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Void Fraction Correlations on Geothermal Two-Phase Flows

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ABSTRACT

Using actual data from geothermal two-phase line tracer flow test measurements, slip ratios and void fractions were correlated to the steam qualities and discharge enthalpies of the wells using different void fraction and drift flux correlations.

The evaluation showed correlation between total discharge enthalpy and flow quality to the calculated void fraction. This correlation can lead to direct measurement of well discharge enthalpies based on void fraction determination (i.e. using gamma ray technique, electrical capacitance tomography, ultrasonic, etc).

1. INTRODUCTION

Two-phase flow is the simultaneous flow of two distinct phases, i.e. liquid water and steam, which is the focus of this study.

Calculations for two-phase flows are more complicated than those of single-phase flows. Different techniques for analyzing two-phase flows include correlations, the phenomenological models, simple analytical model, and other methods such as integral analysis, differential analysis, computational fluid dynamics, and artificial neural network (Awad, 2012).

The general governing equations for two-phase flows require that (a) the fluids may be treated as continua and (b) the physical variables denoting the thermal and dynamic state of the fluid are well-defined. The area of research that takes the approach of solving the full conservation equations is generally referred to as Computational Fluid Dynamics (CFD) (Vij & Dun, 1996).

A comparison of the performance of 68 void fraction correlations based on unbiased data set covering wide range of parameters were done by (Woldesemayat & Ghajar, 2007). They classified the correlations into four categories (a) slip ratio, (b) $K\varepsilon_H$, (c) drift flux, and (d) general void fraction correlations. Slip ratio correlation are expressed as a function of the ratios between wetness fraction (1 - x) and x the ‘‘quality’’ or ‘‘dryness fraction’’, where x is defined as the ratio of gas flow rate to the total flow rate; the ratios of densities of the gas and liquid phase (ρ_G and ρ_L); and the ratios of the viscosities of the liquid and gas phase (μ_L and μ_G). $K\varepsilon_H$ correlations are a constant or some functional multiple of the no-slip or homogeneous void fraction, pressure (P), the Froude number (Fr) based on the two-phase mixture velocity (U_M), liquid input content (λ), or Reynolds number (Re). Drift flux correlations take into consideration the non uniformity in the flow captured by a distribution parameter (C_0), and the drift velocity (U_{GM}), defined as the difference between the gas phase velocity (U_G) and the two-phase mixture velocity (U_M).

In geothermal, the lip-pressure is the standard method of measuring flow of geothermal wells (Grant, James, & Bixley, 1982) (James, Factors Controlling Borehole Performance, 1970) (James, Maximum Steam Flow Through Pipes to the Atmosphere, 1964) (James, Steam-Water Critical Flow through Pipes, 1962).

In 2000, (Zhao, Lee, & Freeston, 2000) derived a correlation from the analysis of two-phase flow velocity distribution using the Seventh Power Law, where the average velocity of the equivalent single-phase flow is used to determine two-phase pressure drop.

In this paper, tracer fluid test (TFT) and/or bore output measurements (BOM) data from multiple wells will be used to analyze the performance or fitness of the different void fraction correlations from prior authors. Different relationships will be shown such as void fraction versus flow quality, discharge enthalpy, slip ratios, and other parameters.

2. METHOD OF ANALYSIS

Taking off from the works of (Woldesemayat & Ghajar, 2007) which recommend correlations with good void fraction prediction for horizontal and upward inclined pipes regardless of flow regimes, this study will analyze the following correlations (a) Toshiba as cited by (Coddington & Macian, 2002), (b) Rouhani I (Rouhani & Axelsson, 1970), (c) Dix as cited by (Coddington & Macian, 2002), (d) Filiminov (Filimonov, Przhizhalovski, Dik, & Petrova, 1957).

Chisholm correlation (Chisholm, 1973) will also be included in the analysis because it is notable that it follows the thermodynamic limits such that when $x \rightarrow 0$, $S \rightarrow 1$, and as $x \rightarrow 1$, $S \rightarrow (\rho_G / \rho_L)^{1/2}$ (Thorne, 2016) .

In addition, a correlation based on the Seventh Power Law derived by (Zhao, Lee, & Freeston, 2000) is also included in the analysis.

Below are basic definitions of the equations as used in the calculations of two-phase flows;

Mass Flow Rate

$$\dot{m} = \dot{m}_L + \dot{m}_G \tag{1}$$

where $\dot{m}$ is the total mass flow rate and the subscripts L and G refer to liquid and steam mass flow rates.

