WAG Injection Compared to Waterflooding and Gas Injection

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Abstract

Two commonly-used EOR methods in the Iranian reservoirs are waterflooding and gas injection. Early breakthrough of the injected fluid in the production wells is the major problem associated with these processes. A solution to this problem is an alternative process called water-alternating-gas (WAG). In recent years there has been an increasing interest in WAG processes, both miscible and immiscible. Many of the Iranian fractured reservoirs are located in the inclined reservoirs. So, WAG injection could increase the recovery by contacting the upswept zones, especially recovery of attic or cellar oil by exploiting the segregation of gas to the top or accumulating of water towards the bottom. The WAG process has been proved beneficial in re-pressurizing the reservoir when compared to a waterflood only process. This higher pressure is caused by the gas slug being injected at an extremely high voidage replacement rate because of its high mobility. WAG injection increases the efficiency of the plain gas injection, too. By alternating the gas injection with water injection, the gas relative mobility in the reservoir is reduced over gas injection only. Therefore, less gas breaks through to producing wells, reducing gas handling requirements. Furthermore, the lower producing GOR associated with WAG injection over straight gas injection results in less erosion of the production equipment.

Keywords: Displacement, Sweep Efficiency, Gravity Segregation, Mobility

1-Introduction

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A substantial amount of oil is left in the reservoir after primary recovery (70 to 80% of OOIP), so there should be some alternatives to produce this oil. Fluid injection into one or more wells has been accepted as a method for increasing oil recovery and productivity above primary production levels. Water and/or natural gas, at pressures where the gas is immiscible with oil have been the injection fluids used almost exclusively for this purpose in the past. Injecting gas into the gas cap, water into the aquifer near the water-oil contact, or either fluid into the oil column are common fluid injection techniques. The improved recovery results from two processes of pressure maintenance and oil displacement to producing wells.

There is about half of the initial oil in place left non-produced in the reservoir after secondary recovery. This oil can be a great source of energy and should be recovered by enhanced oil recovery (EOR) methods, although complete recovery of all the trapped oil is difficult, the target resource base is very large. [1]

The main goals of any EOR method are increasing the capillary number and providing favorable mobility ratios (less than one). The capillary number is defined as the ratio of viscous to capillary forces and the mobility ratio is defined as the mobility of the displacing phase to the mobility of the displaced phase.

The overall efficiency of the EOR process depends on both, the microscopic and the macroscopic sweep efficiencies. While the fluids density difference and rock heterogeneity affect the macroscopic efficiency, the microscopic displacement efficiency is influenced by the interfacial interactions involving interfacial tension and dynamic contact angles. Of the major contending processes for the trapped oil, gas injection appears to be an ideal choice [1].

Gas injection is the second largest process in enhanced oil recovery processes today [2]. The efficiency of the gas injection is controlled by three factors [1]:

- Volume of oil that is displaced by the gas (Displacement efficiency)
- Volume of reservoir that gas enters (Sweep efficiency)
- Volume of the displaced oil that is produced (Capture efficiency)

In most projects waterflooding will do these things better than gas flooding, but in high permeability reservoirs with high vertical span and some fractured reservoirs gas injection results in higher recovery because of gravity segregation process. Also, gas may offer economic advantages because of availability and ease of use. Generally, gas flooding is more effective than waterflooding especially in the carbonate reservoirs because of lower permeability and porosity of the reservoir rock and the heterogeneous nature of the formation [3]. In certain instances, the use of gas instead of water is necessary because of water injectivity problems associated with a tight rock matrix or the presence of swelling clays, or because of the presence of extensive fracturing in the reservoir.

In cases where there are substantial amounts of attic oil (oil trapped in the upstructure) gas injection with segregation is more effective than waterflooding because gravity segregation between oil and water in waterflooding keeps the attic oil out of reach of water, while in gas injection it can be recovered easily [4].

The residual oil saturation in the gas swept zones have been found to be quite low. However, the volumetric sweep of the flood has always been a cause of concern. The mobility ratio, which controls the volumetric sweep, between the injected gas and displaced oil bank in gas processes, is typically highly unfavorable due to the relatively low viscosity of the injected phase. This difference makes the mobility and consequently flood profile control the biggest concerns for the successful application of this process [5].

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These concerns led to the development of the Water-Alternating-Gas (WAG) process for flood profile control. The higher microscopic displacement efficiency of gas combined with the better macroscopic sweep efficiency of water significantly increases the incremental oil production over the plain waterflood. The WAG process, first proposed by Claudle and Dyes in 1958, has remained the industry default mobility control method for gas injection, mainly due to the lack of proven flood profile control alternatives. Reservoir specific parameters such as wettability, interfacial tension, connate water saturation and gravity segregation add complexity to the design of a successful WAG flood [6].

