectedly to long-term energy extraction. This is because their internal structure, nature and properties are often poorly known and can only be observed indirectly. Therefore, the management of geothermal resources can be highly complicated. Successful management relies on proper understanding of the geothermal system involved, which in turn relies on adequate information on the system. This knowledge is continuously gathered throughout the exploration- and exploitation history of a geothermal reservoir.

Management of a geothermal reservoir relies on adequate information on the geothermal system in question (Stefansson *et al.*, 1995). In general the information required for a successful management program involves:

- Knowledge on the volume, geometry and boundary conditions of a reservoir.
- Knowledge on the properties of the reservoir rock, i.e. permeability, porosity, density, heat capacity and heat conductivity.
- Knowledge on the physical conditions in a reservoir, which are determined by the temperature- and pressure distribution.

This knowledge is continuously gathered throughout the exploration- and exploitation history of a geothermal reservoir. The initial data comes from surface exploration, i.e. geological-, chemical- and geophysical data. Consequently, exploratory drilling, in particular through logging and well testing, provides additional information. Based on these data a conceptual model usually emerges. Important data on a geothermal systems nature and properties is obtained through monitoring of its response to long-term production. Mathematical models are commonly developed on the basis of these data, and consequently used to calculate future predictions on the response of a given reservoir to the different management options.

An example of predictions by lumped mathematical model for the Laugaland system in Central N-Iceland is presented in figure 5 (Axelsson and Gunnlaugsson, 2000). These predictions were calculated in the purpose of estimating the maximum allowable production for the next 10 years. The figure also shows the annually averaged water level.

Chemistry of geothermal water

Chemical analysis of geothermal fluid both water, steam and gases can give valuable information for the design of geothermal district heating systems. During long-term exploitation the energy extracted cause pressure drop or drawdown in the system. This may causes the surface activity to change or disappear. In some instances the pressure drawdown creates a potential danger for inflow of colder groundwater or seawater into the system followed by cooling and sometimes change of production characteristics.

The main chemical components in geothermal water are silica (SiO_2), sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), carbonate (total CO_2), hydrogen sulphide (H_2S), sulphate (SO_4), chloride (Cl) and fluoride (F). The concentration of most elements in geothermal water is dependent on temperature. Mixing of geothermal water and colder water often causes deviation from equilibrium. Changes in the chemical composition of geothermal water caused by invasion of cold ground water may precede physical changes. The results of chemical changes may be potential corrosion and scaling. Data obtained from chemical analysis of fluids may therefore give warning in time for preventive actions.

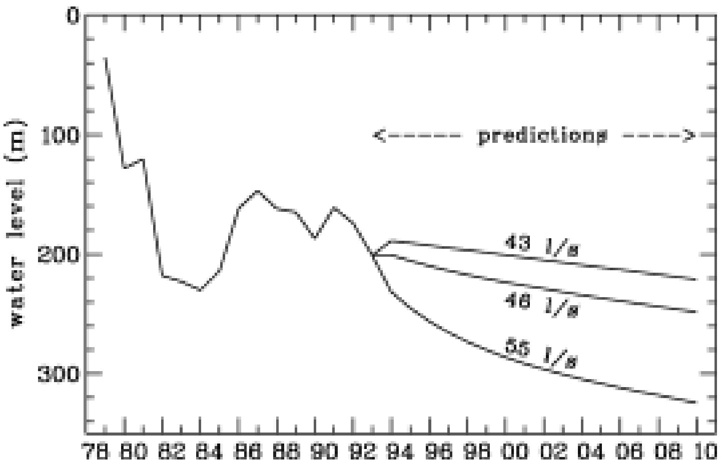

Figure 5. Water level changes in the Laugaland geothermal system, predicted by a lumped model.

Many low temperature geothermal waters can be used directly for space heating if the water is dilute. Sometimes the water has high salinity or it contains relatively high carbonate content. The chemical composition of the water has to be studied to evaluate the scaling and corrosion potential. Although water can be used directly for heating it does not have to be suitable for use as domestic hot tap water. If the water can be used directly for heating there is a possibility to use single distribution system, which can lower the capital investment in the system.

Careful collection of samples for chemical analysis is essential for all evaluation of the results. In many cases the only information available of chemical content of the water is from samples collected during production test of drill holes. Too often the collection has not been carefully planed and the chemical analysis are not representative for the flow from the well due to changes of the chemical content during storage of the sample.

