Evaluating Water Flooding Performance Prediction using Software Program for Determination of Basic Data

[1]Akpoturi Peters, [2]Usuolori O.B.A and [3]Ejelonu Oby Katherine
[1]Department of Petroleum Engineering,
Federal University of Petroleum Resources, Effurun, Nigeria
[2]Department of Petroleum Engineering,
Delta State University of Science and Technology, Ozoro, Nigeria
[3]Department of Economics,
Delta State University of Science and Technology, Ozoro, Nigeria

Abstract. Secondary oil recovery is an essential optimal ultimate hydrocarbon recovery most especially when the reservoir pressure has declined considerably due to primary production. Waterflooding is one of the most common method frequently employed for this purpose.

However, owing to huge capital requirement for the waterflooding project, there is a need to predict the project's performance before investing in it. There are several methods of evaluating waterflooding performance. The time, cost and data (both primary and secondary) required for each of these methods vary from one to another; so also the details and accuracy they provide.

This work develops a general, simple, accurate and user friendly software program for the determination of basic secondary data: Water Saturation at Breakthrough; Average Water Saturation at Breakthrough; Fractional Water Flow at Breakthrough; Fractional Oil Flow at Breakthrough.

The data are required by virtually all the prediction methods for complete evaluation of waterflooding project from few primary data (oil-water relative permeability data). This program is essential in order to reduce the cost and the time required for the determination of these data using the conventional, cumbersome manual calculations and laying of tangents to fractional flow curve.

Keywords: primary and secondary oil recovery, pressure, waterflooding, breakthrough, decline, saturation, reservoir energy and permeability

Introduction

Reservoir Energy

When a well is drilled into a reservoir, the wellbore becomes an area of low pressure. If there is a path for flow, liquid and gas move to the wellbore. The rate at which liquid and gas move is related to the difference in pressure, the geometry of the wellbore and the relative permeabilities of the fluid involved. Energy in a reservoir, represented by reservoir pressure, represents the driving force which causes fluids to flow from the heart of the reservoir to a well. This reservoir energy, stored in the fluids and rocks in the reservoir, occurs as a result of the pressure of the overlying layers of the earth and the heat of the earth's core. It is manifested as high pressure and temperature in the reservoir.

Primary Recovery

As long as the reservoir pressure is high enough, oil and gas are pushed to a wellbore from where they can be recovered. Removing petroleum from a reservoir when the only energy source is the initial reservoir energy is called primary recovery. This continues until the reservoir energy is exhausted or until a prohibitively large volume of water is being produced (i.e. naturally occurring reservoir conditions will no longer support the removal of oil and gas). Figure 1 illustrates fluid flow in primary recovery.

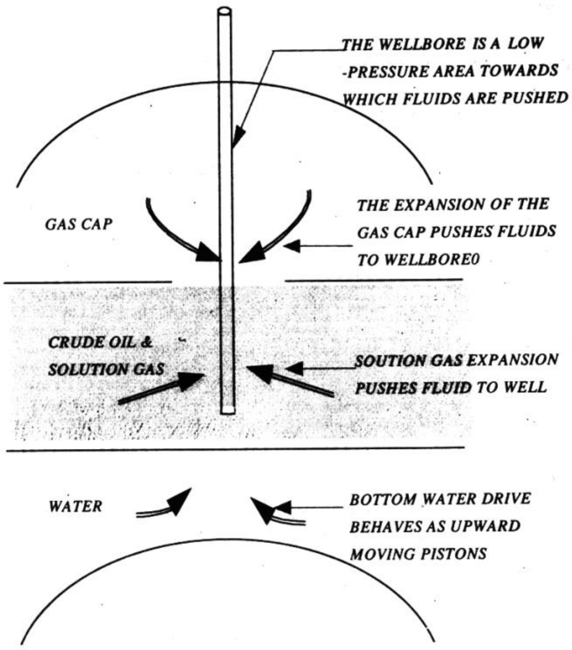


Figure 1. Original energy pushes fluid to wells in primary recovery

Secondary Recovery

Pressure decreases with petroleum production. Hydrocarbon fluids which remains after the reservoir pressure is too low to push fluids to the well must be recovered by transmitting energy to the reservoir from man-made sources. This is called Secondary Recovery. Gas injection and water injection or waterflooding are first methods of secondary recovery utilized with waterflooding becoming the dominant one in the later part. Recently, a number of improved recovery methods have been developed which include the injection of viscous polymer and mixtures of gases to form miscible mixtures of oil gas and water. The techniques used for recovery even water injection have been developed to such a level that most induced recovery techniques are now referred to by the term Enhanced Recovery. Figure 2 illustrates the flow of fluids when secondary or enhanced recovery methods are used.

