Fuel 220 (2018) 89–100

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Statistical and analytical review of worldwide CO_2 immiscible field applications

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ARTICLE INFO

Keywords:
CO_2 immiscible flooding
Field applications
Screening guidelines
Statistical analysis
CO_2 injection efficiency
Economic evaluation

ABSTRACT

CO_2 immiscible flooding is an important enhanced oil recovery (EOR) technology that has demonstrated great potential under varying reservoir and fluid conditions. This paper provides a comprehensive review of worldwide CO_2 immiscible experiences by collecting and analyzing data of 41 field applications from more than 60 publications, including books, DOE reports, AAPG databases, *Oil and Gas Journal* surveys, field reports, and SPE publications. About 100 papers have been reviewed. Two major parts are included in this paper. The first part explores where CO_2 immiscible could be applied, in which screening guidelines have been established and updated by applying statistical methods. Boxplots and histograms were used to detect special cases and to interpret the main distributions of reservoir/fluid properties. The second part discusses the influences of operation to the productions, the performances of each field, and the existing operational problems by using analytical methods, which include injection strategies, gas injection compositions, CO_2 utilization, CO_2 injection efficiency, incremental oil recovery, and incremental oil production rate per well. Results show that CO_2 immiscible flooding could produce an additional 4.7%–12.5% of oil with 10.07 Mscf/stb average CO_2 injection efficiency.

1. Introduction

CO_2 miscible flooding is one of the most effective methods for oil recovery enhancement, and this method has provided the highest daily production rate among all EOR methods in the United States since 2012 [1]. However, not all reservoir conditions can meet the miscible requirements due to either technical difficulties or commercial considerations.

Minimum miscible pressure (MMP) is a critical parameter in CO_2 flooding which is defined as the lowest pressure where oil and injectants achieve miscibility dynamically [2]. Numerous slim-tube tests have shown that the reservoir pressure should be greater than 1100 psi to achieve the miscibility between CO_2 and oil [3–8], and the MMP values could be as high as 3970 psi [9], which is mainly caused by high reservoir temperature or high molecular weight (oil composition) [10,11]. Experimental studies have demonstrated that the CO_2 MMP is directly related to the reservoir temperature [10,12]. With every increase of 10 °F in temperature, the MMP increases by about 130 psi. When reservoir pressure is less than the MMP due to production or initial reservoir conditions, the displacement is considered as immiscible flooding. Even though the immiscibility between the injected gas and the reservoir fluids leads to fewer interchange components in the mixing zone [13], CO_2 is still highly soluble. As the CO_2 contact with the oil in the formation, the oil swells (10–35%) and reduces its viscosity (up to 10% of original values) [14,15], which allowing the oil to flow more easily through the interconnected pore spaces towards the production well, and could also assist for pressure maintenance. These benefits give the rise to the implementation of CO_2 immiscible flooding.

The first CO_2 immiscible flooding project was found in Ritchie Field (USA, Arkansas) in 1968 [16]. Motivated by the success of this field application, the second CO_2 immiscible project in United States was conducted in the nearby Lick Creek Field in 1975, where 7.6 Bscf of CO_2 was injected into a reservoir with a net thickness of 8.6 ft and an oil gravity of 17 °API. Over the decades, a considerable amount of CO_2 immiscible projects has been undertaken not only in the United States, but also in China [17–20], Turkey [21–24], Trinidad [25], Malaysia [26–29], Hungary [22,30,31], Argentina [32,33], Canada [21,34,35], and Brazil [36,37]. Currently, more projects are being planned in oil fields in Thailand and China (Yanchang oil field [38], Shengli oil field [39]). With the global concern of greenhouse gas emission and the development of technologies, more anthropogenic CO_2 sources through carbon capture and storage (CCS) could significantly reduce the cost of CO_2 immiscible flooding, which leads the CO_2 immiscible flooding to become one of the most commercial technology.

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https://doi.org/10.1016/j.fuel.2018.01.140
Received 1 December 2017; Received in revised form 27 January 2018; Accepted 31 January 2018

Table 1
Previous screening guidelines for CO_2 immiscible flooding.

Author	EOR method	Published year	Gravity	Viscosity	Porosity	Oil saturation	Formation type	Average permeability	Depth	Temperature	No. of projects	References
			°API	cp	%	% PV		md	ft	°F		
Taber et al.	Immiscible Gases	1997a	> 12	< 600		> 35	NC	NC	> 1800	NC		[43,44]
Bourdarot and Ghedan	Offshore CO_2 Immiscible	2011	> 22	< 10		> 20	Sandstone or carbonate	NC	> 1800	> 86		[45]
Adasani and Bai	CO_2 Immiscible	2011	11–35	0.6–592	17–32	42–78	Sandstone or carbonate	30–1000	1150–8500	82–198	16	[46]

Table 2
CO_2 immiscible applications and references.

