

Implementing Mechanistic Pressure Drop Correlations in Geothermal Wellbore Simulators

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ABSTRACT

In the last decade pressure drop correlations for two-phase flow in wells have moved away from empirical correlations to being increasingly based on the description of physical characteristics of the flow. Two of these correlations, Ansari and Drift Flux were evaluated in our in-house wellbore simulator Geoflow for use in calculating deliverability curves, pressure gradient and fluid velocity in geothermal wellbore calculations.

It was observed that the Ansari correlation gave discontinuities in pressure profiles as well as in deliverability curves. The Drift Flux model offers a simpler and more robust alternative that compares favorably to data from geothermal wells.

1. INTRODUCTION

Several decades ago, pressure gradient calculation in two phase wellbores were done by means of empirical correlations. Initially no-slip or homogeneous models were applied where the two phases were treated as a single equivalent phase. Those models later evolved into flow correlations such as Duns and Ros that treat each phase separately and deal with different flow regimes. In the last decade a more physically consistent approach was used to derive expressions for different flow regimes. They are called mechanistic models and examples of those are Hasan and Kabir as well as Ansari. The problem with this type of correlations is that they are computationally expensive and not robust enough to be used as the main option for wellbore modeling purposes. Lately a new semi-homogeneous model, known as Drift Flux was presented by Hasan and Kabir (2007b).

The Ansari mechanistic flow correlation has five different flow patterns: bubbly, dispersed bubbly, slug, churn and annular. A physical model for the flow behavior was developed for each flow pattern except for churn that is considered a transition flow regime between slug and annular. The objectives of the physical models for flow behavior are the calculation of the holdup ratio (1 minus the gas volume fraction) that determines the gravity component of the total pressure gradient and the friction loss component of the total pressure gradient. The calculations in the Ansari mechanistic model are more complex than in other models. There are several equations that must be solved iteratively in slug, churn and annular flow regimes. We found most difficulties in the Ansari model for annular flow. This is an important issue for geothermal wells as annular is the dominant flow regime. In bubbly, dispersed bubbly, slug and churn flow regimes, the calculation results show good agreement with measured data. Acuna and Arcedera (2005) showed that these flow regimes are not common in a flowing geothermal well because the transition from liquid to annular flow takes place in just a few hundred feet due to the continuous boiling of the liquid

phase at ever decreasing pressure as it flows up the wellbore.

2. ANSARI PRESSURE GRADIENT CALCULATION IN ANNULAR FLOW

Annular flow receives its name from the gas phase flowing in the center of the pipe carrying with it a small fraction of the liquid phase as entrained droplets, this part is called the core. The liquid phase flows in the wall of the pipe forming a liquid annulus, this part is called the film.

According to Ansari (1994), the total pressure gradient during annular flow in the core can be written as

$$-\left[\frac{dp}{dz}\right]_c = g\rho_c \sin \theta + \frac{f_c v_c^2 \rho_c}{2d(1-2\bar{\delta})} \quad (1)$$

where p is pressure, z is elevation, g is the gravity constant, ρ is density, θ is the well angle with respect to horizontal, f is the Moody friction factor, v is velocity, d is inside pipe diameter and $\bar{\delta}$ is the thickness of the liquid film divided by the pipe diameter. The subscript c refers to core. Meanwhile, the total pressure gradient in the fluid film in annular flow can be written as

$$-\left[\frac{dp}{dz}\right]_L = g\rho_L \sin \theta + \frac{f_{LF} v_{SL}^2 (1-E)^2 \rho_L}{128 d \bar{\delta}^3 (1-\bar{\delta})^3} - \frac{f_c v_c^2 (1-2\bar{\delta}) \rho_c}{8 d \bar{\delta} (1-\bar{\delta})} \quad (2)$$

Here E is the volume fraction of liquid entrained in the gas core as droplets and the subscript L refers to film. Ansari neglects kinetic head loss. The total pressure gradient in the core must be the same as the total pressure gradient in the film, so equations (1) and (2) may be combined as

$$g\rho_c \sin \theta + \frac{f_c v_c^2 \rho_c}{2d(1-2\bar{\delta})} = g\rho_L \sin \theta + \frac{f_{LF} v_{SL}^2 (1-E)^2 \rho_L}{128 d \bar{\delta}^3 (1-\bar{\delta})^3} - \frac{f_c v_c^2 (1-2\bar{\delta}) \rho_c}{8 d \bar{\delta} (1-\bar{\delta})} \quad (3)$$

Rearranging equation (3) gives

$$\frac{f_c v_c^2 \rho_c}{8 d \bar{\delta} (1-\bar{\delta}) (1-2\bar{\delta})} = g \sin \theta (\rho_L - \rho_c) + \frac{f_{LF} v_{SL}^2 (1-E)^2 \rho_L}{128 d \bar{\delta}^3 (1-\bar{\delta})^3} \quad (4)$$

Equation (4) is an implicit equation that must be solved iteratively to get $\bar{\delta}$.