2- WAG Process History and Application

A process where one gas slug is followed by a water slug is by the definition considered as a water-alternating-gas (WAG) process. In the literature WAG injection processes is also named combined water gas injection (CWG). A process where water and gas are injected simultaneous is called SWAG. However the reviews of the fields show that water and gas normally are injected separately because the injectivity for most fields is better when only one phase is injected at the time.

Important technical factors affecting WAG injection are heterogeneity (stratification and anisotropy), wettability of the rock, fluid properties, miscibility conditions, injection technique, WAG parameters, and flow geometry [7].

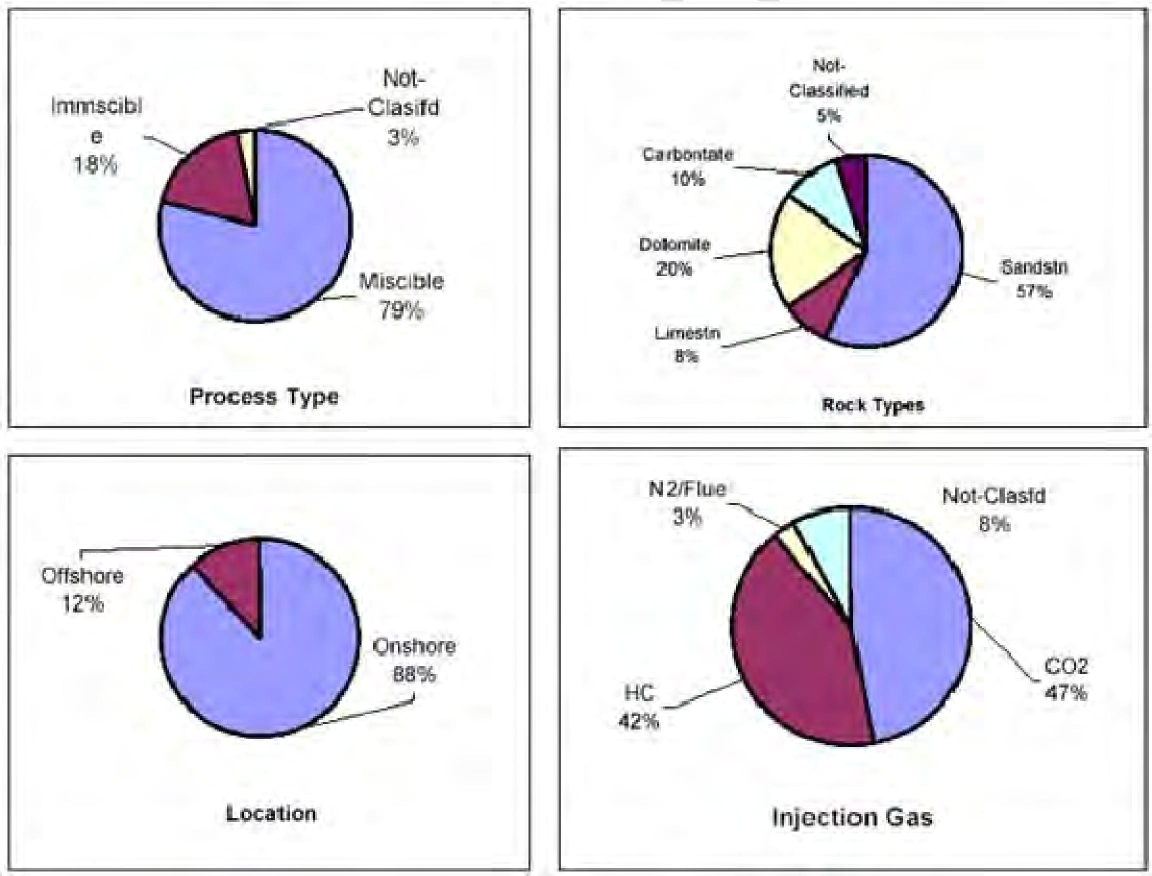

Figure 1: WAG survey – Distribution / Application of WAG

The first field application of the WAG was a pilot in the North Pembina field in Alberta, Canada in 1957 [7]. Almost all the commercial miscible gas floods today employ the WAG

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method [2]. Almost 80% of the WAG flood projects in the USA are reported an economic success [8]. The popularity of the WAG process is evident from the increasing number of projects and many successful field wide applications.

