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Effects of Temperature and Pressure on Corrosion Products in a Steam-Flue Gas Environment: a Simulation Study

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Steam and flue gas injection is an enhanced recovery technique that has generated great interest in studies as it takes advantage of the gases produced in combustion processes, which increase the efficiency of crude oil recovery in the reservoir and diminish the emission of greenhouse gases. The operating conditions together with the injected fluids can result in a highly corrosive environment, degrading the properties of the materials used, in addition to operational and financial risks. This research focused on the study of API N-80 carbon steel exposed to a steam and flue gas atmosphere, at pressure and temperature conditions in the ranges of 800-1,100 psi (55.1-75.8 bar) and 520-560 °F (270.1-290.3 °C), in order to understand the synergy between pressure and temperature and the effect of each variable in the corrosion process. From the conditions described above, a simulation stage in HSC Chemistry software was developed to determine three factors: the theoretical corrosion products, the way they interact with each other, and the effect of further variables. Findings revealed that temperature at a constant pressure generated a decrease in the amounts formed of Fe_2O_3, this percentage decrease was of the order of 1 %, and $FeCO_3$, where the percentage decrease was of the order of 0.23 %, and a greater formation of Fe_3O_4, this percentage increase was around from 18 to 19%. When evaluating the increase in pressure at a constant temperature, a greater amount of Fe_2O_3 and $FeCO_3$ and a reduction of Fe_3O_4 were observed. The temperature variable had a greater effect than the pressure on the variation of the quantities formed in the thermodynamic equilibrium of the theoretical corrosion products.

1. Introduction

Cyclic steam injection (CSS) is the most widely used thermal recovery method worldwide (Pérez et al., 2020). In order to expand the technical-economic limit of the projects, and in turn increase recovery efficiency, the use of new hybrid technologies has been proposed. Among these is steam injection with flue gas, which seeks to improve the performance of steam injection, using the flue gas produced by the combustion of hydrocarbons in steam generators, and results in an alternative for the reduction of greenhouse gas emissions (Pérez et al., 2018). Enhanced oil recovery in processes involving the presence of carbon dioxide (CO_2) is the option with the greatest potential for carbon capture and storage (CCS) (Li et al., 2019).
In the steam-flue gas injection process, different variations can be found in the pressure and temperature of the fluids in the reservoir, and these parameters are directly linked to the corrosion behavior. Thus, it is necessary to understand their relationship with the process (Liu et al., 2011). The effects of temperature on corrosion are reported in the literature; generally, an increase in temperature implies an increase in reaction rates and corrosion (Martín et al., 2014). However, the effect on the reaction rate must be understood with the set of associated parameters. Authors such as Nikitasari et al. (2021), indicate that the increase in temperature also contributes to the acceleration in the corrosion rate of carbon steel pipe in condensate solution from a geothermal power plant.

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Choi et al. (2017), reported that increases in temperature contributed to the corrosion rate up to a maximum peak, after which, protective films began to form, resulting in a decrease in the corrosion rate. Li et al. (2019) found that at higher temperatures corrosion rate decreased due to the formation of protective corrosion layers. Another study, developed by Alviz et al. (2017), showed that high temperatures in combustion processes may reduce the physical properties of involved alloys.
Other studies such as that of Xiang et al. (2013) corroborated that the morphology of the corrosive products varied according to temperatures. At low temperatures, the corrosive products were irregular and weaker. whereas at higher temperatures, they were more compact and denser. Regarding the effect of pressure, similar behaviors have been determined. Bai et al. (2018), identified an increase in corrosion rates when the CO_2 partial pressure was increased from 0 to 1.5 MPa (0 to 217 psia). As evidenced in the studies reported in the literature, variations in pressure and temperature, and the interaction with working atmospheres have important effects on the understanding of the corrosion process. Along these lines, an adequate selection of the materials required for certain working environments should be carried out, as well as the ways to prevent and mitigate corrosion. From the recent research conducted by Moreno et al. (2021), theoretical corrosion products were determined from a thermodynamic simulation step. In the literature, some studies have been conducted regarding the behavior of corrosion as a result of changes in the thermodynamic variables of temperature and pressure (Wang et al., 2019). Most of the research in this area has been conducted at low pressures and temperatures around 150 psia (10.3 bar) and 250 °F (121.1 °C) , although the effects of steam-flue gas synergy in the corrosion of materials, in particular carbon steels, are still not well understood, for this reason, to obtain information about the reactions in the system and determine how the variables were related. This study examines the effects of temperature and pressure on corrosion products in a steam-flue gas environment using API N-80 carbon steel and the thermodynamic simulation tool HSC Chemistry, to high pressures of 800 to 1,100 psia (55.1-75.8 bar) and temperatures that are typical in steam injection processes in Colombian crude oil fields. The research results become a point of reference for further experiments into carbon capture and storage (CCS) processes, especially for applications in enhanced oil recovery taking high pressures and high temperatures conditions into consideration.

