Assessment of Total Skin Factor in Perforated Wells

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Summary

In this study, the available methods and software to predict the well productivity and total skin factor in fully perforated vertical wells have been reviewed. The methods have been compared against the experimental data obtained on an electrolytic apparatus, and their accuracy has been investigated. It has been observed that the 3D semianalytical model, SPAN 6.0 software, and the simple hybrid model described in this paper replicate the experimental results very well. On the other hand, the results estimated from the McLeod method and the Karakas-Tariq method substantially deviate from the experimental data; hence, these models/methods should be used with caution.

The literature hosts many equations to predict the total skin factor in partially perforated vertical wells. Some of the available models have been tested against the results from the 3D semianalytical model. It has been shown that total skin-factor equations based on the summation of individual components do not work.

The 3D semianalytical model has been modified to build an approximate model for fully and partially perforated inclined wells in isotropic formations. Additionally, a simple hybrid model to compute total skin factor in perforated inclined wells has been presented. The hybrid model for perforated inclined wells agrees well with the approximate 3D model. Some of the available models to calculate total skin factor in perforated inclined wells have been compared to the approximate 3D model, and their accuracy has been discussed.

Finally, a simple model to predict total skin factors in perforated horizontal wells has been developed. The application using the simple model has demonstrated that a combination of long wellbore length and perforations bypassing the damaged zone could overcome the destructive effect of severe formation damage around the wellbore.

Introduction

The long-term productivity of oil and gas wells is influenced by many factors. Among these factors are petrophysical properties, fluid properties, degree of formation damage and/or stimulation, well geometry, well completions, number of fluid phases, and flow-velocity type. To isolate and identify the effect of any single parameter on the well performance, a sensitivity study on the parameter of interest is conducted, and the results are compared to a reference base case of an ideal vertical open hole. In the base case, the ideal vertical open hole produces single-phase fluid, the fluid flow obeys Darcy's law, and the formation is neither stimulated nor damaged. The influence of the individual parameters not considered in the base case is quantified in terms of skin factor.

Oil and gas wells may have permeability reduction around the wellbore caused by invasion by drilling mud, cement, solids, and completion fluids. This is generally referred to as formation damage. Formation damage around the wellbore causes additional pressure drop. On the other hand, stimulation operations such as acidizing may decrease the pressure drop in the near-wellbore region by improving the formation permeability around the wellbore. The impact of permeability impairment/improvement around the wellbore caused by drilling, production, and acidizing operations is quantified in terms of mechanical skin factor.

The fluid flow in the near-wellbore region is also influenced by well-completion type. Openhole completion yields a local flow pattern that is radial around the wellbore and normal to the well trajectory. However, in some cases, openhole completion may not be desirable. Different types of well completion may be needed to control/isolate fluid entry into the wellbore, to avoid gas/water coning, and to minimize sand production. Besides the openhole completion, wells may be partially or selectively completed with perforations, slotted liners, gravel packs, screens, and zonal-isolation devices. Also, wells with low productivity may need to be hydraulically fractured. In completed wells, the flow pattern around the wellbore is distorted. Completions result in additional fluid convergence and divergence in the near-wellbore region. For example, partial penetration creates a 2D flow field in the formation. On the other hand, a perforated well experiences 3D flow converging around perforation tunnels. Compared to an ideal open hole, the wells with completions are subject to additional pressure gain/loss in the near-wellbore region. The additional pressure change caused by well completion is quantified in terms of completion pseudoskin factor.

Well performance is naturally influenced by the geometry of the well itself. Based on their geometrical shape, wells may be classified as vertical, inclined, horizontal, undulating, and multibranched. In the literature, the reference well geometry has been that of a fully penetrating vertical open hole. Historically, the differences in the productivity of vertical openhole and other well geometries have also been formulated in terms of pseudoskin factor. However, when it comes to the assessment of completion effects on well productivity, rather than comparing the given completed nonvertical well to an ideal vertical open hole, it may be more appropriate to work with the considered well geometry only and compare the completed and openhole cases of the same well geometry. For this reason, the term geometrical pseudoskin factor is proposed to quantify the differences between the productivities of vertical wells and other well geometries.

Multiphase flow in the formation may evolve because of gas/water coning around the wellbore, gas evaporation from the liquid-hydrocarbon phase, and liquid dropout from gas condensate. Compared to single-phase fluid flow, multiphase flow in the formation creates an additional pressure drop because of the relative permeability effect. If multiphase flow is intensified in the near-wellbore region, only then may the impact of multiphase flow be formulated in terms of multiphase pseudoskin factor.

At relatively low flow velocities, fluid flow in porous media obeys Darcy's law. However, when fluid flows at high velocities, the relationship between in-situ fluid velocity and local pressure gradient becomes nonlinear, resulting in non-Darcy flow. Non-Darcy flow resulting from high fluid velocity increases the pressure drop in the formation. Non-Darcy flow is mostly concentrated in the near-wellbore region, which extends from the wellbore some 5 to 10 ft into the formation. The influence of non-Darcy flow around the wellbore is accounted for in terms of rate-dependent skin factor.

In many cases, the oil and gas wells are under the influence of several skin factors. The combined effects of all the individual skin factors lead to a total skin factor for the well. The literature includes many reliable, accurate methods to predict the individual skin factors and their impacts on well performance. However, the simultaneous effects of several skin factors have been formulated

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quite differently in various studies. In this study, some of the available methods to predict the total skin factor in perforated wells have been examined. For the sake of simplicity, multiphase pseudoskin and rate-dependent skin factors are not considered.

Productivity Model for Vertical Open Holes

The openhole completion is the simplest completion technique. It is also rather easy to develop a productivity model for vertical open holes. By simply integrating Darcy's equation, one could readily obtain a well-productivity model for open holes producing under steady-state flow conditions.

$$\Delta p_{voh} = \frac{141.2\, q_{sc}\, \mu\, B_o}{k\, h} \ln\,(r_e/r_w)\ . \qquad (1)$$

Sometimes, well performance is measured in terms of productivity index. Productivity index is defined as the ratio of flow rate to the pressure drop.

$$J_{voh} = \frac{q_{sc}}{\Delta p_{voh}} = \frac{k\, h}{141.2\, \mu\, B_o \ln\,(r_e/r_w)}\ . \qquad (2)$$

Productivity of Completed Wells and Total Skin

The productivity model expressed in Eqs. 1 and 2 does not account for any one of the skin factors. The combined effects of the mechanical skin, completion pseudoskin, and geometrical pseudoskin constitute a total skin factor for the well. Total skin factor accounts for the difference between the performance of an actual well and that of an ideal vertical open hole. Many studies in the literature treat the total skin factor as a simple summation of the individual skin factors listed above.

$$s_t = s_d + s_{pp} + s_p + s_{cz} + s_\theta + s_f\ , \qquad (3)$$

where s_t = total skin factor, s_d = skin factor due to formation damage or stimulation, s_{pp} = completion pseudoskin due to partial penetration, s_p = completion pseudoskin due to ideal perforations, s_{cz} = skin due to rock compaction around perforation tunnels, s_θ = geometrical pseudoskin due to well inclination, and s_f = completion pseudoskin owing to hydraulic fracturing.

In some publications, the total skin equations differ from Eq. 3. A list of the total skin equations is given in **Table 1.**

The total pressure drop in completed wells can be expressed as

$$\Delta p_t = \frac{141.2\, q_{sc}\, \mu\, B_o}{k\, h} [\ln\,(r_e/r_w) + s_t]\ . \qquad (4)$$

Then, the productivity index for the completed wells becomes

$$J_c = \frac{k\, h}{141.2\, \mu\, B_o [\ln\,(r_e/r_w) + s_t]}\ . \qquad (5)$$

To comprehend the effect of all the skin factors on well productivity, the productivity index of the well with skin factors is compared to that of an ideal open hole. The comparison is quantified in terms of productivity ratio (PR).

$$\mathrm{PR} = \frac{J_c}{J_{voh}} = \frac{\ln(r_e/r_w)}{\ln\,(r_e/r_w) + s_t}\ . \qquad (6)$$

TABLE 1—EQUATIONS FOR TOTAL SKIN FACTOR AND ITS COMPONENTS

Vrbik (1991)	$s_t = s_d + s_{pp} + s_p + s_\theta + s_f$
Daltaban-Wall (1998)	$s_t = s_d + s_{pp} + s_\theta$
McLeod (1983)	$s_{pdc} = s_d + s_p + s_{cz}$
Jones-Slusser (1974)	$s_{pd} = s_d + (k/k_d)\, s_p$ $s_t = (h/h_p)\, s_{pd} + s_{pp}$
Karakas-Tariq (1991)	See Eqs. 17 through 23
Bell-Sukup-Tariq (1995)	$s_t = s_d + s_{pp} + s_\theta$ $s_t = s_{pp} + \frac{h}{h_p}\left[\frac{s_{pdc}}{\gamma_o} + \frac{1}{20}\left(9 + 11\frac{h}{h_p}\right) s_\theta\right]$ $s_{pdc} = s_d + (k/k_d)(s_p + s'_{cz} + s_x)$
Thomas *et al.* (1992)	$s_t = (h/h_p)\frac{s_d}{\gamma_{jw}} + s_{pp} + s_p + s_{cz} + s_\theta$
Penmatcha-Fayers-Aziz (1995)	$s_t = (h/h_p)\frac{s_d}{\gamma_{jw}} + s_{pp} + s_p + s_{cz} + s_\theta$
Golan-Whitson (1991)	$s_t = (h/h_p)(s_d + s_p) + s_{cz} + s_{pp}$
Samaniego-Cinco Ley (1996)	$s_t = (h/h_p)(s_d + s_p) + s_{pp} + s_\theta + s_f$
Economides-Boney (2000)	$s_t = s_d + s_p + s_{\theta pp}$
Elshahawi-Gad (2001)	$s_t = s_d + s_p + s_{\theta pp} + \sum$ more skins
Pucknell-Clifford (1991)	$s_t = \frac{h}{L_w} s_{pdc} + s_{\theta pp}$

Although expressing the total skin factor as a sum of active individual skin factors leads to a simple equation, the resulting equation may not be accurate. In general, total skin factor is not simply the sum of individual skin components. Additionally, the interaction between the total skin factor and some of its components may be nonlinear.

