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# Simulation Studies on Determination of Displacement and Areal Sweep Efficiencies for Hot CO<sub>2</sub> Flooding in Niger Delta Heavy Oilfield

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**Abstract:** Recovery efficiency is very important in enhanced oil recovery (EOR) processes as it helps in the planning, design and selection of EOR methods that will be technically and economically feasible. In this study, Simulation on hot CO<sub>2</sub> flooding is conducted using data from Niger Delta heavy oil reservoir. The compositional simulation process was carried out in ECLIPSE 300 compositional oil simulator. The recovery efficiency and injection calculations were modeled and simulated in Matlab. Numerical equations enabled the determination of the residual oil saturation and the consequent calculation of the injection and recovery before and after solvent breakthroughs. CO<sub>2</sub> of 0.095cp viscosity was injected at pressure of 3500 psia and 200°F to heat up the reservoir at payzone and reduce the viscosity of the reservoir oil at in-situ reservoir condition. The reservoir oil initially at 14.23cp at initial reservoir temperature and pressure was heated and reduced to a viscosity of 2cP making the oil mobile and amenable to flow. Results show recovery of the process before and after breakthroughs. CO<sub>2</sub> breakthrough was realized after 221 days of the flooding process. Of the 2461.2 ft distance from the injection wells to the producer well, CO<sub>2</sub> reached only a distance of 100 ft at breakthrough. Out of the 2.77 PV total volume of CO<sub>2</sub> injected in the flooding process, 0.1222 PV of CO<sub>2</sub> was injected as at breakthrough. The recovery efficiency result show that the displacement efficiency at CO<sub>2</sub> breakthrough and at the end of the flooding process are 15.17% and 78.63% respectively while the areal sweep efficiency at CO<sub>2</sub> breakthrough and at the end of the flooding process are 44.02% and 93.32% respectively. The low displacement and areal sweep efficiency at breakthrough were due to early breakthrough of CO<sub>2</sub> which did not allow sufficient period of time for the CO<sub>2</sub> to contact considerable portions of the reservoir given its viscous nature. Furthermore, at CO<sub>2</sub> breakthrough time, the injected hot CO<sub>2</sub> had no sufficient time to soak the reservoir and reduce the viscosity of the oil; as such only a small fraction of the in-situ oil became mobile. An overall recovery efficiency of 73.33% realized in the flooding process signifies favourable flooding design hence is recommended for the development and recovery of Niger Delta heavy oilfield.

**Keywords:** Areal Sweep Efficiency, Breakthrough, CO<sub>2</sub> Injection, Displacement Efficiency, Pore Volume

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## 1. Introduction

Gas injection EOR processes have continuously attracted more concerns as an EOR method among others since its discovery. The reason is chiefly because of its remarkable performance in oil recovery and because of its added feature of storing greenhouse gases [1, 2]. Gas injection can be classified based on their miscibility status or based on the

nature of injection fluid. Based on miscibility status, gas injection is classified as miscible and immiscible injection processes while based on the nature of injection fluid, gas injection is classified as hydrocarbon (such as natural gas and produced gas methane, propane, enriched methane etc.), and non-hydrocarbon gas injection (such as CO<sub>2</sub>, N<sub>2</sub> and flue gas). For miscible gas injection, the injection gas or solvents not only dissolves in the reservoir oil causing reduction in

viscosity, volumetric expansion, and reduction of interfacial tension (IFT) but additionally helps in dissolved gas drive [3, 4]. Reservoir and fluid condition influence the contribution of these mechanisms which affects the oil recovery and performance of the process [5, 6].

The main factor to consider in the design of a gas injection process is whether the process will be miscible or immiscible with the reservoir oil at reservoir conditions. This can be influenced by the operating conditions [7]. An immiscible gas flood is basically a drive process; the gas injected effectively 'pushes' the oil towards the production interval without any form of mixing between the injected gas and the oil. The drive system is basically in the form of a piston-like displacement process. This process has its demerits; it suffers from viscous fingering and gravity override because of large viscosity contrast between the injected gas and the reservoir oil. Conversely, for miscible gas flood processes, the miscibility and dispersion of the injected solvent in the reservoir oil creates viscosity and density reduction of the oil, IFT decrease which leads to more efficient oil sweep out. In both process, because the injected gas is often more buoyant and less viscous than the reservoir oil, there is potential for the injected gas to channel or finger through the upper reservoir leading to oil bypass and causing the gas to breakthrough and be produced at the production well [8]. Operators curtail this problem by injecting slugs of water and gas in what is called water-alternating-gas (WAG) process.

Among all the solvents used in gas injection EOR processes, CO<sub>2</sub> has attracted the highest interest and applicability. The reason is because it dissolves more readily than other gases at lower reservoir pressures and because of its carbon emission concern as a greenhouse gas [9, 10].

Recovery efficiency of EOR processes is very important because they are useful in the evaluation of the economics and viability of the flooding process. This will influence investment decisions, planning and choice of EOR methods to be deployed to certain field and reservoir conditions [11]. The key aim of any EOR process is to economically increase the recovery efficiency thereby recovering more oil from the field or reservoir. Recovery efficiency can be classified as microscopic efficiency and macroscopic efficiency. While microscopic efficiency relates to the mobilization of the reservoir oil at the pore level, the macroscopic efficiency relates to the ability of the injected displacing fluid to contact the reservoir in a volumetric sense [3]. Microscopic efficiency is more conveniently called displacement efficiency while macroscopic efficiency is called volumetric or sweep efficiency. The product of the displacement and the volumetric sweep efficiency gives the overall oil recovery efficiency.

In this paper emphasis is given to the determination of areal and displacement efficiency for a hot CO<sub>2</sub> flooded reservoir in the Niger Delta heavy oilfield

### 1.1. Literature Review

In analyzing the recovery efficiency of EOR processes, many topical issues arises such as residual oil saturation

determination, the relative permeability of the fluid phases in the flooding process, the fractional flow determination etc. The residual oil saturation can be defined as the fraction of the reservoir oil which does not flow. In core floods experiment, the residual oil saturation can be determined by analyzing the volume of oil left behind in the cores after the flooding process [12-14]. This is expressed as percentage of the initial volume of brine injected into the cores in the first place for the core experiment. Experimentally, residual oil saturation has been determined through the following methods, the alpha factor approach, the double porosity modeling, characterizing the residual oil to be a solid phase, altering the PVT data, the SOR approach.

