

Wellbore integrity and corrosion of low alloy and stainless steels in high pressure CO₂ geologic storage environments: An experimental study



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ABSTRACT

CO₂ corrosion behavior of three different steels that are commonly used as casing material in CO₂ geologic storage environments (i.e., 1018 carbon steel, 5Cr steel, and 13Cr steel) was studied at 30 and 80 bar CO₂ partial pressures and 60 °C in the presence of a simulated brine for the Weyburn–Midale reservoir system. Electrochemical techniques including linear polarization resistance (LPR), and potentiodynamic polarization measurements, were used to monitor the corrosion rate during experiments and study the corrosion mechanism. Scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD), and Raman spectroscopy were used for surface analysis. A weight loss technique was also employed to measure the corrosion rate. Carbon steel showed very high corrosion rates of ~20 mm/y under the test conditions of this research. 5Cr steel can be considered as a replacement for the carbon steel under these conditions by the reduction in the corrosion rate by a factor of 3. However, corrosion rate was still high (~6 mm/y). 13Cr steel showed the best corrosion resistance under testing conditions employed for this research, and can be considered as the best option for combating high pressure CO₂ corrosion if materials selection is considered as the best option for corrosion mitigation.

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1. Introduction

The sequestration of CO₂ in deep geologic formations requires a thorough evaluation of potential leakage through any wellbores. Possible routes for leakage are preferential flow pathways along the rock–cement interface, the casing–cement interface, and through degraded materials. To date, much of the international research community's focus for wellbore integrity research in CO₂ storage applications has been on CO₂–cement interactions. However, during the long-term storage phase, supercritical (or high pressure) CO₂ can be hydrated with brine contained in the reservoir and generate corrosive carbonic acid (H₂CO₃). This now acidic brine has the potential to contact the steel casings in wells, either through the degradation of the cement in the annular space or by migration through channels, fractures or micro-annuli and causes one of the biggest challenges in the integrity of wellbore materials which is the steel corrosion in high pressure CO₂–brine environments (Choi et al., 2013).

One of the important strategies for corrosion control is materials selection. Carbon steel, 5Cr low alloy, and 13Cr stainless steels are common materials which are used for oil and gas applications under sweet production conditions (Kermani and Morshed, 2003). Effect of chromium alloying element on CO₂ corrosion behavior of steel has been extensively studied before under low CO₂ pressure conditions (Changfeng et al., 2003; Chen et al., 2005; Hu et al., 2011; Kermani et al., 2001; Kermani and Morshed, 2003; Muraki et al., 2003). However, there is not much information available about chromium alloy effect on corrosion performance under high pressure CO₂ environment. Our previous researches (Choi and Nestic, 2009; Choi and Nešić, 2011; Choi et al., 2010) showed that the corrosion rate of carbon steel in supercritical CO₂ conditions without a protective iron carbonate (FeCO₃) layer is very high (~20 mm/y). High corrosion rate of carbon steel under supercritical CO₂ conditions has been also reported by other authors (Han et al., 2011, 2012; Lin et al., 2006; Loizzo et al., 2009; Mohammed Nor et al., 2011; Seiersten and Kongshaug, 2005). Considering this high corrosion rate of carbon steel, it has been suggested that 5Cr low alloy steel and 13Cr stainless steel could be good replacements for carbon steel in high pressure and supercritical CO₂ system. Recently, the performance of different materials from low alloy steels up to

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Table 1
Element analysis (wt.%) by Atomic Emission Spectroscopy for the steels used in the corrosion tests.

	C	Mn	Si	P	S	Al	Cr	Ni	Mo	V	Cu	Sb	Fe
1018	0.21	0.05	0.38	0.09	0.05	0.01	–	–	–	–	–	–	Balance
A182	0.11	0.42	0.29	0.02	0.027	0.029	4.65	0.15	0.58	0.05	–	–	Balance
S41000	0.13	0.49	0.23	0.012	0.005	0.006	12.74	0.112	0.017	0.038	0.009	0.015	Balance

high-alloy materials was evaluated in CO₂ saturated brine at 60 °C and 100 bar (Yevtushenko et al., 2014). They have reported pitting corrosion of 13Cr steel at 60 °C and 100 bar whereas 22Cr steel did not have any pitting problem under these conditions. The corrosion properties of 1Cr and 13Cr steels were also compared at 100 bar CO₂ and 60 °C (Pfenning and Kranzmann, 2012).

At certain conditions, the corrosion rate of carbon steel under supercritical CO₂ system can decrease to low values (~0.2 mm/y) in long-term exposure due to the formation of a protective FeCO₃ layers. This is an interesting observation because the pH of water saturated with supercritical CO₂ is relatively low (~3.3 pH units), which creates under-saturated conditions for FeCO₃ precipitation (Choi and Nesic, 2009). This phenomenon can be related to the high initial corrosion rate affecting less acidic local water chemistry at the near surface region during corrosion by consumption of H⁺ and accumulation of Fe²⁺. Thus, it is possible to generate a boundary layer with a higher pH than the bulk solution that favor the formation of FeCO₃ on the steel surface, thus conferring corrosion protection from the more acidic bulk solutions. On the other hand, it is important to note that considerable localized corrosion (mesa-type for carbon steel and pitting-type for corrosion resistance alloys) was observed in supercritical CO₂ condition after long-term exposure. Localized attack, being the most problematic type of CO₂ corrosion attack, is still difficult to predict even at low pressure conditions, where significantly more research has been conducted. Whilst many environmental factors (pH, temperature, flow) can influence the onset of localized corrosion, it appears that much of the evidence points toward stability of corrosion product layers, which could be related to the metallurgical characteristics of the base alloy (Choi and Nesic, 2009; Choi and Nešić, 2011; Choi et al., 2010).

