GAS WELLS DELIVERABILITY DETERMINATION USING FLOW-AFTER-FLOW TEST ANALYSIS

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Abstract

Gas properties vary significantly with pressure change. To take this variation in gas properties into account the Pseudo pressure has to be used instead of pressure in all calculations. This paper presents an analysis of Flow-after-flow test for gas wells. The analysis has been performed through using the Simplified method and Laminar-Inertial Turbulent (LIT) Approach, which includes Pressure, Pressure squared and Pseudo-pressure methods. Wetherford PS software has also been used to analyze the test. IPR curve for a gas well has been constructed by using both C,n and LIT methods and the results have been compared with the results obtained from PS software. To check the applicability of each approach, all results have been compared with Pseudo-pressure method as it is superior to all other methods. AOFP has been determined for all methods. The results have revealed that Pseudo pressure method, manual Simplified and pressure squared under estimate AOFP whereas pressure method over estimate it. On the other hand, PS software results for AOFP from both simplified and LIT method are reasonably close as the software uses pseudo pressure for both methods.

Keywords: Rawlins-Schellhardt analysis, gas wells performance, Laminar-Inertial-Turbulent (LIT), Pressure square Approach, AOFP, Bahr Essalam.

Introduction

Gas Well Test

Modeling liquid flow for well test interpretation considers constant values of both density and compressibility within the range of dealt pressures. For a better mathematical representation, this assumption does not apply for gas flow case in which the gas compressibility factor is included. In other words, contrary to liquids, a gas is highly compressible and much less viscous. In general, gas viscosity is about a 100 times lower than the least viscous crude oil. It is important, however, to try to provide the same mathematical treatment to oil and gas hydrocarbons, so interpretation methodologies can be easily applied in a more practical way. The gas flow equation is normally linearized to allow the liquid diffusivity solution to satisfy gas flow behavior. Depending upon the viscosity-compressibility product, three treatments are considered for the linearization namely square of pressure squared, pseudo-pressure, and linear pressure.

Deliverability Tests

Deliverability testing refers to the testing of a gas well to measure its production capabilities under specific conditions of reservoir and bottom hole flowing pressures (BHFPs). A common productivity indicator obtained from these tests is the absolute open flow (AOF) potential. The AOF is the maximum rate at which a well could flow against a theoretical atmospheric backpressure at the sand face. Although in practice the well cannot produce at this rate, regulatory agencies sometimes use the AOF to allocate allowable production among wells or to set maximum production rates for individual wells. (Chaudhry, 2003).

Another application of deliverability testing is to generate a reservoir inflow performance relationship (IPR) or gas backpressure curve. The IPR curve describes the relationship between surface production rate and BHFP for a specific value of reservoir pressure (either the original pressure or the current average value). The IPR curve can be used to evaluate gas-well current deliverability potential under a variety of surface conditions, such as production against a fixed backpressure. The IPR can also be used to forecast future production at any stage in the reservoir's life. (sincedirect, 2019).

Several deliverability testing methods have been developed for gas wells. Flow-after-flow tests are conducted by producing the well at a series of different stabilized flow rates and measuring the stabilized BHP. Each flow rate is established in succession without an intermediate shut-in period. A single-point test is conducted by flowing the well at a single rate until the BHFP is stabilized. This type of test was developed to overcome the limitation of long testing times required to reach stabilization at each rate in the flow-after-flow test.

Isochronal and modified isochronal tests were developed to shorten tests times for wells that need long times to stabilize. An isochronal test consists of a series of single-point tests usually conducted by alternately producing at a slowly declining sand face rate without pressure stabilization and then shutting in and allowing the well to build to the average reservoir pressure before the next flow period. The modified isochronal test is conducted similarly, except the flow periods are of equal duration and the shut-in periods are of equal duration (but not necessarily the same as the flow periods). (Chaudhry, 2003).

Field Description

The offshore gas and condensate field is owned and operated by Mellitah Oil & Gas (MOG) which is an equal joint venture (JV) between Eni and The National Oil Corporation (NOC) which is a Libyan state-owned oil company. This field started production in 2005 as part of the Bahr Essalam Phase I project. MOG has now proposed the Bahr Essalam Phase II project, which will involve the development of the field's unexploited areas. The Libyan offshore field currently produces approximately 600 million standard cubic feet a day (MMscfd) of sales gas and approximately 30,000bbl/d of condensate. (Company, 2019).

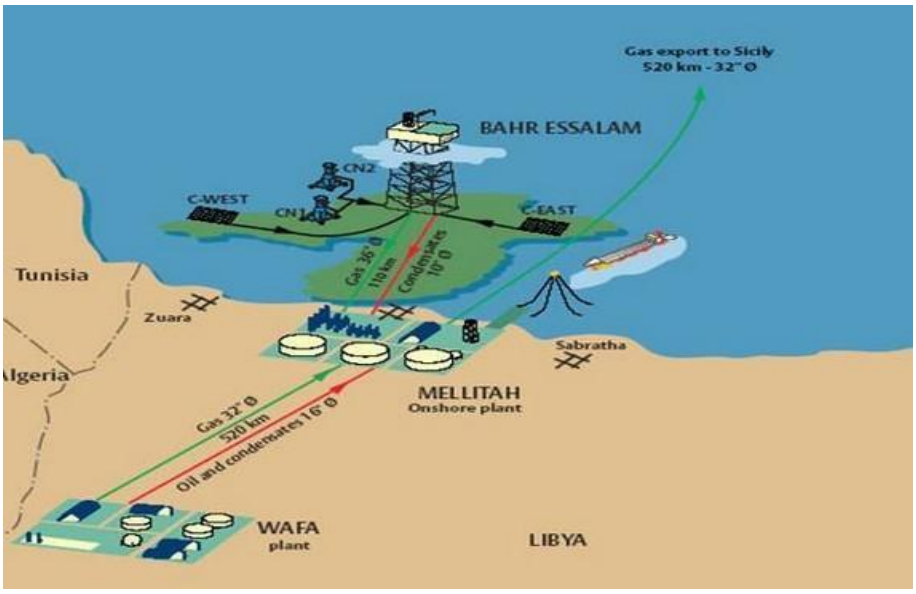


Figure (1): Overview on Bahr Essalam Field (Company, 2019).

Location of Bahr Essalam Field

Bahr Essalam gas and condensate field is located within Block NC41 in the Mediterranean Sea, approximately 110 km from Tripoli, Libya. It is in Sabratha Basin Concession NC 41 as Illustrated in the following location map.

