King Saud University

Petroleum and Natural Gas Engineering

PGE 489: Well Stimulation and Sand Production Management

Tuesday, March 8, 2016

Tutorial-1

Exercise-1

Assume that the well described in Appendix A has a damaged region extending 1 ft beyond the wellbore (r_w = 0.328 ft.) The well is on a 40-acre spacing (r_e = 745 ft). Calculate the ratio of the productivity index after removing this damage with acidizing to the productivity index of the damaged well for a permeability in the damaged region ranging from 5% to 100% of the undamaged reservoir permeability.

Next, assume that the well is originally undamaged and acid is used to increase the permeability in a 1-ft region around the wellbore up to 20 times the original reservoir permeability. Calculate the ratio of the stimulated productivity index to the productivity index of the undamaged well. In both cases, assume steady-state flow and no mechanical skin effects.

Formation data:

k_H = 8.2 md

k_V = 0.9 md

h = 53 ft

p_i = 5651 psi

p_b = 1323 psi

$c_o = 1.4 \times 10^{-5}$ psi^{-1}

$c_w = 3 \times 10^{-6}$ psi^{-1}

$c_f = 2.8 \times 10^{-6}$ psi^{-1}

$c_t = 1.29 \times 10^{-5}$ psi^{-1}

μ = 1.7 cp

B = 1.1 res bbl/STB

R_s = 150 SCF/STB

ϕ = 0.19

S_w = 0.34

API° = 28

r_w = 0.328 ft (7 7/8 well)

Solution The productivity index of a well in an undersaturated reservoir is given by Eq. (2-19). Taking the ratio of the stimulated productivity index to the damaged productivity index, noting that $s = 0$ when the damage has been removed, yields

$$\frac{J_i}{J_d} = \frac{\ln(r_e/r_w) + s}{\ln(r_e/r_w)} \tag{13-1}$$

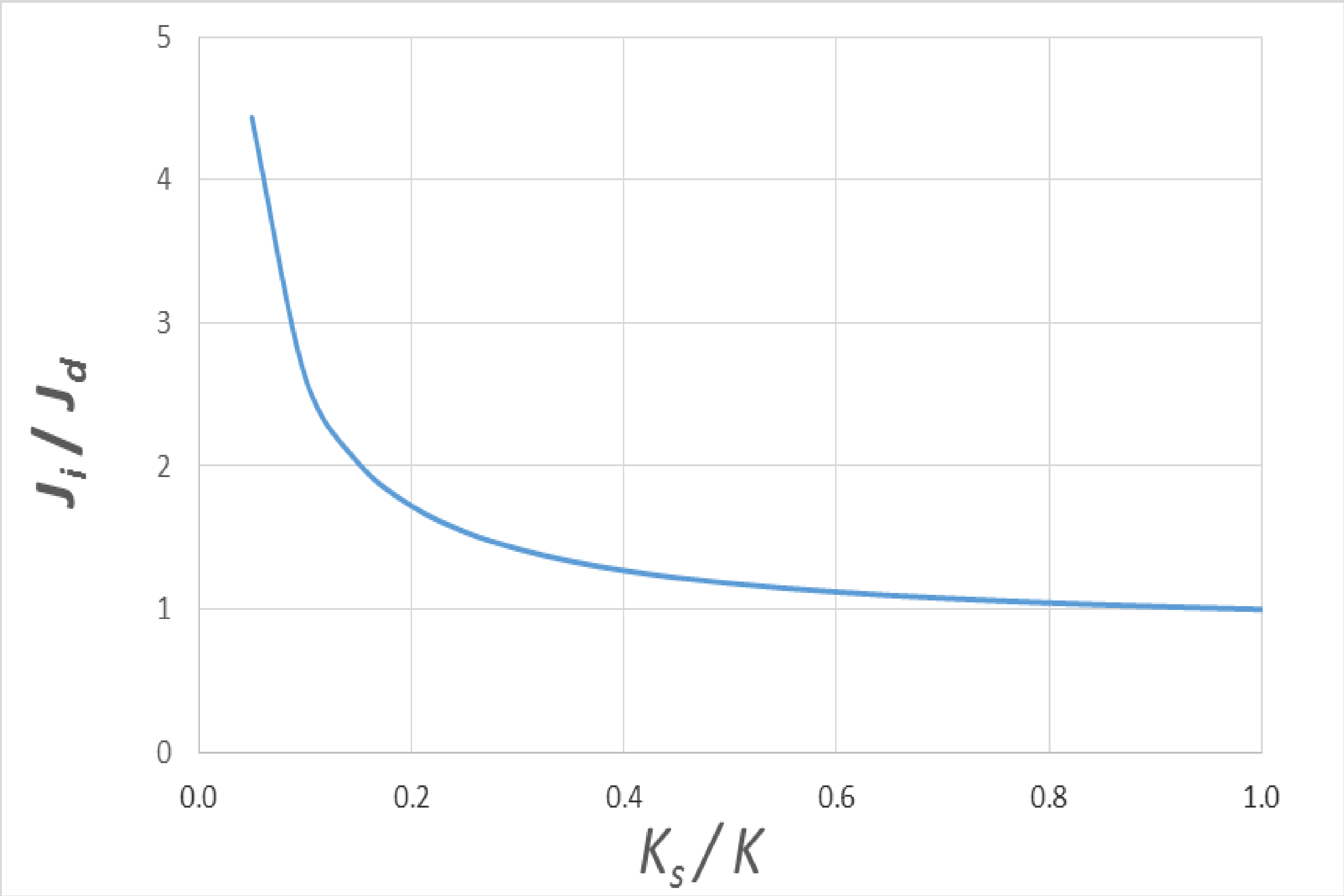
The skin effect is related to the permeability and radius of the damaged region by Hawkins' formula [Eq. (5-4)]. Substituting for s in Eq. (13-1) gives