In commercial compositional simulators, it has been difficult to accurately determine the residual oil saturation and there is no facility for the user to define a realistic residual oil saturation which does not vaporize. The residual oil saturation affects the accuracy of the oil recovery efficiency and impacts on the statistics and information from the recovery process during design stage [13, 15].

Relative permeability is a basic reservoir petrophysical parameter that is utilized in the description of flows involving multi phases in porous media [16]. In many field application and geologic conditions, relative permeability data is scarce and is usually the source of uncertainty and error in reservoir performance calculations. Relative permeability is used to describe the co-existence of many phases in rock systems, such as in reservoir systems where oil, water and/or gas co-exist both in the pore and in the mobile flowing streams [17]. Owing to this, relative permeability is very vital in reservoir simulation studies. In most cases, relative permeability is determined by experiments and the experimental result that best models the actual displacement process in the reservoir is utilized [18].

Fractional flow is the ratio of the flow of one phase to the overall fluid flow. The theory of fractional flow has been used to enhance the understanding of water flooding [19], polymer flooding, carbonated waterflooding, alcohol flooding, solvent flooding, steam flooding and various types of surfactant flooding. Rossen *et al.* [20] utilized fractional flow method in the explanation of the non-Newtonian behavior of fluid in EOR processes. Moghanloo *et al.* [19] also applied fractional flow theory to evaluate CO<sub>2</sub> storage capacity in an aquifer.

Oil recovery during gas injection EOR processes have been studied by many authors using various methods and approaches. Kulkarni and Rao [21] used dimensionless parameters to study the recovery factor of miscible and immiscible CO<sub>2</sub> flooding in dipping reservoir that was initially waterflooded.

Trivedi and Babadagli [22] developed a new approach which they called the matrix-fracture diffusion transfer to determine the recovery and performance of miscible displacement in fractured porous media. Rostami *et al.* [23] conducted many experiments on forced gravity drainage using many petrophysical and operating conditions. In their results, they realized that adequate and accurate prediction of

oil recovery requires combination many factors.

Rostami et al. [24] performed many experiments on PVT, core-flooding etc. in sandstone formations. They aimed to study the type of injectant type, reservoir pressure and rate of injection. In their result, they discovered that viscosity reduction and oil swelling are the most crucial parameters affecting gas injection in high permeable porous media with viscous or semi-heavy crude.

### 1.2. Research Objectives

The objectives of this study are

1. To determine the displacement and areal sweep efficiency of hot CO<sub>2</sub> flooding in Niger Delta heavy oil field
2. To determine the residual oil saturation of hot CO<sub>2</sub> flooding in Niger Delta heavy oil field
3. To determine the pre-breakthrough and post-breakthrough performance of hot CO<sub>2</sub> flooding in Niger Delta heavy oil field
4. To determine the overall recovery efficiency of hot CO<sub>2</sub> flooding in Niger Delta heavy oil field

## 2. Parameter Governing Recovery Efficiency and Their Equations

In this section, the parameters that affect the determination of the recovery efficiency of miscible CO<sub>2</sub> EOR are given together with their appropriate equations

### 2.1. Mobility Ratio

This is the ratio of the effective permeability of a fluid to the viscosity of that fluid.

$$M_o = \frac{K_o}{\mu_o} \quad (1)$$

This can be written in terms of the relative permeability to oil as

$$M_o = \frac{Kk_{r_o}}{\mu_o} \quad (2)$$

Mobility ratio is the ratio of the displacing fluid to the displaced fluid

$$M = \frac{M_D}{M_d} \quad (3)$$

Mobility ratio can be defined in many ways depending on the flow condition of the process. If the fluids involves solvents such that the displacing and the displaced fluids achieves complete miscibility with each other such as in miscible solvent (CO<sub>2</sub>) flooding, the mobility ratio of the displacement process is given as

$$M = \frac{\mu_d}{\mu_D} \quad (4)$$

This is true because the permeability to each solvent is the absolute porous medium permeability.

For a piston-like displacement where there is no miscibility between the displacing and the displaced fluid such as in waterflood processes, the mobility ratio (M) is given as

$$M = \left( \frac{K_{r_w}}{\mu_w} \right)_{S_{or}} \left( \frac{\mu_o}{K_{r_o}} \right)_{S_{iw}} \quad (5)$$

For any immiscible process, the mobility ratio is given as

$$M = \left( \frac{K_{r_D}}{\mu_D} \right) \left( \frac{\mu_d}{K_{r_d}} \right) \quad (6)$$

If there are more than one fluid phases in the displacement process, then the idea of total mobility comes up and is used

$$M_t = \left( \frac{M_{tD}}{M_{td}} \right) \quad (7)$$

Where

$$M_{tD} = \sum_i \left( \frac{K_i}{\mu_i} \right)_D \quad (8)$$

### 2.2. Relative Permeability

Many correlations exist for the determination of the relative permeability of many phases in multi-phase flow process. Amongst the notable correlations used are

i). *The modified Brooks and Corey (MBC) model:*

This is greatly utilized in the industry and is given as

$$K_{r1} = K_{r1}^* \left( \frac{S_1 - S_{1r}}{1 - S_{1r} - S_{2r}} \right)^{n_1} \quad (9)$$

$$K_{r2} = K_{r2}^* \left( \frac{1 - S_1 - S_{2r}}{1 - S_{1r} - S_{2r}} \right)^{n_2} \quad (10)$$

Phase 1 is the gas phase; phase 2 is the other phase.

