HORIZONTAL WELL PERFORMANCE MODELLING USING PSEUDOWELL TECHNIQUE

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ABSTRACT

The potential improvement of horizontal productivity has been recognized since mid 1950s, where horizontal well allows longer flow interval hence higher flow rate with lower pressure drawdown. Such remarkable productivity improvement has fascinated the great interest of petroleum industries around the world to fit the role of effective field development strategy. The objective is to reduce the overall cost of field development. In the case of offshore oil fields, the horizontal well drilling is desired to eliminate required number of vertical wells and utilizing of expensive sub-sea technology.

The continuous development and application of horizontal well drilling technologies have been reported in many publications. Nowadays, the horizontal well drilling and completion with complex trajectory is possible. However, the costs required by horizontal well drilling and completion is still considerably more expensive than the vertical one. The future needs of horizontal well drilling tend to arise depending on the economical aspect by means the horizontal well productivity outweigh the incremental drilling and completion costs. An adequate method is required to estimate it's expected productivity to determine the economic feasibility. This paper proposes a horizontal well performance modeling by the concept of pseudowell technique.

I. INTRODUCTION

Many authors have proposed different approach to model the horizontal well performance. Various assumptions are introduced to simplify the problem. Joshi[1] suggested an analytical equation under assumptions of steady-state flow condition, infinite conductivity wellbore, and elliptical drainage volume. Giger[2] established an analytical equation similar to Joshi on the basis of infinite conductivity wellbore, homogeneous-isotropic reservoir, and horizontal well located in the center of reservoir height. Babu[3] developed an analytical equation under assumptions of uniform flux and pseudo-state flow condition. Goode and Kuchuck[4] generated a model based on assumptions of infinite conductivity wellbore and no-flow or constant pressure outer boundary. Dikken[5] presented a model under assumption of turbulent flow, single phase and finite conductivity (taking into account pressure gradient along horizontal wellbore). The Dikken model facilitates the incorporation of laminar and multiphase flow if a complete mixing of the phases occurs inside the horizontal section assuming a homogeneous fluid phase with average properties. The reservoir properties along the horizontal section are taken as constant (uniform specific productivity index), eventhough the model allows variable specific productivity index.

This paper introduces a new approach to model the horizontal well performance using pseudowell technique. This concept uses several pseudowells to represent a horizontal well. The main goal of this work is to provide an alternative in form of a reliable and practical method for evaluating the horizontal well performance.

II. PSEUDOWELL MODEL

The implementation of pseudowell model to represent a horizontal well is illustrated in Figure 1. The horizontal section is divided into several segments and each segment is represented by a single pseudowell. If L is the total length of horizontal well and N is the number of pseudowell, the

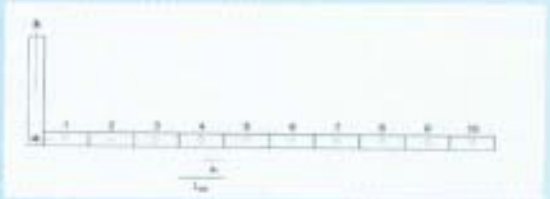

Figure 1
A horizontal well is model 3led as ten pseudo wellbores

length of each pseudowell is equal to L_{ps} =L/ N. All pseudowells are assumed identical as fractured vertical wells with a half-fracture length of x_f =L_{ps}/2. By adopting the concept of apparent wellbore radius, the pseudowell can be considered as a vertical well by substituting the well length with an apparent wellbore radius (r_{wa}). The apparent wellbore radius is calculated depending on the assumption of wellbore hydraulic model. Gingarten[6] suggested the apparent wellbore radius as:

$$r_{wa} = \frac{x_f}{e} = \frac{x_f}{2.7182}$$ Uniform flux hydraulic model (1)

$$r_{wa} = 0.498\ x_f$$ Infinite conductivity hydraulic model (2)