$$\frac{J_i}{J_d} = 1 + \left(\frac{1}{X_d} - 1\right)\frac{\ln(r_s/r_w)}{\ln(r_e/r_w)} \tag{13-2}$$

$$s = \left(\frac{k}{k_s} - 1\right)\ln\frac{r_s}{r_w} \tag{5-4}$$

X_d : the ratio of the damaged permeability to that of the undamaged reservoir [k_s/k]

X_d	J / J_d	S
0.05	4.44	26.57
0.10	2.63	12.59
0.15	2.03	7.92
0.20	1.72	5.59
0.25	1.54	4.20
0.30	1.42	3.26
0.35	1.34	2.60
0.40	1.27	2.10
0.45	1.22	1.71
0.50	1.18	1.40
0.55	1.15	1.14
0.60	1.12	0.93
0.65	1.10	0.75
0.70	1.08	0.60
0.75	1.06	0.47
0.80	1.05	0.35
0.85	1.03	0.25
0.90	1.02	0.16
0.95	1.01	0.07
1.00	1.00	0.00



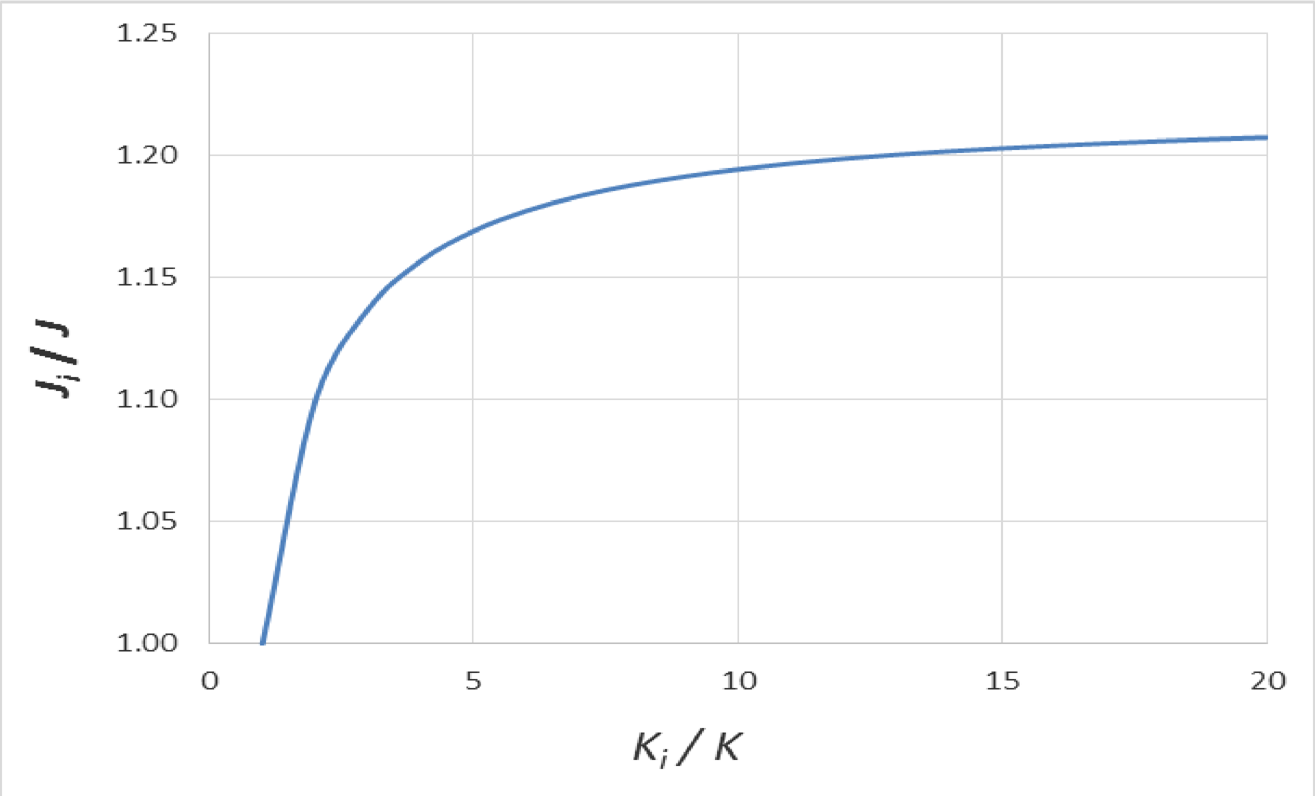
For the case of stimulating an undamaged well, the ratio of the stimulated well productivity index to the original is

$$\frac{J_i}{J} = \frac{1}{1 + [(1/X_i) - 1][\ln(r_s/r_w)/\ln(r_e/r_w)]} \tag{13-3}$$

where X_i is the ratio of the stimulated permeability to the original permeability. Figure 13-2 is obtained by applying Eq. (13-3) for X_i ranging from 1 to 20. For this undamaged well,

X_i : the ratio of the simulated permeability to that the original permeability.

X_i	J_i / J	S
1.00	1.00	0.00
2.00	1.10	-0.70
3.00	1.14	-0.93
4.00	1.16	-1.05
5.00	1.17	-1.12
6.00	1.18	-1.17
7.00	1.18	-1.20
8.00	1.19	-1.22
9.00	1.19	-1.24
10.00	1.19	-1.26
11.00	1.20	-1.27
12.00	1.20	-1.28
13.00	1.20	-1.29
14.00	1.20	-1.30
15.00	1.20	-1.31
16.00	1.20	-1.31
17.00	1.21	-1.32
18.00	1.21	-1.32
19.00	1.21	-1.32
20.00	1.21	-1.33



Exercise-2

A well in Reservoir A, at a depth of 9822 ft, is to be acidized with an acid solution having a specific gravity of 1.07 and a viscosity of 0.7 cp down 2-in.-I.D. coiled tubing with a relative roughness of 0.001. The formation fracture gradient is 0.7 psi/ft. Plot the maximum tubing injection pressure versus acid injection rate. If the skin effect in the well is initially 10, what is the maximum allowable rate at the start of the treatment? Assume that $r_e = 1000$ ft and $\bar{p} = 4500$ psi.