Mass Flux

$$G = \frac{\dot{m}}{A} = \frac{\dot{m}_L}{A} + \frac{\dot{m}_G}{A} = G_L + G_G \tag{2}$$

Volume Flux

$$J = \frac{G}{\rho_m} = \frac{G_L}{\rho_L} + \frac{G_G}{\rho_G} = J_L + J_G \tag{3}$$

where ρ_m is the mixture density.

Two-Phase Mixture Density

$$\rho_m = \alpha\rho_G + (1-\alpha)\rho_L \tag{4}$$

where α is volume fraction of steam in the mixture which can be calculated as

$$\alpha = \frac{x}{x + S(1-x)\dfrac{\rho_G}{\rho_L}} \tag{5}$$

2.1 Data Used in the Analysis

TFT and/or BOM data of multiple wells of varying branchline sizes (10-18” diameter nominal size) from the Energy Development Corporation’s integrated database system were used in the analysis. The measurements were taken from 1997 up to 2018. The following information is available in the database for each TFT data set: (a) total mass flow, (b) water flow, (c) total discharge enthalpy, and (d) wellhead pressure. Using this data set, void fraction, steam flow quality, and other fluid properties were calculated using Engineering Equation Solver (EES) by F-Chart Software.

2.2 Correlation Equations

2.2.1 Zhao et al Correlation (2000)

$$\frac{1-\alpha}{\alpha^{7/8}} = \left[\left(\frac{1}{x} - 1\right)\left(\frac{\rho_G}{\rho_L}\right)\left(\frac{\mu_L}{\mu_G}\right)\right]^{7/8} \tag{6}$$

where α is the void fraction.

2.2.2 Chisholm Correlation (1973)

$$\alpha = \left[1 + \sqrt{1 - x\left(1 - \frac{\rho_L}{\rho_G}\right)}\left(\frac{1-x}{x}\right)\frac{\rho_G}{\rho_L}\right]^{-1} \tag{7}$$

2.2.3 Rouhani and Axelsson Correlation (1970)

$$\alpha = \frac{x}{\rho_G}\left[C_0\left(\frac{x}{\rho_G} + \frac{1-x}{\rho_L}\right) + \frac{U_{GM}}{G}\right]^{-1} \tag{8}$$

where G is mass flux in kg/m^{2}s.

$$U_{GM} = \left(\frac{1.18}{\sqrt{\rho_L}}\right)\left(g\sigma\left(\rho_L - \rho_G\right)\right)^{0.25} \tag{9}$$

$$C_0 = 1 + 0.2\left(1-x\right) \tag{10}$$

2.2.4 Filmonov et al Correlation (1957)

$$\alpha = \frac{U_{SG}}{U_M + U_{GM}} \tag{11}$$

$$U_{GM} = (0.65 - 0.0385P)\left(\frac{D_H}{0.063}\right)^{0.25} \tag{12}$$

for P < 12.7 where DH = hydraulic diameter, P is pressure in MPa.

$$U_{GM} = (0.33 - 0.00133P)\left(\frac{D_H}{0.063}\right)^{0.25} \quad \text{for P > 12.7} \tag{13}$$

2.2.5 Toshiba

$$\alpha = \frac{U_{SG}}{1.08U_M + 0.45} \tag{14}$$

2.2.6 Dix

$$\alpha = U_{SG}\left[U_{SG}\left(1 + \frac{U_{SL}}{U_{SG}}\right)^{\left(\frac{\rho_G}{\rho_L}\right)^{0.1}} + 2.9\left(\frac{g\sigma[\rho_L - \rho_G]}{\rho_L^2}\right)^{0.25}\right]^{-1} \tag{15}$$

where U_{SG} and U_{SL} refers to superficial gas and liquid velocities, respectively.

2. RESULTS AND DISCUSSIONS

2.1 Flow Quality versus Void Fraction

Solving simultaneously equations (1) to (4) using TFT and/or BOM data will give the void/steam fraction of the two-phase flows as shown in Figure 1. Also in the figure is the experimental data from (Ralph Webster Pike, 1962) based on the adiabatic, evaporating, two-phase flow of steam and water in horizontal pipe. Pike used an X-ray tube as a source of monoenergetic gamma radiation to measure void-fraction in two-phase water-steam flow. He concluded that assuming thermodynamic equilibrium is achieved; adiabatic, two-phase flow of steam-water can be described by annular flow equations. It can be seen that Pike's experimental data is consistent with the calculated void/steam fraction based TFT/BOM data.

Correlations by (Zhao, Lee, & Freeston, 2000), (Chisholm, 1973), and (Rouhani & Axelsson, 1970) give very good flow quality – void fraction R-squared values (better than 0.95). Correlations by (Filimonov, Przhizhalovski, Dik, & Petrova, 1957), Toshiba, and Dix show similar trends but with lower coefficient of determination or the data are more scattered. See Figures 2-7.