This paper is focused on the evaluation of the corrosion behavior of carbon steel (AISI 1018), low alloy steel (5Cr) and corrosion resistance alloy (13Cr) under high pressure CO₂/brine environments. This included the determination of corrosion rates and corrosion mechanisms, taking into account the controlling factors (material, pressure, pH, etc.). The corrosion experiments were

carried out in a static high pressure autoclave. Experimental brine chemistry, pressure and temperature were selected that simulate downhole conditions within the Weyburn-Midale system. The corrosion behavior of materials was evaluated using LPR measurements, which reveal details of the corrosion process with time and indicates the type of corrosion mechanism. Simultaneously, weight loss (WL) samples were introduced in the system for validation of corrosion rate calculation by electrochemical techniques. Potentiodynamic sweep was used to study the corrosion mechanism and also determining the Tafel slop for electrochemical corrosion calculation. Surface morphology and corrosion product's characteristics were studied after each test with various analytical tools including SEM, EDS, XRD, and Raman spectroscopy.

2. Materials and methods

The test specimens were machined to be of a rectangular geometry (1.2 cm × 1.2 cm × 0.25 cm for weight loss measurement and surface analysis, 2.5 cm × 1.2 cm × 0.61 cm for electrochemical measurements) from carbon steel (AISI 1018), 5Cr low alloy steel (ASTM A182-F5), and 13Cr steel (UNS S41000) for corrosion study. The chemical compositions of three different steels are shown in Table 1. According to the field data, most wells in Weyburn were completed using J-55 carbon steel (0.19% C, 1.39% Mn, 0.31% Si, 0.014% P, 0.004% S and balance Fe) (Choi et al., 2013) which has similar chemical composition with the carbon steel used in the present study. The specimens were ground with 400- and 600-grit silicon carbide (SiC) paper, cleaned with isopropyl alcohol in an ultrasonic bath, dried, and weighed using a balance with a precision of 0.1 mg.

The corrosion experiments were carried out in a 4-L static stainless steel autoclave equipped to perform in situ electrochemical measurements, as shown in Figs. 1 and 2. The brine chemistry is shown in Table 2, designed to simulate conditions within the Weyburn-Midale system (Shevalier et al., 2011)

Corrosion tests were conducted under different pressures (30 and 80 bar) at 60 °C (Table 3) in order to simulate the pressure condition in the Weyburn-Midale system. CO₂ is in the gas phase

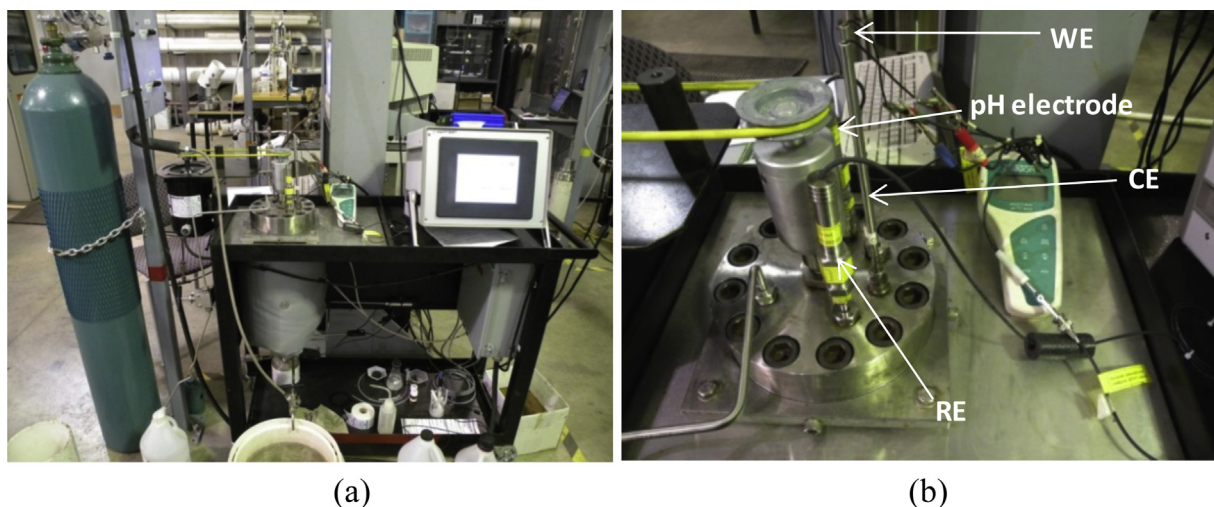


Fig. 1. Experimental setup for corrosion tests under high pressure condition: (a) autoclave system, (b) top lid part with electrode connections for electrochemical and pH measurements.

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