Design Parameters For the WAG Process

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Abstract

In recent years there has been an increasing interest in WAG processes, both miscible and immiscible. Design of WAG process is more complicated than waterflood and gas injection processes, due to existence of three mobile phases simulataneously. Parameters that should be considered for the WAG process include reservoir heterogeneity and stratification, rock and fluid characteristics, injection gas characteristics, injection pattern, tapering (change in water to gas ratio throughout the flood), WAG injection parameters (water to gas ratio, number of cycles, injection rates), flow dispersion effects (relative permeability description for three phases), gravity considerations in WAG and laboratory studies and simulation. Plain gas injection is a WAG process with water to gas ratio of 0:1, hence these these design issues are applicable to gas injection design. The popularity of the WAG process is evident from the increasing number of projects and many successful field wide applications. Waterflooding and plain gas injection are two commonly-used EOR methods in Iranian reservoirs, but their assocciated problems lead to lower production life of the wells. It's been approved that WAG process, in some cases, modifies the demerits of these processes, hence more residual oil is produced. After design of the WAG process pilot tests are required to monitor its performance in the field.

Keywords: WAG Parameters, Heterogeneity, Sweep Efficiency, Gravity Segregation

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1- Introduction

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.

WAG injection is an oil recovery method initially aimed to improve sweep efficiency during gas injection. In some recent applications produced hydrocarbon gas has been re-injected in water injection wells with the aim of improving oil recovery and pressure maintenance. Oil recovery by WAG injection has been attributed to contact of unswept zones, especially recovery of attic or cellar oil by exploiting the segregation of gas to the top or the accumulating of water toward the bottom. Because the residual oil after gasflooding is normally lower than the residual oil after waterflooding, and three-phase zones may obtain lower remaining oil saturation, WAG injection has the potential for increased microscopic displacement efficiency. Thus, WAG injection can lead to improved oil recovery by combining better mobility control and contacting unswept zones, and by leading to improved microscopic displacement [1].

Although mobility control is an important issue; other advantages of the WAG injection should be noticed as well. Compositional exchanges may give some additional recovery and may influence the fluid densities and viscosities. Re-injection of gas is favorable due to environmental concerns, and enforced restrictions on flaring.

Nearly all the commercial miscible gas injection projects today employ the WAG method. The WAG process has long been considered as a tertiary gas injection mobility control process after a secondary waterflood. The low recoveries from the WAG process lead to substantial research of the process and consequently some of its limitations are eliminated [2].

2- Design Parameters for the WAG Process

The WAG review shows that this process has been applied to rocks from very low permeability chalk up to high permeability sandstone [1]. The major design issues for WAG are reservoir characteristics and heterogeneity, rock and fluid characteristics, composition of injection gas, injection pattern, WAG ratio, three-phase relative permeability effects and flow dispersion. It is important to note that plain gas injection is considered as a part of WAG process with a WAG ratio of *0:1*, hence the design issues pertinent to WAG are applicable to plain gas injection as well [2].

2-1- Reservoir Heterogeneity and Stratification

WAG recovery is more sensitive to reservoir heterogeneity than is waterflooding [3]. Reservoir heterogeneities such as permeability variations in the reservoir strata can cause poor vertical sweep of the reservoir pore space by WAG. The injected gas tends to flow in the more permeable zones of the reservoir, which are usually the same zones previously swept by water or gas during a preceding displacement process. This tendency for the gas to channel through the most permeable zones is a serious detriment to oil recovery since the oil in the less permeable zones is not adequately swept by gas. WAG injection is supposed to lower the effective mobility of the fluids in the high permeability layers, thus diverting fluid into other layers [4].

Reservoir heterogeneities also tend to aggravate the effects of viscous fingering and gravity segregation. For stratified reservoirs with layers of varying permeability and thickness,

ISBN ۹۷۸-۶۰۰-۶۷۲۰-۰۰-۵

the effect of these heterogeneities has been shown to depend on the position of these high permeability zones [5]. If the high permeability zones are located near the top of the reservoir formation then gravity override occurs through these zones, bypassing the oil in the lower zones. If the high permeability layers are located near the bottom of the formation then oil recovery is increased because the permeability alignment tends to suppress gravity segregation. The presence of the more permeable layers near the middle causes only a slight reduction in oil recovery.