Overlapped histograms of calculated void fractions from different correlations showed that void fraction of geothermal fluid flows in two-phase lines are consistently almost always greater than 0.60 as can be seen in Figure 8. Note that the calculated void fractions directly from TFT/BOM data are greater than 0.9.

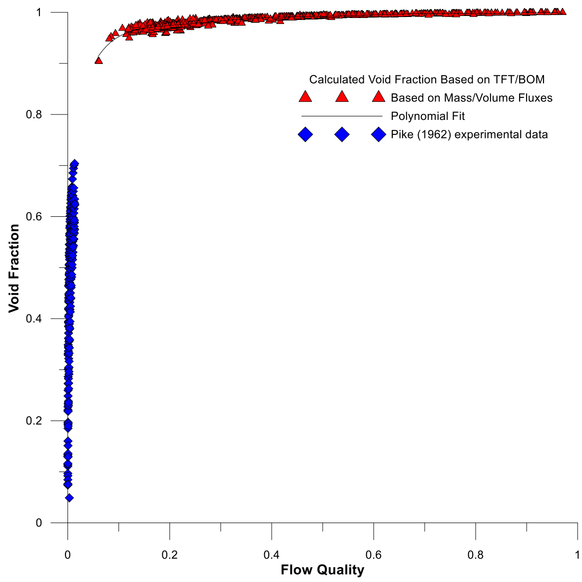

Figure 1. Calculated void fraction based on TFT/BOM data and the experimental data from Pike (1962).

Overlapped histograms of calculated void fractions from different correlations showed that void fraction of geothermal fluid flows in two-phase lines are almost always greater than 0.60 as can be seen in Figure 7. Interestingly, this is consistent with all correlations studied.

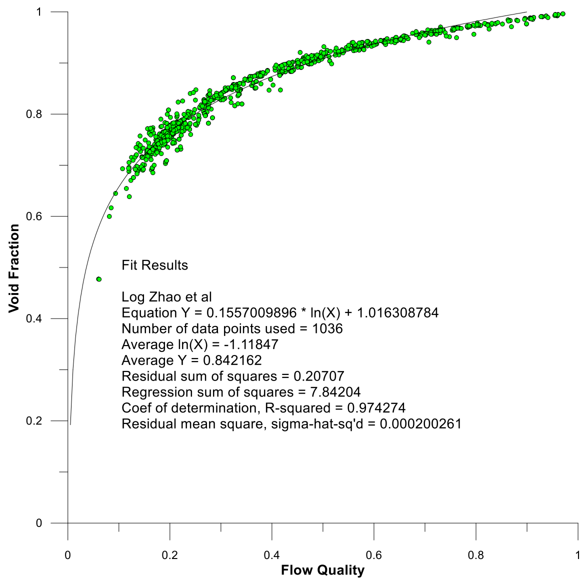

Figure 2. Void fraction versus flow quality using the correlation by Zhao et al (2000).

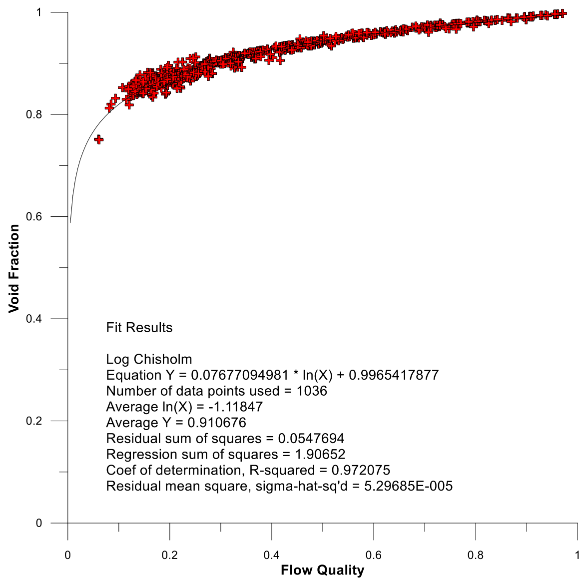

Figure 3. Void fraction vesus flow quality using the correlation by Chisholm (1973).