In CO<sub>2</sub> EOR processes, if we take to CO<sub>2</sub> gas to be phase 1 and the reservoir oil to be phase 2, then the relative permeability of the CO<sub>2</sub> and the oil will be

$$K_{rg} = K_{rg}^* \left( \frac{S_g - S_{gi}}{1 - S_{gi} - S_{oi}} \right)^2 \quad (11)$$

$$K_{ro} = K_{ro}^* \left( \frac{1 - S_g - S_{oi}}{1 - S_{gi} - S_{oi}} \right)^2 \quad (12)$$

ii). *Corey's Model*

Corey determined a simple approach to determine the relative permeability of gas phase [25].

$$K_{r1} = (1 - S)^2(1 - S^2) \quad (13)$$

$$S = \frac{S_1 - S_{1r}}{1 - S_{1r} - S_{2r}} \quad (14)$$

Corey's model applied to gas and oil system can be expressed as a ratio as

$$\frac{K_{rg}}{K_{ro}} = \frac{(S_g^*)(2 - S_g^*)}{(1 - S_g^*)^4}$$

S<sub>g</sub><sup>\*</sup> can be represented mathematically by equation (15)

$$S_g^* = \frac{S_g}{1-S_{oi}} \quad (15)$$

### 2.3. Fractional Flow

For all displacement processes in which the displacing phase (D) displaces the displaced phase (d), the fractional flow of the displacing phase is given as

$$f_D = \frac{1}{1 + \frac{K_{rd}\mu_D}{K_{rD}\mu_d}} \quad (16)$$

$$f_D = \frac{1}{1 + 1/M} \quad (17)$$

The fractional flow of solvent in a CO<sub>2</sub>-oil flow system is given as

$$f_w = \frac{1}{1 + \frac{K_{ro}U_{CO_2}}{U_o K_{rCO_2}}} \quad (18)$$

This may also be written as

$$f_w = \frac{1}{1 + 1/M} \quad (19)$$

### 2.4. Recovery Before Breakthrough Calculations

The equation used in determination of recoveries before solvent breakthrough are given in this section

#### 2.4.1. Water Injection

The cumulative volume of solvent injected at breakthrough is given by

$$S_{ibt} = i_w t_{bt} = \frac{PV}{\left(\frac{df_s}{ds_s}\right)_{s_{sbt}}} \quad (20)$$

$$PV = 7758Ah\phi \quad (21)$$

The cumulative volume of solvent injected at breakthrough can also be expressed as

$$S_{ibt} = PV(\bar{s}_{sbt} - s_{si})E_D E_V \quad (22)$$

$s_{sbt}$  can be determined mathematically as

$$\bar{s}_{sbt} = s_{sbt} + \frac{1-f_{sbt}}{\left(\frac{df_s}{ds_s}\right)_{s_{sbt}}} \quad (23)$$

The time to breakthrough is given by

$$t_{bt} = \frac{PV}{i_w} \left( \frac{1}{\left(\frac{df_s}{ds_s}\right)_{s_{sbt}}} \right) \quad (24)$$

Let  $V_{sbt}$  be the cumulative pore volume of solvent injected at breakthrough

$$V_{sbt} = \frac{S_{ibt}}{PV} = \frac{1}{\left(\frac{df_s}{ds_s}\right)_{s_{sbt}}} \quad (25)$$

The distance travelled at breakthrough is given by

$$(X)_{ssbt} = \frac{K_c S_{ibt}}{A\phi} \left( \frac{df_s}{ds_s} \right)_{s_{sbt}} \quad (26)$$

#### 2.4.2. Oil Recovery to Breakthrough

The cumulative oil recovery to breakthrough is equal to the cumulative volume of solvent injected, assuming piston-like displacement of the oil by the solvent. The oil recovered to breakthrough is given by

$$N_{pbt} = \frac{S_{ibt}}{B_o} = \frac{PV(\bar{s}_{sbt} - s_{si})E_D E_V}{B_o} \quad (27)$$

If the oil produced were to be expressed in pore volume, the pore volume of oil produced to breakthrough is given as

$$V_{obt} = \frac{V_{sbt}}{B_o} = \frac{(\bar{s}_{sbt} - s_{si})E_D E_V}{B_o} \quad (28)$$

### 2.5. Recovery After Breakthrough Calculations

For calculations of recovery after breakthrough, the saturation of the solvent behind the front is used to perform calculations. The saturations of the solvent from  $s_{sbt}$  to  $1 - S_{or}$ . The average solvent saturation ( $\bar{s}_{s2}$ ) behind the front (i.e. after breakthrough is utilized)

#### 2.5.1. Cumulative Water Injection After Breakthrough

The cumulative volume of solvent injected at breakthrough is given by

$$S_i = i_w t = \frac{PV}{\left(\frac{df_s}{ds_s}\right)_{s_{s2}}} \quad (29)$$

The cumulative volume of solvent injected after breakthrough can also be expressed as

$$S_i = PV(\bar{s}_{s2} - s_{si})E_D E_V \quad (30)$$

$$\bar{s}_{s2} = s_{sbt} + \frac{1-f_{sbt}}{\left(\frac{df_s}{ds_s}\right)_{s_{s2}}} \quad (31)$$

The time to breakthrough is given by

$$t = \frac{PV}{i_w} \left( \frac{1}{\left(\frac{df_s}{ds_s}\right)_{s_{s2}}} \right) \quad (32)$$

Let  $V_s$  be the cumulative pore volume of solvent injected after breakthrough

$$V_s = \frac{S_i}{PV} = \frac{1}{\left(\frac{df_s}{ds_s}\right)_{s_{s2}}} \quad (33)$$

The distance travelled at breakthrough is given by

$$(X)_{S_{s2}} = \frac{K_c S_i}{A\phi} \left( \frac{df_s}{ds_s} \right)_{s_{s2}} \quad (34)$$

#### 2.5.2. Cumulative Oil Recovery After Breakthrough

The cumulative oil recovery after breakthrough given by

$$N_p = \frac{S_i}{B_o} = \frac{PV(\bar{s}_{s2} - s_{si})E_D E_V}{B_o} \quad (35)$$

If the oil produced were to be expressed in pore volume,

the pore volume of oil produced after breakthrough is given as

$$V_o = \frac{V_s}{B_o} = \frac{(\bar{s}_{s2} - s_{si})E_D E_V}{B_o} \quad (36)$$

## 2.6. Recovery Efficiency Determination

The recovery efficiency of a flooding process consist of the following

### 2.6.1. The Overall Recovery Efficiency

The overall recovery efficiency of a secondary or EOR flooding process is the total efficiency in the process comprising of two principal recovery efficiencies which are the displacement efficiency and the volumetric (sweep) efficiency

### 2.6.2. The Displacement Efficiency

The displacement efficiency relates to the effectiveness of the process fluids (displacing fluids) in removing oil from the pores of the rock at the microscopic level. It is also known as

$$E_D = \frac{\text{Volume of oil at beginning of flood} - \text{Volume of oil remaining after flood}}{\text{Volume of oil at beginning of flood}} \quad (37)$$

$$E_D = \frac{(\text{Pore volume})\left(\frac{S_{oi}}{B_{oi}}\right) - (\text{Pore volume})\left(\frac{S_o}{B_o}\right)}{(\text{Pore volume})\left(\frac{S_{oi}}{B_{oi}}\right)} \quad (38)$$

$$E_D = \frac{\left(\frac{S_{oi}}{B_{oi}}\right) - \left(\frac{S_o}{B_o}\right)}{\left(\frac{S_{oi}}{B_{oi}}\right)} \quad (39)$$

