



Design and test of a new flow calorimeter for online detection of geothermal water heat capacity



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ABSTRACT

Net power output of geothermal power plants depends on thermal heat, which is delivered by the geothermal water flow. In order to determine the potential, knowledge of temperature, mass flux and heat capacity of thermal water is important. On-site heat capacity of thermal water is only roughly estimated because dissolved gases and minerals influence heat capacity significantly. In order to address this knowledge gap, a new flow calorimeter was constructed which allows for on-site detection of specific heat capacity of geothermal water. It operates at high maximum temperatures (170 °C) and pressures (3 MPa), and can be installed as a bypass loop in geothermal power plants. The flow calorimeter was tested using water and aqueous sodium chloride solutions at a range of temperatures (20–160 °C) and absolute pressures (0.2–2.6 MPa). The experimental results deviate by about 1% from existing data reported in the academic literature.

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1. Introduction

The use of geothermal heat for electricity and heat generation requires increases in power plant efficiency, due to the high investment costs of drilling and the comparatively low energy density of hot water sources. Furthermore, power plant profitability is related to well productivity and geothermal water temperature as well as to physical and chemical water data which frequently lead to higher operational costs than primarily planned if the data are imprecise. For instance, corrosion and scaling problems resulting from fluid chemistry lead to long shut down times of the power plant. In addition, geothermal energy production is related to thermo-physical geothermal water data which determine the energy content of the fluid flow and thus the size of the power plant components. Better knowledge of fluid parameters combined with the enhancement of heat transfer within power plant components is essential for total economic feasibility. Heat transfer enhancement is important especially in binary power plant systems where heat is transferred from geothermal water to a working fluid.

Depending on the local geothermal conditions different types of power plant systems come into consideration such as dry steam power plants, flash power cycles or binary power plants.

Only a few areas worldwide, such as Indonesia, USA (California) and Italy (Larderello) have geothermal dry steam >200 °C available for actuating a steam turbine directly in a dry steam power plant.

Flash power cycles involving pressure reduction is used with hot water at temperatures of 180–220 °C and pressures up to 1.5 MPa to generate electricity via saturated steam. Here, the dry steam for actuating the steam turbine is obtained by separating the water phase. Examples of this process can be found in Costa Rica (Guanacaste) or Nevada (Beowave) (Huenges et al., 2000).

Electricity production using geothermal water at temperatures below 150 °C, such as in central Europe (e.g. Germany, Switzerland, France), require binary power plant cycles. Even in Germany's 'hot spots' such as the Norddeutsches Becken and Molassebecken (Agemar and Schellschmidt, 2012), subsurface temperatures rarely exceed 150 °C below 3500 m. Slightly higher geothermal water temperatures of around 160 °C are available in the Oberrheingraben as reported by Genter et al. (2012). These temperature conditions make direct use of flash cycles inefficient due to low steam parameters (temperature and pressure). Furthermore, the high salinity of this water, such as in the Rhine valley and northern Germany, can lead to corrosion problems within steam turbines.

In the low temperature areas, binary cycles for either electricity production and/or district heating systems are used, in which geothermal heat is transferred to a low-boiling working fluid. Binary cycles therefore require large heat exchangers due to the low temperature difference of about 100 °C between the geothermal

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water and the power plant's working fluid. Under these circumstances Kalina or Organic Rankine Cycles (ORC) are considered state of the art for electricity production. ORCs, for instance, operate with a single component working fluid, such as isopentane, which evaporates in the heat exchanger. The steam produced then actuates a turbine to drive the generator before being collected and re-liquefied in a condenser. A circulating pump enhances the fluid pressure and feeds the fluid back to the heat exchanger; hence, the working fluid cycle remains closed. Within the heat exchanger, both working fluid and geothermal water are in thermal contact. As with the working fluid, the thermal water loop also remains closed, since the geothermal water is re-injected back into the ground. The energy transfer from geothermal water to working fluid takes place in the heat exchanger; therefore, the heat exchanger is an important component of the power cycle. It needs to be adapted quite specifically to the conditions of the local water supply, well productivity and heat demand, according to – for example – power plant operation needs or district heating systems.

Against this background, knowledge of geothermal water properties at power plant operating conditions is important. The total heat content of geothermal water is influenced by its density, temperature and specific isobaric heat capacity. These values are well known for pure water, under a wide range of temperatures and pressures. Depending on geologic conditions, however, geothermal water can have high salinity, ranging from 1 g/l at Molassebecken (Vieth et al., 2008), up to 350 g/l in northern Germany, or a high amount of dissolved gases such as carbon dioxide (CO₂), nitrogen (N₂) or methane (CH₄) (Regenspurg et al., 2010). Salt and gas components change the physical properties of water significantly, especially when they are at high concentrations. When the design of heat exchangers is based on values associated with pure water, assumptions about heat input into the power system will be incorrect.