Mineral equilibrium

The composition of geothermal fluid is controlled by temperature dependent reaction between the geothermal fluid and minerals. The formation of hydrothermal minerals is affected by temperature, pressure, rock type, permeability, fluid composition and duration of activity (Brown 1978). At temperature above 280°C the type of rock is insignificant but at lower temperature it is most pronounced. Chemical equations for formation of alteration minerals can be written to which the water composition is compared. The approach to chemical equilibrium for natural water-rock systems can be tested by comparing the water composition to theoretical composition of alteration minerals using thermodynamic data (Helgeson 1969, Helgeson et al. 1969, Robie et al. 1978).

Fluid composition in many geothermal fields worldwide appear to closely approach chemical equilibrium with secondary minerals for all major aqueous components except Cl and B (Giggenbach, 1980, 1981, Arnórsson et al., 1983, Michard, 1991). The chemical geothermometers are examples of chemical equilibrium used to determine the underground temperature.

To be able to compare the water composition to solubilities of minerals the concentration and activity of the chemical species have to be calculated from the chemical composition. Theses calculations are complex but various computer programs have been written to deal with these calculations such as the WATEQ-series

(Truesdell and Jones, 1974, Plummer et al. 1976), SOLMNEQ (Kharaka and Barnes 1973) and WATCH (Arnórsson et al. 1982) and later versions of these programmes.

Prior to exploitation geothermal water may be in equilibrium with the alteration minerals. Mixing with cooler groundwater may cause deviation from equilibrium and that have to be studied by interpretation of the monitoring data.

Scaling

Troublesome scaling of calcite and silica minerals is often associated with the utilization of geothermal fluid. Knowledge of the physical and chemical conditions causing mineral deposition from geothermal water allows an evaluation of the magnitude of the scaling problems and may aid in visualizing how they could be overcome. During exploitation cooling, heating, degassing or boiling, dissolution of materials from pipes and mixing of inflow from two or more aquifers, each with its characteristic temperature and chemistry can lead to scaling. By comparing the water chemical composition with the solubility of the minerals it is possible to predict scaling. It should be kept in mind that this study does not tell anything about the deposition rate.

Calcite

Calcite is the most common scaling product. The solubility of calcite as function of temperature is shown in fig. 8. The solubility increases with decreasing temperature. Therefore cooling of geothermal water does not cause scaling of calcite. Calcite scaling is on the other hand associated with boiling and mixing of inflow from two or more aquifers, each with different chemistry and temperature. The solubility of calcite can be described by the following reaction:

$$CaCO_3 = Ca^{++} + CO_3^{--} \qquad (1)$$

calcite calcium carbonate

The equilibrium constant for the reaction is

$$K_{calcite} = a_{Ca^{++}} \cdot a_{CO3^{--}} \qquad (2)$$

From the chemical composition the activity of the chemical species and the solubility product for calcite can be calculated.

$$Q_{calcite} = a_{Ca^{++}} \cdot a_{CO3^{--}} \qquad (3)$$

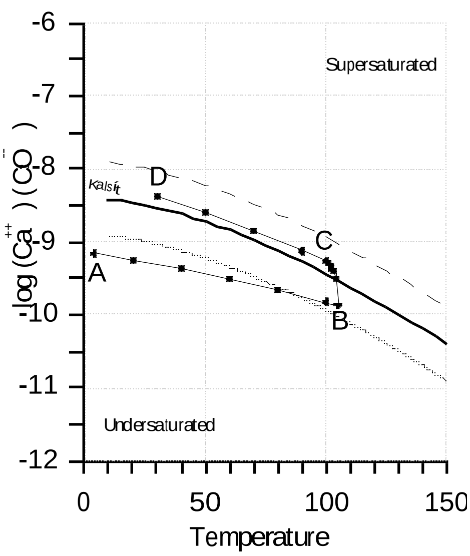

Figure 6. Solubility of calcite. The solid line represents the solubility and the dashed lines the division of error for the

If the solubility product Q is higher than the equilibrium constant for selected temperature the water is supersaturated and calcite can deposit. Experience shows that supersaturation in order of about 0.5 have to be reached before deposition forms.

Boiling or degassing of water increases the solubility product for calcite, which can lead to supersaturation of that mineral.

