RESERVOIR EVALUATION IN UNDERSATURATED OIL RESERVOIRS USING MODERN PRODUCTION DATA ANALYSIS; A SIMULATION STUDY

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ABSTRACT : *Production data analysis methods are frequently applied to analyze long-term production data including flow rate and pressure. The purpose of this analysis is to estimate the oil in place, ultimate recovery and evaluation of reservoir parameters such as permeability and skin factor. The most important priority of production data analysis to well test is that no shut-in is required for production data analysis and the initial oil in place can be estimated as well. In this study, two modern production data analysis methods are presented and their advantages, limitations and applications are discussed. For the purpose of this study, a simulation model is designed and synthetic data are generated for different scenarios. In these scenarios, the effects of rock and fluid compressibility on oil production rate are investigated for an undersaturated oil reservoir. It was observed that any increase in total compressibility value, results in lower decline rate and higher ultimate recovery. Then, the generated data sets are analyzed using different analysis methods, and the results are compared. The results showed that although the Flowing Material Balance method is unable to evaluate the reservoir parameters, it is more powerful in estimation of oil in place rather than the Blasingame method.*

Keywords: *Production Data Analysis, Type Curve, Flowing Material Balance, Decline Curve, Material Balance Time*

1. INTRODUCTION

Production data analysis methods are the methods available to analyze long-term production data (flow rate and pressure data) for different purposes such as estimation of oil in place, ultimate recovery and reservoir parameters such as permeability and skin factor. The analysis quality depends on the quality and quantity of available production data. Since pressure data is often not available for older wells, these analyzes are more applicable for newer wells in which the bottom-hole flowing pressure is recorded using Permanent Down-hole Gauges (PDGs). Production data analysis is accounted as a method to evaluate reservoir parameters, as well-test is, but it uses different data types. The most important priority of production data analysis to well test analysis is that no shut-in is required for the analysis and oil in place can be estimated as well.

Production data analysis methods can be divided into three categories based on their history of development: traditional methods, semi—analytical methods and modern methods. Traditional production data analysis methods were pure empirical like Arps method [1]. In these methods the flow rate data is analyzed using history matching process to tune the parameters of an empirical relationship which forecasts the flow rate at any time. In 1973 Fetkovich [2] presented a semi-analytical method which could analyze flow rate data for a well under constant bottom-hole flowing pressure. After that different efforts were done to analyze production data under variable rate/pressure production which are called modern production data analysis [3-6].

In this study, two modern production data analysis methods are presented and their advantages, limitations and applications are discussed. Also the effects of rock and fluid compressibility on oil production rate are investigated for undersaturated oil reservoirs. For the purpose of this study, a simulation model is designed and synthetic data are generated for different cases. Then, the generated data sets are analyzed using different analysis methods, and the results are compared and discussed.

2. PRODUCTION DATA ANALYSIS METHODS

As mentioned before, the production data analysis methods are categorized into traditional, semi-analytical and modern methods. Two modern methods, Blasingame and flowing material balance, are selected in this study to analyze the production data.

2.1. Blasingame Analytical Type Curve

In 1980, Fetkovich constructed the first type curve for production data analysis [2]. His type curve was a combination of analytical stems for transient flow regime and empirical Arps relations [1] for the boundary dominated flow regime.

Blasingame tried to include the effect of variable rate/pressure conditions by the concepts of material balance time and normalized flow rate [3] in 1991. He constructed a type curve similar to that of Fetkovich [2] in transient flow regime, in which an analytical solution was used for boundary dominated flow, instead of empirical Arps relations which was used in Fetkovich type curve.

