Water condensation in carbon-dioxide-based engineered geothermal power generation

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ABSTRACT

Engineered geothermal systems (EGS) may utilise carbon dioxide as a heat extraction fluid instead of water. Nevertheless, water present in the geothermal reservoir will be extracted into the working fluid, affecting fluid flow behaviour and the required surface plant design for such a system. Dissolved water in a carbon dioxide-rich phase changes thermodynamic properties, and causes corrosion, and erosion where water droplets condense. The conditions for condensation of water in such a system have not been examined. We present condensation curves that predict conditions for water condensation, and bubble curves that predict carbonic acid concentration in a condensed H_2O-rich phase. These diagrams predict concentration thresholds for condensation in the production wellbore and surface equipment. Predicted concentration thresholds for condensation do not change significantly in response to change in water content. The probable minimum CO_2 concentration allowable for direct use of carbon dioxide as a working fluid is 95% for the turbine.

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1. Introduction

Carbon dioxide has been examined previously as a heat extraction and power cycle fluid for geothermal applications (Brown, 2000; Pruess, 2006, 2008; Pruess and Azaroual, 2006; Gurgenci et al., 2008; Atrens et al., 2009a,b, 2010b). It has been identified as a suitable fluid due to its:

- Low viscosity and density within the reservoir.
- Low solubility of polar (ionic) solids.
- Suitability for concurrent sequestration.

A schematic of the CO_2-based EGS concept is shown in Fig. 1.

Since the CO_2-based EGS concept was first proposed site trials of engineered geothermal systems (EGS) have revealed that most are likely to contain some water (Gurgenci, 2009). The interaction between carbon dioxide and water consequently is an important concern if CO_2 is to be used in EGS. Three aspects of carbon dioxide–water interactions are important:

- Reservoir interactions: the interactions between carbon dioxide, water, and reservoir rocks including both reactions and two-phase fluid flow phenomena.
- Thermodynamic interactions: how water effects the thermodynamic properties of the CO_2-rich phase, and the consequent implications for power plant design.
- Liquid water condensation: the conditions under which a liquid H_2O-rich phase condenses.

Small amounts of water dissolved in the carbon dioxide flowing from the production well will have minimal process effects due to a small impact on fluid properties, and will not cause corrosion (Seiersten, 2001). If sufficient water is present to form a condensed H_2O phase, the water droplets carried in a predominantly gas flow may cause erosion or corrosion. The corrosion potential of a condensed water phase is more significant than the solution pH would suggest, due to the buffering provided by dissolved CO_2 and CO_2-related species (Linter and Burstein, 1999). This makes condensation of water a vital consideration for well casing and surface plant design for a CO_2-based EGS. Where water is present in the reservoir it is necessary to identify conditions under which condensation occurs, as they may impact material selection, process design, and determination of when power generation directly with CO_2 may be possible (q.v. Atrens et al., 2011).

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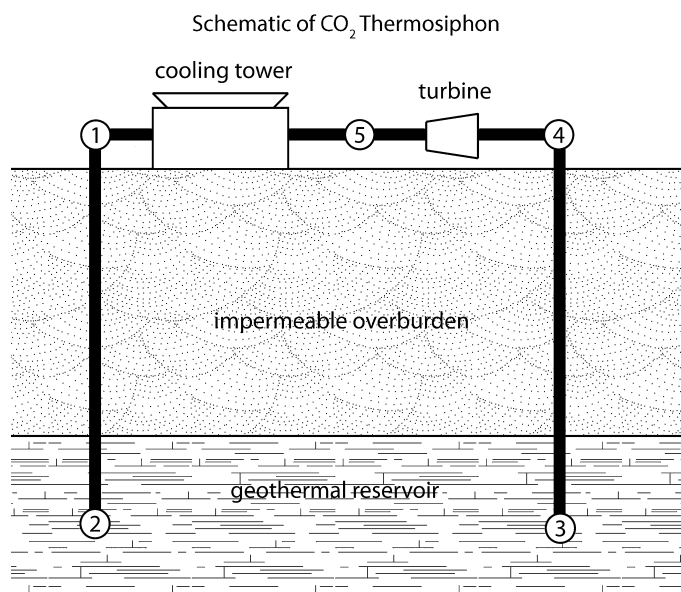 *E-mail address:* aleks.atrens@uq.edu.au (A.D. Atrens).

Schematic of CO$_2$ Thermosiphon

Fig. 1. A depiction of a two-well CO$_2$-based geothermal system. Points 1–5 are: (1) the injection wellhead, (2) injection well-reservoir interface, (3) reservoir-production well interface, (4) production wellhead, and (5) turbine exhaust.