Total skin factor may be estimated from pressure-transient data. However, for the low-productivity wells with high total skin factor, it is necessary to decompose the total skin factor to its components and identify the root cause of the low productivity. The decomposition of the total skin factor to its elements requires an accurate model that relates the total skin factor to its individual constituents. Once the source of high skin factor is singled out, then the proper remedial treatment, which would improve well performance, could be chosen.

Mechanical Skin Factor

Formation damage around the wellbore causes additional pressure drop and reduces well productivity. To evaluate the impact of formation damage around a vertical open hole, Hawkins (1956) proposed to represent the damaged zone as a concentric cylinder around the wellbore. The damaged zone is characterized by a uniform permeability of k_d and radius of r_d. Mechanical skin factor is defined as below.

$$s_d = (k/k_d - 1)\ln(r_d/r_w)\ . \qquad (7)$$

The additional pressure drop caused by the formation damage can be quantified as

$$\Delta p_d = \frac{141.2\, q_{sc}\, \mu\, B_o}{k\, h} s_d\ . \qquad (8)$$

The mechanical skin factor expression above ignores the impact of well completion.

Partial-Penetration Pseudoskin

In partially penetrating vertical wells, only a segment of the wellbore is open to flow. Partially open vertical wells are also referred to as restricted-entry or limited-entry wells. In partially penetrating wells, there still may exist a 1D radial flow deeper in the formation away from the wellbore. However, when fluid approaches the wellbore, it has to converge around the open well segment. Partial penetration creates a 2D flow field around the near-wellbore region, as illustrated in **Fig. 1.** Because of fluid convergence and 2D flow in the near-wellbore region, fluid flows at higher velocities around the wellbore. The net result of partial penetration is that it yields an extra pressure drop in the near-wellbore region and reduces well productivity.

The impact of partial penetration on well productivity has been the subjects of many studies (Nisle 1958; Gringarten and Ramey 1975; Kuchuk and Kirwan 1987; Streltsova-Adams 1979; Papatzacos 1987; Vrbik 1991; Yildiz and Cinar 1998; Odeh 1968, 1977, 1980; Daltaban and Wall 1998; Earlougher 1977; Jones and Watts 1971; Saidikowski 1979; Jones and Slusser 1974). Many analytical models simulating 2D flow into a partially penetrating well have been presented. These analytical models include relatively complex functions, such as Bessel functions, and infinite series. Although the computation of the analytical solutions can be done easily on PCs, they are not very popular because they are contaminated with infinite series and special functions.

It should be pointed out that the analytical solutions for partially penetrating wells consider that the completed interval admits fluid at every point on its completed wellbore surface. These models do not consider the additional fluid convergence owing to perforations and slots.

The effect of partial penetration on well performance is formulated in terms of partial-penetration pseudoskin, s_{pp}. Penetration ratio and permeability anisotropy are the main parameters controlling the s_{pp} value. Location of the completed interval, with respect to the top and bottom reservoir boundaries, and the wellbore size also have some secondary impact on the s_{pp} value.

Besides the 2D analytical solutions, there exist several simpler approximate models to predict the partial-penetration pseudoskin. Among these models, the methods proposed by Odeh (1980), Papatzacos (1987), and Vrbik (1991) have been popular because of their simplicity. These three approximate models were compared against the 2D analytical model described in Yildiz and Cinar (1998). Such a comparison is displayed in **Fig. 2** for $h = 100$ ft, $r_w = 0.25$ ft, $k_z/k_r = 1$, and the open segment being placed at the top of the formation. The Papatzacos and Vrbik models were found to be quite accurate.

Once the s_{pp} value is available, the additional pressure drop caused by partial penetration may be computed with the expression below:

$$\Delta p_{pp} = \frac{141.2\, q_{sc}\, \mu\, B_o}{k\, h} s_{pp}\ . \qquad (9)$$

The simultaneous influences of partial penetration and formation damage/stimulation have been debated in the literature. In some

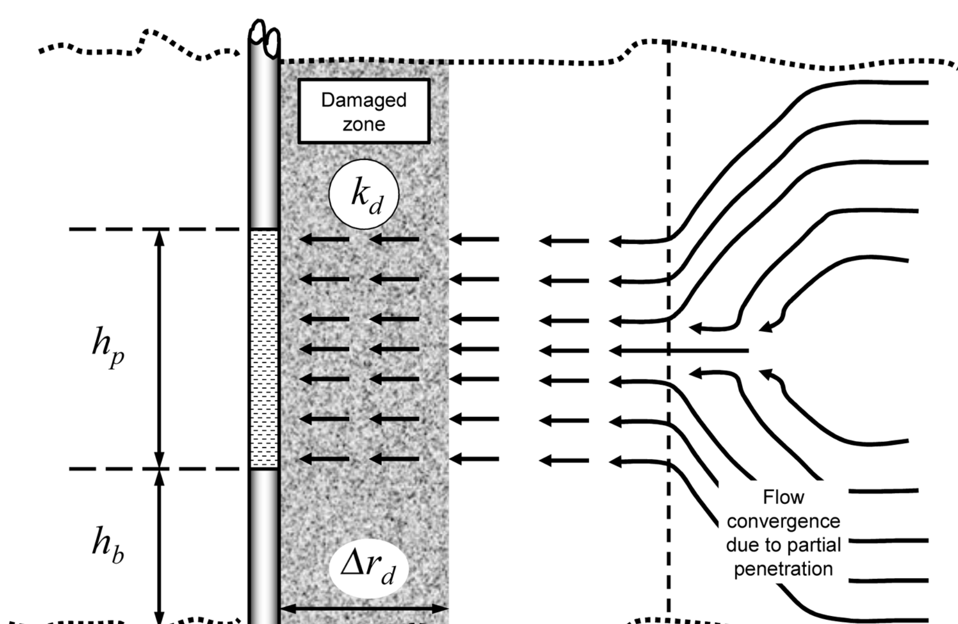

Fig. 1—Partially penetrating well subject to formation damage.

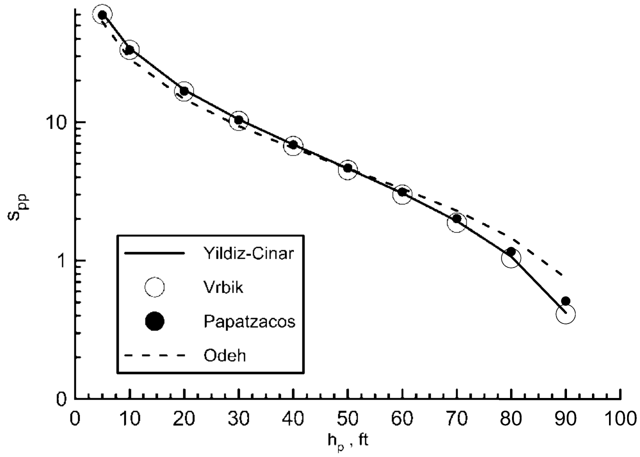

Fig. 2—Comparison of approximate models for partial penetration with the 2D solution.

studies (Vrbik 1991; Odeh 1968; Daltaban and Wall 1998), the combined effects of formation damage and partial penetration are considered to be a simple sum of mechanical skin factor and partial-penetration pseudoskin factor.

$$s_t = s_d + s_{pp} . \quad (10)$$

However, this formulation is inaccurate. Eq. 10 downplays the contribution of formation damage. As it has been shown by Jones and Watts (1971), Odeh (1977), Saidikowski (1979), and Jones and Slusser (1974), the formation damage has a stronger impact on well productivity than Eq. 10 predicts. In a partially penetrating well, the impact of formation damage is magnified. If it is assumed that the damaged zone is relatively thin and flow convergence owing to partial completion is completed before the fluid enters into the damaged zone (as conceptualized in Fig. 1), then it can be analytically shown that the combined impact of formation damage and partial penetration leads to the following total skin factor (Jones and Watts 1971; Odeh 1977; Saidikowski 1979; Jones and Slusser 1974):

$$s_t = \frac{h}{h_p} s_d + s_{pp} . \quad (11)$$

On the other hand, if the flow convergence toward the limited open segment takes place partly outside and partly inside the damaged zone, then the impact of formation damage is somewhat less than what Eq. 11 indicates. For such cases, the total skin factor is formulated as below:

$$s_t = \frac{1}{\gamma} \frac{h}{h_p} s_d + s_{pp} , \quad (12)$$

where γ is greater than 1. Jones and Watts (1971) and Odeh (1977) offer simple equations to compute the γ parameter.

Saidikowski (1979) reported that Eq. 11 works well for even deep formation damage as long as the damaged-zone radius is less than 20 ft and the penetration ratio is greater than 20%.

Eqs. 11 and 12 should be used cautiously when s_d is negative. These equations do not apply when a short interval is completed with a negative s_d value.

Perforation Total Skin Factor

In cased wells, it is necessary to perforate the well to establish communication between the wellbore and the formation. **Fig. 3** depicts a perforated well. Perforations disturb the fluid flow and generate additional flow convergence in the near-wellbore region. The fluid flow toward the perforation tunnels is 3D. Compared to an ideal open hole, an ideal perforated well may experience additional pressure gain or loss. If the well is densely perforated with clean and deep penetrating perforation tunnels, then the total communication surface area between the perforated well and the for-

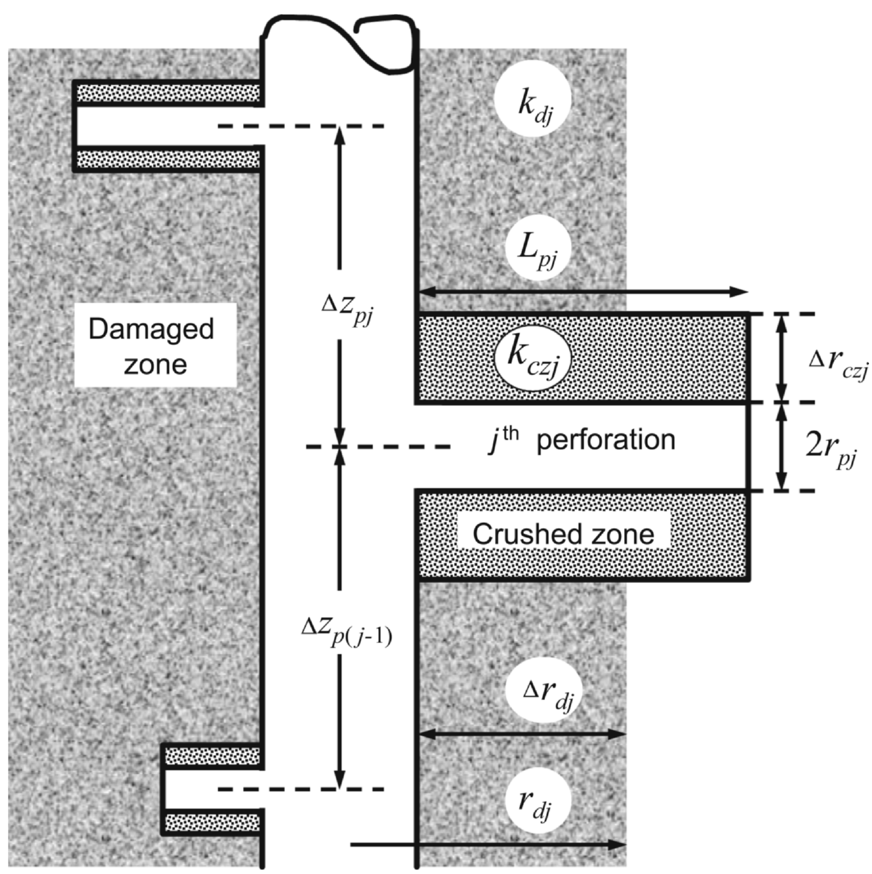

Fig. 3—Schematics of a perforated well.

mation may be greater than that between a vertical open hole and the formation. In such a case, the perforated well may require a lesser pressure drop, and perforating could actually improve the well productivity. On the other hand, if the well is sparsely equipped with short perforations, then perforating causes additional pressure drop in the near-wellbore region and reduces the well productivity.

