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Effect of Non-Uniform Formation Damage on the Inflow Performance of Horizontal Wells.

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Abstract

Horizontal drilling is gaining widespread popularity because of the advantages horizontal wells offer comparatively to vertical ones. However in some instances, the production performance of horizontal wells did not live up to expectation especially in the Middle East where vertical wells are naturally prolific. This has been attributed in general to near well bore formation damage. Because of their large contact area with the reservoir, horizontal wells are more susceptible to drilling and work-over induced formation damage than vertical ones. The effect of skin damage on horizontal wells has been abundantly covered in the literature, however in most cases, an average constant value of skin has been contemplated despite the conic shaped damaged zone that builds up around the horizontal well bore. The reason for this simplification is that the analytical expressions used for the productivity index do not easily accommodate variable skins along the well length. Since it is common now to drill very long horizontal wells, there are more reasons to believe that substantial variations of the skin exist along the horizontal well length. Therefore, it is important to know how the different sections of the horizontal well contribute to the production of the well and what is the role of formation damage and friction in the overall performance of the well.

The present paper addresses the case of high permeability reservoirs displaying variable skin damage along the horizontal section of the well. A literature survey is conducted in order to understand the different skin concepts presented recently in the literature. A semi analytical approach is used to study the simultaneous effect of perforation scenario, near well bore formation damage and friction losses on the production of horizontal wells. The results are presented in the form of a parametric study of the effect of well length, anisotropy ratio, skin, tubing diameter and perforation distribution on the inflow performance of the horizontal well. Some of these results are summarized bellow:

1. The assumption of constant skin along the well length must be weighted carefully.
2. Three different profiles of near well bore damage have been examined: Constant skin with length, linearly decreasing from heel to toe and steep decrease of the skin versus the length. Even though the average skin is the same for the three cases, the results showed completely different inflow performance curves when friction forces are taken into account.
3. Even small skins can have serious effects on the production of horizontal wells.
4. In case of stimulation, removing completely the damage is essential for restoring the original potential of the well.

Introduction

Horizontal well drilling in Saudi Arabia started back in January 1991 when the first horizontal well had been successfully drilled in Hadriya[1] with a length of 2303 feet and a rate, approximately three folds the conventional Hadriya wells. Since then, a large number of horizontal wells have been completed. In the near future, drilling highly deviated and horizontal wells may become the rule rather than the exception.

However, all horizontal wells have not been successful. In some cases, the results have not been up to expectations. This has been in general attributed to formation damage. Formation damage has been always a serious issue in production wells wheather vertical or horizontal wells. A survey of the recent literature shows that horizontal wells are more subject to formation damage than vertical ones as it will be seen later. The effect of formation damage on vertical wells has been studied first by Van Everdingen[2] and Hurst[3] who showed that damage translates into an additional pressure drop that adds to the pressure drop due to the flow in the undamaged zone of the reservoir. Van Everdingen and Hurst introduced the notion of skin S, which is widely used in pressure transient analysis techniques. Hawkins[4] related this skin S to the invasion depth of the mud and the permeability reduction in the well-known Hawkin's' Eq. 1.

$$S = (k/k_D - 1)\ln(r_s/r_w) \ldots\ldots (1)$$

In all the papers related to formation damage in vertical wells, the skin S is assumed to be a single value non-dimensional parameter that measures the near well bore damage and is used to estimate the vertical well production impairment. With the emerging horizontal drilling technology, came the need of adapting the existing transient pressure analysis methods to highly deviated and horizontal wells. Many new flow equations valid for horizontal wells have been presented in the literature lately. In all the equations, the concept of single value skin has been retained. In some recent papers[5,6,7,8], the validity of this concept for horizontal wells is discussed. Since very long horizontal wells can be presently drilled, with lengths reaching sometimes several thousands feet, the validity of single value skin for the whole horizontal section of the well becomes questionable.

Mechanisms of Formation damage

Formation damage, which is a critical issue for vertical wells, has been presented in the literature with mixed feelings when it comes to horizontal wells. Although some authors[9] consider horizontal wells as less sensitive to formation damage than vertical ones, most studies[10,11,12] show that formation damage is actually more crucial for horizontal wells than for vertical ones. The most obvious reasons are:

- Longer exposure time of the reservoir to drilling and completion fluids.
- Inefficient transport of the cuttings from the horizontal well bore to the surface during drilling operations.
- Inappropriate after-drilling clean up due to generally insufficient draw-down pressures.
- Difficulty in designing efficient completions in the case of horizontal wells.
- Difficulty in implementing stimulation techniques since the majority of horizontal wells are still completed open hole.

Different Types of Formation damage

Several mechanisms of formation damage have been identified in the literature. Some of them can be listed briefly as follows:

1. Mechanical due mainly to solid invasion.
2. Chemical related to:
   - Fluid-fluid incompatibility that results in insoluble precipitates, asphaltics, sludges etc.
   - Rock-fluid incompatibility resulting mostly in clay swelling for example.
   - Adsorption resulting in change in wettability and relative permeability.

3. Other mechanisms such as emulsion, internal migration of fines, etc. that result in change of flow characteristics near the well.

Probably, the most important among these mechanisms is the mechanical[13,14] one or mainly the invasion of solids. It has been shown in some early publications on formation damage that the solid contents in drilling fluids, is a major source of formation damage and has a direct effect on near well bore skin damage. In a recent paper[15], Purvis and Smith showed that long horizontal wells are more subject to mechanical damage because of the difficulty for the cuttings to be transported to the surface. Consequently, they are grounded over and over and produce fines of all diameters that penetrate the porous medium and induce formation damage by blocking pore throats after back flow.

