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Evaluating the deliverability of underground gas storage in depleted oil reservoir

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ABSTRACT

Evaluating the deliverability of underground gas storage in depleted reservoir is presented in this work. Production data from a depleted oil reservoir in an oilfield located in the Niger Delta was obtained for analysis. Performance history at the end of eight-year running was obtained from the above data which was used to generate the plot of Log(Pr^2 – Pwf^2) versus Log Q to get the slope. With these figures in place, the Microsoft Visual Basic Computer Program was written and used to generate a table, and a plot of deliverabilities at different well flowing pressures was obtained.

Keywords: deliverability, performance, reservoir, storage, prediction, back-pressure, well flowing pressure, coefficient, absolute open flow.

INTRODUCTION

As global energy demand rises, natural gas now plays an important strategic role in energy supply. It is more difficult to transport and store gas than oil and consequently it lagged behind that commodity for a considerable period. Natural gas is the cleanest and most hydrogen-rich of all the hydrocarbon energy sources and it has high energy conversion efficiencies for power generation [1].

Nigeria has fewer reserves of 125 trillion cubic feet of natural gas but flares 75 percent of the associated gas produced with its oil, which amounts to an estimated 1.5 Bcf per day. Because of new government policies to stop the practice, gas that could have been flared may now be available for nearly free in Nigeria [2].

The exploration, production and transportation of natural gas take time, and the natural gas that reaches its destination is not always needed right away, so it is injected into underground storage facilities [3]. Since the Nigerian market is not sufficient to take in the available produced natural gas, the produced gas is rather stored for future demand. Efficient development and operation of a natural gas reservoir depends upon knowledge of how the reservoir will perform in the future. To predict recovery, sources of energy for producing the gas from the reservoir must be identified and their contribution to reservoir performance evaluated.

Volumetric estimation and decline curve methods are methods which may be used to estimate gas reserve in place in the reservoir; but recoverable reserves are of greatest interest. Their estimation requires predictions of an abandonment pressure at which further production from the well will no longer be profitable. The abandonment pressure is determined principally by economic conditions such as future market value of gas, cost of operating and maintaining wells, and cost of compressing and transporting gas to consumers [4].

The pressure drop required to lift a fluid through the production tubing at a given flow rate is one of the main factors in determining the deliverability of a well [5].

During well tests, field pressures change nominally and well tests indicate instantaneous deliverability, but during high injections or withdrawal rates, field pressures do change substantially thereby altering the instantaneous deliverabilities [6].

Bomar and Deveniewski, (1997) [7] in their paper on Storage Formation Damage Mechanisms identified some major potential causes for deliverability decline as: clay problem, particle, clay swelling, salt, deposition at the surface, deposition with the insavour matrix, compressed oil deposition on the sand face, iron scale deposition and bacterial growth.

The use of static and core analysis has provided theoretical means of computing the production capacity of a well through investigation into the properties of the reservoir. However, more reliable information is obtained by conducting flow tests on the wells and thereby obtaining some measure of "in-situ" formation properties. Such tests include:

- The flow-after-flow method
- The isochronal method

They exist for gas wells as back pressure test techniques, fashioned to obtain data that can be analyzed in accordance with the empirical performance equation below [8].

$$Q = C(P_R^2 - \underline{P^2}_{wf})^n \qquad 1.1$$

The performance coefficient C, determines the characteristics of the back pressure equation and the exponent, n, the inverse of the slope of the curve corresponds to the slope of the straight line when Q and P_R^2 P^2_{wf} are plotted on a logarithm paper as depicted by the linearised form

$$\text{Log } Q = \text{Log } C + n\text{Log}(P_R^2 - \underline{P^2}_{wf}) \qquad 1.2$$

Prior to the development of the back-pressure test, the "open flow" capacity method of testing a well was common. By this method, a new completed well is flowed wide open and the flow rate measured. Such procedure resulted in wasting of gas and pollution of the adjoining environment. In addition, it failed to provide information on the deliverability of the gas to the pipeline. To overcome this shortcoming, the back pressure test was developed.