In order to illustrate the potential consequence of such imprecise data, calculations were made using the in-house computer program GESI (GEOthermal Simulation). The GESI program was developed to simulate energy conversion of sub- and supercritical ORCs for electricity production using geothermal water and is described by Vetter et al. (2013). Based on assumptions about efficiency for all power plant components, such as the heat exchanger, turbine and cooling system, the gross and net energy of ORCs can be ascertained using this program. For example, if the heat input from geothermal water decreases, gross and net energy output of the power cycle similarly decrease. If the geothermal water is highly mineralized, a heat exchanger designed based on the heat capacity of pure water will, therefore, operate only in partial load, due to reduced heat flux. Heat transfer inside the heat exchanger is also affected by fluid properties such as density, heat capacity, viscosity and heat conductivity. Inaccurate data lead to over/underestimation of heat exchanger size and, therefore, to increased investment and/or operational costs of the power plant.

The following examination underlines the impact of heat capacity data on heat exchanger size.

In order to estimate the influence of salinity on heat capacity of water, calculations of geothermal water from "Oberrheingraben" have been made with the computer program OLI (OLI Systems Inc., 2012). The primary components of the geothermal water were sodium, potassium and calcium chloride as analyzed by Pauwels et al. (1993). The isobaric heat capacity, c_p , of this geothermal water was calculated at $T = 25\text{ °C}$, $p = 0.1\text{ MPa}$ and $c_p = 3698\text{ J/kgK}$. The heat capacity of pure water amounts to $c_p = 4181\text{ J/kgK}$ at the same temperature and pressure conditions, which is calculated with REFPROP, a computer program accessing the NIST database (Lemmon et al., 2010). This pure water value is 13% higher than the OLI value. Consequently, heat exchangers that are designed based on pure water data would have an unnecessarily large heat transfer area.

For instance, using heat capacity data of thermal water (Pauwels et al., 1993), and pure water (Lemmon et al., 2010), calculations are made with our own heat exchanger dimensioning programs which are described by Schröder et al. (2014). The required area for the heat exchangers can be reduced by 30% if heat capacity is assumed to be 15% lower than the pure water values. Since investment costs are coupled with heat exchanger area (Schröder et al., 2014), designing this equipment using precise heat capacity values can result in meaningful financial savings.

Additionally, REFPROP was used as well to estimate the influence of dissolved gases in geothermal water (Lemmon et al., 2010), by comparing carbon dioxide and water mixtures to pure water. At low gas concentrations of 1 wt% CO₂ in water at 2.6 MPa, isobaric heat capacity of the mixture differed only slightly from water. Higher gas concentrations led to significantly reduced heat capacity, in the order of 5% at gas concentrations of $m_{\text{CO}_2}/m_{\text{water}} = 0.1$.

In order to determine the physical and chemical properties of geothermal water, samples are typically taken on site and analyzed in a laboratory. This procedure introduces the risk of miscalculation, since it cannot be assured that sample temperature and pressure is kept constant. Changes in temperature and pressure in turn influence the solubility of the minerals and gases in the brine. The analyzed probes may, therefore, differ quite significantly from the original fluid. Consequently, a measuring technique that allows for online detection of brine heat capacity without modification could improve power plant design.

The influence of salinity on the heat capacity of water is discussed in various scientific publications. The most frequently investigated natural aqueous salt solution is seawater, due to problems that arise in association with desalination processes. For systematic studies and establishing of thermodynamic models, artificial salt water mixtures instead of seawater are used to simplify the influence parameters and assure reproducibility. Binary mixtures of water and sodium chloride (NaCl) are favored because NaCl is the main seawater salt component that assures both relevance and reduction of parameters.

Aqueous solutions of sodium chloride have been modeled theoretically in a wide range of temperatures and pressures. Tanger and Pitzer (1989) studied the thermodynamic properties of aqueous NaCl solutions in the temperature range of 300–600 °C and pressures up to 100 MPa. Besides the description of vapour and liquid composition, enthalpies, entropies, chemical potentials, as well as solution volumes and heat capacities are reported as a function of salt content. The authors claim that isobaric heat capacity is calculated with reasonable accuracy for NaCl concentration up to 10 wt%. Archer (1992) investigated NaCl solutions between –23 °C and 326 °C at pressures up to 100 MPa. His correlation equations were established using a large database of experimental and theoretical results. Driesner (2007) formulated the specific heat of aqueous NaCl solutions and compared his correlations to the experimental data of Gates et al. (1987) at 17.9 MPa. For low to moderate NaCl concentrations the fitted data agree well with the experimental data of Gates et al. (1987), but at higher NaCl concentrations (for example, >0.5 mol kg⁻¹) theoretical and experimental results differed by about 10%. Several heat capacity correlations of seawater are provided by Sharqawy et al. (2010) and Sharqawy et al. (2011, 2012) as a function of temperature and salinity, based on the experimental results of Jamieson et al. (1969) and others. These correlations are limited to moderate concentrations of at most 180 g salt/kg seawater. From these references, specific heat capacity was shown to decrease with increasing salt content, but increase with rising temperature. Pressure dependence was of minor influence compared to the effects of salinity and temperature, as published in Sharqawy et al. (2010), Driesner (2007) and Sun et al. (2008). The correlation data, given in Sun et al. (2008) is valid in the range of 0–374 °C, 0.1–100 MPa and salt content up to 40 g/kg.

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