Variation of Skin along the Length

A major difference between vertical and horizontal wells is that unlike the case of vertical wells, formation damage is uneven both in the radial direction and along the horizontal section of the horizontal wells. Purvis and Smith[15] showed also that, the constant erosion of the filter cake due to friction of the drilling string against the bottom part of the horizontal well bore, results in a non-symmetric invasion zone. The invasion zone will be more elongated towards the bottom part of the well bore than the upper part. Economides[5] showed also that the anisotropy ratio plays an important role in the shape of the invasion zone, which will be affected by the direction of the axis of higher permeability. More importantly, several papers[5,6,7,8] published recently show that formation damage is non-uniform along the well length. Economides[5], using a numerical simulator showed for example that the heel of the horizontal well is exposed to drilling fluids during a longer time than the toe. This results in a damaged zone having the shape of a truncated elliptical cone with the larger base near the heel and the smaller base near the toe. The direct application of Hawkins[4] relation to estimate the skin S for this particular form of damaged zone will result in a decreasing function S with the distance along the horizontal well section. Engler et al[7] used a different approach to characterize formation damage along the horizontal well length. They proposed a model to estimate the skin as a function of length. Their model takes into account the drilling rate of penetration as well as the filtrate invasion rate. Engler showed also that the skin S decreases from a maximum value near the vertical section of the well to a minimum value near the toe of the horizontal well. Nabzar and Chauveteau[8] studied also the different mechanisms leading to permeability damage and found that fines and particules deposition, are among the most important causes of formation damage. They presented a theoretical model based on a completely different approach from the previous studies, to predict permeability damage. The skin derived from their model is also found to be decreasing with distance from the heel to the toe of the horizontal well.

Types of Skin Profiles along the Horizontal Length

The main conclusion of all the studies mentioned above is that the skin along the horizontal well length is not constant. This is true especially for long horizontal wells. The profile of skin variation along the length depends on the severity of the damage in each section of the well, which depends on the exposure time, the characteristics of the drilling fluids, the drilling parameters as well as the nature of the formation. The skin profile along the length can vary from a mild variation of S along the horizontal length to a drastic one.

Performance Prediction of Horizontal Wells

The skin S is an important parameter in the analytical expression predicting the flow rate in vertical wells. As shown earlier, the notion of skin in vertical wells implies radial flow and uniformity of formation damage around the well bore. For horizontal wells, neither the flow is radial, nor the skin is uniform around or along the well bore. It is also not constant along the well as shown in the studies discussed above. It should be observed that, in the analytical flow equations for horizontal wells published in the literature up to now, the skin is assumed to be a single value parameter and no equation can accommodate presently a variable skin along the well.

- **Combined Effect of Skin and Friction on Flow Behavior.**

As shown in the previous sections, the longer it takes to drill a horizontal well, the less chances for the skin to be uniform and constant along the horizontal section of the well. In the case of long horizontal wells, not only does the skin vary significantly but also, friction is important and has to be taken into consideration. This is especially the case for some reservoirs in the Middle East where the wells are several thousands feet long and the rates are extremely high, due to extra large permeability. To understand how the variable skin along the horizontal section of the well combined with friction can affect significantly the flow performances of the well, one should compare first a well producing with a constant skin to a well producing with variable skin in the absence of friction forces. Since the magnitude of the skin is in general higher at the heel than at the toe, the flux will not be uniform but the distribution of flow along the horizontal well will be similar regardless of the flowing pressure at the well bore. In this case the variable skin profile is equivalent to a constant skin profile along the horizontal well. When friction forces are taken into account, equilibrium between the flow contribution of the reservoir to each section of the well bore and the friction forces in the well bore itself has to be reached before the flow rate stabilizes. This equilibrium depends on the skin distribution along the well length and the flow rate distribution. Since there is no analytical equation that takes into account all the forces involved, the flow has to be simulated numerically using some iterative techniques.

- **Performance Prediction Model.**

For this purpose, a similar method to the one used in a previously published paper[16] is utilized in the present study. This method of solution is implemented in two steps. In the first step, the inflow performances of the reservoir, which depend on the reservoir and well characteristics, are estimated. The well can be either completed open hole or cased and selectively perforated. The skin profile can be either estimated from the available well and formation characteristics or assumed as input data. In the second step the outflow performance of the horizontal well are evaluated. This takes into consideration the fluids characteristics as well as the length and diameter of the well. The approach consists of dividing the horizontal section of the well into a number of cells as in finite difference methods. The flux in each cell is estimated using the inflow performance, the skin, and the ambient pressure in this particular cell. A new cell pressure drop is evaluated next before the calculations are repeated in an iterative manner until accurate rate and pressure distributions along the well are obtained. A computer program is utilized to perform these calculations. After an initial estimation of the inflow performance of the horizontal well, the program conducts the iterative process until convergence. The estimation of skin, friction forces, and other process variables is performed using a number of utility subroutines associated with the main program. A flow chart of the main program is shown in the Appendix.

Field Example

A field example is used to validate the method. Data related to this well which is cased and perforated are presented in **Table 1**. Other data such as the distribution of skin is presented in **Fig. 1**. **Fig. 2** presents the well performances calculated by the model as compared to the flow distribution obtained from flow-meter measurement. As it is seen in this figure, the match is fairly good.

Result and Discussion

It appears from what has been seen above that, despite the various studies showing that the skin decreases from the heel to the toe of the horizontal well, flow rates are still computed assuming constant skin S in the analytical equations predicting the flow rates for horizontal wells. The question is how does this assumption affect the well performance predictions.