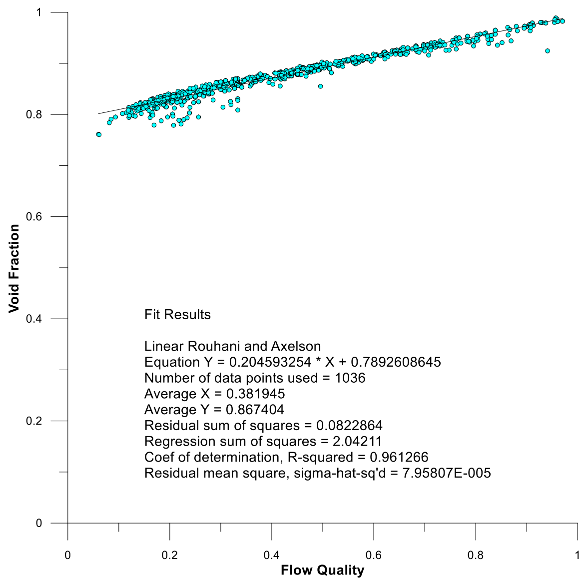

Figure 4. Void fraction vesus flow quality using the correlation by Rouhani and Axelson (1970).

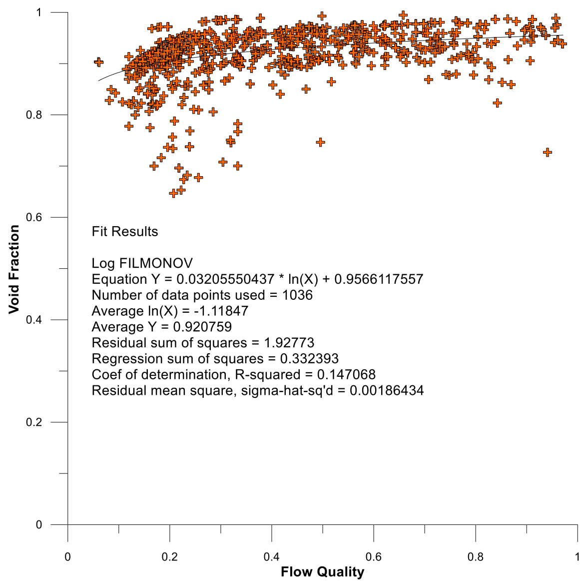

Figure 5. Void fraction vesus flow quality using the correlation by Filmonov et al (1957).

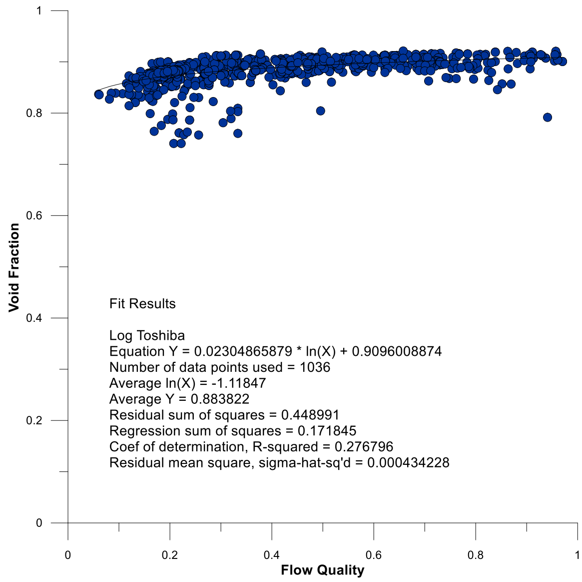

Figure 6. Void fraction vesus flow quality using the correlation by Toshiba.

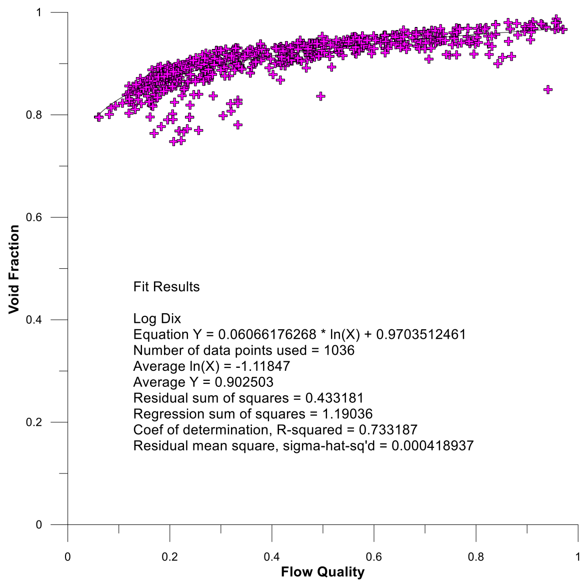

Figure 7. Void fraction vesus flow quality using the correlation by Dix.

