Frick, S., Regenspurg, S., Kranz, S., Milsch, H., Saadat, A., Francke, H., Brandt, W., Huenges, E. (2011): Geochemical and process engineering challenges for geothermal power generation. - Chemie Ingenieur Technik, 83, 12, 2093-2104

DOI: 10.1002/cite.201100131

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Geochemical and process engineering challenges for geothermal power generation

Geochemische und verfahrenstechnische Herausforderungen bei der geothermischen Stromerzeugung

Abstrakt

Die Handhabung geothermischer Fluide bzw. von Thermalwässern, welche meist eine komplexe Mischung aus gelösten Salzen und Gasen sind, ist eine der großen Herausforderungen bei der Planung und beim Betrieb verlässlicher und effizienter geothermischer Kraftwerke. Im Thermalwasserkreislauf müssen ungewollte Mineralausfällungen und Fluid-Material-Wechselwirkungen verhindert werden und die Auslegung und Dimensionierung aller Komponenten ist an die Thermalwassereigenschaften anzupassen. In diesem Artikel werden geochemische und verfahrenstechnische Aspekte sowie aktuelle Forschungsaktivitäten in diesen Fachgebieten aufgezeigt und der Standort Groß Schönebeck als zentraler Standort für geothermische Forschung vorgestellt.

Abstract

Handling of the geothermal fluid, which is typically a complex mixture of salt solution and dissolved gases, is one of the main challenges for designing and operating reliable and efficient geothermal power plants. In the geothermal fluid loop, undesired mineral precipitation and fluid-material interactions must be prevented and the design and dimensioning of all components must be adapted according to the characteristics of the geothermal fluid. This paper outlines geochemical and process engineering aspects as well as research activities in these fields and introduces the Groß Schönebeck site, which is a central site for geothermal research.

1. Introduction

The use of geothermal energy for electricity generation has gained increasing interest due to the political goals of reducing greenhouse gas emissions, reducing the consumption of finite energy resources, and increasing sustainability of energy supply. Geothermal power plants generate power from an alternative source of energy that is independent of season and time of day and offers a significant potential on a world wide scale (e.g. [1], [2]). Only a small part of this huge potential is currently being used. The globally installed electrical power in 2011 summed up to about 11 GW [1]. The largest share of this capacity is generated from high-enthalpy or high-temperature geothermal reservoirs that are located at exceptionally favourable geological sites (e.g. Italy, Iceland, Philippines) with a high geothermal gradient. Less than 1 % of the currently installed capacity, but the predominant part of the still unexploited geothermal potential, is located outside these geological areas and is found in reservoirs of low temperature (typically between 100 and 200 °C), of large depths and often of low natural permeabilities. In Germany, a region with typical low enthalpy geothermal resources, four geothermal power plants are currently installed and several more are being planned/constructed (e.g. [3]).

For the sustainable and effective exploitation of these reservoirs, at least two deep wells, a production and an injection well, are drilled. In order to obtain a sufficient fluid flow from the geothermal reservoir, further technical reservoir engineering measures to obtain higher permeabilities (enhanced geothermal systems, EGS) are undertaken at many sites [4]. During operation, the geothermal fluid is pumped from the geothermal reservoir to the surface (see Fig. 1), where it is used to supply power and/or heat and/or chill. For power generation, part of the heat contained in the geothermal fluid is transferred in a heat exchanger to a so called binary conversion cycle. In the binary unit, a working fluid with low boiling point is circulated, mostly because the direct use of the geothermal fluid in the conversion cycle is not as efficient from a thermodynamic point of view (e.g. [5],[6]).

An important aspect for the successful use of geothermal heat is related to geochemical and process engineering issues. Geothermal fluids are complex mixtures consisting of salt solution and dissolved gases, which differ site-specifically. The properties of geothermal fluids hence depend on the reservoir characteristics, as well as on the temperature and pressure changes that occur during operation. The knowledge of the fluid properties throughout the geothermal fluid loop is essential for a proper plant design and operation. In contrast, improper design and operating conditions could lead to precipitation of minerals (=scaling) or undesired fluid-material interactions (=corrosion). The induced chemical reactions might cause failure of plant components and/or damage the reservoir upon fluid reinjection. Misperformance of single components, such as pumps and heat exchangers in the geothermal fluid loop, might decrease the efficiency and can even cause failure of the plant.

In this paper, we will give an overview on geochemical and process engineering aspects relevant for low enthalpy geothermal systems. Currently, these topics are investigated at the in-situ geothermal laboratory Groß Schönebeck, which is the central site for geothermal research at the German Research Centre for Geosciences GFZ. Activities at this research platform will be presented in more detail within the next section. Afterwards, general overviews of geothermal fluid composition and how it can affect design and operation of geothermal power plants will be addressed both, generally and for the example of Groß Schönebeck. The scientific experience that was achieved by developing this research site over the last years has been compiled by Huenges [4], which serves also as main base for this paper.

2. Geothermal in-situ laboratory Groß Schönebeck

The geothermal research laboratory Groß Schönebeck serves to investigate, understand and optimize all steps involved for the use of deep geothermal systems – from reservoir exploration to energy supply aboveground - and is a central site for geothermal research not only at GFZ. All development and operating stages have been and will be scientifically monitored so that the comprehensive data base enables a better understanding of interactions between the subsurface and the plant part aboveground. An overview on the ongoing and future research work is given by Saadat et al. [7].

At the Groß Schönebeck site, which is located about 50 km north of Berlin, two deep wells have been completed for geothermal applications. The injection well is an abandoned gas well that was reopened and deepened in 2001 (final measured depth of 4309 m). The production well is a geothermal well that has been drilled by GFZ in 2006 (final measured depth of 4400 m). The horizontal distance between the two wells aboveground is about 28 m and in the reservoir about 475 m. Fluid temperature at depth is about 150 °C and the reservoir pressure is 45 MPa.

To improve fluid flow from the deep geothermal reservoir and hence to decrease the effort for pumping the geothermal fluid from the reservoir to the surface, different reservoir engineering measures have been performed. Detailed information about the reservoir development and stimulation experiments in Groß Schönebeck, such as hydraulic and gel-proppant fracs as well as acid treatment can be retrieved from literature ([4], [8], [9]). Currently, a long-term hydraulic experiment is being set-up in order to obtain more information on the reservoir characteristics and the sustainability of the reservoir engineering measures.

The hydraulic experiment will also be used to supply a corrosion test rack at the surface with hot geothermal fluid. This is because the main challenge after developing the geothermal reservoir is to cope with the high salinity and gas content of the geothermal fluid. In the corrosion test rack, which is installed in parallel to the main piping of the geothermal fluid loop, the corrosion resistance of different metallic materials will be analyzed over time and under in-situ conditions. The tested materials are different material coupons (metal samples), and test components, such as a heat exchanger with different plate materials, pipes and a down-hole pump. With the emerging research power plant, which will be completed in 2011, further process engineering investigations will be performed. In the future, the Groß Schönebeck site should serve as research platform for the development of methodologies, component tests and further investigations together with various partners from science and industry. Fig. 2 gives an overview of the infrastructure at the Groß Schönebeck site.

