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Estimation of Developed Reserves in Gas Lifted wells.

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Abstract

Reliable estimates of petroleum reserves are invaluable in reservoir management decisions and economic evaluation. Classical decline curve analysis techniques have been routinely used and are generally accepted in the industry to reliably estimate developed reserves up to a predetermined economic limit q_{ec} in oil wells. However Decline curve analysis techniques are based on the assumption that past production trends and their controlling factors will continue in the future and therefore can be extrapolated for predictions.

During gas lifting, production trends could be distorted hence there is need to modify the classical decline curve analysis equation.

In this study, the principle of superposition has been applied to the entire duration of production (t) of wells producing under gas lift. This resulted in the so called Double Semi log equation for well decline analysis. Model validation with two fields in the Niger Delta area show excellent results and the economic advantage of gas lifting. The Models showed excellent correlation coefficients with available field data.

It is concluded that gas lift could increase the reserves in some wells. Furthermore the Double Semi log technique provides a better and more reliable theoretical foundation, easier and more reliable technique for decline analysis in gas lifted wells.

Introduction and Review of literature

Reliable estimates of reserves are useful in petroleum economics and reservoir management policy formulations and practice. More over, reserves are directly proportional to the income accruable from an acreage or oil block. An error in reserves estimation can lead to either over overvaluing of an acquisition thereby leading to several unpleasant economic consequences such as loss of return on investment, overtaxation, etc. Many methods are currently in for the estimation of reserves. These include volumetric method, Material balance, Decline curve analysis, Extrapolation of observed reservoir trends, reservoir simulation techniques, Classical techniques etc. These methods are often used in combination. The most frequently-used technique for developed reserves estimation is the Decline Curve Analysis. The basic equation for decline curve analysis was given by Arps[1] in 1945 his famous paper 'Analysis of Decline Curves' as

$$q(t) = \frac{q_i}{[1 + bD_i t]^{1/b}} \qquad (1)$$

which describes a hyperbola. The values of b ranges between 0 and 1.

For b=0, the **exponential decline** is obtained and is given from equation (1) as

$$\frac{q_i}{q_t} = \frac{1}{D_i t} \qquad (2)$$

It can also be written as

$$q_t = q_i e^{-ct} \qquad (3)$$

where $D_i \equiv c$

Many authors have attempted to determine production decline behavior using a completely theoretical approach but still largely depend on the empirical models to validate their theoretical model.[8]

An analysis usually involves the plotting of the production rate versus either time or cumulative production as the abscissa. The area under the rate-time curve gives the cumulative production to date thus enabling the engineer to determine the developed reserves as well as productive life of the well or reservoir.

Gas lift helps to lower the hydrostatic pressure exerted by the liquid column through the introduction of gas into the oil stream in the tubing in order to reduce the fluid density and hence the hydrostatic pressure. This in turn lowers the bottom hole flowing pressure thus increasing the pressure draw down which in turn results in either flow increase or flow resumption as the case may be.

The goal of gas lift is to deliver the fluid to the top of the wellhead while keeping the bottomhole pressure low enough to provide high pressure drop between the reservoir and the bottomhole. This tends to distort the production decline trend and the classical decline curve techniques become in adequate foranalyzing the well decline

Higgins and Lechtenberg[6] proposed the equation

$$y = ae^{bt} + ce^{dt} \quad (4)$$

as'The Double Semi Log' because it is the sum of two exponentials which in general did not form another exponential. The values of the constants are obtained by using two semi log equations. In their work Higgins and Lectenberg[6] observed that the double semi log was better than the Semi log and Arps' equation during history matching of flow rate data in some fields

Russel and Prat[7] applied the double semi log equation to the total production rate from both layers of a stratified reservoir separated by a continuous black shale at pseudo-steady state producing a single phase liquid at the same constant wellbore pressure

Fetkovich, M.J.[2], used the double Semi log to match rate –time data to a type curve and found that by using the difference method, he determined a predictive equation for the reservoir of interest. He asserted that the separate flows of the reservoirs could be superposed to give the total flow rate, which is modeled by the double semi log equation.

This paper presents an approach for the determination of developed reserves in wells after the wells have been put on gas lift using the Double Semi Log. The principle of superposition was used to determine the developed reserves for the two periods in the productive life of the gas lifted well viz. natural production and gas lift periods.