General solution of pressure transient for radial flow in vertical well has been presented in many publications. The solution in dimensionless form is expressed as:

$$P_D(t_D, r_D) = -\frac{1}{2} E_i\left[\frac{-r_D}{4t_D}\right] \quad (3)$$

Where:

$$P_D = \frac{2\pi kh(P_i - P_w)}{Q\mu B}$$

$$t_D = \frac{kt}{\phi\mu c_t r_w^2}$$

$$r_D = \frac{r}{r_w}$$

$$E_i(x) = \int_x^{\infty} \frac{e^{-u}}{u}\, du$$

For the value of $t_D > 100$, then the E_i-function can be approximated as the logarithmic function of :

$$E_i\left(\frac{-r_D}{4t_D}\right) = -\left[\ln\left(\frac{t_D}{r_D^2}\right) + 0.80907\right] \quad (4)$$

By substituting equations 3 and 4, then a new equation can be obtained as :

$$P_D(t_D, r_D) = \frac{1}{2}\left[\ln\left(\frac{t_D}{r_D^2}\right) + 0.80907\right] \quad (5)$$

If no physical outer boundary, according to Diezt shape factor the infinite acting period of radial flow geometry in vertical well will end at time t_D=0.1. The ultimate radius of investigation of the well is reached at time t_D=0.25. Radius of investigation is described as:

$$r_i = \sqrt{\frac{4kt}{\phi\mu c_t}} \quad (6)$$

The pressure solution for pseudo steady-state condition can be derived from equations 5 and 6 with t_D= 0.25.

$$P_D(r) = \frac{1}{2}\left[\ln\left(\frac{r_i^2}{r^2}\right) - 0.57722\right] \quad (7)$$

By analogy, the pressure solution for pseudowell can be obtained from equation 7 by substituting r with r_{wa} as:

$$P_D(r) = \frac{1}{2}\left[\ln\left(\frac{r_i^2}{r_{wa}^2}\right) - 0.57722\right] \quad (8)$$

In many oil fields, the reservoir may not isotropic (i.e, vertical permeability is normally less than lateral permeability) and the horizontal well location does not always in the center of reservoir height. The pseudo skin factor should be then taken into account in equation 8 to accommodate the effect of reservoir anisotropy and well eccentricity resulting in:

$$P_D(r) = \frac{1}{2}\left[\ln\left(\frac{r_i^2}{r_{wa}^2}\right) - 0.57722 + 2S_p\right] \quad (9)$$

The pseudo skin factor (S_p) is defined by Joshi as:

$$S_p = \frac{\beta h}{L_{ps}} \ln\left[4\,\frac{\left(\frac{\beta h}{2}\right)^2 - (\beta\delta)^2}{\beta h D}\right] \quad (10)$$

where:

$$\beta = \sqrt{\frac{k_h}{k_z}}$$

$$k_h = \sqrt{k_x k_y}$$

δ = distance from reservoir midheight to horizontal wellbore

III. PSEUDOWELL INTERFERENCE

The position of each pseudowell along the horizontal well section is expressed as:

$$X_n = (n - 0.5)\ \frac{L}{N} \qquad (11)$$

The interference between pseudowells are connected by superposition principle which is illustrated in Figure 2. The superposition principle to represent a horizontal well by N pseudowells is expressed as:

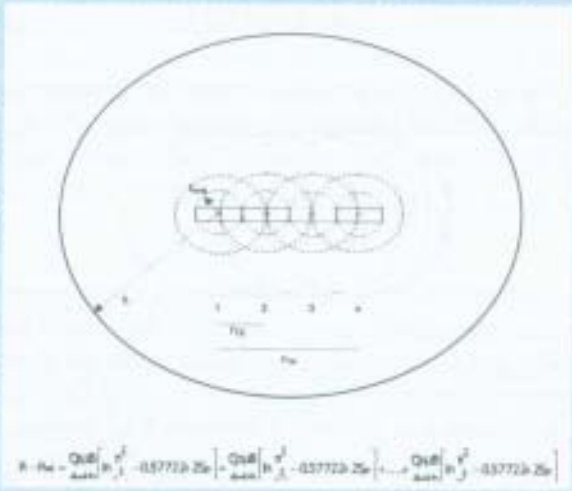

Figure 2

Superposition principal

In order to simplify the equation 12, a new parameter is defined with respect to pseudowell location as below:

$$Z = \frac{\mu B}{4\pi kh}\left[\ln\frac{r_i^2}{r} - 0.57722 + 2S_p\right] \qquad (13)$$

By combining equations 12 and 13 can be generated matrix form as:

$$\begin{bmatrix} P_i - P_{w1} \\ P_i - P_{w2} \\ P_i - P_{wn} \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{1n} \\ Z_{21} & Z_{22} & Z_{2n} \\ Z_{n1} & Z_{n2} & Z_{nn} \end{bmatrix} * \begin{bmatrix} Q_1 \\ Q_2 \\ Q_n \end{bmatrix} \qquad (14)$$

If the hydraulic wellbore model assumed infinite conductivity, then $P_{w1} = P_{w2} = P_{wn}$ implying no pressure gradient along the horizontal well section. The flow rate distribution along horizontal section is represented by Q_1, Q_2, ...Q_n, while the total flow rate is provided by the summation of Q_1 through Q_n.

IV. EXAMPLE

A simple horizontal well drilling is conducted in homogeneous and undersaturated oil bearing zone. The objective is to calculate the inflow performance of horizontal well and flow rate distribution along the horizontal section !

A. *Reservoir Data*

Reservoir thickness (h =75 feet)
Radius drainage model (A = 120 acres)
Lateral permeability in x-direction (kx = 150 mD)
Lateral permeability in y-direction (ky =150 mD)
Vertical permeability in z-direction (kz= 60 mD)
Initial reservoir pressure (Pi = 1750 psi)
Bubble point pressure (Pb= 450 psi)
Oil viscosity (μ_o = 3.5 cp)
Oil formation volume factor (B_o=1.2).

$$P_i - P_{w1} = \frac{Q_1\mu B}{4\pi kh}\left[\ln\frac{r_i^2}{r_{wa}^2} - 0.57722 + 2S_p\right] + \frac{Q_2\mu B}{4\pi kh}\left[\ln\frac{r_i^2}{r_{12}^2} - 0.57722 + 2S_p\right] + ... + \frac{Q_n\mu B}{4\pi kh}\left[\ln\frac{r_i^2}{r_{1n}^2} - 0.57722 + 2S_p\right]$$

$$P_i - P_{w2} = \frac{Q_1\mu B}{4\pi kh}\left[\ln\frac{r_i^2}{r_{21}^2} - 0.57722 + 2S_p\right] + \frac{Q_2\mu B}{4\pi kh}\left[\ln\frac{r_i^2}{r_{wa}^2} - 0.57722 + 2S_p\right] + ... + \frac{Q_n\mu B}{4\pi kh}\left[\ln\frac{r_i^2}{r_{2n}^2} - 0.57722 + 2S_p\right]$$

$$P_i - P_{wn} = \frac{Q_1\mu B}{4\pi kh}\left[\ln\frac{r_i^2}{r_{n1}^2} - 0.57722 + 2S_p\right] + \frac{Q_2\mu B}{4\pi kh}\left[\ln\frac{r_i^2}{r_{n2}^2} - 0.57722 + 2S_p\right] + ... + \frac{Q_n\mu B}{4\pi kh}\left[\ln\frac{r_i^2}{r_{wa}^2} - 0.57722 + 2S_p\right] \qquad (12)$$

B. *Horizontal Well Data*

Well diameter (D= 8.5 inch)
Total well length (L=750 feet)
Number of pseudowell (N=10)
Well position (δ =10 ft)
Infinite conductivity wellbore.