Rearranging equation (4) as a function of $\bar{\delta}$, we get

$$F(\bar{\delta}) = \frac{f_c v_c^2 \rho_c}{8 \bar{\delta} (1-\bar{\delta}) (1-2\bar{\delta}) g \sin \theta (\rho_L - \rho_c)} - \frac{f_{LF} v_{SL}^2 (1-E)^2 \rho_L}{128 \bar{\delta}^3 (1-\bar{\delta})^3 g \sin \theta (\rho_L - \rho_c)} - d = 0 \quad (5)$$

The correct value of δ makes $F(\delta)$ equal to zero. After knowing the value of δ , total pressure gradient in the core can be calculated as well as in the film. Unfortunately the correct estimation of δ value requires knowledge of: (1) the liquid entrainment in the core, E , (2) the liquid film friction factor, f_{FL} , (3) the gas-liquid friction factor, f_C , and (4) the core fluid velocity, v_c . Hasan and Kabir (2007a) noted that all these parameters introduced significant uncertainty.

Figure 1 shows four cases of $F(\delta)$ as a function of δ with various pressure values for a well with low enthalpy. The flowing wellbore pressure varies from 14 to 20 bara, with total mass flow of 123 kg/s, constant fluid enthalpy of 1121 kJ/kg and wellbore diameter of 0.384 m. Lower pressure increases the liquid entrainment (E) in the gas core. Larger values of liquid entrainment E result in decreasing δ . The liquid entrainment value (E) is obtained from an empirical correlation derived by Wallis (1969).

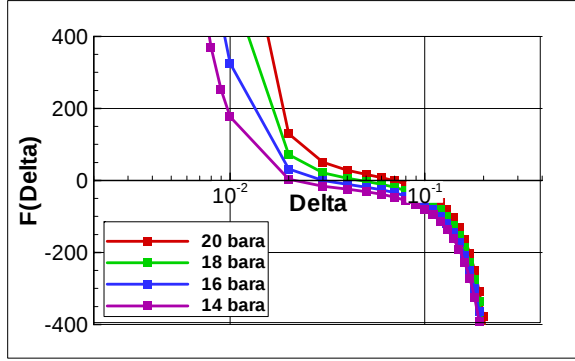


Figure 1: Plots of $F(\delta)$ as a function of δ for different wellbore pressure for a low enthalpy well (1121 kJ/kg).

Figure 2 shows deliverability curves for a well calculated using the Mechanistic Hasan-Kabir, Duns and Ros and Ansari models. Tables 1 and 2 show the well geometry and reservoir conditions used in the calculation of the curves shown in Figure 2. The Ansari model shows a peculiar shape with discontinuities that are not present in the other models. Hasan Kabir (2007a) presented the Ansari model equation in annular flow as

$$\frac{f_C v_C^2 \rho_C}{2d \delta (1 - \delta)(1 - 2\delta)} = g \sin \theta (\rho_L - \rho_C) + \frac{f_{LF} v_{SL}^2 (1 - E)^2 \rho_L}{128 d \delta^3 (1 - 2\delta)^3} \quad (6)$$

Equation (6) derived by Hasan and Kabir looks like equation (4) but the coefficients on the left side and right side of the denominator are different. Kabir confirmed that there was a problem with this derivation and the Ansari equation as described in equation (4) is the correct one.

Our in-house wellbore simulator Geoflow was used to reproduce a flowing pressure, temperature and spinner (PTS) survey. The Ansari model shows a significant deviation in spinner velocity above 500 m, where the regime is annular as shown in Figure 3. This again could be caused by uncertainty in the calculation of δ . Hasan and Kabir (2007a) also describe higher uncertainty when the fluid velocity is high near the wellhead.

Another complexity of Ansari equation is that with increasing well enthalpy and decreasing wellhead pressure there are several possible values of δ that are real and positive.

Table 1 : Well geometry for simulated results.

Cellar Elevation (m)		1088.7		
Measured Depth (m)	Elevation (m)	Casing Type	Casing ID (m)	Absolute Rugosity (m)
393.2	695.5	Blank Casing	0.384	4.597E-05
1224.4	-118.1	Blank Casing	0.315	4.597E-05
1423.4	-303.9	Perforated Liner	0.255	0
1652.0	-517.3	Perforated Liner	0.206	0
2240.3	-1070.1	Perforated Liner	0.164	0

Table 2 : Reservoir characteristic for simulated results.