Table 2, represents selected data that has been used in this study. This data is closely related to a typical field in the Middle East. Different skin profiles are assumed for this well. For the first skin profile (case-1), which is also taken as the base case, a single value of the skin is considered all along the horizontal well. This constant value of the skin is computed using the method suggested by Economides[5]. Based on this profile, the well performances are computed using the model described above. Three different profiles are assumed next for the same well characteristics. In one of them (case-2), the variation of skin S is linear, in the other (case-3), the skin is calculated according to Yan's[6] method and in the last profile (case-4), a polynomial decrease of the skin is assumed. **Fig. 3** shows the variation of skin for the four cases including the base case. For all these profiles which have also all the same average value of skin along the horizontal section of the well length, the well performances have been calculated. The results for this 2000 ft and 6” diameter horizontal well are presented in **Fig. 4**. The cumulative flow rates given in this figure are reported in dimensionless form by reference to the base case. It can be seen from this figure, that the well performances for the four cases are far from being identical even though the average value of the skin is the same. The steeper the skin profile, the higher the performance. The difference of cumulative flow rate between the polynomial profile and the constant skin case can be as high as 40%. This difference can be even larger when the well bore diameter is smaller. See **Fig. 5.**

Similar calculations have been performed for the same well characteristics and different lengths. The results are reported in **Fig. 6 and 7** for a 1000 ft and 6” diameter wellbore and in **Fig. 8 and 9** for a 3000 ft horizontal well and 6’’ diameter well. The examination of these figures confirms the importance of friction forces. For a 3000 ft horizontal well and a 6” diameter, the difference in flow rates can be as high as 60%. See **Fig. 9**. To show the importance of friction forces, some runs have been performed for the same horizontal well lengths but a smaller well bore diameter of 4.5”. The results which are presented in **Fig. 10 and 11** successively confirm the fact that the higher the friction forces the higher the difference in flow rate between the base case where the skin is assumed constant and the more realistic steeper profile. This difference can reach up to 100% in the case of 3000 ft horizontal well and 4.5” diameter. This means that if for such a well, a constant skin of 24 is assumed instead of a real skin varying from 60 to zero, the flow rate performances are under evaluated by a factor of two even though the average skin is 24 for both cases.

Performances after Stimulation

In the next set of experiments, the well performances are estimated under different conditions of stimulation. First a skin profile is estimated using Engler’s approach[7]. Four cases of stimulation are assumed. In the first case it is assumed that only 25% of the formation damage are removed and in the fourth case all the damage is removed. See **Fig. 12**. The results presented in **Fig. 13** show as expected that, the more damage removed the better the performance. More importantly, **Fig. 13** shows that the last 25% of the damage to be removed are responsible for more production loss than the first 75% of formation damage. In other words, even a small formation damage level can cost significant production loss to the well and an incomplete stimulation job will barely recover the full potential of the well.

In the skin profile represented in case 4 which corresponds to a polynomial decrease, removing the skin from the area near the heel, results as expected in more production gain than removing the damage from the area near the toe. This is especially true when the friction forces are not very important. See **fig. 14 and 15**. This is not the case for the constant skin profile case 1. As shown in **Fig. 16 and 17**, stimulating the area near the toe in a 3000 ft well results in a production gain almost twice the gain obtained from stimulating the area near the heel.

Conclusions

The following conclusions can be drawn from this study:

1. A good characterization of the skin profile along the horizontal well is necessary in order to calculate accurately the performance of horizontal wells.
2. If instead of the actual skin profile along the horizontal length, a constant value of the skin is used, the error in calculating the well performance may be significant. Some examples of calculation showed up to 100% error.
3. The more important the friction forces in the horizontal well bore, the more significant the deviation between constant and non constant skin profiles even in the case of the same average value of the skin.
4. Even small values of skin damage can have serious effects on the performance of horizontal wells.
5. In case of stimulation, removing completely the damage is essential in restoring the original potential of the well.

Nomenclature

D= *well diameter, ft*
h= *height of the reservoir, ft*
k= *permeability, md*
k_d= *damaged permeability*
L_w= *Well Length, ft*
L_x= *Reservoir Length, ft*
L_y= *Reservoir width, ft*
N_p= *No. of open intervals*
P= *Pressure, psia*
Qo= *Oil Rate, bbl/day*
Q_D= *Dimentionless rate*
r_w= *Well Radius, ft*
RSo_i= *Initial GOR scf/res.bbl*
S= *Skin Factor*
S_g= *Gas gravity*
T= *Temperature, ^{o}F*
β= *Permeability anisotropy*

Subscript

avg= average
D= damaged
e= external
g= gas
o= oil
R= reservoir
s= skin
wf= well flowing
x= x-direction
y= y-direction
z= z-direction

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TABLE-1 FIELD EXAMPLE DATA

k_{avg}	2700md
h	100 ft
L_w	1150 ft
N_p	8
Open % of the Well	67 %
D	0.523 ft
P_R	2297 psia
T_R	160^{o}F
Q_o	8800 bbls/day
^{o}API	28.0
S_g	0.90
Rs_{oi}	100

TABLE-2 TYPICAL DATA USED IN THIS STUDY

$k_x = k_y$	2500 md
k_z	1000 md
β	1.58
L_x	4000 ft
L_y	2000 ft
h	80 ft
L_w	1000ft, 2000ft, 3000 ft
N_p	5
Open percentage of well	50 %
D	4.5 inches & 6 inches
P_R	2250 psia
T_R	160 ^{o}F
^{o}API	30
S_g	0.90
RSo_i	400 scf/bbl

Appendix-Main Program Flow Chart

In this study, we have employed computer modeling as a tool to combine the influence of both friction and skin distribution to predict the overall performance of horizontal well. The well consists of finite number of open segments that account for certain open percentage of the well. The specific productivity index obtained from the inflow performance[17] is no longer constant along the well length because of the skin distribution. The flow rate into the wellbore is compounded along the length from the toe to heel as each open segment contribute to the production.

The influx to each open segment is assumed by dividing the segment into 'n' finite sections. See Fig. A-1. This approach relates with finite difference scheme. Flow rate into the section is obtained by;

$$q^{nth} = J_h^{\ nth} \times (P_R - P_{TOE}) \times (Lp/n) \text{ ......(A-1)}$$

Based on the flow rate obtained the pressure drop in the nth section of the wellbore is estimated from the correlations[18]. As the fluid enters the next section it experiences another addition of influx from the reservoir. A certain differential pressure is assumed and influx is calculated i.e., 'P_{TOE}' in the Eq. A-1 is replaced by 'P_{wf}'. The methodology is repeated in an iterative way until accurate prediction of both pressure and flow rate distribution is obtained.

To acquire more realistic performance, several utility programs are also employed to account for changes in the fluid properties with the variation in the pressure along the well length while the temperature is assumed constant. These include calculation of Z-factor, formation volume factors, gas and oil viscosity, and solution GOR etc. The main program flow chart is shown in Fig. A-2.