For transient flow regime, Fetkovich has used the solution of governing equation with constant flowing pressure. He showed that the solution to constant flowing pressure in Laplace space is:

$$\bar{q}_D(u) = \frac{1}{u^2} \cdot \frac{1}{\bar{p}_D(u)} \quad (1)$$

where $\bar{p}_D$ is the solution to the constant flow rate case used in well test analysis which is:

$$\bar{p}_D(u) = \frac{1}{u} \cdot \frac{K_0(\sqrt{u} r_D)}{\sqrt{u} \cdot K_1(\sqrt{u})} \quad (2)$$

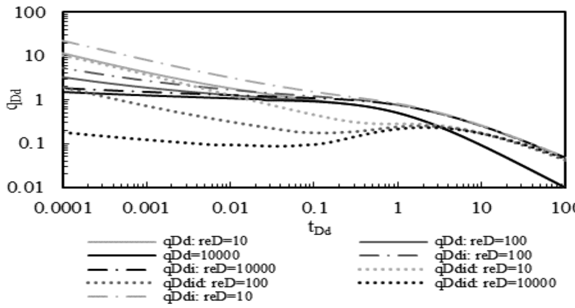


Fig. 1. Blasingame type curve (log-log scale)

K_0 and K_1 are second type modified Bessel functions of first and second order respectively.

Fetkovich also defined the dimensionless flow rate and dimensionless time for transient flow regime as below:

$$q_{Dd} = \frac{q(t)}{q_i} = [\ln(r_{eD}) - 0.5] \cdot q_D \qquad (3)$$

$$t_{Dd} = \frac{t_D}{\frac{1}{2}\left[\left(\frac{r_e}{r_w}\right)^2 - 1\right] \cdot \left[\ln\left(\frac{r_e}{r_w}\right) - \frac{1}{2}\right]} \qquad (4)$$

In order to model boundary dominated flow regime, Blasingame derives an analytical relation [7] which suggests a linear relationship between material balance time and pressure normalized flow rate as follows:

$$\frac{\Delta p}{q} = m\bar{t} + b_{pss} \qquad (5)$$

where definition of different parameters comes below:

$$\Delta p = p_i - p_{wf} \qquad (6)$$

$$m = \frac{1}{N \cdot c_t} \qquad (7)$$

$$b_{pss} = 141.2\,\frac{B_o \mu}{kh}\left[\frac{1}{2}\ln\left(\frac{4}{e^{\gamma}}\frac{A}{C_A \cdot r_{wa}^2}\right)\right] \qquad (8)$$

$$\bar{t} = \text{material balance time} = \frac{N_p}{q} \qquad (9)$$

$$D_i = \frac{m}{b_{pss}} = 7.9545 \times 10^{-2}\,\frac{\frac{k}{\phi \mu c_t A}}{\ln\left(\frac{4}{e^{\gamma}}\frac{A}{C_A \cdot r_{wa}^2}\right)} \qquad (10)$$

He also defines the dimensionless variables for boundary dominated flow regime as:

$$q_{Dd} = \frac{q/\Delta p}{(q/\Delta p)_{initial}} \qquad (11)$$

$$\bar{t}_{Dd} = D_i \bar{t} \qquad (12)$$

Using Eq. (11) and (12), after some mathematics, the analytical Eq. (5) can be changed into dimensionless form as:

$$q_{Dd} = \frac{1}{1 + \bar{t}_{Dd}} \qquad (13)$$

Blasingame type curve is plotted for three dimensionless radii (r_e/r_w =10, 100 and 100,000) by using above definitions as shown in Fig. 1. He also introduced the rate integral (q_{Ddi}) and rate integral-derivative (q_{Ddid}) stems to smooth the noises in production data and reduce non-unique solutions.

Both Fetkovich and Blasingame plots have a diagnostic feature. Fetkovich says that the flow rate profile, in log-log scale, is concaved up during the transient flow while it will be concaved down as boundary dominated flow starts.

Blasingame type curve can be used to estimate the values of permeability, skin factor and oil in place by matching production data history as plot of pressure normalized flow rate versus material balance time on Blasingame type curve. Permeability and skin factor values are estimated from the concaved up transient part of the type curve and oil in place is estimated using the boundary dominated part.