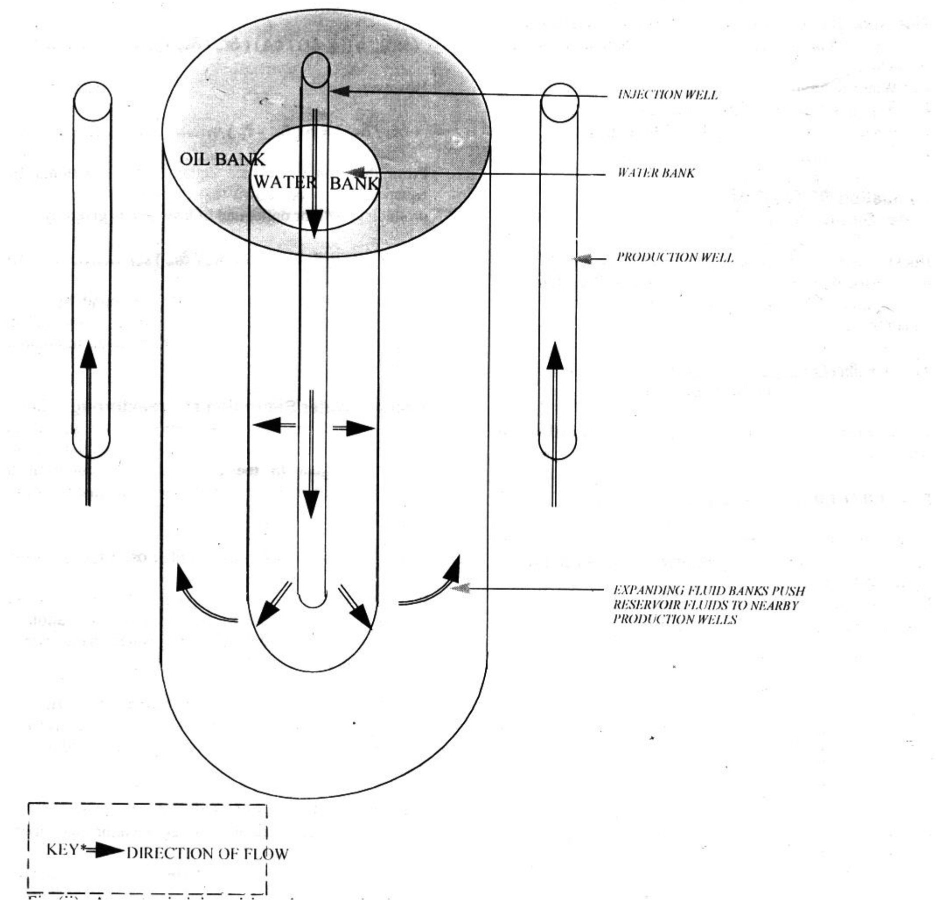


Figure 2. As water is injected into the water bank, it expands outward and pushes petroleum ahead toward offsetting

Definition

Waterflooding is a process of injecting water through injection wells into reservoirs for the primary purpose of enhancing ultimate oil recovery. It may also be used for

- reservoir pressure maintenance when the expansion of the aquifer or gas - cap is insufficient and
- disposal of the brine produced with the oil if surface discharge is not possible.

Waterflooding prediction methods are means of forecasting ultimate waterflood oil recovery, composite values of injection rate, producing water - oil - ratio (WOR) and other relevant data necessary for detail analysis of waterflood projects. Some of the common methods that are frequently employed are:

- Buckley-Leverett method
- Stiles method
- Muskat method
- Craig-Geffen-Morse method
- Dykstra-Parsons method
- Hurst method

The time, cost and data (both primary and secondary) required for each of these methods vary from one to another and so also the detail they give and their accuracy when compared with the actual performance of waterflood project.