A survey conducted by Christensen et al. showed that the average incremental oil recovery due to WAG is about 5 to 10%, this survey encompassed 59 projects [5]. Expected incremental oil recoveries due to WAG flooding, over waterflooding, in some of the projects presented in the literature are: 10-15% in the Permian Basin miscible CO2 injection projects, about 7% at Rangely miscible CO2 injection project, and about 7% at lower Statfjord field by down-dip miscible hydrocarbon gas injection [9]. Immiscible WAG-injection in some of the North Sea reservoirs is expected to yield 6-12% incremental oil recovery, over waterflood or gas injection.

This survey also has indicated the application scenario and distribution of the WAG process in the figure 1. USA had the largest share of WAG applications of 62.7%, followed by Canada at 15.3 %. The popularity of the miscible flood was evident from the fact that 79% of the WAG projects employed are miscible.

3- WAG Process Classification

The large-scale reservoir applications need a good classification system for better understanding and design of WAG process. Although Caudle and Dyes suggested simultaneous injection of oil and gas to improve mobility control, the field reviews show that they are injected separately [5]. In the field, water and gas are injected in alternate slugs rather than simultaneously because:

- Gas and water segregate in the wellbore when injected simultaneously.
- Alternate injection is more convenient operationally than simultaneous injection.
- Injectivity of either fluid remains higher than would be the case with simultaneous injection. Injectivity remains higher for alternate injection because the saturation and relative permeability of the fluid being injected are higher in the near wellbore region [1].

Christensen *et al*. attempted to systematically classify the WAG process. They grouped the process into four types: miscible, immiscible, hybrid and others based on injection pressures and method of injection. These processes are discussed as follows [5]:

3-1- Miscible WAG (MWAG)

Miscible projects are mostly found onshore and the early cases used expensive solvents like propane and NGL, which seem to be a less economic favorable process at current time. Most of the miscible projects usually are re-pressurized in order to bring the reservoir pressure above the minimum miscibility pressure (MMP) of the fluids. Since failure to maintain sufficient pressure, meaning loss of miscibility, real field cases may oscillate between miscible and immiscible gas during the life of the oil production.

3-2- Immiscible WAG (IWAG)

A successful IWAG can potentially show a faster response than a miscible flood with less cost because it operates at current reservoir pressure [10]. This type of WAG process has been applied with the aim of improved frontal stability or contacting unswept zones. Applications have been in reservoirs where gravity stable gas injection can not be applied, because of limited gas resources or the reservoir properties like: low dip of strong heterogeneities.

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Sometimes the first gas slug dissolves to some degree into the oil. This can cause mass exchange (swelling and stripping) and a favorable change in the fluid viscosity-density relations at the displacement front. The displacement can then become near miscible.

3-3- Hybrid WAG (HWAG)

When a large slug of gas is injected followed by a number of small slugs of water and gas the process is referred to as hybrid WAG injection. When hybrid WAG is used the initial slug can be up to *40%* of hydrocarbon pore volume.

3-4- Other Classifications

Based on the injection pressure and injection rate Surguchev *et al*. classified the WAG process into two types of stationary and non-stationary [11]. In the stationary WAG injection the injection pressure and injection rate are constant during each cycle. The non-stationery or hydrodynamic injection process is performed by combining cyclic injection with variation of flow directions. The cyclic injection is implemented by cycling either the injection pressure, or the injection and production rates. For example, a value of the pressure increase during the first half of a cycle is equal to a consecutive pressure decrease in a second half of it. This means that an average value of cyclic injection pressure is kept equal to its value in the case of stationary injection. The same rule is used in cycling the injection or production rates in order to maintain the average rate in a whole cycle similar to that of stationary injection. The main purpose of the process is to exert a non-stationary influence on a reservoir with micro- and macro-heterogeneity. Stratified reservoirs with communicating layers of different reservoir properties (permeability, porosity, fractures, shale content etc.) are good candidates for its application.

4- WAG Advantages Over Waterflooding and Gas Injection

Micromodel experiments by Sohrabi *et al*. indicated that in the water-wet systems by injecting gas and water alternately more oil can be produced than would otherwise be produced by water or gas injection alone [12].

Reservoir simulation has indicated that an additional *5* to *10* percent of the *OOIP* can be recovered as a result of the WAG process [13]. Conventional gas or waterfloods usually leave at least *50%* of the oil and the WAG displacement leaves in average less than *20% OOIP* as the residual oil [14]. Experimental study by Dyer *et al*. indicated that using the WAG process as the secondary recovery mode, incremental oil recovery over that from a waterflood was more significant for the heavy oil than the light oil (*8%* vs. *4%*) [15].

