Determination of thermodynamics in a CO_2 injection well using pressure and distributed temperature sensing

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Abstract The injection of CO_2 into the subsurface at the Ketzin pilot site, Brandenburg (Germany), is monitored simultaneously by distributed temperature sensing (DTS) and two pressure sensors located at the wellhead and at 550 m depth. The data is used to recalculate a continuous pressure profile along the entire length of the injection well. The data allow calculation of the thermodynamic properties of the CO_2 inside the injection well, as well as potential phase transitions during the injection process. Due to compression a heat flux establishes between the injection well and the subsurface that can be quantified based on the thermodynamic state.

Key words CO_2; injection; distributed temperature sensing; heat flux

INTRODUCTION

The injection of CO_2 into the subsurface by the means of a well is an essential part of carbon capture and storage. Several physical processes may occur in the injection well. These are mass transfer, heat transfer, compression, wall friction and Joule-Thomson heating. Depending on the instrumentation of the injection well, the processes may be characterised with different approaches. Main processes are laminar/turbulent flow, heat transfer and Joule-Thomson heating. For the Sleipner pilot site this was carried out by Lindeberg (2011). This paper reports results for the injection well of the Ketzin pilot site, Brandenburg (Germany). An analysis of the thermodynamic state in the observation wells has been carried out by Henninges *et al*. (2011). Data on the injection is based on monitoring pressure as point data and continuous distributed temperature sensing (DTS). An approach is adapted to characterise the processes during injection and to calculate the reservoir pressure.

SET-UP

Figure 1 shows the cross section of the injection borehole Ktzi 201. The wellhead is located in a 3-m deep cellar. The borehole has a total depth of 755 m and is completed with a 5.5 inch (13.97 cm) casing. Inside this casing a 3.5 inch (8.89 cm) injection tubing is installed. It is suspended at the well head and ends at a depth of 560 m. At this depth a packer is installed which holds the fluid in the annular space between tubing and casing. The CO_2 is fed at the well head and conducted down by the injection tubing. Below 560 m the CO_2 is conducted in the open casing up to the reservoir depth of about 640 m.

The DTS cable enters the wellhead at 1 m above ground and finishes at 550 m below ground. It is attached to the exterior of the injection tubing. At 550 m a combined pressure and temperature sensor is installed which uses the above-mentioned DTS cable for data transmission (Fig. 1).

The CO_2 is injected at the wellhead with a pressure of about 57 to 62 bar and a temperature of about 28 to 40°C. The injection rates show temporal variations, with a maximum nominal rate of 0.9 kg/s. During the first injection stops, the injection tubing is filled with N_2.

METHODS

The phase state at the well head is gaseous and the injection is designed to be carried out without phase change. By application of the Gibbs phase rule for fluids the thermodynamic behaviour is defined.

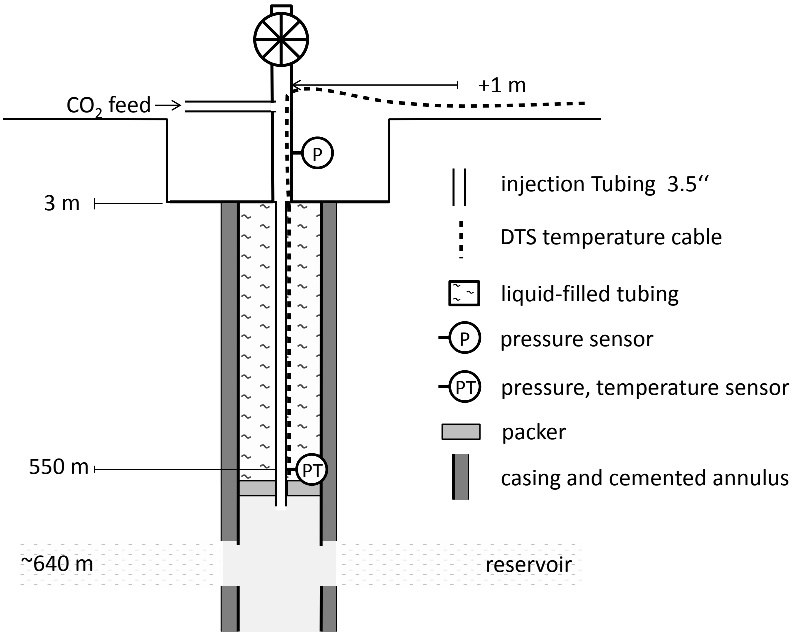

Fig. 1 Schematic cross section of the injection well Ktzi 201. Elevations refer to ground level.

