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Predicting Stabilized Oil Well Inflow Performance Relationship on Unconventional Reservoir

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Abstract

Unconventional reservoirs are described as any reservoir that requires special recovery operations besides the conventional operating practices. However, low permeability affects the time it requires to attain stability. Presently, most of deliverability test is only carried out in a maximum 24-hour time. Limited test time makes it almost impossible to attain the reservoir stabilization time while carrying out the deliverability test. Meanwhile, to construct Inflow Performance Relationship (IPR) curve, the properties from stabilized time are required. This study aims to discuss how to predict the IPR curve by determining the stabilized flow coefficient value (C) on unconventional reservoir. Furthermore, the stabilized C was used to determine the Inflow Performance Relationship (IPR) for low porosity and permeability reservoir model, also known as Tight Oil Reservoir. The stabilized time and deliverability exponent value need to be determined before the stabilized C value. The stabilized time also known as pseudo-steady state time was evaluated from John Lee and Chaudry equation with validation from the reservoir model. The method proposed by Hashem and Kazemi, which employed the use of transient data in determining the flow coefficient value was also used. In addition, deliverability exponent (n) was determined using an equation proposed by Johnston and Lee. Furthermore, the backpressure equation from Rawlins and Schellhardt was used to construct the IPR curve.

INTRODUCTION

BACKGROUND

Unconventional reservoirs are described as any reservoir that requires special recovery operations aside the conventional operating practices. They include heavy oil, tight gas-sands, coalbed methane, gas-hydrate deposits and this study focused only on low permeability oil reservoir. This type of reservoir is sometimes difficult to define and perceived differently by individuals. Some refer to low permeability reservoir as something less than 0.01 mD. Meanwhile, to another category of individuals, a reservoir with permeability less than 10 mD is considered low. This low permeability affects the time required to reach the pseudo-steady state or stabilization time, by making it prolonged compared to normal permeability reservoir. Some low permeability reservoirs may require days or even months to attain its stabilized time. Meanwhile, to construct Inflow Performance Relationship (IPR) curve, the properties from stabilized time is needed.

The multirate deliverability tests for oil have been well developed from gas well deliverability tests. One of the methods is backpressure testing using flow-after flow test (Rawlins & Schellhardt, 1935), which was first used for gas well. However, a well test is required before the deliverability test can be carried out. Presently, most deliverability test cannot be carried out for a long time, with usually only maximum of 24 hours. Due to this limited time, it is impossible for the reservoir to attain its stabilized time. Meanwhile, as earlier mentioned, it is important for the test to attain the stabilized time in order to construct the IPR curve.

In this study, the low permeability reservoir model was computed using CMG IMEX to carry out the deliverability test. The isochronal test for the reservoir deliverability test simulation was also carried out. Isochronal data is the well test data which is carried out when the well is opened for a period of time, after which it is shut until the reservoir pressure returns to the initial pressure. This routine is repeated for several times.

The backpressure tests Rawlins & Schellhardt (1935) represent the pressure squared data and rate in the log-log plot, which turns out as a straight line in the plot and is represented by the power equation shown below:

$$Q = C (P_{res}^2 - P_{wf}^2)^n \quad (1)$$

where C is the flow coefficient and n is the deliverability exponent. The equation above was used to construct IPR from the stabilized C and deliverability exponent that has been previously obtained. Furthermore, the Absolute Open Flow (AOF) value was obtained when the Pwf was equal to zero.

Objectives

The objectives of this study are as follows:

1. To evaluate the difference between result of Absolute Open Flow (AOF) using transient data and stabilized data on unconventional reservoirs.
2. To determine which method is better for determining the stabilized time which will be evaluated with the reservoir simulation on unconventional reservoirs.
3. To determine which method is better for predicting the Inflow Performance Relationship on unconventional reservoirs.

BASIC THEORY

The flow of fluid in the reservoir differs with time. The flow regimes were categorized into time region that they can occur and the kind of well that is used (vertical or horizontal). In the transient period, the well is not affected by the boundary effect yet, but it appears to be draining an infinite acting reservoir. During the transient period, the bottom hole pressure was in linear function with log time. The boundary starts to affect the reservoir when the flow regimes reach pseudo-steady state flow, where bottom hole pressure is the linear function of time. The illustration of the concept is shown in Figure 1.

$$t_s = 948 \frac{\phi \mu C_t r_e^2}{k} \quad (2)$$

Stabilized time equation Lee (1982) is derived from the diffusivity equation for an instantaneous line source in an infinite medium.

Other equation for stabilized time, also called time pseudo-steady state (Amanat Chaudhry, 2004). The equation is derived from dimensionless time which is used to define various flow regimes and substituted to the area-based dimensionless time. The time pseudo-steady state is given by the eq. (3):

$$t_{pss} = \frac{379 \phi \mu C_t A}{k} \quad (3)$$

The deliverability test is useful in predicting AOF (Absolute Open Flow), where in reality, it is unpredictable. Furthermore, it is commonly associated with rate and the bottom hole flowing pressure. It is also used to generate the reservoir inflow performance relationship (IPR). Meanwhile, it was used in this study to validate the stabilization time and determine flow coefficient in order to generate IPR. The flow coefficient to be determined is the stabilized C where the reservoir has reached its stabilization time. This is because as earlier mentioned the IPR curve needs to be constructed by properties from stabilized time.