Figure 6 shows also the affect of heating, boiling and cooling of geothermal water with regard to the saturation of calcite. Point A represents cold water composition and the dashed line to point B represents heating of that water to 105°C. It is assumed that the water is deareated with boiling from 105°C to 100°C, point C. The solubility product change significantly during boiling and the water, which was undersaturated, becomes slightly supersaturated. The curve from the point C to the point D shows cooling of the water to 30 °C. Calcite scaling associated with boiling is always far the strongest at the first level of boiling. The magnitude of calcite supersaturation caused by boiling depends on the salinity of the unboiled water and its temperature. Strongest supersaturation is produced at the lowest temperatures and at highest salinity.

Mixing of inflow from two or more aquifers, each with different chemistry and temperature often affects the solubility product of calcite towards supersaturation. Equilibrium is reached again by precipitating calcite. Calcite depositions can be found immediately after mixing such as in deep well pumps.

Dissolution of calcium from asbestos pipelines can increase the solubility product of calcite, which may cause supersaturation and formation of calcite depositions.

Various inorganic and organic compounds, which are termed inhibitors have been shown to have an inhibitory effect on the rate of $CaCO_3$ dissolution. If inhibitors are needed to prevent scales it increase the operational cost of district heating.

Silica

The concentration of silica increases with increasing temperature and it depends on the solubility of quartz and chalcedony. During cooling the silica is in solution until solubility of amorphous silica is reached. At still lower temperature the water is supersaturated and silica depositions can be expected. Water in equilibrium with rock in low temperature areas up to about 130°C can be cooled down to 30°C without deposition of silica. Therefore geothermal water at up to about 130°C can be used in district heating systems without deposition of silica. Water in equilibrium with rock at 220°C reaches amorphous silica saturation if cooled down to about 90-100°C. During boiling the concentration of silica increases due to steam loss and the amorphous silica saturation curve is reached at higher temperature. Due to high silica content water from high temperature areas cannot be used directly in district heating systems.

Magnesium silicate

Depositions of magnesium silicate can form where fresh groundwater is mixed with geothermal water. Experiments in order to determine the solubility of magnesium silicate under these conditions are described by Hauksson et al. 1995. The solubility of magnesium silicate can be described by the following reaction:

$$MgSiO_3 \cdot H_2O + H_2O = Mg^{++} + H_3SiO_4^- + OH^- \qquad (4)$$

The equilibrium constant for reaction (4) is given by

$$K_{Mg\text{-}silicate} = a_{Mg++} \cdot a_{H3SiO4^-} \cdot a_{OH^-} \qquad (5)$$

The calculated solubility product (Q) for these species in the water sample can be compared with the equilibrium constant similar as for calcite.

$$Q_{Mg\text{-}silicate} = a_{Mg^{++}} \cdot a_{H3SiO4^-} \cdot a_{OH^-} \qquad (6)$$

Figure 7 shows the solubility of magne-sium silicate as a function of temperature in range of 60 – 120°C. The reaction shows that the solubility depends on the activity of magnesium, silica and hydroxide (pH) as well temperature.

If the solubility product (Q) for magnesium silicate is higher than the equilibrium constant for selected temperature the water is supersaturated and magnesium-silicate can deposit.

Cold fresh groundwater always contains some magnesium but the concentration of silica is relatively low. If cold water is heated and deareated through boiling the pH of the water increases. These changes could lead to supersaturation of magnesium silicate.

The content of magnesium in geothermal water is usually very low and the water calculates to be undersaturated with respect to magnesium-silicate. The content of silica is on the other hand higher than in cold fresh water and the content increases with increasing temperature. Mixing of cold fresh water and geothermal water may therefore cause deposition of magnesium silicate.

Corrosion

Corrosion of carbon steel has been experienced in association with water containing dissolved oxygen at low temperatures (< 80°C), carbon dioxide waters (pH<8.5) below 100 °C and water with rather high chloride content.

Corrosion is one of the parameters often follows mixing of fresh water and geothermal water where dissolved oxygen is increased. A very slight increase in salinity will catalyse oxygen corrosion considerably. If dissolved oxygen is detected it will result in increased corrosion.

To avoid corrosion the dissolved oxygen has to be removed. This can by done by boiling or adding chemicals, which react with the oxygen. Addition of sodium sulphite to the water (10 ppm Na_2SO_3 per 1 ppm O_2) is widely used. The dissolved oxygen is then removed owing to the reaction:

$$2\ Na_2SO_3 + O_2 = 2\ Na_2SO_4 \qquad (7)$$

Dissolved oxygen and hydrogen sulphide cannot exist together in solution (or only to a certain extent). Sulphide is therefore a good natural eliminator of dissolve oxygen if it enters the system from the atmosphere for example in storage tanks. The empirical results from Reykjavik Energy show that 1.6 ppm of hydrogen sulphide is needed to remove 1 ppm of dissolved oxygen. This indicates that the reaction is not only sulphate production as shown in the reaction $S^{--} + 2O_2 = SO_4^{--}$ where 0,5 ppm of sulphide is needed for each 1 ppm of dissolved oxygen.

