Learning from Modified Isochronal Test Analysis Middle East Gas well Case Study

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PROFESSIONAL PAPER

The natural gas has recently become the main source of energy and determining the optimum production of gas wells is very important for efficient production planning. A modified isochrone test was performed as a tool in evaluating a hydraulic fracturing treatment on a gas well. Pressure test analysis was performed to investigate the success of the treatment. Inflow performance curves, and pressure and production forecast were also performed using diffusivity equation as well as Material Balance equation. The study was conducted on a gas well in a Middle Eastern reservoir.

The analysis shows that the hydraulic fracturing treatment on the gas well was successful through an improvement in well productivity. Reservoir properties were also determined from the pressure test and the inflow performance curves were successfully generated and can be used for further study.

Key words: isochronal test, hydraulic fracturing, inflow performance curve, absolute open flow

1. INTRODUCTION

The inflow performance can be defined as the relationship between the flow rate and the pressure drop or flow rate and flowing pressure. Figure 1 shows the movement of gas from the reservoir to the well and from the well through the tubing or casing to the surface. The inflow performance depends on reservoir and fluid properties such as permeability and viscosity. Inflow performance determines the well deliverability where the well can deliver only what the reservoir provides.

The objectives of inflow performance study are as follows:

1. To determine the flow rate at which a well will produce with a given wellbore geometry and completion (first by natural flow).
2. To determine under what flow conditions a well will cease to produce. This is a function of time as the reservoir deplete.
3. To optimize the well conditions and geometry system in order to most economically produce the objective flow rate.
4. To analyze each component in the well system to determine if it is restricting the flow rate unnecessarily when compared to the flow capacities of the other system components.

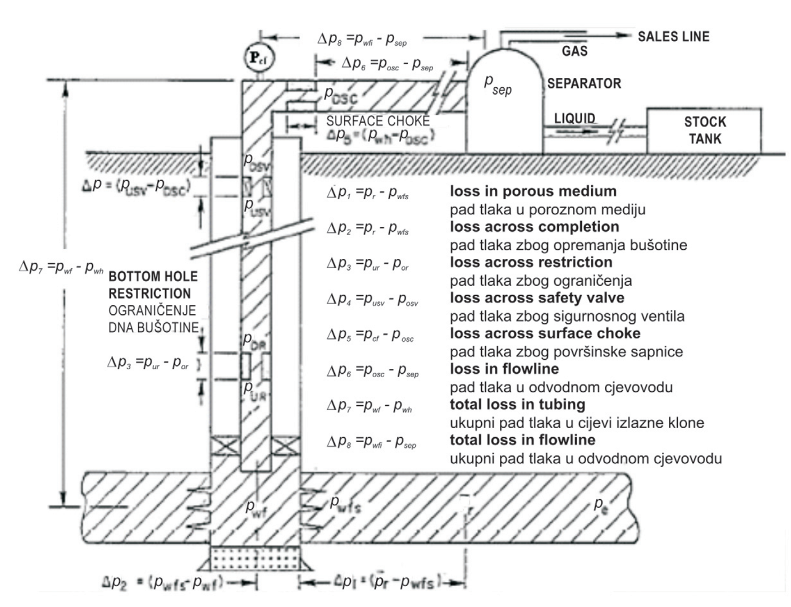

Fig. 1. Possible pressure losses in complete system.Brown[3]
Sl. 1. Mogući pad tlaka u cjelokupnom sistemu, Brown[3]

In general inflow performance allows quick recognition by the operator's management and engineering staff of means to increase production rates. This is a very important feature of being able to graphically display the wells performance with "production optimization".

Literature Review:

Predicting the inflow performance of gas wells is a process that has relied almost exclusively on some form of multipoint well testing procedure. The conventional backpressure or flow-after-flow test, isochronal test, and modified isochronal test have been used to predict the deliverability of gas wells.

Rawlins and Schellhardt[16] presented the back-pressure method of testing gas wells. It is dependent upon the requirement that a series of flow rates and corresponding pressure data be obtained under stabilized flow conditions. The conventional backpressure equation is given by:

$$q_{g_{sc}} = C\left(\bar{p}_R^{\,2} - p_{wf}^2\right)^n \tag{1}$$

These data are plotted on logarithmic coordinates of the difference in the pressures squared versus the flow rate in order to determine the constants, *C*, and, *n*. Once *C* and *n* are determined, flow rates can be estimated as a function of flowing bottomhole pressure.

As the use of the method presented by Rawlins and Schellhardt[16] spread through the industry, it became evident that the method of testing was applicable for those wells which approached stabilized producing conditions within a relatively short period of time. Stabilized performance characteristics could not be determined by this method for wells that approached stabilized producing conditions slowly, which usually occur in lower permeability reservoirs.

To overcome slow stabilization, Cullender[4] proposed the isochronal test method of determining the flow characteristics of gas wells. Cullender used the term isochronal because only those conditions existing as a result of a single disturbance of constant duration are considered. The expression žsingle disturbance of constant duration' is intended to define those conditions existing around a well as a result of a constant flow rate existing for a specific period of time from shut-in conditions. Cullender developed an empirical method whereby the deliverability exponent, *n*, of the back pressure curve may be determined for a particular gas well. Once the deliverability exponent is determined, the characteristic slope is applied to an extended stabilized flow point to determine the deliverability coefficient *C*. Although Cullender's method was an improvement, it still had the drawback of extended shut in periods to reach the stabilized pressure before each flow period.