Measured Depth (m)	Reservoir Characteristic		Flow Rate (kg/s)	Productivity Index (kg/s.bar)
	Pressure (bara)	Enthalpy (kJ/kg)		
1264.9	47.3	2765.5	2.5	0.0174
1639.8	71.1	1122.5	24.0	1.1820
1697.7	75.4	1122.5	83.2	6.1862
2203.7	113.7	1115.5	12.9	1.4424

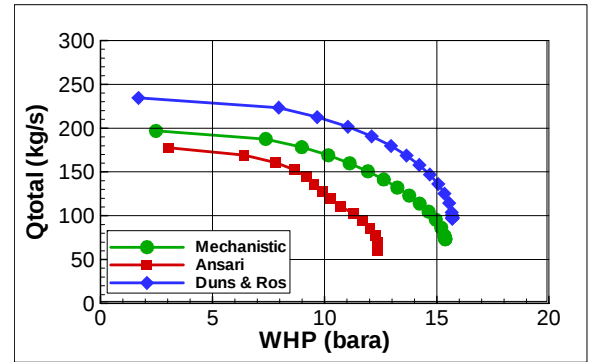


Figure 2: Deliverability curve calculated for different flow correlations.

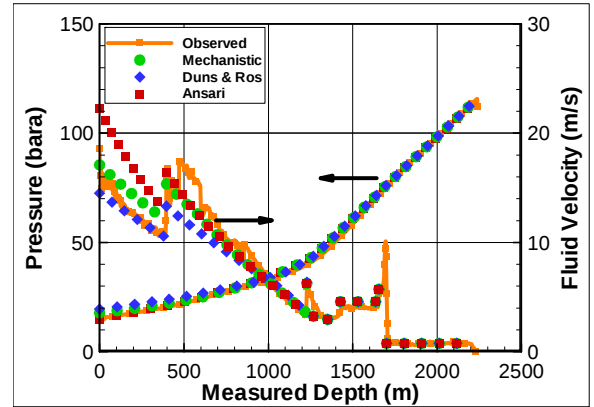


Figure 3: Pressure gradient and fluid velocity match obtained with Geoflow with different flow correlations.

Figure 4 shows four cases of $F(\delta)$ as a function of δ with various pressure values for a high enthalpy well. Since there is more than one value of δ , it is not clear which is the correct one. Different attempts of consistently selecting a given value such as the smallest one also resulted in discontinuities. Further study is needed to determine how the selection should be made.

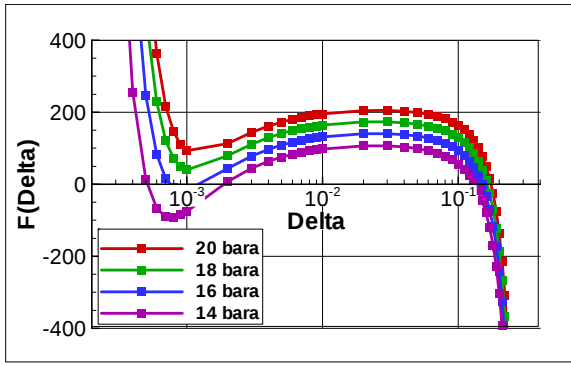


Figure 4: Plots of $F(\delta)$ as a function of δ with variation of wellbore pressure for higher enthalpy well (2600 kJ/kg).

3. DRIFT FLUX MODEL

As an alternative to the Ansari model, the Drift Flux model (Hasan and Kabir 2007b) offers a simplified yet robust two phase flow model alternative.

In the Drift Flux model, the gas volume fraction is determined using a single equation but with flow-pattern dependent parameters. With knowledge about gas volume fraction, density of fluid mixture (ρ_m) can be calculated and then a simple homogeneous flow approach used to calculate the total pressure gradient in each segment of wellbore.

The Drift flux model avoids the discontinuity in the estimated gradients by gradually changing the parameter values near transition boundaries. The transition from one flow regime to another is smoothed by a weighting scheme. The algorithm hierarchy of flow regime transitions criteria in drift flux model consist of checking for flow regimes in the following order: liquid, gas, annular, dispersed bubbly, bubbly, slug and churn.

Figure 5 shows the deliverability curve of well calculated with the Drift Flux model. The discontinuities were eliminated and the result compares well with other flow correlations currently implemented in our in-house wellbore simulator.

