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GEOTHERMAL TWO-PHASE WELLBORE FLOW: PRESSURE DROP CORRELATIONS AND FLOW PATTERN TRANSITIONS

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ABSTRACT

In this paper we present some basic concepts of two-phase flow and review the Orkiszewski (1967) correlations which have been suggested by various investigators to perform well for geothermal wellbore flow situations. We also present a flow regime map based on the transition criteria used by Orkiszewski (1967) and show that most geothermal wells flow under slug flow regime. We have rearranged bubble- to slug- flow transition criterion used by Orkiszewski (1967) to show that the transition depends on the dimensionless pipe diameter number in addition to dimensionless liquid and gas velocity numbers. Our aim is also to identify what research may lead to improvements in two-phase pressure drop calculations for geothermal wellbore flow.

INTRODUCTION

The Orkiszewski (1967) two-phase vertical upward flow correlations have been used by several investigators to model steam/water wellbore flow. In a companion paper we use a geothermal wellbore simulator based on the Orkiszewski (1967) correlations to calculate the flowing pressure and temperature profiles in several wells (Ambastha and Gudmundsson, 1986). There we study under what flowing conditions the measured and calculated profiles match. Our study differs from others because we use data sets from several geothermal wells, but only one set of two-phase flow correlations.

In addition to identifying the conditions when measured and calculated wellbore data match, we want to identify what research may lead to improvements of geothermal wellbore simulators. For this we need to know the details of the wellbore simulator used, flow regime transitions, and pressure drop calculations. We also need to know how the correlations relate to two-phase flow studies in general. The purpose of this paper is to present the details of the Orkiszewski (1967) two-phase vertical flow correlations used in a geothermal wellbore simulator, described by Ortiz-R. (1983). We also present a flow regime map based on the transition criteria used by Orkiszewski (1967) as applied to geothermal wells.

PREVIOUS WORK

Early studies of two-phase flow in geothermal wells are those of Gould (1974) and Nathenson (1974). The Gould (1974) study is based on flow pattern specific correlations; the applications considered were wellbore deposition and deliverability. The Nathenson (1974) study considered no-slip (homogeneous) wellbore flow, coupled to porous media flow in the reservoir. The problems considered by Nathenson (1974) were the same.

Geothermal wellbore flow simulators have been developed by universities, national laboratories, industry, and consultants. However, progress has been slow since the initial Gould (1974) and Nathenson (1974) studies. Upadhyay *et al.* (1977) compared calculated and observed pressure drops in geothermal wells producing steam/water mixtures. They compared flowing pressure profiles to several two-phase flow correlations and concluded that the Orkiszewski (1967) correlations are satisfactory - the Hagedorn and Brown (1965) correlations came second. Fandriana *et al.* (1981) developed the first version of the wellbore simulator used by Ortiz-R. (1983) and us. They compared four correlations and found that the Orkiszewski (1967) method was the best - the Hagedorn and Brown (1965) and Duns and Ros (1963) methods were found to give reasonable results also. Miller (1979) and Mitchell (1982) wrote geothermal wellbore simulators based on the Orkiszewski (1967) correlations. The above authors agreed on the general applicability of the Orkiszewski (1967) correlations to geothermal wellbore flow. Therefore, we think they form the best basis to compare predicted and measured pressure/temperature profiles in geothermal wells.

TWO-PHASE FLOW

The total pressure drop in wellbores consists of three components: frictional, accelerational, and gravitational. In typical two-phase wells the gravitational component dominates; the frictional component contributes only at high flow rates; and the accelerational component is usually insignificant. In *homogeneous* steady-state flow the total pressure drop in a constant cross-section duct is given by

$$-\frac{dp}{dz} = \frac{\tau S}{A} + \frac{d(G_M^2/\rho_M)}{dz} + g\,\rho_M \sin\theta \tag{1}$$

In terms of pressure drop components the equation takes the form

$$\frac{dp}{dz} = \frac{dp_f}{dz} + \frac{dp_a}{dz} + \frac{dp_g}{dz} \tag{2}$$

In *separated* steady-state flow the total pressure drop in a constant cross-section duct is given by

$$-\frac{dp}{dz} = \frac{\tau S}{A} + G_M \frac{d}{dz}\left[\frac{x^2}{\rho_G \alpha} + \frac{(1-x)^2}{\rho_L^*(1-\alpha)}\right] \qquad (3)$$

where α is the void fraction given by

$$\alpha = \frac{A_G}{A} \qquad (4)$$

An examination of Equations 1 and 3 shows that in homogeneous flow the wall shear stress τ is the unknown, while in separated flow both the wall shear stress and void fraction α are unknown. The wall shear stress is used to calculate the frictional component in both homogeneous and separated flow. The void fraction is used to calculate the gravitational component in both models, and the accelerational component in separated flow.

