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Review article

A comprehensive review on Enhanced Oil Recovery by Water Alternating Gas (WAG) injection

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ABSTRACT

Water-Alternating-Gas (WAG) injection is a relatively mature oil recovery technique in hydrocarbon reservoirs that has long attracted the interest of the oil and gas industry due to its successful performance. The main goal of the WAG projects is to control the mobility and to decrease the problem of viscous fingering, leading to improved oil recovery by combining the benefits of Gas Injection (GI) and Waterflooding (WF). Implementation of a new EOR/IOR project requires a comprehensive knowledge of previous successful and failed experiences, and adequate understanding of the technical and non-technical aspects of the recovery process. This knowledge may be attained from reviewing similar projects that were reported in the literature. Despite great applications of the WAG injection in hydrocarbon reservoirs and extensive studies, the last comprehensive review goes back to 1998, focusing on the field applications only. There are a few review papers that are more updated; however, they are either dedicated to a particular aspect of the WAG (such as CO_2 abnormalities), or applications in a specific geographical region (such as North Sea). An updated comprehensive study, covering recent experiences and lessons that are learnt from previous studies, seems to be imperative. This paper reviews the WAG theory, applications, governing mechanisms of fluid displacement and oil production from pore to field scale. It also addresses the most common challenges and operational problems along with the remedies during WAG projects. The effects of important variables such as reservoir properties, fluid properties, and operating conditions on the performance of WAG are studied from experimental, simulation and modeling, and pore-scale investigations.

1. Introduction

For a typical oilfield, the average recovery factor is approximately 40%. Thus, a significant quantity of oil is still left behind after primary oil recovery despite the extensive production infrastructures. Improving the recovery factor and accelerating the oil production rate are among the main goals of EOR applications in petroleum reserves [1]. Due to the low gas viscosity, and considerable density difference between the gas and reservoir crude oil, gas injection processes exhibit a poor microscopic sweep efficiency which results in bypassing a part of the oil, fluids front instability (e.g., viscous fingering), and early breakthrough in the swept area of a reservoir [2–4]. Initially, Water-Alternating-Gas (WAG) injection as an EOR technique was introduced to enhance the macroscopic sweep efficiency in gas injection processes [3]. This technique was first implemented in 1957 in Alberta, Canada in a sandstone reservoir by Mobil as a combination of two conventional approaches; namely, gas injection and WF [5,6]. Currently, WAG injection is recognized as a common technology to enhance the total oil recovery through re-injection of produced gas in water injection wells in mature petroleum fields [2]. However, WAG is a difficult process which may not be practical in reducing the fluids front instabilities due to high completion costs, operational conditions complexities, and gravity segregation problems [7]. Generally, a WAG process combines the advantages of two conventional methods including WF and Gas Injection (GI). Hence, enhancement of macroscopic sweep efficiency in WF operation and high displacement efficiency in gas injection process are involved in WAG to improve the incremental oil production [8]. In the case of alternating injection of water after gas, water (because of its higher density) will sweep the bottom part of the reservoir and will stabilize the displacing front through creating a more favorable mobility ratio [9]. This technique is profitable in terms of economic prospective by lowering the gas volume required to be injected into the reservoir [10]. It was reported that 80% of the USA WAG field projects are fruitful [11]. Skauge et al. reviewed 59 WAG fields. Their study revealed that the average oil recovery increases up to 10% Originally Oil In Place (OOIP) for all WAG cases [12]. WAG processes have been successfully applied (mostly by down dip injection) in the North Sea fields such as Gullfaks, Statfjord, South Brae, Snorre, and Oseberg Ost