The additional pressure drop/gain caused by ideal perforations is measured in terms of perforation pseudoskin s_p. The numerical value of s_p depends on the parameters such as shot density, perforation length, diameter, phasing angle, formation anisotropy, and wellbore diameter. s_p could be positive or negative. It should be pointed out that s_p only accounts for the flow convergence around the perforations in an ideal perforated well without formation damage and a crushed zone around the perforation tunnels.

In the perforation process, the rock around the perforation tunnels is compacted. The compaction around the perforation tunnels decreases the permeability, causes additional pressure drop, and reduces the well productivity. The impact of reduced permeability in the crushed zone is formulated in terms of crushed-zone skin factor, s_{cz}. Besides the perforation pseudoskin and crushed-zone skin factor, perforated-well performance is also influenced by the formation damage around the wellbore. The interaction between the ideal perforation pseudoskin, crushed-zone skin factor, and skin factor due to formation damage may be quite complex. The combined effects of ideal perforations, permeability reduction in the crushed zone around perforation tunnels, and formation damage due to drilling/production operations around the wellbore will be represented in terms of perforation total skin factor, s_{pdc}. Once the s_{pdc} value is available, the additional pressure change resulting from the combined effect of formation damage, perforations, and the crushed zone can be expressed as

$$\Delta p_{pdc} = \frac{141.2\, q_{sc}\, \mu\, B_o}{k\, h} s_{pdc} \,. \quad \text{(13)}$$

A great number of experimental, numerical, empirical, and semi-analytical models have been constructed to predict the perforation pseudoskin and perforation total skin (Jones and Slusser 1974; Harris 1966; Klotz *et al.* 1974; Hong 1975; Locke 1981; Tariq 1987; McLeod 1983; Karakas 1991; Bell *et al.* 1995; SPAN 1999; SPAN 2002; Thomas *et al.* 1992; Yildiz 2002; Pan and Tang 1989). Some of these models will be described briefly below.

Jones and Slusser Method. In an earlier unappreciated study, Jones and Slusser (1974) accurately combined the simultaneous effect of mechanical skin factor caused by formation damage and perforation pseudoskin. Jones and Slusser proposed that

$$s_{pd} = s_d + \frac{k}{k_d} s_p \,. \quad \text{(14)}$$

Eq. 14 is accurate for perforations terminated inside the damaged zone (PTIDZ). Eq. 14 could be derived analytically if it is assumed that (1) all the perforations are terminated inside the damaged zone, (2) perforations do not disturb the radial-flow geometry in the undamaged portion of the formation, and (3) the flow convergence toward the perforation tunnels completely takes place inside the damaged zone. However, the applicability of the method put forward by Jones and Slusser to the perforations extending beyond the damaged zone (PEBDZ) is questionable.

Jones and Slusser (1974) have suggested using the results presented by Harris (1966) to compute perforation pseudoskin s_p.

Hong and Locke Nomographs. Hong (1975) and, later, Locke (1981) presented nomographs to estimate s_p. These two nomographs also account for skin factors owing to formation damage and rock compaction around the perforation tunnels. The results from these nomographs may be digitized, tabulated, and integrated into well-performance models. Thomas *et al.* (1992) used a table lookup procedure to incorporate the results from Locke's nomograph into their well-performance software.

McLeod Method. McLeod (1983) proposed the following simple equation combining the effects of perforation pseudoskin, formation damage, and rock compaction around the perforation tunnel:

$$s_{pdc} = s_d + s_p + s_{cz} \,, \quad \text{(15)}$$

where s_p is the perforation pseudoskin obtained from either the Hong or Locke nomograph. s_{cz} is the skin factor due to the crushed zone around the perforation tunnels and is given as

$$s_{cz} = \frac{\Delta z_p}{L_p}\left(\frac{k}{k_{cz}} - \frac{k}{k_d}\right) \ln(r_{cz}/r_p) \,. \quad \text{(16)}$$

Eq. 15 has been used widely owing to its simplicity.

Karakas and Tariq Method. Based on the results from a finite-element simulator, Karakas and Tariq (1991) developed empirical equations to predict the total skin factor in a fully perforated vertical well. The core of their study is the equation for perforation pseudoskin. For the sake of completeness, the Karakas-Tariq method is summarized briefly here. The original work of Karakas and Tariq should be consulted for additional information and details.

Ideal Perforations. For ideal perforations influenced by neither the crushed zone nor the formation damage, their equation for estimating perforation pseudoskin has the following form:

$$s_p = s_H + s_v + s_{wb} \,. \quad \text{(17)}$$

The first term represents the flow convergence in the horizontal plane. The second term accounts for the flow convergence in the vertical plane. The effect of the cylindrical wellbore itself is considered in the last term. Karakas and Tariq presented simple expressions for s_H, s_v, and s_{wb}.

Perforations With Crushed Zone Only. To account for the pressure losses in the compacted zone around the perforations, Karakas and Tariq used an expression similar to Eq. 16.

$$s'_{cz} = \frac{\Delta z_p}{L_p}\left(\frac{k}{k_{cz}} - 1\right) \ln(r_{cz}/r_p) \,. \quad \text{(18)}$$

The addition of perforation pseudoskin and crushed-zone skin factors describes the combined effects of these two parameters.

$$s_{pc} = s_p + s'_{cz} \,. \quad \text{(19)}$$

Perforations With Formation Damage Only. For the simultaneous impact of perforation pseudoskin and formation damage, Karakas and Tariq (1991) proposed two different procedures. The first procedure is for the PTIDZ and is very similar to the method proposed by Jones and Slusser 17 years earlier.

$$s_{pd} = s_d + \frac{k}{k_d}(s_p + s_x) \,. \quad \text{(20)}$$

For most cases, the s_x term is negligible. The second procedure is for deeply penetrating PEBDZ. To compute the total skin factor resulting from formation damage and ideal perforation pseudoskin owing to long perforations, Karakas and Tariq defined effective perforation length and effective wellbore-radius terms and suggested to replace the actual perforation length and wellbore-radius terms with the effective ones in the calculation of s_H, s_v, s_{wb}, and s_p terms in Eq. 17. The effective perforation length and effective wellbore radius are defined below.

$$L'_p = L_p - (1 - k_d/k)\Delta r_d \,. \quad \text{(21)}$$

$$r'_w = r_w + (1 - k_d/k)\Delta r_d \,. \quad \text{(22)}$$

Perforations With Both Formation Damage and Crushed Zone. When it comes to the combined effects of formation damage and compacted zone, Karakas and Tariq (1991) suggested a procedure for the PEBDZ only. For this case, Karakas and Tariq proposed to replace the perforation length and wellbore radius with effective perforation length and effective wellbore radius not only in the calculation of s_H, s_v, s_{wb}, and s_p in Eq. 17 but also in the calculation of s'_{cz} in Eq. 18 and s_{pc} in Eq. 19.

Karakas and Tariq (1991) did not explicitly describe a procedure for the PTIDZ under the combined effects of formation damage and compacted zone. However, to quantify the combined impacts of formation damage, perforations, and compacted zone for such perforations, some engineers replace the s_p term in Eq. 20 with the s_{pc} term in Eq. 19. Along these lines, Bell *et al.* (1995) suggested the equation below for the PTIDZ:

$$s_{pdc} = s_d + \frac{k}{k_d}(s_p + s_x + s'_{cz}) \; . \qquad (23)$$

SPAN Software. SPAN is a software package to design perforating variables (SPAN 1999; SPAN 2002). The model equations are developed from the detailed finite-element simulations. Several versions of the software have been released. SPAN 6.0 was used in the original version of this paper; it uses a modified version of the Karakas-Tariq method for both the PTIDZ and the PEBDZ.

SPAN 6.11, released after the original meeting presentation of this current paper, uses the original Karakas and Tariq method for the PTIDZ and a modified version of the Karakas-Tariq algorithm for the PEBZD.

When the perforation length is exactly equal to the thickness of the formation damage zone, SPAN 6.0 and 6.11 seem to be using the algorithm for the PEBDZ.

3D Semianalytical Method. In all the previous methods described above, it is assumed that all perforations are equivalent and are distributed uniformly. In Yildiz (2002), a general 3D semianalytical model considering arbitrary and nonuniform perforation parameters and distribution was developed. The 3D semianalytical model considers flow convergence toward perforations, formation damage, and compacted zone around the perforation tunnels. Additionally, the model can handle selective perforating at multiple open segments. However, the 3D semianalytical model also has several limitations. For additional information, the reader is referred to Yildiz (2002).

Hybrid Method for Perforation Total Skin. The hybrid method is obtained by modifying the Jones-Slusser method in two manners. First, perforation pseudoskin s_p is computed with the Karakas-Tariq algorithm. The Jones-Slusser method does not include the effect of the crushed zone around the perforation tunnels. Here, it is proposed to add the crushed-zone skin factor to Eq. 14 and modify it as below.

$$s_{pdc} = s_d + \frac{k}{k_d} s_p + s_{cz} \; . \qquad (24)$$

It should be emphasized that Eq. 24 could be analytically verified only for the PTIDZ. Additionally, Eq. 16 has to be used to calculate the s_{cz} term. The hybrid method is not expected to be accurate for perforation designs resulting in large negative s_p values.