If the oil formation volume factor is constant over the flooding process, then

$$B_{oi} = B_o \quad (40)$$

Then

$$E_D = \frac{S_{oi} - \bar{S}_o}{S_{oi}} \quad (41)$$

Note that

$$S_{oi} = 1 - S_{wi} - S_{gi} \quad (42)$$

However if initial gas saturation is zero as in many cases, then  $S_{gi} = 0$ , then

$$S_{oi} = 1 - S_{wi} \quad (43)$$

Also, note that in the swept zone, gas saturation is always zero, thus

$$\bar{S}_o = 1 - \bar{S}_s \quad (44)$$

It is more convenient to express the  $E_D$  in terms of water saturations, this is given as

$$E_D = \frac{\bar{S}_s - S_{wi} - S_{gi}}{1 - S_{wi} - S_{gi}} \quad (45)$$

For situations where no gas is present at the start of the

microscopic efficiency. For crude oil system, displacement efficiency ( $E_D$ ) is manifest in the magnitude of the residual oil saturation remaining in the reservoir pore space after the flooding process ( $S_{or}$ ) due to the contact by the displacing fluids. Typically displacement efficiency is a measure of the effectiveness of the displacing fluid in mobilizing the oil at those places in the reservoir where the displaced fluid contacts the oil. In other words the displacement efficiency  $E_D$  is the fraction of movable oil that has been displaced from the swept zone at any given time or pore volume injected [26].

Several factors affect the displacement efficiency of a flooding process. They are

- i. Mobility of the fluids
- ii. Type of flood pattern
- iii. The areal heterogeneity
- iv. Total volume of injected fluids

The displacement efficiency is analyzed mathematically below

flood, then  $E_D$  becomes

$$E_D = \frac{\bar{S}_s - S_{wi}}{1 - S_{wi}} \quad (46)$$

Note that the displacement efficiency will continue to increase as water saturation increase. The maximum value of the displacement efficiency is obtained when the residual oil saturation is reached. At this point

$$\bar{S}_s = 1 - S_{or}$$

#### i). Displacement efficiency at breakthrough

The displacement efficiency at breakthrough is given as

$$E_{D_{bt}} = \frac{\bar{S}_{sbt} - S_{gi}}{1 - S_{wi} - S_{gi}} \quad (47)$$

#### ii). Displacement efficiency after breakthrough

The displacement efficiency after breakthrough is given as

$$E_{D_{bt}} = \frac{\bar{S}_{s2} - S_{gi}}{1 - S_{wi} - S_{gi}} \quad (48)$$

### 2.6.3. Volumetric or Sweep Efficiency

Volumetric efficiency is a quantitative measurement of the fraction of the reservoir contacted by displacing fluid. This may also be stated as the fraction of the reservoir invaded by the displacing fluid. It is a function of time and it may be sometimes referred to as macroscopic efficiency.

#### i). Areal sweep efficiency at breakthrough

After breakthrough, the fractional flow of the displacing phase  $f_D$  need to be calculated before the areal sweep efficiency is determined. However before breakthrough, the fluid recovery is equal to the volume of injected fluid (assuming there is piston-like displacement)

Furthermore, the areal sweep efficiency at breakthrough

can be determined from correlation given below.

$$E_{ASbt} = 0.54602036 + \frac{0.03170817}{M} + \frac{0.30222997}{e^M} - 0.00509693M \quad (49)$$

ii). *Areal sweep efficiency after breakthrough*

There will be an increase in the areal sweep efficiency after breakthrough due to increased injection of the displacing fluid which leads to gradual further increase in the total swept area.

$$E_A = E_{ASbt} + 0.2749 \ln \frac{V_i}{V_{ibt}} \quad (50)$$

#### 2.6.4. Residual Oil Saturation After CO<sub>2</sub> Flood Equations

Cumulative oil produced (N<sub>p</sub>)=Oil in initial place (N<sub>i</sub>) – Oil remaining in place (N<sub>r</sub>)

$$(51)$$

The formula for N<sub>i</sub>, N<sub>p</sub>, and N<sub>r</sub> in field units with appropriate conversion factors are given below as

$$N_i = \frac{7758Ah\phi S_{oi}}{B_{oi}} \quad (52)$$

$$N_p = 7758Ah\phi \left( \frac{S_{oi}}{B_{oi}} - \frac{S_{or}}{B_o} \right) \quad (53)$$

$$N_r = \frac{7758Ah\phi S_{or}}{B_o} \quad (54)$$

$$N_r = N_i - N_p = \left[ \frac{7758Ah\phi S_{oi}}{B_{oi}} \right] - 7758Ah\phi \left( \frac{S_{oi}}{B_{oi}} - \frac{S_{or}}{B_o} \right) \quad (55)$$

Since the cumulative oil produced is known at the end of the recovery, equation 55 can be written as

$$N_r = \left[ \frac{7758Ah\phi S_{oi}}{B_{oi}} \right] - N_p \quad (56)$$

Equation 56 can be expanded further to be

$$\frac{7758Ah\phi S_{or}}{B_o} = \left[ \frac{7758Ah\phi S_{oi}}{B_{oi}} \right] - N_p \quad (57)$$

Making S<sub>or</sub> the subject of the formula we divide through by  $\left( \frac{7758Ah\phi}{B_o} \right)$ . Equation 57 becomes

$$S_{or} = \frac{\left[ \frac{7758Ah\phi S_{oi}}{B_{oi}} \right]}{\left( \frac{7758Ah\phi}{B_o} \right)} - \frac{N_p}{\left( \frac{7758Ah\phi}{B_o} \right)} \quad (58)$$

Simplifying, equ 58 reduces to

$$S_{or} = \frac{\left[ \frac{S_{oi}}{B_{oi}} \right]}{\left( \frac{1}{B_o} \right)} - \frac{N_p}{\left( \frac{7758Ah\phi}{B_o} \right)} \quad (59)$$

Simplifying further equ 59 becomes

$$S_{or} = \frac{(S_{oi}B_o)}{(B_{oi})} - \frac{N_p}{\left( \frac{7758Ah\phi}{B_o} \right)} \quad (60)$$

Equation 60 is the equation for the residual oil saturation after EOR process when the cumulative oil produced is known

### 3. Methods

Simulation study of hot CO<sub>2</sub> flooding was conducted using ECLIPSE 300 compositional simulator. Well, reservoir data and various operating conditions are given.