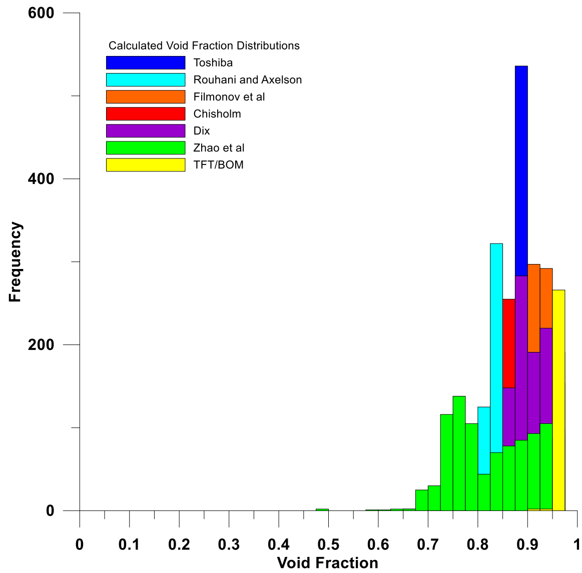

Figure 8. Overlapped histograms of calculated void fractions based on different correlations.

2.2 Void fraction versus Discharge Enthalpy

The plot of total discharge enthalpy versus calculated void fraction based on Equations (1) to (4) and TFT/BOM data showed asymptotic line corresponding to void = 1 which means that the total enthalpy increases exponentially as the void fraction approaches 1.

Plots of total discharge enthalpy versus calculated void fraction showed near very good coefficient of determination using the correlations of Zhao et al, Chisholm, and Rouhani and Axelson. This observation is consistent with that observed with flow quality versus void fraction wherein the correlations of Zhao et al, Chisholm, and Rouhani and Axelson showed very good R^2 values since flow quality and total discharge enthalpy are directly related.

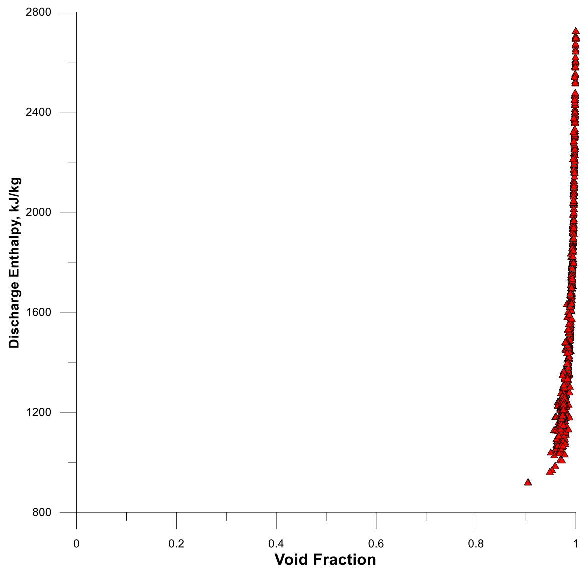

Figure 9. Relationship of total discharge enthalpy versus the calculated void fraction based on TFT/BOM data.

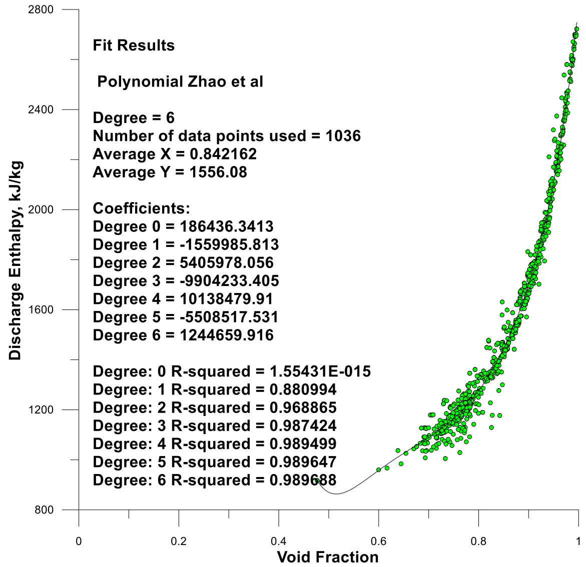

Figure 10. Plot of total discharge enthalpy versus void fraction using Zhao et al correlation.