3. Geothermal fluids

Chemical composition and classification

The geothermal fluid is defined as a heated multiphase substance, which flows within pores of a geological formation (= bedrock) of a geothermal reservoir. There are strong differences between low and high enthalpy geothermal system fluids with respect to fluid composition and classification. This paperwill focus only on low enthalpy geothermal fluids. The kind of the fluid bedrock as well as interactions of the fluid with the surrounding rocks during migration determines the chemical composition of geothermal fluids. During migration, the fluids undergo elemental separation and segregation due to interactions with minerals, organic matter and microbiological processes leading to mineral saturation or dissolution. Consequently, with increasing age and depth of the fluid/bedrock, the salinity of a geothermal fluid usually increases (e.g. [10],[11]). Roughly, fluids can be divided according to their geological source: sedimentary basin fluids and crystalline rock fluids [12].

Apart from their geological source, low enthalpy fluids are furthermore classified according to their major chemical compounds or according to their salinity. Depending on their dominant ions, fluids are grouped in different types representing the major components of the system. In sedimentary basin fluids, the most frequently occurring compounds are sodium (Na^+), calcium (Ca^{2+}) and chloride (Cl^-). In crystalline rocks, besides Na^+, Ca^{2+} and Cl^- also bicarbonate (HCO_3^-) and sulphate (SO_4^{2-}) might play a major role [11]. A depth distribution of main components (log Ca, Na, Cl in g/L) from sedimentary basin fluids of various origins is shown in Fig. 3 (left). Fig. 3 (right) shows the correlation between the depth of the fluid origin and the TDS (Total Dissolved Solids) content in sedimentary basins compared to crystalline rock fluid. Hot geothermal fluids are typically brines (highly saline solutions) because they derive from great depths, required to access the temperatures necessary for power generation from geothermal heat. An exception where hot but low saline fluids are used for geothermal energy production, are fluids from the Malm limestone formation of the South German Molasse Basin (e.g. Unterhaching, Fig. 3, right)

Due to the energetic use, the temperature of the geothermal fluid decreases from reservoir temperature (between 100 to 200 °C) to the temperature at the outlet of the geothermal power plant (between 50 to 80 °C). Similarly, the pressure decreases from several hundred bars in the reservoir to a few bars in the surface plant equipment. Both, pressure and in particular temperature changes strongly influence physico-chemical fluid properties and can provoke a change in fluid composition due to a change of mineral saturation (induced for example by degassing) and results in precipitation of minerals. Furthermore, chemical processes that may change the fluid composition can result from reactions between fluid and surrounding materials (e.g. pipes) or gases (e.g. atmospheric oxygen).

Even though the compounds Na, Cl and Ca are the main components in deep geothermal fluids, other compounds, which occur only in minor and trace amounts, may have stronger effects on the plant operation due to their higher reactivity. The total composition of a typical geothermal fluid in the North German Basin is shown for the example of the Groß Schönebeck fluid in Fig. 4. The gases are composed mainly of nitrogen and methane. While the first represents no problem, considerations are necessary how to deal with the latter. If methane degasses, the gas should be flared due to its GWP (Global Warming Potential) which is larger than the one of CO_2, and in order to use the resulting heat. However, gases with low methane content cannot be flared without additional effort. Also, the small amounts of CO_2 (0.3 %) could represent a problem when they degas, thereby shifting the pH of the solution to higher values and inducing mineral oversaturation. Regarding the components of the solution, especially Cl can cause strong problems due to its ability to cause pitting corrosion (see chapter 4 on corrosion). Compounds, which need further attention in the Groß Schönebeck brine are dissolved iron and manganese, which could react with oxygen to form oxides and hydroxides as well as heavy metals (e.g. Ba, Pb and Zn). The latter could also easily precipitate – especially with sulphate (see chapter 4 on scaling).

A detailed analysis of the development of the Groß Schönebeck fluid in the two wells over time is given by Regenspurg et al. [15]. Further general information on fluid components and their effect in geothermal plants is addressed by Saadat et al. [5].

Thermophysical properties

In addition to chemical fluid composition, knowledge of thermophysical fluid properties plays a central role in successful geothermal site development and use as exemplified below. These properties comprise fluid density, specific heat, viscosity, electrical and thermal conductivity as well as speed of sound as a function of pressure, temperature and chemical composition. These properties are important for the characterization of the reservoir itself (e.g. its state of stress), the design of the down-hole pump (e.g. installation depth and flow rate), and the various components of the aboveground installations (e.g. heat exchangers). Due to varying fluid compositions these properties are site specific and may furthermore change over time due to changing thermodynamic pT-conditions during operation. Chemical reactions related therewith may cause precipitation of solid phases from the fluid.

Thermophysical fluid data can be determined with suitable measuring devices. For simple systems a plethora of work exists and an extensive review was performed by Valyashko [16]. Based on such measurements empirical functions can be derived that describe an individual fluid property. However, the range of validity of existing functions is limited and hence also restrictedly useful to investigate systems over wide ranges of temperature, pressure, composition, and phase state of the fluid. For more complex fluid compositions the derivation and evaluation of mixing-rules will require an ongoing experimental effort. Referring to the Groß Schönebeck site, laboratory measurements of density, viscosity, and electrical conductivity [17] as well as first calculations based on existing fluid property correlations [18] were performed. At the GFZ, nationally funded research is conducted on developing experimental methods, the physical properties of complex fluids, and interrelations between thermophysical parameters and chemical reactions.

In addition to investigations on real systems and to laboratory experiments, simulations of chemical reactions and of reactive transport are necessary to determine the controlling factors for e.g. mineral precipitation. Additionally, coupled chemo-hydraulic-thermal transport modeling permits an estimation of process propagation with distance and time which often is experimentally not possible. However, many parameters necessary for the calculation of activity coefficients and thus the solubility of minerals and aquatic complexes are unknown. At the GFZ and with external partners the existing thermodynamic database is extended by solubility, sorption and flow-through experiments. Additionally and based on these experiments, geochemical batch and transport modeling is performed in view of model benchmarking.

Once a geothermal plant is in operation, knowledge of in-situ physical and chemical fluid parameters at representative installation points and as a function of time is essential to monitor chemical changes and processes. This enables taking measures to avoid e.g. corrosion and scaling. The data gathered can also be used for geochemical modeling of the fluid transport reactions. A suitable monitoring program is strongly site specific due to different conditions of each reservoir. For the Groß Schönebeck site a versatile fluid-chemical monitoring unit has been developed that enables online and in-situ measurements of a variety of physico-chemical parameters at different locations of the geothermal fluid loop aboveground [18]. The scientific and technical purpose of the system is to monitor (a) a compositional variability of the produced fluid and (b) chemical processes potentially occurring within the plant. Sensors are provided for pressure, temperature, volumetric flow-rate, density, pH-value, redox potential and oxygen content.

In summary, a full physico-chemical characterization of the geothermal fluid and the processes occurring within it, as planned at the Groß Schönebeck site, should be an integrated combination of in-situ measurements, laboratory experiments on fluid samples and synthetic fluids, numerical modeling as well as extensive monitoring within the operating fluid loop.

4. Fluid flow phenomena

Two-phase flow and degassing

The large pressure difference between the geothermal reservoir and the aboveground facilities due to the hydrostatic pressure difference and friction losses can induce degassing of the dissolved gases (e.g. N_2, CH_4, CO_2) and/or evaporation. In some components of the geothermal fluid loop (e.g. those with a nozzle effect) also local flow conditions might cause these effects. Degassing occurs if the gas solubility of the fluid, depending on pressure and temperature, is lower than the existing gas content, and the dissolved gas separates from solution. Water evaporates when the absolute pressure sinks below the bubble point pressure. Once a gas phase exists, degassing/evaporation or dissolution/condensation continues towards equilibrium of partial pressures and saturation pressures.