Copper and copper alloys are widely used in district heating systems, e.g. in pipes, valves flow meters, heat exchangers and pumps. It has long been recognized that copper corrodes in sulphide containing environment. The sulphide corrosion problem is sometime related to sulphate-reducing bacteria in the literature, but in geothermal systems, especially those with sulphide of magmatic origin, the corrosion is believed to be of chemical nature. In sulphide containing environment the copper become coated, almost at once with thin black coating of copper sulphide, which is easily removed with the flowing water resulting in further corrosion of the metal. Copper pipes should therefore be avoided if the water contains hydrogen sulphide.

Gas in geothermal water

Geothermal fields are commonly classified on the bases of reservoir temperature in high- and low-temperature systems. The high-temperature systems usually contain high content of dissolved solids and gases and cannot be used directly in district heating systems. High content of gases are sometimes associated with low-temperature geothermal water, causing some problems during utilization.

If pumps have to be installed in geothermal drill holes with high content of gases special attention have to be taken. At lower pressure the gas will separate from the water sometime causing cavitations in the pump. Sometimes release of gases can cause disturbance of chemical equilibrium followed by precipitation and scaling. Study of chemical composition of water and gas content can avoid expensive damage of pumps and other equipments. From the composition, pressure of boiling and/or gas separation can be

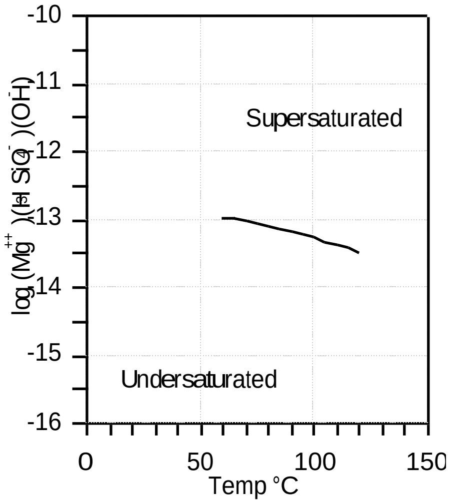

Figure 7. Solubility of magnesium silicate as a function of temperature.

calculated which can be used to determine the minimum depth of pumps in wells.

Composition of hot water used as tap water

Although water can be used directly for space heating it does not have to be suitable for use as domestic hot water. The water composition has then to be compared to the values recommended in drinking water codes. Some elements require special attention. The concentration of fluoride is often higher then recommended in drinking water. Too high concentration cause teeth and bone diseases. If the concentration of iron is too high the water may become brownish due to oxydation when it comes in contact with air. Hydrogen sulphide is not allowed in drinking water. Its presence in cold water is usually due to decomposition of some organics in the system. In the case of geothermal water its source is often magmatic. Although hydrogen sulphide is harmful compound low concentration in geothermal water should not affect humans.

District heating technique

Various factors are affecting the cost of district heating. The geothermal reservoir, the temperature and the chemistry of the fluid are most essential.

The cheapest geothermal district heating services are those using water of suitable temperature from about 70 °C to 150 °C and low in dissolved solids and carbonate. At higher temperature deposition of silica can be expected and at lower temperature the heat may not be enough and more costly solutions are needed as heat pumps or geo-ground heat systems.

Direct flow through systems

If water is of suitable composition the water can be directly used in flow through systems. This is the most common system used in Iceland. The water is pumped out of the wells using down hole pumps.

Collecting mains carry the water to the main buster pumping stations, which push the water through transmissions mains to distribution pumping stations and storage tanks. The distribution system can either be single pipe system or double pipe distribution system. In the double pipe system the return flow from the consumer runs back to the pumping station. If the temperature of the geothermal water is in the higher range this water can be used to mix with the geothermal water to provide the proper (80°C) for the distribution. If the disposal have to be injected this water would then be piped to the injection wells. In single pipe systems the backflow drains directly into the sewer system. Figure 8 shows simplified diagram of the Reykjavik system which both consist of single pipe system and double pipe distribution systems.