THEORETICAL FRAME WORK

The model was developed based on the generalized empirical Arp's decline curve analysis equation.

The nominal decline constant as a result of the gas lift effect ε, was determined for the gas lift period using the Arp's Decline Curve Analysis equation. The nominal decline constant for natural flow c, is the same for both before and during the period of gas lift.

The principle of superposition was used to determine the total rate of flow $q_{oT}(t)$ for the well/reservoir. This was found to result in the sum of two exponentials which has been named the Double Semi log.

The Double Semi log was used to history match the production rate for both periods with excellent results.

Extrapolation of total flow rate,q_{oT} to a pre determined economic limit of production enables the Engineer to determine the well cumulative production and the well/reservoir life for both natural flow alone and gas lift supported flow. The time to reach the economic limit during gas lift, other factors being constant, is the total productive life of the well or reservoir as the case may be. The developed reserves may be determined by integrating the equation with respect to time.

Developed reserves Q_1 and Q_2 for the natural and gas lift supported flow respectively up to the pre determined economic limit , q_{ec} may then be easily determined.

The increase in reserves due to gas lift is given by $Q_2 - Q_1$.

PRINCIPLE OF SUPERPOSITION

The principle of superposition may be defined as 'the total flow rate q_{oT} at a time t, is the sum of the natural flow rate and the gas lift induced flow rate.' Stated mathematically,

$$q_{oT}(t) = q_{onf}(t) + q_{ogl}(t) \quad (5)$$

For the case where the natural flow rate declined to zero before the onset of gas lift the flow during gas lift is given completely by the gas lift induced flow rate. i.e

$$q_{oT}(t) = q_{ogl}(t) \quad (6)$$

Applying the Superposition Principle to the hypothetical case shown in fig 1.0, the developed reserves is determined by summing regions A and B. This is given by

$$Developed\ reserves = \int_0^{t_1} q_{onf}\,dt + \int_{t_1}^{t_2} q_{ogl}\,dt$$

(7)

DETERMINATION OF DEVELOPED RESERVES

In general, the developed reserves up to the economic limit rate of flow is given by the integral of the rate –time curve with respect to time. i.e.

$$Developed\ reserves = \int_0^t q.dt \quad (8)$$

For gas lifted wells, flowing from time 0 to t_2, two periods of flow may be identified. (see fig.1) These are

(1) Natural flow from time 0 to t_1

(2) Gas lifted flow from t_1 to t_2

In the natural flow period, the flow rate is determined by reservoir and well performance characteristics such as average reservoir pressure, productivity index, gas liquid ratio and well depth, among others. However, the rate in the gas lift period is influenced tremendously by the gas lift effect as well as other factors.

During gas lift, the flow rate decline is caused by the same reservoir properties as the rate decline during the natural flow period since the gas lift only affects oil in the well bore (tubing).The change in decline rate is principally as a result of a different rate of drawdown change with time at the well bottom among other changes. The flow rate before gas lift is therefore given by the Arps' Equation in this study while the flow rate for the gas lift period is given by the superposition of the natural flow and gas lift induced rate using the double semi log equation.

Gas lifting a well not only increases the rate of production, it also increases the life of the well thereby increasing the developed reserves for the well. The rate of gas lift q_g influences the rate of oil production q_o i.e

$$q_o = f(q_g) \quad (9)$$

The greatest flow efficiency occurs when the oil and gas are flowing under no-slip conditions. Assuming no slip flow conditions, and gas lift rate declines uniformly with oil flow rate the general equation for the gas lift well decline is given by

$$\frac{1}{q_{ogl}}\frac{dq_{gl}}{dt} = -\varepsilon \quad (10)$$

Integrating equation 10 and taking limits,

$$q_{ogl}(t) = q_{oigl}e^{-\varepsilon t} \quad (11)$$

Where q_{oigl} is the optimum or maximum oil flow rate obtained due principally to the gas lift effect before a continuous rate decline sets in.