The reservoir fluid data are given below

Table 1. Reservoir data used in this work.

Parameter	Values
Reservoir Porosity	0.28
Reservoir Permeability	600 - 800mD
Wellbore ID	5.921 inches
Compressibility factor	5.07E-6 psi <sup>-1</sup>
Payzone thickness	100 ft
Reservoir depth	7466ft
Reservoir Acreage	50 acres

#### 3.1. Case Study

The case study considered in this study is Z field in the Niger Delta region of Nigeria. Z field has oil of very high viscosity. Owing to the viscous nature of the reservoir oil, Z field was not developed because operators are not prepared to face the risk for enhance oil recovery in the region due to many uncertainties.

But when oil price became favourable, opportunities lie in the development of this resource. Following the reservoir characteristics, it was concluded that the only method to produce Z-field is EOR. Selection criteria was conducted based on the petrophysical and lithological properties of the reservoir and it was concluded that the best EOR method for Z-field is either thermal or miscible or both if available. Hot CO<sub>2</sub>-EOR was then suggested because it possesses the characteristics of thermal and miscible floods.

The hot CO<sub>2</sub> achieves both thermal and miscibility effects on the reservoir fluids. The heat in the CO<sub>2</sub> reduces the oil viscosity causing oil swelling and viscosity reduction while the CO<sub>2</sub> itself mixes intimately with the heavy oil when injected above the miscibility pressure of the system. The CO<sub>2</sub> achieves miscibility with the reservoir oil through interfacial tension reduction at the CO<sub>2</sub>-oil interface and increasing oil mobility to the production interval.

The Assumptions used in this study are given below

- i. The reservoir is homogenous
- ii. There is continuity in payzone
- iii. The reservoir has uniform porosity across the grids
- iv. The reservoir is of uniform permeability across the layers
- v. The reservoir is of uniform thickness across layers
- vi. There is miscibility of injected fluid with reservoir oil
- vii. There is constant production and injection rates throughout the flooding process

#### 3.2. PVT Parameters

PVT data for this work was obtained from analyses conducted on fluid samples from Z-field in the Niger Delta. The data for PVT as obtained from laboratory sampling already conducted on fluid samples from Z-field is given in

table 3 while table 2 shows the composition of the reservoir fluid sample.

**Table 2.** Composition of Reservoir fluid used in this study.

Component	Symbol	Mol %
Carbon dioxide	CO <sub>2</sub>	0.36
Nitrogen	N <sub>2</sub>	0.12
Methane	C <sub>1</sub>	28.02
Ethane	C <sub>2</sub>	0.24
propane	C <sub>3</sub>	0.09
iso- Butane	i-C <sub>4</sub>	0.15
n- Butane	n-C <sub>4</sub>	0.03
iso- pentane	i-C <sub>5</sub>	0.13
n- pentane	n-C <sub>5</sub>	0.16
Hexane	C <sub>6</sub>	0.33
Heptanes plus	C <sub>7+</sub>	70.36
Reservoir Temp=136°F		

The PVT data used for the simulation are given below.

**Table 3.** PVT data.

Parameter	Values
Initial Reservoir pressure	3118psia
Formation volume factor at Reservoir pressure	1.0686 rb/stb
Formation volume factor at Burble point pressure	1.0785 rb/stb
Oil density	58.87lb/ft <sup>3</sup>
API gravity	18.6 API
Water density	62.4 lb/ft <sup>3</sup>
Gas density	0.269 lb/ft <sup>3</sup>
viscosity	14.225 cP
Reservoir Temperature	136°F

### 3.3. Reservoir and Well Models

The reservoir is five spots pattern consisting of four injection wells and one producer well. The production well is located at the centre of the reservoir as shown in figure 1.

**Table 4.** Reservoir model showing well location and configurations.

Configurations	
Producers	Injectors
	(1,1)
	(11,1)
(6, 6)	(1,11)
	(11,11)

The grid cells are for the (x, y, z) are (11, 11, 10). Table 1 describes the well location in relation to the grid cells for the injectors and the producer.

### 3.4. Grid

The grid is rectangular with a total of 1210 grid cells comprising (11, 11, 10) for (x, y, z) directions. The reservoir has a payzone thickness of 100ft. Each grid cell represents 316.44 ft x 316.44 ft x 10 ft in the x, y and z directions respectively. Table 6 below gives the permeability and thickness of each layer.

**Table 5.** Permeability and thicknesses of layers.

GRID	X-Permeability Per Layer	Y-Permeability Per Layer
1-11	800 mD	800 mD
LAYERS	Z-Permeability Per Layer	Thickness Per Layer
1-10	600 mD	10 ft per layer

The reservoir has an initial pressure of 3118 psia at 7466 ft depth.

The reservoir grid block depicting the cells and well locations is shown in figure 1.

As shown in figure 1, there are 4 injection wells and one producer well. The injection fluid is CO<sub>2</sub>. Four Injection wells were scheduled for injecting the hot CO<sub>2</sub> using the eclipse simulation tool. The hot CO<sub>2</sub> injection rate is 188 Mscf/day with group well control injection/limit of 5000Mscf/day.

The 4 injector wells share same properties. The nature of Injected Gas is GRUP. GRUP is Eclipse injected Gas nature that enable each of the injection well to immediately be under group control, to inject its share of a group or field target/limit set. A key property of Eclipse is that fluid specified as injection fluid type is only water or gas. If the injected fluid is gas, Eclipse relies on nature of injected gas and its composition to know the kind of gas which in this case is CO<sub>2</sub> at high temperature (Hot CO<sub>2</sub>). The density of the injected CO<sub>2</sub> is 47.13 lb/ft<sup>3</sup> at 136°F reservoir temperature and 3118 psia reservoir pressure. The molar mass of the CO<sub>2</sub> used for the simulation is 44.01g/Mol.

## 4. Results and Discussion

The result of the hot CO<sub>2</sub> flooding from the simulation conducted are given and discussed in this section.

### 4.1. Relative Permeability Curve

The relative permeability curve for the solvent and oil is given in figure 2 below.