This work develops a general, simple, accurate and user-friendly software program for the determination of basic secondary data:

- Water Saturation at Breakthrough

- Average Water Saturation at Breakthrough
- Fractional Water flow at Breakthrough and
- Fractional Oil Flow at Breakthrough

Evaluation of Key Data

Water Saturation at Breakthrough, S_{wf}

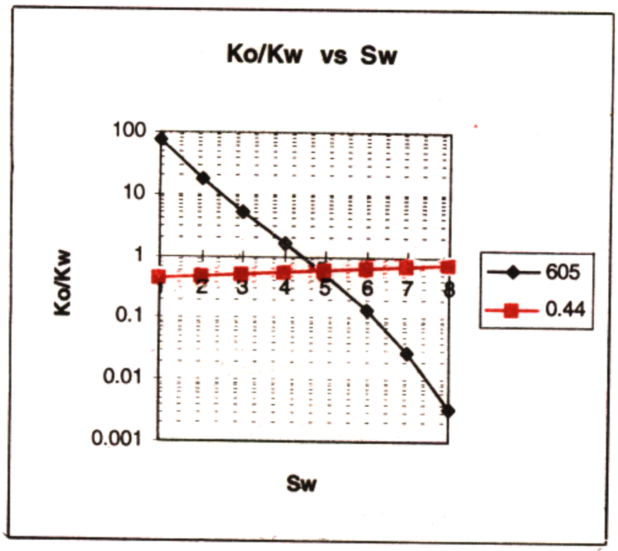
The fractional flow equation developed by Buckley and Leverett from Darcy's law is the fundamental mathematical statement describing immiscible fluid-fluid displacement in porous media. A generalized form of the equation is:

$$fw = \frac{1+.001127\,(k_oA/\mu_o q_t)(\frac{\delta Pc}{\delta L}0.433\Delta\rho sin\alpha)}{1+(k_o/k_w)(\mu_w/\mu_o)} \quad (1)$$

The simplified form of the equation for a horizontal system when is neglected is:

$$f_w = 1.0\;/\;(1.0 + (k_o/k_w)(\mu_w/\mu_o)\;) \quad (2)$$

A plot of relative permeability ratio k_o/k_w, versus water saturation, S_w on semi-logarithmic graph paper gives a curve with the central portion of the curve being quite linear - Figure 3. This linear relationship can be represented by the equation below:



$$k_o/k_w = ae^{-bSw} \quad (3)$$

Where

a = intercept

b = slope of the straight line portion

Substituting for k_o/k_w in equation (2) gives:

$$f_w = 1.0/(1.0 + (\mu_w/\mu_o)ae^{-bSw}) \quad (4)$$

The second relationship developed by Buckley and Leverett is an expression for the Continuity Equation known as the Frontal Advance Equation:

$$(\Delta_x)_{sw} = ((q_t\Delta t)/\emptyset A)(\delta f_w/\delta s_w)_{sw}) \quad (5)$$

However,

$$(\delta f_w/\delta s_w) = b(f_{w^2} - f_w) \quad (6)$$

From the frontal advance equation and fractional flow equation, it can be shown that the water saturation at the producing well or outlet end of a system is given by:

$$S_{wf} = S_{wi} + (f_{wf} - f_{wi})/(\delta f_w/\delta s_w)s_{wf} \quad (7)$$

Conventionally, this saturation can be found by tangent construction to the fractional flow curve or by trial and error method. The later method is best suited to computer solution.

