A NOTE ON DOWNHOLE PRESSURE IN A FLOWING OR STATIC STEAM WELL

K. P. Goyal

Diamond Shamrock Thermal Power Company
3333 Mendocino Avenue, Suite 120
Santa Rosa, California 95401

ABSTRACT

An expression, to calculate downhole/bottomhole pressure in a flowing/shut-in well is derived. This relation also considers a well which may or may not be directionally drilled. Finally, an equation is developed to calculate an equivalent diameter for a well with multiple inside diameters for friction loss considerations. The pressure calculations using these formulas are relatively fast since these equations do not require iterations. The estimates obtained by these methods are as good as those obtained by other methods currently available in the literature.

NOMENCLATURE

C - Constant, defined in equations (4) and (6)
D = Inside pipe diameter, inches
d_e = Equivalent diameter, inches
f_M - Moody friction factor
H - Total vertical depth, feet
ℓ = Length of the wellbore, feet
p = Pressure, psia
P_{tf} = Flowing wellhead pressure, psi
P_{ts} = Shut-in wellhead pressure, psi
P_{wf} = Flowing bottomhole pressure, psi
P_{ws} = Shut-in bottomhole pressure, psi
W = Steam flow rate, lbm/hr

α - Constant, 0.01267 lbm/ft^3
β - Constant, 0.00212 lbm/ft^3 - psi
γ - Constant, 3.35×10^{-6}
θ = Well angle from vertical, degrees
ρ_s - Density of steam, lbm/ft^3

INTRODUCTION

The calculation of downhole pressure from the measured wellhead data is routinely done by reservoir engineers and field engineers under flowing and/or shut-in conditions. The purpose of these calculations may vary from determining reservoir characteristics, well productivity to casing design. Iglesias et al (1983) utilize a wellbore computer model to compute bottomhole pressure for a given wellhead pressure and flow rate. Economides (1979), Grant et al (1982) and Drenick (1986) calculate downhole pressure by assuming an average temperature and gas law deviation factor over the length of the wellbore and iterate the calculations until the assumed and the calculated values converge.

This paper presents a general method to calculate downhole pressure in a vertical or directional hole under static or flowing conditions without using the iterative procedure. A simplified method to calculate bottomhole pressure, for a multiple inside diameter well, is also included.

DOWNHOLE PRESSURE CALCULATIONS

The flowing pressure gradient in a uniform diameter, directional well can be expressed by the following relation (Grant et al, 1982)

$$\frac{dp}{d\ell} = \frac{\rho_s}{144} \cos\theta + \frac{\gamma f_M W^2}{\rho_s D^5} \qquad (1)$$

Equation (1) implies that the total pressure drop in a pipe over a small length interval is equal to the sum of the pressure drop due to friction and that due to elevation change. The density of the saturated or slightly superheated steam approximates a linear relation with the pressure in the range of interest. Using a least square fit, Economides (1979) obtained the following relations for the density as a function of pressure.

$$\rho_s = \alpha + \beta p \qquad (2)$$

The values of α and β, given in the nomenclature, suggest that the calculated steam density is within 0.4% of the actual density in the pressure range of 100 psia to 500 psia. However, in the larger pressure range of 50 psia to 700 psia, the error is less than 2%.

Substitution of (2) in (1) and the integration of the resulting equation leads to the following expression.

$$\left(\frac{\alpha}{\beta}+p\right)^2 = \left[\left(\frac{\alpha}{\beta}+p_{tf}\right)^2 + C\right] e^{\frac{\ell\beta\cos\theta}{72}} - C \qquad (3)$$

Where

$$C = \frac{144}{\cos\theta}\,\frac{\gamma f_M W^2}{D^5\beta^2};\quad 0^\circ \le \theta < 90^\circ \qquad (4)$$

A further simplification of (3) and (4) can be made by substituting the values of α, β and γ, as given below.

$$(6+p)^2 = \left[(6+p_{tf})^2 + C\right] e^{(2.944\times10^{-5}\,\ell\cos\theta)} - C \qquad (5)$$

$$C = 107.54\,\frac{f_M W^2}{D^5\cos\theta} \qquad (6)$$

Expressions (5) and (6) are general relations which can be used to calculate downhole pressure (p) at any depth, (ℓ) for a directional well at an angle, (θ) from vertical. These equations can be further reduced for special cases as follows:

Flowing Vertical Well: For a vertical well, angle, (θ) becomes zero, measured length, (ℓ) equals total depth, (H) and the downhole pressure (p) equals pwf. Under these conditions, (5) and (6) simplify to

$$(6+p_{wf})^2 = \left[(6+p_{tf})^2 + C\right] e^{2.944\times10^{-5}H} - C \qquad (7)$$

$$C = 107.54\,\frac{f_M W^2}{D^5} \qquad (8)$$

The bottomhole flowing pressure (pwf) can be calculated from (7) and (8) for the given values of the flow rate, casing inside diameter, total depth and wellhead pressure (p_{tf}).