2.2. Flowing Material Balance (FMB) Method

Flowing Material Balance (FMB) method [4] is similar to conventional material balance analysis but does not need any shut-in pressure except initial reservoir pressure. This method is based on analytical pseudo steady state equation of undersaturated oil reservoir as follows:

$$\Delta p_D = 2\pi t_{DA} + \left(\ln\left(\frac{r_e}{r_w}\right) - \frac{3}{4}\right), \quad t_{DA} > 0.1 \qquad (14)$$

After some mathematics and using dimensionless variables definition and material balance time application [7], the equation will become into the following form:

$$\frac{q}{\Delta p} = -\frac{Q}{\Delta p \cdot c_t}\frac{1}{N \cdot b_{pss}} + \frac{1}{b_{pss}} \qquad (15)$$

So plotting $q/\Delta p$ versus $Q/\Delta p \cdot c_t$ on a Cartesian plot will yield N (oil in place) as the x-intercept. As a result, FMB method can be used for oil in place estimation and it cannot evaluate reservoir parameters. Since FMB method uses the material balance concept, oil in place can also be estimated for the case of variable rate/pressure production data.

3. METHODOLOGY

In this research different scenarios are designed to monitor the effect of rock and fluid compressibility values on oil production. For this purpose, synthetic data sets are generated by simulation and then analyzed by using modern production analysis methods.

3.1. Designing a Controlled Simulation Model

A reservoir model is designed and simulated using a commercial simulator in order to generate synthetic data of different scenarios. The designed model is radial with a centered well of 0.25 ft wellbore radius. The reservoir external radius is 10,000 ft, so large to achieve a long transient flow regime during the production scenarios. The model is 300 ft in height with a porosity of 10% and permeability of 100 md. The reservoir fluid properties are summarized in the table 1.

Table 1. Model Fluid Properties

Property	Value
ρo (pcf)	51.78
Gravity (°API)	39.02
Rsb (scf/STB)	1127
Bob (bbl/STB)	1.522
Pb (psi)	4043

In each production scenario the bottom-hole pressure will be set above the bubble point pressure and the reservoir will be always undersaturated.

3.2. MODELS

In order to monitor the effects of both rock and fluid compressibility values, the scenarios are categorized into two model series, A and B.

3.2.1. Model Series A: Rock Compressibility Effect

In order to study the effect of rock compressibility, four rock compressibility values are defined in different scenarios and the other parameters such as reservoir conditions, rock and fluid properties are the same. The selected rock compressibility values are given in table 2.

Table 2. Model Series A Specifications

Scenario Code	Rock Compressibility (psi-**1**)
A1	3.55E-06
A2	5.59E-06
A3	7.63E-06
A4	9.67E-06

The reservoir initial pressure is set at 5000 psi. The well is completed open hole and the bottom-hole pressure is kept constant at the value of 4960 psi.

The simulation is run for an approximately 10 years of production on constant bottom-hole pressure condition. The flow rate profile and cumulative oil production curve for different scenarios are presented in Figs. 2 and 3 respectively. Fig. 2 shows that the flow rate profile are similar in different scenarios at early times but at late times, the rate of decline in flow rate is greater for scenarios with lower rock compressibility values. Also Fig. 3 declares that the ultimate recovery holds a greater value for scenarios with higher rock compressibility values.

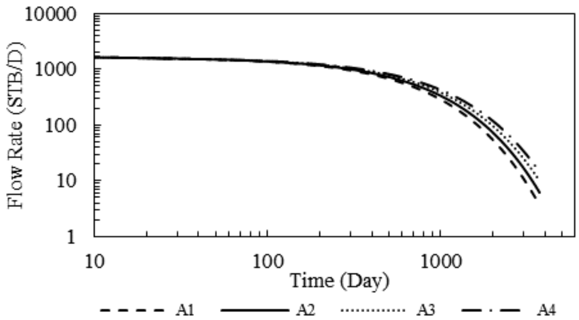


Fig. 2. Flow rate versus time for model series A.

