Although equations (2.42) and (2.44) appear similar except for the term Dq_g, they represent two different flow models. While the first one expresses the linear rate–pressure relationship of Darcy's law, the second one expresses the Forchheimer model. This similarity in form is very useful. It allows for all equations that are developed with Darcy's law to be modified to account for high-velocity effects by merely adding a rate-dependent skin term. Example 2.4 illustrates the use of the radial flow equation for gas wells producing at low reservoir pressures.

EXAMPLE 2.4 INFLOW PERFORMANCE CALCULATIONS FOR A GAS WELL PRODUCING AT LOW RESERVOIR PRESSURES

A two-rate drawdown/buildup test was run on a new gas discovery well in Kansas, the Medicine Lodge No. 1. For the first buildup following an eight-hour flow period at 6.4 MMscf/D, Horner analysis indicated a permeability-thickness (kh) of 790 md-ft and a skin of +3.62. The second buildup followed a 12-hour flow period at 8.7 MMscf/D, and Horner analysis indicated a kh of 815 md-ft and a skin of +4.63. Other reservoir data included initial reservoir pressure of 1623 psia at a temperature of 128°F. From standard gas property correlations, the initial gas viscosity and Z-factor are 0.0134 cp and 0.879, respectively.

Determine the high-velocity flow term D, used in the radial flow equation (2.44). What is the steady-state skin factor (i.e., when rate equals zero)? Write the IPR equation using the pressure-squared, low-reservoir pressure assumptions. Assume an average kh of 800 md-ft and $\ln(r_e/r_w) - 0.75 = 7$.

SOLUTION

First, we determine the rate-dependent skin coefficient D using skins reported from buildup test analysis. However, since a different kh is reported for each test, it is necessary to calculate an average kh and then correct the skin accordingly. Assuming stabilized flow, the corrected test skin s_{tc} is found from the actual test skin s_t from the relation

$$\frac{(kh)_{\text{test}}}{\ln(r_e/r_w) - 0.75 + s_t} = \frac{(kh)_{\text{avg}}}{\ln(r_e/r_w) - 0.75 + s_{tc}}$$

In this example we assume $\ln(r_e/r_w) - 0.75 = 7$ and $(kh)_{\text{avg}} = 800$ md-ft. The corrected test skin for the first test with rate of 6.4 MMscf/D is

$$\frac{790}{7 + 3.62} = \frac{800}{7 + s_{tc}}$$

or

$$s_{tc} = (800/790)(7 + 3.62) - 7$$

$$= 3.75.$$

EXAMPLE 2.4 continued

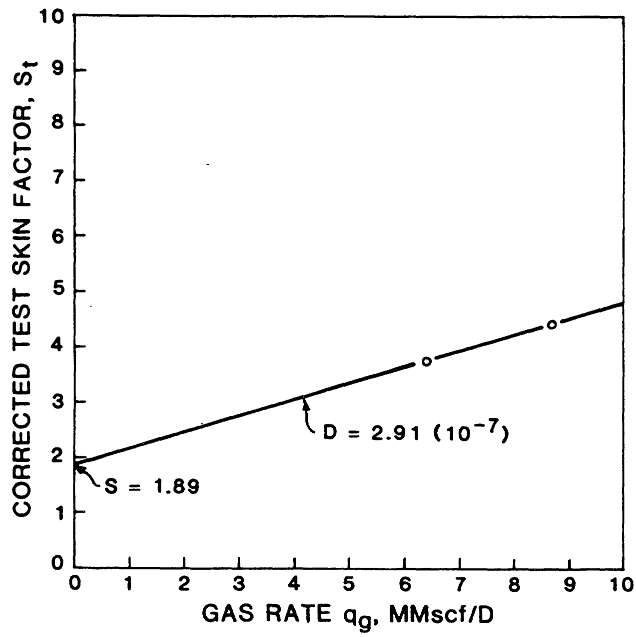

Figure E2.4a Rate-dependent skin factor in the Medicine Lodge No. 1 gas well.

For the second test with rate of 8.7 MMscf/D, corrected skin is

$$\frac{825}{7+4.63}=\frac{800}{7+s_{tc}}$$

or

$$s_{tc} = (800/815)(7+4.63)-7$$

$$=4.42.$$

A plot of corrected test skin versus gas rate is shown in figure E2.4a. The slope of the straight line gives a value of $D = 2.91 \times 10^{-7}$ (scf/D)$^{-1}$. The intercept at zero rate equals the steady-state skin, $s = +1.89$, indicating slight formation damage.

A common error is to plot test skin versus rate without making the kh correction. Had this been done for this example the steady-state skin would be underestimated, rate-dependent skin would be overestimated, and AOF would be underestimated by 1.0 MMscf/D (corresponding to about $700,000 per year for a gas price of $2/Mscf). *It must be emphasized that the skin-versus-rate plot is not valid if kh associated with each skin is different.*

EXAMPLE 2.4 continued

Table E2.4 Calculated Gas IPR for the Medicine Lodge No. 1 Well

p_{wf} (psia)	$p_R^2 - p_{wf}^2$ (psia^2)	q_g (MMscf/D)
0	2.63×10^6	15.8 (AOF)
500	2.38×10^6	14.7
750	2.07×10^6	13.2
1000	1.63×10^6	11.0
1250	1.07×10^6	7.78
1500	3.84×10^5	3.18
1550	2.32×10^5	1.99