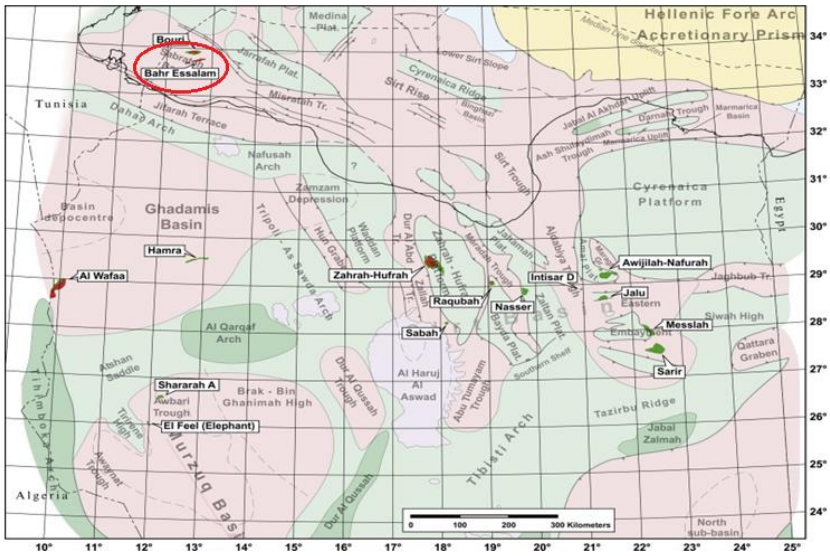
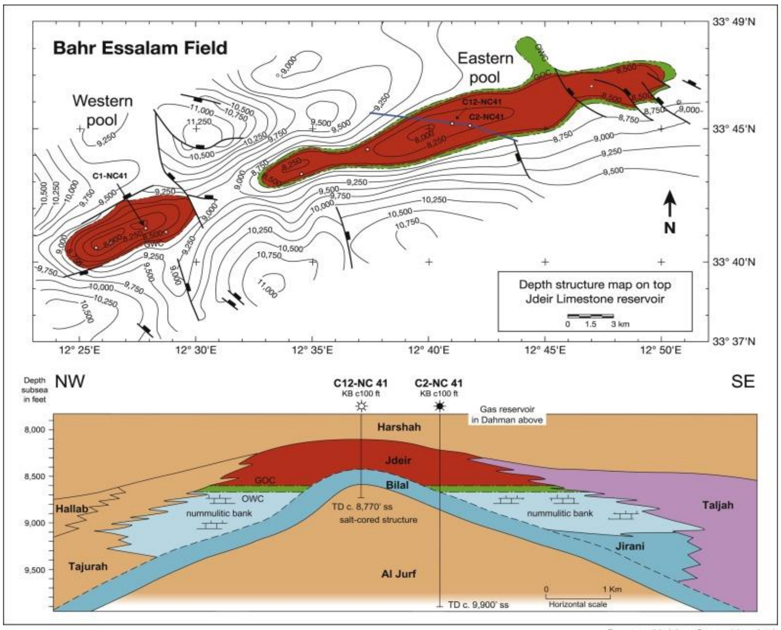


Figure (2): Field Location Map (H. Moore, 2019).

Reservoir Formation Structure

Depth structure map shows top Jdeir Limestone reservoir with north-west to south-east cross-section. Contour interval is 250 ft. The discovery wells C1-NC41 (Western Pool) and

C2-NC41 (Eastern Pool) are separately identified. Cross-section illustrates gas cap with small oil leg of the Jdeir reservoir in the eastern pool.



Source: Nubian Consulting Ltd.

Figure (3): Reservoir Formation Structure (Source Nubian consulting Ltd).

Methodology

Data and used Approaches

The following chart presents Flow-After-Flow test data.

Table (1): Flow-After-Flow Test Data

Test type DD or BU	(P_{wf}) Psi	(Ψ) PSI2/cp	Flow Period (Hrs)	Choke size	Q g (MMScf/day)
DD	3160	723	6	32 %	13.881
DD	3228	744.8	6	40%	19.758
DD	3262	756.5	6	48 %	25.961
DD	3291	766.35	8	64%	36.489
BU	3336	781	12	S/I	0

Theory

Gas density can vary significantly with pressure (ρ∝p/Z), and gas viscosity (µg) also varies with pressure, but not to the same degree (Guo & Ghalambor, 2005). To deal with these gas changing properties, the concept of pseudo-pressure (ψ) was developed by Al-Hussainy et al. (1966). This concept is defined as follows:

$$\psi(p)= 2\int_{p_b}^{p}\left(\frac{p}{\mu z}\right)dp \qquad (1)$$

Figure 4 shows a typical plot of the gas pressure functions (2p/µg z) and (1/µg Bg) versus pressure. Pressure function exhibits the following three distinct pressure application regions (Ahmed, 2019).

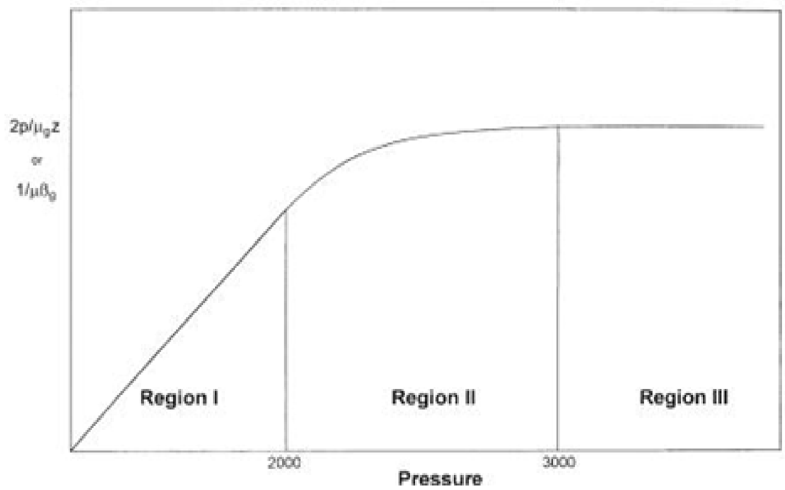


Figure (4): Gas PVT Data (Ahmed, 2019).

There are two separate empirical treatments that can be used to represent the turbulent flow problem in gas wells.

- Simplified treatment approach.
- Laminar-inertial-turbulent (LIT) treatment.

The Simplified Treatment Approach

Based on the analysis of flow data which were obtained from a large number of gas wells, Rawlins and Schellhardt (1936) postulated that the relationship between the gas flow rate and pressure can be expressed as:

$$Q_g=C\left(\bar{p}_r^2-p_{wf}^2\right)^n \qquad (2)$$

Where:

Qg = gas flow rate, Mscf/day.

$\bar{P}_r$= average reservoir pressure, psi.

n = exponent.

C = performance coefficient, Mscf/day/psi2.

The exponent n is intended to account for the additional pressure drop caused by the high-velocity gas flow, i.e., turbulence. Depending on the flowing conditions, the exponent n may vary from 1.0 for a completely laminar flow to 0.5 for a fully turbulent flow. The performance coefficient C in Equation 2 is included to account for reservoir rock properties, fluid properties and reservoir flow geometry.