To overcome extended shut in periods to reach the stabilized pressure, Katz[12] introduced the modified isochronal test method. Katz proposed flow periods of equal length and shut-in periods between flow periods of equal length followed by an extended, stabilized flow point and shut-in period. Once the data is obtained, it is analyzed in a manner very similar to Cullender, with the deliverability exponent determined from the transient test data, which is then applied to the extended, stabilized flow data to determine the deliverability coefficient.

Houpeurt[10] presented an analytical deliverability equation that accounts for the non-Darcy flow effect. Houpeurt's equation is given by

$$q_{sc} = \frac{703 \cdot 10^6\, kh\left(\bar{p}_R^{\,2} - p_{wf}^2\right)}{T\bar{\mu}\bar{z}\left[\ln\left(0.472 r_e / r_w\right) + s + Dq_{sc}\right]} \tag{2}$$

Houpeurt's equation uses the Forcheimer form of the flow equation as it includes the acceleration term.

2. Flow regime:

When a well is opened to production from a shut-in condition, the pressure disturbance created at the well propagates through the porous media at a velocity governed by the rock and fluid properties. The various flow regimes are discussed with respect to the behaviour of this pressure disturbance.

2.1. Steady state:

Steady state implies that pressure does not change with time at any location in the reservoir. This occurs when there is a continuous pressure support such as water drive reservoir, whereby the water influx rate equals the producing rate as shown in figure 2.

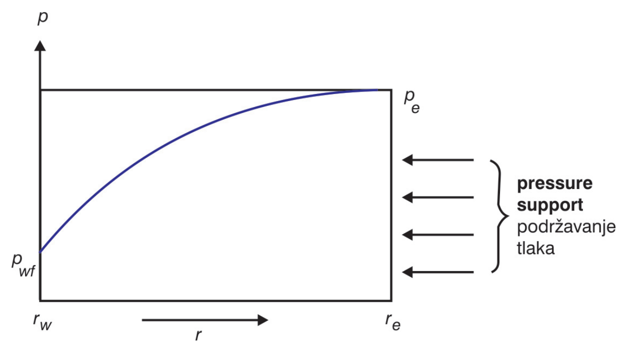

Fig. 2. Schematic diagram of steady state flow regime
Sl. 2. Shematski dijagram režima ustaljenog strujanja

2.2. Pseudo-Steady state:

Pressure changes with time, but at the same rate everywhere in the reservoir (including at sand face). Most of the life of a reservoir will exist in pseudo-steady state flow as shown in figure 3.

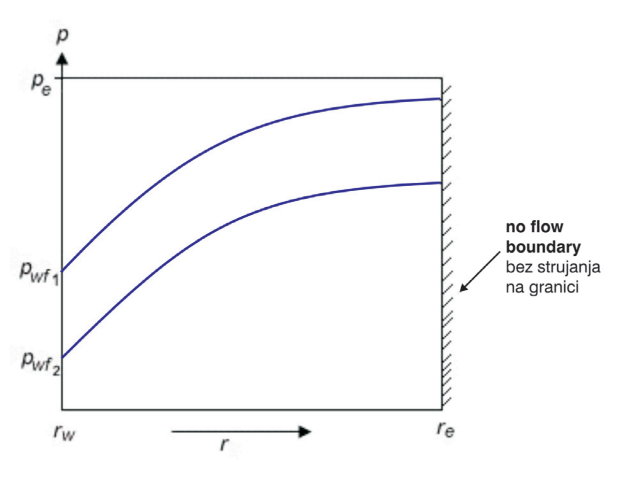

Fig. 3. Schematic diagram of Pseudo-Steady state flow regime
Sl. 3. Shematski dijagram režima pseudo ustaljenog strujanja

2.3. Transient Flow

Reservoir pressure changes with time at all locations in the reservoir. The rate of change of pressure with time is different at different locations and time. Locations far from the well may not be experiencing any pressure change. Although the flow capacity of a well is desired for pseudo-steady state or stabilized conditions, much useful information can be obtained from transient tests. This information includes permeability, skin factor, turbulence coefficient, and average reservoir pressure as shown in figure 4.

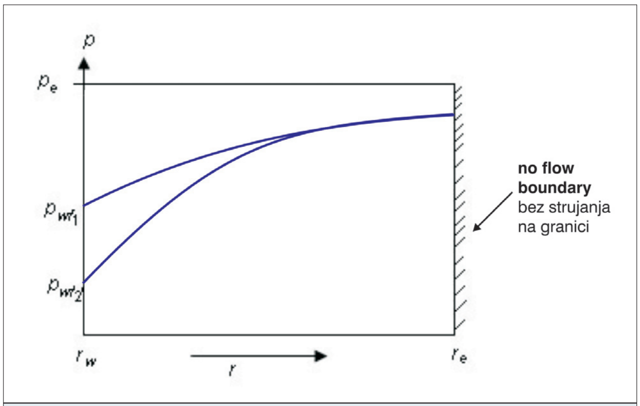

Fig. 4. Schematic diagram of transient flow regime
Sl. 4. Shematski dijagram režima prijelaznog strujanja