During the transient flow, the following equation is commonly used for the compressible flow:

$$P_i^2 - P_{wf}^2 = 1422 \frac{\mu z T}{kh} q \left[\ln \left(\frac{k t}{1688 \phi \mu C_t r_w^2} \right)^{\frac{1}{2}} + s + D|q| \right] \quad (4)$$

Where:

$$D = 1.8295 \times 10^{-13} \frac{\beta \rho k B}{2 \phi h \mu r_w} \quad (5)$$

Where eq. (3) can be rewritten in similar forms with the Forchheimer equation as shown below:

$$P_i^2 - P_{wf}^2 = a(t)q + bq^2 \quad (6)$$

Where:

$$a(t) = 1422 \frac{\mu z T}{k h} \left[\ln \left(\frac{k t}{1688 \phi \mu C_t r_w^2} \right)^{\frac{1}{2}} + s \right] \quad (7)$$

Eq. (6) shows that when $a(t)$ is plotted against $\log t$, a straight line with a slope and intercept b was obtained. When it was extrapolated until the stabilized time, a more stabilized value of a was obtained. Therefore, eq. (5) was rearranged as shown below:

$$\frac{P_i^2 - P_{wf}^2}{q} = a(t) + bq \quad (8)$$

Furthermore, from the backpressure equation (Rawlins & Schellhardt, 1935), to obtain the stabilized C , eq. (1) was rearranged as shown below:

$$P_i^2 - P_{wf}^2 = \frac{1}{C \bar{n}} q^{\frac{1}{n}} \quad (9)$$

Comparing eq. (8) with (3), the following was obtained:

$$\frac{1}{C \bar{n}} q^{\frac{1}{n}} = 1422 \frac{\mu z T}{k h} q \left[\ln \left(\frac{k t}{1688 \phi \mu C_t r_w^2} \right)^{\frac{1}{2}} + s + D|q| \right] \quad (10)$$

$$\frac{1}{C \bar{n}} q^{\frac{1}{n}} = 1637 \frac{\mu z T}{k h} q \left[\log \left(\frac{k}{1688 \phi \mu C_t r_w^2} \right) + \log t + 0.869 s \right] + bq^2 \quad (11)$$

For the $Q = 1$ Mscfd and $t = 1$ hour inputted to the slope, eq. (10) becomes:

$$\frac{1}{C \bar{n}} = 1637 \frac{\mu z T}{k h} \left[\log \left(\frac{k}{1688 \phi \mu C_t r_w^2} \right) + \log t + 0.869 s \right] + b \quad (12)$$

From the equation above, a straight line was obtained with a slope by plotting $\frac{1}{C^{(1/n)}}$ with $\log t$ and the eq. (13) was produced:

$$\frac{1}{C \bar{n}} = m \log t + constanta \quad (13)$$

Where m is the gradient of the slope and t was substituted by the stabilized time. The main concept was to extrapolate eq. (12) until the stabilization time. The stabilized flow coefficient was obtained after substituting the obtained deliverability exponent.

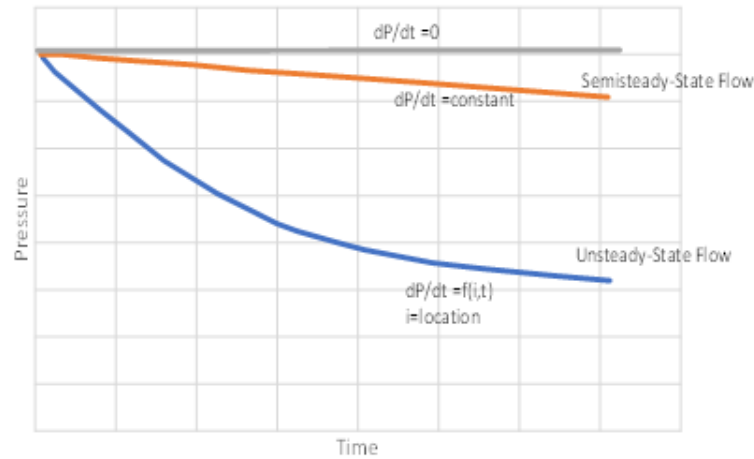
The deliverability exponent (n) value is required in order to determine the value of C . Meanwhile, Johnston et al (1991) equation was used to determine n :

$$n = \frac{N \sum_{j=1}^N (\log Q \log \Delta P_p)_j - \sum_{j=1}^N \log Q \sum_{j=1}^N (\log \Delta P_p)_j}{\sum_{j=1}^N (\log \Delta P_p)_j^2 - \left[\sum_{j=1}^N (\log \Delta P_p)_j \right]^2} \quad (14)$$