Shut-in Vertical Well: For a shut-in well, (7) and (8) can be further reduced by substituting zero for flow rate. This implies that the value of constant, C in (8), is zero. The resulting equation (7) is as follows:

$$p_{ws} = -6 + (6+p_{ts})\,e^{1.472\times10^{-5}H} \qquad (9)$$

EQUIVALENT DIAMETER FOR MULTIPLE CASING SIZES

If we consider a well which has N types of casings, each having a different diameter and a different length, then the total depth of the well is equal to the sum of the individual casing lengths open to inside of the well. Also the total frictional pressure drop is the sum of the pressure drop in each individual casing. Assuming an equivalent diameter de, which allows the same pressure drop over the entire length of the well as that caused by all the N casings, then the following relation can be obtained from (1).

$$\frac{\gamma W^2}{d_e^5}\sum_{j=1}^{N}\frac{f_M \ell_j}{\rho_s} = \sum_{j=1}^{N}\frac{\gamma f_M \ell_j W^2}{\rho_s D_j^5} \qquad (10)$$

Equation (10) can further be simplified by assuming that the friction factor is same in all the casings and that the effect of steam density (ρ_s) is similar on both sides of (10). The error introduced by these assumptions is quite small as shown in example 2. Under these assumptions, equation (10) simplifies to:

$$d_e = \left(\frac{\sum_{j=1}^{N}\ell_j}{\sum_{j=1}^{N}\frac{\ell_j}{D_j^5}}\right)^{0.2} \qquad (11)$$

The calculated values of the equivalent diameter (d_e) from (11) can be used in (5) to (8) for internal diameter to obtain the value of C under flowing conditions. This procedure is faster than calculating pressures in each individual string to arrive at the bottomhole pressure.

EXAMPLES

1. Bottomhole Pressure Calculation: Consider the following data for a flowing well as given in Economides (1979).

p_{tf} - 400 psia
W - 100,000 lbm/hr
D - 9.625 inches
f_M - 0.0135
H - 7500 feet

Substitution of these data in (8) and (7) results in the following values for C and p_{wf}.

C - 175,752
p_{wf} - 493 psia

Economides (1979) obtained the same value for p_{wf} after several iterations.

2. Bottomhole Pressure in a Geysers Well Completed With Multiple Diameter Casings. Consider the following data for a flowing well in the Geysers (Drenick, 1986).

p_{tf} - 153 psia
W - 158,000 lbm/hr.

Topmost Casing:

Outside diameter - 16 inches
Inside diameter, D_1, - 15.25"
(assume a casing weight of 65 lbm/ft).
Length, ℓ_1 - 2000 ft.

Intermediate Casing:

Outside diameter - 11.75 inches
Inside diameter, D_2, - 10.88"
(assume a casing weight of 65 lbm/ft).
Length, ℓ_2 - 4000 ft.

Bottommost Open Interval:

Inside diameter, D_3 - 10.625"
Length, ℓ_3 - 3000 feet

Method A: In this method, we use the specifications of the topmost casing and the flowing pressure at its top to calculate its downhole pressure from (7) and (8). This calculated downhole pressure becomes the pressure at the top of the second string. Using the specifications of this intermediate casing, its downhole pressure can be estimated in a manner similar to the topmost string. One can continue to use (7) and (8) until the bottomhole pressure is calculated for the liner or the open interval. For an assumed value of f_M - 0.0135, one obtains:

C_1 - 43,941, p_{wf1} - 166 psia
C_2 - 237,724, p_{wf2} - 245 psia
C_3 - 267,654, p_{wf3} - 300 psia

This bottomhole pressure of 300 psia compares with that of 310 psia (Drenick, 1986) calculated by the method of Economides (1979). The actual measured pressure at this 9000 foot depth is about 278 psia. The assumed friction factor and internal diameter of the casing may cause this discrepancy.

Method B: In this method, we use the concept of equivalent diameter to calculate the bottomhole pressure from equations (7), (8) and (11). The calculated values are as follows:

de - 11.21 inches
C - 204,638
p_{wf} - 302 psia

The calculated bottomhole pressure of 302 psia by Method B compares with that of 300 psia by Method A. The error introduced in Method B is quite small, about 0.7%. This suggests that the equivalent diameter method should be used to obtain reasonable estimates of the bottomhole pressure and to save a lot of calculating time.

REFERENCES

Drenick, A. (1986), "Pressure-Temperature-Spinner Survey in a well at The Geysers" Presented at the Eleventh Workshop on Geothermal Reservoir Engineering At Stanford University (Preprint).

Economides, M. J. (1979), "Shut-in and flowing bottomhole pressure calculations for geothermal steam wells" in Proceedings Fifth Workshop on Geothermal Reservoir Engineering, SGP-TR-40, Stanford Geothermal Program, Stanford University, pp 139-151.

Grant, M.A., I.G. Donaldson and P.F. Bixley (1982), "Geothermal Reservoir Engineering", Academic Press, pp 135-136.

Iglesias, E., V. Arellano, A. Grafias, C. Miranda, J. Hernandez and J. Gonzales (1983), "A method to recover useful geothermal reservoir parameters from production characteristic curves (1) steam reservoirs", in Proceedings, Ninth Workshop on Geothermal Reservoir Engineering, SGP-TR-74, Stanford Geothermal Program, Stanford University, pp 285-290.