3. Flow Equation:

The steady state relationship developed from Darcy's law for an incompressible fluid (oil) was presented as:

$$p_e - p_f = \frac{141.2\,q\,B\mu}{kh}\left(\ln\frac{r_e}{r_w}\right) \tag{3}$$

This relationship can be adjusted for gas well by converting the flow rate from stb/d to Mscf/d and using an average value of the gas formation volume factor between pe and pwf. Therefore,

$$\overline{B_g} = \frac{0.0283\bar{z}T}{(p_e + p_{wf})/2} \tag{4}$$

$$p_e - p_{wf} = \frac{141.2(1000/5.615)\,q(\mathrm{Mscf/d})(0.0283)\,\bar{z}\,T\,\bar{\mu}}{\left[(p_e + p_{wf})/2\right]kh}\ln\frac{r_e}{r_w} \tag{5}$$

This results, after rearrangement and gathering of terms, is

$$p_e^2 - p_{wf}^2 = \frac{1422\,q\,\bar{\mu}\,\bar{z}\,T}{kh}\ln\frac{r_e}{r_w} \tag{6}$$

The above steady state flow equation assumes no turbulent flow in the formation and no skin damage around the wellbore. The effects of turbulence and skin will be examined in the following section.

Although steady state flow in a gas reservoir is seldom reached, the conditions around the wellbore can approach steady state. The steady state equation including turbulence is

$$p_e^2 - p_{wf}^2 = \frac{1422\,q\,\bar{\mu}\,\bar{z}\,T\ln(r_e/r_w)}{kh} + \frac{3.161\cdot 10^{12}\,\beta\gamma_g\,\bar{z}q_{sc}^2T}{h^2}\left(\frac{1}{r_w} - \frac{1}{r_e}\right) \tag{7}$$

4. Gas Well Deliverability

The Deliverability of a gas well can be defined as the well's capacity to produce against the restrictions of the well bore and the system into which the well must flow. These restrictions are barriers which must be overcome by the energy in the reservoir. Reducing the size of the well bore or increasing the pressure of the system into which the well must produce, increases the resistance to flow and therefore reduces the deliverability of the well. The Deliverability test allows prediction of flow rates for different line and reservoir pressures. There are three test to predict gas well deliverability, Flow-after-flow test, Isochronal test and Modified isochronal test as shown in figure 5, 6 and 7.

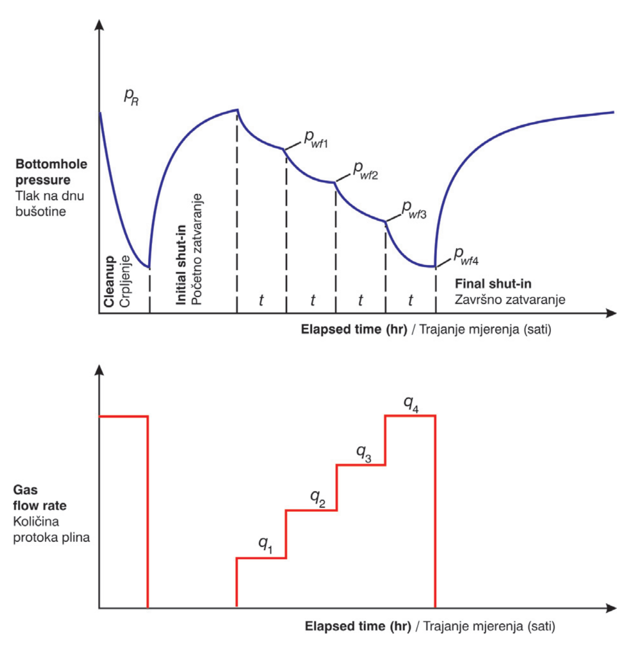

Fig. 5. Flow-after-flow test. (Well test interpretation, Schlumberger)
Sl. 5. Ispitivanje metodom protok za protokom (Interpretacija testa bušotine,Schlumberger)

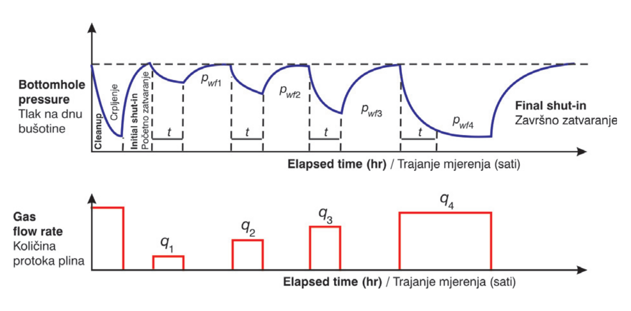

Fig. 6. Isochronal test. (Well test interpretation, Schlumberger)
Sl. 6. Izokronalno ispitivanje (Interpretacija testa bušotine, Schlumberger)

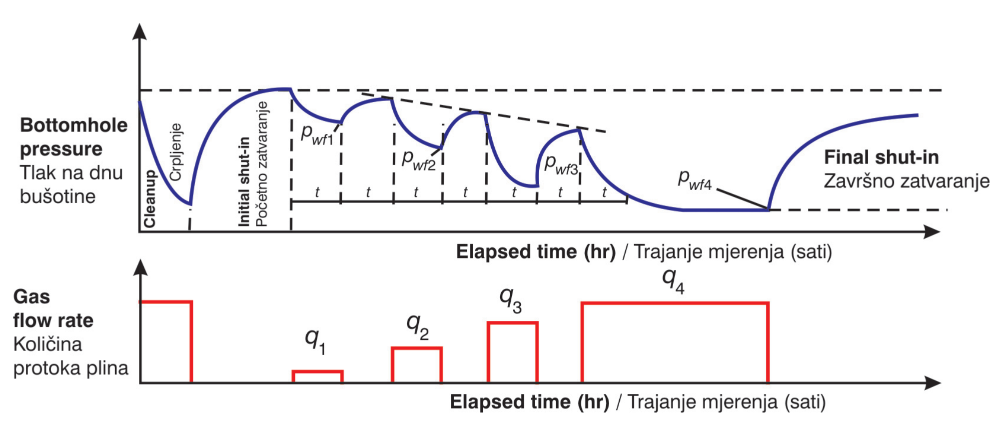

Fig. 7. Modified isochronal test. (Well test interpretation, Schlumberger)
Sl. 7. Modificirano izokronalno ispitivanje (Interpretacija testa bušotine, Schlumberger)