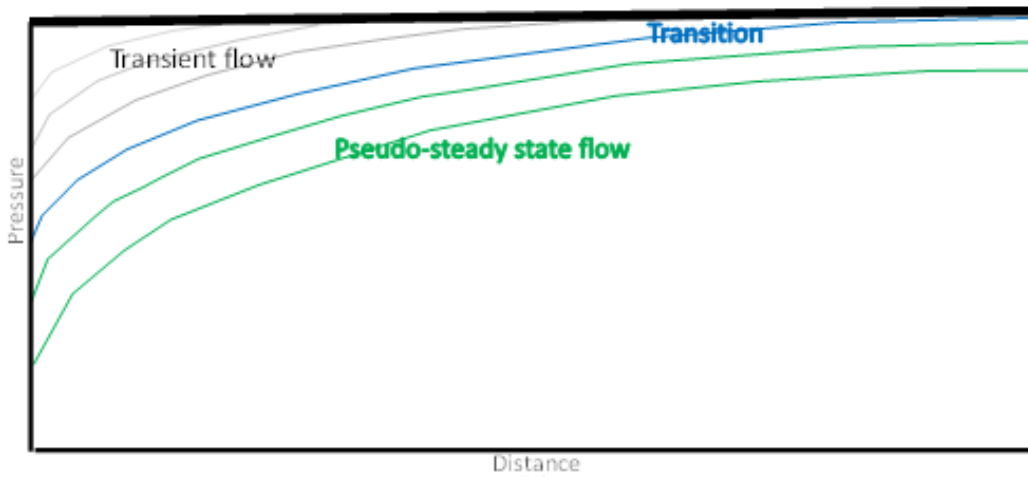
After the deliverability exponent of each isochronal test was determined, the average deliverability exponent was used to determine C . Therefore, average n was calculated using the eq. (15):

$$\bar{n} = \frac{\sum_{j=1}^M n_i}{M} \quad (15)$$

Where M is the number of isochronal tests that have been carried out. The value of n was further substituted into $\frac{1}{C^{(1/n)}}$ to determine the value of C in eq. (12).



(A)



(B)

Figure 1. Illustration difference between flow regimes. (B) Illustration of the boundary effect when pseudo-steady state flow starts to happen

METHODOLOGY

The reservoir model employed was built by using the Computer Modelling Group (CMG) IMEX. The required output data from CMG was the well test data, which was later imported into Microsoft Excel to further analyze the pseudo-steady state time. As earlier mentioned, the bottom-hole pressure data will have a linear relationship with time when the reservoir attains its pseudo-steady state. The imported data was analyzed using charts to decide the pseudo-steady state time. Furthermore, isochronal test was carried out on the reservoir model in order to determine the deliverability exponent and flow coefficient value using the methods explained before. All the methodology steps and flowchart are shown in Figure 2.

Reservoir Modelling

Every reservoir has its own characteristics and as previously mentioned, tight oil or low permeability reservoir is perceived differently by individuals. To some, reservoir permeability with less than 10 mD is considered low, while others refer to low permeability reservoir as one with permeability less than 0.1 mD. Table 1 shows low permeability reservoir model data that has used for other studies. Furthermore, the data was considered for building the proposed reservoir model.

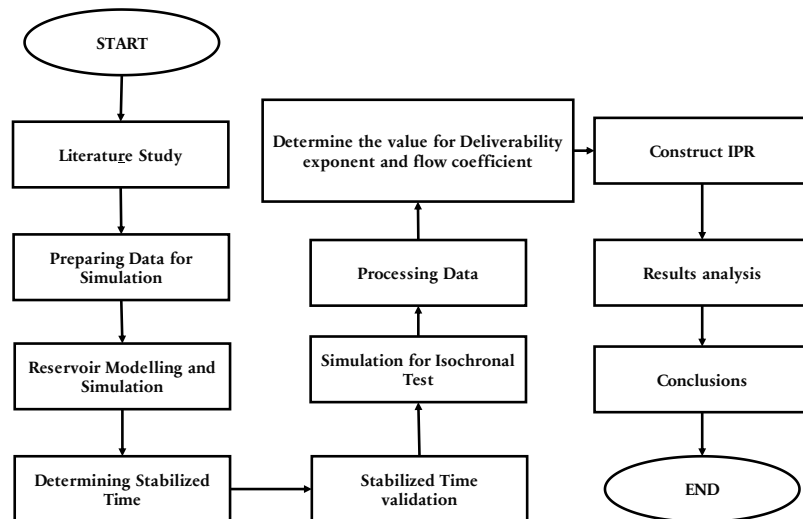


Figure 2. Methodology used for this study

The reservoir model used in this study was in a radial model (20 x 8 x 100) with porosity of 10%. Its top was at a depth and height of 5000 ft and 200 ft, respectively. The pressure at the depth was 2330 psia with temperature of 200 °F. The reservoir was homogenous with permeability of 1 mD and its fluid model's API Gravity was 44 API. All data were inputted in the Computer Modelling Group (CMG) Builder and the finished reservoir model is shown in Figure 3. After that, a single producer well was located in the middle of the reservoir and the drainage radius used was 1000 ft. The well was set to produce at a rate of 5 bbl/day. Furthermore, the CMG IMEX was used to numerically calculate the data inputted in the builder. As the output, a well test curve was shown in the results curve after plotting the bottom hole pressure against time.