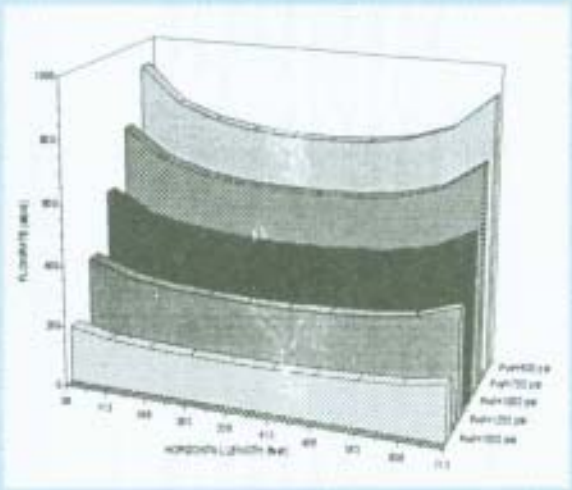

Figure 3
Flow rate distribution in horizontal well (Infinite conductivity wellbore model)

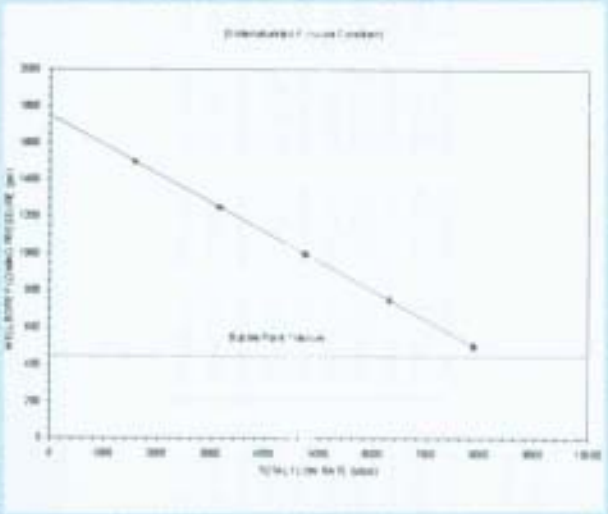

Figure 4
Inflow performance relationship (IPR) of horizontal well (undersaturated pressure condition)

By implementing equation 12, 13 and 14, the problem can be solved using Gauss elimination method. The flow rate calculation for various P_{wf} are tabulated in Table 1 through Table 5. The calculation process is performed in SI units in order to minimize errors due to the use improper unit conversion factor. However, input and output data are still presented in field unit aimed at convenience of practical operator. The result of flow rate distribution along the horizontal section for various P_{wf} is presented in Figure 3, while inflow performance relationship (IPR) is exhibited in Figure 4.

V. DISCUSSION

The assumption of infinite conductivity wellbore model is normally valid for relatively short horizontal section and under laminar fluid flow regime inside the wellbore. Although the above simple example used an infinite conductivity wellbore model, however, the concept described in this paper can be easily modified to accommodate more complex cases. For instance, by taking into account the pressure gradient along the horizontal well that can be made by modifying equation 12. The pressure gradient along the horizontal section becomes significant for multiphase flow condition, viscous fluid, gravitational effect and the effect of radial flow from reservoir through perforations.

VI. CONCLUSIONS

The conclusions of this paper can be summarized as :

1. An alternative approach to evaluate the horizontal well performance has been provided by implementing the concept of pseudowell technique. Hopefully, it will help to obtain the most prospective horizontal well drilling in the field development strategies.
2. The proper evaluation horizontal well performance is important before the decision to drill is taken. It is intended to ensure that the expected well productivity improvement outweighs drilling and completion cost when compare to vertical well drilling.