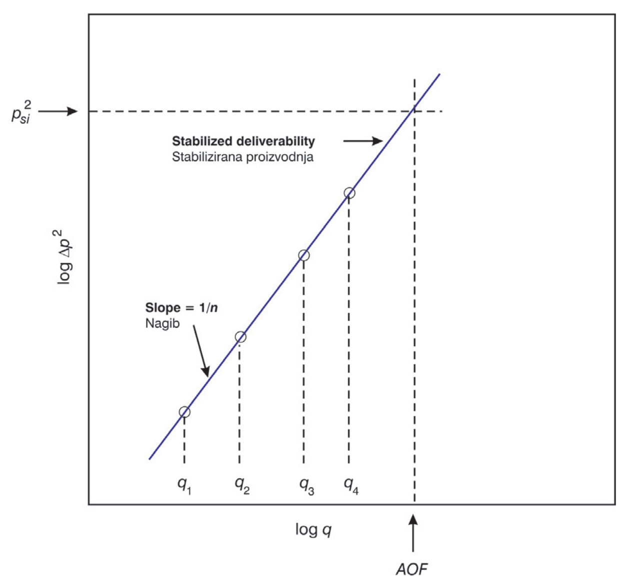

Fig. 8. Deliverability test plot. (http://www.spidr.com/spidr/technotes.html)
Sl. 8. Prikaz ispitivanja radnog kapaciteta bušotine (http://www.spidr.com/spidr/technotes.html)

Backpressure tests were conducted to estimate the true skin effect, to determine deliverability curves and the potential absolute open flow (*AOF*) as show in figure 8. Deliverability curves are used to predict flow rates against values of backpressure. For gas wells, the relationship between rate and bottomhole pressure is given by the following backpressure equation:

$$q_{g_{sc}} = C\left(\bar{p}_R{}^2 - p_{wf}^2\right) \qquad (8)$$

5. Result and Discussion

A vertical gas well was hydraulically fractured to improve productivity and the analysis was run to determine the fracturing efficiency and well and reservoir characteristics using the above mentioned techniques. The characteristics of the reservoir as well as the description of the completion are summarized in Table 1.

5.1 Gas Well Analysis

Modified isochronal test was conducted on the subject gas well to obtain reservoir inflow performance data. The well was flowed on four choke sizes and the corresponding data . The data was plotted to explain the behaviour of the flow rate and pressure with time as can be seen in figure 9.

Table 1. Gas well data

Type of well	=	Vertical well
Total depth of well	=	9 233 ft = 2 814 m
Formation parameters		
Net pay (*h*)	=	200 ft = 61 m
Porosity (φ)	=	8%
Gas saturation (S_g)	=	70%
Water saturation (S_w)	=	30%
Oil saturation (S_o)	=	0%
Wellbore radius (r_w)	=	0.26 ft = 0.08 m
Permeability (*k*)	=	1.7 mD
Formation temperature (*T*)	=	286 ºF = 141 ºC
Initial reservoir pressure (p_i)	=	3 366 psia = 232 bar
Fluid properties		
Gas gravity (air=1)	=	0.607
CH_4	=	90.95%
C_2H_6	=	0.04%
CO_2	=	7.20%
N_2	=	1.82%
H_2S	=	Nil
Perforation Data		
Perforation density	=	10 SPF
Perforated interval	=	2 716-2 724 m=8 910-8 938.6 ft
Fracturing Data		
Propped half length (*xf*)	=	83.5 m
Propped fracture width (*w*)	=	0.167 in. = 0.05 m
Height	=	71.6 m
Average fracture conductivity	=	1,1 mD·m =3,7 mD·ft
Average conductivity	=	584,6 mD·m =1 918 mD·ft

5.2. Pre Fracture and Post Fracture Inflow Performance Curve

The well history for pre fracturing is show in Table 2 and also post fracturing is show in Table 3.

To analyze the gas well test, we first prepare the data as shown in Tables 4 and 5. After that, the differential pressure,

$$\Delta\left(p^2\right) = p_{ws}^2 - p_{wf}^2,$$

is plotted versus q_{sc} in order determine the value of the exponent n. The value of the coefficient C is then calculated using the initial static or average reservoir pressure and the extended test values for p_{wf} and q_{sc}. Figures 10 and 11 illustrate the pre fracturing and post fracturing modified isochronal test respectively.