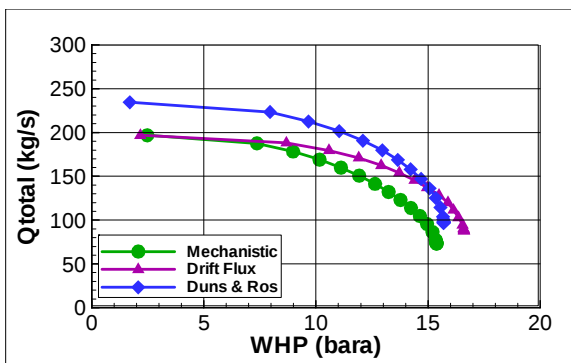


Figure 5: Deliverability curve calculated with Geoflow with different flow correlations including Drift Flux.

Figure 6 shows the pressure gradient and fluid velocity profile for the same well of Figure 3. Comparisons with Figure 6 reveal how the drift flux correlation produces a better profile than Ansari.

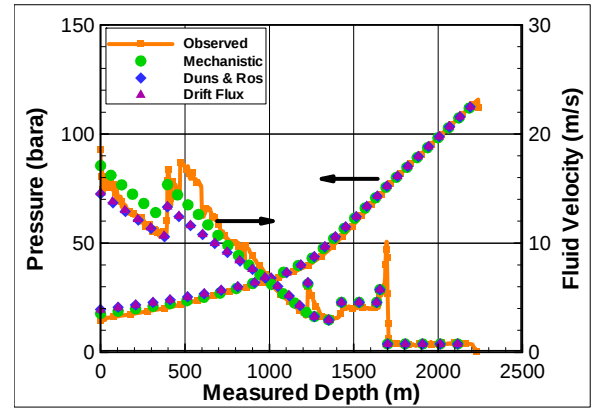


Figure 6: Pressure gradient and fluid velocity match obtained with Geoflow with different flow correlations.

The Ansari model and Drift Flux model have been compared in several more two phase flow wells in Salak Geothermal Field and the results show that the Drift Flux model performs better than Ansari model.

CONCLUSIONS

An evaluation of the Ansari fluid flow correlation as described in two references: Ansari (1994) and Hasan Kabir (2007a) has been performed for geothermal wells. Calculations of deliverability curves, pressure gradient and fluid velocity were compared. It was found that the Ansari correlation produces discontinuities in velocity profiles as well as in deliverability curves. We believe that those are due to uncertainty in the calculation of the film thickness parameter, δ .

The Drift Flux correlation as described also by Hasan Kabir (2007b) was also explored for use in deliverability curves, pressure gradient and fluid velocity calculations in geothermal wells. This model offers a simpler and more robust alternative that compares favorably to data as well as to other correlations currently implemented in our wellbore simulator.

NOMENCLATURE

- d = inside pipe diameter, m.
- E = entrainment factor, volume fraction of total liquid entrained in core fluid, dimensionless
- f_c = Moody friction factor at the interface of core fluid and liquid film in annular flow, dimensionless
- f_g = in-situ gas volume fraction, dimensionless
- f_{LF} = Moody friction factor for the liquid film in annular flow, dimensionless
- g = gravitational acceleration, m/s^2
- v_c = in-situ velocity of core fluid, m/s
- v_{sL} = superficial velocity of liquid, m/s
- v_{sg} = superficial velocity of gas, m/s
- δ = ratio of film thickness to pipe diameter ($=\delta/d$), dimensionless
- ρ_g = gas density, kg/m^3
- ρ_L = liquid density, kg/m^3
- ρ_c = core fluid density, kg/m^3
- θ = well angle with respect to horizontal, degrees
- $F(\delta)$ = iteration equation as function of δ

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REFERENCES

- Acuna, J.A. and Arcedera, B.: Two Phase Flow Behavior and Spinner Data Analysis in Geothermal Wells. *Proceedings*, 30th Stanford Geothermal Reservoir Engineering Workshop, (2005).
- Ansari, A.M., Sylvester, N.D., Sarica, C., Shoham, O., and Brill, J.P.: A Comprehensive Mechanistic Model for Upward Two-Phase Flow in Wellbores. *SPEPF* 9 (2), 143–151 (1994).
- Hasan, A.R. and Kabir, C.S.: A Simple Model for Annular Two-Phase Flow in Wellbores, *SPEPO* 22 (2), 168–175 (2007a).
- Hasan, A.R., Kabir, C.S., Sayarpour, M.: A Basic Approach to Wellbore Two-Phase Flow Modeling, *SPE Paper* 109868, (2007b).
- Hasan, A.R. and Kabir, C.S.: Fluid Flow and Heat Transfer in Wellbores. *SPE book*, (2002).
- Jefferson, Lorri., Kung, Florence., L. Corcoran III, Arthur: TUFFP Core Software Users Manual, Tulsa University, Tulsa (1989).
- Wallis, G.B.: One-Dimensional-Two-Phase Flow, McGraw Hill Book Co. Inc., New York City (1969).