Table 1. Tight Oil Reservoir Model References – Several data taken from Osaliana Budiarto (2014)

No	Reference	k (mD)	Porosity	Pressure (psi)	Depth (ft)	Fluid (API)	C _t (psi ⁻¹)
1	Clarkson, C, Pedersen, P (2011)	0.28	0.12	2017	-	-	1.32 E ⁻⁵
2	X. Li, H. Wei (2008)	0.05 – 0.3	0.11- 0.135	2100	6200	35	-
3	Saputra, W, Kirati, W., et al (2019)	0.045	0.046	5340	-	42.2	9 E ⁻⁶
4	Xinghui Liu, Pinnacle (2012)	0.05-0.3	0.08- 0.105	800	2500	44	-
5	Shengnan, Chen (2012)	1-20	0.05- 0.115	4000	6700	41	-
6	Ghaderi, S.M., et al (2012)	<1	0.12	2520	5300	36	-
7	Budiarto, Osaliana (2014)	0.001-6.4	0.02-0.18	2330	5000	33- 53	-

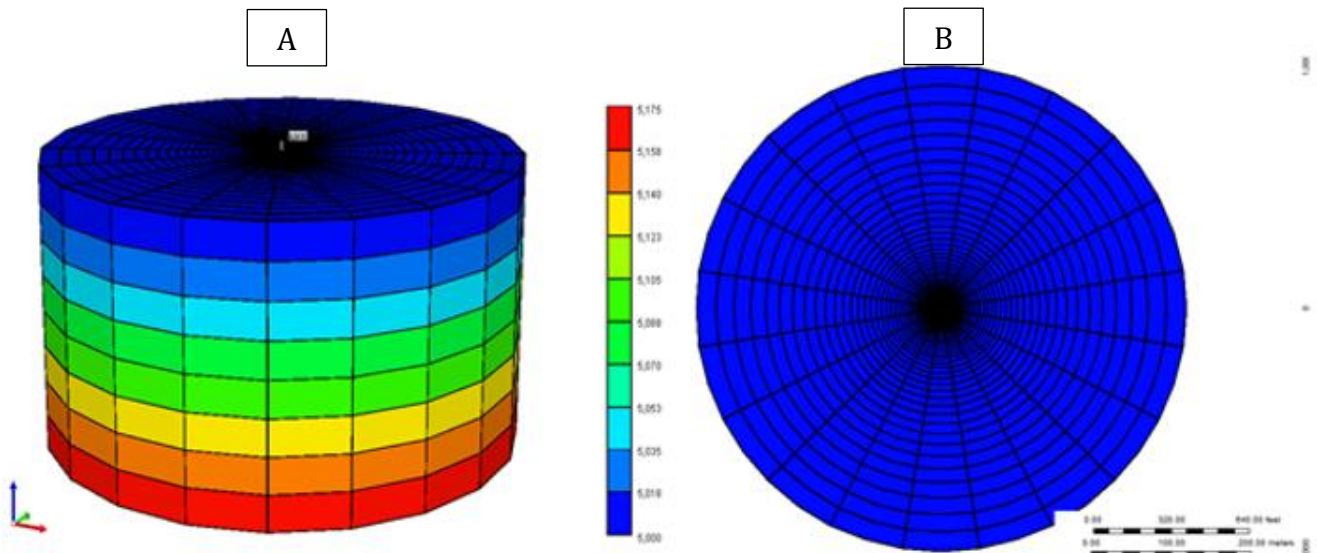


Figure 3. (A) Reservoir Model used in this study in 3D model (B) Reservoir Model used in this study from top view

Stabilized Time Determination

Furthermore, the stabilized time was calculated using equation (1) and (2). This implies that it was evaluated by two equations, one proposed by Lee (1982) and the other by Amanat Chaudhry (2004) The validation for the stabilization time was carried out by comparing the results obtained to reservoir simulation carried out by Computer Modelling Group (CMG) IMEX. One of the results of the numerical calculation in IMEX is bottom-hole pressure data, which was plotted against time, to produce a test data for the well. The required data was exported to Microsoft Excel in order to obtain the time stabilization and was further analyzed using charts to ascertain the stabilized time from reservoir simulation result. In this study, only the drawdown or pressure data from production phase of the well test was analyzed. This is because, it provides information concerning the reservoir boundary that will lead to a pseudo-steady state time.

As earlier mentioned, the bottom-hole pressure data should have a linear relationship with time, which was made from the chart in excel. Furthermore, during the prediction of the Inflow Performance Relationship, which described the reservoir's productivity, the Productivity Index was used as the indicator, where:

$$PI = \frac{Q}{P_{res} - P_{wf}} \quad (16)$$

When the PI produced a constant slope with time, it was assumed that the reservoir has started the pseudo-steady state period, i.e., it has attained its stabilized time. The determination of stabilized time from reservoir simulation is shown in Figure 5. As earlier mentioned, the results from this method were used as a validation for both equations proposed by Lee (1982) and Amanat Chaudhry (2004). Furthermore, all the stabilized time results were used to analyze the best method for determining the flow coefficient value and AOF.