Accuracy of Perforation Total Skin Models. Pan and Tang (1989) constructed an electrolytic model to simulate the effect of perforating on well productivity. They measured the well productivity under the influence of perforation pseudoskin, formation damage, and rock compaction around the perforation tunnels. Both the PTIDZ and PEBDZ were experimentally investigated. Their miniaturized electrolytic model was intended to represent realistic field cases in terms of the length dimensions. The representative field dimensions were scaled back with a factor of 0.1158. Additional details on the experimental work may be obtained from Tang.*

To investigate the accuracy of the skin-factor models for perforated wells, the models described above are compared with the experimental data collected by Pan and Tang (1989).

Fig. 4 compares the results simulated using the McLeod model with the experimental data. The solid symbols represent the measured data; the dashed lines show the results computed from the McLeod method (Eq. 15). The s_p value used in the McLeod model is calculated with the Karakas-Tariq model instead of Hong's or Locke's nomograph, as suggested by McLeod. As can be observed in Fig. 4, the McLeod method markedly overestimates the well productivity for the PTIDZ. On the contrary, for the deep penetrating PEBDZ, the productivity ratios are substantially underestimated. A comparison of Eqs. 15 and 24 identifies the reason for the overestimated well productivity. The McLeod model downplays the effect of formation damage and underestimates perforation total skin for the PTIDZ. It should be reiterated that the McLeod method is implicitly limited to short perforations placed inside the damaged zone. However, this implicit assumption has not stopped others from using the McLeod method for the long perforations piercing through the damaged zone. The McLeod model should not be expected to give good productivity estimates for the PEBDZ to start with.

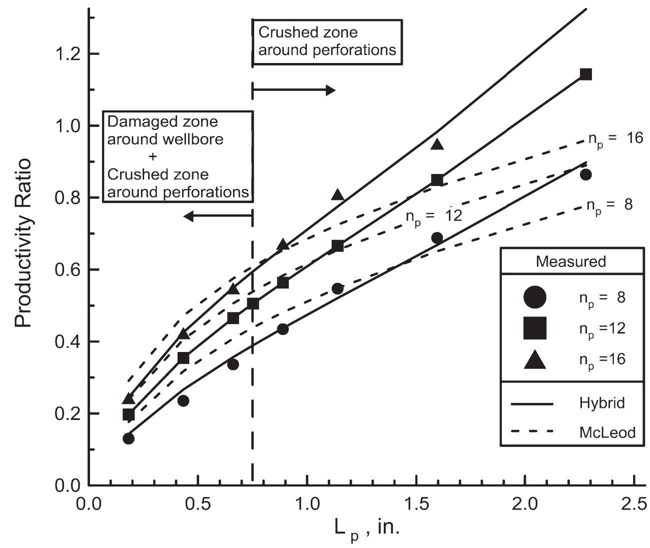

Fig. 4—Comparison of the hybrid and McLeod models with the experimental data of Pan and Tang (1989).

The hybrid method for perforation total skin has also been tested against the experimental data. The comparison is shown in Fig. 4. As it can be observed in the figure, the calculated results from Eq. 24 agree well with the experimental results, but when the perforation pseudoskin (s_p) term is negative, the results calculated from Eq. 24 deviate from the measured data. Eq. 24 is not recommended for perforation designs yielding a large negative s_p value.

Eq. 24 could be derived analytically for the PTIDZ. However, the applicability of Eq. 24 to the PEBDZ is questionable. In the experimental data, the crushed zone contributes the most to the total skin; the perforation pseudoskin and formation damage skin are small compared to the skin due to the crushed zone. This is basically the reason for the good agreement between the results from the hybrid model and the experimental data belonging to the PEBZD. The impact of the crushed zone is not influenced by the extent of the perforations relative to the damaged zone. If there had not been the overwhelming crushed-zone effect in the experimental data, the calculated results from Eq. 24 would have deviated from the measured data for the PEBDZ. The hybrid method is not recommended for the PEBDZ.

The comparison of the experimental data against the simulated results from the Karakas-Tariq method is displayed in **Fig. 5**. In Fig. 5, the solid lines represent the results from the Karakas-Tariq method. The results from the Karakas-Tariq model are significantly lower than the measured values for both the PTIDZ and PEBDZ. It should be reiterated that, for the PTIDZ, Karakas and Tariq did not clearly describe a procedure to estimate the perforation total skin, including the effects of perforation pseudoskin, formation damage, and rock compaction. However, Bell *et al.* (1995) have used the Karakas-Tariq algorithm for the PTIDZ by replacing the s_p term in Eq. 20 with the s_{pc} predicted from Eq. 19,

* Personal communication with Y. Tang, Chevron EPTC, Houston (2005).

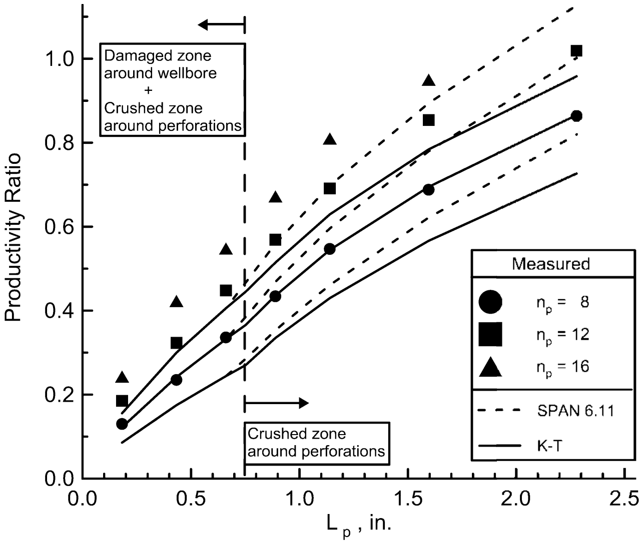

Fig. 5—Comparison of the Karakas-Tariq model and SPAN 6.11 results with the experimental data of Pan and Tang (1989).

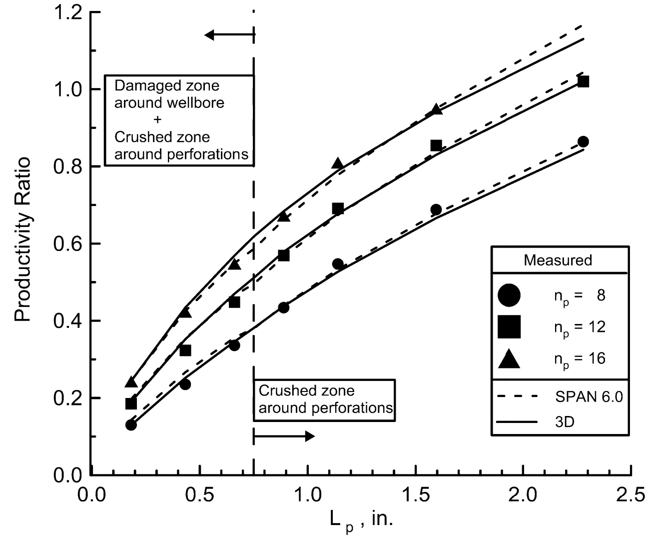

Fig. 6—Comparison of the results from SPAN 6.0 and the 3D semianalytical model with the experimental data.

resulting in Eq. 23. This approach overestimates the perforation total skin factor. On the other hand, an algorithm to compute the perforation total skin factor for the long perforations passing through the damaged zone has been proposed by Karakas and Tariq (1991). Unfortunately, the results from their PEBZD algorithm deviate substantially from the experimental data. The Karakas-Tariq method was scrutinized further by comparing it with SPAN 6.0 and the 3D semianalytical model. It has been observed that the Karakas-Tariq method accurately predicts the value of perforation pseudoskin itself. The algorithm also works fine as far as the perforation-pseudoskin/crushed-zone combination is concerned. The Karakas and Tariq method also yields reasonable estimates for the combined effects of formation damage and perforation pseudoskin. However, when both the formation-damage and rock-compaction effects are compounded with the perforation pseudoskin, the Karakas and Tariq method calculates unreasonably high perforation total skin factor. This is true for both the PTIDZ and PEBDZ.

Fig. 5 also depicts the comparison of the results simulated from SPAN 6.11 against the experimental data. The dashed lines on Fig. 5 correspond to the results from SPAN 6.11. As stated before, SPAN 6.11 uses the Karakas-Tariq method (Eq. 23) for the PTIDZ; hence, SPAN 6.11 and the Karakas-Tariq model yield identical results for such perforations. For the PEBDZ, SPAN 6.11 uses a modified version of the Karakas-Tariq method. The modifications improve the predicted results to some degree. However, even with the modifications, there are significant deviations between the SPAN 6.11 results and the experimental data for the PEBDZ.

The comparison of experimental data against the simulated results from SPAN 6.0 and the 3D semianalytical model is displayed in **Fig. 6**. In Fig. 6, the symbols, dashed lines, and solid lines show the measured data, SPAN 6.0 results, and the 3D semianalytical model results, respectively. Both SPAN 6.0 and 3D semianalytical model replicate the experimental data very well. It should be restated that SPAN 6.0 uses a modified version of the Karakas-Tariq method for both the PTIDZ and PEBDZ.

Besides being tested against the experimental data, the methods to compute the perforation total skin are also compared for a representative field case. The data set used in the comparison is given in **Table 2.** Additionally, $n_{spf}=8$ and $\theta_p=90°$ are specified. The results for all the methods are shown in **Fig. 7.** As can be seen on the graph, the results from the 3D semianalytical model and SPAN 6.0 agree well. The hybrid method gives good results as long as the perforations are terminated inside the damaged zone, $L_p < \Delta r_d$. The Karakas-Tariq method and SPAN 6.11 deviate substantially from the 3D semianalytical model and SPAN 6.0. Compared to the 3D model and SPAN 6.0, the perforation total skin values from the McLeod method is lower for the PTIDZ and higher for the PEBDZ.