The stabilized IPR equation for the Medicine Lodge No. 1 is found by substituting reservoir and test data in equation (2.44).

$$q_g = \frac{0.703(800)(1623^2 - p_{wf}^2)}{(128+460)(0.0134)(0.879)[7 + 1.89 + 2.91 \times 10^{-7} q_g]}$$

$$= 81.2\frac{(2.63 \times 10^6 - p_{wf}^2)}{(8.89 + 2.91 \times 10^{-7} q_g)}$$

or

$$\frac{2.63 \times 10^6 - p_{wf}^2}{q_g} = 0.1095 + 3.58 \times 10^{-9} q_g,$$

giving $A = 0.1095$ and $B = 3.58 \times 10^{-9}$. Solving the quadratic equation for rate,

$$Bq_g^2 + Aq_g - \Delta p^2 = 0$$

$$q_g = \frac{[A^2 + 4B\Delta p^2]^{0.5} - A}{2B}$$

$$= \frac{[(0.1095)^2 + 4(3.58 \times 10^{-9})(2.63 \times 10^6 - p_{wf}^2)]^{0.5} - 0.1095}{2(3.58 \times 10^{-9})}$$

$$= \frac{[0.0120 + 1.43 \times 10^{-8}(2.63 \times 10^6 - p_{wf}^2)]^{0.5} - 0.1095}{7.16 \times 10^{-9}}.$$

Table E2.4 gives a few rates and flowing pressures, which are plotted in figure E2.4b on log–log paper. From about 5 MMscf/D to the maximum rate (AOF) of 16 MMscf/D, the IPR curve is a straight line on the log–log plot. The slope is 1.89, corresponding to a backpressure exponent of $n = 0.766$.

EXAMPLE 2.4 continued

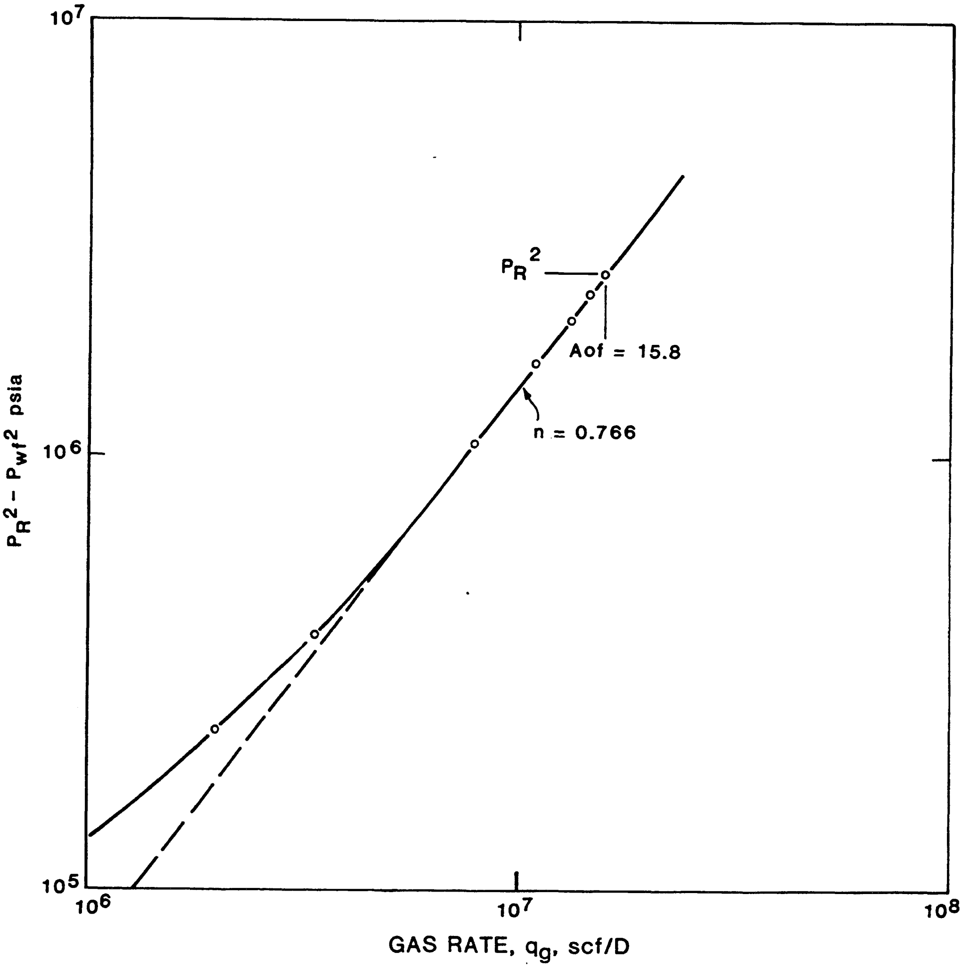

Figure E2.4b Backpressure curve of the Medicine Lodge No. 1 gas well.

At high pressures, usually greater than 3000 to 3500 psia, the pressure function $p/\mu_g Z$ is nearly constant. The pressure integral in equation (2.40) is solved analytically to give

$$2\int_{p_{wf}}^{p_R} \frac{p}{\mu_g Z} dp = 2\frac{p}{\mu_g Z}(p_R - p_{wf}), \tag{2.45}$$