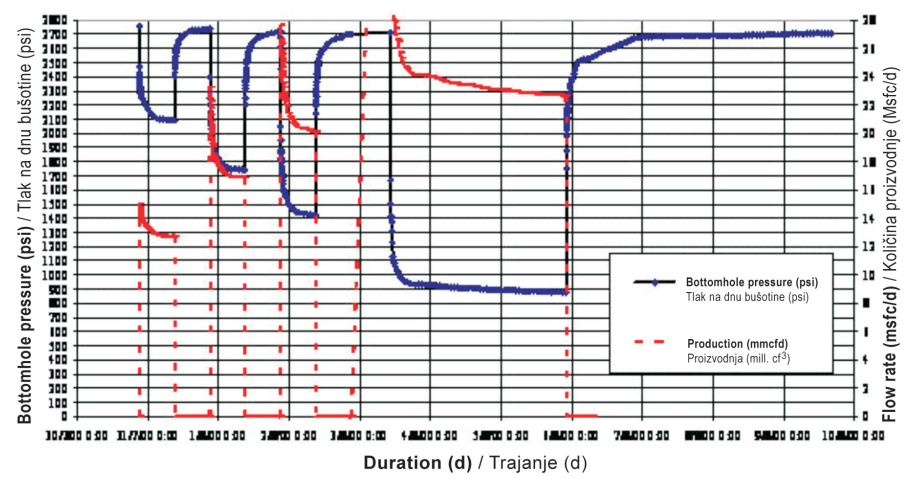

Fig. 9. Modified Isochronal Test of gas well (from 30/07/2000 21:00 to 09/08/2000 16:00)
Sl. 9. Modificirano izokronalno ispitivanje plinske bušotine (od 30.7. 2000. 21:00 do 9.8.2000. 16:00)

Pre fracturing analysis

The parameter n was determined as 0.978 from the slope of the line. On the other hand, the parameter, *C* was determined as 2.54 x E-6 using the *n* and the coordinates of any point on the stabilized deliverability line (e.g. the stabilized point). The *AOF* is then calculated as follows:

$$AOF = C\left(p_R^2\right) = 2.54 \cdot 10^6\left(2766^2\right) = 13.76\ \text{Mscf / d}$$

For post fracturing:

The parameter *n* was determined as 0.904 from the slope of the line. On the other hand, the parameter, *C* was determined as 1.51 x E-5 using n and the coordinates of

Table 2. Pre fracturing flow history

Period	Time hrs	Choke size In.	BHP psia	Flow rate Mscf/d
Shut-in	136.00	0	2 766	0
First flow	3.95	24/64	2 019	6.69
First shut-in	4.00	0	2 749	0
Second flow	4.00	32/64	1 513	9.25
Second shut-in	4.00	0	2 736	0
Third flow	4.00	40/64	1 145	11.14
Third shut-in	4.00	0	2 725	0
Forth flow	4.00	48/64	871	12.31
Extended flow	32.00	48/64	868	12.04
Final shut-in	201.50	0	2 758	0

Table 3. Post fracturing flow history

	Date & Time					
Period	Start	End	Duration hrs	Choke size in.	BHP psia	Flow rate Mscf/d
Shut-in		30/07/2000 21:00		0	2 757	0
First flow	30/07/2000 21:00	31/07/2000 09:00	12.00	32/64	2 092	12.75
First shut-in	31/07/2000 09:00	31/07/2000 21:00	12.00	0	2 737	0
Second flow	31/07/2000 21:00	01/08/2000 09:00	12.00	40/64	1 739	16.87
Second shut-in	01/08/2000 09:00	01/08/2000 21:00	12.00	0	2 718	0
Third flow	01/08/2000 21:00	02/08/2000 09:00	12.00	48/64	1 419	20.14
Third shut-in	02/08/2000 09:00	03/08/2000 10:20	25.33	0	2 715	0
Forth flow	03/08/2000 10:20	03/08/2000 22:00	11.67	64/64	932	24
Extended flow	03/08/2000 22:00	05/08/2000 22:00	48.00	64/64	878	22.7
Final shut-in	05/08/2000 22:00	09/08/2000 16:00	90.00	0	2 707	0

Table 4. Modified isochronal test data for pre fracturing

q_g Mscf/d	p_{ws}, psi	p_{wf}, psi	$p_{ws}^2 - p_{wf}^2$ psi²
6.69	2 766.00	2 019.00	357 439 5.00
9.25	2 749.00	1 513	526 783 2.00
11.14	2 736.00	1 145.00	617 467 1.00
12.31	2 725.00	871	666 698 4.00
12.04			
(Stabilized)	2 725.00	868.00	667 220 1.00

Table 5. Modified isochronal test data for post fracturing

q_g Mscf/d	p_{ws}, psi	p_{wf}, psi	$p_{ws}^2 - p_{wf}^2$ psi^2
12.75	2 757	2 092	322 458 5
16.87	2 737	1 739	446 704 8
20.14	2 719	1 419	537 940 0
24	2 715	932	650 260 1
22.7 (Stabilized)	2 715	878	660 034 1

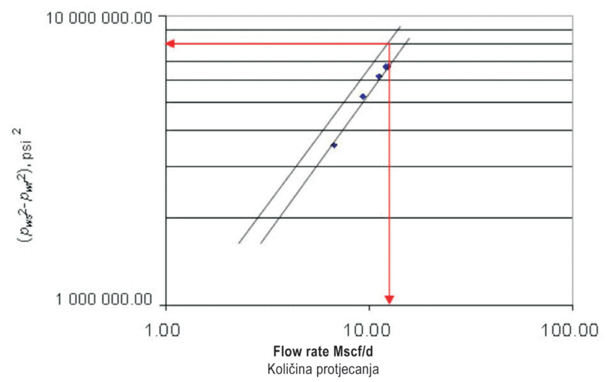

Fig. 10. **Δp^2 versus q_q (pre fracturing)**
Sl.10 Odnos Δp^2 i q_q (prije frakturiranja)