The decline constant for gas lift is defined as ε

$$\varepsilon = \lambda c \quad (12)$$

Therefore equation 10 can be written as

$$q_{ogl}(t) = q_{oigl}e^{-\lambda ct} \quad (13)$$

From (12), the ratio of the gas lift to the natural flow decline constant, $\lambda = \frac{\varepsilon}{c}$

(14)

But, by superposition principle, total oil flow rate at time t,

$$q_{oT}(t) = q_{onf}(t) + q_{ogl}(t) \quad (15)$$

Putting equations (13) and (14) into (15)

$$q_{oT}(t) = q_{o\inf}e^{-ct} + q_{oigl}e^{-\lambda ct} \quad (16)$$

We define a ratio, $\beta = \frac{q_{oigl}}{q_{o\inf}}$ (17)

The Ratio of intercepts of gas lift flow to Natural flow on the flow axis.

Therefore equation 16 can be written as

$$q_{oT}(t) = q_{o\inf}\left(e^{-ct} + \beta e^{-\lambda ct}\right)$$

(18)

BOUNDARY CONDITIONS

1) When λ=1, and β=0, since q_{oigl} = 0 ,therefore equation (18) reduces to equation (3) i.e. natural flow only.

2) Attainment of optimum oil flow rate is necessary for application of equation (18) since it only captures the period of declining flow rate.

Equation (18) is the model for determination of total oil flow rate in gas lift wells under exponential decline.

Using equation (8) ,the developed reserves is therefore given by

$$Developed\ reserves, Q_T = \int_0^t q.dt \quad (19)$$

$$Q_T = \int_0 q_{oT}(t)dt \qquad (20)$$

Since gas lift commenced at time t_1, equation (20) may also be written as .

$$Q_T = \int_0 q_{onf}(t)dt + \int_{t_1}^{t_2} q_{ogl}(t)dt \qquad (21)$$

Integrating equation 21 with respect to time, and evaluating definite integrals,

$$Q_T = q_{o\inf}\left(\frac{1-e^{-ct}}{c}\right) + q_{ogl}\left(\frac{e^{-\lambda ct_1} - e^{-\lambda ct}}{\lambda c}\right) \qquad (22)$$

Putting equation 17 into 22

$$Q_T = q_{o\inf}\left[\left(\frac{1-e^{-ct}}{c}\right) + \beta\left(\frac{e^{-\lambda ct_1} - e^{-\lambda ct}}{\lambda c}\right)\right] \qquad (23)$$

Simplifying equation 23

$$Q_T = \frac{q_{o\inf}}{\lambda c}\left[\lambda\left(1-e^{-ct}\right) + \beta\left(e^{-\lambda ct_1} - e^{-\lambda ct}\right)\right]$$

(24)

Expanding equation 24 and collecting like terms,

$$Q_T = \frac{q_{o\inf}}{\lambda c}\left[\left(\lambda + \beta e^{-\lambda ct_1}\right) - \left(\beta e^{-\lambda ct} + \lambda e^{-ct}\right)\right] \qquad (25)$$

$$\lambda c Q_T = q_{o\inf}\left[\left(\lambda + \beta e^{-\lambda ct_1}\right) - \left(\beta e^{-\lambda ct} + \lambda e^{-ct}\right)\right] \qquad (26)$$

let

$$q'_{o\inf} = q_{o\inf}\left(\lambda + \beta e^{-\lambda ct_1}\right) \qquad (27)$$

and,

$$q'_{oT}(t) = q_{o\inf}\left(\lambda e^{-ct} + \beta e^{-\lambda ct}\right) \qquad (28)$$

Therefore equation 26 can be written as

$$q'_{oT}(t) = q'_{o\inf} - \lambda c Q_T \qquad (29)$$

Equations (18) and (29) is the model for estimation of the total flow rate and developed reserves in gas lifted wells following exponential decline rfespectively. Equations (18) and (28) are classical examples of the **Double Semilog**. A term used by Higgins and Lechtenberg to name the sum of two exponentials. This implies that the plot has two different slopes each representing one of the two regimes of flow. The equations have been simplified such that only the initial flow rate of natural flow regime is shown. This gives a more realistic picture of the data.

Equation (29) is a simpler form of equation (26) and is readily plotted on a Semi log graph to yield the cumulative production, Q_T for the period of interest.