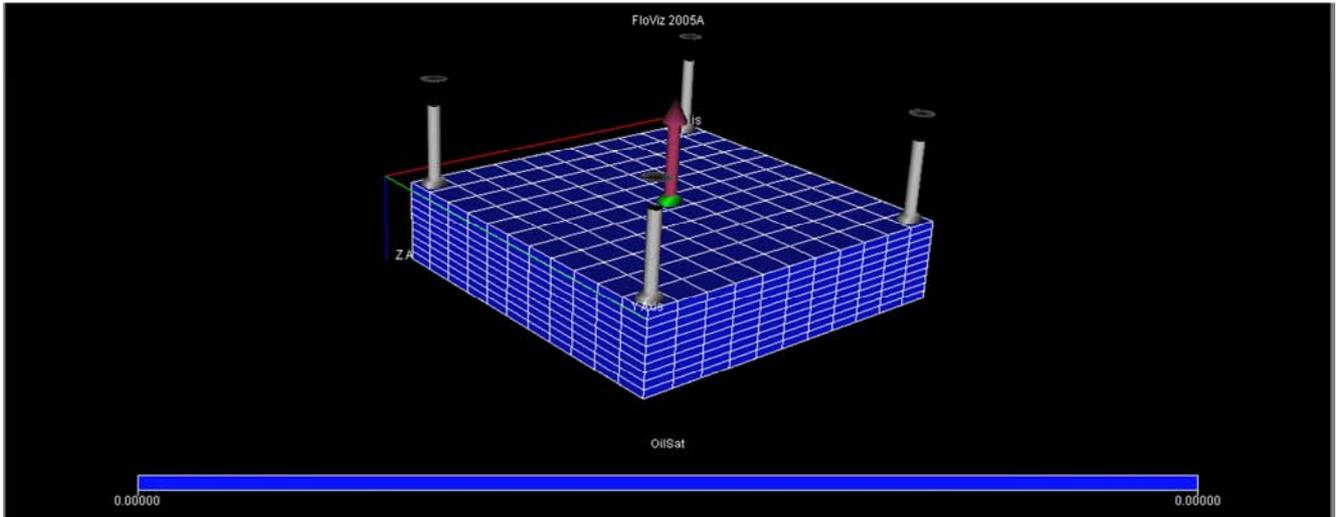


Figure 1. Reservoir model of Hot CO<sub>2</sub> flooding using 5-spot pattern showing injectors and producer.

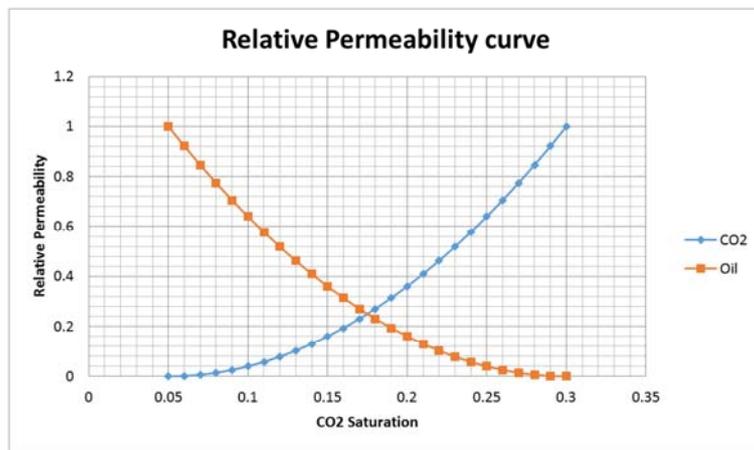


Figure 2. Relative permeability curve (CO<sub>2</sub> and oil).

4.2. Fractional Flow of Displacing Phase (CO<sub>2</sub>)

Figure 3 below gives the fractional flow of the displacing phase.

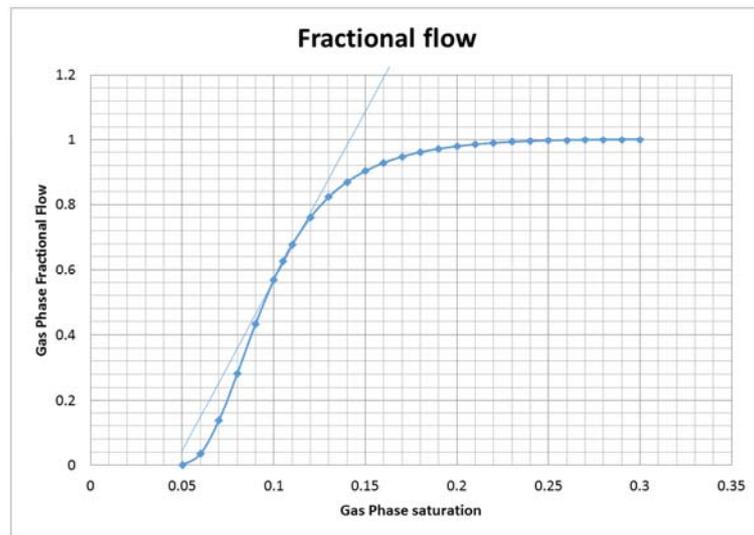


Figure 3. Fractional flow of CO<sub>2</sub> in the flooding.

From figure 3, it can be observed that the point of tangency to the fractional flow curve is at (0.105, 0.62). This means that the gas (solvent) saturation at breakthrough ( $s_{sbt}$ ) is 0.105 while the fractional flow of the solvent at breakthrough is (0.62). This means that the leading edge of the CO<sub>2</sub> front (the stabilized zone) has a constant saturation of 0.105 and CO<sub>2</sub>-cut of 10.5%.

Since this paper is intended to highlight the recoveries and recovery efficiency for the hot CO<sub>2</sub> flooding, the recovery results to CO<sub>2</sub> breakthrough and the recovery results after CO<sub>2</sub> breakthrough shall be analyzed and discussed

**4.3. Recovery Result to CO<sub>2</sub> Breakthrough**

Figure 4 below gives the shows the relationship between

the CO<sub>2</sub> injected and oil recovered from the beginning of flood to solvent breakthrough. Before breakthrough, the solvent injected is equal to the oil produced since there is no solvent production at the producer well. The difference in the red and the blue line comes only from the oil formation volume factor at breakthrough, which makes the oil to shrink at stock tank conditions. At breakthrough, the CO<sub>2</sub> injected is equivalent to 0.1222 PV (188 Mscfd of CO<sub>2</sub>) while the oil produced is 0.1133 PV (6849868 stb of oil). The time to reach breakthrough is 221 days. The distance covered at breakthrough was calculated to be 100 ft. The total distance from the injection well to the production well is 2461.36 ft. The displacement and areal sweep efficiencies at breakthrough are 15.15% and 44.02% respectively.