Solution The breakdown pressure from Eq. (14-40) is

$$p_{bd} = \mathrm{FG}(H) \tag{14-40}$$

$$p_{bd} = (0.7\ \text{psi/ft})(9822\ \text{ft}) = 6875\ \text{psi} \tag{14-43}$$

The maximum tubing injection pressure is given by Eq. (14-42). Using Eq. (7-22), the potential energy pressure drop, which is independent of flow rate, is

$$p_{ti,\max} = p_{wf} - \Delta p_{\mathrm{PE}} + \Delta p_F \tag{14-42}$$

$$\Delta p_{\mathrm{PE}} = 0.433\gamma_w\ \Delta z \tag{7-22}$$

$$\Delta p_{\mathrm{PE}} = (0.433\ \text{psi/ft})(1.07)(9822\ \text{ft}) = 4551\ \text{psi} \tag{14-44}$$

The frictional pressure drop is given by Eq. (7-31), which, for q_i in bpm and all other quantities in the usual oilfield units, is

$$\Delta p_F = \frac{1.525\rho q_i^2 f L}{D^5} \tag{14-45}$$

$$N_{\mathrm{Re}} = \frac{1.48 q\rho}{D\mu} \tag{7-7}$$

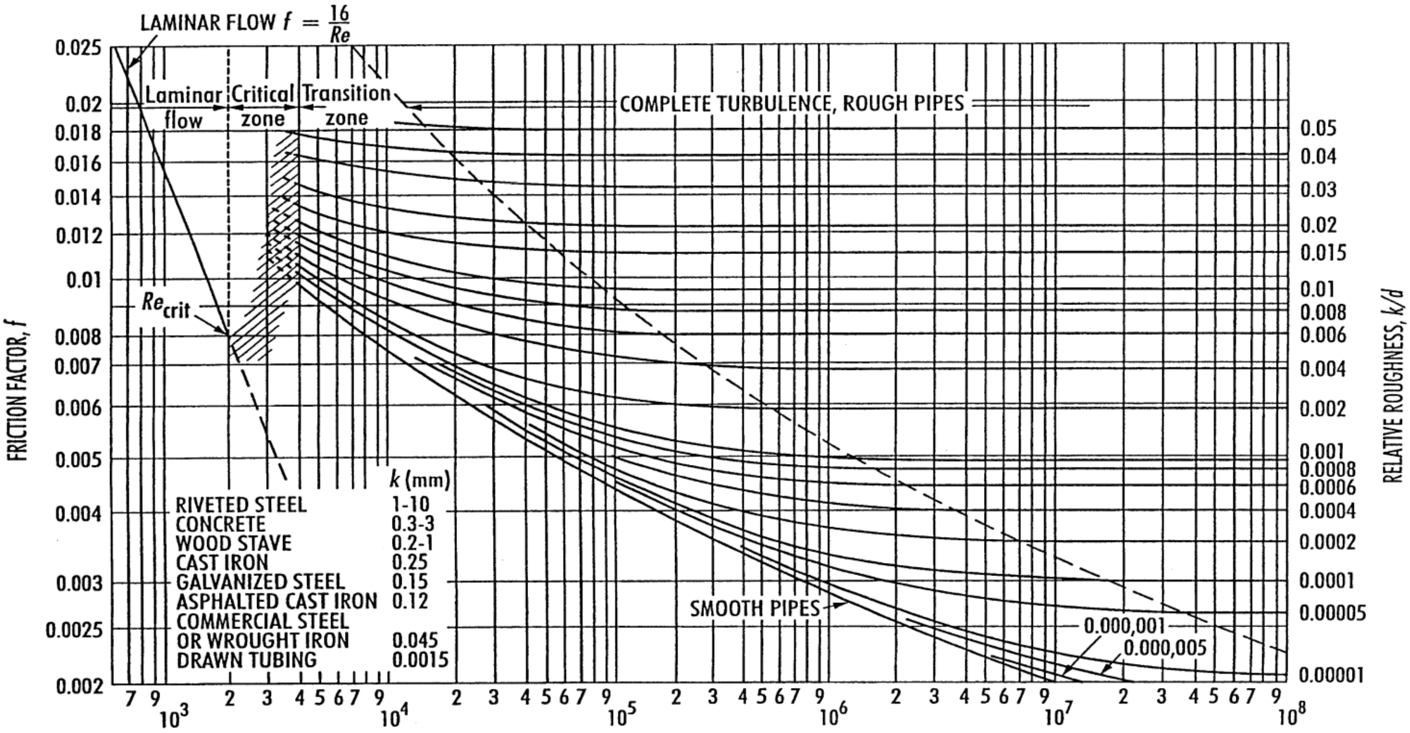
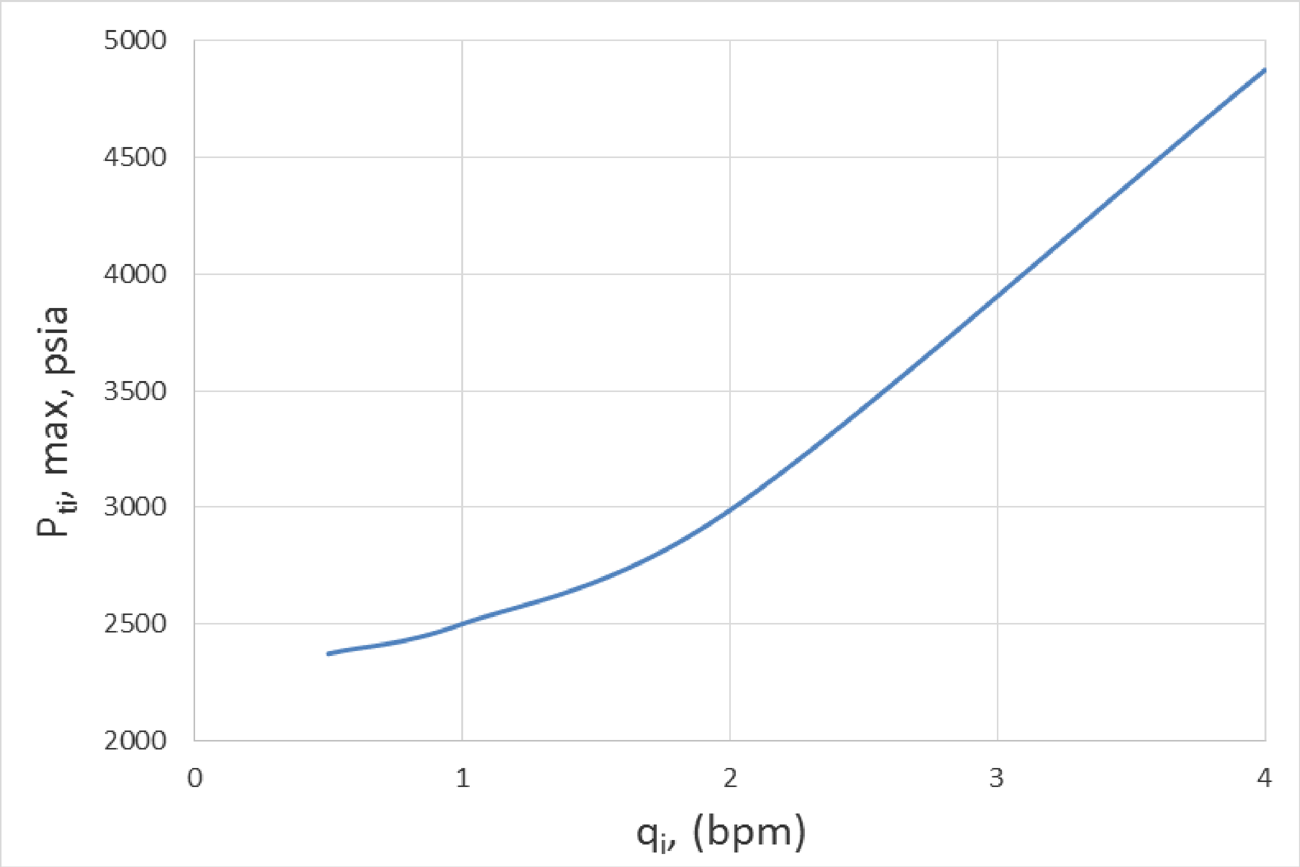