$$f = N - P + 2 \tag{1}$$

The fluid consists of one component (*N*) only, which is CO_2 during injection and may be N_2 in case of an injection stop. The injection is designed to avoid a phase transition, therefore the number of phases (*P*) is equal to one. Therefore two degrees of freedom exist, which must be defined to obtain a well-defined thermodynamic description.

At two points (0 and 550 m), the injection well temperature and pressure are measured simultaneously, which fixes the two degrees of freedom and allows calculating phase state and all thermodynamic properties. For these two points the state variables, e.g. density, may be calculated by an equation of state (e.g. Span & Wagner, 1996):

$$\rho = f(p,T) \tag{2}$$

Between these points only temperature measurements are available, therefore only one degree of freedom is defined. Pressure defines the second degree of freedom and must be computed. Two factors exist which may affect pressure: hydrostatic pressure of the gas column and frictional losses.

The pressure is calculated iteratively by using the density of one elevation to calculate the pressure of the next elevation. At this elevation the density is calculated using the measured temperature. This is applied to the entire injection well. The starting point is the lower P-T sensor at 550 m. In this first step the frictional losses are neglected.

$$\Delta p = \lambda \frac{L}{D} \frac{v^2 \rho}{2} \tag{3}$$

The frictional losses are determined using the Darcy-Weisbach equation (equation (3)) where L is the length of the pipe, D the hydraulic diameter, v the average velocity and ρ is the density of the fluid. The friction factor λ is parameterised with the Colebrook-White equation (Colebrook, 1939) with a roughness of 0.1 mm.

By the above-described combination of measured temperature data and static pressure the necessary two degrees of freedom (equation (1)) are defined that are required for a complete thermodynamic description of the injection borehole. Generally the thermodynamic change does not follow an idealized scheme, therefore it has to be described as polytrophic. Kinetic energy can be neglected. The heat production can be calculated with equation (4).

$$Q_{1,2} = U_2 - U_1 - \int_{V_1}^{V_2} p \, dV \tag{4}$$

Therefore work and heat transfer can be directly calculated for the injection borehole.

RESULTS

The injection rates and friction losses between August 2008 and March 2009 are shown in Fig. 2. The pressure losses are almost proportional to the injection rates, which is reasonable because the fluid pressure and temperature, and therefore density and viscosity, do not vary over a large range. Flow is turbulent in the transition zone between hydraulic smooth and rough conditions with a maximum friction factor of 0.37. Frictional pressure losses do not exceed 180 Pa, which is considered negligible for further considerations.

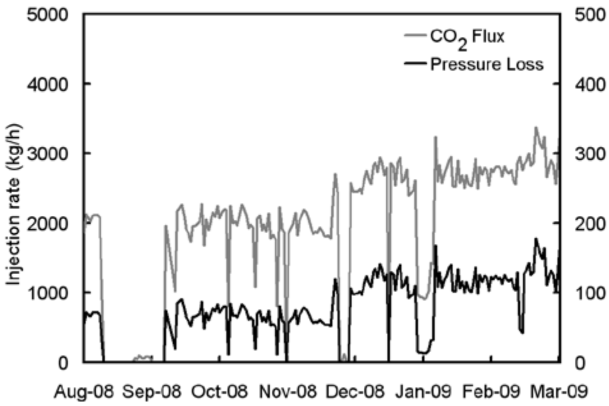

Fig. 2 Injection flux of CO_2 and corresponding frictional losses in the injection borehole Ktzi 201 between 0 and 550 m.