Equation 2 is commonly called the deliverability or back-pressure equation. If the coefficients of the equation (i.e., n and C) can be determined, the gas flow rate Qg at any bottom-hole flow pressure pwf can be calculated and the IPR curve can be constructed. Taking the logarithm of both sides of Equation 2 gives:

$$\log\left(Q_g\right) = \log(C) + n\log\left(\bar{p}_r^2 - p_{wf}^2\right) \quad (3)$$

Equation 4 suggests that a plot of Qg versus ($\bar{P}_r^2 - P_{wf}^2$) on log-log scales should yield a straight line that has a slope of n. In the natural gas industry the plot is traditionally reversed by plotting ($\bar{P}_r^2 - P_{wf}^2$) versus Qg on the logarithmic scales to produce a straight line with a slope of (1/n). This plot as shown schematically in Figure (5) which is commonly referred to as the deliverability graph or the back-pressure plot (Ahmed, 2019).

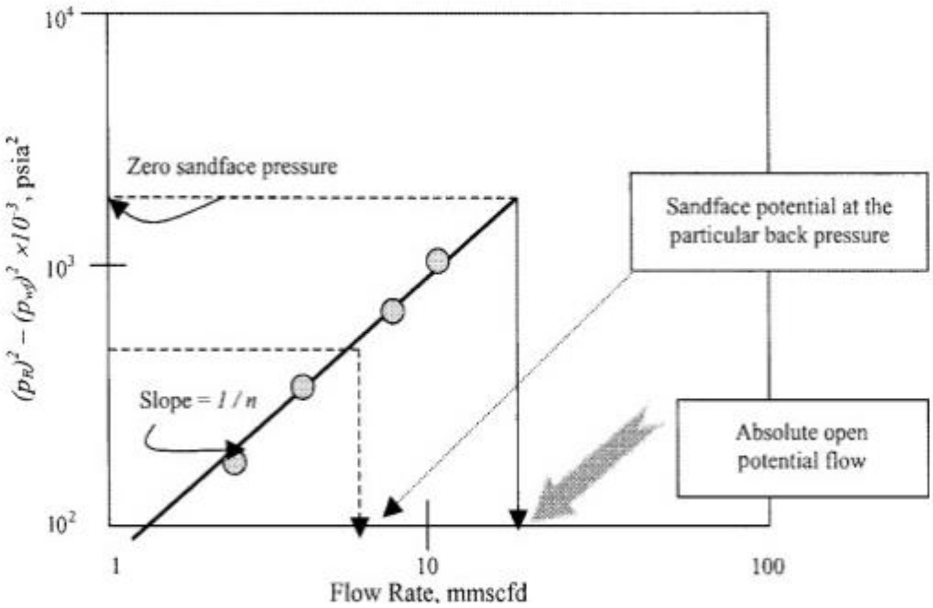


Figure (5): Well Deliverability Graph (Chaudhry, 2003).

The deliverability exponent n can be determined from any two points on the straight line, i.e., (Qg1, ΔP_1^2) and (Qg2, ΔP_2^2), according to the flowing expression:

$$n = \frac{log(Q_{g1}) - log(Q_{g2})}{log(\Delta p_1^2) - log(\Delta p_2^2)} \quad (4)$$

Given n, any point on the straight line can be used to compute the performance coefficient C from:

$$C = \frac{Q_g}{(\bar{p}_r^2 - p_{wf}^2)^n} \quad (5)$$

The coefficients of the back-pressure equation or any of the other empirical equations are traditionally determined through analyzing gas well testing data. Deliverability testing has been used for more than sixty years by the petroleum industry to characterize and determine the flow potential of gas wells.

The Laminar-Inertial-Turbulent (LIT) Approach

Pressure-Squared Quadratic Form

Gas flow equation can be written as:

$$\bar{p}_r^2 - p_{wf}^2 = BQ_g + FQ_g^2 \quad (6)$$

and,

$$B = \left(\frac{1422\ T\mu_g z}{kh}\right)\left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s\right] \quad (7)$$

$$F = \left(\frac{1422\ T\mu_g z}{kh}\right) D \quad (8)$$

where:

B = laminar flow coefficient.

F = inertial-turbulent flow coefficient.

Qg = gas flow rate, Mscf/day.

z = gas deviation factor.

k = permeability, md.

μg = gas viscosity, cp.

The term B Qg in Equation 8 represents the pressure-squared drop due to laminar flow while the term F Qg2 accounts for the pressure-squared drop due to inertial turbulent flow effects.

Equation 6 can be linearized by dividing both sides of the equation by Qg to yield:

$$\frac{\bar{p}_r^2 - p_{wf}^2}{Q_g} = B + FQ_g \quad (9)$$

The coefficients B and F can be determined by plotting $\frac{\bar{p}_r^2 - p_{wf}^2}{Q_g}$ versus Qg on a Cartesian scale and should yield a straight line with a slope of F and intercept of B. As it will be presented later in this chapter, data from deliverability tests can be used to construct the linear relationship as shown schematically in Figure (6).

Given the values of B and F, the quadratic flow equation, i.e., Equation 6, can be solved for Qg at any pwf from:

$$\mathbf{Q_g} = \frac{-\mathbf{B} + \sqrt{\mathbf{B}^2 + 4\mathbf{F}\left(\bar{\mathbf{p}}_r^2 - \mathbf{p}_{wf}^2\right)}}{\mathbf{2F}} \qquad (\mathbf{10})$$

Furthermore, by assuming various values of pwf and calculating the corresponding Qg from Equation 10, the current IPR of the gas well at the current reservoir pressure $\bar{P}_r$ can be generated.

It should be pointed out that the following assumptions were made in developing Equation 6:

- Single phase flow in the reservoir
- Homogeneous and isotropic reservoir system
- Permeability is independent of pressure
- The product of the gas viscosity and compressibility factor, i.e., (μg z) is Constant.

This method is recommended for applications at pressure values below 2,000 psi (Ahmed, 2019).

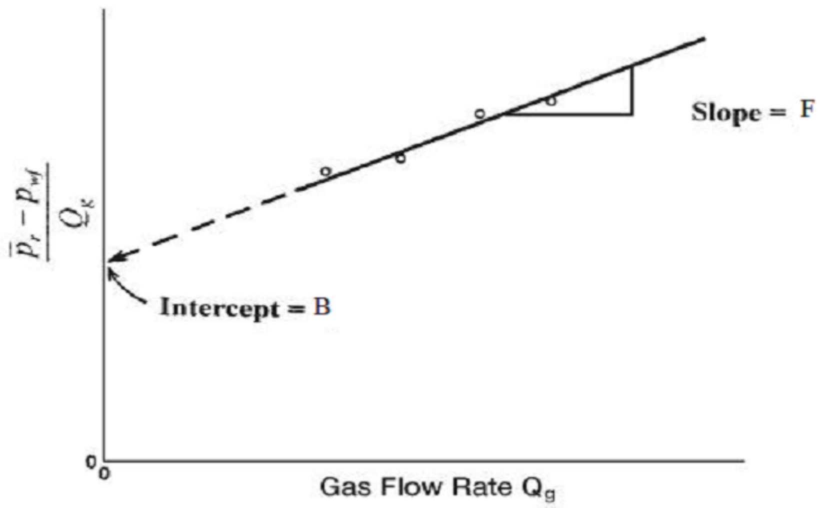


Figure (6): Graph of the Pressure-Squared (Ahmed, 2019).