The aim of this paper is to determine the concentration threshold, or the required minimum carbon dioxide concentration to prevent condensation of liquid water in important parts of the power system. Furthermore, the impact of dissolved water on the thermodynamic properties of a carbon dioxide-rich fluid is also discussed. Finally, the carbon dioxide content in the condensed water, present as various carbonate species is determined. The purpose is to provide a basis for examining the feasibility of a carbon dioxide cycle for application in EGS reservoirs.

2. Methods

2.1. Dew and bubble lines

The conditions under which water condenses from a carbon dioxide–water fluid mixture can be calculated from equilibrium data. To assess these conditions for a range of temperatures and pressures relevant for geothermal power plant designs, a diagram of iso-compositional dew lines has been constructed. These dew lines provide a method to assess the concentration threshold for dewing at any pressure and temperature to prevent condensation in any section of the well and plant system.

A diagram of iso-compositional bubble lines has also been constructed to examine CO$_2$ concentration in the resulting H$_2$O-rich liquid phase (the condensate). The concentration of carbonic acid can be determined from the CO$_2$ concentration in the H$_2$O-rich phase. Materials selection and corrosion tolerance calculation utilise carbonic acid concentration information.

2.2. Diagram construction

Use of equations of state to derive dew and bubble lines was considered. There are a range of equations of state dealing with the CO$_2$–H$_2$O system, and additionally in some cases examine the influence of salts. However these are limited compared to using dew point data directly (for example, (Spycher et al., 2003) and (Spycher and Pruess, 2005) only examine temperatures below 100 °C, (Duan et al., 2008) does not address dew point curves, and comprehensive studies such as (Ji et al., 2007) have large deviations at higher pressures).

Data on CO$_2$–H$_2$O mutual solubility was obtained from (Wiebe and Gaddy, 1939, 1940, 1941; Wiebe, 1941; Takenouchi and Kennedy, 1964; King and Coan, 1971; Patel and Eubank, 1988; Fenghour et al., 1996; Bamberger et al., 2000; Han et al., 2009). Some of these sources discuss the CO$_2$–H$_2$O system in detail (particularly Takenouchi and Kennedy, 1964). None of these sources individually covered the full range of temperatures and pressures relevant to CO$_2$-based EGS, and equilibrium dew and bubble line information was typically at varying compositions. Data from these sources were transformed to give dew and bubble lines at constant composition. This was accomplished by linear interpolation, or, on occasion, linear extrapolation. Not all compositional data has been reported in mol%; where necessary to convert units, a Standard Temperature and Pressure of 0 °C and 0.101325 MPa (abs) was used.

The original data ranged in temperature from 25 °C to 350 °C, and pressures from 0.1 MPa to 150 MPa. The relevant range for usage of CO$_2$ in EGS is from 0 °C to 300 °C and 5 MPa to 60 MPa. Some data outside those ranges were used to construct the iso-composition curves.

The triple line for the liquid CO$_2$–liquid H$_2$O-hydrate equilibrium (Sloan and Koh, 2008) has been included on dew and bubble line diagrams to indicate the conditions under which a H$_2$O-rich liquid phase solidifies into a hydrate phase.

2.3. Iso-compositional dew line contours

Constant composition dew lines are presented in Fig. 2. These lines represent concentration thresholds. That is, they indicate the pressure–temperature conditions at which a H$_2$O-rich liquid phase will first condense from a fluid of the specified overall composition.

For any overall fluid composition, a dew line divides the pressure–temperature plane into a region where the compounds are fully miscible, and a region where two phases are present. To the right of the dew line, a single phase exists. To the left of the dew line, two phases coexist. The two phases are a CO$_2$-rich fluid phase and a H$_2$O-rich liquid phase. The H$_2$O-rich phase also contains carbonic acid in equilibrium with the dissolved carbon dioxide, and associated carbonate, bicarbonate, and hydrogen ions, resulting in acidity. The H$_2$O-rich liquid phase condenses if temperature or pressure conditions of a fluid move from the right side to the left side of the dew line.

2.4. Iso-compositional bubble line contours

Constant composition bubble lines are presented in Fig. 3. These lines provide the maximum mole fraction of CO$_2$ that can be dissolved in a condensed liquid water phase at a given temperature and pressure. If the conditions change so that the CO$_2$ dissolution threshold is exceeded then CO$_2$ effervesces from the solution.

When both a CO$_2$-rich fluid and a condensed H$_2$O-rich phase are present, the CO$_2$-rich phase has a composition corresponding to its dew point, and the H$_2$O-rich phase has a composition corresponding to its bubble point. This allows determination of CO$_2$ solubility in a condensed H$_2$O-rich liquid within the CO$_2$-based EGS. That compositional information can be used with temperature-dependant equilibrium constants to determine the carbonic acid content and pH of the liquid phase.

3. Results

3.1. Liquid water condensation in power system operation

The dew line diagram can be used to determine concentration thresholds for the CO$_2$-based EGS power system. The thresholds can be found by overlaying the pressure–temperature range for a section of the process onto the dew line diagram. The