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Understanding well load-up behaviour in CO_2 wells during CO_2 back-production field test at the Ketzin pilot site, Germany – Turner criterion revisited

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Abstract

A CO_2 back-production test was performed at the pilot site for geological CO_2 storage at Ketzin, Germany. Over thirteen days 240 tons of CO_2 were safely back-produced from the reservoir; 55 m^3 of saline reservoir fluid was continuously co-produced. Throughout different rate stages of the back-production experiment downhole pressure conditions were very stable and the gas/fluid ratio remained constant, indicating that no well load-up occurred. The calculated minimum flow velocities based on the standard Turner criterion are, however, up to one order of magnitude higher than the actual flow velocities. Thus, a modified Turner parameterization is required for CO_2-dominated well.

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Keywords: Ketzin pilot site; CO_2 backproduction; Turner criterion, CO_2 wells

1. Introduction

Back-production of formerly injected CO_2 may provide a suitable technique to i) mitigate and/or remediate undesired migration of CO_2 in the reservoir by inducing a pressure-gradient driven directed flow of CO_2 in the reservoir and ii) manage reservoir pressure. Production of CO_2 will also form an integral part of any temporary

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storage of CO_2 in the frame of the different CCUS and/or power-to-x concepts. In CO_2 storage combined with enhanced hydrocarbon recovery CO_2 will be co-produced with the recovered hydrocarbons. The production ratio of gas to reservoir fluid is an important design parameter in all these contexts. Below a minimum flow velocity in a well, the critical Turner velocity, the gas stream is no longer capable to transport the entrained fluid droplets and fluid will accumulate in the well leading to well load-up [1, 2]. Eventually, well load-up may kill the well and prohibit any further gas production. However, the traditional Turner criterion, although based on sound physical concepts, has been empirically adjusted to field data from natural gas production and it remains open whether it can be applied also to CO_2 dominated wells.

Here we report on results from a CO_2 back-production experiment performed at the German pilot site for geological CO_2 storage at Ketzin [3]. This experiment was conducted under the scope of the EU MiReCOL project [4] to evaluate whether CO_2 back-production operation can be used as a corrective measure for pressure management of a storage reservoir. At Ketzin, slightly more than 67 ktons of CO_2 have been injected between June 2008 and August 2013 into a saline sandstone reservoir at 630 to 650 m depth [5, 6]. The CO_2 back-production experiment has been executed between October 15th and 27th 2014 – i.e. within the post-injection period – and a total of 240 tons of CO_2 were safely back-produced from the reservoir in a controlled manner and vented to the atmosphere via a vent-off stack (Fig. 1); a total of 55 m^3 of reservoir fluid was continuously co-produced, separated from the CO_2 in a 3-phase separator, degassed in a gauge tank and finally disposed. Continuous process monitoring during the experiment allow address in-well fluid pressure-temperature-density conditions and calculate fluid flow velocities, forming the basis for the here presented study.

2. Execution of the experiment

Back-production was performed through the former injection well Ktzi 201, which was converted into a producing well for the experiment [3]. Well Ktzi 201 consists of a 5.5” production string with inner 3.5” production tubing down to 550 m. At the end of the production tubing a pressure and temperature gauge is installed [6]. The back-production experiment was monitored by continuous pressure and temperature measurements in the producing well at 550 m depth at the lower end of the production tubing – i.e. ~ 80 m above the reservoir – and at the wellhead; flow rate of the produced stream was measured by a Coriolis type mass flow meter and regulated and controlled by a choke manifold. After initial commissioning and testing of the equipment during the first hours, during which also production rates of up to 3,200 kg/h, which corresponds to the previous maximum CO_2 injection rate, were tested, the experiment was performed in three main operational regimes (Fig. 1): Continuous operation with mean flow rates of ~ 800 kg/h from 15th to 20th October 2014 and ~ 1,600 kg/h from 20th to 23rd October and an alternating regime from 23rd to 27th October with a mean flow rate of ~ 800 kg/h during day shift and shut-in during night shift. At the end of the experiment flow rate was ramped down over 6 hours in 100 kg/h steps from 800 kg/h to 200 kg/h. Throughout the entire back-production experiment, formation brine was continuously co-produced.

