Preliminary assessment of CO$_2$ injectivity in carbonate storage sites

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A R T I C L E   I N F O

A B S T R A C T

Depleted gas reservoirs are used for a large-scale carbon dioxide (CO$_2$) storage and reduction of the greenhouse gas released into the atmosphere. To identify a suitable depleted reservoir, it is essential to do a preliminary and comprehensive assessment of key storage factors such as storage capacity, injectivity, trapping mechanisms, and containment. However, there are a limited number of studies providing a preliminary assessment of CO$_2$ injectivity potential in depleted gas reservoirs prior to a CO$_2$ storage operation. The aim of this study is to provide a preliminary assessment of a gas field located in Malaysia for its storage potential based on subsurface characterization prior to injection. Evaluation of the reservoir interval based on the facies, cores, and wireline log data of a well located in the field indicated that the pore type and fabrics analysis is very beneficial to identify suitable locations for a successful storage practice. Although the results obtained are promising, it is recommended to combine this preliminary assessment with the fluid-mineral interactions analysis before making any judgment about reliability of storage sites.

1. Introduction

It is generally known that CO$_2$ can be safely stored in depleted oil and gas reservoirs through a large-scale injection operation [1—4]. Depleted gas reservoirs are the best candidates for the storage practice due to their proven storing capacity, suitable petrophysical characteristics, and in place infrastructures [5]. Retrograde gas reservoirs, in particular, may have dual applications, on these occasions, and CO$_2$ injection may help to have a better gas and condensate recovery, due to re-vaporization and reservoir re-pressurization [6,7]. Comparatively, depleted condensate gas reservoirs are more favourable then condensate gas because of their higher compressibility which is the sign of a high storage capacity [8]. However, there are many studies carried out in recent years pointing out the significance potential of a condensate gas reservoir as a suitable storage site [6,7,9—11].

To identify a suitable CO$_2$ storage medium, a preliminary analysis is performed based on different screening criteria [12—14]. This is followed by the analysis of storage capacity [15,16], injectivity [16—20], trapping mechanisms [16,21—23], and reservoir/seal integrity [5,16,24] through numerical and lab based techniques. A comprehensive injectivity analysis based on facies and petrophysical descriptions is one of the strategies taken as a part of the storage site selection [25,26], where few important indicators are selected to highlight the potential zones for a favourable CO$_2$ storage.

Upon injection, CO$_2$ changes its phase and becomes a dense (supercritical) fluid at the pressure and temperature of higher than 30.98 °C (87.76 °F) and 7.38 MPa (1070 psi), respectively. This density can also be achieved at a depth of greater than 2625 ft (800 m), in a low temperature gradient medium where

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the pressure would be a key factor to achieve the supercritical condition [27,28], which favours the injectivity potential [29] because a dense CO_2 occupies smaller pore volumes [19]. Furthermore, porosity, permeability and heterogeneity are major factors controlling an effective CO_2 storage capacity [26,30,31]. Particularly, permeability along with the thickness of the targeted medium are the key parameters for a successful injectivity [29], which ultimately controls the cost and efficiency of the injection operation [32,33]. Residual gas [18,34] and condensate (oil phase) saturations [35] are other factors which are linked to an efficient injectivity. A high percentage of water or gas saturation can also reduce the chance of having an effective storage capacity [34,36,37]. The amount of remaining oil in a retrograde reservoir significantly affects the relative permeability and injectivity of a depleted site [35]. On the other hand, the heterogeneity level of the storage medium controls the brine displacement which has a significant influence on the plume migration and storage capacity [38,39]. These properties have gained a lot of attention during the preliminary assessment of any geologic mediums for a storage practice in the past decade [14,18,19,26—28,31,40—45] as highlighted in Table 1.