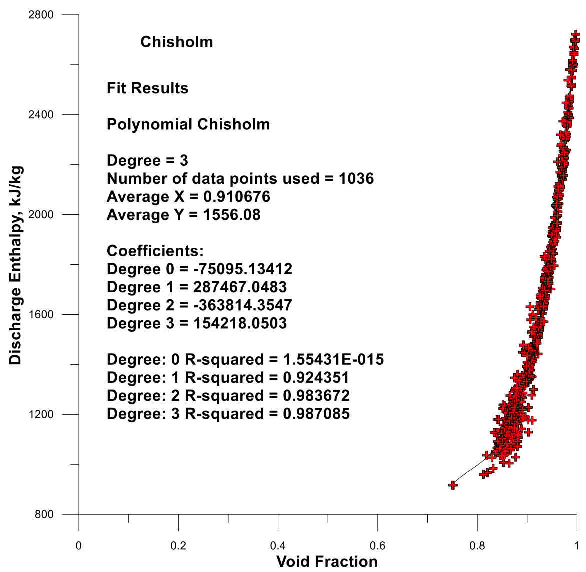

Figure 11. Plot of total discharge enthalpy versus void fraction using Chisholm correlation.

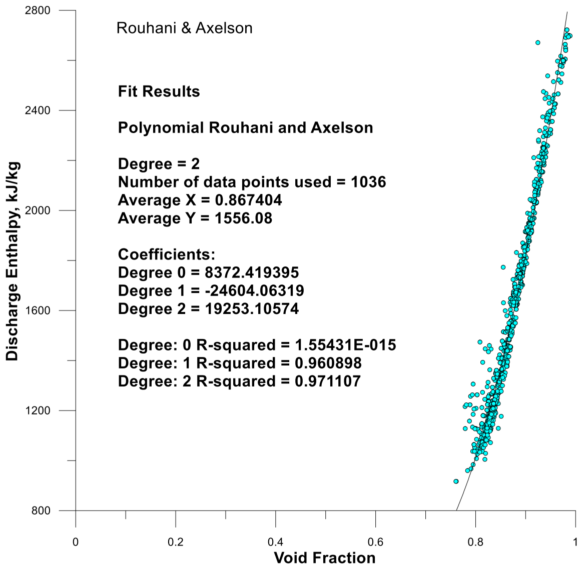

Figure 12. Plot of total discharge enthalpy versus void fraction using Rouhani and Axelson correlation.

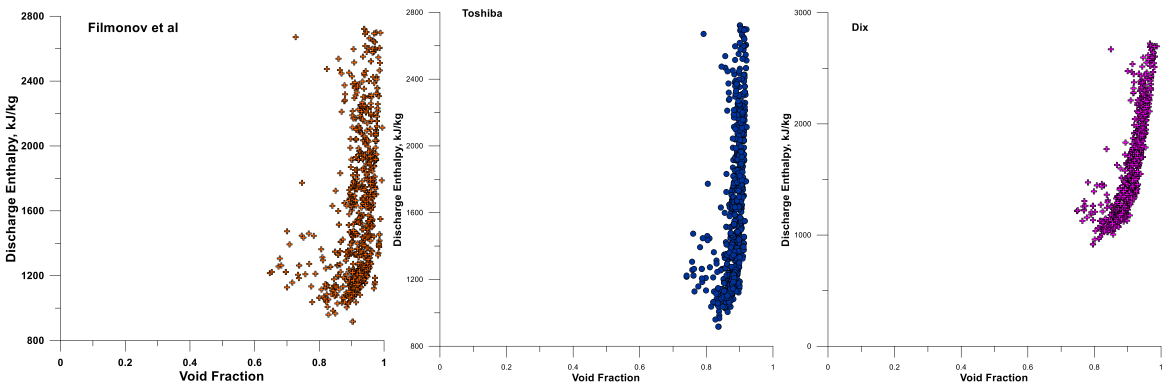

Figure 13. Plot of total discharge enthalpy versus void fraction using Filmonov et al, Toshiba, and Dix correlations.

2.3 Slip Ratio versus Void Fraction

Directly calculating the slip ratio based on the definitions of mass and volumetric fluxes (Equations 1 to 5) and using TFT/BOM data revealed that the slip ratio is equal to 1 which means that the two-phase steam and water flow is homogenous at all steam fractions (quality). All other correlations give higher than 1 slip ratios. Chisholm correlation gives the best coefficient of determination for slip ratio and void fraction. Based on these results, it is possible to directly measure output of the well if we know any two parameters; void fraction, water/steam/mix velocities, mix densities, and/or the flow quality.