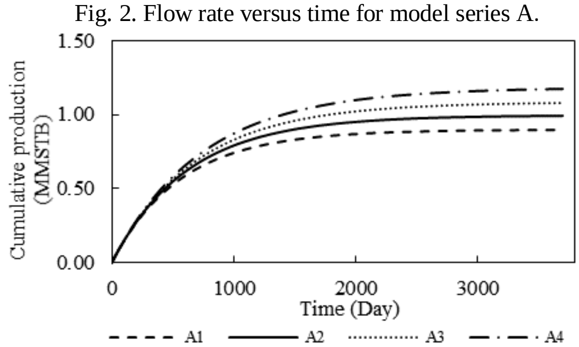


Fig. 3. Cumulative production versus time for model series A.

3.2.2. Model Series B: Fluid Compressibility Effect

Another parameter that affects the oil production in an undersaturated oil reservoir is the fluid compressibility. A change in initial pressure condition and bottom-hole pressure is applied in order to consider the effect of fluid compressibility while the pressure drawdown is the same as previous model. In this model series, two scenarios are run as given in table 3.

Table 3. Model Series B Specifications

Scenario Code	Initial Reservoir Pressure (psi)	Bottom-hole Pressure (psi)	Pressure Drawdown (psi)
B1	5000	4960	40
B2	4500	4460	40

Like model series A, the models are run for approximately 10 years and Figs.4 and 5 show the flow rate profile and cumulative oil production respectively.

Fig. 5. Cumulative production versus time for model series B.

4. ANALYZING PRODUCTION DATA SETS

Reservoir evaluation by using Blasingame method needs a typecurve matching process which is carried out from a

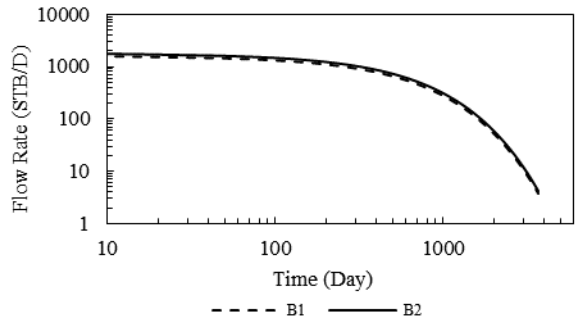


Fig. 4. Flow rate versus time for model series B.

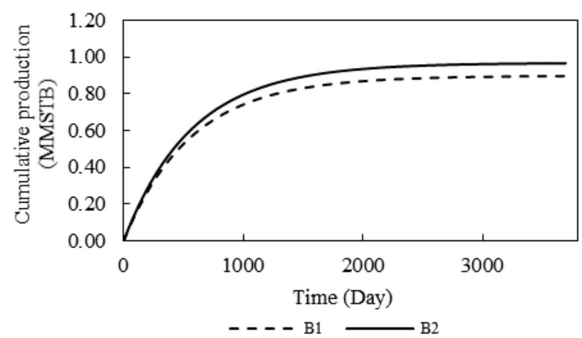


Fig. 5. Cumulative production versus time for model series B.

commercial production data analysis software. For the estimation of oil in place by FMB method the Curve Fitting toolbox of MATLAB software is used.

4.1. Blasingame Analysis

Plotting rate functions, rate, rate integral and rate integral derivative, the following matches for Blasingame type curve are obtained as illustrated in Fig. 6.