Pressure-Quadratic Form

Gas flow equation can also be written as:

$$\bar{p}_r - p_{wf} = B_1 Q_g + F_1 Q_g^2 \quad (11)$$

Where:

$$B_1 = \frac{141.2(10^{-3})(\mu_g B_g)}{kh}\left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s\right] \quad (12)$$

$$F_1 = \left[\frac{141.2(10^{-3})(\mu_g B_g)}{kh}\right] D \quad (13)$$

The term (B1 Qg) represents the pressure drop due to the laminar flow, while the term (F1 Qg2) accounts for the additional pressure drop due to the turbulent flow condition. In a linear form, Equation 9 can be expressed as:

$$\frac{\bar{p}_r - p_{wf}}{Q_g} = B_1 + F_1 Q_g \quad (14)$$

The laminar flow coefficient B1 and the inertial-turbulent flow coefficient F1 can be determined from the linear plot of the above equation as shown in Figure (7). Having determined the coefficient B1 and F1, the gas flow rate can be determined at any pressure from:

$$Q_g = \frac{-B_1 + \sqrt{B_1^2 + 4F_1(\bar{p}_r - p_{wf})}}{2F_1} \quad (4.15)$$

The application of Equation 11 is also restricted by the assumptions listed for the pressure-squared approach. However, the pressure method is applicable at pressures higher than 3,000 psi.

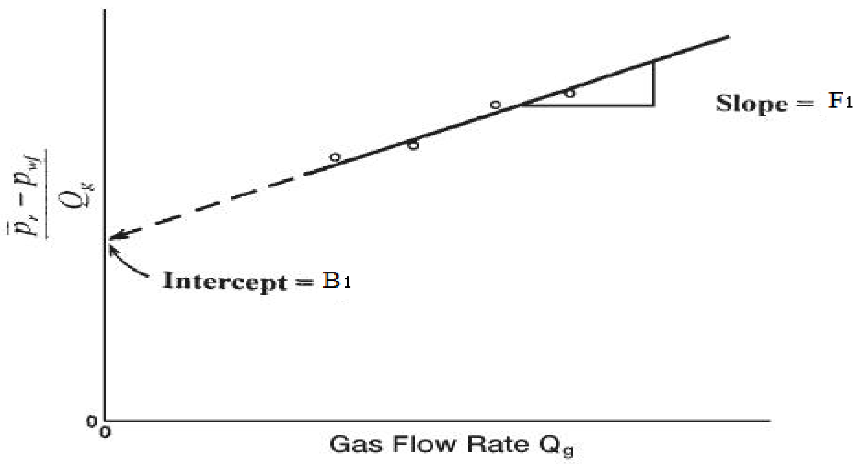


Figure (7): Graph of the Pressure-Method (Ahmed, 2019).

Pseudo-Pressure Quadratic Approach

Gas flow equation expressed in pseudo-pressure form is:

$$\bar{\Psi}_r - \Psi_{wf} = B_2 Q_g + F_2 Q_g^2 \qquad (16)$$

Where:

$$B_2 = \left(\frac{1422}{kh}\right)\left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s\right] \qquad (17)$$

$$F_2 = \left(\frac{1422}{kh}\right) D \qquad (18)$$

The term (B2 Qg) in Equation 16 represents the pseudo-pressure drop due to the laminar flow while the term (F2 Qg2) accounts for the pseudo pressure drop due to the inertial-turbulent flow effects.

Equation 16 can be linearized by dividing both sides of the equation by Qg to yield:

$$\frac{\bar{\Psi}_r - \Psi_{wf}}{Q_g} B_2 + F_2 Q_g \qquad (4.19)$$

The above expression suggests that a plot of ($\frac{\bar{\Psi}_r - \Psi_{wf}}{Q_g}$) versus Qg on a Cartesian scale should yield a straight line with a slope of F2 and intercept of B2 as shown in Figure (8).

Given the values of B2 and F2, the gas flow rate at any pwf is calculated from:

$$Q_g = \frac{-B_2 + \sqrt{{B_2}^2 + 4F_2(\bar{\Psi}_r - \Psi_{wf})}}{2F_2} \qquad (4.20)$$

It should be pointed out that the pseudo-pressure approach is more rigorous than either the pressure-squared or pressure-approximation method and is applicable to all ranges of pressure (Ahmed, 2019).

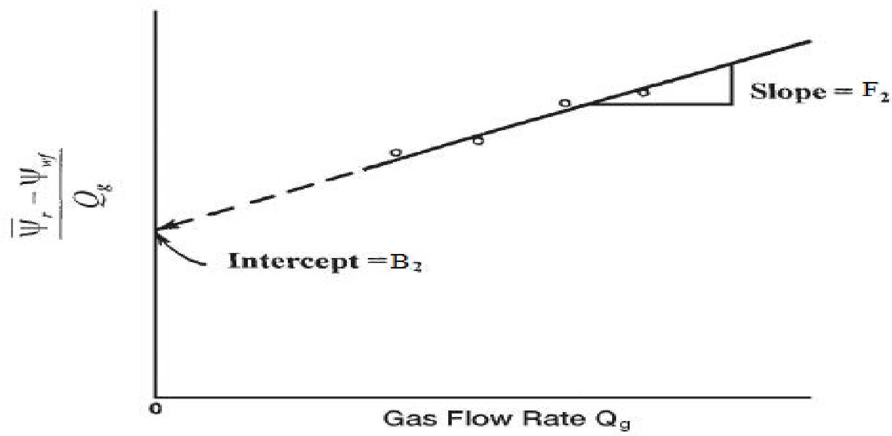


Figure (8): Graph of Real Gas Pseudopressure (Ahmed, 2019).