SI Metric Conversion Factors

cp × 1.0* E-03=Pa-s
ft × 3.048* E-01=m
ft^2 × 9.290 304* E-02=m^2
ft^3 × 2.831 685 E-02=m^3
in. × 2.54* E+00=cm
lbf × 4.448 222 E+00=N
md × 9.869 233 E-04=μm^2
psi × 6.894 757 E+00=kPa

*Conversion factor is exact

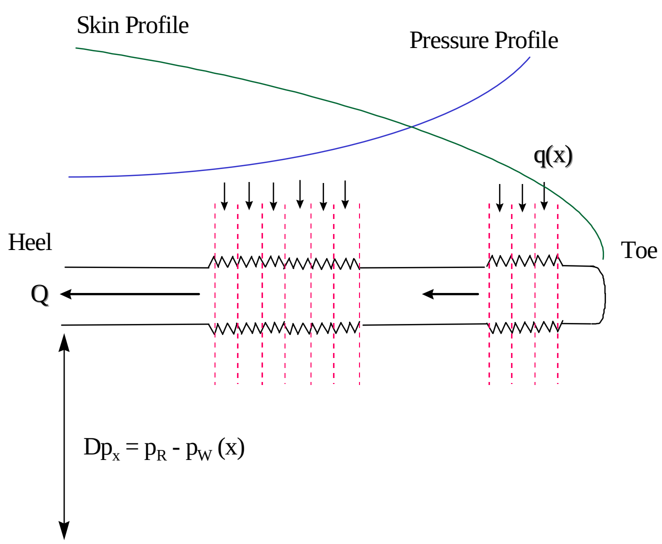


Fig.A-1, Horizontal Well Schematic Diagram, Showing Expected Skin and Pressure Profiles.

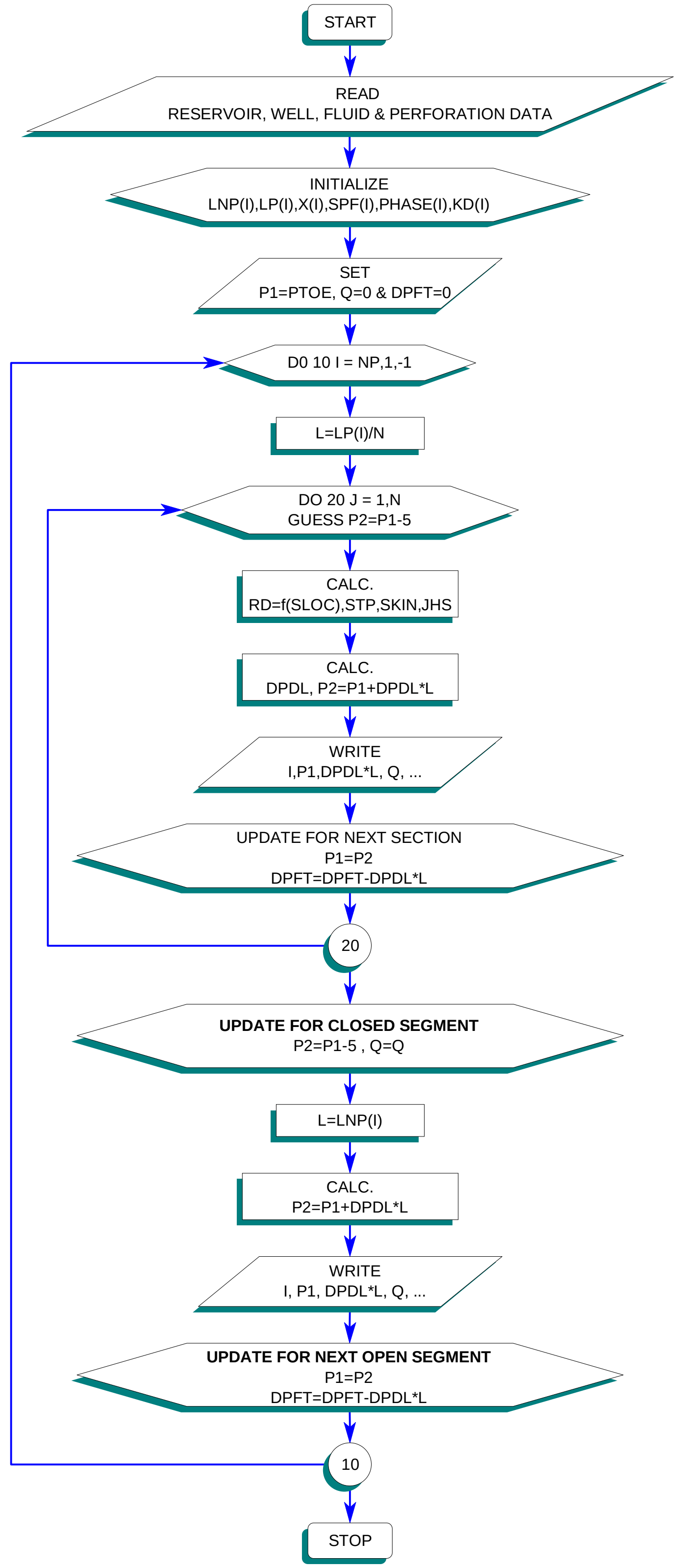
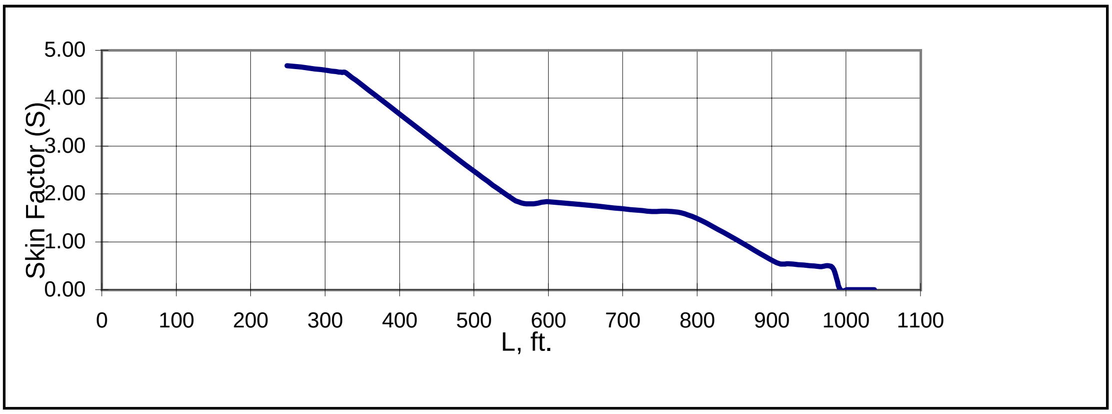