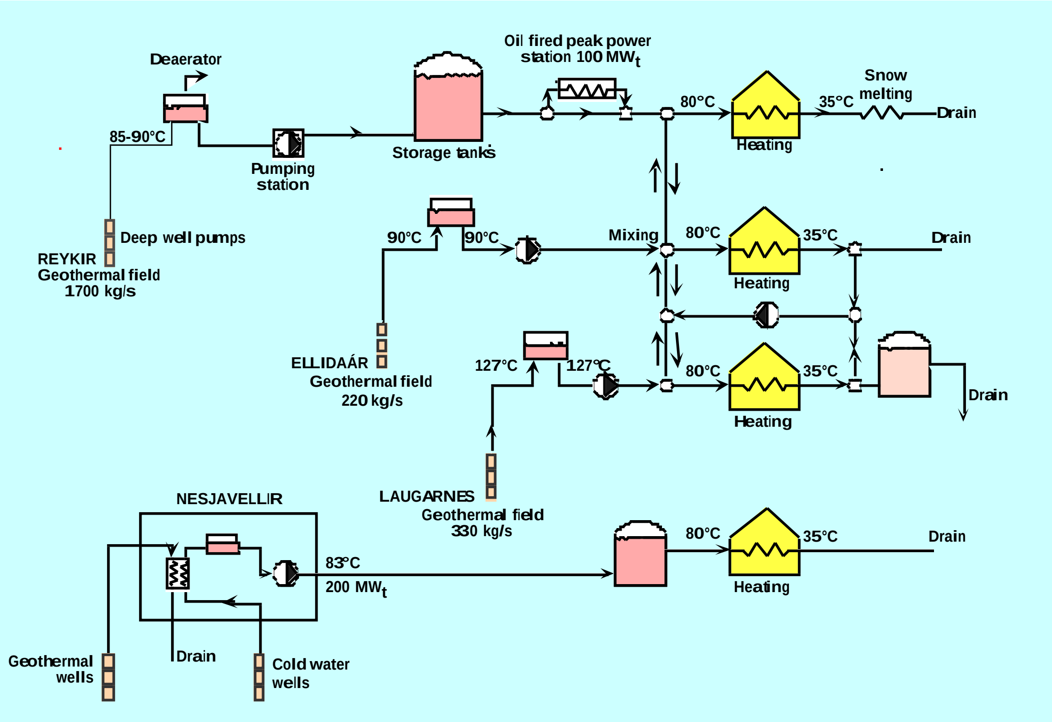

Figure 8. Simplified diagram of the district heating system in Reykjavik, Iceland.

Heat exchangers

In many cases hot water cannot be used directly due to unsuitable chemical composition. In such cases it is possible to transfer the heat to other media by use of heat exchangers. The two main types of heat exchanger available are plate heat exchangers and tube heat exchangers. The design is depending on the proposed use. Examples of both types are shown in figure 9.

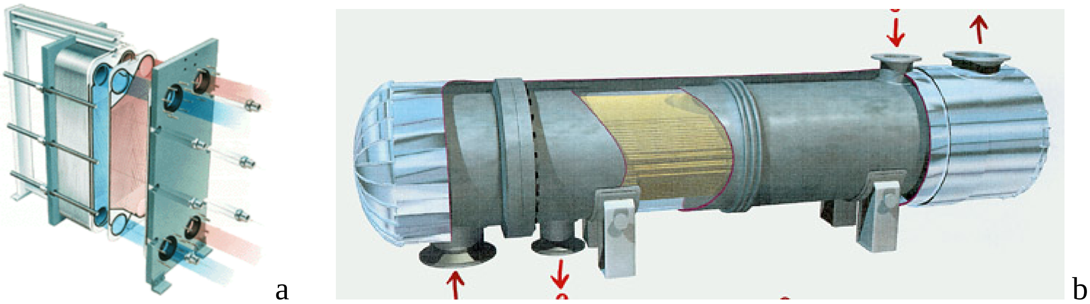

Figure 9. Plate heat exchanger (a) and tube heat exchanger (b)

Heat pumps

Where the temperature of the geothermal water is not high enough to be used directly or by using heat exchangers heat pump might be used. Heat pump is a kind of reverse heat engine. It transports heat from low temperature environments to high temperature ones by performing a certain amount of mechanical work. This is therefore expensive solution and is sometimes also used to increase the heat efficiency of the geothermal water.