Due to the different densities of the phases, even the degassing of small amounts of gas can cause a significant increase of the volume gas fraction. The resulting changes of the thermophysical properties and the particularities of handling two-phase flow are important aspects for the design and operation of the components in the geothermal fluid loop.

The presence of a gas phase, for example, lowers the effective density of the medium. At constant mass flow this will lead to an increase of the medium's mean velocity and therefore an increased wall friction. Also inner friction is intensified if fluid and gas phase are moving against each other (buoyancy effect) which is especially the case for the flow in the deep well. Regarding the deep wells it must also be considered that a lower effective density increases the pressure at the well head, since the pressure at the well bottom is defined by the reservoir. The well head pressure thereby has a significant effect for designing/operating fluid production from and injection into the reservoir.

Designing and dimensioning the geothermal fluid loop for two-phase flow is a complex task since no specific property functions for brines, being a mixture of varying composition, exists. The fluid properties have to be calculated using correlations for two-phase media and property functions from the literature for density, specific enthalpy and solubility for aqueous solutions of chlorides and nitrogen as well as carbon dioxide (e.g. [20], [21]).

Besides the increasing pressure loss due to friction and the change of the flow regime in the fluid loop it must be considered that degassing of CO_2 as consequence of pressure drop furthermore increases the pH-value. This can lead to precipitation of solids and cause scaling and corrosion, which will be dealt with in more detail in the next sections. Detailed information on multiphase flow in wells can be retrieved from [22].

Scaling

Scaling characterizes the formation of a solid within a solution as consequence of over-saturation of a certain salt. Saturation depends on the concentration of the chemical compounds as well as fluid properties such as temperature and pressure, pH-value, redox conditions, ionic strength, and flow dynamics of the solution. For example, as long as geothermal fluids are not in contact with the atmosphere or mixed with O_2 containing surface water or shallow ground water, O_2 gas dissolved in water would not be expected to occur in geothermal fluids. However, if O_2 enters the fluid it would quickly react to oxidize the reduced species of the fluid such as Fe(II) to form Fe(III) oxides or hydroxides which precipitate immediately.

For many compounds, the kinetics of solid precipitation is often slow and thus even when a solution is oversaturated, precipitation would not occur. However, the presence of solid surfaces or microorganisms can strongly catalyze precipitation reactions.

Within the tubing of the geothermal fluid loop, scaling effects can be crucial for plant operation due to precipitation directly either on heat transfer surfaces or a pipe wall and thus clogging the pipes and limiting fluid flow. Besides direct precipitation and coating of plant components, the soils could also form small (colloidal) particles which remain suspended in the fluid. Thus, they can be transported over large distances in the well and the fluid loop, they can accumulate and cause clogging somewhere else in the system. Fig. 5 shows an example of lead scale observed on the pump cable in Groß Schönebeck probably formed by changed flow conditions and consequent redox reactions.

Depending on the scale composition and location in the geothermal fluid loop, scaling can be dealt with in a variety of ways: To avoid scale formation such as barite scales ($BaSO_4$) induced by cooling the fluid, the geothermal fluid should not be cooled down below a certain temperature (which might be a higher temperature than the optimum cool down temperature from a thermodynamic viewpoint). However, for this measure, caution is essential if the fluids are rich in calcium (Ca^{2+}) and bicarbonate (HCO_3^-), because calcite ($CaCO_3$) precipitation is increased at higher temperatures. Other options are the addition of scaling inhibitors to the fluid (usually polymers which prevent the formation of sulphide minerals), as it is often applied for oilfield wells or the acidification of the fluid to increase mineral solubility. Furthermore, biocides or disinfectants would be added to the fluids to prevent microbiologically catalyzed mineral precipitation. Saadat et al. [5] give a detailed overview on scale forming processes as well as scale prevention and removal.

Monitoring some relevant chemical parameters of the fluid and calculating the mineral precipitation with adequate chemical simulation codes at given pT-conditions can help to estimate the potential risk of mineral precipitation. Attempts to predict mineral scale formation in geothermal systems by modeling have been made. However, modeling so far is strongly simplified and lacks adequate equilibrium constants [5]. In order to improve the prediction of mineral precipitation, different research activities are carried out at GFZ. The aim is to validate computer solubility models and develop methods of scale prediction through experimental determination of mineral solubilities in synthesized geothermal brines.

Currently laboratory experiments are performed at GFZ in autoclaves to determine which minerals precipitate at certain pT-conditions for brines of various compositions. Mineral solubilities in a Na-Ca-Cl brine (6M Cl) are being determined experimentally in batch reactions using autoclaves at conditions relevant to the Groß Schönebeck site aboveground installations (10-15 bar; 50-150 °C).

Corrosion

Corrosion is the destruction of a material due to chemical reactions with its surrounding environment (gas or liquid) e.g. by reaction with water and oxygen. Corrosion occurs in a variety of conditions, which involve two basic mechanisms: electrochemical corrosion and (hot gas) oxidation. Many properties of geothermal fluids are relevant for corrosive effects, such as the pH-value, redox potential, chloride concentrations or the gases H_2S and O_2.Within a plant, corrosion can occur locally to form a pit or crack, or it can extend across a wide area to produce general attack. This uniform corrosion, which involves a uniform thinning of the metal, is the most common form, but can be controlled relatively easily with appropriate engineering design. In contrast, non-uniform corrosion such as crevice attack is more difficult to control [5]. Pitting corrosion describes the local corrosion which occurs when the protective film of a metal (the oxidation layer) is defected e.g. due to high amounts of chloride ions in solution. Inter-granular corrosion characterizes the attack along grain boundaries in the steel causing whole grains to fall out. Finally, the effect of mechanical stress often combined with local electrochemical corrosion can cause rapid cracking in equipment, e.g. pipes and reactors (e.g. by H_2S).

To minimize corrosion either the oxidizing species (O_2, H^+) need to be removed from the solution or the (potentially corroding) materials such as iron or steel should be protected by providing a barrier against the reacting species in the fluid. In most cases, this implies the formation of a uniform, nonporous, adherent protective film. The formation of these films can be achieved either by alloying the iron or by addition of inhibitors into the aqueous phase. Similarly, anti-corrosive paints containing chemically active pigments can form protective coatings at the paint-metal interface which consist, for example, of iron oxides or iron phosphates. While some efforts to reduce corrosion merely redirect the damage into less visible, less predictable forms, controlled corrosion treatments such as passivation and chromate-conversion will increase a material's corrosion resistance. Best corrosion prevention, of course, is the choice of the adequate material, which depends mainly on fluid properties.

In general, alloying the iron with more noble elements such as nickel or chromium increases the corrosion resistance, because a higher electromotive force (emf) would be required for corrosion to take place. CRA (corrosion resistant alloy) development is a broad field in materials sciences developing all kinds of mixed materials. However, until now, little corrosion data and material recommendation for materials used in geothermal plants are available, especially for the highly saline fluids as expected in low enthalpy geothermal systems. Within a research project about corrosion in geothermal plants, several metallic materials have been tested for their general corrosion resistance in hot, saline fluids. Eight different materials were evaluated by exposure and electrochemical tests [23]. The use of high-alloyed materials like stainless steels, duplex steels and nickel-based alloys has been considered as a good choice for geothermal plants due to their remarkable corrosion resistance and appropriate mechanical properties. Nevertheless, the corrosion behavior of those metallic materials in geothermal fluids at service conditions has in many cases not been determined. Recent electrochemical investigations and exposure tests showed in fact the limits of suitability concerning localized corrosion of three different high-alloyed materials in a highly saline fluid [24].