Two kinds of correlations have been developed for frictional pressure drop in two-phase flow; called generalized and specific correlations. The generalized correlations are empirical and make no reference to the flow pattern and physical nature of two-phase flow phenomena. Nevertheless, many engineering calculations are carried out using generalized methods; for example that of Hagedorn and Brown (1965). The specific correlations are specific to the flow pattern (bubbly, slug, churn, annular) and flow situation (vertical, inclined, horizontal).

The Orkiszewski (1967) correlations are the specific kind. They are specific to vertical upward flow in oil and gas wells and can also be used for geothermal wells. In addition to prescribing what correlation to use for pressure drop in different flow regimes, it is necessary to prescribe the criteria for transition between flow regimes. Small discontinuities in pressure drop can occur at transitions between flow patterns.

FLOW PATTERN TRANSITIONS

Our presentation follows that of Orkiszewski (1967), Brill and Beggs (1977), and Upadhyay *et al.* (1977). The flow regime transition criteria are essentially those of Ros (1961), and Duns and Ros (1963). They defined the following limits for the transition between flow regimes:

Bubble Flow $L_{b/s} > v_{SG}/v_{ST}$

Slug Flow $L_{b/s} < v_{SG}/v_{ST}$, $L_{s/t} > N_{GV}$

Transition Flow $L_{s/t} < N_{GV} < L_{t/m}$

Mist Flow $L_{t/m} < N_{GV}$

The definition of these terms are given in the nomenclature. The N's are dimensionless expressions of superficial velocities, the v's are superficial velocities, and the L's are flow regime boundary terms. They are given by the expressions:

$$L_{b/s} = 1.071 - 0.2218\,\frac{v_{ST}^2}{d} \geq 0.13 \qquad (5)$$

$$L_{s/t} = 50 + 36\,N_{LV} \qquad (6)$$

$$L_{t/m} = 75 + 84\,(N_{LV})^{0.75} \qquad (7)$$

$$N_{LV} = 1.938\, v_{SL}\left[\frac{\rho_L}{\sigma}\right]^{0.25} \qquad (8)$$

$$N_{GV} = 1.938\, v_{SG}\left[\frac{\rho_L}{\sigma}\right]^{0.25} \qquad (9)$$

$$v_{SL} = \frac{q_L}{A} \qquad (10)$$

$$v_{SG} = \frac{q_G}{A} \qquad (11)$$

$$v_{ST} = v_{SG} + v_{SL} \qquad (12)$$

Note that the constant 1.938 in Equations 8 and 9 arises when engineering units are used. If we use the following definition of dimensionless pipe diameter number

$$N_D = 120.872\, d\sqrt{\frac{\rho_L}{\sigma}} \qquad (13)$$

the criterion for bubble-to-slug flow can be rewritten as

$$\frac{N_{GV}}{N_{LV}+N_{GV}} < 1.071 - 13.8335\,\frac{\left[N_{LV}+N_{GV}\right]^2}{N_D} \qquad (14)$$

Thus, the transition from bubble to slug flow involves a nonlinear relationship between liquid and gas velocity numbers for a particular value of pipe diameter number. We prepared a flow pattern map using the above flow regime transition criteria. In our companion paper (Ambastha and Gudmundsson, 1986), the pipe diameter number varied in the range of 60 to 100. Therefore, the boundary between bubble and slug flow regime was evaluated for a representative pipe diameter number of 80. Figure 1 presents the flow pattern map on log-log coordinates. Figure 2 provides the same information on cartesian coordinates. Chierici *et al.* (1974) also present this flow pattern map on log-log coordinates. They note that the boundary between bubble and slug flow regimes results in a family of curves, corresponding to different sets of ρ_L, σ and d. We observe that the three parameters can be combined into a dimensionless pipe diameter number and that the boundary between bubble and slug flow regimes can be represented by Equation 14.