Reservoirs with higher vertical permeability are influenced by cross flow perpendicular to the bulk flow direction. Viscous, capillary, gravity forces and dispersion generally influence this phenomenon [6,7]. Crossflow due to viscous forces is generally not very significant. Gravity contribution to crossflow, on the other hand may be pronounced for fractured reservoirs, and for layered reservoirs with tilt angles in the range of $5\text{-}15^0$ [8]. Phase behavior effects which include component transfer and volume change due to mixing and incorporation of these effects on the crossflow term may be important. Firoozabadi *et al*. using an analytical one-dimensional model showed that with crossflow, bulk of the oil is transferred from the less permeable layer to the more permeable layer and then produced from the more permeable layer [8]. In this respect, layered and fractured media behave the same.

Crossflow depends on gravity and the total flowrate of the medium. This may influence to increase the vertical sweep, but generally the effects are detrimental to oil recovery – mainly due to the gravity segregation and decreased flow velocity in the reservoir. This leads to reduced frontal advancement in lower permeability layer. WAG recoveries and continuous gas injections are more strongly affected by these phenomena.

The ratio of viscous to gravity forces is the prime variable for determining the efficiency of WAG injection process and controls vertical conformance of the flood. Cross-flow can substantially increase reservoir sweep even in the presence of low vertical to horizontal permeability ratios. The reservoir simulation studies for various k_v/k_h (vertical to horizontal permeability) ratios suggest that higher ratios adversely affect oil recovery in WAG process [1]. Therefore, reservoir heterogeneity controls the injection and sweep patterns in the flood.

2-2- Rock and Fluid Characteristics

Fluid characteristics are generally black-oil or compositional PVT properties obtained in the laboratory by standardized procedures. Very accurate determination of fluid properties can be obtained with current techniques. In some reservoirs cooling effect has been reported with water injection, especially those that had been undergoing waterflooding for many years [9]. If reservoir cooling has a significant impact on the fluid properties, several PVT experiments should be performed to provide temperature dependent PVT data for modeling the process.

Reservoir properties like wettability and trapping nature play an important role in a WAG displacement process. In reservoir simulators all these rock-fluid interactions are generally lumped into one parameter that is relative permeability.

Micromodel experiments by Sohrabi *et al*. indicated that WAG efficiency is higher for mixed-wet and oil-wet experiments as compared to water-wet experiments [10].

2- 3- Injection Gas Characteristics

The injection gases used in the WAG projects today can roughly be classified into three groups: CO_2, hydrocarbons and non-hydrocarbons (CO_2 excluded). CO_2 is an expensive gas and is generally used when miscible drive should be achieved, or if special options for deliverance exist. It is worth noticing that corrosion problems often is mentioned and seems

ISBN ۹۷۸-۶۰۰-۶۷۲۰-۰۰-۵

not to be totally avoided when using CO_2. Hydrocarbon gas is available directly from the production. For this reason all offshore WAG injection today utilizes hydrocarbon gases.

Gas requirement is a parameter used to assess the economics of any gas injection process, and is defined as the ratio of the total injected gas to the volume of oil produced at standard conditions [11]. Iran has the second largest gas reserves in the world and most of the production fields produce associated gas that is burnt in the flares, so there is enough gas available. Also many of Iran's naturally-fractured reservoirs are currently either undergoing gas injection operations, or are being considered for such operations. WAG process can be used to increase the ultimate recovery by gas injection.

2- 4- Injection Pattern

The WAG process review clearly shows the popularity of the 5-spot injection pattern with close well spacing on on-shore [1]. In spite of higher costs, the 5-spot injection pattern with closed well spacing is still popular since it gives better control over the process. In the case of miscible WAG operations, many wells will give a good control of the field pressure and thus of the performance of the WAG injection. Whereas a regular pattern is normally applied on-shore, they are seldom used offshore. This is due to the increased price of drilling and data collection.