Deliverability Exponent Value

The flow coefficient value was determined from the Isochronal test, which requires several bottom-hole pressures at a time duration for further calculation of the flow coefficient. The isochronal data was obtained from the model with the sensitivity of the well production rate and the results are shown in Figure 4. Furthermore, the required bottom-hole pressure was obtained and is shown in Table 2. Furthermore, the isochronal data was used in calculating the deliverability exponent value and the stabilized flow coefficient.

Using isochronal data, the deliverability exponent value was determined with eq. (14). The value of deliverability exponents depends on the flow characteristics and usually within a range of 0.5 – 1.0. The closer it is to 1.0, the more likely the flow is to be laminar. The deliverability exponent calculation results are shown in Table 3. Validation for deliverability exponent was carried out using the Backpressure test method Rawlins & Schellhardt (1935), where the pressure squared was plotted against rate and was further analyzed using the power relationship. The inverse of the exponent value should be similar to the results from Johnston and Lee's deliverability exponent. To simplify the validation, a plot of rate against pressure squared was analyzed using a power relationship. Furthermore, the value of deliverability

exponent has to be the same as the exponent value from the power equation. In addition, all the deliverability exponent of each time step in each isochronal test needs to be calculated. The calculated deliverability exponent values were calculated using eq. (15) to determine the averaged deliverability exponent values, which was further used to determine the stabilized coefficient value.

Table 2. Isochronal test result data

Pres (psia)	Rate (bbl)	Duration (hour)	Pwf (psia)
2333	3	6	2328.33
	3	9	2328.13
	3	12	2327.98
	3	15	2327.86
2333	5	6	2324.85
	5	9	2324.50
	5	12	2324.25
	5	15	2324.05
2333	10	6	2316.23
	10	9	2315.39
	10	12	2314.79
	10	15	2314.32
2333	15	6	2307.20
	15	9	2305.85
	15	12	2304.88
	15	15	2304.10

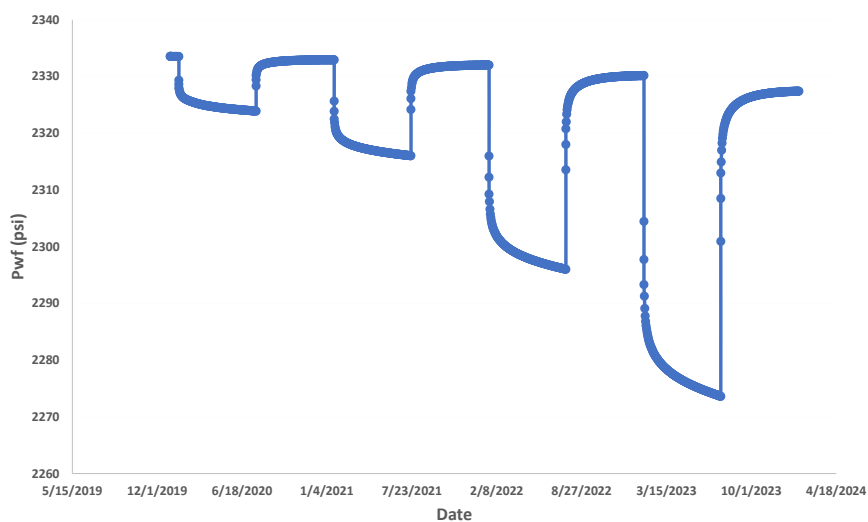


Figure 4. Isochronal data from well test result.

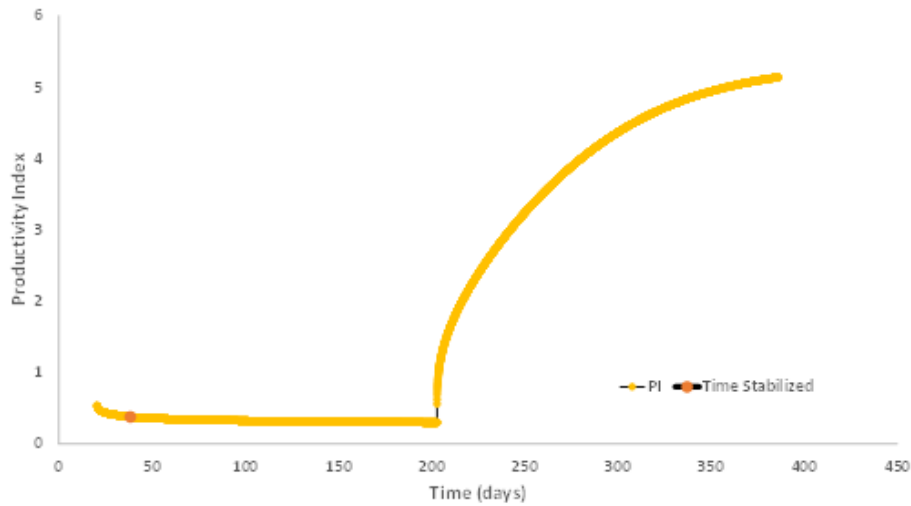


Figure 5. Productivity Index vs Time on base reservoir model for validating the stabilization time obtained from other methods

Stabilized Flow Coefficient Value

After the deliverability exponent has been calculated, the flow coefficient value was further calculated. Firstly, the value of $\frac{1}{C^{1/n}}$ for each time step from isochronal data using eq. (9) was calculated. Subsequently, the average value for each time step was obtained based on the number of isochronal tests that have been previously carried out. The results obtained were plotted with $\log t$ and a linear relationship was obtained, which was similar to eq. (13). Furthermore, the averaged deliverability exponent and stabilized time was substituted into the linear equation for determining stabilized C

RESULTS AND DISCUSSION

The comparison result for time stabilization using John Lee (1982), Chaudry (2004), and reservoir simulation is shown in Table 5. The graph result from the reservoir simulation can be seen in Figure 5. From the results, we can see there is a little difference in the amount of time needed for the reservoir to reach its stabilized time. Also, if it is seen from the perspective of bottom hole pressure difference, there are not many differences between them. Then, the stabilized time obtained will be used as an input for flow coefficient equation.