Partially Perforated Vertical Wells

Many previous studies (Vrbik 1991; Thomas *et al.* 1992; Penmatcha *et al.* 1995; Golan and Whitson 1991; Samaniego-V. and Cinco Ley 1996; Economides and Boney 2000; Elshahawi and Gad 2001; Beggs 1984, 1991) have focused on quantifying total skin factor in partially perforated vertical wells. In some publications (Beggs 1984, 1991), the pseudoskin due to partial completion and the pseudoskin due to perforations are completely mixed up. Beggs (1984, 1991) suggested using Saidikowski's (1979) equation for partial-penetration pseudoskin as an alternative to using the Hong (1975) or Locke (1981) nomographs for perforation pseudoskin. The exact forms of the equations to compute the total skin factor in partially perforated wells can be seen in Table 1.

The flow convergence around a partially perforated vertical well differs from that around a partially penetrating well and that about a fully perforated vertical well. As depicted in **Fig. 8**, there are two scales of flow convergence in the near-wellbore region of a partially perforated well. At the far field away from the wellbore, flow is approximately radial and 1D. As fluid approaches the wellbore, it first sees the effect of partial completion and starts to converge toward the completed interval without feeling the impact of perforations. This flow convergence is 2D and practically iden-

TABLE 2—INPUT DATA SET USED IN COMPARISONS

k_z/k_r	1
h, ft	100
r_w, in.	3
r_d, in.	7.5
Δr_d, in.	4.5
k_d/k	0.25
n_{spf}	4, 8
L_p, in.	2–12
θ_p, degrees	90, 180
r_p, in.	0.1
r_{cz}, in.	0.3
Δr_{cz}, in.	0.2
k_{cz}/k	0.1

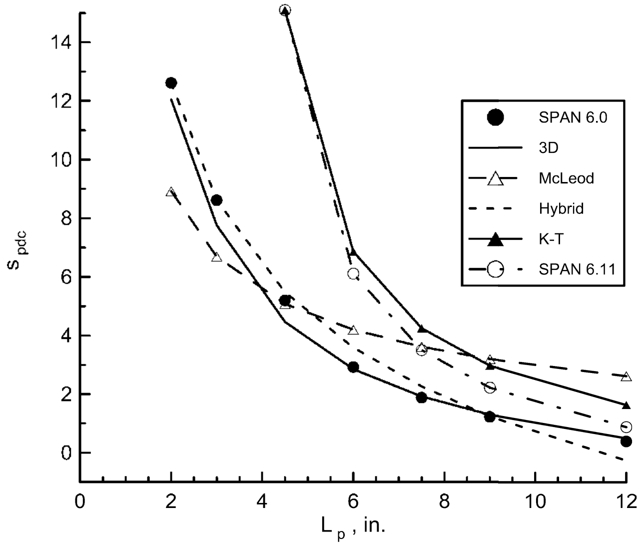

Fig. 7—Comparison of s_{pdc} calculation methods for a fully perforated well (n_{spf}=8, θ_p=90°).

tical to the same phenomena experienced in a partially penetrating well whose completed segment is barefoot. There may be a pseudoradial flow across the completed segment before the second flow convergence emerges. When fluid comes within reach of perforations, it goes through a new flow-pattern change. A 3D flow field grows when fluid converges around the perforation tunnels. Two scales of flow convergence are likely to take place in different locations around the wellbore and should be treated separately.

The interaction between two scales of flow convergence, formation damage, and rock compaction around the perforation tunnels should be formulated delicately. The formation damage and rock compaction have more dynamic interaction with the flow convergence around the perforation than that due to partial penetration. Therefore, formation-damage and rock-compaction effects should be incorporated into the perforation model. First, one should consider a unit-thickness perforated segment and compute perforation total skin accounting for formation damage, 3D flow convergence, and the compacted zone. Second, only the pseudoskin due to partial completion should be estimated. Then, perforation total skin and partial-penetration pseudoskin should be combined as shown below:

$$s_t = \frac{h}{h_p} s_{pdc} + s_{pp} . \quad (25)$$

Eq. 25 will be referred to as the hybrid model for partially perforated vertical wells. In the hybrid model, partial-penetration pseudoskin, s_{pp}, is computed with the Vrbik (1991) model. For the PTIDZ, the s_{pdc} term is calculated with Eq. 24, which is the hybrid model for perforation total skin. The accuracy of Eq. 24 is questionable for the PEBDZ. Thus, for the PEBDZ in the hybrid model for partially perforated wells, the s_{pdc} values from the 3D semianalytical model are incorporated into Eq. 25.

A special case of the formulation expressed in Eq. 25 was originally proposed by Jones and Slusser (1974); they did not consider the effect of the crushed zone around the perforation tunnels. Later, Bell *et al.* (1995) advocated a slightly different form of Eq. 25. They scaled the perforation total skin factor by $h/h_p\gamma_o$ instead of h/h_p. For Eq. 25 to hold true, the perforation total skin factor, s_{pdc}, has to be calculated accurately. Bell *et al.* (1995) advocated the use of the Karakas-Tariq method to predict the perforation total skin factor.

The simple expression given in Eq. 25 has been tested against the results from the 3D model presented in Yildiz (2002). The 3D model has the capability to simulate the flow into selectively perforated wells. It has been observed that the results from Eq. 25 and the 3D model agree well.

SPAN 6.0 and SPAN 6.11 also can calculate the total skin factor for partially perforated wells. Both versions of SPAN seem to be using Eq. 25. However, they differ from each other in the way that the s_{pdc} term is computed.

A representative field case is considered to compare all the methods to estimate the total skin factor in a partially perforated vertical well. The basic data set given in Table 2 is used. Additionally, $h_p = 10$ ft, $n_{spf} = 8$, and $\theta_p = 90°$ are chosen. The perforated segment is located at the top of the formation. **Fig. 9** shows the results from all the methods. The results from the 3D semianalytical model, SPAN 6.0, and the hybrid model given in Eq. 25 agree very well. The models proposed by Vrbik (1991), Bell *et al.* (1995), Thomas *et al.* (1992), Penmatcha *et al.* (1995), Golan and Whitson (1991), Samaniego-V. and Cinco Ley (1996), Economides and Boney (2000), and Elshahawi and Gad (2001) predict substantially different results. The total skin equations for the different methods are listed in Table 1. When computing the total skin factor for the models in Vrbik (1991), Economides and Boney (2000), and Elshahawi and Gad (2001), the perforation skin factor also included the effect of rock compaction around the perforation tunnels. SPAN 6.11 results also significantly deviate from the common response predicted from SPAN 6.0, the 3D semianalytical model, and the hybrid model. The Bell *et al*. method and SPAN 6.11 generate similar results.

After the simple expression given in Eq. 25 is verified against the 3D semianalytical model and SPAN 6.0, it is used to investigate the impact of perforated interval length on the total skin factor. The data set is the same as previously described. The results are given in **Fig. 10.** If a short interval (less than 10%) in the well is completed with short perforations (L_p < 3 in.), the total skin factor is enormously high.

Perforated Inclined Wells

Transient flow solutions have revealed that three distinct flow regimes may be observed in the pressure-transient behavior of inclined wells: early-time radial flow, transitional flow, and late-time pseudoradial flow. (Cinco-Ley *et al.* 1975a, 1975b; Ozkan and Raghavan 2000). During the early-time period, only the formation in the immediate vicinity of the wellbore contributes to flow, and the flow is perpendicular to the well axis. Thus, the effective length involved in the early-time flow period is the total length of the inclined well. During the late-time period, the pressure response of an inclined well is similar to that of a vertical open hole with an additional pseudoskin factor. The formation thickness is the effective length characterizing the pressure behavior at large times. The information described above may be used in the formulation of total skin factor for perforated inclined wells.

In an inclined open hole, the effect of well inclination is quantified in terms of inclination pseudoskin factor, s_θ. Several researchers have presented equations to compute the pseudoskin due to inclined well geometry (Cinco-Ley *et al.* 1975a, 1975b; Besson 1990; Rogers and Economides 1996; Ozkan and Raghavan 2000). The slant pseudoskin equation presented by Cinco-Ley *et al.* (1975a) has been used widely to predict the influence of inclination on well productivity. Once the inclination pseudoskin is available, the additional pressure change due to well deviation is formulated as below.

$$\Delta p_\theta = \frac{141.2\, q_{sc}\, \mu\, B_o}{k\, h} s_\theta . \quad (26)$$

Notice that the effective length involved in Eq. 26 is the formation thickness.

As mentioned previously, transient inclined-well solutions have revealed that, during the early-time period, there exists a radial flow around the inclined-well length. This observation may be used to formulate the combined impact of formation damage and well deviation. If the damaged zone is relatively thin, then flow convergence owing to well deviation may take place away from the near-wellbore region before fluid enters the damaged zone. **Fig. 11** conceptually illustrates the flow convergence around

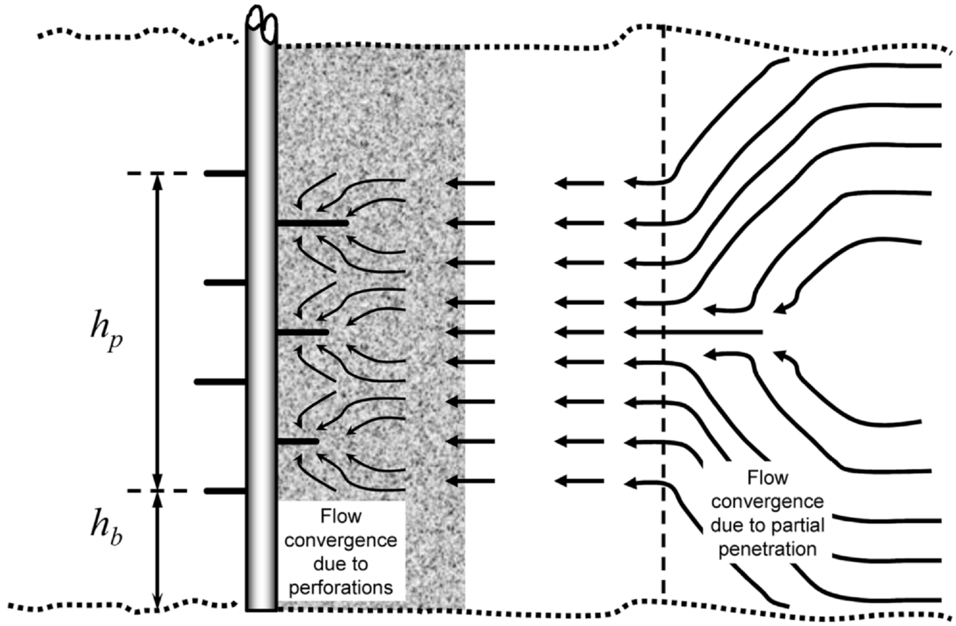

Fig. 8—Flow convergence phenomena around partially perforated vertical wells.

a deviated well with formation damage. If a radial-flow regime normal to the inclined-well axis emerges before the fluid enters the damaged zone, then the additional pressure drop due to formation damage may be expressed as follows:

$$\Delta p_d = \frac{141.2\, q_{sc}\, \mu\, B_o}{k\, L_w}\, s_d \,. \qquad (27)$$

It should be noted that the effective length involved in Eq. 27 is the length of the inclined well.