RESULTS AND DISCUSSION

The Field data were obtained from two fields in the Niger Delta region and was analyzed using exponential decline. Plots of flow rate versus time for both the data and model were made for each of the wells as shown in the appendices. The graphs were plotted on semi log paper using available data and the nominal decline constants and intercepts on the rate axis determined for each period of flow. The maximum gas lift rate is the intercept of the gas lift induced rate plot on the flow rate axis and can be read from the graphs. (Figs A-1 and A-3 for well A-1 and Well A-2 respectively.)

These values are then input in equation 18 to obtain the rate at a desired time bearing in mind the boundary conditions. Alternatively, the graph may be extrapolated to the rate of interest to determine the time the well will have declined to that rate and vice versa. After the fore going has been done, the natural flow rate and the gas lift induced rate are superposed and plotted on semi log paper also. The superposed rate time curve can then be extrapolated to the time of interest to determine the rate. The predetermined economic rate may be used to estimate the life of the well.

Figs A- 1 & A-2 are plots for well A-1 dataFig.A-1 is a semi-log plot of flow rate versus time. It shows that the flow pattern follows a conventional trend up to the point of gas lift.

Generally, the rate is seen to decline more rapidly during gas lift than for natural flow. This is may be due in part to the inefficiency of the flow regimes for which the data is obtained. It can also be seen from chart 1 that the sum of gas lift induced flow rate and natural flow rate is the total flow rate at time t, after gas lift has been implemented. The plot of the superposed rates is found to coincide with the plot of the field data from the point of maximum gas lift flow rate.

If the time to reach the maximum gas lift is assumed negligible, the model results almost exactly overlie the field data from the beginning of flow to any point of extrapolation (R^2=0.994736)

The total duration of flow increased by three months and the reserves by 1.05 million barrels as a result of gas lifting the well over natural flow.(see table1.0)

Fig A-2 is the Corrected rate versus cumulative production for data, Arps and model for well A-1. The plot was made on semi log paper since the reduced rate is a double semi log. It is a discontinuous straight line graph at the point of commencement of gas lift. It can be extrapolated to the rate of interest to determine the developed reserves at such reduced rates for the period of interest. The actual rate may then be determined by applying equation (28).

Well A-2 data are plotted in Figs A-3 & A-4. Fig A-3 is a semi- log plot of flow rate versus time. It shows that the flow pattern follows a conventional trend up to the point of gas lift similar to well A-1. The rate declines more rapidly during gas lift than the natural flow periods. This may be due in part to the fact that there exists an optimum gas lift gas flow rate. This in conjunction with reservoir characteristics induce a faster decline rate since the oil rate is declining at the prevailing lift gas rate thus inducing a backpressure on the reservoir before been restored to the optimum gas lift gas rate for the oil rate at that time. The impact of this double decline is an increase in the overall decline constant as shown by the two wells.

It can also be seen from Fig A-3 that the sum of gas lift induced flow rate and natural flow rate is the total flow rate at time t, after gas lift has been implemented. The plot of the superposed rates is found to coincide with the plot of the field data from the point of maximum gas lift flow rate.
The total duration of flow was found to have increased by one month due to gas lift as well as an increase in developed reserves of 0.55 million barrels of oil. (see table 3).

Also, if the time to reach the maximum gas lift is assumed negligible, the model results almost exactly overlie the field data from the beginning of flow to any point of extrapolation as well. (R^2=0.9995792)
The decline constant was calculated from the plots using equation 18. The total developed reserves for both the gas lift and natural flow periods were determined from these plots and are shown in table 3.

Fig A-4 is the Corrected rate versus cumulative production for data, Arps and model for well A-2. Similarly, the plot was made on semi log paper since the reduced rate is a double semi log. It is a discontinuous straight line graph at the point of commencement of gas lift. It can be extrapolated to the rate of interest to determine the developed reserves at such reduced rates for the period of interest. The actual rate may then be determined by applying equation (28).
plot was made on semi log paper since the reduced

CONCLUSION AND RECCOMENDATION

Based on the present study, the following conclusions may be reached.

1. The frequently used Arps equation in its original form, though useful in analysis of naturally flowing wells/ reservoirs, is in adequate for accurately estimating and forecasting of reserves in gas lift wells/reservoirs.

2. The principle of superposition can be used to derive a double semi log equation which is made up of the Arps equations for the two flow periods.