Although much has been written on the laws of flow of gas through porous formation, the original development of back pressure relationship was based entirely on empirical methods. Back pressure behavior provides the engineer a detailed information essential in predicting the future development of a field. It also permits the following:

i. calculation of gas deliverability into a pipeline at pre-determined line pressure.
ii. to design and analyse the gathering lines.
iii. to determine spacing and number of well to be drilled during development of a field to meet gas purchasers' requirements.
iv. to solve other technical and economic problems.

Application of flow-after-flow method or back pressure testing to fast stabilizing and usually high capacity wells as described by Rawling and Schelldart (1935) [8]. This currently characterized the behavior of the wells. The flow-after-flow method of testing could be used to describe the behavior of slowly stabilizing back-pressure behavior of a gas well. This was based on the requirements that the data is to be obtained from the well under stabilizing condition. That is C is constant and does not vary with time but depends on the physical properties of the flowing fluids. Flow in highly permeable formations requires only a short period of time to stabilize. For a given well, n is always a constant with values ranging between 0.5 and 1.0 [8].

For low permeability reservoir, determination of stabilized performance behaviour of gas well is a very tedious task. Tek et al (1957), [9] in one of their works showed that it took some of the mesa Verde well in San Juan gas field several weeks to reach stabilization hence the need to develop a procedure for predicting the stabilized back-pressure behavior and eliminating the necessity for using the log flow test becomes necessary. Such a test procedure has been evolved from both field experience and theoretical consideration of Tek et al, (1957) [9].

The isochronal performance method of determining the flow characteristics of gas well described by Cullender, (1955), [10] in his work found from experience that the steady flow condition are necessary to establish n for back pressure curve. He also established that n will always vary with time as long as transient condition exists. The flow will have stabilized with C as constant which is illustrated by shifting the back pressure curve towards the left at increasing time, while the slope remains constant.

Poettmann and Schilson, (1955), [11] described a procedure for calculating the variation of C with time for low permeability wells. Other reservoir data along with this curve are used to obtain the stabilized back pressure performance curve of a well for various spacing pattern.

Wells et al, (1992), [12] in their work on Engineering Evaluation and Performance Analysis of the loop Gas Storage Field, described a reservoir performance from both preliminary depletion and storage operations. They designed several model cases to evaluate current field deliverability and fracture enhancement potential. Based on this model, the storage field was expanded from a deliverability of 50 MMCF/D and a working gas of 5.0BCF to a deliverability of 200MMCF/D and a working gas of 9.4BCF, with 2.625BCF of cushion gas being converted to working gas.

MATERIALS AND METHODS

PROCEDURE FOR EVALUATION

In evaluating the deliverability/performance of a storage reservoir, a deliverability test (back pressure test) was carried out on the reservoir for the prediction of well flow rate against any pipeline back pressure.

It was observed that a plot of $P_R^2 - P_{WF}^2$ (difference of the squares of reservoir pressure and well flowing pressure) versus Q_{sc}, (flow rate at standard condition) yields a straight line on logarithm plot, which represents the reservoir performance curve.

The straight line relationship for a particular well applies throughout the lifetime of the well, as long as the production remains in single phase (gas or liquid). Eq 1.1 which is the back-pressure (deliverability) equation as developed by Rawlins and Schellhardt (1935) [8] is also expressed as:

$$Q_{sc} = C\,[\Delta P]^n \qquad 2.1$$

By extending the performance curve, the absolute open flow, (AOF) is obtained. Although this AOF does not reflect reality, it does approximate the capacity of the well [13].