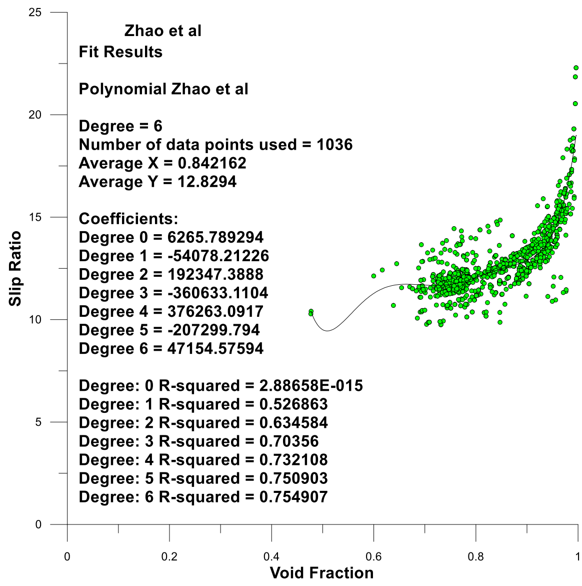

Figure 14. Slip ratio versus void fraction using Zhao et al correlation.

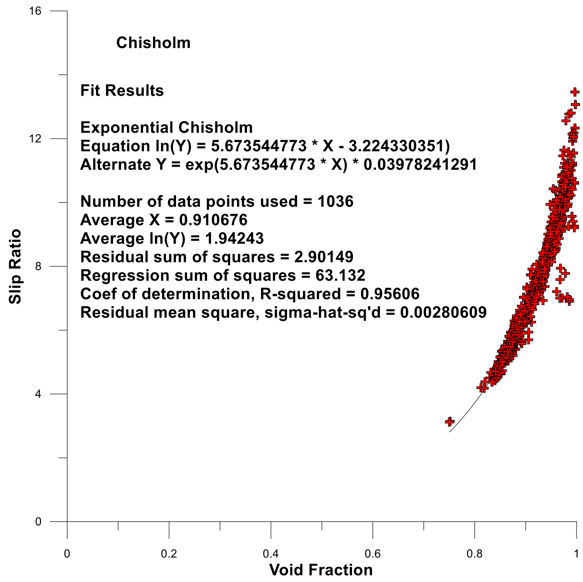

Figure 15. Slip ratio versus void fraction using Chisholm correlation.

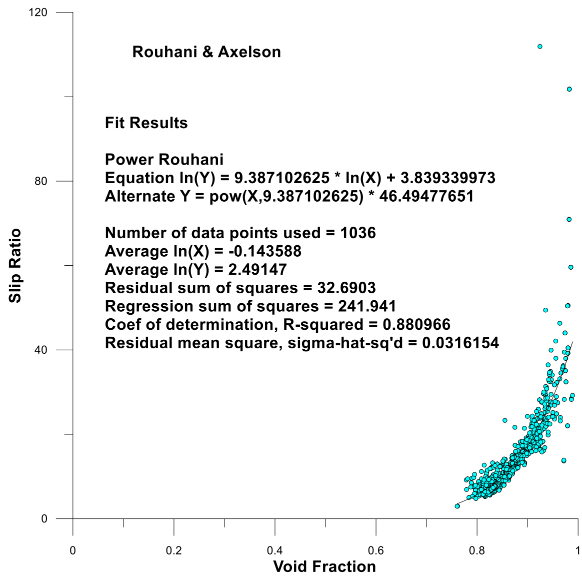

Figure 16. Slip ratio versus void fraction using Rouhani and Axelson correlation.

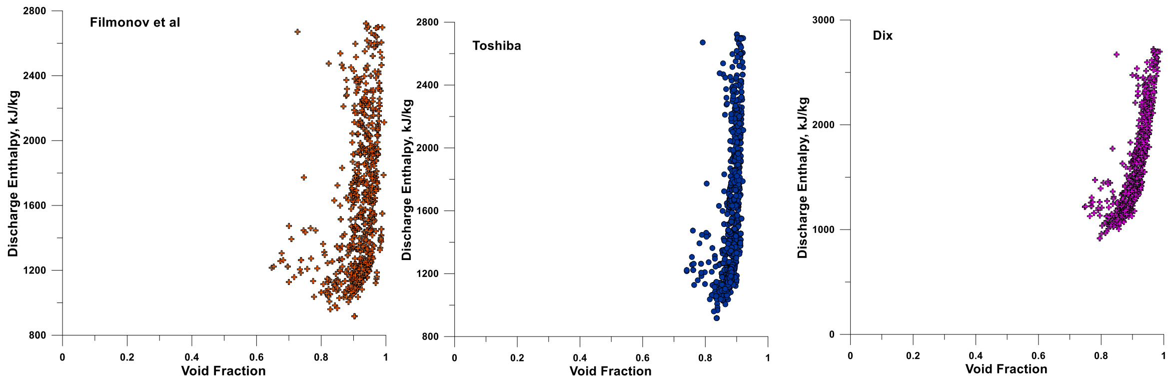

Figure 17. Slip ratio versus void fraction using Filmonov et al, Toshiba, and Dix correlations.