At the Groß Schönebeck site, different in-situ experiments are conducted with partners from industry and material research institutes to qualify materials for geothermal applications. For that purpose, a corrosion test rack has been developed, consisting of a bypass system branched off from the main pipe. Therein, corrosion resistivity of several metallic components can be tested at in-situ conditions. Besides material components (tube sections) and material coupons, also electrodes will be installed for electrochemical monitoring of corrosion processes. Additionally, a plate heat exchanger will be installed in this test rack consisting of many different plate materials allowing to test the most adequate plate material for a geothermal plant.

5. Implications of geothermal fluid composition on process engineering

The previous paragraphs have pointed out the importance of proper handling of geothermal fluids. Design and operation of reliable geothermal power plants must hence prevent undesired mineral precipitation, fluid-material interactions and clogging in the geothermal fluid loop. Regarding plant efficiency, the knowledge of the fluid characteristics are furthermore important for the design and dimensioning of the components. In the following paragraphs, the implications of the Groß Schönebeck fluid on the most important process engineering tasks will be addressed for the examples of the specification of the down-hole pump, the set-up of the geothermal fluid loop as well as the specification of heat exchangers.

Down-hole pump specification

For pumping the geothermal fluid from a deep reservoir to the surface, so called down-hole pumps are installed below the fluid level in the production well. In the oil and gas industry, down-hole pumps are an established technology for the production of fluids. Pumping geothermal fluids, however, differs from this typical application due to the much larger volume flow rates and higher temperatures. Especially durability but also efficiency of down-hole pumps are not yet satisfying regarding geothermal applications. In most cases, selecting a down-hole pump is presently a compromise between efficiency and reliability aspects that must be based on a careful estimation of the expected operating conditions.

Down-hole pumps are distinguished depending on their mode of drive in line shaft pumps or electrical submersible pumps. Line shaft pumps are driven by a shaft and an electrical motor located aboveground, which limits their application to vertical wells and installation depths. In contrast, electrical submersible pumps are driven by an electrical motor located in the production well and have therefore a wider range of application. However, overheating of the motor is an issue since the cooling of it must be realised by the streaming hot fluid. Aspects of corrosion, scaling, and thermal expansion are also more complex to handle in contrast to line shaft pumps. More information on down-hole pumps are given, e.g., in [5], [25], [26].

Besides typical component selection aspects, such as corrosion resistant materials and the capability for certain temperatures, an important issue is the calculation of the installation depth according to the maximum fluid draw down that will occur during operation and the necessary intake pressure in order to avoid degassing and cavitation within the pump. Fig. 6 shows the scheme of a down-hole pump installation. In the Groß Schönebeck production well, the static fluid level is at about 300 m and the down-hole pump is installed at 1.200 m depth. The deep installation depth is caused by the wide range of flow rates necessary for the research activities.

For the selection and dimensioning of down-hole pump, the fluid properties during operation (e.g. density and viscosity) must be known since they have significant influence on static and dynamic fluid level as well as friction losses. In most cases, no valid in-situ or experimental data will be available so that these properties have to be estimated by means of numerical models. The estimation of the fluid properties must thereby be handled with care. Francke & Thorade [18], for example, evaluated the sensitivity of down-hole pump dimensioning for various density and viscosity functions. The results pointed out the importance of using suitable property functions that can represent the geothermal fluid at a specific site accurately. They also addressed that improvements are necessary regarding both, modelling the flow in deep wells as well as knowledge of composition- and pT-dependent fluid properties.

The development, application and evaluation of improved numerical models for brine flow is hence an ongoing project at GFZ. The modelling activities are accompanied by comprehensive monitoring. For the Groß Schönebeck site, a special monitoring system for the deep wells has been developed. With this system, pressure and temperature changes during fluid circulation can be monitored along the wells. In the depth of the reservoir, a new hybrid monitoring approach is implemented which combines fibre optics technology (e.g. [27]) with conventional electronic well logging (e.g. [28]).

Geothermal fluid loop set-up

Down-hole pump, heat exchangers and, at some sites, an injection pump are the main components of a geothermal fluid loop. However, mixtures of salt solution and dissolved gases need additional components to ensure the reliable and efficient operation of the plant. The selection of suitable materials and component designs is an engineering task that depends on the geothermal fluid characteristics and the operating conditions of the fluid loop at a specific site. A simplified geothermal fluid loop set-up is shown in Fig. 7 for the example of the Groß Schönebeck site. Besides general fittings and instruments, this set-up contains the following components:

- Down-hole pump: pumping of the geothermal fluid from the reservoir to the surface. In Groß Schönebeck it is installed at 1,200 m depth. In parallel to the down-hole pump, a special monitoring system for deep wells has been installed. The production string is equipped with a special Y-tool-assembly in order to monitor pressure and temperature changes during fluid circulation along the well [29].
- Insulated piping system: transport of the geothermal fluid at the surface and prevention of the entrance of oxygen into the system. The pressure in the piping is always maintained above 10 bar in order to avoid degassing of CO_2 and evaporation. The maximum system pressure is 22 bar. The aggressiveness of the geothermal fluid is met with regular steel that is coated with special epoxy resin [30].
- Nitrogen supply: maintenance of system pressure to prevent O_2 contamination or CO_2 release from the fluid. Degasser: separation of free gas (the down-hole pump is capable of pumping the geothermal fluid with a free gas content of up to 10 %), which is necessary to obtain the desired performance of other components in the fluid loop, such as the heat exchanger.
- Surge tank: compensation of variations in volume flow and maintenance of system pressure in case of operational stop and cooling of the geothermal fluid contained in the piping.
- Coarse filter unit: separation of solid particles (>10 to 20 µm) in filter bags to prevent clogging of plant components.
- Fine filter units: separation of solid particles (>1 to 2 µm) in filter bags to prevent clogging of the injection well. The filter units are operated in pendulum mode.

Injection pump: admission of necessary injection pressure. Injection pump and the down-hole pump are identical in construction. Regarding the design of the filter units, filter bags have been preferred over reverse flow filters. Experience from existing plants shows, that during the design phase, stripping intervals are very hard to predict so that a risk of wrong dimensioning - under-dimensioning for technical and over-dimensioning for economic reasons - is likely. By realizing the single coarse filter unit with a bypass and the fine filter unit as parallel set-up, the change of filter bags for all units can be performed during operation.

An aspect that is still being researched is the disposal of the free gas separated from the fluid. The accumulated gas is mainly nitrogen and some methane that is currently removed from the thermal water loop in the degasser, mixed with air and blown off since the caloric content is too low to be flared with conventional burners. In order to use this wasted energy in the future, a special catalytic burner is currently being developed and will be tested at the site.

Heat exchanger specification

Heat exchangers are one of the most important components in geothermal power plants and their performance is crucial for the total plant performance. Within the heat exchanger thermal energy is transferred from the geothermal fluid to a secondary fluid. In case of a geothermal power plant the secondary fluid is the working fluid (e.g. butane or pentane). The thermal energy has to be transferred efficiently and reliably. Hence for the specification and design of heat exchangers several particularities have to be considered.