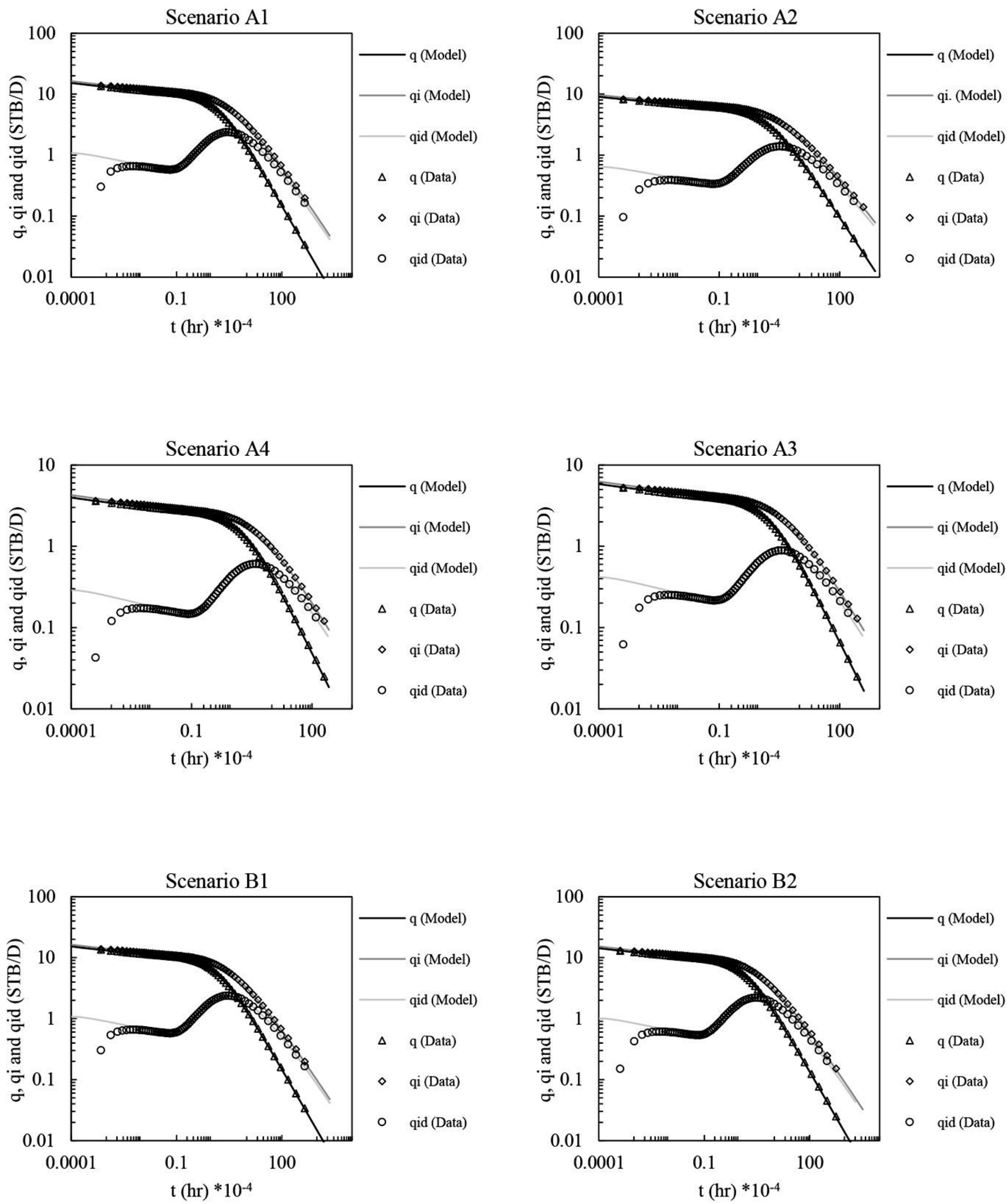


Fig. 6. Blasingame type curve analysis of all the scenarios

4.2. Flowing Material Balance Analysis

Plotting $q/\Delta p$ versus $Q/\Delta p \cdot c_t$ and extrapolating the data for x-intercept is done using Curve Fitting tool in MATLAB. The constructed plots are shown in Figs. 7 and 8.

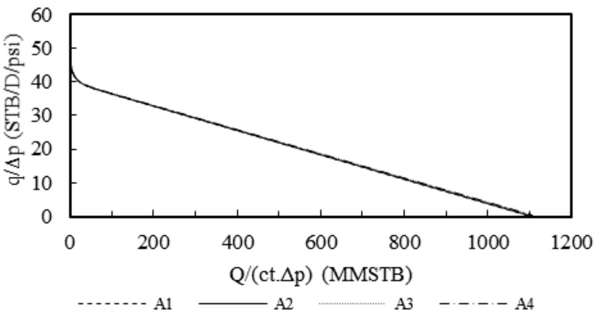


Fig. 7. FMB plot for model series A.

