Produced Water Re-Injection (PWRI) Compatibility Investigations: Comparison Between Geochemical Simulators and Laboratory Results

Introduction

From a technological standpoint, reservoir engineers are concerned with injectivity impairment in water injection projects. Before conducting any water injection test, it is vital to examine the filtration of the suspended particles and oil content as well as the deposition and precipitation of inorganic scale. Scale generation is a complicated phenomenon that can result from variations in pressure, temperature, and pH as well as chemical incompatibilities between the injection water and formation brine (Shabani et al., 2019). Each water injection project must include compatibility check due to wide range of parameters and concurrent changes in the process. Aside from the experimental methods which are available to verify this compatibility check, geochemical simulators are recently introduced to compute the generated inorganic scale types and its amounts. Theses simulators are working based on the assumption that fluids are at the super-saturation condition. For example, as any of the components in the water phase is super-saturated, scale generation starts. Another traditional way of compatibility check is a laboratory test. This type of investigations is design to mimic the injection process and evaluating scales' generation in different stages. In this study laboratory results of the static compatibility check for mixing injection and formation water compared with the geochemical simulators and the accuracy of the simulators based on lab results are presented.

Method and/or Theory

The standard procedure for testing compatibility in a laboratory involves mixing two or three water phases with various compositions at the desired pressure and temperature and then wait until the liquid reaches equilibrium. By filtration, the precipitation is separated from liquid phase and the filtrated scales are dried and weighted to evaluate total solid generated. Scanning Electron Microscopy (SEM) with Energy Dispersive X-Ray Analysis (EDX) are applied on the scales to detect the type and amount of each scale. It is worth mentioning that the accuracy of these laboratory tests depends on an accurate brine sampling at reservoir pressure and temperature which is very time consuming and expensive at the same time.

Due to complexity of brine composition and liquid-liquid interactions, geochemical simulators are used as computational investigators (Jiménez et al., 2018). Geochemical simulators are both fast and low-cost. By importing desired condition (i.e.: different brines ratio, at desired pressure and temperature), simulators predict the possible scale generation. Generally, the simulators have access to a vast database of chemical reactions that can take place at reservoir or near surface condition and is able to make predictions based on stability of equilibrium and the fluid saturation conditions of the fundamental ions (Mostafavi et al., 2021). According to these chemical reactions, geochemical simulators would predict scale formation only if any ions are in supersaturation condition, which is necessary but not enough. Inorganic scaling phenomena have three main steps, super saturation, nucleation, and crystal growth (Kamalipour et al., 2018). In this study for the very first time we use two widely used geochemical simulators, Oli ScaleChem and PHREEQC, and compare their results with laboratory compatibility tests to examine the accuracy of the scale formation simulators.

*Table 1: Compositions of the candidate injection water and the formation brine*

Property/ Water sample	pH	HCO_3^-	SO_4^{2-}	Cl^-	S	Fe^{2+}	Ca^{2+}	Mg^{2+}	Na^+	K^+	Sr^{2+}	TDS
Unit	_	mg/L	mg/L	mg/L	mg/L	ppm	mg/L	mg/L	ppm	ppm	ppm	mg/L
IW	5.3	138	410	125000	-	12	11400	1900	61000	850	660	201370
FW	6.5	545	320	112000	40	4	9800	1100	56000	2400	900	183100

Case Study

This article investigates the use of produced water reinjected into an oil reserve in one of the matured oil fields in south-west of Iran. The produced water and formation brine compositions are summarized in table 1.

The compatibility study was first carried out using PHREEQC and Oli ScaleChem simulators to assess the scaling potential of the fluids in a ratio of 25% formation water and 75% injection water. The predicted scale type and total scale amount for each simulator are shown in Figure 1.

Due to different equilibrium constants in each simulator's database, results from the two geochemical simulators are different in scale types or amounts. Although they both predict Strontium Sulfate as the most common scale and results Quartz, Iron Sulfide and Pyrite are completely different.
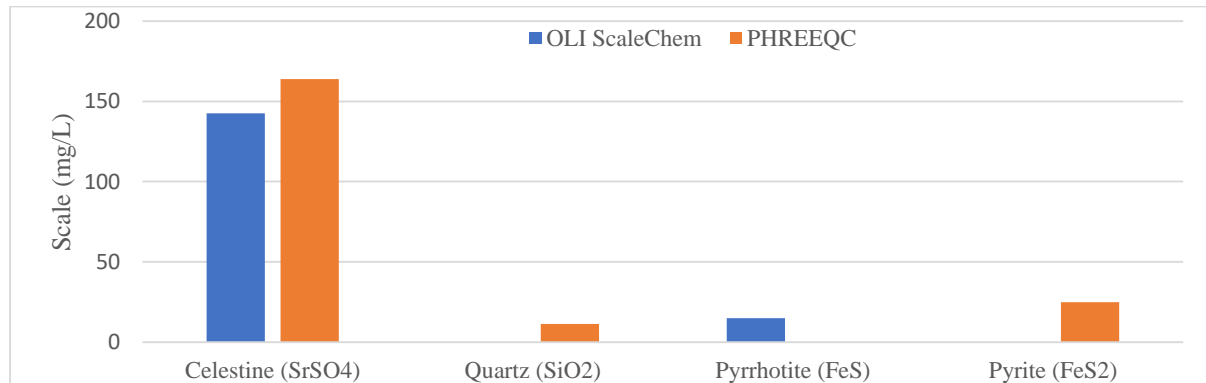
Figure 1 Predicted scale types and amounts in mixed waters in each geochemical simulator. Blue for Oli ScaleChem and orange for PHREEQC