3. A Double Semi Log equation can be used to accurately and reliable estimate the developed reserves in wells/ reservoirs put on gas lift.
It is hereby recommended that the model is best applied to wells/reservoirs in which the optimum or maximum gas lift oil flow rate has been determined and attained.

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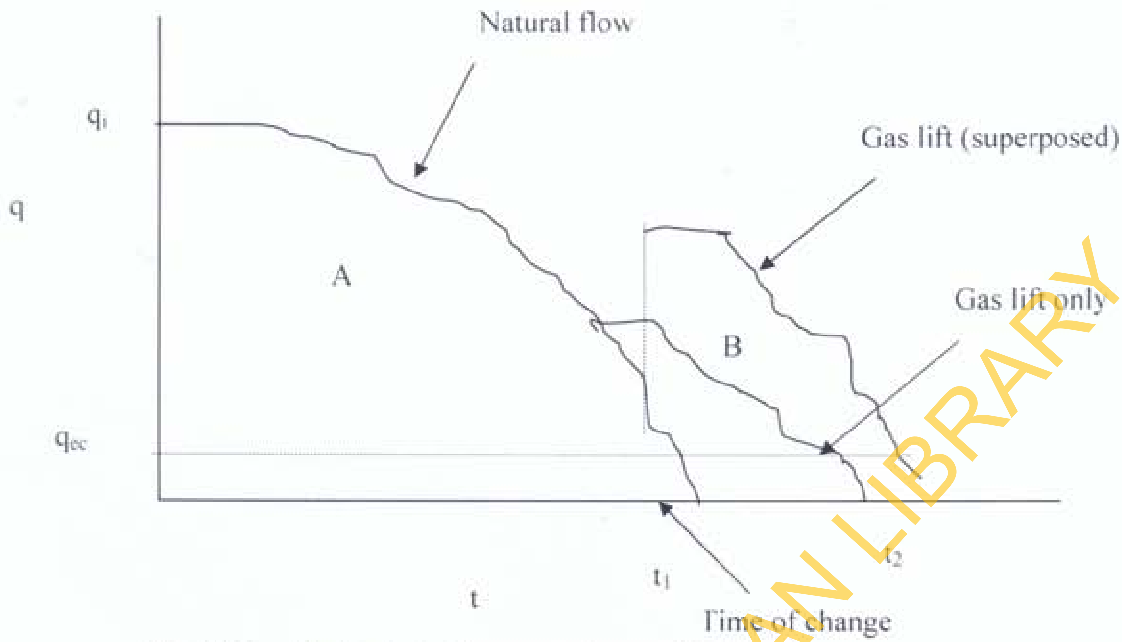

Fig.1.0 Hypothetical rate-time curve for gas lifted well

Fig. A-1: Production rate versus Time Well A-1.