2-5- Tapering

Tapering is when the water to gas ratio in the WAG process is increasing or decreasing throughout the flood. This is generally done to control the gas mobility and channeling as well as to prevent early breakthrough of the gas. This step is important especially when the injected gas is expensive and needs recycling. Tapering is generally done in most of the CO_2 and hydrocarbon floods and prevailed even in the earliest WAG flood trials [1,12].

2-6- WAG Injection Parameters

The WAG injection parameters (water to gas ratio, number of cycles, injection rates) influence the recovery efficiency from the high and low permeability layers. The optimum WAG ratio is influenced by the wetting state of the rock and often is determined by the reservoir simulation [13]. Laboratory [14] and simulation [15] studies indicated that if water to gas ratio can be maintained at *1:1*, better results can be obtained. Experimental study by Jackson *et al.* in a water-wet bead pack revealed an optimum WAG ratio of *0:1* (continuous gas injection) for tertiary miscible CO_2 floods, while the same floods in oil-wet packs showed the optimum recoveries at the WAG ratios of about *1:1* [16].

Injecting below the optimum WAG ratio produces a high concentration profile directly behind the oil bank and creates mobility or viscous instability and this increases the gas recycling [1,6]. Gas breakthrough occurs earlier at higher injection rates for all WAG ratios, creating flow channels between the injection wells and subsequent high gas production rates [11,13].

Laboratory results indicated that multiple alternating displacement is better than single alternating drive and the efficiency improves with more alternating times [14]. Optimum conditions of oil displacement by WAG would be achieved, if gas and water travel in the reservoir at equal speed. This effect may occur for a short time in the water-gas mixture zone, but has a limited extend in the reservoir because of difference in viscous and gravity forces. Therefore portioning of water-gas banks and cycling are required to tune the injection scheme for particular reservoir conditions [17].

ISBN ۹۷۸-۶۰۰-۶۷۲۰-۰۰-۵

2-7- Flow Dispersion Effects

WAG injection results in a complex saturation pattern as both gas and water saturations increase and decrease alternatively. This gives special demands for the relative permeability description for the three phases (oil, gas and water) [1]. Pore-scale physics, laboratory investigations, and field experience, dictate that three-phase relative permeabilities exhibit strong dependence on the saturation path and the saturation history. Also a realistic prediction of reservoir behavior demands a correct treatment of history dependent saturation functions for drainage and imbibition processes. Such dependency is especially relevant in the WAG processes, which are characterized by a sequence of three-phase drainage and imbibition cycles [18].

Relative permeability is a lumping parameter and includes the effects of wetting characteristics, heterogeneity of reservoir fluids and rock (Interfacial tensions), and fluid saturations, as well as other micro- and macro-influences [6]. The relative permeability is the connecting link between the phase behavioral and transport properties of the system. It is an important petrophysical parameter, as well as a critical input parameter in predictive simulation of WAG floods. Relative permeability data are generally measured in the laboratory by standardized procedures with actual reservoir fluids and cores and at reservoir conditions.

2-8- Gravity Considerations in WAG

Gravity determines the gravity segregation of the reservoir fluids and hence controls the vertical sweep efficiency of the displacement process. Segregated fluid flow in the fractures leads to smaller matrix-fracture fluid transfer rate and hence lower oil recovery [19].

Green and Willhite [20] suggested that the density difference, between injected gas and displaced oil that causes problems of poor sweep efficiencies and gravity override in these types of processes can be used as an advantage in dipping reservoirs. Gravity-stable displacements of oil by plain gas injection or WAG in dipping reservoirs as secondary or tertiary process results in very high oil recovery. This has been confirmed by laboratory tests, pilot tests as well as field applications [1].

Although the purpose of WAG injection is to mitigate the gravity segregation effects, especially in miscible displacements, and provide a stable injection profile, WAG in down dip reservoirs have shown better profile control and higher recoveries. This is achieved by injecting the gas updip and producing the reservoir at a rate low enough for gravity to keep the less dense gas segregated from the oil, suppressing fingers of gas as they try to form. The effectiveness of gravity segregation in improving displacement efficiency decreases rapidly after the displacement rate exceeds the critical rate. In reservoirs with low permeability and dip, the critical rate often is too low to be practical [5].