Project No.	Scale	Country	Field	Pay zone	Project start date (year)	Producer /injector	Formation type	References
1	Field	USA	Ritchie	Baker	1968	4.3	Sandstone	[16]
2	Field	Trinidad	Forest Reserve	Upper Forest, EOR 26	1974	2	Sandstone	[25]
3	Field	Trinidad	Forest Reserve	Lower Forest, EOR 33	1976	3	Sandstone	[25]
4	Field	USA	Lick Creek	Ozan	1976	2.375	Sandstone	[54,55]
5	Field	Hungary	Nagylengyel		1980	5	Limestone /dolomite	[30,31]
6	Pilot	USA	Wilmington	Fault Block III	1981		Unconsolidated Sandstone	[56]
7	Field	USA	Huntington Beach	Fault Block F	1982		Sandstone	[57,58]
8	Pilot	Canada	Retlaw Upper Mannville 'V' Pool		1983		Sandstone	[21,34,35]
9	Field	Turkey	Camurlu	Alt Sinan	1984		Limestone	[21]
10	Pilot	Turkey	Camurlu	Beloka	1984		Limestone	[21]
11	Pilot	Turkey	Camurlu	Mus	1984		Limestone	[21]
12	Field	Turkey	Bati Raman		1986	3.58	Limestone	[23,24]
13	Field	Trinidad	Forest Reserve	Upper Cruse, EOR 4	1986	2	Sandstone	[25]
14	Pilot	USA	Paradis		1987		Sandstone	[59,60]
15	Field	Trinidad	Oropouche	AO-8, EOR 44	1990	1	Sandstone	[25]
16	Field	Brazil	Buracica	Sergi	1991	6	Sandstone	[36,37]
17	Field	USA	Halfmoon	Phosphoria	1992[a]		Limestone /dolomite	[61]
18	Field	USA	Halfmoon	Tensleep	1992[a]		Sandstone	[61]
19	Field	Hungary	Szank	SE	1992		Sandstone	[22]
20	Pilot	Turkey	Ikiztepe	Sinan	1997[a]	4	Limestone	[62]
21	Field	USA	Sho-vel-tum	Aldridge	1998	6	Sandstone	[63–66]
22	Pilot	Malaysia	Dulang	E12/13	2002	1	Sandstone	[26–29]
23	Pilot	Malaysia	Dulang	E14	2002	1	Sandstone	[26–29]
24	Pilot	China	Changqing	Chang 6	2003	5	Sandstone	[67]
25	Field	USA	Yates	San Andres	2004	4.9	Dolomite	[68]
26	Field	USA	Salt Creek	Wall Creek 2	2005	4	Sandstone	[69]
27	Pilot	Argentina	Chihuido de la Sierra Negra		2005		Sandstone	[32,33]
28	Field	USA	Eucutta	Eutaw	2006	1.1	Sandstone	[64–66]
29	Field	USA	Martinville	Wash-Fred 8500	2006		Sandstone	[64–66]
30	Field	USA	Tinsley	Woodruff	2007		Sandstone	[65,66]
31	Field	USA	Heidelberg, West	Eutaw	2008		Sandstone	[65,66]
32	Field	USA	West Hastings	Frio	2010		Sandstone	[65,66]
33	Field	USA	Heidelberg, East	Eutaw	2011		Sandstone	[65,66]
34	Pilot	China	Yaoyingtai		2011	4.3	Sandstone	[18–20]
35	Field	USA	Heidelberg, East	Christmas	2012		Sandstone	[65,66]
36	Pilot	China	Tuha		2013[a]	3.7		[17]

Note: a. Publication year.

Like any other EOR, the successful implementation of CO_2 immiscible flooding requires extensive knowledge and experience from previous successful field applications [40]. CO_2 immiscible screening guidelines are useful for this purpose, and it is considered as a first step in selecting the potential of EOR techniques for given reservoirs, which is crucial at the start of an EOR project [41]. During the past 30 years, many research studies have focused on establishing and updating the screening criteria for different EOR techniques. Table 1 summarizes the screening criteria for CO_2 immiscible flooding that was published by different investigators. Taber et al. proposed one of the earliest technical screening criteria for seven main EOR methods based on oil recovery mechanisms [42]. The researchers updated their work in 1997 since more EOR projects had been conducted in fields [43,44]. Taber et al. developed the screening criteria for all immiscible gas injections, but no specific investigation has been found for CO_2 immiscible flooding, and reservoir porosity was not considered for all EOR screenings. In addition, formation type, permeability, and temperature are not critical for conducting CO_2 immiscible flooding in their results. Bourdarot and Ghedan presented the EOR screening criteria for offshore carbonate reservoirs [45]. They conclude that application of CO_2 immiscible flooding is suitable for reservoirs with depths greater than 1800 ft and with oil viscosity less than 10 cp because the oil in offshore reservoirs has a low viscosity. Adasani and Bai established EOR screening criteria based on 652 EOR projects gathered from the *Oil and Gas Journal* Biannual EOR Survey [46], but only 16 of them, including duplicate projects were related to CO_2 immiscible flooding. In fact,