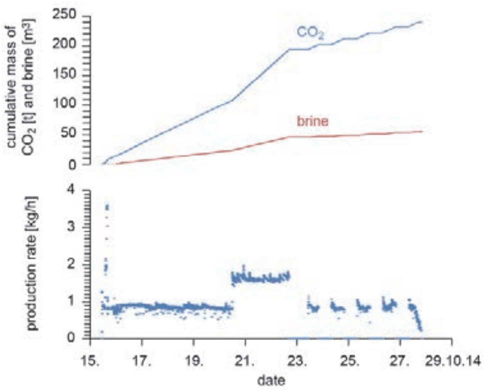

Fig. 1. Production rate and amount of produced CO_2 and continuously co-produced brine.

3. Results

3.1. Pressure and temperature evolution during back-production experiment

Pressure and temperature were continuously recorded downhole at the lower end of the production tubing and at the wellhead. With onset of back-production there is a clear drop in downhole and wellhead pressure. Downhole pressure decreases by about 6 bar from pre back-production conditions of ~ 65 bar to ~ 59 bar at the onset of back-production but then slightly regained and stabilized at ~ 61 bar steady-state conditions already after one day (Fig. 2). Pressure drop at the wellhead is much more pronounced and wellhead pressure decreases from ~ 53 bar pre back-production conditions to ~ 40 bar after about one day. It then slowly increases to steady-state conditions of ~ 46.5 bar after about 4 days. After reaching steady-state conditions, downhole and wellhead pressure are almost constant during active production phases without any significant dependency upon production rate or later alternating start/stop regime. During shut-in phases of the later start/stop regime, downhole pressure almost immediately increases to about 0.5 bar below the initial pressure within a matter of hours and returns to steady-state values of ~ 61 bar once the back-production commences. The wellhead pressure response during the alternating regime is as fast as the downhole pressure reaction to a similar 0.5 bar stand-off below the original pressure before the test.

Downhole temperature is almost constant over the entire course of the test. Neither the start-up phase nor stable operation at different rates and start/stop conditions affected the temperature significantly. Nevertheless, there are slight bumps in the start-up phase followed by a smooth transition to stationary conditions. During the start/stop conditions the downhole temperature slightly rises by approximately 0.5 °C during shut-in phases and releases once the back-production commences. On the contrary, wellhead temperature shows stronger, basically diurnal variations over time, especially pronounced during the start/stop regime from October 23rd onwards and less pronounced during the first phase of the experiment with production rate of ~ 800 kg/h until late afternoon October 20th. These variations reflect day-night changes in ambient temperature additionally intensified by the start/stop regime. With the doubling of the production rate on October 20th, wellhead temperature is almost exclusively dominated by the wellbore fluid damping any influence of day-night temperature changes.

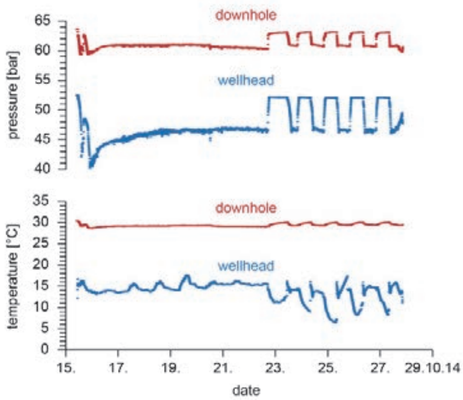

Fig. 2. Pressure and temperature evolution within production well Ktzi 201 during the back-production test as recorded downhole at the end of the production tubing and at the wellhead.

3.2. Density conditions within the well

The recorded pressure and temperature data allow calculate the density of the produced CO_2 stream downhole and at the wellhead with the EOS for pure CO_2 by [7] (Fig. 3). Data show almost constant downhole density during active production between 175 and 180 kg/m^3. During shut-in phases density slightly increases to 185 to 190 kg/m^3 reflecting the pressure increase during these phases. Calculated wellhead density is generally lower during active production with 125 and 140 kg/m^3 but due to the more pronounced temperature fluctuations shows higher variability than downhole density. During shut-in phases calculated wellhead density notably increases indicating condensing liquid CO_2 and two-phase conditions in the uppermost parts of the well consistent with the marked decrease in temperature. For active production, however, the data clearly show single-phase CO_2 conditions throughout the entire well.