In a companion paper (Ambastha and Gudmundsson, 1986), we present flowing data for 10 two-phase geothermal wells. The flowrate ranges from 12.9 kg/s to 68.6 kg/s; the enthalpy from 965 kJ/kg to 1966 kJ/kg; wellhead pressure from 245 kPa to 6027 kPa; well depth from 913 m to 2600 m; wellbore diameter from about 7-5/8" to 9-5/8". We used our Orkiszewski-based geothermal wellbore simulator to calculate the flowing pressure and temperature profiles in the 10 wells. The two-phase flow patterns encountered in these calculations are shown in Figure 3. The

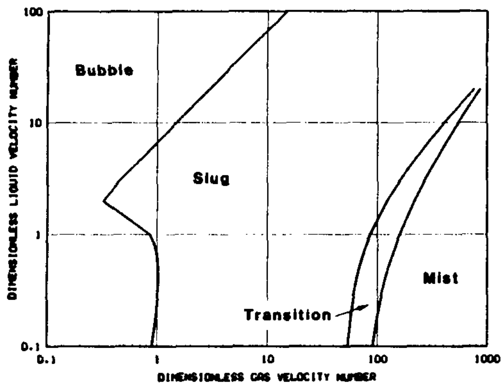

Figure 1. Orkiszewski flow pattern map (log-log coordinates).

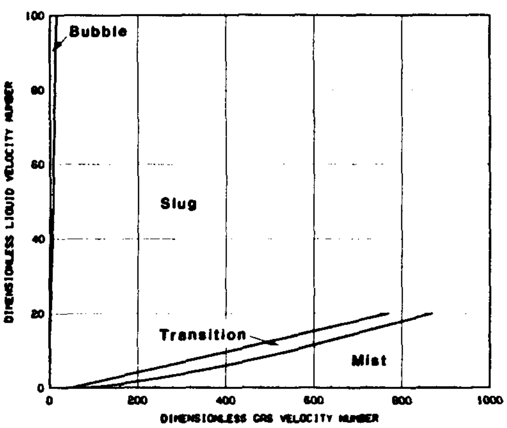

Figure 2. Orkiszewski flow pattern map (cartesian coordinates).

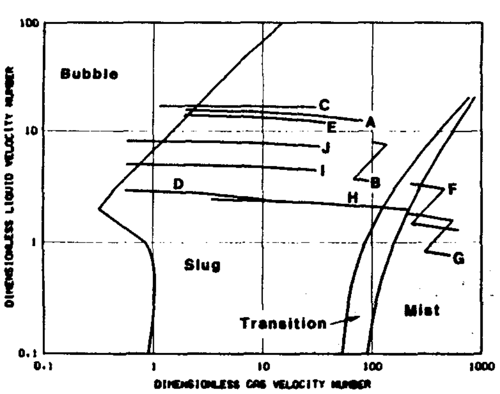

Figure 3. Flow regimes for geothermal wells.

figure gives the dimensionless superficial velocity of liquid water against steam vapor, so the flow lines for individual wells go from left to right. Low enthalpy wells tend to be in the upper left hand part of Figure 3, and high enthalpy wells in the lower right hand part. The steps in the lines result from wellbore diameter changes; increased flow area reduces the superficial velocity of both phases. Figure 3 shows that slug flow is the dominant flow regime in the 10 wells.

PRESSURE DROP CORRELATIONS

The Orkiszewski (1967) correlations for pressure drop calculations are based on several works: Griffith and Wallis (1961) for bubble flow regime, and Duns and Ros (1963) for transition and mist flow regimes. Orkiszewski (1967) developed a new correlation for slug flow based upon the experimental data of Hagedorn and Brown (1965). The pressure drop correlations for different flow regimes are presented below.