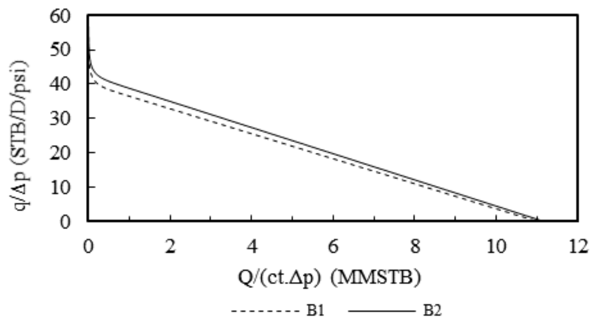
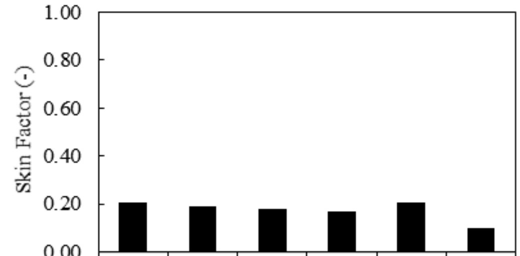


Fig. 8. FMB plot for model series B.

5. RESULTS AND DISCUSSION

The quantitative results of reservoir evaluation of the scenarios are shown in Figs. 9 and 10.



	A1	A2	A3	A4	B1	B2
Skin Factor (-)	0.21	0.19	0.18	0.17	0.21	0.10

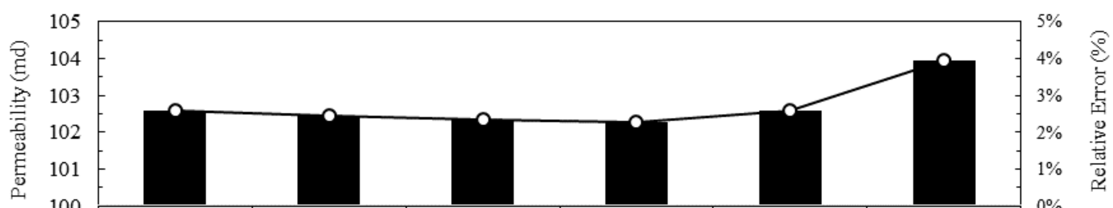
Fig. 9. Evaluated skin factor values

The results show that the evaluation of reservoir permeability and skin factor has an excellent accuracy in all scenarios. One of the most reasons of this high accuracy is that the reservoir has a relatively large amount of transient flow regime data in all cases which is used in reservoir evaluation methods. If early time data is lost, non-uniqueness solutions may cause significant errors in reservoir evaluation.

Fig. 11 illustrates the calculated values of oil in place by both the FMB and Blasingame methods.

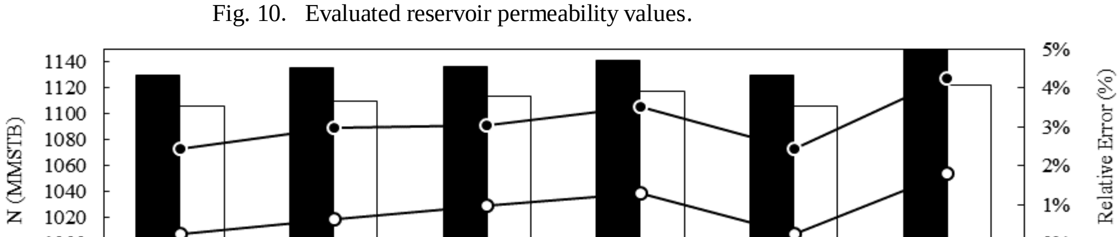
As it can be seen, changes in compressibility values has not changed the estimation of oil in place significantly. Although the flow rate profiles are different in all scenarios, the FMB plots are very similar in each model series and have a higher accuracy. The good accuracy in estimation of oil in place by the Blasingame method is because of using enough data in boundary dominated flow regime which is used for this purpose.