Proper design of heat exchangers for geothermal applications requires accurate knowledge of thermo-physical fluid properties such as specific heat capacity, viscosity and density. With regard to geothermal fluids the manifold chemistry may hinder the calculation of properties with required accuracy. Methods for calculating density, heat conductivity and viscosity depending on temperature, pressure and salinity are given e.g. in [31]. Methods for calculating the specific heat capacity are given e.g. in [32] and [33]. However the validity of available methods is limited and often these methods don’t comprise the site specific fluid composition or the required temperature and pressure levels. In case sufficient methods for calculating these properties are not available, the data need to be measured. Thermo-physical properties of fluids are necessary to calculate the heat transfer area for transferring certain amounts of heat while considering a specific temperature difference. For calculating the pressure loss due to friction, thermo-physical properties are needed as well. The more secure the properties are, the lower is the design uncertainty.

Geothermal fluids contain dissolved gases and depending on pressure and temperature degassing occurs. The knowledge of the resulting two phase flow regimes are important for heat exchangers and their performance. In general two phase flow reduces heat transfer and increases pressure loss. The heat transfer is reduced due to a considerable lower thermal conductivity of gases. Furthermore the heat transfer area might be reduced because of gas accumulation inside the heat exchanger. The pressure loss is increased because of higher flow velocities due to low gas densities and in case of gas accumulations reduced flow cross sections. For reducing the effect of two phase flow, specific design criteria have to be considered. While operating the heat exchanger, system pressure maintenance and gas removal reduces the free gas content and hence the negative effects on heat exchanger performance.

Fouling of heat exchangers affects both, the efficiency and reliability. For that reason fouling must be considered in heat exchanger design e.g. precipitation of minerals such as silica and deposits which might accumulate on the heat transfer surface. The layer of deposits represents an additional heat transfer resistance between the hot and the cold fluid. This effect can be considered as a fouling factor which has to be incorporated in the calculation of the overall heat transfer coefficient. Different fouling mechanisms have been identified: precipitation fouling, corrosion fouling, chemical reaction fouling, biological fouling, particulate fouling, and freezing fouling [34]. Apart from the latter, all fouling mechanisms are relevant in geothermal applications. Precipitation and corrosion fouling are the most important mechanism. The determination of the fouling factor is somewhat indefinite and is based on experiences made with different geothermal fluids. In addition, the definition of the fouling factor suggests steady-state conditions, whereas fouling occurs time-dependent and the effect of fouling typically increases while operating the heat exchanger.

The material used for the construction of a heat exchanger for geothermal applications is a further important issue. In particular the chemical properties of the geothermal fluid as well as the fluid on the secondary side of the heat exchanger, such as the working fluid in a binary cycle, may require corrosion resistant materials such as stainless steel and titanium, or coatings. It must be considered that the material choice also influences the heat exchanger layout due to the different machining properties and tensile strengths of the materials. Titanium, for example, has a good corrosion resistance but a limited deep drawability which restricts the plate design of a plate heat exchanger and hence might affect its thermal performance. Furthermore titanium has a low pressure resistance in comparison to carbon steel which limits the applicability especially when using standard plate heat exchangers.

Due to the aspects addressed above, the specification of heat exchangers for geothermal power plants is not a common application, particularly when using geothermal fluids with high contents of dissolved salts and gases. Within the geothermal research power plant in Groß Schönebeck, different types of heat exchangers (plate, shell and tube) for different applications (e.g. preheater, evaporator) will be installed and investigated. Effectiveness, thermal capacity and pressure losses are monitored and analysed for full load and different part load conditions. The purpose of the investigation is to compare the heat exchanger design with operating data, to evaluate existing design correlations and if necessary to improve these design correlations for geothermal applications.

6. Summary

The paper showed that coping with complex geothermal fluid mixtures is a main challenge for designing and operating reliable and efficient geothermal power plants. In this context the state of the art as well as research activities, which are being dealt with in running projects at the German Research Centre for Geosciences GFZ, have been outlined. In this context, the geothermal research laboratory Groß Schönebeck has been introduced as central site for geothermal research that serves to investigate, understand and optimize all steps involved for the use of deep geothermal systems. All development and operating stages have been and will be scientifically monitored so that the comprehensive data base enables a better understanding of interactions between the subsurface and the plant part aboveground.

The knowledge of the geothermal fluid properties is important for both, proper design and operation of a geothermal power plant. These properties are site specific, vary throughout the geothermal fluid loop due to changing pT-conditions during operation and may furthermore change over time. Chemical challenges hence refer to the characterization of the fluid and the prediction of chemical processes for the pT-changes that occur in fluid during operation on the way from the reservoir up to the aboveground facilities and back into the reservoir. Due to the complexity of geothermal fluids, a full physico-chemical fluid characterization cannot be retrieved from existing experience and literature. Such a characterization should be an integrated combination of in-situ measurements, laboratory experiments on fluid samples and synthetic fluids, numerical modeling as well as extensive monitoring within the operating fluid loop. New approaches for experimental methods and numerical modeling, which are currently under development, will improve the quality and the realization of the physico-chemical fluid characterization in the future.

Once the geothermal fluid is characterized, process engineering challenges refer to the adaptation of the geothermal fluid loop design according to the site-specific fluid characteristics in order to ensure both, plant reliability and efficiency. Regarding plant reliability, undesired mineral precipitation, fluid-material interactions (i.e. scaling and corrosion) and clogging must be prevented in order to avoid the failure and misperformance of plant components and the damage of the reservoir. This includes, for example, the maintenance of a certain system pressure in all components in order to avoid degassing of CO_2 and evaporation, the filtration of the fluid to remove solid particles and the use of suitable materials. Regarding the latter, however, corrosion behavior of many metallic materials has not been determined for geothermal applications. For that purpose, a corrosion test rack has been developed, with which corrosion resistivity of several metallic components can be tested at in-situ conditions. Regarding plant efficiency, the implications of the geothermal fluid composition on the specification of the down-hole pump and heat exchangers have been addressed. For the selection and dimensioning of the down-hole pump, the fluid properties during operation must be known since they have a significant influence on the static and dynamic fluid level as well as friction losses. Proper design of heat exchangers for geothermal applications requires accurate knowledge of thermo-physical fluid properties such as specific heat capacity, viscosity and density.

The Groß Schönebeck site serves as a research platform for the development of methodologies, component tests and further investigations together with various partners from science and industry. With the knowledge and experience gained at this site, important contributions to face the addressed geochemical and process engineering challenges for geothermal power generation can be expected in the future.

Acknowledgments

The realization of the geothermal research site Groß Schönebeck would not be possible without third-party funds. For the financial support in several research projects we would like to thank three Ministries:

- Federal Ministry for the Environment, Nature Conservation and Nuclear Safety:
  Nachhaltige Produktion und Injektion von Thermalwasser der tiefen sedimentären geothermischen Lagerstätten in Groß Schönebeck, Grant 0325088;
  Qualification of geothermal technology - integration of subsurface and surface systems, Grant 0325217;
  Longterm-Corrosion investigations and -monitoring in saline thermal waters, Grant 0325069A;
  Development of thermodynamic data for modeling thermodynamic equilibria of processes in deep geothermal reservoirs, Sub-project: Experimental validation of thermodynamic data, Grant 0325256C;

- Federal Ministry for Education and Research (GeoEn, Grant 03G0671A/B/C).
- Federal State of Brandenburg, Ministry for Science, Research and Culture.