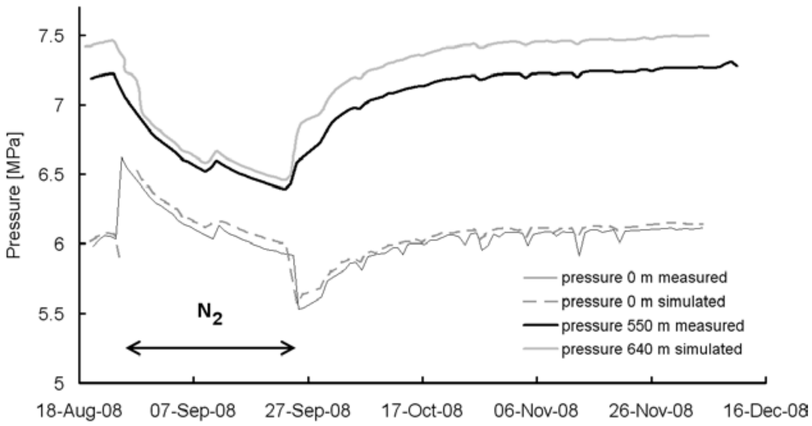

Fig. 3 Measured and simulated pressure for the observation well Ktzi 201. Pressure at 0 m corresponds to well head pressure, the pressure at 640 m corresponds to the reservoir pressure (Fig. 1). Between 25 August and 24 September injection of CO_2 is stopped and the tubing is filled with N_2.

The measured and calculated pressure values are shown in Fig. 3. The simulated pressure at 0 m is in good agreement with the measured pressure. It is calculated in upward direction based on the sensor data at 550 m. Since the pressure difference is matched it can be concluded that the (mean) density and therefore the thermodynamic state is calculated correctly.

Injection has been stopped between 25 August and 24 September 2008, with an intermediate N_2 injection phase on 11 September. It is important to consider that the tubing is filled with N_2 during the injection stop because it has a lower density than CO_2. This replacement of the CO_2 induces an immediate increase in well-head pressure, which cannot be observed at 550 m.

For reservoir simulations the correct value of pressure at reservoir depth is essential. Therefore the pressure at 550 m is extrapolated to a depth of 640 m with the above-described method using a spatially constant temperature as measured at 550 m. A sensitivity analysis using realistic temperature scenarios shows a small impact, smaller than 8%, on the pressure difference for CO_2.

During injection the pressure difference between the sensor at 550 m and the reservoir at 640 m of about 0.25 MPa is rather constant. During injection stop the tubing is filled with N_2 to avoid condensation and backflow of CO_2 and the difference decreases to about 0.06 MPa. This is of particular importance to obtain the correct picture of the reservoir dynamics at the change of the injection regime.

Two snapshots from the injection well Ktzi 201 directly after injection restart (a+b) and nine days later (c+d) are shown in Fig. 4. Figures (a) and (c) show the temperature profile measured with DTS. The temperature at the upper 3–5 m is biased because it is affected by the atmosphere and therefore smaller compared to deeper regions. From a depth of about 5 m the temperature decreases to a minimum value located between 150 and 300 m. This occurs because the CO_2 is heated and the heat is transferred to the subsurface. As the geothermal temperature increases, the heat transfer is reduced and the temperature rises due to compression. The temperature increases with the duration of injection (compare Fig. 4(a) and (c)).