On the experimental part of this study, samples of both waters were filtered with 0.45-micron filter paper to separate suspended solids. Later the formation brine was mixed with the injection water in the desired ratio (25% formation brine with 75% injection water) and the mixture was left in stable condition for 14 days. This time is sufficient for all the probable reactions to take place. After drying the filtrated scales, atomic identification was conducted with SEM-EDX experiment. Total scale amount was 134 mg/l and the SEM-EDX results are shown in Figure 2.

As the result of bulk scale SEM-EDX experiment, Oxygen, Chlorine and Iron are detected as fundamental minerals of the filtered scales. Sodium, Calcium and Silicon also participated in separated solids. Based on the detection of Sodium Chloride, Iron Oxide, Iron Sulfide and/or Pyrite and Silicon Oxide are confirmed. Table 2 summarizes the scale prediction in simulators and laboratory results.

Table 2: Predicted scale types and amounts in mixed waters with different simulators

Scale (mg/l) / Evaluation tool	Celestine ($SrSO_4$)	Quartz (SiO_2)	Pyrrhotite (FeS)	Pyrite (FeS_2)	Calcium Chloride ($CaCl_2$)	Iron Oxide (Fe_2O_3)	Sodium Chloride (NaCl)	Total
Oli ScaleChem	142	0	15	0	0	0	0	157
PHREEQC	164	11	0	25	0	0	0	200
SEM-EDX	Trace	Generated	Generated	Generated	Generated	Generated	Generated	134

Ions	W%	A%
O	27.98	45.95
Na	11.2	12.8
Mg	0.69	0.75
Al	0.44	0.43
Si	5.06	4.73
S	3.19	2.61
Cl	27.34	20.25
K	0.47	0.32
Ca	7.58	4.96
Fe	14.43	6.79
Sr	1	0.3
Ba	0.63	0.12
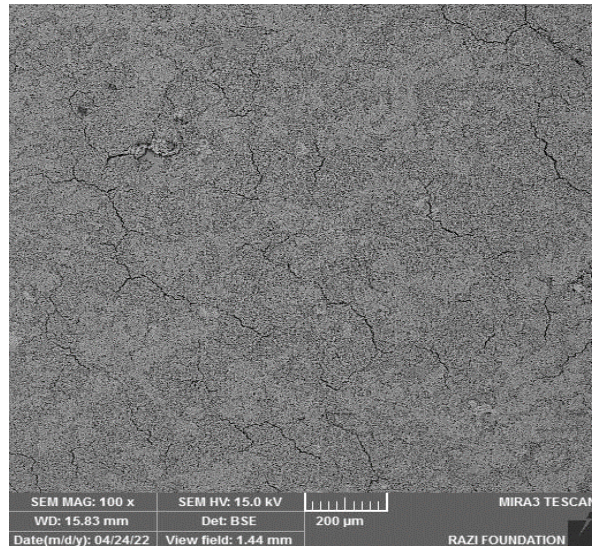
Figure 2 *SEM-EDX results for bulk of the filtered scales*

This experiment was repeated for certain points to analyze the scale types. The SEM results are shown in Figure 3 and the corresponding EDX data are in table 3. SEM-EDX analysis indicated almost pure Sodium Chloride in points A and D while in points B and E scale are mixture of Iron Oxide, Calcium Chloride and Silicon Oxide. In point C, the concentration of Oxygen, Chlorine and Magnesium ions are high.