2. Materials and Methods

2.1 Methodology

Figure 1 shows the methodology used in this work

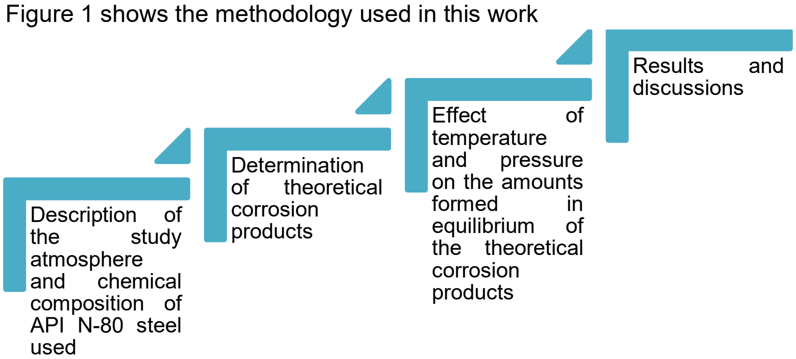

Figure 1: Methodology proposed

2.2 Description of the study atmosphere and chemical composition of API N-80 steel used

From the recent study by Moreno et al. (2021), based on a steam-flue gas mixture with a mass percentage of steam (47.4 %) and flue gas (52.3 %), API N-80 carbon steel was taken as a case study. Simulation tests were carried out under the same conditions, considering the operating window of the process in the range from 200 to 300 °C, using pressure conditions that guaranteed the presence of saturated steam under reservoir conditions (Núñez et al., 2021). Table 1 reports API N-80 the steel mass composition used as the basis to conduct the simulations in this research work, taking the study by Li et al. (2019) as a reference.

Table 1: Chemical composition of the API N-80 grade steel used in the study (Li et al, 2019)

Element	C	S	Si	Mn	P	Cr	V	Fe
% weight	0.35	0.015	0.30	1.45	0.02	0.12	0.11	97.64

2.3 Determination of theoretical corrosion products

From the previous corrosion behavior for API N-80 steel research, in a steam-flue gas injection process by Moreno et al., (2021), used Pourbaix, Ellingham and equilibrium diagrams to determine the theoretical corrosion products and found that the compounds present in greater quantities in equilibrium for the system studied were the following: Fe_2O_3, Fe_3O_4 and $FeCO_3$.

2.4 Effect of temperature and pressure on the amounts formed in equilibrium of the theoretical corrosion products

In order to analyze the effects of the variables temperature and pressure on the theoretical corrosion products, the equilibrium quantities formed for the main compounds obtained in the previous research and their variation as a function of each variable were determined using the equilibrium diagrams on HSC.
On the other hand, each component was analyzed separately, using both variables (temperature and pressure), a joint analysis was conducted of the variation's effects of the studied parameters on the main theoretical corrosion products formed (Fe_2O_3, Fe_3O_4, $FeCO_3$). For this purpose, the variation calculation of the substance's amount formed in equilibrium with respect to the temperature at a constant pressure Eq(1), as well as with respect to the pressure at a constant temperature Eq(2).

$$\left(\frac{\partial_n}{\partial_T}\right)_P = \left|\frac{n_2 - n_1}{T_2 - T_1}\right| \tag{1}$$

$$\left(\frac{\partial_n}{\partial_P}\right)_T = \left|\frac{n_2 - n_1}{P_{2-}P_1}\right| \tag{2}$$

Where,
$\left(\frac{\partial_n}{\partial_T}\right)_P$ y $\left(\frac{\partial_n}{\partial_P}\right)_T$: represent the variation of the substance's amount (kmol) with respect to temperature at constant pressure (kmol/°F) and with respect to pressure at constant temperature (kmol/psia).
n: moles at the indicated condition (kmol).
T: temperature (°F).
P: pressure (psia).

3. Results and Discussion

3.1 Effect of temperature and pressure on the amounts formed in equilibrium of the theoretical corrosion products under steam-flue gas injection conditions

In the following sections, the plots of variation in the equilibrium quantity for each component (Fe_2O_3, Fe_3O_4, $FeCO_3$) in regard to the pressure variable at constant temperature are reported. In order to facilitate the visualization of results, the points evaluated for each condition were joined using curves that do not necessarily represent trends, but that allow to show ascending or descending behaviors accordingly.