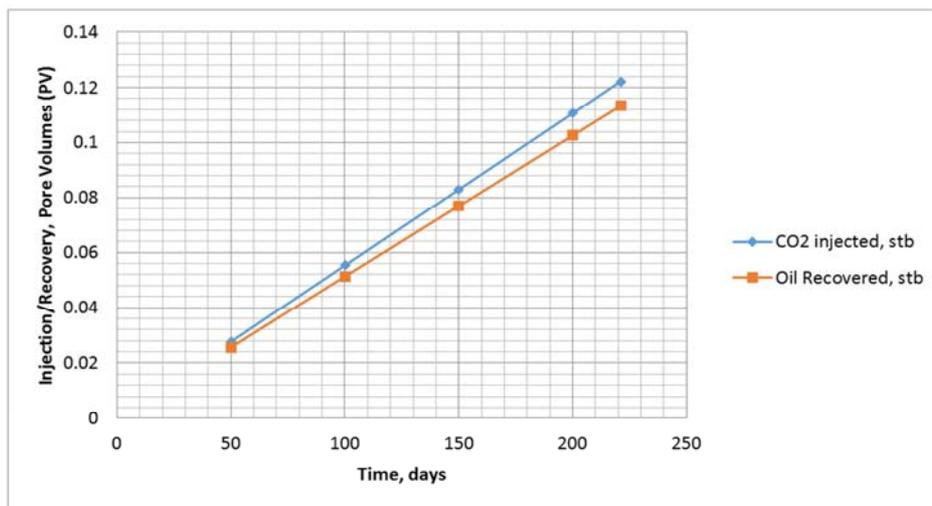


Figure 4. Injection/Recovery before breakthrough in Pore Volumes (PV).

**4.4. Recovery Result to CO<sub>2</sub> Breakthrough**

Figure 5 below shows the recovery after breakthrough of CO<sub>2</sub> given in pore volumes. At breakthrough there is no CO<sub>2</sub> produced at the producer well. After breakthrough, CO<sub>2</sub> production at the producer well begins to rapidly increase.

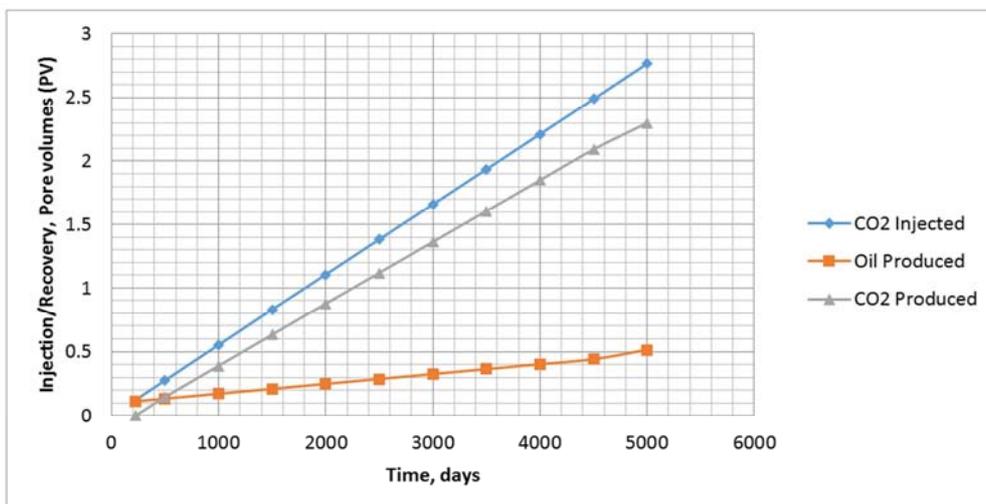


Figure 5. Injection/ Recovery after Breakthrough in Pore Volumes.

Figure 5 shows the relationship between the CO<sub>2</sub> injected oil recovered and CO<sub>2</sub> produced from the beginning of flood

to solvent breakthrough.

#### 4.5. Summary of Results

Table 6 below gives the summary of the result gotten from the simulations performed.

Table 6. General summary of results.

Parameters	Breakthrough	After breakthrough
Original oil in place, stb	42410708	42410708
Oil produced, stb	6849868	31119347
Oil produced, PV	0.1133	0.52
Solvent Injected, MMscf	41.48	938.39
Solvent injected, PV	0.1222	2.77
Solvent Produced, MMscf	0	780.67
Solvent Produced, PV	0	2.3
Time, days	221	5000
Distance, feet	100	2461.26
Displacement Efficiency	15.17%	78.63%
Overall Efficiency	6.67%	73.33%
Areal Efficiency	44.02%	93.32%
Residual oil saturation	0.151	0.151

From table 6, above the performance of the flood after breakthrough is more favourable than that before breakthrough.

#### 4.6. Discussion

This section discusses the results obtained from the simulation conducted on hot CO<sub>2</sub> flooding for Niger Delta heavy oil field. Performance results of the flooding process was analyzed before and after CO<sub>2</sub> breakthrough. The overall recovery efficiency at breakthrough was 6.67% while the overall efficiency after breakthrough at the end of the flooding process was 73.33%. Thus 73.37% of the oil in initial place was produced at the end flooding process. There were poor displacement and efficiency before breakthrough due to poor microscopic displacement of the oil by the solvent injected. Before breakthrough (i.e. 221 days) most of the reservoir had not been contacted by the injected CO<sub>2</sub>, and because of the viscous nature of the reservoir oil, the hot CO<sub>2</sub> have not achieved proper miscibility with the oil before breakthrough. This hindered large volume of oil from being mobile at the early stage of the flooding process.

At the end of the flooding process, the displacement efficiency increased from 6.67% at breakthrough to 78.63%. At sufficient time during the flooding process when most of the injected CO<sub>2</sub> had contacted considerable portions of the reservoir and the thermal effects of the injected hot CO<sub>2</sub> had achieved considerable viscosity reduction of the in-situ reservoir oil, there was higher and favourable expulsion of the reservoir fluid from the pores. This was not only attributed to the viscosity reduction effects but also to interfacial tension reduction as CO<sub>2</sub> achieved multiple contact miscibility with the reservoir oil.