Results from these investigations show that none of the geochemical simulators were able to accurately predict some of the mineral scales produced in the laboratory; i.e. Sodium Chloride, Calcium Chloride and Iron Oxide. Additionally, both simulators anticipated large concentrations of strontium Sulphide scale but laboratory investigation demonstrates that this scale formation is modest. Besides, Silicon oxide precipitation was only predicted with PHREEQC simulator. The choice of which simulator to use for field development in the case of full-field implementations can cause serious problems.
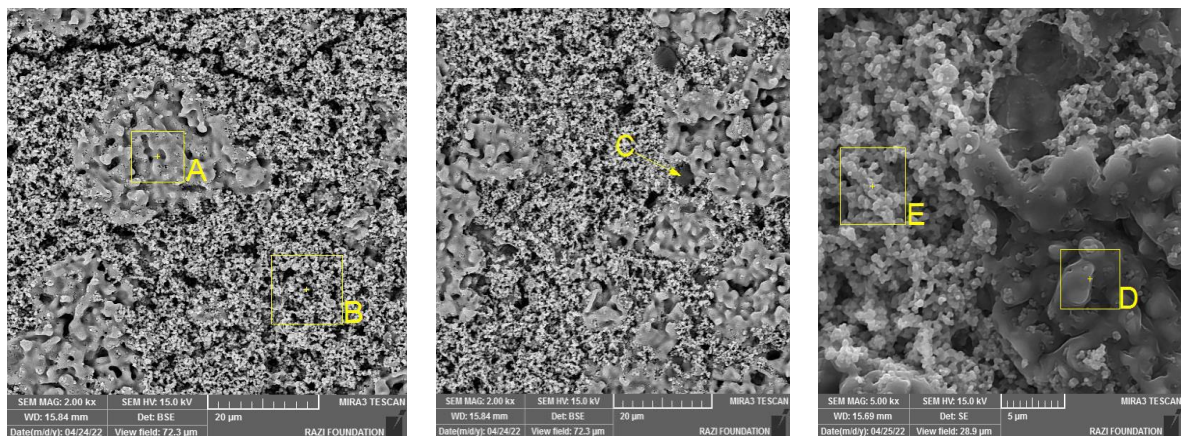
Figure 3 *SEM pictures for selected points A to D*

Table 3: *Corresponding EDX data for points A to D*

Points/ Ions	point A		point B		point C		point D		point E	
	W%	**A%**	**W%**	**A%**	**W%**	**A%**	**W%**	**A%**	**W%**	**A%**
O	12.62	21.91	35.25	56.71	43.37	60.81	12.62	21.91	38.67	60.73
Na	25.95	31.35	2.79	3.12	5.31	5.18	25.95	31.35	0.87	0.95
Mg	0.64	0.73	0.9	0.96	8.95	8.26	0.64	0.73	1.4	1.45
Al	0.5	0.52	0.54	0.52	0.65	0.54	0.5	0.52	0.62	0.58
Si	2.28	2.25	6.94	6.35	1.62	1.29	2.28	2.25	6.92	6.19
S	3.18	2.76	3.29	2.64	0.54	0.38	3.18	2.76	0.74	0.58
Cl	45.24	35.43	19.42	14.09	29.5	18.67	45.24	35.43	19.25	13.65
K	0.34	0.24	0.73	0.48	5.03	2.88	0.34	0.24	0.81	0.52
Ca	3.16	2.19	8.93	5.73	1.61	0.9	3.16	2.19	10.78	6.76
Fe	4.51	2.24	19.42	8.95	1.9	0.76	4.51	2.24	17.94	8.07
Sr	0.55	0.17	1.03	0.3	0.76	0.2	0.55	0.17	1.46	0.42
Ba	1.03	0.21	0.77	0.14	0.76	0.12	1.03	0.21	0.54	0.1

Conclusions

Due to the numerous problems after scale formation in water injection into the reservoirs, compatibility tests are an inevitable step in selection of the injection fluid. Thereafter finding an inexpensive method beside the laboratory methods is crucial. Geochemical simulators which are lately introduced as an alternative to the experimental methods are here compared to the experimental results from a real field data from one of the oil reservoirs in south west of Iran. The comparison between the two main computational simulators, PHREEQC and OLI ScaleChem, and the results from compatibility experiments shows that both simulators consider only the super-saturation condition as the main reason for the scale generation, which is not enough. According to the experimental results, one can conclude that aside from the thermodynamic conditions, nucleation and crystal growth should be considered too. Moreover, the total amount of scale generated in laboratory tests was 134 mg/l which was lower than computed values from both simulators but closer to OLI ScaleChem. Last but not least, the generated scale minerals predicted in simulators were different from laboratory results: Although both simulation results show formation of a great amount of Celestine, laboratory tests do not confirm it. Besides, Sodium Chloride, Calcium Chloride and Iron Oxide which were observed in SEM experiments, were not predicted with geochemical simulators and only PHREEQC could correctly predict Silicon Oxide scale generation. In conclusion, even though laboratory compatibility checks are time consuming and more expensive, their results are more reliable.

References

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