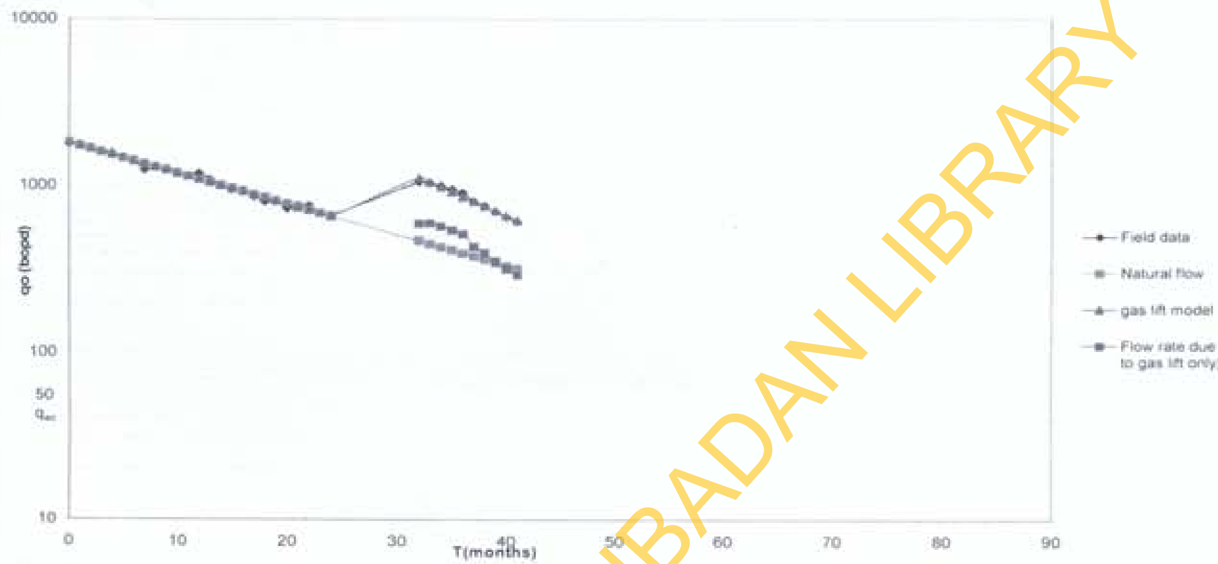

Fig.A-2: Corrected rate versus Cumulative production Well A-1

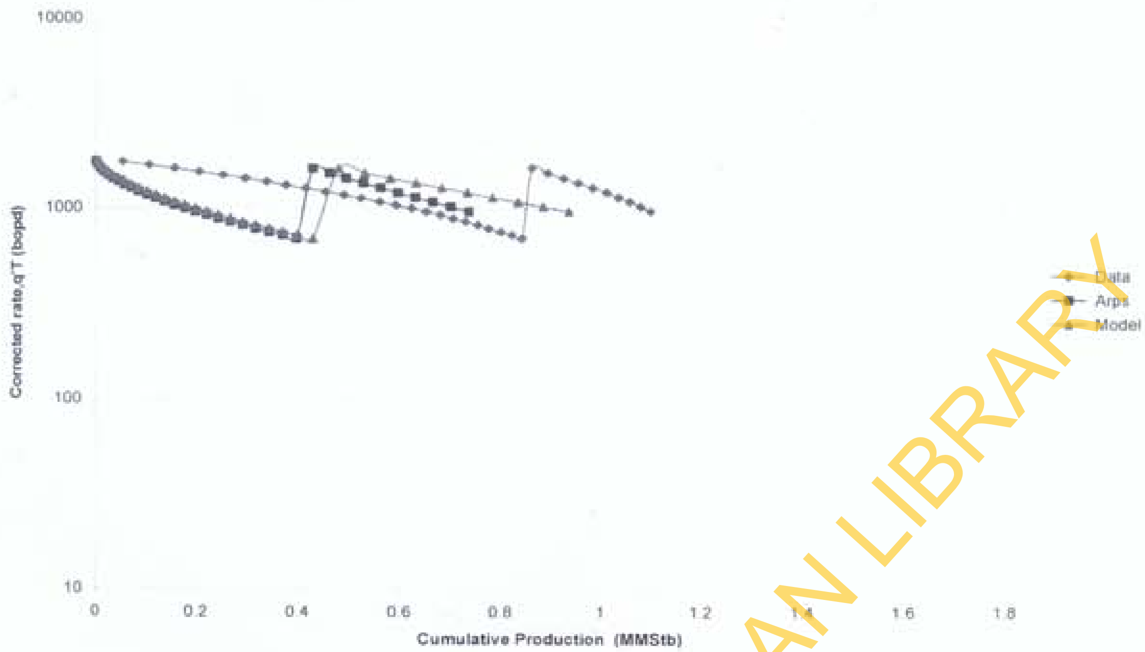

Fig.A-3: Production rate versus time well A-2

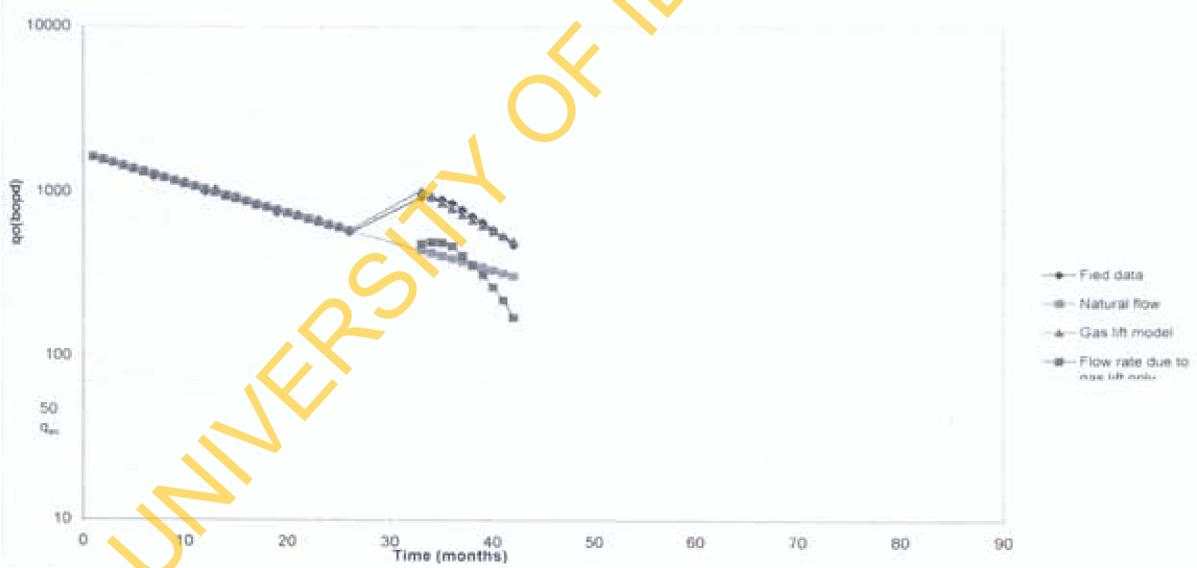