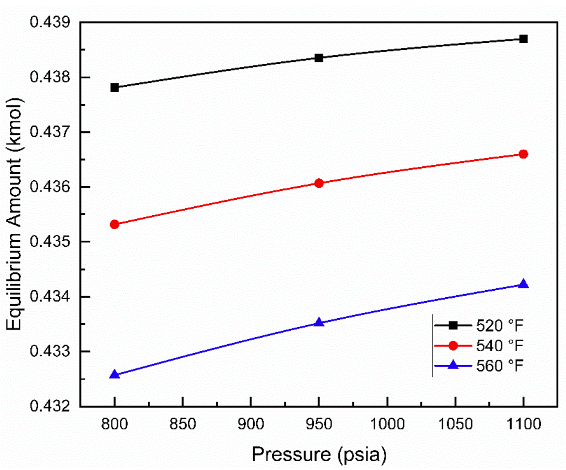

Figure 2: Variation in the equilibrium amount of Fe2O3 regarding pressure

3.1.1 Effect of temperature and pressure on the equilibrium amounts of Fe_2O_3 formed

Figure 2 shows the variation of the equilibrium amount of Fe_2O_3 regarding pressure at different temperatures. As for Fe_2O_3, it was observed that the increase in the variable pressure at constant temperature generated an increase in the formation of this compound. This percentage increase was equal to 0.20 % at a constant temperature of 520 °F (271.1 °C), 0.29 % at a constant temperature of 540 °F (282.2 °C), and 0.38 % at a constant temperature of 560 °F (293.3 °C). On the other hand, increases in temperature at constant pressure generated a decrease in the amounts formed. This percentage decrease was equal to 1.19 % at a constant pressure of 800 psia (55.1 bar), 1.10% at a constant pressure of 950 psia (65.5 bar), and 1.02 % at a constant pressure of 1100 psia (75.8 bar).

3.1.2 Effect of temperature and pressure on the equilibrium Fe_3O_4 amounts

Figure 3 shows the variation of the equilibrium amount of Fe_3O_4 with respect to pressure at different temperatures. When it comes to Fe_3O_4 oxide, the increases in the pressure variable at constant temperature implied decreases in the amounts formed of this compound. This percentage decrease was equal to 7.19 % at a constant temperature of 520 °F (271.1 °C), 7.05 % at a constant temperature of 540 °F (282.2 °C), and 6.93 % at a constant temperature of 560 °F (293.3 °C). On the other hand, the increase in temperature at constant pressure contributed to the increase in the amounts formed of the studied component. This percentage increase was equal to 18.74 % at a constant pressure of 800 psia (55.1 bar), 19.14 % at a constant pressure of 950 psia (65.5 bar), and 19.07 % at a constant pressure of 1,100 psia (75.8 bar).

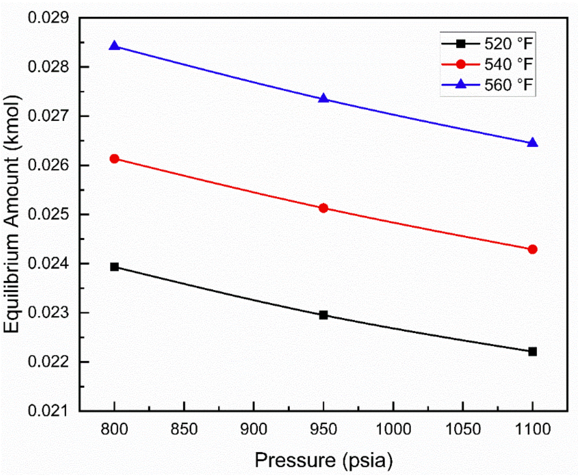

Figure 3: Variation in the equilibrium amount of Fe3O4 regarding pressure

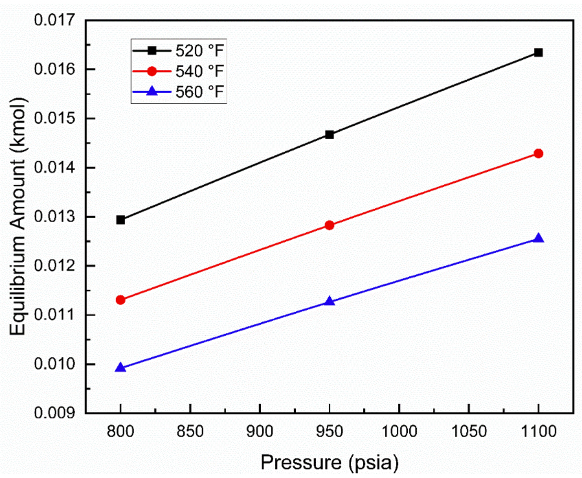

Figure 4: Variation in the equilibrium amount of FeCO3 regarding pressure

3.1.3 Effect of temperature and pressure on the equilibrium $FeCO_3$ amounts

Figure 4 reports the variation of the equilibrium amount of $FeCO_3$ concerning pressure at different temperatures. As for this component, increases in the pressure variable at constant temperature caused increases in the amounts formed. For each study condition, the percentage increase was of the order of 0.26 %. On the other hand, increasing the temperature at constant pressure generated decreases in the equilibrium formation of this corrosion product. For each study condition, the percentage decrease was of the order of 0.23 %.