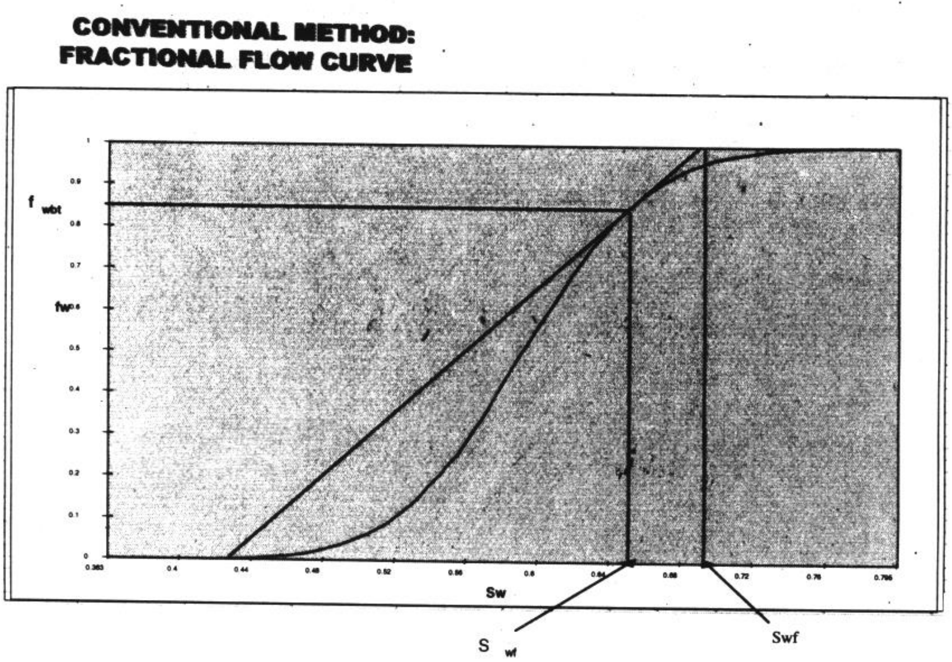
Average Water Saturation at Breakthrough, S_{wf}

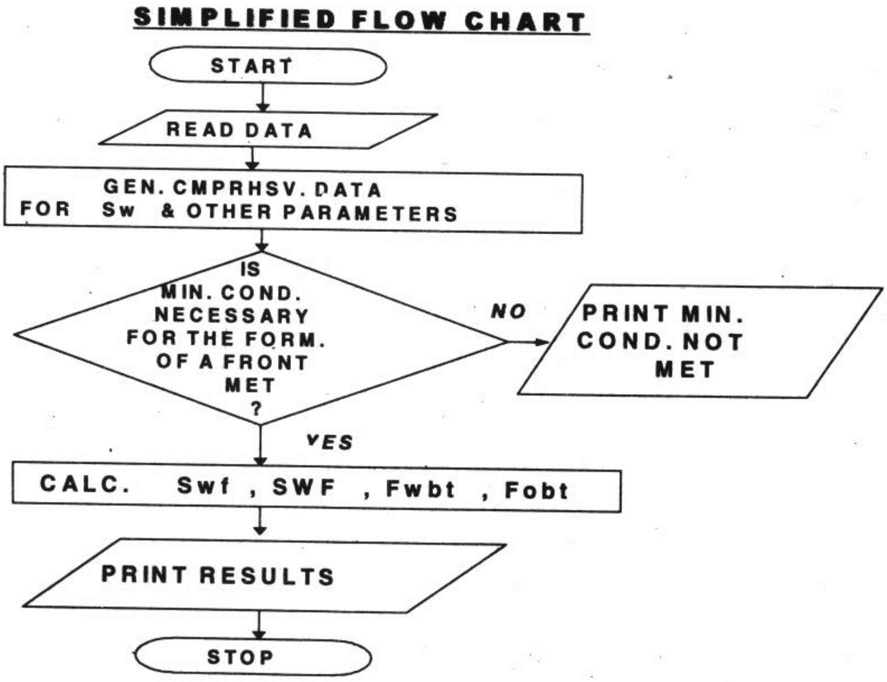
The average water saturation, S_{wf} in the flooded portion of the reservoir is the value of water saturation at which a tangent to the fractional flow curve at the producing wellbore saturation intersects the line $f_w = 1.0$

In the generalized form:

$$Swf = S_{wf} + (1.0 - f_w)s_{wf})/(\delta f_w/\delta s_w)s_{wf} \quad (8)$$

Figure 4 shows a typical fractional flow curve with initial water saturation S_{wi}. water saturation at breakthrough, S_{wf} and average water saturation at breakthrough, Swf.