For the active support in Groß Schönebeck as well as in the GFZ labs we would also like to thank our colleagues Claudia-Tamara Rach, Mathias Poser, Jörg Schrötter, Ronny Giese and Andreas Kratz.

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Figure Description

Figure 1: Schematic drawing of a well doublet with geothermal fluid loop and heat extraction.

Figure 2: Well head of the injection well (top left), detail of the corrosion test rack (top right), detail of the geothermal fluid pipeline and equipment facility containing e.g. the corrosion test rack, filters and the injection pump (bottom).

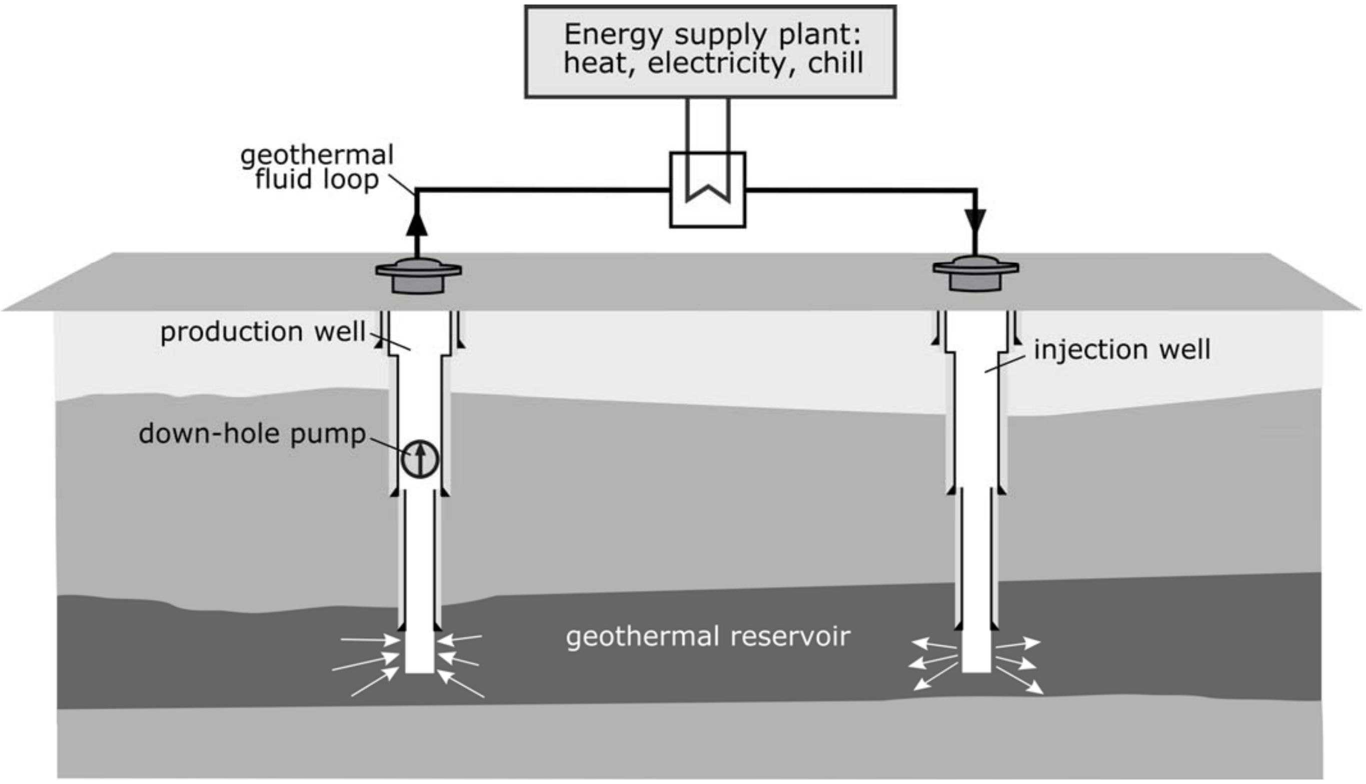
Figure 3: Depth distribution of main elements of sedimentary basin fluids plotted versus depth. They represent 78 to 98 wt.-% of total fluid salt content [10] (left).
Depth distribution of dissolved solids (log TDS); data from sedimentary basins (black diamonds; [10],[13],[14]) and crystalline rock formations (white squares; [11]) (right)

Figure 4: Composition of the Groß Schönebeck fluid for the liquid phase (top) and the gas phase (bottom)

Figure 5: Lead containing scales near the pump in the Groß Schönebeck well (Germany).

Figure 6: Scheme of a production well showing down-hole pump, static fluid level and dynamic fluid level (left) and the pressure curve during fluid production (right)

Figure 7: Simplified scheme of the Groß Schönebeck geothermal fluid loop



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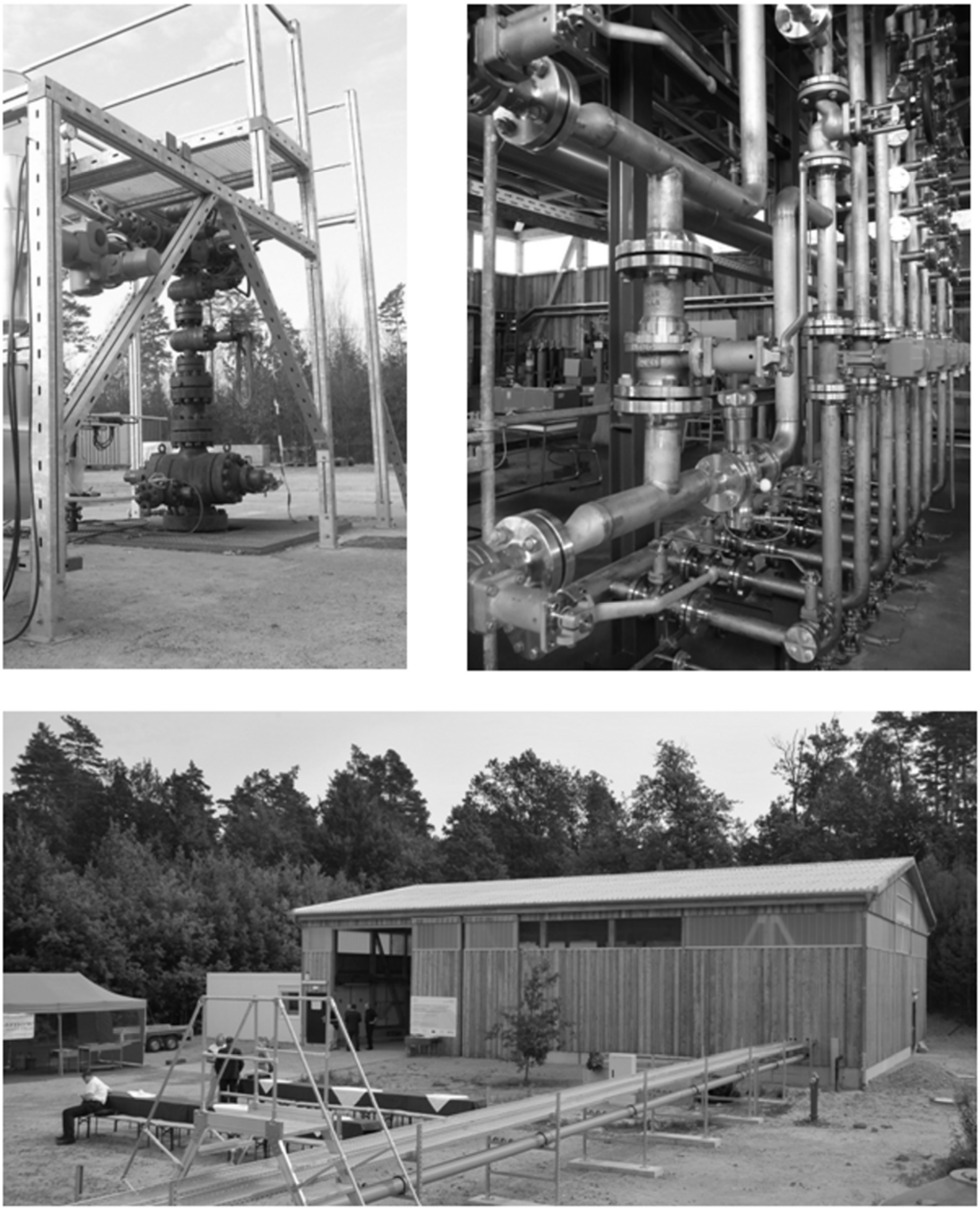