The result of deliverability exponent can also be seen on Table 3, where the averaged deliverability exponent will be used to determine the value of C. Figure 6 show the validation for deliverability exponent using a bakcpresure test method (Rawlins and Schellhardt, 1935). The inverse of exponent value in the power equation shows the same value as the deliverability exponent calculated using the method Johnston proposed

Table 3. Deliverability Exponent Value of each Isochronal data

t1 = 6 hr	n1	0.9974
t2= 9 hr	n2	0.9899
t3 = 12 hr	n3	0.9852
t4 = 15 hr	n4	0.9815
n_{avg}		0.9885

In order to obtain the stabilized flow equation, a graph of $\frac{1}{C^{1/n}}$ against $\log t$ was made as shown in Figure 7. The linear equation below was obtained from the graph:

$$\frac{1}{C^{1/n}} = 2.036 \log t + 6.3068 \quad (17)$$

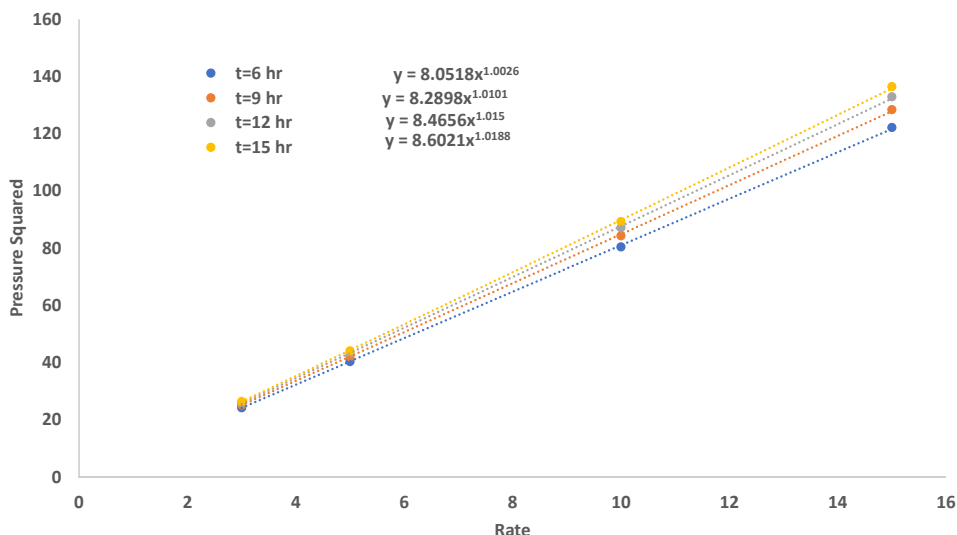


Figure 6. Pressure Squared (Mpsia) vs Rate (bbl) plot with power trendline for validating deliverability exponent from Johnston and Lee (1991) proposed equation

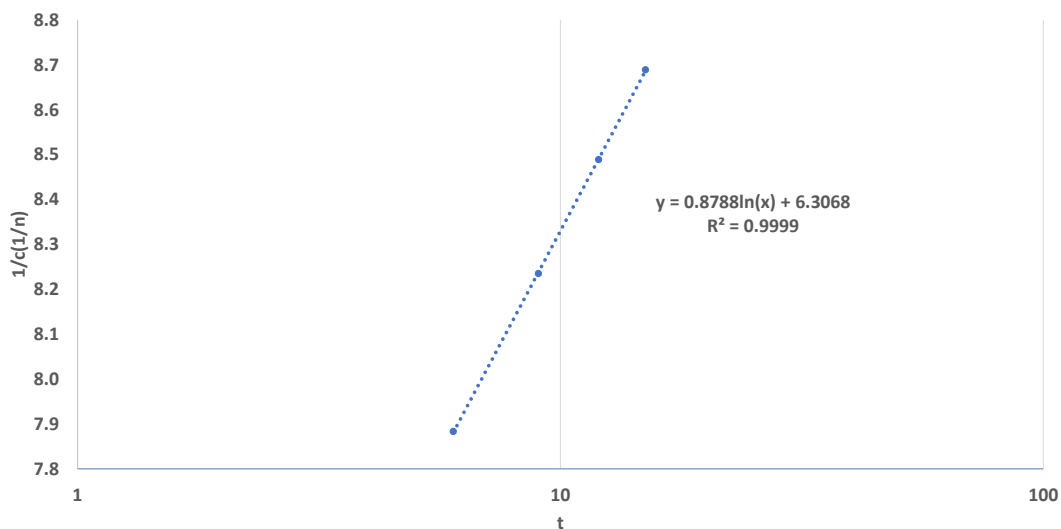


Figure 7. $\frac{1}{C^{1/n}}$ plot versus log t

Each of the time stabilization obtained was inputted into the eq. (17), alongside the averaged deliverability exponent that was previously calculated. The obtained stabilized C comparison for each time stabilization is shown in Table 4. Using eq. (1), IPR curve was further constructed from the variables obtained, as shown in Figure 8. The Absolute Open Flow (AOF) obtained from each method is shown in Table 5.