Fig. A-2 -Main Program Flow Char



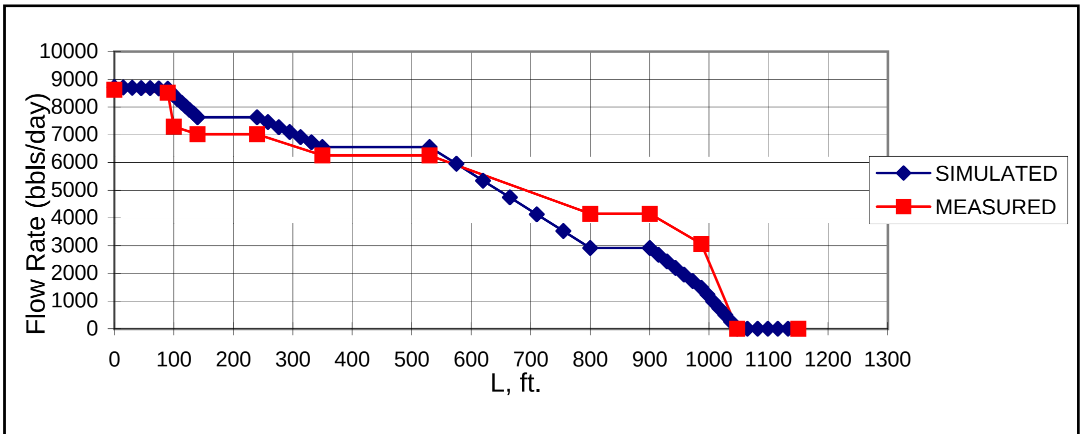


Fig. 2- Actual Well vs Simulated Performance

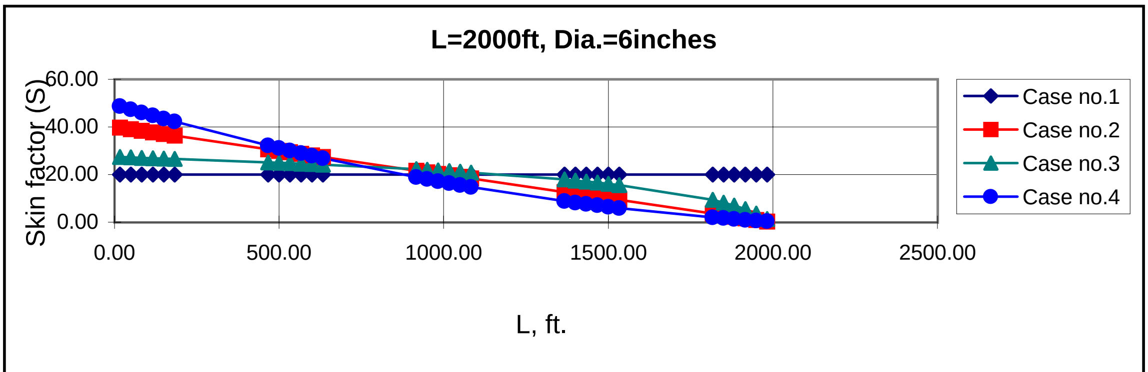


Fig. 3-Four cases of selected skin profiles

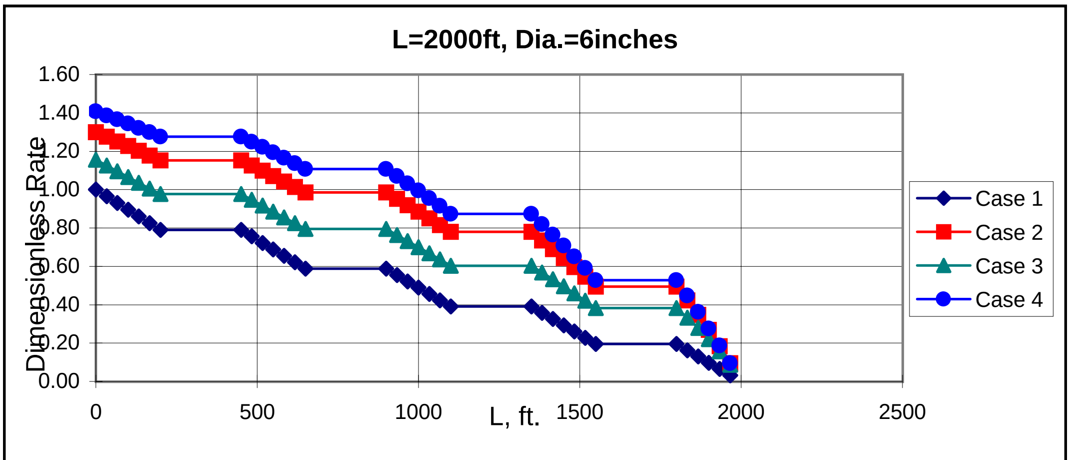


Fig. 4-Well performance with different skin profiles

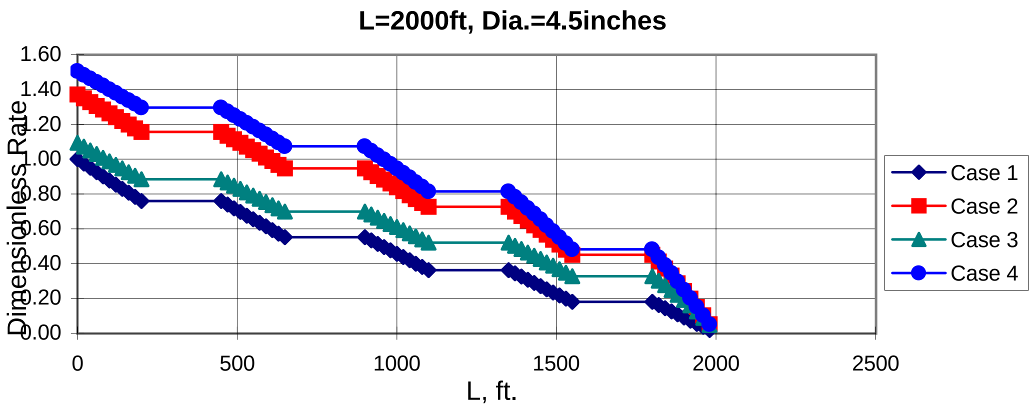