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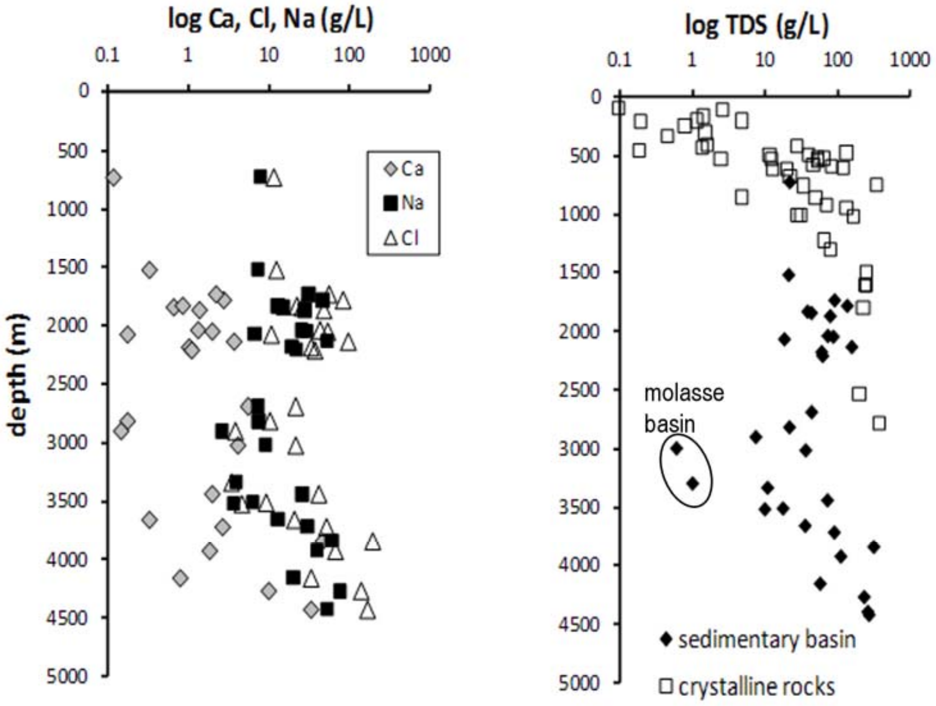

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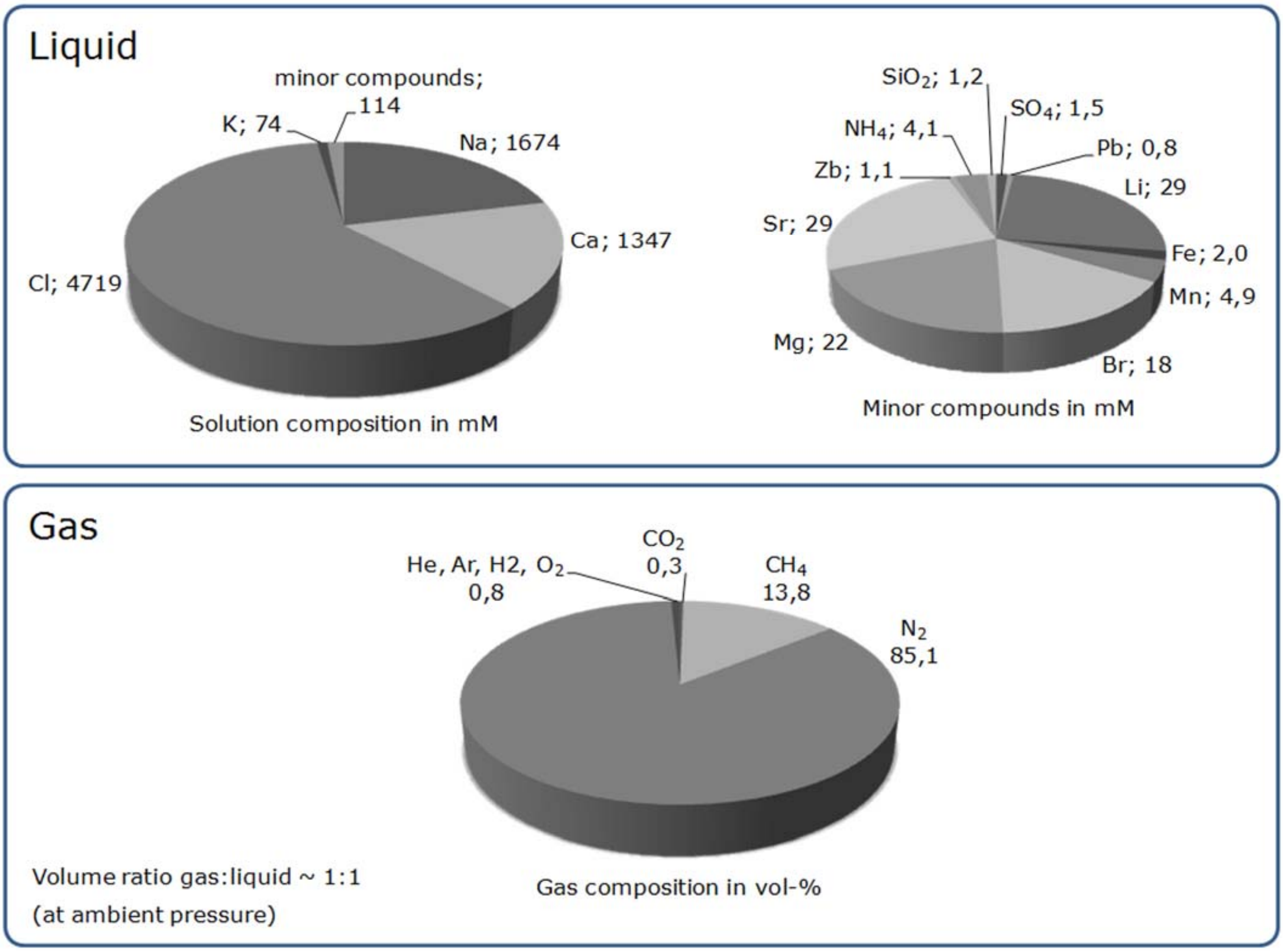