The slope of the plot of Log $(P_R^2 - P_{wf}^2)$ versus Log Q is computed and used to obtain the back-pressure exponent as:

$$n = 1 / \text{slope} \qquad 2.2$$

Then the flow capacity at standard condition is given as:

$$Q_{sc} = C\,[P_R^2 - P_{wf}^2]^{(1/SLOPE)} \qquad 2.3$$

At $P_{WF} = 0$, equation 2.3 reduces to:

$$Q_{sc} = C\,[P_R^2]^n \qquad 2.4$$

But the reservoir flow coefficient, C is expressed as:

$$C = \frac{Q}{[P_R^2 - P_{wf}^2]^n} \qquad 2.5$$

According to Katz and Coats (1968), [14] flow tests on individual wells are employed for gas storage obtained as in gas production operations. From gas inventory and/or reservoir pressure measurements plus deliverability data, it is possible to predict the field flow at several stages of the storage cycle.

The performance of storage reservoirs become less predictable during high withdrawal rates due to pressure sinks which develop as a result of heterogeneities. Another problem of continuing interest relates to interference by water reaching the wellbore. The presence of water not only reduces the permeability to gas but also effectively cuts down the bottomhole pressure drawdown available for gas flow due to increased density of well fluid. For aquifers, water interference problems are likely to subside as the gas bubbles thickens with growth in stored gas. Each reservoir and set of wells must be tested to give assurance for future years with regard to which well will have water intrusion at a given stage of the withdrawal cycle. Deliverability of storage wells after several years of repetitive use decreases as a result of sandface contamination. For the purpose of this work, a duration of eight years of running the gas storage reservoir was assumed.

In gas storage reservoirs, injection pressures of approximately 0.55 psi/ft are often used, but pressures as high as 0.7 psi/ft have been used. In other words, an approximate injection rate can be estimated using the relationship below [14].

$P_{inj} \propto I_{rate}/hk$, 2.6

A Microsoft Visual Basic Program was written using eqn 1.1, and was used to obtain the deliverabilities of the depleted reservoir, Q (MMscf/d) at different well flowing pressures, P_{wf} (psig). The sample of the Microsoft visual basic program for the evaluation of deliverability from reservoirs is as shown in fig 2.1.

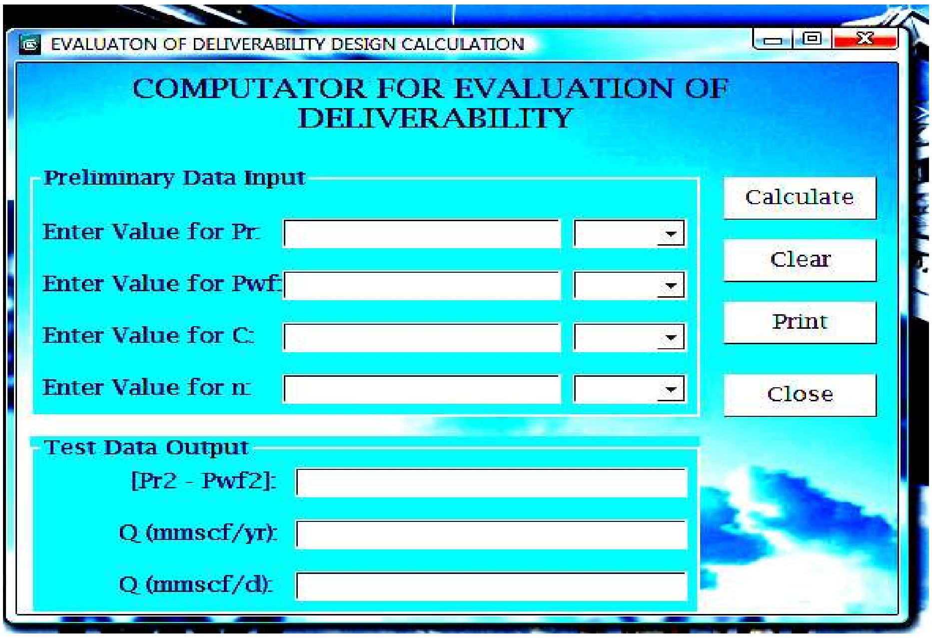

Fig 2.1: Program computator for evaluation of deliverability at given well flowing pressure

