Applied Geochemistry 69 (2016) 28–41

Contents lists available at ScienceDirect

Applied Geochemistry

journal homepage: www.elsevier.com/locate/apgeochem

Measurements of the density, speed of sound, viscosity and derived thermodynamic properties of geothermal fluids from south Russia Geothermal Field. Part II

Ilmutdin M. Abdulagatov [a, *], Lala A. Akhmedova-Azizova [b], Rasul M. Aliev [c], Gasan B. Badavov [a]

[a] Geothermal Research Institute of the Dagestan Scientific Center of the Russian Academy of Sciences, Makhachkala, Dagestan, Russia
[b] Azerbaijan Technical University, Department of Industrial Ecology and Industrial Safety Properties of Aqueous Systems, Baku, Azerbaijan
[c] OAO "GeothermOilGas", Makhachkala, Dagestan, Russia

A R T I C L E I N F O

Article history:
Received 21 January 2016
Received in revised form
21 March 2016
Accepted 9 April 2016
Available online 27 April 2016

Keywords:
Geothermal fluids
Geochemistry
Density
Vibrating tube densimeter
Speed of sound
Viscosity
Water

A B S T R A C T

Density, (ρ), speed of sound, (W), and viscosity, (η) of natural geothermal fluids from south Russia Geothermal Fields (Dagestan, Caspian seashore) have been measured over the temperature range from (277–353) K at atmospheric pressure. The measurements were made using the Anton Paar DMA4500 densimeter and Stabinger SVM3000 viscodensimeter for four geothermal fluid samples from the various hot-wells Izberbas (No. 68 and 129), Ternair (No. 27T and No. 38T). A sound-speed analyzer (Anton Paar DSA 5000) was used for simultaneously measurement of the speed of sound and density of the same geothermal fluid samples. The average differences between the measured geothermal fluids densities and viscosities and pure water values (IAPWS formulation) are within (0.1–1.77) % and (0.13–2.1) %, respectively, which are considerably higher than their experimental uncertainties. This differences are caused by the high concentrations of some type of ion species, such as (Na^{+}: 7.7 g/*l* (#38T); Cl^{-1}:7.7 g/*l* (#38T); SO_4^{-2}: 0.75 g/*l* (#68); S^{+}: 0.24 g/*l* (#68); K^{+}:0.15 g/*l* (# 27T); Ca^{+2}: 0.074 g/*l* (#27T); B^{+}:0.06 g/*l* (#38T); and Mg^{+2}: 0.033 g/*l* (#38T)), in the geothermal fluids, which strongly effect on salt concentration dependence of the measured properties. Measured values of density and speed of sound were used to calculate other derived thermodynamic properties such as adiabatic coefficient of bulk compressibility (β_S), coefficient of thermal expansion (α_P), thermal pressure coefficient (γ_V), isothermal coefficient of bulk compressibility (β_T), isochoric heat capacity (C_V), isobaric heat capacity (C_P), enthalpy difference (ΔH), partial pressure derivative of enthalpy $\left(\frac{\partial H}{\partial P}\right)_T$, and partial derivatives of internal energy (internal pressure) $\left(\frac{\partial U}{\partial V}\right)_T$, of the geothermal fluid samples. Measured values of density, viscosity, and speed of sound were used to develop correlation models for the temperature and ion species concentration dependences, which reproduced the measured values within 0.03% (density), 2.47% (viscosity), and 0.20% (speed of sound). To confirm the accuracy and predictive capability of the developed correlation models for density, speed of sound, and viscosity, we have applied the models to well-studied binary aqueous salt solutions (H_2O + NaCl). The prediction of the density and viscosity of aqueous sodium chloride solutions based on the developed models were very close to their experimental uncertainties (within 0.03% for density and 1.56% for viscosity). The measured properties at atmospheric pressure have been used as a reference data for prediction of the high-pressure thermodynamic behavior. The predictive capability of the model has been checked on reliable experimental data for binary aqueous NaCl solutions at high pressures reported by Kestin and Shankland (1984) and Rogers and Pitzer (1982). The prediction for density and viscosity is within 0.03% and 1.57%, respectively.

1. Introduction

The thermodynamic and transport properties of geothermal fluids are very important for determining the natural state of a

* Corresponding author.
E-mail address: ilmutdina@gmail.com (I.M. Abdulagatov).

http://dx.doi.org/10.1016/j.apgeochem.2016.04.003

geothermal system and its behavior under exploitation. Geothermal power plants use geothermal fluids as a resource and create waste residuals as part of the power generation process. Both the geofluid resource and waste stream are considered produced fluids. The chemical and physical nature of produced fluids can have a major impact on the geothermal power industry and influence the feasibility of power development, exploration approaches, plant design, operating practices, and reuse/disposal of residuals. Geothermal heat and power plants use hot geothermal fluids as a transport medium to extract thermal energy from the deep underground. A downhole pump in the production well lifts the brine up to the surface, where it is cooled in heat exchanger and reinjected subsequently (binary geothermal cycles). Knowledge of the thermophysical properties of geothermal brines is extremely important for determination of design characteristics and sizes of the downhole pump (Saadat et al., 2008). The flow characteristics (multiphase underground flows) of the brine in the well depends on their thermal properties, such as density and viscosity. The thermodynamic and transport property data of geothermal brines are also needed for geothermal energy utilization devices. Geothermal energy production operations require the ability to predict the thermodynamic properties of the geothermal brines as a function of temperature, pressure, and concentration. Particularly, knowledge of the geothermal fluid properties is important in geothermal exploration and energy production, to establish optimal operations for the productions of geothermal brine fields. For example, the total heat content of geothermal fluid depends on the density, temperature, and heat capacity (Schröder et al., 2015). For the effective utilization of geothermal resources, a precise thermodynamic and transport properties data are required for the initial resource estimates, production and reservoir engineering study of the geothermal field, reservoir modeling, and power cycle optimization.