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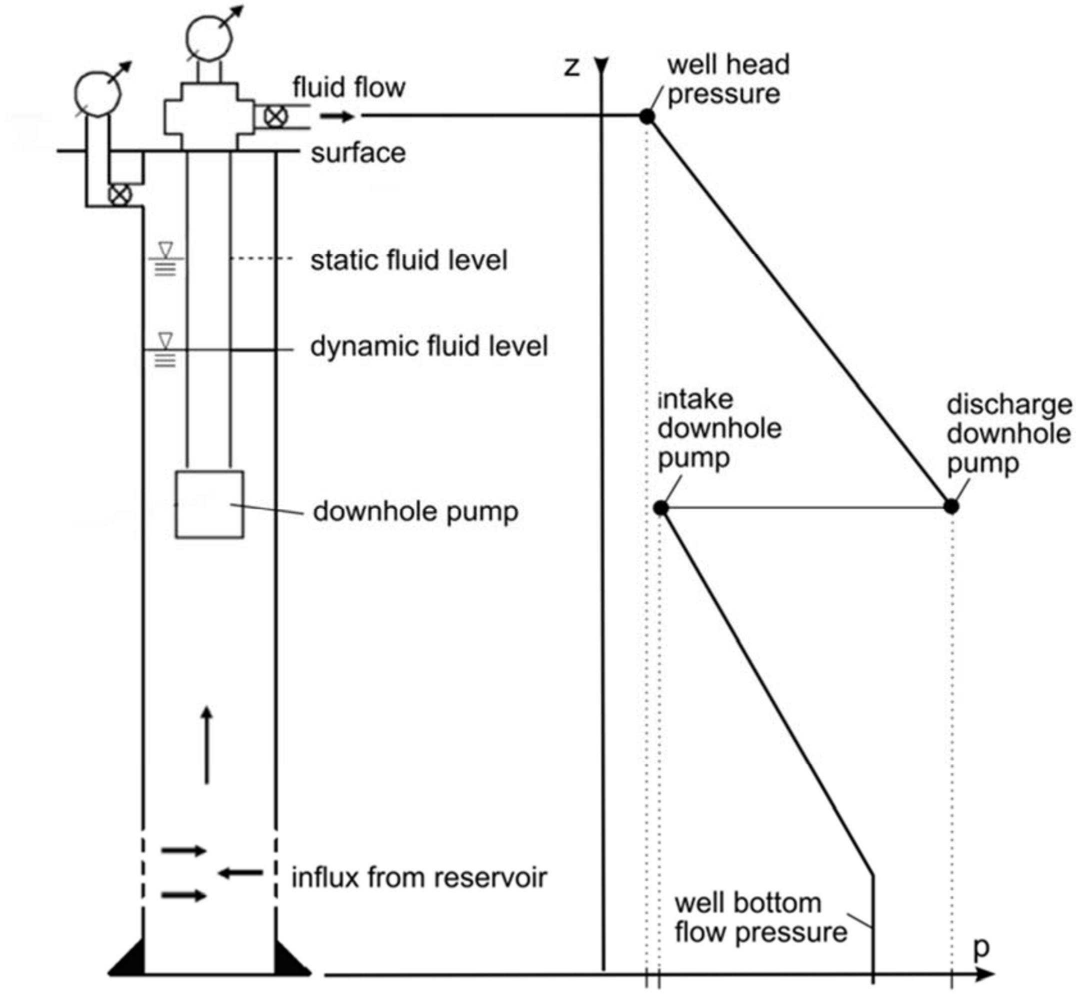

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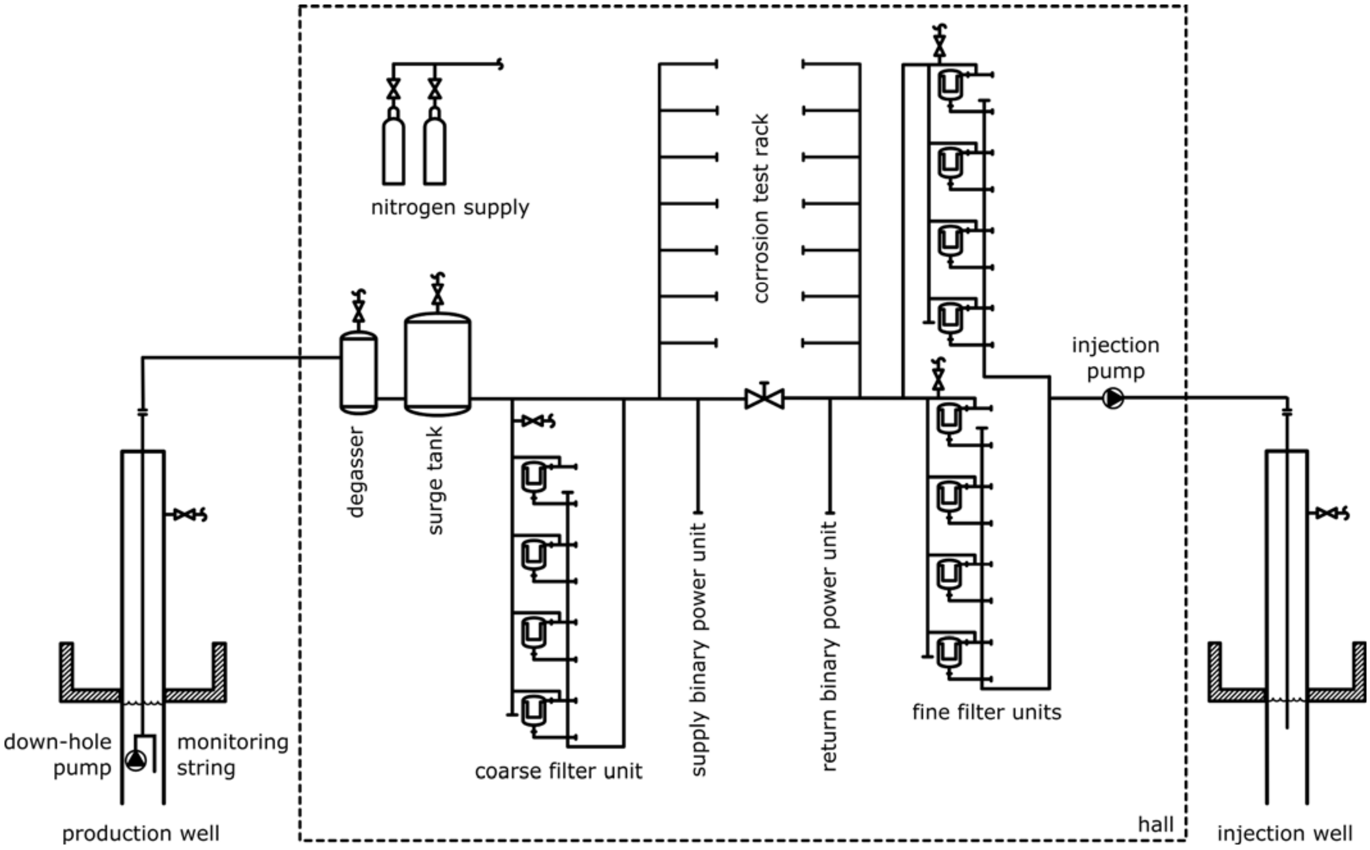

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