Results

Manual Calculation

Simplified Method

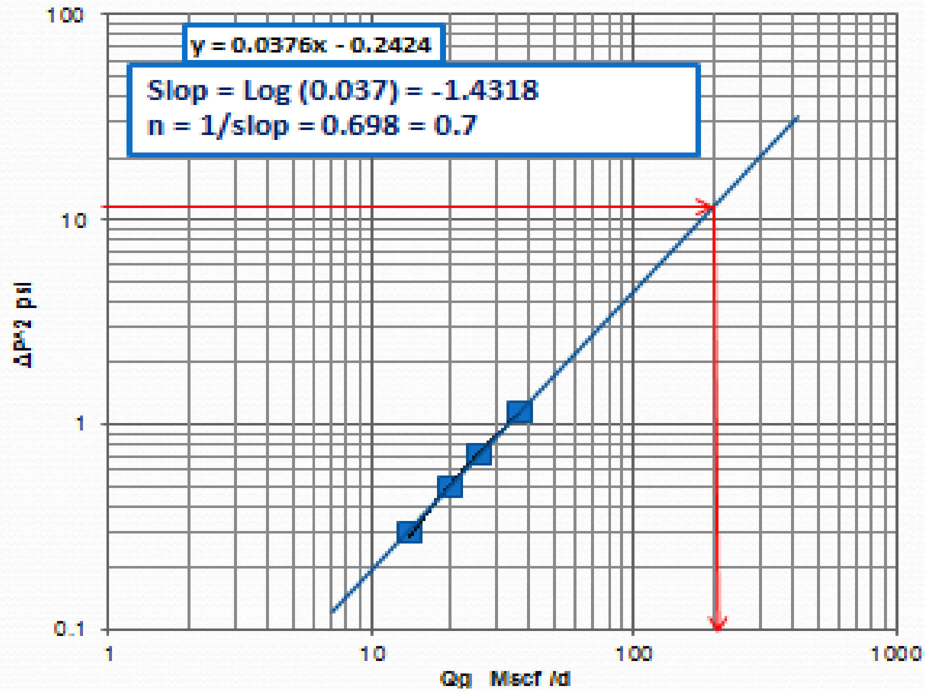


Figure (9): Simplified Approach.

LIT Approach

Pressure Square Method

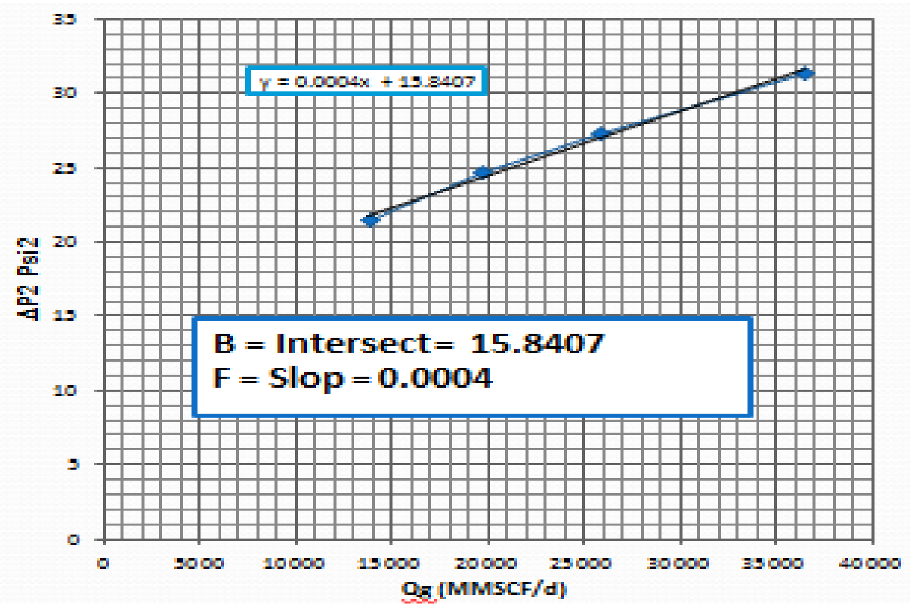


Figure (10): Pressure Square Method.

Pressure Method

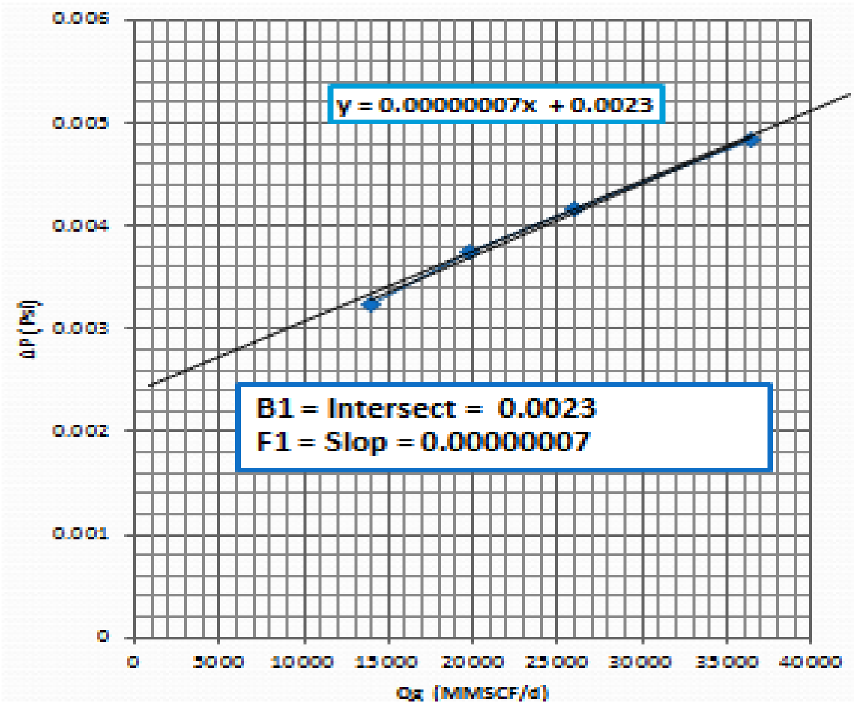


Figure (11): Pressure Method.

Pseudo-Pressure Method

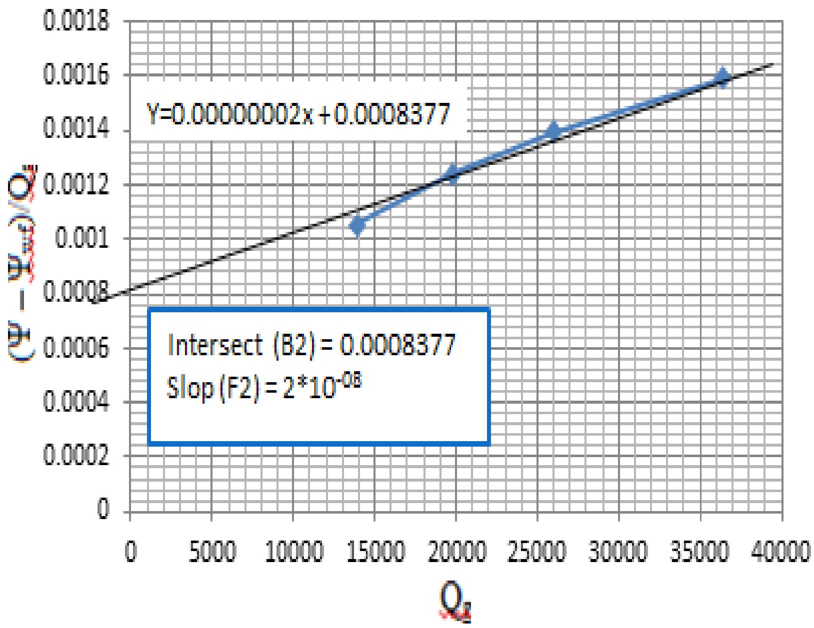


Figure (6): Pseudo Pressure Method.