Bubble Flow (Griffith and Wallis, 1961)

Liquid holdup in this flow regime is given by the equation

$$H_L = 1 - 0.5 \left[1 + \frac{v_{ST}}{v_B} - \sqrt{(1+v_{ST}/v_B)^2 - 4v_{SG}/v_B} \right] \qquad (15)$$

The bubble velocity, v_B (also called the slip velocity) is assumed to have a constant value of 0.8 ft/sec. Once the liquid holdup is obtained, the mixture density can be determined from

$$\rho_M = \rho_L H_L + \rho_G (1 - H_L) \qquad (16)$$

The holdup is related to void fraction by

$$H_L = 1 - \alpha \qquad (17)$$

The pressure drop due to friction is given by

$$\frac{dp_f}{dz} = \frac{f\rho_L \left[\frac{v_{SL}}{H_L}\right]^2}{2g_c d} \qquad (18)$$

The friction factor f is obtained from the Moody diagram. The Reynolds number for this purpose is given by

$$N_{Re} = \frac{1488\ \rho_L\ v_{SL}\ d}{H_L\ \mu_L} \qquad (19)$$

Note that the constant 1488 in Equations 19, 22 and 23, arises when engineering units are used. In this flow regime, pressure drop due to acceleration is considered negligible.

Slug Flow (Orkiszewski, 1967)

The mixture density in this flow regime is calculated by

$$\rho_M = \frac{\rho_L(v_{SL} + v_B) + \rho_G\ v_{SG}}{v_{ST} + v_B} + \rho_L\delta \qquad (20)$$

where v_B is bubble rise velocity and is given by

$$v_B = C_1 C_2 \sqrt{gd} \quad (21)$$

C_1 is a function of N_{ReB} and C_2 is a function of both N_{ReB} and N_{ReL}, defined as

$$N_{ReB} = \frac{1488\ \rho_L\ v_B\ d}{\mu_L} \quad (22)$$

$$N_{ReL} = \frac{1488\ \rho_L\ v_{ST}\ d}{\mu_L} \quad (23)$$

The Griffith and Wallis (1961) coefficients, C_1 and C_2, were presented by Orkiszewski (1967) in the form of figures. Because of the interrelationship of v_B and N_{ReB}, the calculation of v_B requires an iterative procedure. v_B can also be calculated using Equations 24 through 27.

When $N_{ReB} \leq 3000$,

$$v_B = (0.546 + 8.74 \times 10^{-6} N_{ReL})\sqrt{gd} \quad (24)$$

When $N_{ReB} \geq 8000$,

$$v_B = (0.35 + 8.74 \times 10^{-6} N_{ReL})\sqrt{gd} \quad (25)$$

When $3000 < N_{ReB} < 8000$,

$$v_B = 0.5 \left[\psi + \sqrt{\psi^2 + \frac{13.59\mu_L}{\rho_L \sqrt{d}}}\right] \quad (26)$$

$$\psi = (0.251 + 8.74 \times 10^{-6} N_{ReL})\sqrt{gd} \quad (27)$$

where ψ is an arbitrarily defined parameter.

The Orkiszewski (1967) liquid distribution coefficient δ, which is an empirical coefficient relating theory to reality, is given by the expressions:

For $v_{ST}<10$,

$$\delta = (0.013 \log \mu_L)/d^{1.38} - 0.681 + 0.232 \log v_{ST} - 0.428 \log d \quad (28)$$

with the limit $\delta \geq - 0.065\ v_{ST}$

For $v_{ST}>10$,

$$\delta = (0.045 \log \mu_L)/d^{0.799} - 0.709 + 0.162 \log v_{ST} - 0.888 \log d \quad (29)$$

with the limit

$$\delta \geq - \frac{v_B}{v_{ST} + v_B}\left[1 - \frac{\rho_M}{\rho_L}\right]$$

Pressure drop due to friction is given by

$$\frac{dp_f}{dz} = \frac{f \rho_L v_{ST}^2}{2g_c d}\left[\left[\frac{v_{SL} + v_B}{v_{ST} + v_B}\right] + \delta\right] \quad (30)$$

The friction factor f is obtained from the Moody diagram using the Reynolds number given by Equation 23. The pressure drop due to acceleration in the slug flow regime is neglected.