Fig.A- 4: Corrected rate versus Cumulative production Well A-2

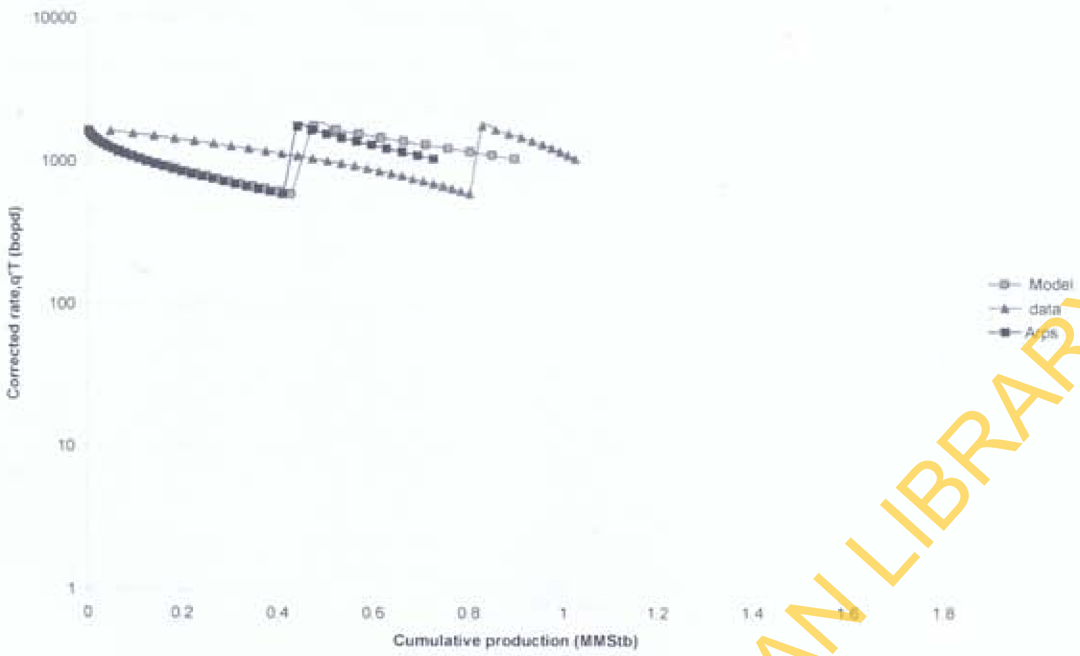

Table 1: Values of flow rates at different times for the data, natural flow and model (Gas lift flow)