Nomenclature

B	:	formation volume factor
C_t	:	total compressibility
D	:	wellbore diameter
k_x	:	permeability in x-direction
k_y	:	permeability in y-direction
k_z	:	permeability in z-direction
L_{ps}	:	length of pseudowell
P_D	:	dimensionless pressure
P_i	:	initial pressure
$P_{wf} = P_w$	:	wellbore pressure
Q	:	flow rate

Table 1

Flow Rate Distribution (Pwf = 1500 psi)

ΔP Pascal		SI Units											Flow Rate m³/sec
1723689		2355876298	586941419	443683545	382847241	347900605	326293782	312216843	302644656	295895611	290986729		0.00033787
1723689		586941419	2355876298	586941419	443683545	382847241	347900605	326293782	312216843	302644656	295895611		0.00029581
1723689		443683545	586941419	2355876298	586941419	443683545	382847241	347900605	326293782	312216843	302644656		0.00027778
1723689		382847241	443683545	586941419	2355876298	586941419	443683545	382847241	347900605	326293782	312216843		0.00026850
1723689	=	347900605	382847241	443683545	586941419	2355876298	586941419	443683545	382847241	347900605	326293782	x	0.00026813
1723689		326293782	347900605	382847241	443683545	586941419	2355876298	586941419	443683545	382847241	347900605		0.00026813
1723689		312216843	326293782	347900605	382847241	443683545	586941419	2355876298	586941419	443683545	382847241		0.00026850
1723689		302644656	312216843	326293782	347900605	382847241	443683545	586941419	2355876298	586941419	443683545		0.00027778
1723689		295895611	302644656	312216843	326293782	347900605	382847241	443683545	586941419	2355876298	586941419		0.00029581
1723689		290986729	295895611	302644656	312216843	326293782	347900605	382847241	443683545	586941419	2355876298		0.00033787

Table 2

Flow Rate Distribution (Pwf = 1250 psi)

ΔP Pascal		SI Units											Flow Rate m³/sec
3447379		2355876298	586941419	443683545	382847241	347900605	326293782	312216843	302644656	295895611	290986729		0.00067596
3447379		586941419	2355876298	586941419	443683545	382847241	347900605	326293782	312216843	302644656	295895611		0.00059181
3447379		443683545	586941419	2355876298	586941419	443683545	382847241	347900605	326293782	312216843	302644656		0.00055556
3447379		382847241	443683545	586941419	2355876298	586941419	443683545	382847241	347900605	326293782	312216843		0.00053900
3447379	=	347900605	382847241	443683545	586941419	2355876298	586941419	443683545	382847241	347900605	326293782	x	0.00053227
3447379		326293782	347900605	382847241	443683545	586941419	2355876298	586941419	443683545	382847241	347900605		0.00053227
3447379		312216843	326293782	347900605	382847241	443683545	586941419	2355876298	586941419	443683545	382847241		0.00053900
3447379		302644656	312216843	326293782	347900605	382847241	443683545	586941419	2355876298	586941419	443683545		0.00055556
3447379		295895611	302644656	312216843	326293782	347900605	382847241	443683545	586941419	2355876298	586941419		0.00059181
3447379		290986729	295895611	302644656	312216843	326293782	347900605	382847241	443683545	586941419	2355876298		0.00067596

Table 5
Flow Rate Distribution (Per 1 = 1000 psi)

Δ P Percel		Distance											Flow Rate m³/hour
0.171088		2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00	2.26E+37	2.12E+08	3.02E+05	2.95E+55	2.92E+07		0.001011
0.171088		5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00	2.26E+37	2.12E+08	3.02E+05	2.95E+55		0.000888
0.171088		4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00	2.26E+37	2.12E+08	3.02E+05		0.000833
0.171088		3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00	2.26E+37	2.12E+08		0.000804
0.171088	*	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00	2.26E+37	*	0.000798
0.171088		2.26E+37	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00		0.000788
0.171088		2.12E+08	2.26E+37	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21		0.000804
0.171088		3.02E+05	2.12E+08	2.26E+37	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03		0.000833
0.171088		2.95E+55	3.02E+05	2.12E+08	2.26E+37	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19		0.000888
0.171088		2.92E+07	2.95E+55	3.02E+05	2.12E+08	2.26E+37	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78		0.001012