Fig. 5-Well performance with different skin profiles

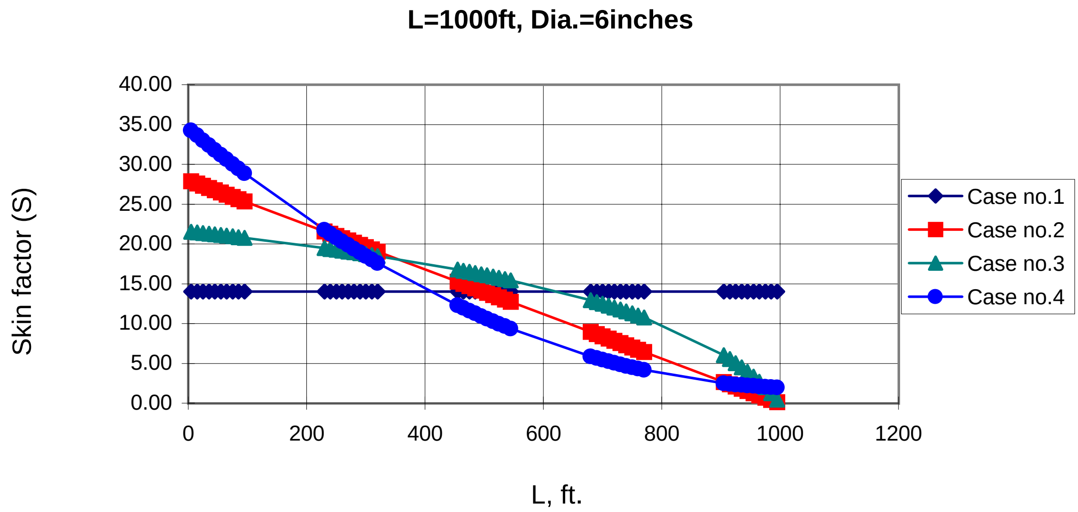


Fig. 6-Four cases of selected skin profiles

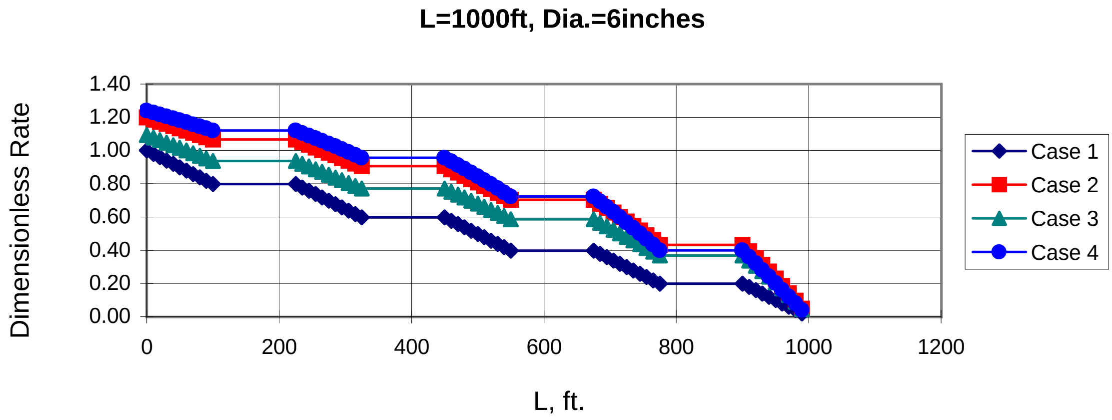


Fig. 7-Well performance with different skin profiles

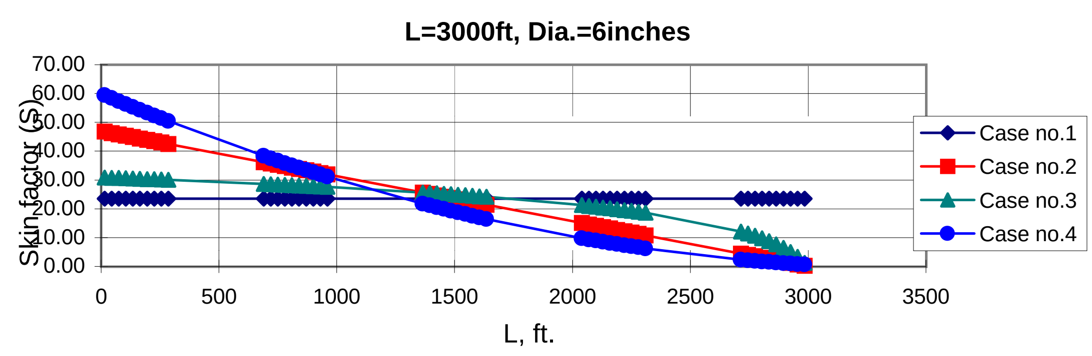


Fig. 8-Four cases of selected skin profiles

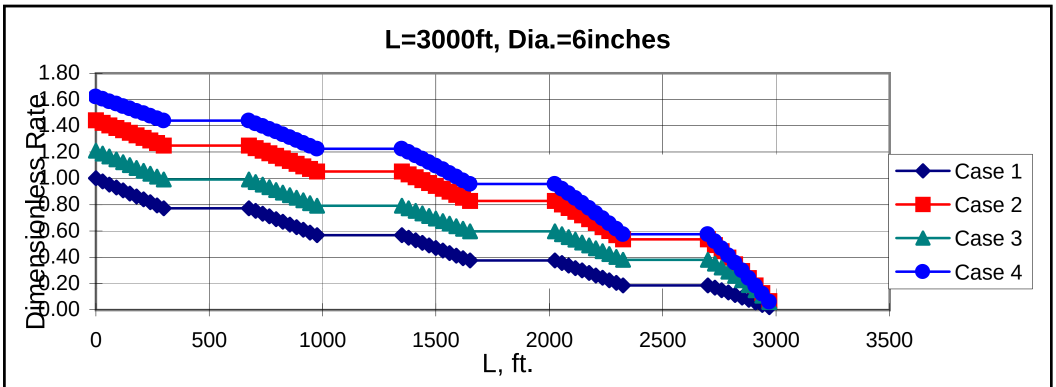