The areal sweep increases from 44.02% at breakthrough to 93.32% at the end of the flood process. The process can be said to have favourable areal sweep efficiency.

The areal sweep was considered as the only volumetric sweep efficiency because the effect of gravity segregation

was neglected as the reservoir was treated as a single layered reservoir.

The oil produced at the point of solvent breakthrough was only 6849868 stb of oil as compared to the total of production of 31119347 stb of oil. This represents 22% of the total oil produced. The breakthrough of CO<sub>2</sub> occurred relatively early. Of the 2.77 PV of CO<sub>2</sub> injected in the process, breakthrough occurred at 0.1222 PV of CO<sub>2</sub> injected. At this point, only small fraction of the mobile oil was recovered. The remaining mobile oil was recovered after CO<sub>2</sub> breakthrough with CO<sub>2</sub> accompanying the oil to the producer well.

At breakthrough, the solvent had only travelled 100ft out of the 2461.2 ft distance between the injection well and the producer well, at this point, CO<sub>2</sub> had only travelled 4% of the distance to the producer.

In hot CO<sub>2</sub> injection, care must be taken to ensure that the heat content of the water does not contrast that of CO<sub>2</sub> such that the thermal capability of the hot CO<sub>2</sub> is compromised.

## 5. Conclusion

A simulation study on Hot CO<sub>2</sub> flooding has been performed. The study determined the performances and efficiencies of hot CO<sub>2</sub> flooding in Niger Delta heavy oilfield. From the study, the following conclusion was drawn.

- There was poor displacement efficiency before CO<sub>2</sub> breakthrough due to early breakthrough which hindered considerable portions of the reservoir to be contacted by the injected CO<sub>2</sub>
- Displacement efficiency after breakthrough increased drastically from 15.17% to 78.63% due to large volumes of CO<sub>2</sub> injection and good CO<sub>2</sub> contact with the reservoir.
- There was favourable areal sweep efficiency due to thermal effects of the hot CO<sub>2</sub> in reducing the viscosity of the heavy oil and the miscible effects of the CO<sub>2</sub> in achieving IFT reduction.
- The injected CO<sub>2</sub> only travelled 4% of the distance to production well before breakthrough hence, there was early breakthrough. This accounted for much of the injected CO<sub>2</sub> being produced at the production well.
- The project was wholly favourable when considering an overall recovery efficiency of 73.33% at the end of the flooding process.
- The residual oil saturation at the end of the flooding process was 0.1510. Thus, oil was depleted from an initial oil saturation of 0.7 to a residual oil saturation of 0.1510. About 21% of the initial oil in place was left unrecovered at the end of the flooding process.
- Because of its favourable performance in terms of recovery and efficiency, hot CO<sub>2</sub> flooding is recommended for implementation as an EOR means in the development of Niger Delta heavy oil field especially now that the conventional light oil are drastically exhausting with almost no new discovery of conventional light oil pools.

## Nomenclature

$\left(\frac{df_s}{dS_s}\right)_{S_{s2}}$  = the slope of the fractional flow curve after breakthrough.

$\left(\frac{df_s}{dS_s}\right)_{S_{sbt}}$  = the slope of the fractional flow curve at breakthrough.

$\bar{S}_o$  = Average oil saturation in the flood pattern at a particular point during the flood

$\bar{S}_s$  = average solvent saturation in the swept area

$\bar{S}_{s2}$  = the average solvent saturation after breakthrough

$(X)_{S_{s2}}$  = the distance travelled after breakthrough of solvent from injection well

$(X)_{S_{sbt}}$  = the distance travelled at breakthrough of solvent from injection well

$B_o$  = current formation volume factor, stb/stb

$B_{oi}$  = initial formation volume factor, stb/stb

$E_A$  = areal sweep efficiency at solvent breakthrough

$E_{ASbt}$  = areal sweep efficiency at solvent breakthrough

$E_D$  = displacement efficiency at the end of the flood

$E_{Dbt}$  = displacement efficiency at breakthrough

$f_D$  = fractional flow of displacing phase

$f_w$  = fractional flow of water

$K_c$  = conversion factor to ft.

$K_o$  = effective permeability to oil

$K_{r1}^*$  = end-point relative permeability for phases 1.

$K_{r2}^*$  = end-point relative permeability for phases 2.

$K_{rD}$  = relative permeability to the displacing phase

$K_{rd}$  = relative permeability to the displaced phase

$M_d$  = mobility of the displaced phase

$M_D$  = mobility of the displacing phase

$Mt_D$  = the sum of all mobilities of all the phases flowing behind the displacement front measured at the average saturation behind the front.

$n_1$  = Corey exponents for phase 1, to be calculated from experiment.

$n_2$  = Corey exponents for phase 2, to be calculated from experiment.

$N_i$  = oil in initial place, stb

$N_p$  = cumulative oil produced, stb

$N_r$  = remaining oil in place after flood, stb

$S_{1r}$  = initial saturations for phases 1

$S_{2r}$  = initial saturations for phases 2

$S_g$  = gas saturation

$S_{gi}$  = Initial gas saturation at the start of the flood.

$S_{ibt}$  = Cumulative solvent volume injected at the time of breakthrough

$S_{o2}$  = oil saturation after some time interval

$S_{oi}$  = initial oil saturation at the start of flood

$S_{or}$  = Residual oil saturation after the flood

$S_{sbt}$  = Pore volume of solvent injected at solvent breakthrough

$\bar{S}_{sbt}$  = average solvent saturation at breakthrough

$S_{wi}$  = Initial water saturation at the start of the flood

$V_i$  = cumulative volume of solvent injected, stb

$V_{sbt}$  = volume of solvent injected at breakthrough, stb

$V_s$  = Number of pore volumes of solvents injected.

$\mu_d$  = viscosity of the displaced phase

$\mu_D$  = viscosity of the displacing phase

$\mu_o$  = oil viscosity

$\emptyset$  = porosity of the reservoir

$A$  = reservoir area, acres

$B_{oi}$  = oil FVF at start of flood, stb/STB

$CO_2$ -EOR =  $CO_2$  enhanced oil recovery

cP = Centipoise

$h$  = payzone thickness

$M$  = mobility ratio

mD = Millidarcy

MMP = Minimum miscibility pressure

stb = stock tank barrels

WAG = Water alternating gas

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