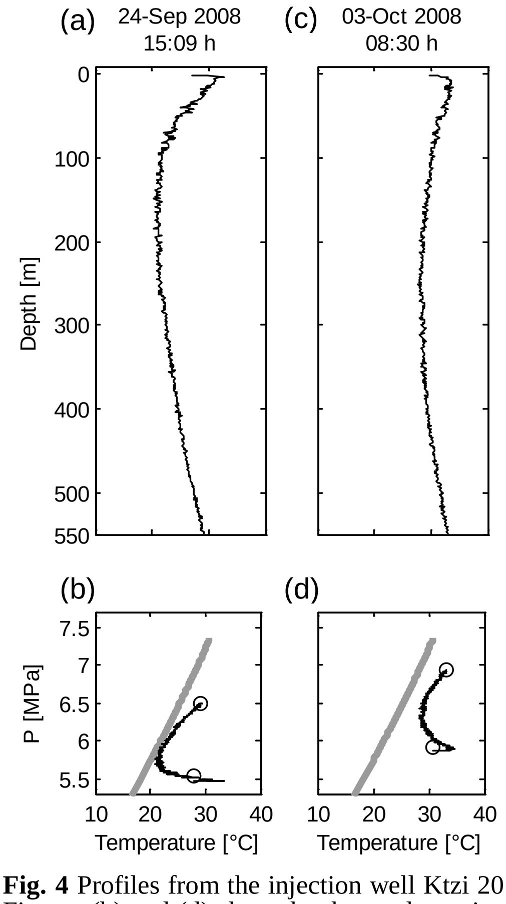

Fig. 4 Profiles from the injection well Ktzi 201. Figures (a) and (c) are measured temperature profiles. Figures (b) and (d) show the thermodynamic state with temperature and pressure. The grey line is the CO_2 phase boundary, the black line the calculated phase state and the circles are measured state variables at 0 and 550 m. Figure (a) and (c) also refer to the temperature axes from (b) and (d).

The thermodynamic state is clearly subcritical (P_{crit} = 7.38 MPa, T_{crit} = 31.1°C) in the gaseous region for the measurement points at 0 and 550 m (Fig. 4(b)). However, between these points the temperature is lower and the pressure is different, the thermodynamic state is close to condensation. As injection continues, the borehole is heated and also the pressure increases. For regular operation, as shown in Fig. 4(d) the injection well between 0 and 550 m is clearly in the gaseous region with a safety of 3°C to the condensation line.

During injection a continuous heat flux from the borehole to the subsurface establishes (Fig. 5). The heat flux varies between 10 and 100 W/m, referred to the depth of the injection well. The values vary due to different injection rates and wellhead temperature (not shown), and the variations decrease with depth. Negative values close to the surface occur because the measurements are biased by atmospheric temperature. Values are only presented down to a depth of 400 m. Below, the calculated heat flux may become negative, which is not in agreement with the temperature dynamic during injection.

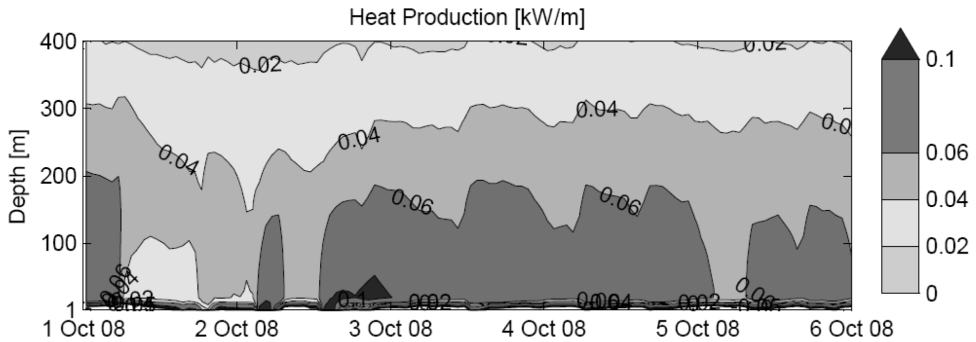

Fig. 5 Heat transfer from the injection well Ktzi 201 in kW per meter tube length.

CONCLUSIONS

– The temperature of CO_2 can be monitored by a DTS sensor cable that is attached to the injection string.
– In combination with at least one pressure measurement and an iterative method the thermodynamic state is calculated. Calculated pressure shows good agreement.
– A pressure correction to reservoir elevation is necessary, in particular to consider the exchange of CO_2 to N_2 when injection is stopped.
– Frictional losses are negligible.
– Based on these results the heat flux from the injection well into the subsurface is determined.

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