Inflow Performance Relationship Curve

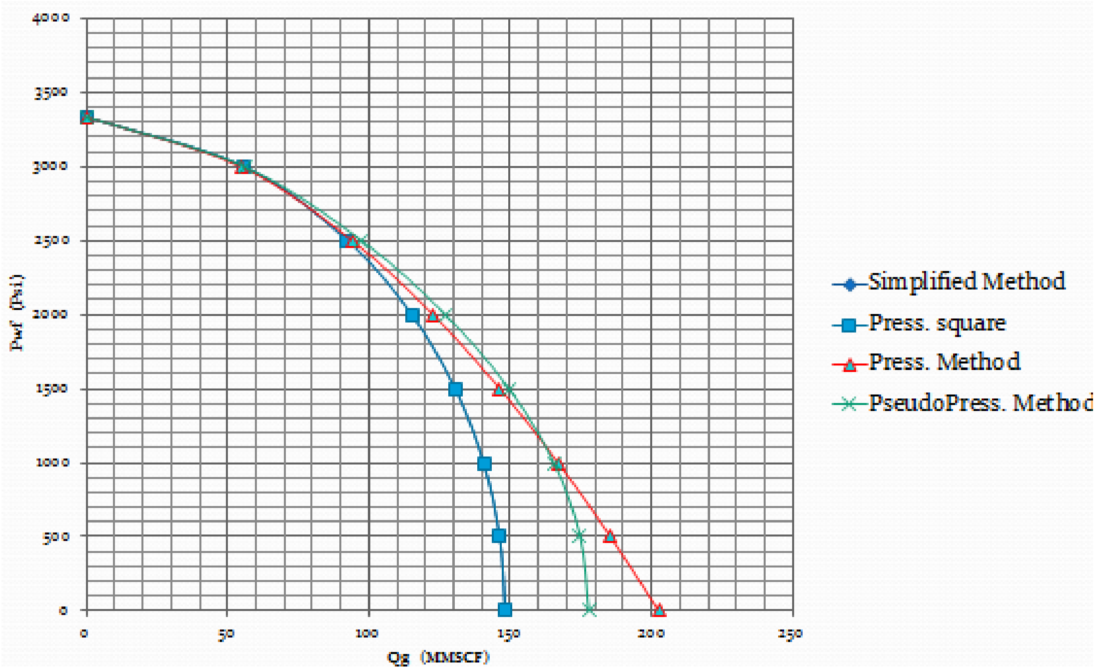


Figure (13): IPR Curves.

Pan System Software Results

Test Overview

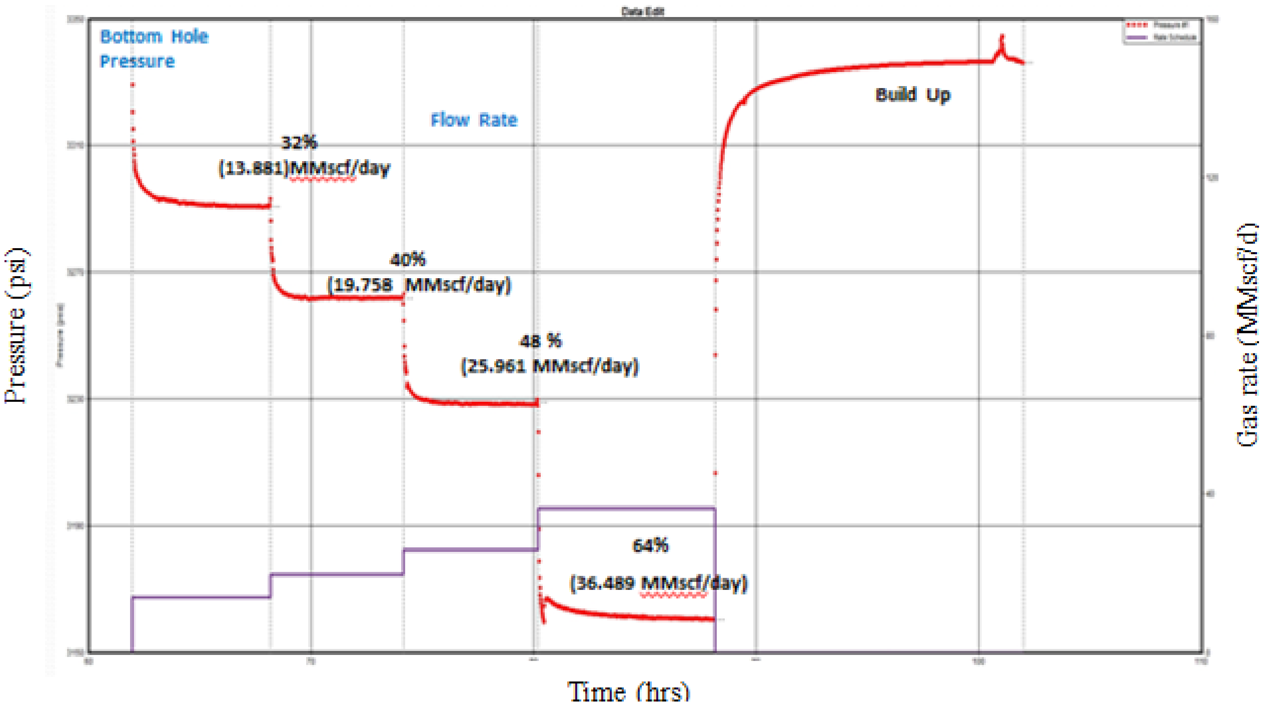


Figure (14): Test Overview.