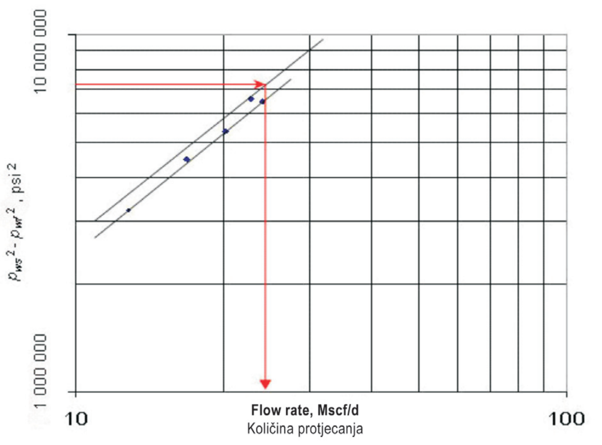

Fig. 11. **Δp^2 versus q_q (post fracturing)**
Sl.11. Odnos Δp^2 i q_q (poslije frakturiranja)

any point on the stabilized deliverability line (e.g. the stabilized point). The *AOF* is then calculated as follows:

$$AOF = C\left(p_R^2\right) = 1.51 \cdot 10^6 \left(2757^2\right) = 25 \text{ Mscf / d}$$

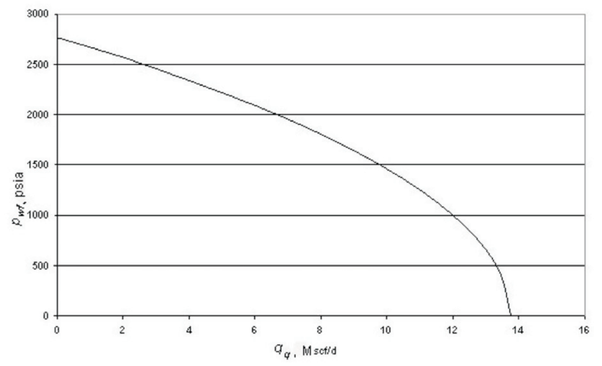

Fig. 12. Inflow performance curve (pre fracturing)
Sl.12. Indikatorska krivulja (prije frakturiranja)

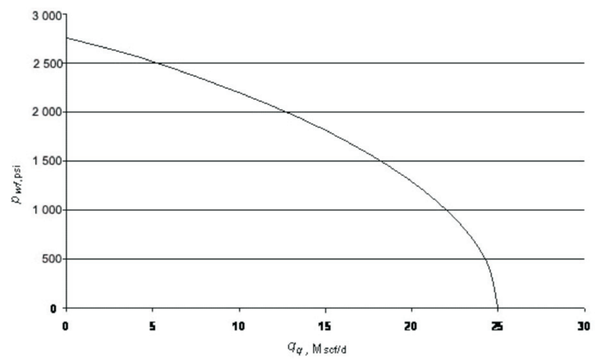

Fig. 13. Inflow performance curve (post fracturing)
Sl. 13. Indikatorska krivulja (poslije frakturiranja)

6. Gas Well Performance Forecast

To predict the gas well performance, future inflow performance curves were generated at values of average reservoir pressure of 2 000 psia, and 1 500 psia. An approximation of the effect of changes in p_R on C can be made by modifying C as follows:

$$\frac{C_1}{C_2} = \frac{\left(\overline{\mu z}\right)_2}{\left(\overline{\mu z}\right)_1}$$

In order to correct for the changes in viscosity and compressibility factor, the parameters are calculated based on the estimated value of reservoir pressure as in Table 6 and then the gas rate, q_g, is calculated based on p_R as in Table 7.

For instance, the calculation can be performed as follows:

For p_R =2 000 psia, $q_q = 1.629\,46 \times 10^{-5} \left(2\,000^2 - p_{wf}{}^2\right)^{0.904}$

For p_R =1 500 psia, $q_q = 1.697\,77 \times 10^{-5} \left(1\,500^2 - p_{wf2}\right)^{0.904}$

Table 6. Viscosity and Compressibility data

p_R psia	μ mPa·s	z	μz mPa·s	C
2 757	0.018 811	0.969 692	0.018 241	1.505 33E-05
2 000	0.017 526	0.961 497	0.016 851	1.629 46E-05
1 500	0.016 789	0.963 32	0.016 173	1.697 77E-05

Table 7. p_R –based gas flow rate calculation

	q_g Mscf/d		
p_{wf}, psia	p_R=2 757 psia	p_R=2 000 psia	p_R=1 500 psia
2 757	0		
2 500	5.245 156		
2 000	12.724 58	0	
1 500	18.202 9	7.173 817	0
1 000	22.007 05	11.677 81	5.514 223
500	24.255 57	14.287 89	8.433 519
0	25.000 08	15.146 28	9.381 034

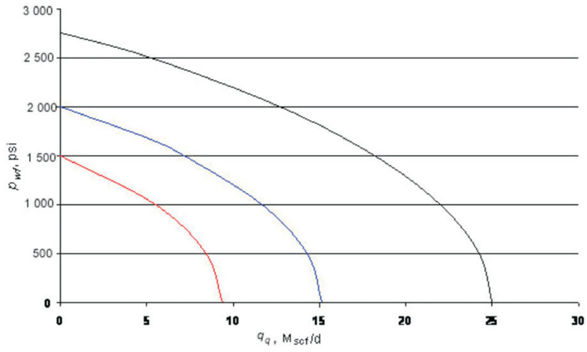

Fig. 14. Future performance curves
Sl. 14. Buduće indikatorske krivulje bušotine

6.1. Well Deliverability

The well Deliverability was conducted by plotting the bottom hole pressure versus flow rate in each chock size and inflow performance (IPR) curve are plotted in figure 15.