Recalling the flow rate behavior for model series A and B, we may now discuss about the rock and fluid compressibility effect. As Figs. 2 and 4 suggest, increase in compressibility values causes the flow rate to decline with a lower speed. Furthermore, Figs. 3 and 5, show that any increase in rock or



	A1	A2	A3	A4	B1	B2
Permeability (md)	102.59	102.46	102.36	102.28	102.59	103.95
Relative Error (%)	2.59%	2.46%	2.36%	2.28%	2.59%	3.95%

Fig. 10. Evaluated reservoir permeability values.



	A1	A2	A3	A4	B1	B2
N-Blasingame (MMSTB)	1129.74	1135.78	1136.45	1141.55	1129.74	1149.64
N-FMB (MMSTB)	1105.55	1109.82	1113.82	1117.22	1105.55	1122.63
Blasingame-R.E. (%)	2.44%	2.99%	3.05%	3.51%	2.44%	4.24%
FMB-R.E. (%)	0.25%	0.63%	1.00%	1.31%	0.25%	1.80%

Fig. 11. Estimated oil in place values.

fluid compressibility, causes a higher ultimate recovery due to the increase in the total compressibility value.

6. CONCLUSIONS

From this study, the following conclusions may be drawn:

1) Any increase in total compressibility yields in lower decline speed in an undersaturated oil reservoir. Also as total compressibility increases, ultimate recovery will also increase and a higher recovery factor will be achieved.
2) Flowing material balance (FMB) method holds a higher accuracy in estimation of oil in place while it cannot evaluate reservoir parameters. According to this, the Blasingame method is more powerful since both estimation of oil in place and reservoir evaluation are done at the same time by its type curve.
3) As the results show, production decline analysis method has an excellent accuracy when production data are in high frequency and quality. Recording production data in such quality will allow engineers to have a cheap and simple analysis which can estimate the oil in place and evaluate the reservoir parameters.

Nomenclature

A : Drainage area [acres]
Bo : Oil formation volume factor [bbl/STB]
b_{pss} : Inverse productivity index [psi/bbl]
C_A : Reservoir shape factor [-]
c_t : Total compressibility [psi-1]
D_i : Decline Factor [day-1]
h : Net pay [ft]
k : Permeability [md]
N : Original oil in place [STB]
N_p : Produced oil volume [STB]
$p_i - p_{wf}$: Flowing pressure drop [psi]
Q : Cumulative production [STB]
$q(t)$: Flow rate at time t [STB/day]
q_i : Initial flow rate [STB/day]
q_D : Dimensionless flow rate [-]
q_{Dd} : Decline dimensionless flow rate [-]
q_{Ddi} : Decline dimensionless rate-integral [-]
q_{Ddid} : Decline dimensionless rate-integral-derivative [-]
$q/\Delta p$: Pressure normalized rate [STB/day/psi]
R.E.% : Relative error percent [%]
r_e : Reservoir radius [ft]
r_D : Dimensionless radius [-]
r_{eD} : Dimensionless reservoir radius [-]
R_{sb} : Bubble point solution gas oil ratio [scf/STB]
r_w : Wellbore radius [ft]
r_{wa} : Apparent wellbore radius [ft]
$\bar{t}$: Material balance time [days]
t_D : Dimensionless time [-]
t_{DA} : Dimensionless time based on area [-]
t_{Dd} : Decline dimensionless time [-]
$\bar{t}_{Dd}$: Decline dimensionless material balance time [-]
u : Laplace space variable

Greeks

$\emptyset$: Porosity [fraction]
γ : Euler's constant
μ : Viscosity of oil [cp]
Δp : Pressure drawdown [psi]
Δp_D : Dimensionless pressure drawdown [-]

Subscripts

D : Dimensionless
d : decline
i : initial
pss : pseudo steady state

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