Thermodynamic and transport properties (density, heat capacity, viscosity, thermal conductivity, etc.) of geothermal fluids determine the transfer of heat and mass by geothermal systems. The energy properties of the geothermal fluids may be extracted directly from the *PVTx* properties of the geothermal fluid through standard thermodynamic approaches (Haas, 1976a, b). The available *PVTx* properties of geothermal fluids are not sufficient to meet the needs of the geothermal industry for complex solutions such as those found in geothermal reservoirs. Modeling geothermal wells (geothermal engineering, geothermal or reservoir installations) need accurate thermophysical property data (Reindl et al., 2009; Stefánsson et al., 2012). Thus, one of the key factors when planning the exploitation of geothermal resources is the availability of reliable thermodynamic and transport properties data of geothermal brines. Initially geothermal fluids were modeled as pure water. Thermodynamic and transport properties of pure water are well-known (see IAPWS formulations for thermodynamic and transport properties, Wagner and Pruβ, 2002; Huber et al., 2009; and Huber et al., 2012). Used pure water or geothermal brine models (synthetic brines like binary or ternary aqueous salt solutions) properties leads to inaccuracies and impossible accurately estimate the effect all of the dissolved salts on the thermophysical properties due to extremely complexities. Also, the presence of the dissolved gases in geothermal fluids considerable influencing the thermodynamic properties. Due to pressure difference between underground and the near surface conditions (geothermal operations at 0.101 MPa), degassing occurs during geothermal energy production. Thermophysical properties of geothermal fluids such as density, viscosity, heat capacity, and enthalpy play a fundamental role in mass and heat transfer in the Earth's interior. In order to provide numerical modeling of the heat and mass flow processes in various geothermal energy generating (production) systems (reservoirs, pipe systems, power plants, binary geothermal cycles, heat-exchangers) definitions of the thermodynamic properties of density (ρ), viscosity (η), and enthalpy (H) of geothermal fluids as a function of temperature, pressure, and concentration are required (McKibbin and McNabb, 1995; Palliser, 1998; Palliser and McKibbin, 1998a,b; Dolejs and Manning, 2010). Solution of the set of differential equations (equations of mass conservation, linear momentum, and energy conservation), which may be used to describe the transport of mass and heat in a porous media for mathematical simulations of the Earth's interior, considerably depends on thermodynamic properties of geothermal brines (density, enthalpy, and viscosity) as a function of temperature, pressure, and concentration of salt (minerals). Solving these sets of equations enables the determination of such quantities as temperature and pressure gradients at a point in the flow, and T, P, x profile in time and space (Francke and Thorade, 2010; Francke et al., 2013). However, solving these equations requires knowledge of the thermodynamic properties of density, enthalpy, and viscosity of the geothermal fluids. Since the measurements in this work were performed at atmospheric pressure, the present study is not considering the effect of dissolved gases on the thermophysical properties of geothermal brines. High pressure measurements or reliable high pressure predictive models are needed for heat and mass transfer phenomena study in Earth interior.

Viscosity and density are key factors in fluid flow simulation (influencing the flow of reservoir fluids). Relatively little data has been published on the viscosity of natural geothermal brines. Most reported data only for binary or ternary aqueous salt solutions (see review Abdulagatov and Assael, 2009) as a main component of geothermal brines (basically for synthetic geothermal brines). Adams and Bachu (2002) reviewed various functions for the calculation of geothermal brine density and viscosity. Battistelli et al. (1993), and Oldenburg et al. (1995) also described models of brines flows that require knowledge of the three key thermodynamic properties (density, viscosity, and enthalpy). Because of the scarcity of data for the density, dynamic viscosity, and enthalpy a different approach to the one used for these properties was adopted (Dittman, 1977; McKibbin and McNabb, 1995; Palliser and McKibbin, 1998a,b). Potter and Haas (1977) indicated that geothermal fluids might be represented by the properties of aqueous NaCl solution as a model of the eothermal brine. This model predicts the density of geothermal brines and seawater within experimental uncertainty at a temperature of 150 °C. The simplest way of determining of the thermodynamic properties of geothermal fluids is based on pure water properties, because pure water is the dominant constituent, therefore, governs the properties (thermodynamic behavior) of aqueous salt solutions and geothermal brines. Most reliable predictive models for aqueous salts solutions are representing their thermodynamic properties relative to pure water (Wahl, 1977; Horvath, 1985; Aseyev and Zaytsev, 1996; Aseyev, 1998; Abdulagatov et al., 2005a), because the behavior of the thermodynamic properties of geothermal brines also governs by the properties of pure water (see below Figs. 1–4).

Using direct experimental thermodynamic data for particular natural geothermal fluids allows minimize the errors arising from the empirical prediction data for geothermal brines models. Moreover, the brine composition can be changed during production. Thus, more direct measurements of the natural geothermal brines from various regions of the world with various concentrations of dissolved salts are needed. This allows generalize the properties of geothermal fluids from various geothermal fields (wells) with various solutes to develop prediction models for geothermal brines with any chemical composition. Unfortunately, available theoretical models frequently cannot describe real