There are, however, few mechanisms which may cause complications in the analysis. For instance, if a formation is composed of carbonates, the geochemical reactions between brine and formation rocks increase the pH of brine causing an enhanced CO_2 solubility upon injection [46,47]. Carbonates like calcite, magnesite and siderite are more likely to precipitate as reacting cations because of dissolution reactions with carbonate brine [48] as given in Table 2. These precipitation reactions may occur in a relatively short period of time in carbonates compared to silicate minerals which can be a function of the pressure and temperature variation. Changes induced due to the precipitation depend on mineralogy and permeability of formations and often affect the rock characteristics [29]. For instance, Mohamed and Nasr-El-Din [49], experimentally tested heterogeneous Silurian

dolomite and heterogeneous Indiana limestone. Their study indicated that more damages are induced on heterogeneous rocks compared to the homogeneous cores because of high precipitation reactions taking place in high permeability rocks [49]. However, some researches carried out in recent years have shown that even the rock permeability reduction causes a significant drop in injectivity [50—55], although carbonate mineralization [56] and mineral dissolution may also contribute into this decline [54]. This mineral dissolution and precipitation may also have an impact on the storage integrity during and after injection which may lead to damage to the wellbores, the overlying seal, and any fault/seal systems. Therefore, it is essential to evaluate CO_2/brine/rock chemical reactions during and after any storage practices [57,58]. Therefore, carbonates are not easy rocks to characterize due to their complex pore structures, micro-porosities, wide heterogeneities, and high reactivity [57,59].

The aim of this study is to perform a preliminary assessment for injectivity in a carbonate gas field located in Malaysia. Having known that porosity, permeability and thickness favour injectivity, two steps are taken to achieve the objective of this study: 1) characterization of the reservoir in terms of its lithological and petrophysical properties based on the core description, well log, and facies analysis, and 2) discussing the relationship between petrographical and petrophysical properties of the medium with CO_2 injectivity.

2. Site description

The field of this study is one of the major retrograde gas fields in a Miocene age sedimentary basin of Malaysia. The Miocene age geologic succession of the field consists of the transgressive cap phase, intermediate phase, main build-up phase upper, and main build phase lower which are mainly divided into five zones. The reservoir is capped by a massive shale rock (>500 m) and

Table 1
The proposed indicators to justify the good zones for favourable CO_2 storage.

Parameters	Positive indicators	Cautionary indicators	Indication of aspect	Reference
Depth	>800 m	800 m > depth > 2000 m	Storage capacity	[27,28,45]
CO_2 density	high	low	Storage capacity	[19,45]
Porosity	>20%	<10%	Storage capacity	[30,31,45]
Thickness	≫ 50 m	<20 m	Injectivity	[30,31,45]
Permeability (near-wellbore)	>100mD	10—100mD	Injectivity	[30,31,45]
Pore throat size distribution	less heterogeneous	highly heterogeneous	Injectivity	[45]
Residual gas/water saturation	low	high	Injectivity	[18,34,45]
Condensate (oil phase) saturation	low	high	Injectivity	[35]
Lithofacies types	Good Quality	Low Quality	Injectivity	[26]

Table 2
Mineral-CO_2-brine interactions taking place in reservoirs [48].

Primary mineral	Reaction	Secondary mineral
Dissolution Reactions	$CO_2(g) \rightarrow CO_2(aq)$	
	$CO_2(g) + H_2O(l) \rightleftharpoons H_2CO_3(aq)$	
	$H_2CO_3(aq) \rightleftharpoons H^+(aq) + HCO_3^-(aq)$	
	$HCO_3^-(aq) \rightleftharpoons H^+(aq) + CO_3^{2-}(aq)$	
Precipitation Reactions	$Ca^{2+}(aq) + CO_3^{2-}(aq) \rightarrow CaCO_3(s)$	Calcite
	$Fe^{2+}(aq) + CO_3^{2-}(aq) \rightarrow FeCO_3(s)$	Siderite
	$Mg^{2+}(aq) + CO_3^{2-}(aq) \rightarrow MgCO_3(s)$	Magnesite
	$Ca^{2+}(aq) + SO_4^{2-}(aq) \rightarrow CaSO_4(s)$	Anhydrite
	$K^+(aq) + 3Al^{3+}(aq) + 2SO_4^{2-}(aq) + 6H_2O(l) \rightarrow KAl_3(SO_4)_2(OH)_6(s) + 6H^+(aq)$	Alunite
	$Ca^{2+}(aq) + Mg^{2+}(aq) + 2HCO_3^-(aq) \rightarrow CaMg(CO_3)_2(s) + 2H^+(aq)$	Dolomite