Fig.2 REFERENCE [2]

q_i	N_{Re}	f	Δp_F	$p_{ti,\,max}$
0.5	50820	0.0061	48	2372
1.0	101640	0.0056	175	2500
2.0	203280	0.0053	663	2987
4.0	406560	0.0051	2550	4875



The maximum injection rate at the start of the treatment can be obtained from Eq. (14-41).

$$p_{bd} - \bar{p} = \frac{141.2 q_{i,\max} \mu}{kh} \left(\ln \frac{0.472 r_e}{r_w} + s \right) \quad (14\text{-}41)$$

$$q_{i,\max} = \frac{(6875 - 4500)(8.2)(53)}{(141.2)(1.7)\{\ln[(0.472)(1000)/0.328] + 10\}} \quad (14\text{-}46)$$

$$= 250 \text{ bbl/d} = 0.17 \text{ bpm}$$

Exercise-3

Calculate the radius of penetration of wormholes after the injection of 50 gal/ft of 15 wt% HCl at a rate of 0.1 bpm/ft into a limestone formation with a porosity of 0.2 using Daccord's fractal model. The molecular diffusion coefficient is 10^{-9} m^2/sec.

Solution The radius of wormhole penetration for Daccord's model is calculated with Eq. (15-8). Since the constant b is given in SI units and its units are complex, it is simplest to convert the units of injection rate and volume to SI units. Using conversion factors from Table 1-1

$$r_{wh} = \left[\frac{b N_{Ac} V}{\pi h \phi} D^{-2/3} \left(\frac{q}{h} \right)^{-1/3} \right]^{1/d_f} \qquad (15\text{-}8)$$

Table 1-1

Typical Units for Reservoir and Production Engineering Calculations[a]

Variable	Oilfield Units	SI	Conversion (Multiply Oilfield Unit)
Area	acre	m^2	4.04×10^3
Compressibility	psi^{-1}	Pa^{-1}	1.45×10^{-4}
Length	ft	m	3.05×10^{-1}
Permeability	md	m^2	9.9×10^{-16}
Pressure	psi	Pa	6.9×10^3
Rate (oil)	STB/d	m^3/s	1.84×10^{-6}
Rate (gas)	MSCF/d	m^3/s	3.28×10^{-4}
Viscosity	cp	Pa-s	1×10^{-3}

$$\frac{q}{h} = \left(0.1\frac{\text{bbl}}{\text{min-ft}}\right)\left(0.159\frac{\text{m}^3}{\text{bbl}}\right)\left(\frac{\text{min}}{60\text{ s}}\right)\left(\frac{\text{ft}}{0.3048\text{ m}}\right) = 8.69\times10^{-4}\text{ m}^3/\text{s-m}$$

$$\frac{V}{h} = \left(50\frac{\text{gal}}{\text{ft}}\right)\left(3.785\times10^{-3}\frac{\text{m}^3}{\text{gal}}\right)\left(\frac{\text{ft}}{0.3048\text{ m}}\right) = 0.621\text{ m}^3/\text{m} \qquad (15\text{-}10)$$

The acid capacity number for the injection of 15 wt% HCl into a 0.2-porosity limestone is

$$N_{\text{Ac,HCl}} = \frac{\phi\beta_{\text{HCl}}C^0_{\text{HCl}}\rho_{\text{acid}}}{(1-\phi)V^0_{\text{CO}_3}\rho_{\text{CO}_3}} \qquad (14\text{-}85)$$

Table 13-3

Dissolving Power of Various Acids[a]