The total additional pressure change resulting from the combined effects of inclination and formation damage is the sum of the pressure changes given in Eqs. 26 and 27. This leads to

$$\Delta p_{\theta d} = \frac{141.2\, q_{sc}\, \mu\, B_o}{k\, h} \left(\frac{h}{L_w} s_d + s_\theta \right) . \qquad (28)$$

Hence, the total skin factor owing to well deviation and formation damage can be expressed as below:

$$s_t = \frac{h}{L_w} s_d + s_\theta = \cos\theta_w\, s_d + s_\theta \,, \qquad (29)$$

where θ_w is the inclination angle measured with respect to the vertical axis.

Inclined wells may be partially or selectively completed. If the inclined well is partially completed, then the analytical models presented by Cinco-Ley *et al*. (1975b) and Ozkan and Raghavan (2000) may be used to estimate the compounded pseudoskin factor due to partial completion and inclination. Let $s_{\theta pp}$ represent the skin factor accounting for both the well inclination and partial completion. Once $s_{\theta pp}$ is available, then the additional pressure change caused by the combined effect of inclination and partial completion may be expressed as

$$\Delta p_{\theta pp} = \frac{141.2\, q_{sc}\, \mu\, B_o}{k\, h}\, s_{\theta pp} \,. \qquad (30)$$

During the early-time flow period in partially completed and inclined wells, a pseudoradial flow develops only around the open segment length, L_{wpc}. If the partially completed inclined well is damaged and the damage zone is thin, then it is likely that a pseudoradial flow normal to the axis of the completed interval develops before fluid enters the damaged zone. In such a case, the effective length affecting the additional pressure drop caused by formation damage is the length of the completed segment. Thus, the additional pressure drop caused by formation damage may be quantified as

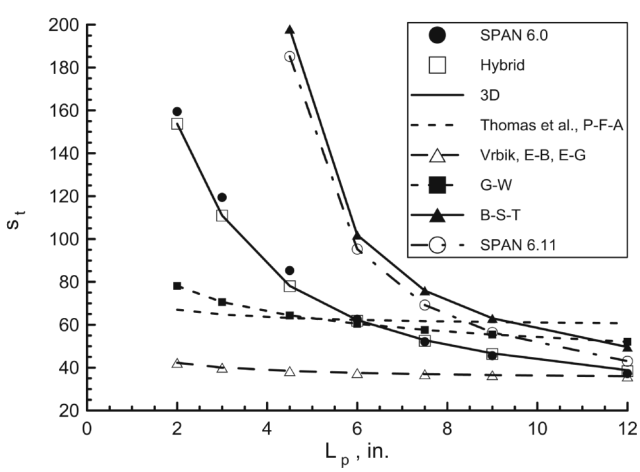

Fig. 9—Comparison of total skin calculation methods for a partially perforated well. Perforated segment at the top.

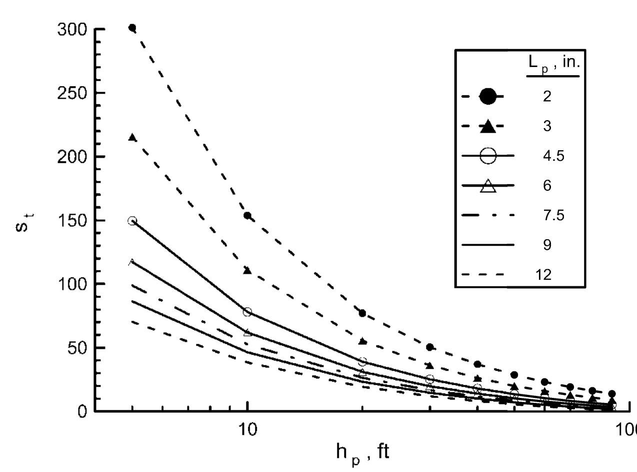

Fig. 10—The effect of perforated segment length on total skin for several perforation lengths.

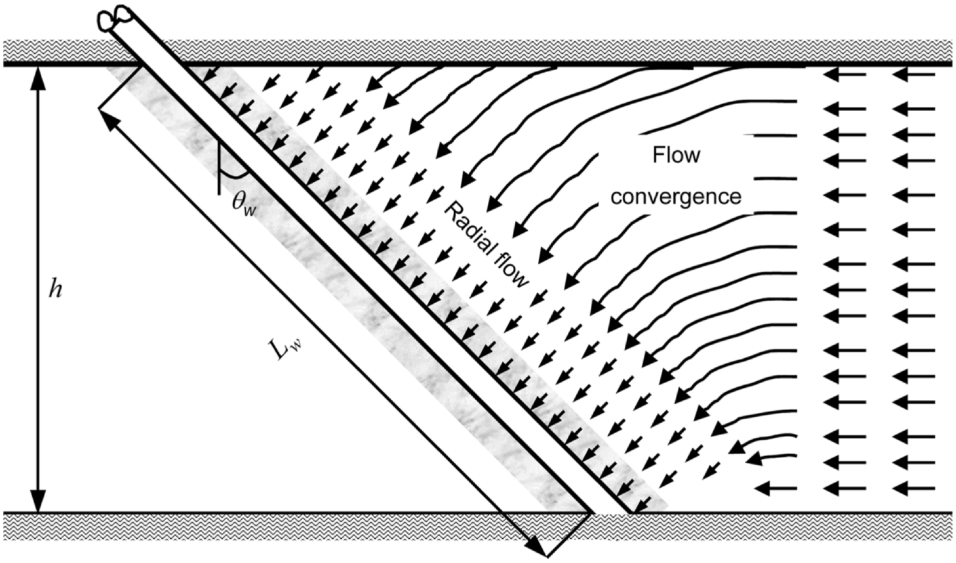

Fig. 11—Flow convergence around a damaged inclined open hole.

$$\Delta p_d = \frac{141.2\, q_{sc}\, \mu\, B_o}{k\, L_{wpc}}\, s_d\,. \quad (31)$$

The total additional pressure change resulting from the combined effects of partial completion, well inclination, and formation damage may be obtained by adding the pressure changes given in Eqs. 30 and 31.

$$\Delta p_{\theta ppd} = \frac{141.2\, q_{sc}\, \mu\, B_o}{k\, h} \left(\frac{h}{L_{wpc}} s_d + s_{\theta pp} \right). \quad (32)$$

Therefore, the total skin factor in a partially completed, inclined, and damaged well is

$$s_t = \frac{h}{L_{wpc}} s_d + s_{\theta pp}\,. \quad (33)$$

Now, a fully perforated inclined well is considered. Similar to the partially perforated well case, there may be two scales of flow convergence around a fully perforated inclined well, as illustrated in **Fig. 12.** At farther distances away from wellbore, fluid flows radially toward the wellbore, as in the case of a partially perforated vertical well. At these locations, fluid streamlines are influenced neither by the well inclination nor by the perforations. When fluid approaches the wellbore, it starts to see the effect of well inclination, and all the fluid streamlines gradually converge and become perpendicular to the wellbore axis. A pseudoradial flow appears around the inclined wellbore before fluid reaches the vicinity of the perforated well. The pseudoradial flow is characterized by the actual inclined well length, L_w. Once the fluid arrives in the near-wellbore region, its streamlines are influenced by the formation damage and perforations. In the near-wellbore region, a 3D flow convergence takes place around the perforations. Similar to the partially perforated well case, two different scales of flow convergence may happen at different locations. In other words, the flow convergence caused by well inclination may not interfere with the flow convergence caused by perforations and formation damage.

It is hypothesized that, in a perforated inclined well, formation damage is mostly interrelated to the 3D fluid convergence around the perforations and across the crushed zone. The formation damage, ideal perforations, and crushed zone all should be considered as near-wellbore phenomena; thus, their combined effect should be formulated as independent of the flow convergence caused by well deviation.

If the inclined well is fully perforated, then perforation total skin (s_{pdc}) should be computed for a representative unit-thickness segment of wellbore. As in the case of partially perforated vertical

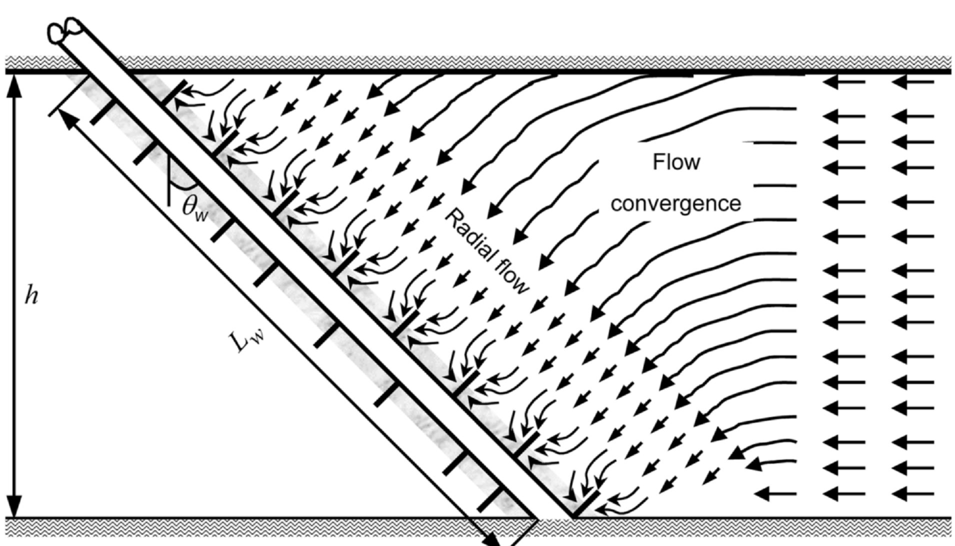

Fig. 12—Flow convergence around a perforated inclined well.

wells, s_{pdc} would account for the combined effect of formation damage, perforations, and compacted zone. Then, inclination pseudoskin and perforation total skin should be put together as follows:

$$s_t = \frac{h}{L_w} s_{pdc} + s_\theta = \cos\theta_w\, s_{pdc} + s_\theta\,. \quad \text{(34)}$$

If the inclined well is partially perforated, then the total skin factor equation becomes

$$s_t = \frac{h}{L_{wpc}} s_{pdc} + s_{\theta pp}\,. \quad \text{(35)}$$

The scaling of s_d and s_{pdc} in Eqs. 29, 33, 34, and 35 is consistent with that in the expressions for partially perforated vertical wells and horizontal wells.