Fractional Water Flow at Breakthrough, fwbt

The fractional water flow value that corresponds to the water saturation at breakthrough is referred to as the fractional water flow at breakthrough, fwbt.

Fractional Oil Flow at Breakthrough, fobt

The fractional oil flow at breakthrough, fobt is given by the equation below

$$fobt = 1.0 - fwbt \quad (9)$$

Algorithm

The following steps are the algorithm for the Software Program.

1. Determination of water saturation at breakthrough, Swf and average water saturation at breakthrough, Swf from relative permeability and water saturation data given and other relevant parameters.

- Generation of comprehensive data for water saturation using equation (3).
- Establish whether or not minimum conditions necessary for the formation of a flood front are met or not.
- Calculate S_{wf} and Swf.

2. Determination of fractional water flow at breakthrough and fractional oil flow at breakthrough.
3. Output the results.
4. Stop and end

The Main Program

```
C THIS SOFTWARE PROGPAM COMPUTES BASIC ‘SECONDARY DATA
C REQUIRED BY VIRTUALLY ALL THE PREDICTION METHODS FOR A
C COMPLETE EVALUATION OF A WATERFLOODING PROJECT.
C FORTRAN COMPILER USED WATFOR-77
            DIMENSION SW(20), PRW(20), PRO(20), C(20), FW(1000),
            DIMENSION DFW(I000)
            DIMENSION Q(1O0),CSW(1OOO),H{1OOO),H(10OO)
            OPEN (UNIT1, FILE=’DATl.IN)
            OPEN (UNIT6, FILESPEFOR.OUT)
C M DENOTES THE NUMBER OF WATER SATURATION & RELATIVE
C PERMEABILITY DATA GIVEN WHILE VISO & VSW REPRESENT OIL C AND
WATER VISCOSITIES RESPECTIVELY
            READ (1,22)M,VSO,VISW
      22     FORMAT(2X,I5,2(2X,F4.2))
            READ (1,23) (SW (I),PRW(I),PRO(I),I=1,M)
      23     FORMAT(2X,3(F6.4,2X))
            WRITE (6,17)M
      17 FORMAT(//10X, BASIC DATA REQUIREMENTS,//5X, INPUT
            1 PRAMETERS (PRIMARY DATA)' ,//5X, 'M=',I4,/f10X,’SW’,
      1     15X, Krw,13X, Kro)
            DO 13I=1M
      13    WRITE(6,19)SW(I),PRW(I),PRO(I)
      19    FORMAT(/,3(10X,F6.4))
      DO    5 I=1,M
      IF (PRW(I .EQ.0.0 PRW(I)=.00001
            C(I)=PRO(I)/PRW(I)
      5     CONTINUE
```

```
C CALCULATE CONSTANTS A B REQUIRED FOR THE GENERATION OF
C COMPREENSIVE SW
      B(ALOG(C(4)/C(7H)/(SW(4)—SW(7))
      A=C(4)/EXP(B*SW(4))
      DVISW/VISO -- -
      TSW=SW(1) - - - -
      ESW(1)*1000.0 -
      FSW(M)* 1000.0
      G=F-E
      J=INT (G)
C GENERATE COMPREHENSIVE WATER SATURATION AND OTHER RELATED
C PARAMETERS
      DO10 10 I=1,J
      CSW (I) TSW
      FW(I) =1. 0/(1.0+ D*A* EXP (B*CSW(I) ) )
      DFW(I)B*(FW(I)**2-FW(I) )
      Q(I)1.0/DFW(I)
      IF(I.LT.200)GO TO 12
      HD(I)=ABS(CSW(I)—H(I))
      12 TSW=TSW+.001
      10 CONTINUE
C COMPUTE THE AVERAGE WATER SATURATION AT BREAKTHROUGH
C (CSWF)
      HDMIN=HD(200)
      DO 15 I=200,J
      IF(HDMIN.LE.HD(I))GQ TO 15
      HDMIN=HD(I)
      FWFFW(I)
      QF=Q(I)
      CSWF=CSW(I)
      DFWF=DFW(I)
15 CONTINUE
C ESTABLISH WHETHER MINIMUM CONDITIONS NECESSARY FOR THE
C FORMATION OF A FLOOD FRONT ARE SATISIFIED OR NOT
      IF(FW(1).GE.DFWF)GO TO 95
C CALCULATE THE AVEBAGE WATER SATURATION AT BREAKTHROUGH
C (ASW)
      FO=1.0C-FWF
      ASW=CSWF+FQ*QF
      WRITE(6,11)CSWF,ASW,FWF,FO
11 FORMAT(//10X, ‘OUTPUT PARAMETERS (SECONDARY DATA)
      1 ARE:’,//5X,
1 ‘THE WATER SATURATION AT SREAKTHROUGH=’,F1O.5,//5X,
1 ‘THE AVERAGE WATER SATURATION AT BREAKTHRUOGH=’,
1 ‘THE FRACTIONAL WATER FLOW AT BREAKTHROUGH’,
1 ‘THE FRACTIONAL OIL FIW AT DREAKTHROUGR=’,F10.5)
GO TO 5O
95 WRITE( *,*)MINIMUM CONDITIONS NECESSARY FORT E
1 FORMATION OF A’
WRITE(*,*) ‘FLOOD FRONT ARE NOT SATISIFIEDT -
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50      STOP
        END
```