3.2 Analysis of the effect of temperature and pressure variables

The effects of pressure and temperature can be observed in Figure 5, the bars in blue and purple correspond to the variation of the amounts formed at the initial and final temperatures of the research work: 520 and 560 °F (270 and 290 °C) for each value of constant pressure, taking as reference the values of 800 and 1,100 psia (55 and 75 bar). Similarly, the bars in green represent the variation of the quantities formed for the initial and final pressure of study, 800 and 1,100 psia (55 and 75 bar) for each value of constant temperature, taking as reference the values of 520, 540 and 560 °F (270, 280, 290 °C).

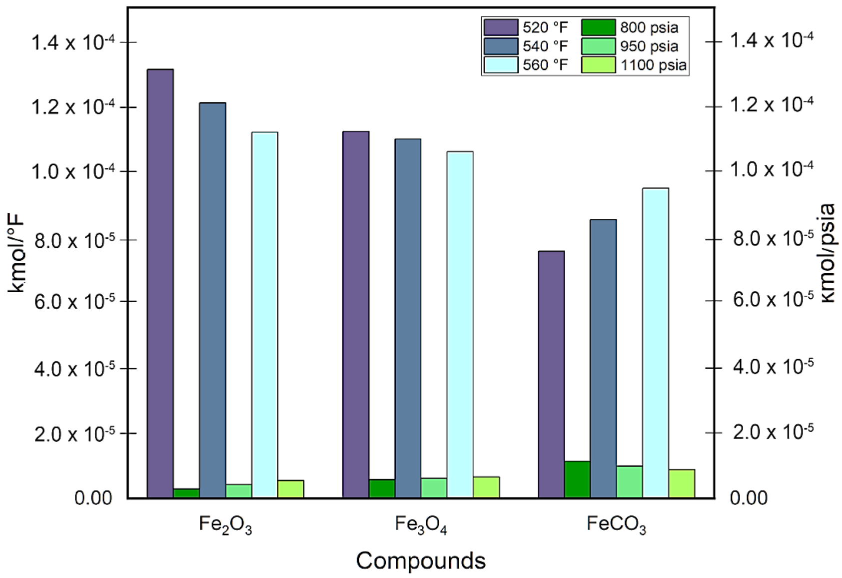

Figure 5: Equilibrium amount variation regarding temperature and pressure compounds Fe_2O_3, Fe_3O_4, $FeCO_3$

From the behavior observed in Figure 5 it is possible to indicate that the temperature variable presents a greater effect on the variations of the substance amounts of the theoretical corrosion products formed compared to the influence of the pressure variable. The greater effect of temperature can also be confirmed from what was observed in Figures 2, 3 and 4, where the highest percentage values were associated with the temperature variable.

Although no research has been conducted for the same study environment and working conditions, the results obtained in this study are comparable to those reported by (Sui et al., 2018), which examined the effects of temperature and pressure changes, using carbon steel X65 in a CO_2-H_2S-H_2O environment at temperatures of 27, 35, and 50 °C, and pressures of 1,160 psi (80 bar) and 1,450 psi (100 bar). It was found that the rate of change for the pressure variable in relation to the amount of corrosion products formed was greater than for the temperature variable.

4. Conclusions

It was evidenced that the increase in temperature at a constant pressure generated a decrease in the amounts formed of Fe_2O_3 and $FeCO_3$, and a greater formation of Fe_3O_4. When evaluating the increase in pressure at a constant temperature, a greater amount of Fe_2O_3 and $FeCO_3$ and a reduction of Fe_3O_4 were observed. The highest values of change in the formation of corrosion products were presented for the formation of Fe_3O_4, where was obtained a percentage decrease of 7.19 % at a constant temperature of 520 °F (271.1°C), and 19.14 % at a constant pressure of 950 psia (65.5 bar).

It was established that for the different study conditions, the temperature variable had a greater effect than the pressure on the variation of the quantities formed in thermodynamic equilibrium of the theoretical corrosion products. This research work becomes a point of reference for experimental studies where the effects of temperature and pressure variables are evaluated using carbon steels and that also allows validation of the results obtained in the simulation stage.

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