Eqs. 34 and 35 will be referred to as the hybrid model for perforated inclined wells. In this model, the s_{pdc} term is calculated using Eq. 24 for the PTIDZ and the 3D semianalytical model for the PEBDZ. Additionally, for fully perforated inclined wells, the inclination pseudoskin s_θ is estimated with the equation presented by Cinco-Ley *et al.* (1975a). For partially perforated inclined wells, the $s_{\theta pp}$ term, accounting for both the well inclination and partial completion, is estimated with the Ozkan-Raghavan (2000) model.

The literature hosts many other equations to predict the total skin factor in perforated inclined wells. Some of these equations are reported in Table 1. Most of the equations given in Table 1 are substantially different from the expressions in Eqs. 34 and 35. Further elaboration on some of the total skin-factor models is provided below.

To the author's knowledge, Pucknell and Clifford (1991) were the first to accurately scale the perforation total skin factor in perforated inclined wells. Although the details and applications are not clearly described, Pucknell and Clifford (1991) proposed expressions that are nearly identical to Eqs. 34 and 35. The formulation presented above confirms the approach proposed previously by Pucknell and Clifford. However, in conjunction with Eqs. 34 and 35, Pucknell and Clifford advocated the use of the Karakas-Tariq algorithm to calculate the perforation total skin factor, s_{pdc}. Unfortunately, as has been demonstrated earlier, the Karakas-Tariq method substantially overestimates the s_{pdc} term. Here, it is proposed to use the results from SPAN 6.0, the 3D semianalytical model, or the hybrid model to predict the s_{pdc} term and then incorporate it to the total skin models for perforated inclined wells.

Later, Bell *et al.* (1995) proposed the expression below to forecast the perforation total skin factor in partially perforated and inclined wells:

$$s_t = s_{pp} + \frac{h}{h_p}\left[\frac{s_{pdc}}{\gamma_o} + \frac{1}{20}\left(9 + 11\frac{h}{h_p}\right) s_\theta\right], \quad \text{(36)}$$

where h = formation thickness and h_p = vertical length of perforated interval. For a fully perforated inclined well, Eq. 36 reduces to

$$s_t = s_{pdc} + s_\theta\,. \quad \text{(37)}$$

A comparison of Eqs. 34 and 37 indicates that the s_{pdc} term is not properly scaled in the Bell *et al.* (1995) model. Additionally, the Karakas-Tariq method is used to estimate the s_{pdc} term in the Bell *et al.* model.

SPAN 6.0 and SPAN 6.11 seem to be using Eqs. 36 and 37 (Carnegie 1997). However, the s_{pdc} term in both versions of SPAN is calculated differently. SPAN 6.0 uses a modified version of the Karakas-Tariq algorithm for both PTIDZ and PEBDZ. On the other hand, SPAN 6.11 works with the original Karakas-Tariq method for the PTIDZ and a modified version of the Karakas-Tariq scheme for the PEBDZ.

The 3D semianalytical model may be modified to approximate the flow into fully or partially perforated inclined wells. The 3D model has its limitations and drawbacks. One of the limitations of the 3D semianalytical model is the orientation of the perforations with respect to top and bottom reservoir boundaries. Perforations have to be parallel to the bedding plane. However, in perforated inclined wells, perforations are normal to the well axis, and they all deviate from the horizontal plane with an angle of θ_w. In the 3D semianalytical model, the perforations around the inclined wells are forced to be oriented parallel to the bedding plane, as illustrated in **Fig. 13.** This should be a reasonable approximation in isotropic formations.

Some of the methods for predicting the total skin factor in perforated inclined wells are compared by considering representative field cases. The first set of comparison is done for a fully perforated well. The basic data set is given in Table 2. Additionally, n_{spf} = 4 and θ_p = 180° are selected. The results are displayed in **Fig. 14.** Inclination pseudoskin predicted from the Cinco-Ley *et al.* (1975a) is also plotted in Fig. 14. The results for the Pucknell-Clifford (1991) model are obtained by incorporating the s_{pdc} formulation from the Karakas-Tariq algorithm into Eq. 34. The hybrid model also uses Eq. 34; however, the s_{pdc} term is calculated differently. As can be observed on Fig. 14, SPAN 6.11 and the Bell *et al.* (1995) method yield nearly identical results. For smaller slant angles, the Pucknell-Clifford method gives results similar to SPAN 6.11 and the Bell *et al.* method. However, for larger inclination angles, the results predicted by the Pucknell-Clifford method deviate substantially from those given by SPAN 6.11 and the Bell *et al.* method. Total skin factors predicted from the hybrid model and the approximate 3D model agree well. For low deviation angles,

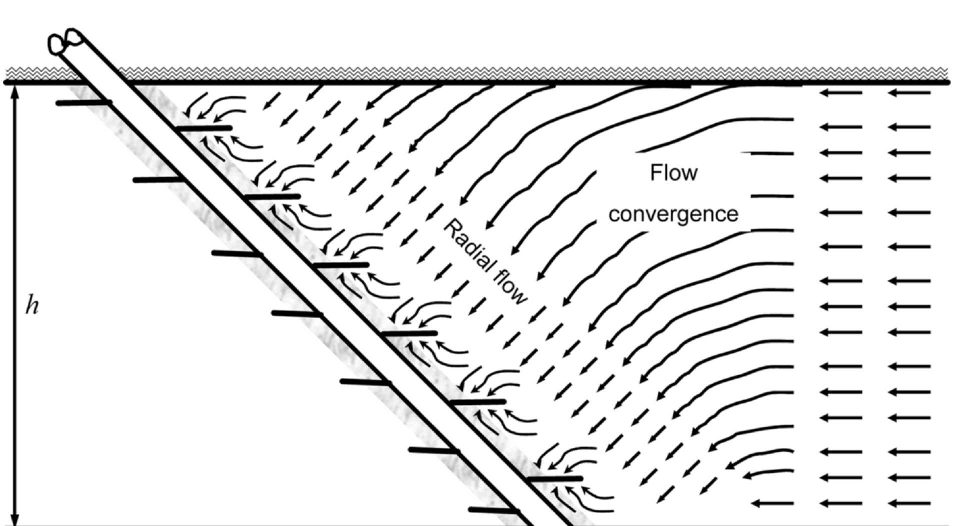

Fig. 13—Representation of a perforated inclined well in the 3D semianalytical model.

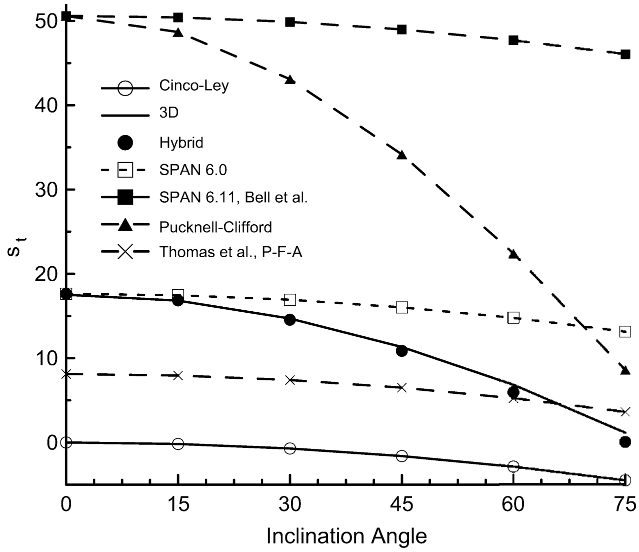

Fig. 14—Comparison of total skin calculation methods for a fully perforated inclined well.

SPAN 6.0 gives results similar to those from the hybrid and 3D models. However, for a larger inclination angle, SPAN 6.0 results significantly deviate from the hybrid and 3D estimates. Compared to the other methods, the algorithm proposed by Thomas *et al.* (1992) and Penmatcha *et al.* (1995) forecasts substantially lower total skin-factor values.

In the partially perforated inclined well example, only a half-length of the well is perforated. The perforated interval is at the top of the formation. Total skin factors estimated from some of the available models are compared in **Fig. 15.** Pseudoskin due to inclination and partial completion, calculated from the Ozkan-Raghavan (2000) model, is also displayed in Fig. 15. For $\theta_w = 0$, the Vrbik (1991) model is used to compute the partial-penetration pseudoskin. SPAN 6.0 and SPAN 6.11 run only for the inclination angles less than 60°. A comparison of the results depicted in Figs. 14 and 15 indicates that total skin factors for partially perforated inclined wells are significantly higher than those for fully perforated inclined wells. The hybrid and 3D approximate models agree well in the case of partially perforated inclined wells. The results from all the other models substantially disagree with those from the hybrid and 3D models.

It should be noted that total skin factors in perforated inclined wells may be reduced considerably by increasing the inclination angle, as the results from the hybrid and 3D models demonstrate in Figs. 14 and 15.

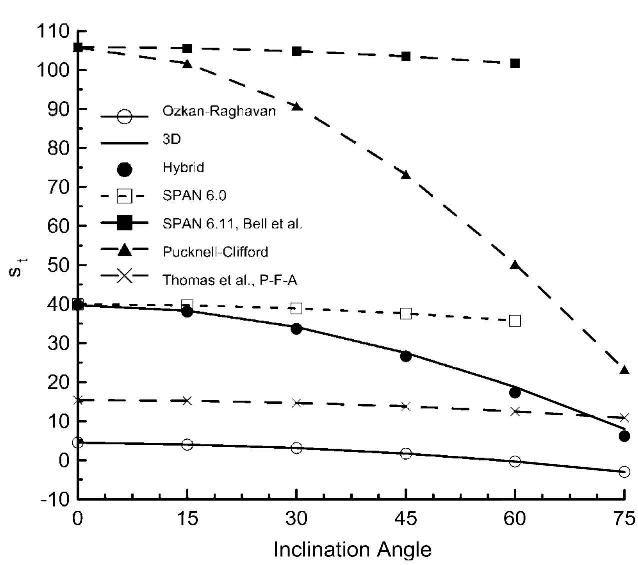

Fig. 15—Comparison of total skin calculation methods for a partially perforated inclined well. Perforated segment at the top.