Discussion of Results/Conclusion

Using the conventional method the input data below gives the fractional flow curve (Figure 4).

Viscosity of oil = 2.0 cp
Viscosity of water 1.0 cp

SW	Krw	Kro
0.3630	0.0000	1.0000
0.4000	0.0000	0.7900
0.4400	0.0000	0.6000
0.4800	00100	0.4400
0.5200	0.0100	03100

SW	Krw	Kro
0.5600	0.0400	0.2100
0.6000	0.0900	0.1200
0.6400	0.1400	0.0700
0.6800	0.2400	0.0300
0.7200	0.3800	0.0100
0.7600	0.5700	0.0000
0.7900	0.7800	0.0000

From the fractional flow curve (Figure 4):
THE WATER SATURAT1ON AT BREAKTHROUGH = 0.65
THE AVERAGE WATER SATURATION AT BREAKTHRUOGH = 0.69
THE FRACTIONAL WATER FLOW AT BREAKTHROUGU = 0.86
THE FRACTIONAL OIL FLOW AT BREAKTHROUGH = 0.14

However, the software program gives the output on the next page using the same input data. The table below shows the percentage accuracy for each of the calculated values.

	Conven Mtd.	**Software Mtd.**	**% Accuracy**
Swbt	0.65	0.655	99.2
Avrg. Swbt	0.69	0.694	99.4
Fwbt	0.86	0.882	97.5
Fobt	0.14	0.118	84.2

The low accuracy of the fractional oil flow value at breakthrough, Fobt is due to the lower base value and the slight difference between the software value and the conventional value. Thus, the software program offers

- Considerable reduction in the cost and time requirements needed for the determination of these secondary data.
- Very high accuracy.
- Facilitation of its incorporation into any existing prediction method.
- Development optimization in the next millennium.

Basic Data Requirements

INPUT PARAMETERS (PRIMARY DATA) M= 12

SW	Krw	Kro
0.3630	0.0000	1.0000
0.4000	0.0000	0.7900
0.4400	0.0000	0.6000
0.4800	0.0100	0.4400
0.5200	0.0100	0.3100
0.5600	0.0400	0.2100
0.6000	0.0900	0.1200
0.6400	0.1400	0.0700
0.6800	0.2400	0.0300
0.7200	0.3800	0.0100
0.7600	0.5700	0.0000
0.7900	0.7800	0.0000

OUTPUT PARAMETERS (SECONDARY DATA) ARE:

THE WATER SATURATION AT BREAKTHROUGH = 0.65500

THE AVERAGE WATER SATURATION AT BREAKTHRUOGH = 0.69392

THE FRACTIONAL WATER FLOW AT BREAKTHROUGH = 0.88163

THE FRACTIONAL OIL FLOW AT BREAKTHROUGH = 0.11837

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