Simplified (C &n) Method

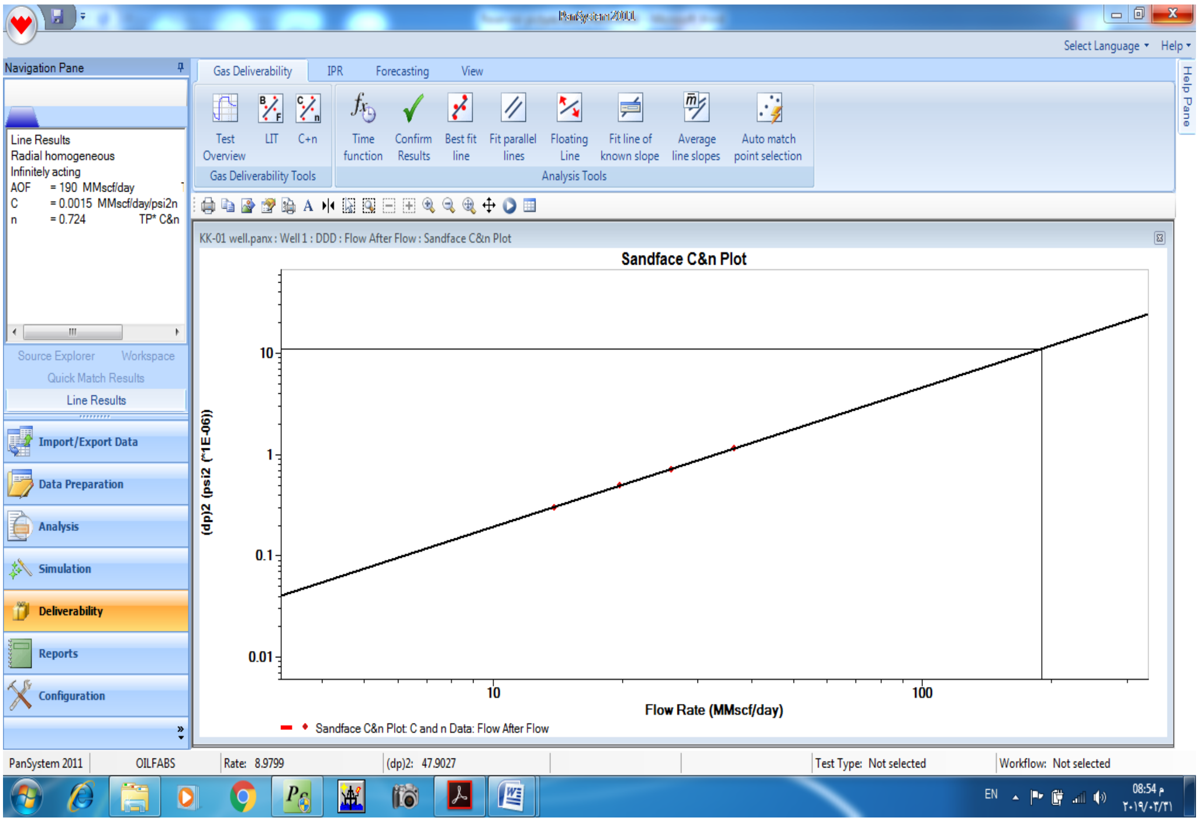


Figure (15): Simplified Method.

Inflow Performance Relationship Curve

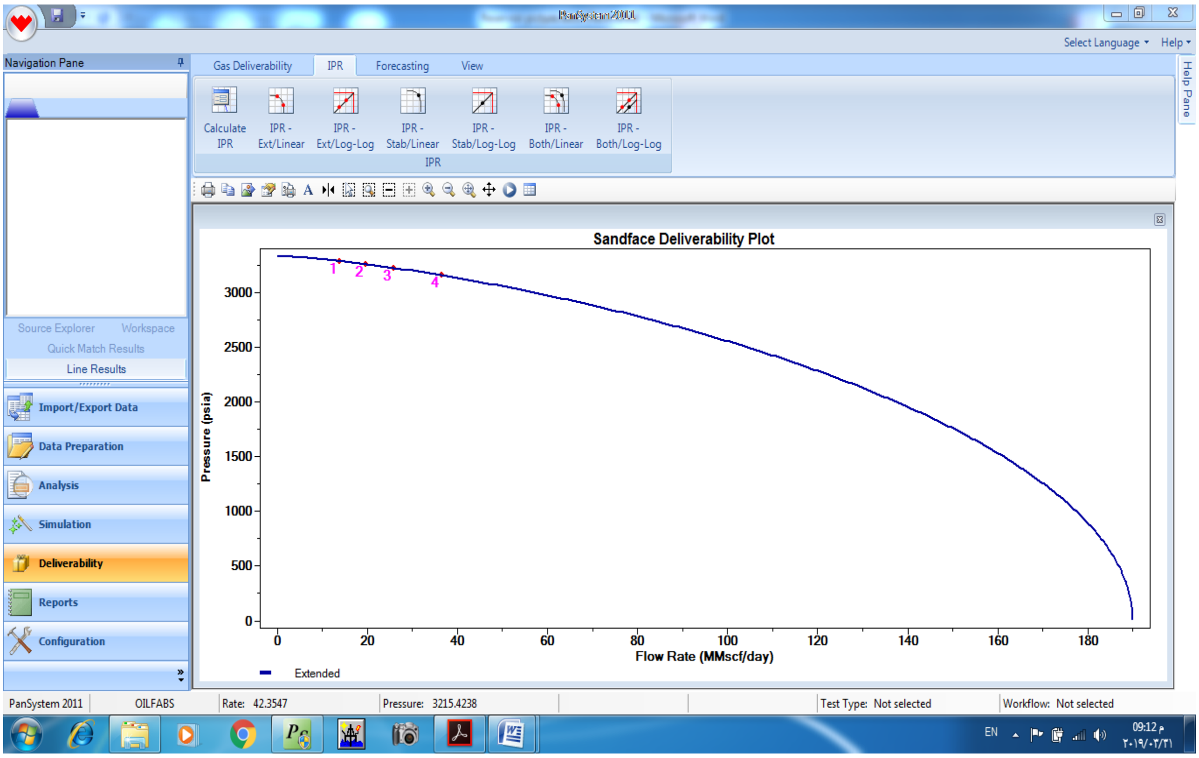


Figure (16): IPR Curve.