Perforated Horizontal Wells

In this section, the methodology described for the partially perforated vertical and inclined wells is extended to horizontal wells. The formulation is illustrated on the horizontal-well model proposed by Borisov (Joshi 1991). The Borisov model is one of the simplest steady-state productivity models for horizontal wells. In this model, the pressure drop in an ideal horizontal open hole is given as

$$\Delta p_h = \frac{141.2\, q_{sc}\, \mu\, B_o}{k\, h}\left[\ln\,(r_e/r_w) + s_h\right]. \quad \text{(38)}$$

$$s_h = -\ln\frac{L_h}{4\, r_w} + \frac{h}{L_h}\ln\frac{h}{2\,\pi\, r_w}. \quad \text{(39)}$$

Now, a perforated horizontal well is considered. **Fig. 16** illustrates the flow convergence toward a perforated horizontal well. It is assumed that flow convergence caused by horizontal-well orientation and perforations takes place in different locations inside the formation, and a pseudoradial flow characterized by the horizontal-well length develops around the wellbore before fluid flows in the near-wellbore region. In such a case, the additional pressure change caused by perforations can be quantified as:

$$\Delta p_{pdc} = \frac{141.2\, q_{sc}\, \mu\, B_o}{k\, L_h}\, s_{pdc}. \quad \text{(40)}$$

Total pressure drop in a perforated horizontal well may be obtained by adding Eqs. 38 and 40:

$$\Delta p_t = \frac{141.2\, q_{sc}\, \mu\, B_o}{k\, h}\left(\ln\frac{r_e}{r_w} + s_h + \frac{h}{L_h}\, s_{pdc}\right). \quad \text{(41)}$$

Eq. 41 indicates that total skin factor in perforated horizontal wells is

$$s_t = s_h + \frac{h}{L_h}\, s_{pdc}. \quad \text{(42)}$$

As a final example application, total skin factor in a perforated horizontal well is calculated as a function of well length. The data set given in Table 1 applies. $n_{spf} = 8$ and $\theta_p = 90°$ are specified. Total skin factor predicted from Eq. 42 is presented in **Fig. 17.** The results indicate that longer well length could neutralize the harmful effect of high perforation pseudoskin and eventually generate negative total skin factors.

Conclusions

This study examines the methods used to predict the total skin factor for perforated and damaged wells. Some of the methods were compared against the experimental data on the basis of fully perforated vertical wells. Later, the study was extended to cover partially perforated vertical wells, fully and partially perforated inclined wells, and perforated horizontal wells. The following conclusions have been reached. It should be noted that the conclusions listed pertain to the range of data considered. Some of the conclusions may not apply to perforated wells with substantially different data sets.

1. The perforation total skin equation given by McLeod does not replicate the experimental results. The McLeod method downplays the effect of formation damage. For the PTIDZ, the method underestimates the perforation total skin. On the other hand, for the PEBDZ, it overestimates the perforation total skin.
2. The Karakas-Tariq method has been compared against the experimental data and the other models. The algorithm works fine for ideal perforation tunnels and perforations with a compacted zone around them. However, the Karakas-Tariq method does not work when the effects of ideal perforations, formation damage, and rock compaction around the perforations are compounded. For such cases, the Karakas-Tariq algorithm overpredicts the perforation total skin factor.

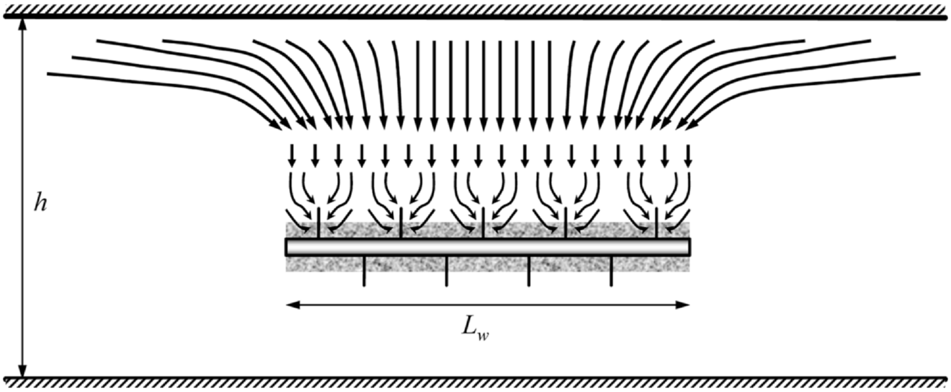

Fig. 16—Flow convergence around a perforated horizontal well.

3. The Jones-Slusser method has been modified to account for the rock compaction around the perforations, and a hybrid method is obtained. The hybrid method has been tested against the experimental data. It has been observed that the hybrid method compares very well with the experimental data when perforations are terminated inside the damaged zone.
4. SPAN 6.0 software, using a modified version of the Karakas-Tariq algorithm, has been tested against the experimental data. The results from the software and the experiments agree well. However, SPAN 6.11, using the original Karakas-Tariq method for the PTIDZ, generates perforation total skin values deviating significantly from the experimental results.
5. Some of the total skin-factor models for partially perforated vertical wells are compared with the 3D semianalytical model. The simple hybrid model and SPAN 6.0 agree well with the 3D model. It has been shown that the total skin-factor equations based on the addition of individual components do not work in the case of partially perforated vertical wells.
6. The 3D semianalytical model has been modified to approximate the flow into perforated inclined wells in isotropic formations. Additionally, a simple hybrid model is presented. The hybrid model for perforated inclined wells agrees well with the approximate 3D model.
7. Most of the available models to calculate total skin factor in perforated inclined wells treat the total skin factor as a sum of the individual skin factors. It has been demonstrated that such models result in incorrect total skin-factor values.
8. Limited sensitivity studies conducted in this paper indicate that larger inclination angles may offset the negative impact of high perforation total skin factors and substantially improve the performance of perforated inclined wells.
9. A simple model is presented to estimate total skin factors in perforated horizontal wells. It has been demonstrated that a combination of long wellbore length and perforations bypassing the damaged zone could overcome the effect of severe formation damage around the wellbore and increase the well productivity significantly.

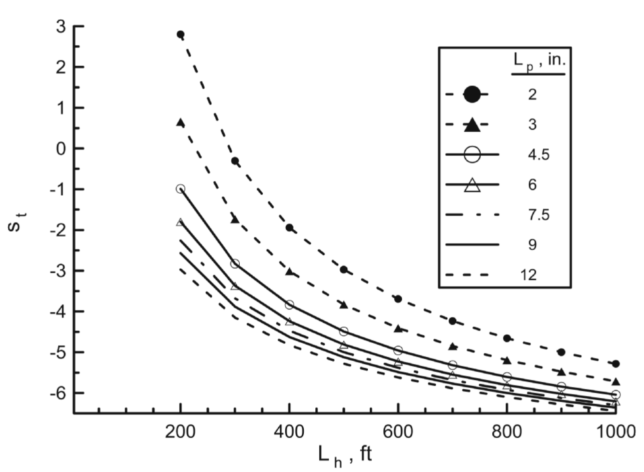

Fig. 17—The effect of horizontal-well length on total skin for several perforation lengths.

Nomenclature

B_o = formation volume factor, dimensionless, res bbl/STB
h = formation thickness, L, ft
h_p = length of the completed interval, L, ft
J_c = productivity of completed well, STB/D/psi
J_{voh} = productivity of open hole, STB/D/psi
k = formation permeability, L^2, md
k_{cz} = permeability of crushed zone, L^2, md
k_d = permeability of damaged zone, L^2, md
k_r = horizontal permeability, L^2, md
k_z = vertical permeability, L^2, md
L_h = horizontal-well length, L, ft
L_p = perforation length, L, ft
L_w = fully completed inclined-well length, L, ft
L_{wpc} = partially completed inclined-well length, L, ft
n_p = number of perforations
n_{spf} = number of shots per foot
p = pressure, m/Lt^2, psi
q_{sc} = flow rate at surface, L^3/t, STB/D
r_{cz} = radius of crushed zone around perforation, L, ft
r_e = reservoir radius, L, ft
r_p = perforation radius, L, ft
r_w = wellbore radius, L, ft
s_{cz} = skin due to rock compaction around perforations in the presence of formation damage
s'_{cz} = skin due to rock compaction around perforations in the absence of formation damage
s_d = skin due to formation damage/stimulation
s_f = completion pseudoskin due to hydraulic fracturing
s_p = pseudoskin due to ideal perforations
s_{pc} = total skin combining flow convergence toward perforations and crushed-zone skin
s_{pd} = total skin combining flow convergence toward perforations and formation damage
s_{pdc} = perforation total skin including ideal perforation pseudoskin, formation damage, and rock compaction around perforation tunnels
s_{pp} = pseudoskin due to partial penetration
s_θ = geometrical pseudoskin due to well inclination
$s_{\theta pp}$ = pseudoskin combining the effect of well inclination and partial penetration
s_t = total skin factor
s_x = boundary skin in Karakas-Tariq model
μ = viscosity, m/Lt, cp
Δp_d = additional pressure change due to skin, m/Lt^2, psi

Δp_{pdc} = additional pressure change caused by the combined effects of formation damage, perforations, and crushed zone, m/Lt^2, psi
Δp_{pp} = additional pressure loss due to partial penetration, m/Lt^2, psi
Δp_t = total pressure drop, m/Lt^2, psi
Δp_{voh} = pressure drop for an open hole, m/Lt^2, psi
Δr_{cz} = thickness of the crushed zone, L, ft
Δr_d = damaged zone thickness around wellbore, L, ft
γ = skin scaling factor
γ_o = skin scaling factor suggested by Odeh
γ_{jw} = skin scaling factor suggested by Jones and Watts
θ_p = perforation phasing angle
θ_w = well inclination/slant angle

Subscripts

d = wellbore damage
p = perforation
t = total
w = wellbore

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SI Metric Conversion Factors

bbl × 1.589 873	E–01	=	m^3
cp × 1.0*	E–03	=	Pa·s
ft × 3.048*	E–01	=	m
ft^3 × 2.831 685	E–02	=	m^3
in. × 2.54*	E+00	=	cm
lbf × 4.448 222	E+00	=	N
lbm × 4.535 924	E–01	=	kg

* Conversion factor is exact.

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