Table 4. Data for plotting $\frac{1}{C^{1/n}}$ versus log time

t (hr)	$\frac{1}{C^{1/n}}$
6	7.8833
9	8.2352
12	8.4889
15	8.6891

From the results it was seen that the transient data which describes the limited time for deliverability test and is usually carried out in 4 hours, has a big difference in the AOF result compared to the reservoir simulation where the reservoir has already been stabilized. This proves that there are big AOF differences between the transient time test with reservoir simulation – the stabilized time. Furthermore, it was seen that the AOF result from Amanat Chaudhry (2004) t_{pss} has smaller differences to the reservoir simulation compared to Lee (1982) t_s equation. It shows about 1.5% difference in the result of AOF between John Lee’s and Chaudry’s method. This makes Amanat Chaudhry (2004) t_{pss} more preferable for determining the AOF, because it shows a better result than Lee (1982) t_{pss} AOF Result.

Out of curiosity, the author aimed at testing how total compressibility affects the AOF results, since it is a sensitive property of the reservoir. The total compressibility also affects the AOF and stabilized time result. The higher the total compressibility, the longer it is for the reservoir to reach its stabilized time. The value of total compressibility also affects the AOF value and the results of the calculation are shown in Table 6. Therefore, the bigger the total compressibility value, the smaller the AOF value becomes. The comparison of IPR curve is shown in Figure 9, while the calculation flow and method used are shown in Figure 10.

Table 5. Stabilized flow coefficient calculation results

Method	Time Stabilized (hrs)	BHP (psia)	Flow Coefficient Value (bbl/Mpsia ²)	AOF (bbl/day)	% Difference with Res. Sim.
Transient			0.1360	670.83	54.43
John Lee	314.58	2320.83	0.0905	446.44	2.77
Chaudri	394.91	2320.49	0.0890	438.81	1.01
Reservoir Simulation	452.00	2320.29	0.0881	434.40	

Table 6. AOF Value between $C_t = 9e-6$ using Lee (1982) and Amanat Chaudry (2004) stabilization time

	John Lee (1982)		Chaudry (2004)	
	$C_t = 9e-6$	$C_t = 1.32e-5$	$C_t = 9e-6$	$C_t = 1.32e-5$
AOF (bbl/day)	446.44	433.74	438.81	426.54