			X			
Formulation	Acid	β_{100}	5%	10%	15%	30%
Limestone:	Hydrochloric (HCl)	1.37	0.026	0.053	0.082	0.175
$CaCO_3$	Formic (HCOOH)	1.09	0.020	0.041	0.062	0.129
$\rho CaCO_3 = 2.71$ g/cm^3	Acetic (CH_3COOH)	0.83	0.016	0.031	0.047	0.096
Dolomite:	Hydrochloric	1.27	0.023	0.046	0.071	0.152
$CaMg(CO_3)-2$	Formic	1.00	0.018	0.036	0.054	0.112
$\rho CaMg(CO_3)_2 = 2.87$g/cm^3	Acetic	0.77	0.014	0.027	0.041	0.083

$$N_{\text{Ac}} = \frac{(0.2)(1.37)(0.15)(1.07)}{(1-0.2)(2.71)} = 2.03\times10^{-2} \qquad (15\text{-}11)$$

$$r_{\text{wh}} = \left[\frac{bN_{\text{Ac}}V}{\pi h \phi} D^{-2/3} \left(\frac{q}{h} \right)^{-1/3} \right]^{1/d_f} \tag{15-8}$$

Applying Eq. (15-8),

$$r_{\text{wh}} = \left[\frac{(1.5 \times 10^{-5})(0.0203)(0.621)}{\pi(0.2)} (10^{-9})^{-2/3} (8.69 \times 10^{-4})^{-1/3} \right]^{1/1.6} \tag{15-12}$$

$$= 2.05 \text{ m} = 6.74 \text{ ft}$$

Exercise-4

Calculate the volume (gal/ft) of 28% HCl needed to propagate wormholes 3 ft from a 0.328-ft-radius wellbore in a limestone formation with a porosity of 0.15, using both Daccord's model and the volumetric model. The injection rate is 0.1 bpm/ft, the diffusion coefficient is 10^{-9} m^2/sec, and the density of 28% HCl is 1.14 g/cm^3. In linear core floods, 1.5 pore volumes are needed for wormhole breakthrough at the end of the core.

Solution Daccord's model: Solving Eq. (15-8) for the volume of acid per unit thickness of formation yields

$$\frac{V}{h} = \frac{r_{\mathrm{wh}}^{d_f} \pi \phi D^{2/3} (q/h)^{1/3}}{b N_{\mathrm{Ac}}} \tag{15-21}$$

The acid capacity number for 28% HCl reacting with a 0.15 porosity limestone is

$$N_{\mathrm{Ac}} = \frac{(0.15)(1.37)(0.28)(1.14)}{(1-0.15)(2.71)} = 2.85 \times 10^{-2} \tag{15-22}$$

It is more convenient to use SI units in Eq. (15-21); from Example 15-1, 0.1 bpm/ft is 8.69×10^{-4} m^3/sec-m. The desired wormhole radius is 3 ft + 0.328 ft = 3.328 ft, or 1.01 m. Then

$$\frac{V}{h} = \frac{(1.01)^{1.6}(\pi)(0.15)(10^{-9})^{2/3}(8.69 \times 10^{-4})^{1/3}}{(1.5 \times 10^{-5})(2.85 \times 10^{-2})} \tag{15-23}$$

$$= 0.107 \text{ m}^3/\text{m} = 8.6 \text{ gal/ft}$$

The model predicts that only 8.6 gal/ft are needed to propagate wormholes 3 ft from the wellbore.

Volumetric model: First, substituting for η from Eq. (15-14) into Eq. (15-13) gives

$$r_{wh} = \sqrt{r_w^2 + \frac{V}{\pi \phi h PV_{bt}}} \tag{15-24}$$

and solving for V/h yields

$$\frac{V}{h} = \pi\phi(r_{wh}^2 - r_w^2)PV_{bt} \tag{15-25}$$

which shows that the acid volume needed is just the volume of the pore space in the region penetrated by wormholes multiplied by the number of pore volumes required to propagate wormholes through a given volume of rock. For the case given,

$$\frac{V}{h} = (\pi)(0.15)(3.328^2 - 0.328^2)(1.5) = 7.75 \text{ ft}^3/\text{ft} = 58 \text{ gal/ft} \tag{15-26}$$

Comment

A significantly larger volume is predicted by the volumetric model than by Daccord's model. Field experience suggests that the larger volume predicted by the volumetric model is more realistic than the small volume predicted by Daccord's model.