Geothermal heat pumps

Another geothermal technology is the geothermal heat pump (figure 11). They do not use geothermal reservoirs, so they can be used almost everywhere in the world. By pumping fluid through loops of pipes buried underground or in drill holes under the buildings, these systems take advantage of the relative constant temperature 7-13 °C.

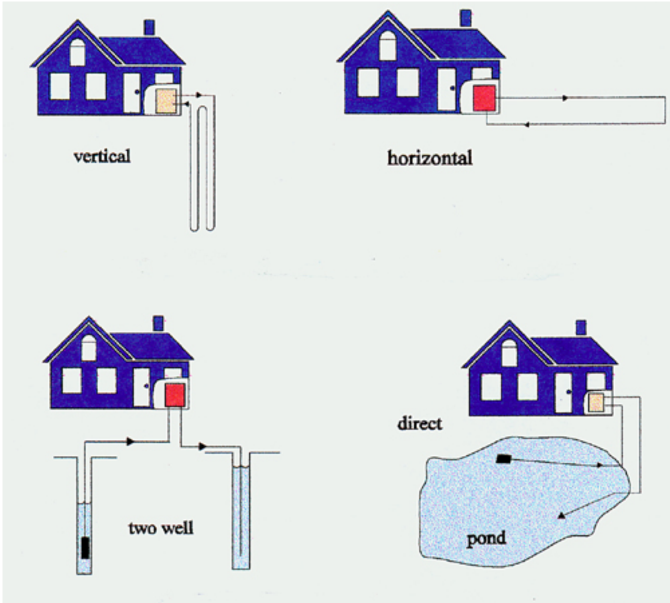

Figure 11. Geothermal heat pump (from Lund, 2001)

During winter, heat is extracted from the fluid in the earth connection by the geothermal heat pump and distributed to the home or building, typically through a system of air ducts. Cooler air from the building is returned to the geothermal heat pump, where it cools the fluid flowing to the earth connection. The fluid is then rewarmed as it flows through the earth connection.

In summer, the process is reversed, as excess heat is drawn from the building, expelled to the loop, and absorbed by the earth.

Disposal of used geothermal water

Spent geothermal water cannot always be disposed at the surface. In some cases the water contain some chemicals and in other cases the temperature may be too high for surface discharge. In many countries there are strict regulations on disposal both regarding temperature and chemicals. This may led to injection of spent geothermal water. Injection may also be required to remain pressure and fluid in the reservoir. If injection is required it will increase the cost considerable.

Managements of geothermal reservoir during exploitation

Management of a geothermal resource involves deciding between different courses of action in the exploitation of the resource (Grant *et al.*, 1982). Most often management decisions are made to improve the operating conditions of a geothermal reservoir. In some cases unfavourable conditions may have evolved in a reservoir, while in others improvements in production technology may justify changes in production strategy. The operators of a geothermal resource must have some idea of the possible results of the different courses of action available to be able to make these decisions. This is why careful monitoring is an essential ingredient of any management program.

The parameters that need to be monitored to quantify a reservoirs response to production differ, of course, somewhat from one geothermal system to another. In addition the methods of monitoring as well as monitoring frequency may differ. Below there is a list of the basic aspects that should be included in conventional geothermal monitoring programs:

1. Mass discharge history of production wells.

2. Enthalpy or temperature (if liquid or dry steam) of fluid produced.
3. Wellhead pressure (water level) of production wells.
4. Chemical content of water and steam produced.
5. Reservoir pressure (water level) in observation wells.
6. Reservoir temperature through temperature logs in observation wells.

Careful monitoring of a geothermal reservoir during exploitation is, therefore, an indispensable part of any successful management program. If the understanding of a geothermal system is adequate, monitoring will enable changes in the reservoir to be seen in advance. These can be undesirable changes such as decreasing generating capacity or possible operational problems such as scaling in wells and surface equipment or corrosion. Thus, the importance of a proper monitoring program for any geothermal reservoir being utilised can never be stressed too much.

Benefits of geothermal district heating

Clean air is one of the main benefits of utilization of geothermal energy for space heating and it can also influence the health of the inhabitants. Clean air and reduction of coal-soot and other particles are undoubtedly the main reason. Other benefits of the use of geothermal energy for district heating is that the energy is in all cases domestic and fossil fuels do not have to be transported. In most cases this energy source is compatible in price to other alternatives, especially if environmental issues are taken into account. Space heating using geothermal water also allows cascading uses such as for swimming pools, greenhouses, heated garden conservatories and snow melting.

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