Some layered reservoirs may represent favorable geological conditions for WAG injection. For instance, if a high-permeability layer is situated below a low-permeability layer, it prevents quick gravity-segregated tonguing in the top zone towards the production intervals [17].

Spivak found that Gravity segregation in two-phase displacement processes increases with [13]:

- Increasing permeability
- Increasing density difference
- Increasing mobility ratio
- Decreasing production rates, and
- Decreasing level of viscosity for fixed viscosity ratio

ISBN ۹۷۸-۶۰۰-۶۷۲۰-۰۰-۵

2-9- Laboratory Studies and Simulation

Detailed laboratory studies coupled with reservoir simulation are of paramount importance for successful WAG design. The quality of data input to the simulator is the key to provide quality predictions. For compositional simulations phase behavior and slim-tube experiments should be performed and used to tune the EOS model. This tuned model helps in accurate characterization of reservoir fluid.

A very important issue that has to be determined in order to take adequate steps in the modeling and prediction of this process is to what extent compositional effects play a role in oil recovery. While some of them can be accounted for in a black-oil model (e.g. swelling and viscosity reduction), significant mass transfer between phases and its associated effects (such as significant IFT reduction) can not and, if present, can dictate the need for compositional simulation [22].

Reservoir simulation of WAG injection does not reflect the complexity of the process without accounting for three phase effects. Relative permeability and capillary pressure hysteresis modeling for three-phase flow is a requirement when simulating WAG floods [17].

Direct measurement of three-phase relative permeabilities is costly and very time consuming, it is a standard practice to rely on two-phase relative permeability experimental data, and use of interpolation model to evaluate the relative permeabilities under three-phase flow conditions. From the two-phase input data, relative permeabilities are commonly estimated assuming [18]:

- Water relative permeability is a function of water saturation only
- Gas relative permeability is also a function of gas saturation only
- Oil relative permeability is a function of all three saturations

In fact, third assumption is justified only if the rock is strongly water-wet, a condition that is rarely met in practice.

There are several correlations for calculating three-phase relative permeability in the literature. The most commonly-used interpolation models in the reservoir simulators are *Stone I*, *Stone II* [18]. Test simulations have shown that the incremental recovery due to immiscible WAG injection is minimal using Stone's second method because it tends to be inconsistence at higher water saturations [23].

The most severe limitation of simple interpolation models is their inability to re-produce hysteresis effects, that is, dependency on the saturation path and saturation history. Such dependencies are the result of process-dependence in the microscopic contact angle, and trapping of the non-wetting phase. Hysteresis effects are larger in processes with strong flow reversals [18]. This is the case of WAG injection, in which the gas phase is trapped during waterflooding after a gas flood. Experimental data strongly suggest that the non-wetting phase experiences much more pronounced hysteresis than the wetting phase. Therefore, in water-wet systems, the gas phase shows the largest hysteretic effects, and oil displays hysteresis in the water-oil systems, but much less in the oil-gas displacements at connate water. Empirical and theoretical models have been proposed in order to describe the hysteresis phenomenon including *Land*, *Killoug*h, and *Carlson* correlations [18,24].

Among the different models typically available in reservoir simulators, the largest improvements in recovery predictions are obtained with the three-phase WAG hysteresis model in combination with the *Stone I* interpolation method [18]. However, the limited ability of commonly used relative permeability models to reproduce water-alternating-gas three-phase scenarios translates into a source of uncertainty in the numerical simulations.

To acquire a history match, in most simulations the relative permeability information is altered significantly. These extreme adjustments are made to compensate for more

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heterogeneity and are a faster and more convenient way to match waterfloods than to change geological models. Altering the relative permeability data also allows one to account for poorer sweep efficiency. Because of this, an excellent waterflood history match obtained by altering the relative permeability does not guarantee a correct WAG forecast [6].

3. conclusion

Design parameters for the WAG process discussed breifly here. Two important parameters that influence the design process are determination of three phase relative permeability and compositional effects of the injected gas. Laboratory investigation and simulation should be carry out to consider these parameters. History matching of the results of pilot tests is of paramount importance for successful WAG design.

Nomenclature

k_h: Horizontal Permeability
k_v: Vertical Permeability

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