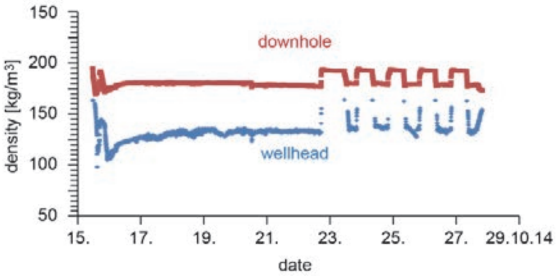

Fig. 3. Calculated density of produced CO_2 stream downhole at the end of the production tubing and at the wellhead based on recorded pressure and temperature data.

3.3. In-well flow velocity

Based on the calculated CO_2 stream density and the mass production rate determined by the flow meter, flow velocities of the CO_2 stream have been calculated for downhole and wellhead conditions. For comparison, actual calculated CO_2 stream densities are used to calculate critical Turner velocities. Wellhead velocities are calculated only for the 3.5” production tubing while downhole velocities are calculated for the 3.5” production tubing as well as the 5.5” production string. Data clearly shows that lowest actual flow velocities occur downhole in the 5.5” production string. Towards decreasing depth, flow velocities increase due to decreasing CO_2 stream density. Following presentation therefore restricts itself to flow conditions in the 5.5” production string (Fig. 4). Depending on production rate, actual flow velocities are 0.10 to 0.15 m/s for production rate of ~ 800 kg/h and 0.20 to 0.25 m/s for production rate of ~ 1600 kg/h. Due to almost constant downhole CO_2 stream density, calculated critical Turner velocity is roughly constant with 1.15 to 1.17 m/s.

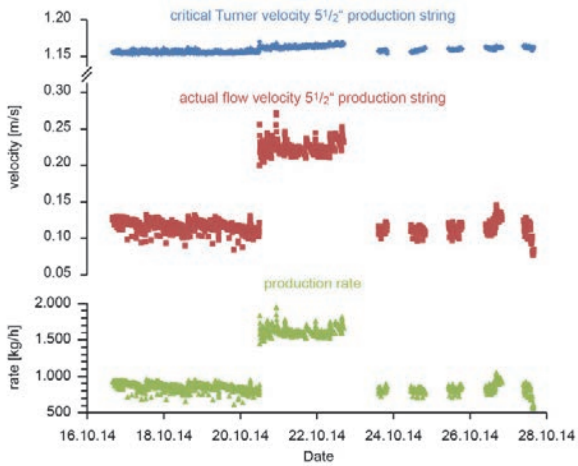

Fig. 4. Calculated actual flow velocities based on calculated CO_2 stream density and mass production rate compared to calculated critical Turner velocity based on calculated CO_2 stream density.

4. Discussion and conclusion

The field experiment conducted at the Ketzin pilot site in October 2014 indicates that a safe back-production of CO_2 is generally feasible and can be performed at both, stable reservoir and wellbore conditions. The almost constant downhole pressure conditions, measured ~ 80 m above the reservoir at the lower end of the production tubing, indicate that no well load-up occurred during the back-production operation. Any accumulation of brine below the production tubing would have been mirrored by a decrease in downhole pressure conditions due to the increased fluid column density. This interpretation is also supported by a constant gas/fluid ratio during the different rate stages of the experiment. The data therefore clearly indicate that the in-well flow velocities did not reach or even fall below the actual critical Turner velocity. However, using the actual, calculated CO_2 stream densities, the calculated theoretical minimum (critical) velocities based on the Turner criterion are notably higher (up to one order of magnitude) than the actual velocities during the back-production experiment, wherefore well load-up is predicted to occur. The results clearly suggest that the traditionally developed Turner criterion that is adjusted to natural gas production overestimates the minimum (critical) velocity for fluid entrainment in a CO_2 dominated well. For future experimental and operational design a modified Turner parameterisation is required.

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