6.2. Pressure Transient Testing Analysis

We plot p_{ws}^2 versus log(t+Δt)/Δt) as shown in figure 16 where the data are read off from the final shut-in period of modified isochronal test. The pressure test result is tabulated in Table 8 and shows that the well is stimulates indicating the success of the hydraulic fracturing treatment.

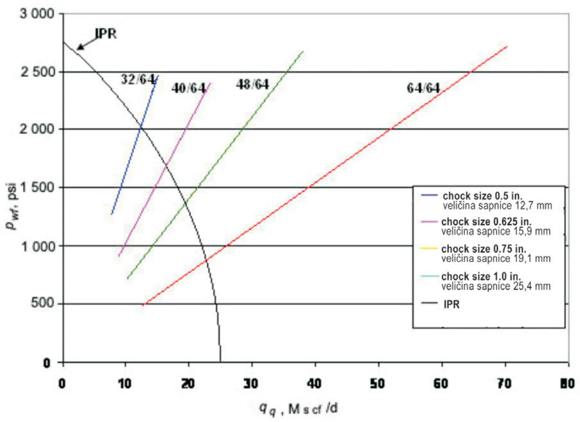

Fig. 15. Chock performance and IPR curve
Sl.15. Odnos promjera sapnica i indikatorske krivulje

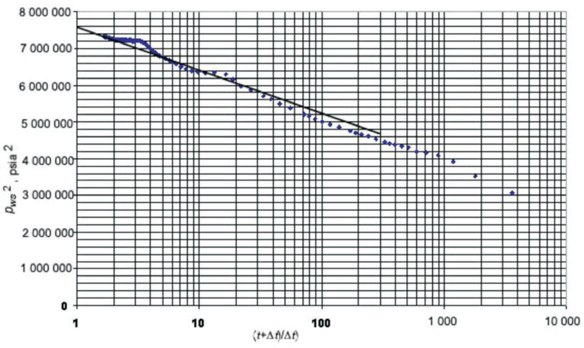

Fig. 16. p_{ws}^2 versus log(t+Δt)/Δt)
Sl.15. Ovisnost p_{ws}^2 versus log(t+Δt)/Δt)

Table 8. Pressure test analysis

final rate, Mscf/d	22.7
net pay, ft	200
porosity, %	8
wellbore radius, ft	0.26
formation temperature, ºF	286
permeability, mD	1.7
kh, mD·ft	340
skin	-1.76

6.3. Gas Well Production Forecast

Forecasting post fracture pressure and production performance was carried out using Diffusivity Equation and gas Material Balance equation. The forecasting result is plotted as shown in figures 19, 20, 21, 22, 23, and 24.

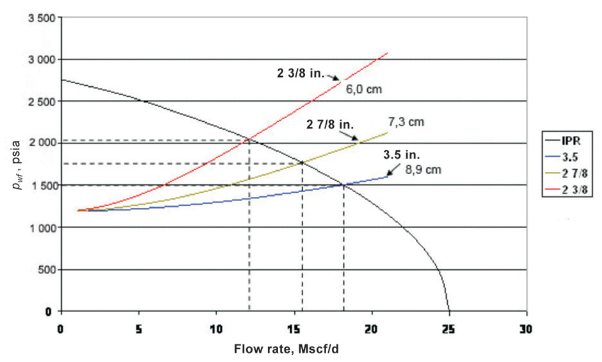

Fig. 17. Tubing size effect with constant wellhead pressure
Sl. 17. Utjecaj promjera tubinga na proizvodnju pri konstantnom tlaku na ušću bušotine

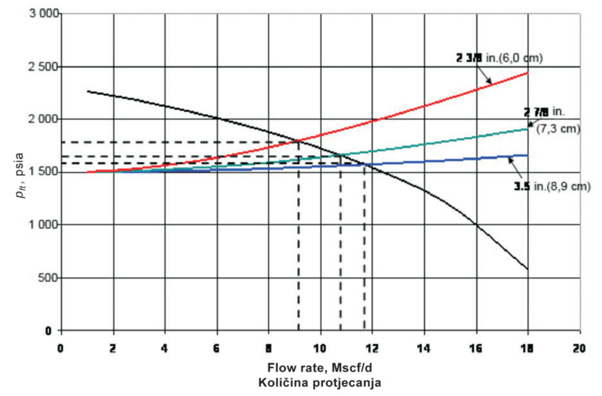

Fig. 18. Tubing size effect with variable wellhead pressure
Sl. 18. Utjecaj promjera tubinga na proizvodnju pri različitim tlakovima na ušću bušotine

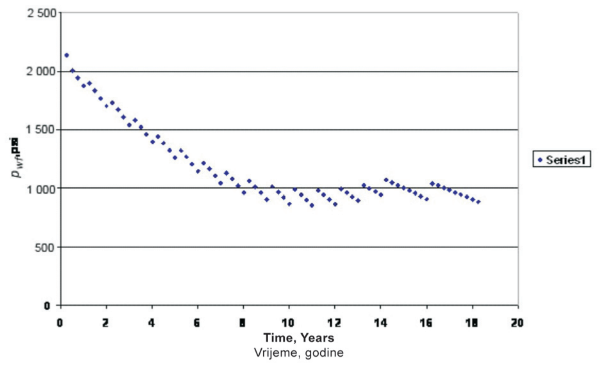

Fig. 19. Forecasting pressure performance post fracturing
Sl. 19. Prognoziranje tlaka nakon frakturiranja