Fig. 9-Well performance with different skin profiles

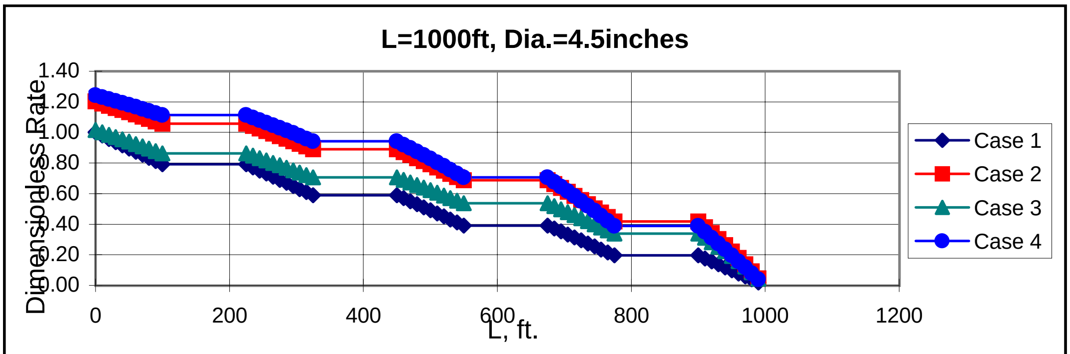


Fig. 10-Well performance with different skin profiles

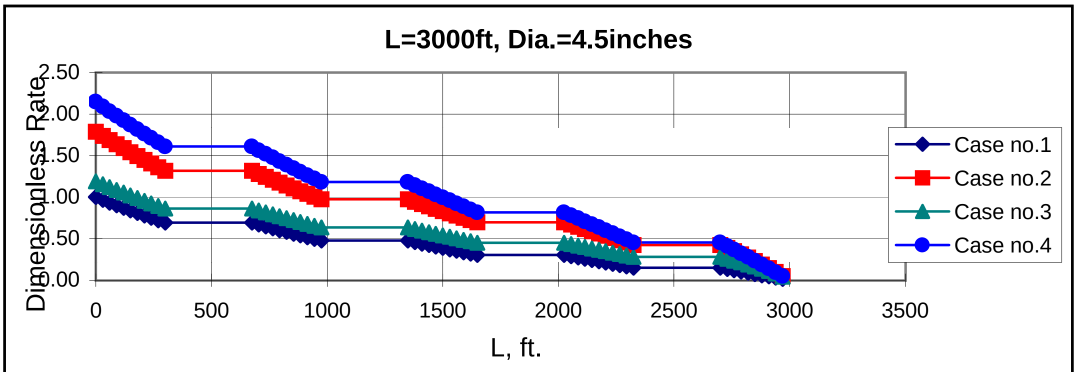


Fig. 11-Well performance with different skin profiles

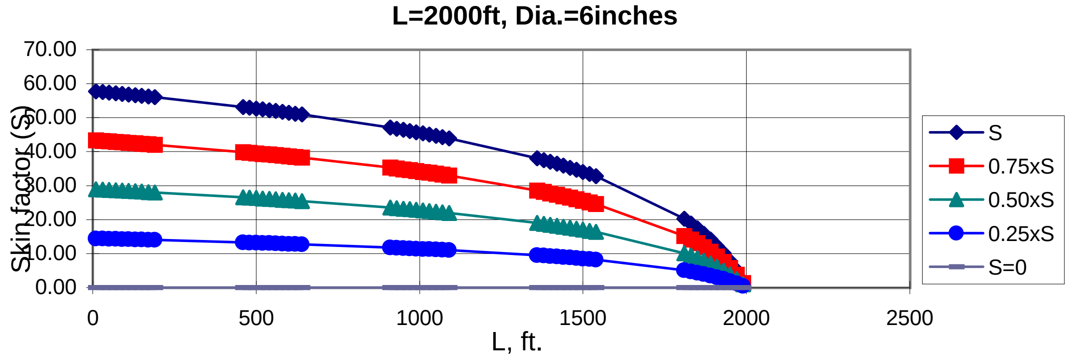


Fig. 12-Gradual decreasing skin profiles along well length.