RESULTS

The performance history of the depleted oil reservoir is shown in Table 3.2, which was generated from the production data given in Table 3.1 and the slope of the performance curve; Log ($P_R^2 - P_{WF}^2$) versus Log Q shown in Fig 3.1 is obtained as 1.25

Table 3.1: Production Data from Depleted Oil Reservoir

Time (year)	P (psig)	Np (MMstb)	Rp (scf/rb)	Cumulative oil Production (MMstb)	Oil Flow Rate (stb/d)	Wp (bbl)	We (bbl)
1.	3955	0.582458	3200	0.582	5868	2777.612	31255.78
2.	3900	0.607124	3440	1.189	3296	2895.24	32579.41
3.	3782	0.811398	3960	2.000	1671	3869.377	43541.14
4.	3534	0.908459	4980	2.908	3118	4332.239	48749.62
5.	3350	1.406055	6030	4.314	9279	6705.163	75451.54
6.	3288	1.823687	10010	6.137	9466	8696.757	97862.46
7.	3212	2.468388	11540	8.605	5014	11771.19	132458.3
8.	3199	2.847551	11980	11.453	7827	13579.34	152804.9

Table 3.2: Performance History of Depleted Oil Reservoir

Time Year	$Q=R_pN_p$ (MMscf)	Flowing Pressure Pwf (Psig)	Pwf^2	P_R^2-Pwf^2 ($Psig^2$)	Log (P_R^2-Pwf^2)
1	681.156	3900	15210000	432025	5.635509
2	1157.37	3700	13690000	1952025	6.290485
3	1566.18	3500	12250000	3392025	6.530459
4	2515.942	3300	10890000	4752025	6.676879
5	5110.378	3100	9610000	6032025	6.780463
6	11119.864	2900	8410000	7232025	6.85926
7	10320.56	2700	7290000	8352025	6.921792
8	294721.21	2500	6250000	9392025	6.972759

From eqn 2.2, the back-pressure exponent is estimated as:

n = 1.000 / 1.25 = 0.80

For the reservoir, values of Q, P_R and P_{WF} were chosen from the Table 3.2 at 8th year of operating the underground storage vessel as stated and substituted into equation 2.5.

$$C = \frac{29471.21}{(88288)^{0.80}} = 3.256$$

Therefore, from eqn 2.1, $Q_{sc} = 3.256\,(3199^2\text{-}2500^2)^{0.80}$
= 620733.3 MMscf/year
= 1700.639 Mscf/d which represents the AOF

Following the reservoir performance of the reservoir, the back pressure exponent, n, is 0.80, C = 3.256 and the AOF = 80.74 MMscf/day

The deliverability of the reservoir at reservoir pressure of 3955psig and at a given well flowing pressure is calculated from eqn 2.3,

$$Q = C\,[P_R^2 - P_{WF}^2]^n$$

In the equation, Q is the deliverability in MMscf/yr.