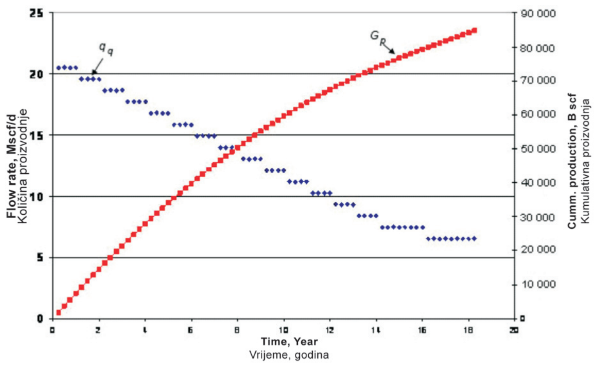

Fig. 20. The forecasts production performance post fracture
Sl. 20. Prognoziranje proizvodnje nakon frakturiranja

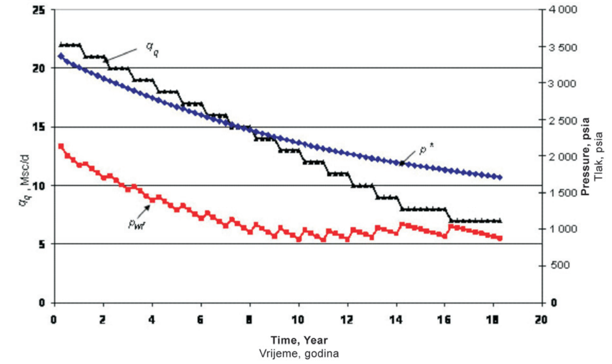

Fig. 21. Forecasts production performance post fracture production
Sl. 21. Prognoziranje proizvodnje nakon frakturiranja

A plot of p/z versus G_p will produce a straight line and the estimated initial gas in place, G is about 190 Bscf as determined by extending the line to the intercept at $p/z = 0$ as shown in figure 22.

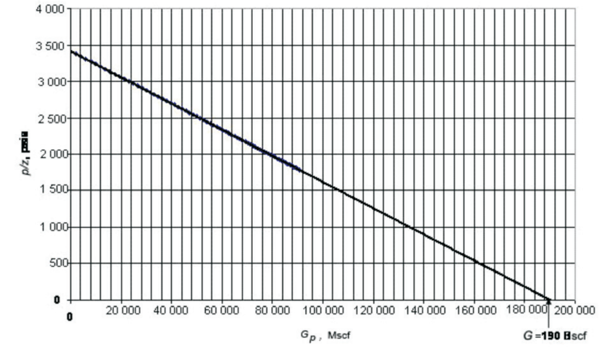

Fig. 22. Plot of p/z versus G_p
Sl. 22. Ovisnost G_p i p/z

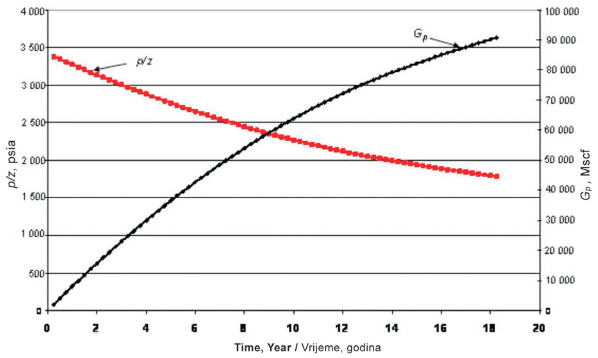

Fig. 23. Forecasts production performance post production (material balance)
Sl. 23.Ovisnost *p/z* i G_p o vremenu

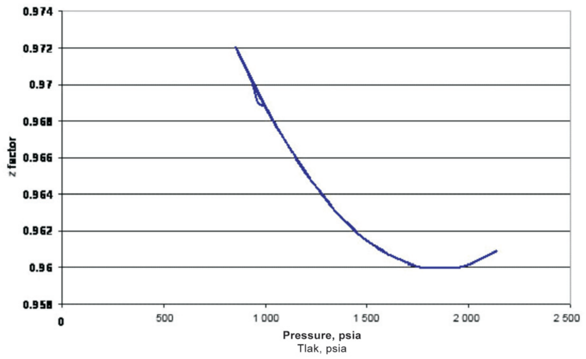

Fig. 24. *z*-factor versus pressure
Sl. 24. Ovisnost kojeficijenta odstupanja (*z*) i tlaka

7. CONCLUSION

Based on the research performed in the course of this study, the following conclusions are presented.

Hydraulic fracturing showed improvement in Deliverability i.e. *AOF* potential has increased from 13.76 to 25 Mscf/d for pre treatment and post treatment respectively.

Production rate and pressure test, and IPR curves indicate that the well could produce 7 Mscf/d for 18.25 years which total approximately 90.794 Bscf.

It is not possible to calculate the reserves since the reservoir was acting as infinite system and there is no indication of closed outer boundary.

ACKNOWLEDGMENT

We would like to express our deep appreciation to Dr. Hazim N. Al-Dmour from Petroleum and Natural Gas Engineering Dept at King Saud University for his supervision this study and his encouragement and guidance throughout this study

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