Transition Flow (Duns and Ros, 1963)

In the transition flow regime, the total pressure gradient is obtained by linear interpolation between the slug and mist flow boundaries. The pressure gradient in the transition flow regime is then

$$\frac{dp}{dz} = M \left[\frac{dp}{dz}\right]_{slug} + (1-M)\left[\frac{dp}{dz}\right]_{mist} \quad (31)$$

where

$$M = \frac{L_{t/m} - N_{GV}}{L_{t/m} - L_{s/t}} \quad (32)$$

Mist Flow (Duns and Ros, 1963)

The gas phase is continuous in this flow regime. The slip velocity is assumed to be zero; that is, homogeneous flow. The mixture density is given by

$$\rho_M = \rho_L\ v_{SL}/v_{ST} + \rho_G\ v_{SG}/v_{ST} \quad (33)$$

The frictional pressure drop is calculated as:

$$\frac{dp_f}{dz} = \frac{f \rho_G\ v_{SG}^2}{2g_c d} \quad (34)$$

The friction factor f is obtained from the Moody diagram and the Reynolds number defined by

$$N_{Re} = \frac{1488\ \rho_G\ v_{SG}\ d}{\mu_G} \quad (35)$$

A modified relative roughness factor (e/d) is calculated to be used with the Moody diagram. This is done to take into account the effect of the liquid film on the pipe.

Pressure drop due to acceleration is given by

$$\frac{dp_a}{dz} = \frac{v_{ST}\ v_{SG}\ \rho_M}{g_c P}\left[\frac{dp}{dz}\right] \quad (36)$$

WELLBORE SIMULATOR

The wellbore simulator used in our work is that of Fandriana *et al.* (1981) and Ortiz-R. (1983). It is based on the Orkiszewski (1967) recommended flow regimes and pressure drop correlations. The computer code is written such that we can start the calculations from the wellhead or wellbottom. We divide the wellbore into segments and calculate the pressure drop due to friction, gravity, and acceleration. To calculate the frictional pressure drop, the casing roughness needs to be specified. The heat transfer to/from the wellbore can also be calculated. We specify the geothermal gradient and the overall heat transfer coefficient, which are then used to calculate the heat loss/gain between each wellbore segment and surrounding formation. Thermodynamic properties used in the computer code are from steam tables. However, when calculating the density of liquid water, its salinity is included. The effect of non-condensible gases is not included in our simulator.

SUMMARY

Most of the geothermal wells tested in our companion paper (Ambastha and Gudmundsson, 1986), flowed in the slug flow regime, as shown in Figure 3. As reported in the companion paper (Ambastha and Gudmundsson, 1986), we obtained not-so-good matches for some of the wells, and those wells also fall in the slug flow regime. Therefore, further research for geothermal two-phase flow applications should be directed towards the slug flow regime.

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NOMENCLATURE

A	Pipe inside area, sq. ft.
A_G	Pipe area occupied by gas, sq. ft.
C_1–C_2	Parameters to calculate bubble rise velocity
d	Pipe inside diameter, ft
e	Absolute pipe roughness, ft
f	Moody friction factor
G_M	Total mass flux, lbm/sec- ft^2
g	Acceleration due to gravity, 32.2 ft/ sec^2
g_c	Conversion constant, 32.2 lbm-ft/lbf- sec^2
H_L	Liquid holdup, fraction
$L_{b/s}$	Bubble-slug boundary term
$L_{s/t}$	Slug-transition boundary term
$L_{t/m}$	Transition-mist boundary term
M	Parameter defined by Eq. 32
N_D	Pipe diameter number
N_{GV}	Gas velocity number
N_{LV}	Liquid velocity number
N_{Re}	Reynolds number
N_{ReB}	Bubble Reynolds number
N_{ReL}	Liquid Reynolds number
P	Pressure, psf
dp_a/dz	Acceleration pressure gradient, psf/ft
dp_f/dz	Frictional pressure gradient, psf/ft
dp_g/dz	Gravitational pressure gradient, psf/ft
S	Wetted Perimeter, ft
v_B	Bubble rise velocity, ft/sec
v_{ST}	Total superficial velocity, ft/sec
v_{SG}	Superficial gas velocity, ft/sec
v_{SL}	Superficial liquid velocity, ft/sec
z	Vertical length, ft

Greek symbols

α	Void fraction
δ	Liquid distribution coefficient
μ_G	Gas viscosity
μ_L	Liquid viscosity
μ_M	Mixture viscosity
ψ	Parameter defined by Eq. 27
ρ_G	Gas density, lbm/ ft^3
ρ_L	Liquid density, lbm/ ft^3
ρ_M	Mixture density, lbm/ ft^3
σ	Interfacial tension, dynes/cm
τ	Wall shear stress, dynes/ cm^2
θ	Inclination angle, radian

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