At P_{wf} of 3900 psig, $Q = 3.256\,[3955^2 - 3900^2]^{0.80}$

Q = 104976.35 MMscf/yr

Then Q in MMscf/d = 287.61 MMscf/d

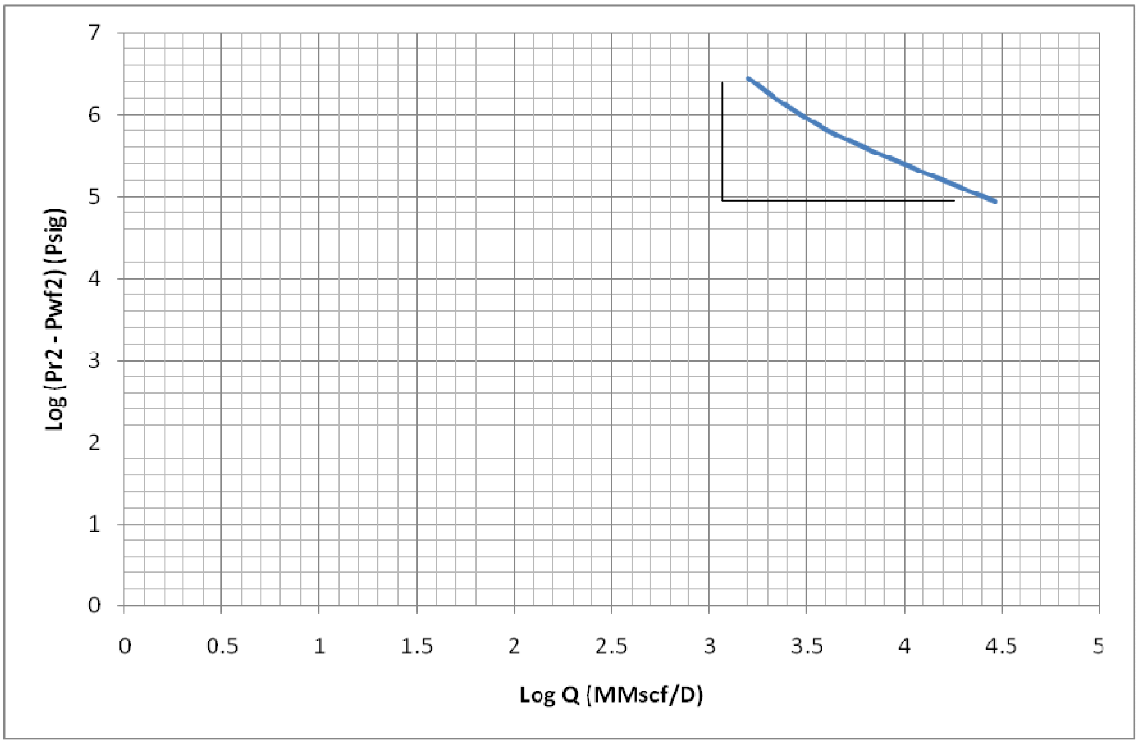

Fig. 3.1: Plot of Log [P_R^2-P_{wf}^2] Vs. Log Q for the Depleted Oil Reservoir

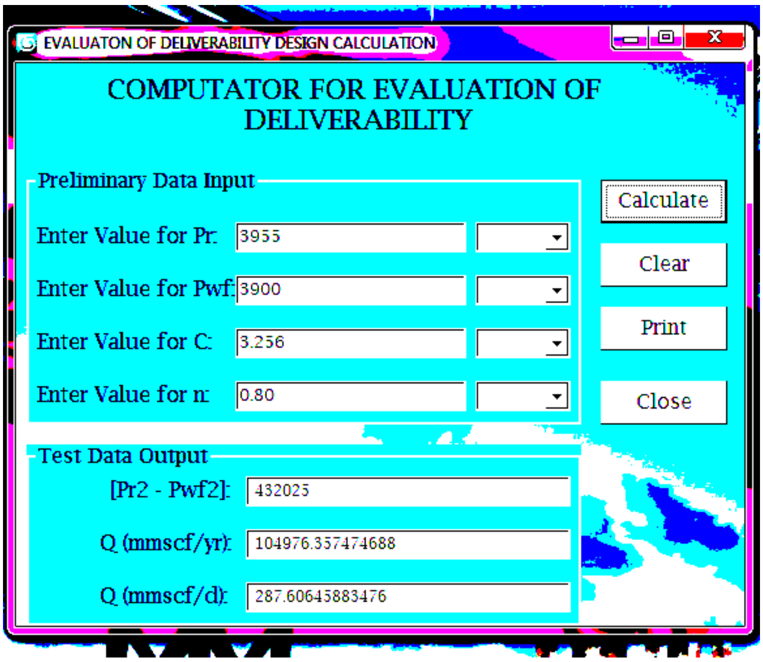

Fig 3.2: Deliverability at well flowing pressure of 3900psig

3.1 Evaluation of Deliverability of the Reservoir using Microsoft Visual Basic Program

Fig. 3.2 shown below is a Microsoft Visual Basic Program which was used in evaluating the deliverability of the storage reservoir at any given well flowing pressure.