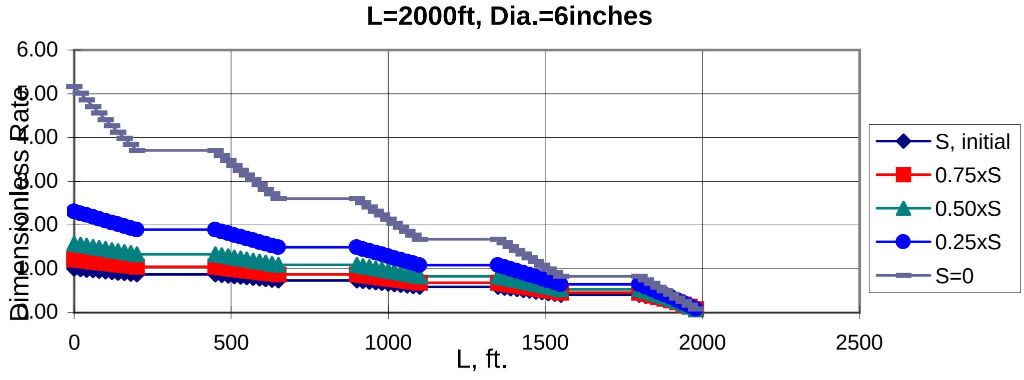


Fig. 13-Well performance with decreasing skin profiles

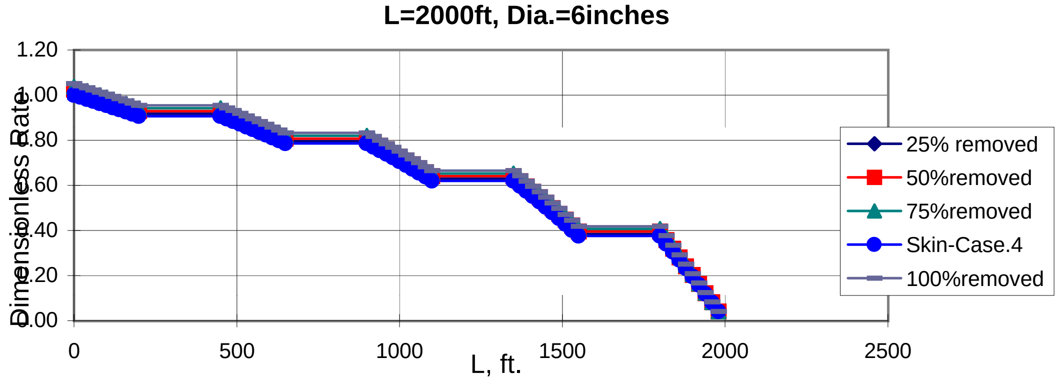


Fig. 14-Well stimulation near toe end

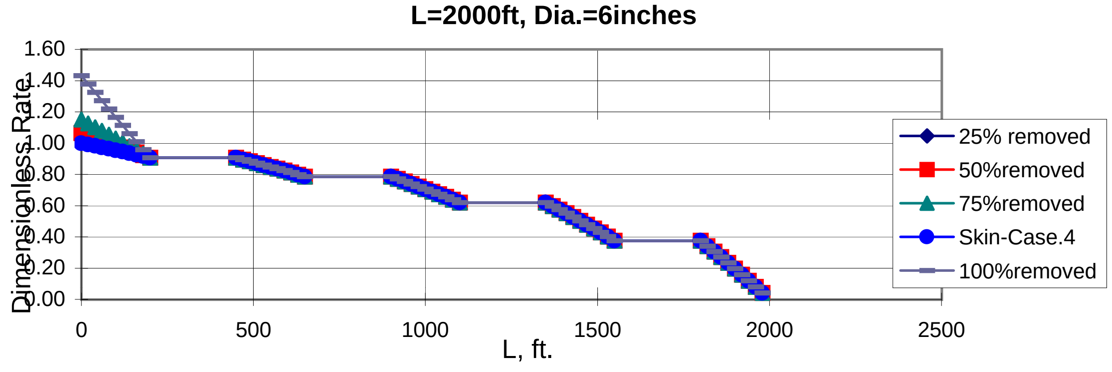


Fig. 15-Well stimulation near heel end.

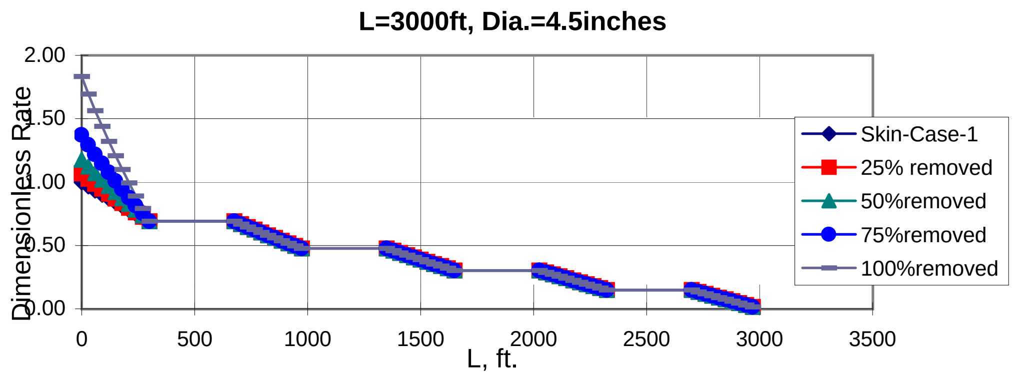


Fig. 16-Well Stimulation Near Heel End

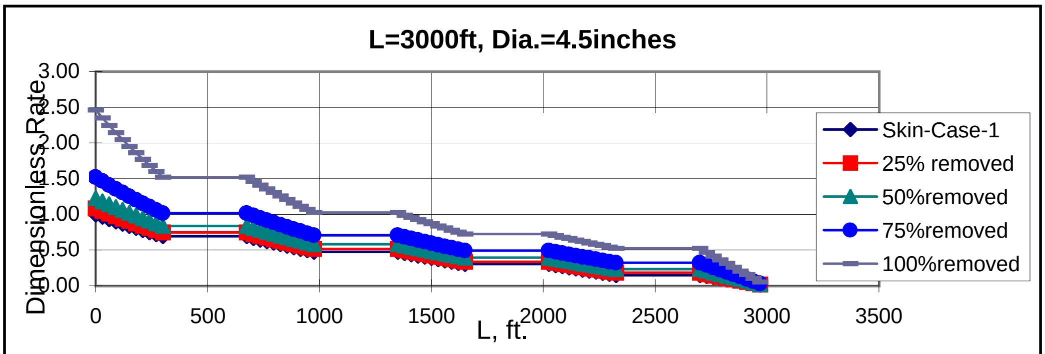


Fig. 17-Well Stimulation Near Toe End