Well A-1

t(months)	q_o(bopd)	Natural flow) qpredicted(bopd)	Gas lift flow(bopd) (model)
0	1801	1833.8	1833.8
1	1786	1757.144972	1757.144972
2	1688	1683.694215	1683.694215
3	1620	1613.313787	1613.313787
4	1583	1545.875346	1545.875346
5	1490	1481.255911	1481.255911
6	1407	1419.337646	1419.337646
7	1251	1360.007639	1360.007639
8	1291	1303.157697	1303.157697
9	1278	1248.68415	1248.68415
10	1205	1196.487662	1196.487662
11	1147	1146.47305	1146.47305
12	1189	1098.549108	1098.549108
13	1091	1052.628444	1052.628444
14	1004	1008.627319	1008.627319
15	954	966.4654936	966.4654936
16	934	926.0660826	926.0660826
17	867	887.3554152	887.3554152
18	802	850.2628999	850.2628999
19	810	814.7208959	814.7208959
20	731	780.6645902	780.6645902
21	761	748.0318787	748.0318787
22	760	716.7632534	716.7632534
23	686	686.8016941	686.8016941
24	665	658.0925636	658.0925636
25	754	630.5835091	1833.765245
26	812	604.2243659	1708.146588
27	857	578.9670663	1591.818439
28	904	554.765552	1484.059195
29	961	531.5756898	1384.204909
30	986	509.3551916	1291.644611
31	1007	488.0635367	1205.816016
32	1060	467.6618984	1126.201576
33	1044	448.113073	1051.91463
34	1001	429.3814117	983.3708354
35	954	411.4327563	919.7194244
36	908	394.2343761	860.5886527
37	810	377.7549087	805.6361124
38	760	361.9643027	754.5463667
39	701	346.8337629	707.0287788
40	652	332.3356977	662.8155167
41	611	318.4436689	621.6597213

Table 2: Values of flow rates at different times for the data, natural flow and model (Gas lift flow)

Well A-2

t(months)	q_o(bopd)	Natural flow) qpredicted(bopd	Gas lift flow(bopd) (model)
1	1618	1628.972436	1628.972436
2	1573	1564.317159	1564.317159
3	1498	1502.228104	1502.228104
4	1461	1442.603415	1442.603415
5	1388	1385.34528	1385.34528
6	1341	1330.359769	1330.359769
7	1235	1277.556678	1277.556678
8	1234	1226.849386	1226.849386
9	1185	1178.154709	1178.154709
10	1156	1131.392764	1131.392764
11	1092	1086.48684	1086.48684
12	1005	1043.36327	1043.36327
13	1037	1001.95131	1001.95131
14	963	962.1830252	962.1830252
15	913	923.9931771	923.9931771
16	887	887.3191159	887.3191159
17	832	852.1006788	852.1006788
18	824	818.280091	818.280091
19	754	785.8018705	785.8018705
20	753	754.6127377	754.6127377
21	742	724.6615277	724.6615277
22	697	695.8991062	695.8991062
23	683	668.2782893	668.2782893
24	635	641.7537656	641.7537656
25	631	616.2820225	616.2820225
26	579	591.8212741	591.8212741
27	712	568.3313933	1743.661921
28	769	545.7738455	1589.867725
29	817	524.1116256	1451.622656
30	837	503.3091972	1327.254945
31	896	483.3324347	1215.276932
32	918	464.1485665	1114.364613
33	935	445.7261222	1023.339465
34	929	428.03488	941.1522895
35	909	411.045818	866.8688687
36	867	394.731066	799.657209
37	791	379.0638602	738.7762114
38	723	364.0184989	683.565601
39	665	349.5703005	633.4369795
40	601	335.6955633	587.865872
41	544	322.3715259	546.3846607
42	483	309.5763307	508.5763034

Name of well	Period of flow	$q_{ec(bopd)}$	Liquid hold up ,λ	Time to reach q_{ec} (months)	Decline constant, c / ε	Developed Reserves, Q (million barrels)	Percent increase in developed reserves	Correlation coefficient R^2	Percentage relative error, E_r
Well A-1	Natural	50	2.016	85	-0.0427	2.20	47.73	0.994736	-0.03509
	Gas lift	50		88	-0.0861	3.25			
Well A-2	Natural	50	2.921	87	-0.0405	2.45	22.45	0.995792	-0.41493
	Gas lift	50		88	-0.1184	3.0			

Table3. Results of model calculations