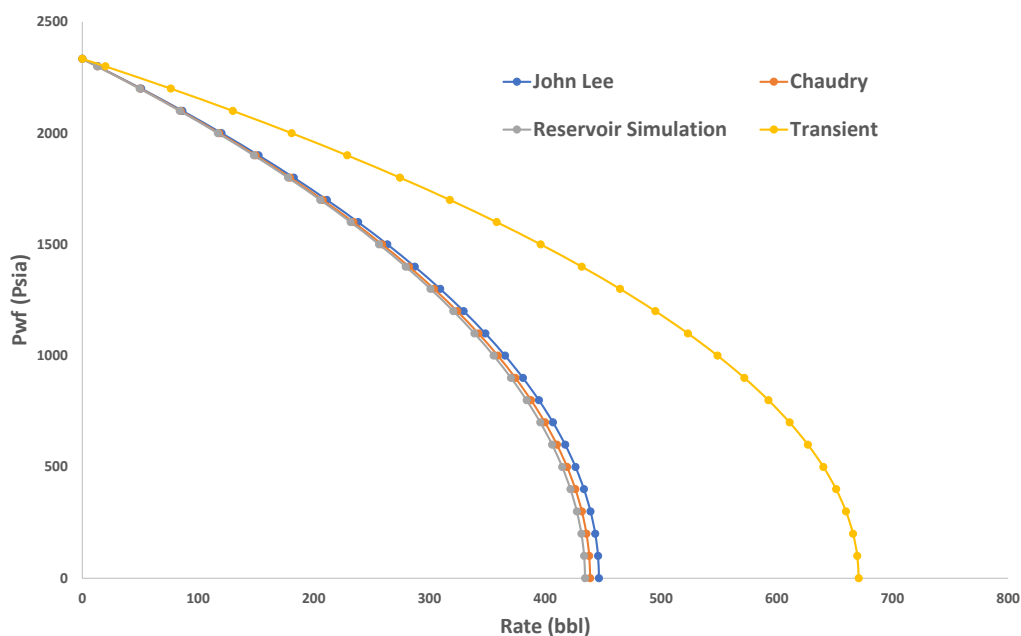


Figure 8. IPR Curve comparison

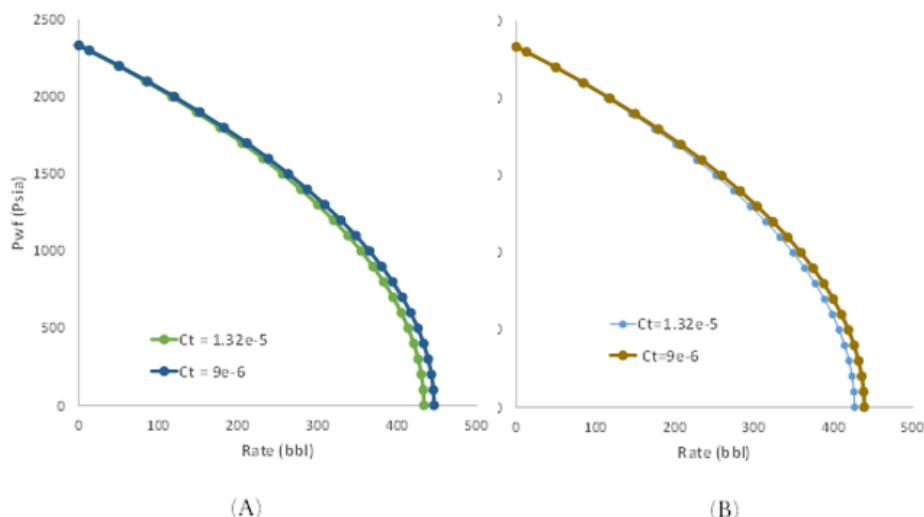


Figure 9. (a) IPR Curve comparison for Total compressibility sensitivities using t_s (Lee, 1982) (b) IPR Curve comparison for Total compressibility sensitivities using t_{pss} (Amanat Chaudry, 2004)

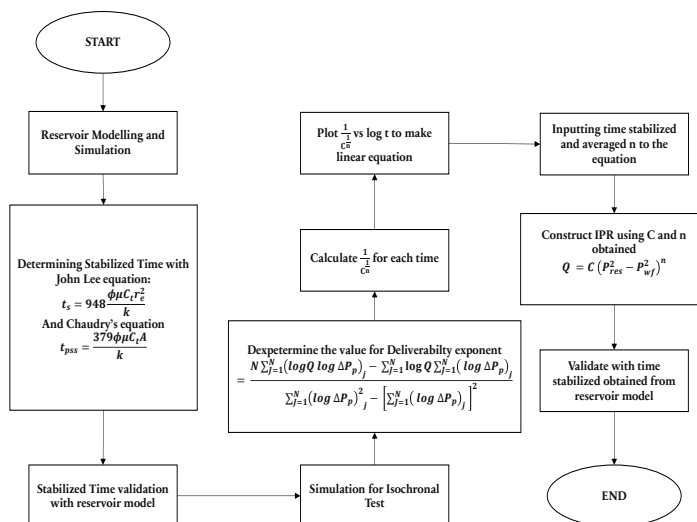


Figure 10. Work flow for the calculation used in this study

CONCLUSIONS

From the results obtained, several conclusions were made, which include:

- The transient data will yield over-optimistic results compared to the stabilized data. This was seen from the AOF result that the difference between transient data and reservoir simulation is 54.43%.
- Chaudry (2004) showed better results for the determination of stabilized time, which was 1.5% more accurate compared to John Lee (1982) method. Although, the time difference with the reservoir simulation was significant, when analyzed from the BHP perspective, Chaudry (2004) t_{pss} only showed less than 1% difference from the reservoir simulation BHP at stabilized time.
- For predicting the IPR curve, Chaudry (2004) t_{pss} also showed better results compared to John Lee (1982) t_{pss} . The two methods showed 1.5% difference with Chaudry (2004) t_{pss} AOF result being closer to the reservoir simulation AOF result.

RECOMMENDATION

Regarding the processes and results of this study, further studies is suggested using field data with a heterogenous low permeability reservoir to analyze the difference between the results of Inflow Performance Relationship using transient and stabilized data.

NOMENCLATURE

A	= area, ft ²
b	= coefficient in pseudo-steady state equation (Mpsia ² /bbl)
B	= Formation volume factor (res bbl/ bbl)
C	= Flow Coefficient (bbl/Mpsia ²)
C _t	= Total compressibility (psia ⁻¹)
D	= Non-Darcy Flow constant (1/bbl)
h	= Thickness (ft)
k	= Permeability (mD)
m	= Slope of straight line (Mpsia ² /bbl/cycle)
M	= Number of time duration in isochronal test
n	= Deliverability exponent
P _i	= Initial reservoir pressure (psia)
P _p	= Pseudopressure (psia ² /cP)
P _{wf}	= Bottom-hole pressure (psia)
Q	= Oil flow rate (bbl)
R _e	= Radius exterior reservoir (ft)
R _w	= Wellbore radius (ft)
S	= Skin factor
t	= Time (hr)
t _{pss}	= Pseudo-stabilization time (hr)
t _s	= Stabilized time (hr)
T	= Temperature (oR)
z	= Gas deviation factor
ϕ	= Porosity
μ	= Oil viscosity (cp)

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