Table 6
Flow Rate Distribution (Per 1 = 750 psi)

Δ P Percel		Distance											Flow Rate m³/hour
6.88E+17		2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00	2.26E+37	2.12E+08	3.02E+05	2.95E+55	2.92E+07		0.001351
6.88E+17		5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00	2.26E+37	2.12E+08	3.02E+05	2.95E+55		0.001183
6.88E+17		4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00	2.26E+37	2.12E+08	3.02E+05		0.001111
6.88E+17		3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00	2.26E+37	2.12E+08		0.001077
6.88E+17	*	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00	2.26E+37	*	0.001064
6.88E+17		2.26E+37	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00		0.001064
6.88E+17		2.12E+08	2.26E+37	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21		0.001077
6.88E+17		3.02E+05	2.12E+08	2.26E+37	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03		0.001111
6.88E+17		2.95E+55	3.02E+05	2.12E+08	2.26E+37	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19		0.001183
6.88E+17		2.92E+07	2.95E+55	3.02E+05	2.12E+08	2.26E+37	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78		0.001351

Table 8
Flow Rate Distribution (Per 1 = 500 psi)

Δ P Percel		Digits											Flow Rate m³/hour
9.61E+16		2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00	2.26E+37	2.12E+08	3.02E+05	2.95E+55	2.92E+07		0.001887
9.61E+16		5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00	2.26E+37	2.12E+08	3.02E+05	2.95E+55		0.001679
9.61E+16		4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00	2.26E+37	2.12E+08	3.02E+05		0.001589
9.61E+16		3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00	2.26E+37	2.12E+08		0.001547
9.61E+16	*	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00	2.26E+37	*	0.001533
9.61E+16		2.26E+37	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21	3.47E+00		0.001533
9.61E+16		2.12E+08	2.26E+37	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03	3.62E+21		0.001547
9.61E+16		3.02E+05	2.12E+08	2.26E+37	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19	4.42E+03		0.001589
9.61E+16		2.95E+55	3.02E+05	2.12E+08	2.26E+37	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78	5.88E+19		0.001679
9.61E+16		2.92E+07	2.95E+55	3.02E+05	2.12E+08	2.26E+37	3.47E+00	3.62E+21	4.42E+03	5.88E+19	2.253E+78		0.001887

Q	:	total flow rate
r_D	:	dimensionless radius
r_i	:	radius of investigation or reservoir radius
r_w	:	wellbore radius
r_{wa}	:	apparent wellbore radius
S_p	:	pseudo skin
t	:	time
t_D	:	dimensionless time
x_f	:	Half fracture length
β	:	Joshi parameter
δ	:	Disrance wellbore to midheight reservoir
ϕ	:	porosity
μ	:	viscosity.

REFERENCES

1. **Joshi, S.D.** , 1988, "Augmentation of Well Productivity with Slant and Horizontal Wells", *JPT*, June.
2. **Giger, F.M.**, 1985, "Horizontal Wells Production Technique in Heterogeneous Reservoirs", *SPE Middle East Oil Technical Conference and Exhibition*, Bahrain, March 11-14.
3. **Babu, D.K.** and **Odeh, A.S.**, 1989, "Productivity of Horizontal Wells", *SPE Reservoir Engineering Journal*, November.
4. **Goode, P.A.** and **Kuchuck, F.J.**, 1991, "Inflow Performance of Horizontal Wells", *SPE Reservoir Engineering Journal*, August.
5. **Dikken, B.J.**, 1990, "Pressure Drop in Horizontal Wells and Its Effect on Production Performance", *JPT*, November.
6. **Gringarten, A.C.** et.al., 1974, "Unsteady-state Pressure Distribution Created by a Well with a Single Infinite Conductivity Fracture", *SPEJ*, August.□