For a given oil saturation, because of the reservoir volume occupied by the trapped gas, the water saturation must be less in the WAG case than in the waterflood only case. As a result, the water relative mobility, and therefore the water-oil ratio (WOR) must be less for a given oil saturation. In the fields where WOR is the economic limit criterion, WAG injection reduces the WOR as a function of recovery. Therefore; the economic life of the pattern is extended and incremental oil reserves are recovered.

WAG injection increases the sweep efficiency of the waterflooded thick reservoirs. Specially, when it is a heterogeneous reservoir and the permeable layer is at the bottom. Gravity segregation of the injected gas makes it move and accumulate at the top of the reservoir and sweep the non-producing oil zone at the top of this kind of reservoir. WAG injection can decrease the water permeability of areas with relatively high water saturation and relatively good water entry, thereby adjusting the vertical permeability contrast in the oil reservoir, and forcing injected gas to enter the non-producing thickness with relatively high

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oil saturation. Meanwhile the area that formerly absorbed a lot of water stops absorbing gas because differential pressure of gas injection is generally smaller than that of water injection. During water injection, former water entry layer and newly added gas entry layers are working together because of the increased wellhead injection pressure. Thus the water entry thickness increases [16].

The WAG process has been proved beneficial in re-pressurizing the reservoir when compared to a waterflood only process. This higher pressure is caused by the gas slug being injected at an extremely high voidage replacement rate because of its high mobility. The increased water bank pressure could also be a sign that trapped gas is slowing the movement of the injected water.

WAG injection increases the efficiency of the plain gas injection, too. By alternating the gas injection with water injection, the gas relative mobility in the reservoir is reduced over gas injection only. Therefore, less gas breaks through to producing wells, reducing gas handling requirements. Furthermore, the lower producing GOR associated with WAG injection over straight gas injection results in less erosion of the production equipment [13].

During a WAG injection, saturation changes are cycling. The non-wetting phase, which is bypassed by the wetting phase due to capillary forces, becomes entrapped in a discontinuous and immobile state. The increasing volume of trapped phase reduces the relative permeability of injected fluids. The degree of oil saturation reduction and the corresponding trapped gas saturation depend on the initial gas saturation to waterflooding. The higher the gas saturation prior to waterflooding, the larger the amount of gas can be trapped up to a certain limit, which is characteristic for the particular properties of each given reservoir (typically *20-30%*). So, the volume of injected gas bank in each cycle should be large enough to create sufficiently high gas saturation prior to the next water injection cycle. After waterflood, the large pores in water-wet reservoirs or water-wet parts of the reservoir contain residual oil which can be displaced by non-wetting free gas into mobile water saturated channels [3].

In a water-wet system, oil tends to occupy the larger pore spaces. Gas is non-wetting with respect to oil and water. Therefore free gas tends to displace oil from the larger pores into the more mobile channels occupied by water. The pore space initially occupied by residual oil is occupied by both residual oil and gas, and previously immobile oil is mobilized [13].

In a reservoir with mixed wettability, the larger pores tend to be oil-wet with residing oil compounds and small pores tend to be water-wet. This is a result of altered wettability which occurs in the initially water-wet reservoir. From the fluid distribution point of view these changes which take place in mixed-wet reservoir are not significant in comparison with the water-wet rock. Therefore, the mixed-wet system may be most closely represented by a water-wet model [6].

In the oil-wet reservoirs, because of the water being a non-wetting phase it had to be driven into, against the capillary forces and by-passes the oil. Surface forces between the fluids and the rock; locate the water (non-wet) in the middle of the pores. Also interfacial tension (IFT) of gas-water is higher than IFT of gas-oil, consequently the gas which follows an initial water flood finds it difficult to displace water. When faced with water and oil, the injected gas selects the oil-filled pores, and bypasses water-filled ones. As a result of this gas tendency to displace oil rather than water, some more oil, in addition to what has been produced during an initial (conventional) waterflood, would be recovered during the gas injection [17].

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5- Conclusion

WAG process could, in some cases, modify demerits of gas injection and waterflooding and increases the sweep efficiency. This modification results from:

- Decrease in produced water-oil ratio and GOR due to reduction of injected fluids relative permeabilities.
- Displacement of the cellar and attic oil by water and gas, respectively.
- Lowers the effective mobility of the fluids in the high permeability layers, thus diverting fluid into other layers.
- In oil-wet reservoirs water displaces the oil in large pores and gas displaces the oil in smaller pores.
- In water-wet reservoirs gas displaces the oil in larger pores into the more mobile channels occupied by water.
- Interfacial tension reduction allows gas to displace oil through small pore throats not accessible by water alone.

Abbreviations

OOIP: Original Oil In Place
GOR: Gas-Oil Ratio
WOR: Water-Oil Ratio
IFT: Interfacial Tension

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