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Nomenclature

Acronyms

AOIR	Allocation Of Injection Rate
CGI	Continuous Gas Injection
CWAG	Chemically Enhanced Water Alternating Gas
EOR	Enhanced Oil Recovery
EWAG	Emulsion WAG
FAWAG	Foam Assistant Water Alternating Gas
GI	Gas Injection
GOR	Gas Oil Ratio
GWR	Gas Water Ratio
HCPV	Hydrocarbon Pore Volume
HSWAG	High Salinity WAG
HWAG	Hybrid WAG
IFT	Interfacial Tension
IOR	Improved Oil Recovery
IWAG	Immiscible WAG
LSWAG	Low Salinity WAG
LSWF	Low Salinity Water Flooding
MMP	Minimum Miscible Pressure
MRF	Mobility Reduction Factor
mw	Mixed-Wet
MWAG	Miscible WAG
NPV	Net Present Value
nMWAG	Near Miscible WAG
OOIP	Original Oil In Place
ow	Oil-Wet
PAG	Polymer Alternating Gas injection
PWAG	Polymer WAG Injection
RF	Recovery Factor
RRF	Residual Resistant Factor
S	Fluid Saturation
SAG	Surfactant Alternating Gas Injection
SWAG	Simultaneous Water And Gas
SW	Sea Water
TWAG	Tapered WAG
VDP	Dykstra-Parson Permeability Variation Coefficient
VRI	Viscosity Reduction Injectant
VRR	Voidage Replacement Ratio
WAG	Water Alternating Gas
WAHPAI	Water Alternating High Pressure Air Injection
WASP	Water Alternating Steam Process
WF	Water Flooding
WOR	Water Oil Ratio
ww	Water-Wet

Subscript

ca	capillary
ed	displaced
g	gas
gr	gravity
gt	trapped gas
h	horizontal
i	initial
ing	displacing phase
n	non-miscible
nm	near-miscible
o	oil
or	residual oil
r	relative
Tot	total
v	vertical
w	water

English letters

E	Total recovery efficiency
g	Gravity force
K	Permeability
L	Wells' distance
M	Mobility ratio
N_{ca}	Capillary number
$R_{v/g}$	Ratio of viscous force to gravity force
v	Darcy velocity

Greek letters

λ	Mobility
μ	Viscosity
ϕ	Porosity
ρ	Density
σ	Interfacial tension

[13]. Because of the gravity segregation problem, a majority of the attic oil is displaced by the gas phase and that of the bottom oil by the water. The down dip injection scheme results in dispersed flow zones as the attic oil is being produced [13]. In 1991, the technical potentials of surfactant flooding and WAG injection were evaluated by the Norwegian Petroleum Directorate (NPD) and three Norwegian oil companies [14]. Since then, WAG injection was extensively applied in the Norwegian Shelf; chemical EOR techniques were also used in a few pilot studies [14]. The WAG performance is highly affected by the injection strategies (e.g., injection well pattern, WAG ratio, number of WAG cycles, volume of each cycle, and injection rate and pressure). Different optimal strategies in terms of recovery factor and economic aspects were found in the literature. Simulation results reported in the literature show that multiple WAG cycles with high Voidage Replacement Ratio (VRR) in the gas cycles at a WAG ratio of 1:1 result in the optimum oil recovery [15]. Different WAG scenarios have been studied. For instance, Kulkarni and Rao performed a set of tertiary immiscible and miscible core flood experiments to compare WAG and Gas Injection (GI) processes [16] in which WAG injection was found to be superior to GI [16]. WAG is also found effective in heterogeneous reservoirs. In low permeability heterogeneous reservoirs, WF features poor injectability, low production rate, high Water Oil Ratio (WOR), and low oil recovery factor [17]. Through numerical simulations, Liao et al. investigated three different technologies to implement WAG injection: 1) Allocation Of Injection Rates (AOIR), 2) Tapered Water Alternate Gas (TWAG), and 3) AOIR-TWAG. All of these methods provided a higher recovery factor, compared to the conventional WAG injection [17].

Experimental and modeling studies have demonstrated that a high recovery of up to 90% is achievable in simultaneous water and gas injection using the five-spot pattern, while gas injection alone usually results in a residual oil saturation of 20–50% [18]. One of the best WAG strategies was applied in the Brent reservoir of the Stafjord field [19] in which WAG injection horizontal wells were practiced; the injection well was deeply perforated, while the production well was sidetracked [19]. Panda et al. proposed an optimal design strategy through applying WAG injection in Eileen West End (EWE) reservoir, Prudhoe Bay field [15].

The WAG injection process combines the imbibition and drainage mechanisms during successive injections of gas and water cycles in a three-phase regime in the reservoir [5,20]. Designing an optimal WAG