The deliverabilities of the storage reservoir at various withdrawal pressures are presented in Table 3.3 which is used to obtain the plot of the deliverabilities at various well flowing pressures as shown in Fig 3.3.

Table 3.3: Deliverability of the Depleted Reservoir

P_{wf} (psig)	P_{wf}^2 (psig^2)	P_R^2-P_{WF}^2 (psig^2)	Q (MMscf/yr)	Q (MMscf/d)
3900	15210000	432025	104976.3575	287.6064588
3700	13690000	1952025	350810.5913	961.1249075
3500	12250000	3392025	545822.7482	1495.40479
3300	10890000	4752025	714804.651	1958.368907
3100	9610000	6032025	865077.2729	2370.07472
2900	8410000	7232025	1000212.623	2740.308556
2700	7290000	8352025	1122322.901	3074.857263
2500	6250000	9392025	1232797.622	3377.527733

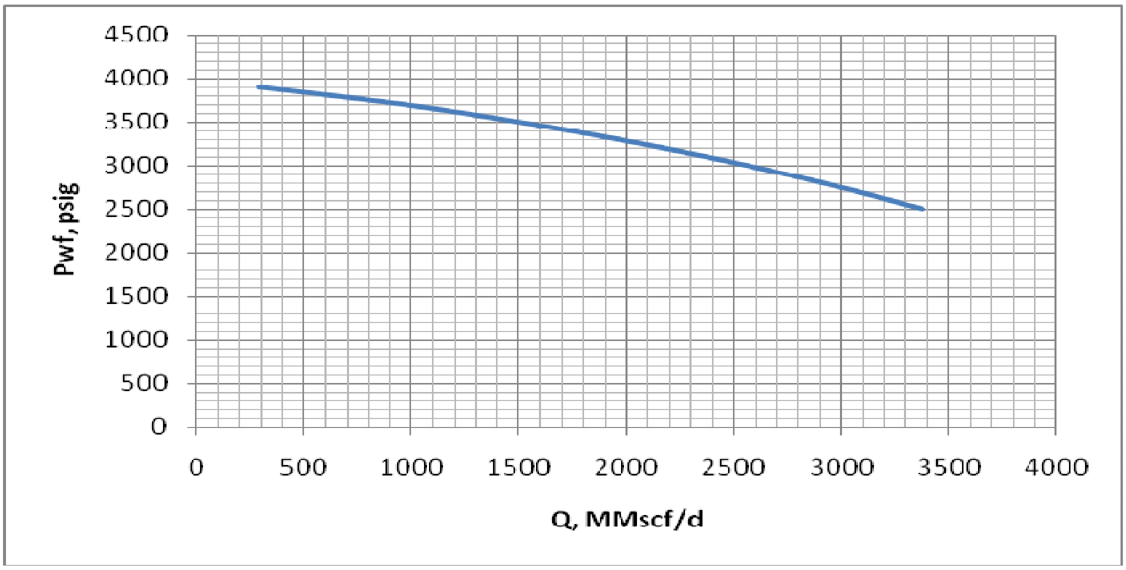

Fig. 3.3: A Plot of Well Flowing Pressure versus Deliverability

CONCLUSION

In conclusion, this work on estimating the deliverability of underground gas storage in depleted oil reservoir has shown that;

- The reservoir delivers more gas as the well flowing pressure decreases.
- After using the reservoir for underground gas storage purpose, it is still capable of delivering gas after injection.
- Absence of water in the reservoir aids the deliverability of gas.

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NOMENCLATURE
AOF = Absolute open flow
C = Performance coefficient
h = Reservoir thickness
I_{rate} = Injection rate
k = Permeability
MMscf = Million standard cubic foot
Mscf = Thousand standard cubic foot
n = Back-pressure exponent
P_{inj} = Injection pressure
P_r = Reservoir pressure
P_{wf} = Well flowing pressure
Q = Deliverability
Q_{sc} = Deliverability at standard conditions