LIT Method

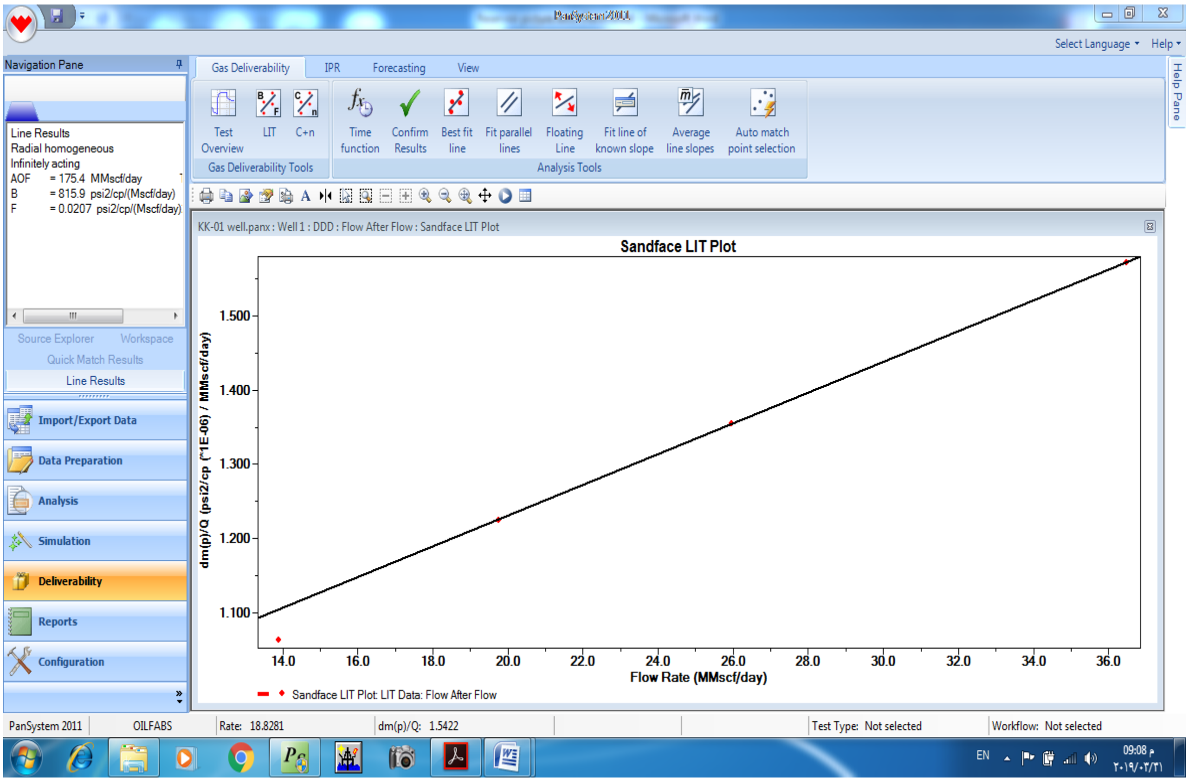


Figure (17): LIT Method.

Inflow Performance Relationship Curve

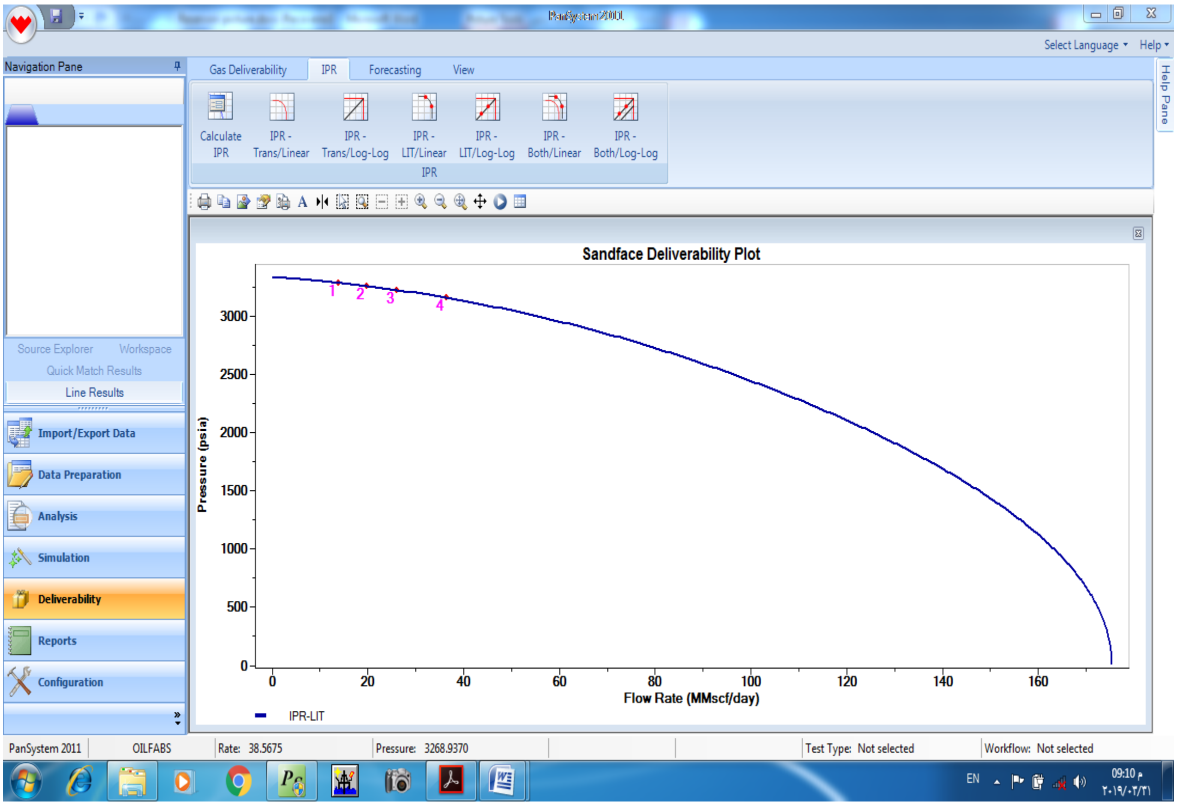


Figure (18): IPR Curv.

Results of Comparison

Table (2): AOFP reslts Comparison

Method	Manual Calculation				Software	
	Simplified Method	Pressure Square Method	Pressure Method	Pseudopressure method	N/C method	LIT Method
AOFP (MMSCF/d)	148.17	148.17	202.49	177.77	190	175.4
Comment	Under estimation	Under estimation	Over estimation	Excellent estimation	Reasonable estimation	Excellent estimation

Conclusion

- Pseudo-pressure approach is superior to any other approaches. (AOFP = 178 MMSCF/D).
- n = 0.7 meaning the flow condition is more likely to be turbulent.
- Simplified Method (c, n) and Pressure square approach underestimates AOFP, (AOFP = 148 MMSCF/D).
- Pressure approach overestimates AOFP, (AOFP = 202 MMSCF/D).
- Weatherford (PS) software saves time and gives reliable results giving (AOFP = 175MMSCF/D obtained by LIT method).

Recommendations

- As the gas is flowing under Turbulent flow condition causing the reservoir to be damaged by sand and dust, it is recommended to bean down the chock to protect the reservoir.
- As KK-10 is a gas well drilled in a newly discovered reservoir whose deliverability may change with production, it is recommended to carry out an isochronal test as it takes less time just to confirm the well's deliverability.
- A pressure build-up analysis is highly recommended to obtain the reservoir parameters characteristics such as permeability, skin factor and flow efficiency from the last shut-during the period of the test.

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Abbreviations

- API America Petroleum Institute
- Q Flow Rate
- IPR Inflow performance relationship
- MOG Mellitah oil and gas
- AOF Absolute open flow
- BHP Bottom hole pressures
- C Performance coefficient
- Qg Gas flow rate
- T Temperature
- K Permeability
- $\bar{\Psi}r$ Average reservoir real gas pseudopressure
- Ψwf Bottom-hole flowing real gas psudopressure
- Ψr Reservoir real gas pseudopressure
- Pr Reservoir pressure
- Pwf Bottom-hole flowing pressure
- µg Gas viscosity
- γg Gas gravity
- β Turbulence parameter
- n Exponent
- F Inertial-turbulent flow coefficient
- B Laminar flow coefficient
- BHFPS Bottom hole flowing pressures
- α Non-Darcy flow coefficient
- D The inertial orturbulent flow factor
- Pavg Average pressure
- $\bar{P}r$ Average reservoir pressure
- φ Porosity fraction
- ts Stabilization fraction

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