2.4 Comparison with the Homogenous Model

Based on the two-phase mass and volume fluxes definitions, thermodynamic fluid properties, and historical TFT/BOM data collected, the calculated void fraction of two-phase water-steam flow has a very narrow range with high values at between 0.90 to 1 (Figure 18). As previously mentioned, the calculated slip ratio on all data sets is equal to 1 which implies homogenous and fully mixed flow. It is possible that the flow falls within the "mist flow regime".

Examining the histogram of calculated steam velocities based on different correlations showed similar values with average speeds of 19 to 20 m/s (Figure 19). On the other hand, the calculated homogenous mix velocities have slightly lower average at ~18 m/s (Figure 20).

As shown in the distribution of water phase velocities in Figure 21, the average velocity is 1.6 - 2.6 m/s except for Filmonov correlation with an average of ~4.1 m/s. Given the calculated slip ratios, it is most likely that the flow fall in the annular flow regime with thin liquid water layer flowing in the pipe wall.

The compressibility factor, z, of steam at the range of flowing wellhead and pipe operating pressures (0.5-3 MPaa) is greater or equal to 0.97 while liquid water is considered incompressible or $z = 1.0$. Given this information, the volume occupied by the steam is much greater than the brine/water hence high void/steam volume fraction is expected. This is in alignment with the calculated void fraction using the different correlations and homogeneous model.

The homogenous fluid mix density has an average of ~20 kg/m^3 (Figure 22) while the calculated equivalent local mix densities based on different correlations are higher with average values greater than 75 kg/m^3. This can be explained by the fact that the void fractions predicted by different correlations are lower than the homogenous model.

A plot of homogenous mix density versus total discharge enthalpy of all well data showed good correlation as shown in Figure 24. If this relationship can be established for each well with good precision and accuracy, this could pave a way to directly measure two-phase flow using differential pressure measurements and wellhead pressure-discharge enthalpy plot of each well.

In general, the equation to get the total mass passing thru an orifice is given by

$$\dot{m} = \frac{C_d}{\sqrt{1-\beta^4}} \varepsilon \frac{\pi}{4} \sqrt{2\rho_m \Delta p} \tag{16}$$

Where:
C_d= coefficient of discharge, dimensionless, typically between 0.6 and 0.85, depending on the orifice geometry and tappings
β = diameter ratio of orifice diameter d to pipe diameter D, dimensionless
ε = expansibility factor, 1 for incompressible gases and most liquids, and decreasing with pressure ratio across the orifice, dimensionless
d = internal orifice diameter under operating conditions, m
ρ_m = mix fluid density in plane of upstream tapping, kg/m³
Δp = differential pressure measured across the orifice, Pa

Given the orifice flow equation above, the mix fluid density can be determined using an established fluid mix density- total discharge enthalpy plot similar to Figure 24 per well. James use sharp-edged orifices for metering steam-water two-phase flow with some level of success where he estimated the steam dryness at the orifice to equal $x^{1.5}$ (James R. , 1965). The error on the total mass flow calculated from this method can be greater than 10% in the region x = 0.1 to x =0.2.

Alternatively, fluid mix density can be determined accurately using gamma attenuation, electrical capacitance/resistivity methods, ultrasonic, vibration, and other means.

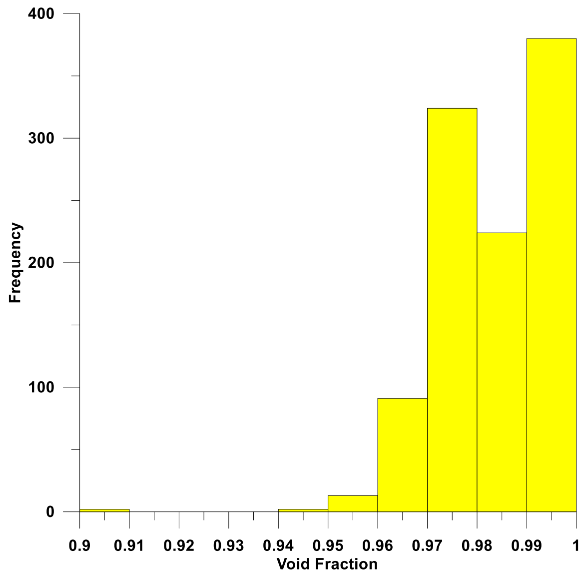

Figure 18. Void fraction distribution of steam-water two phase flows of multiple wells based on TFT/BOM data using homogenous model.

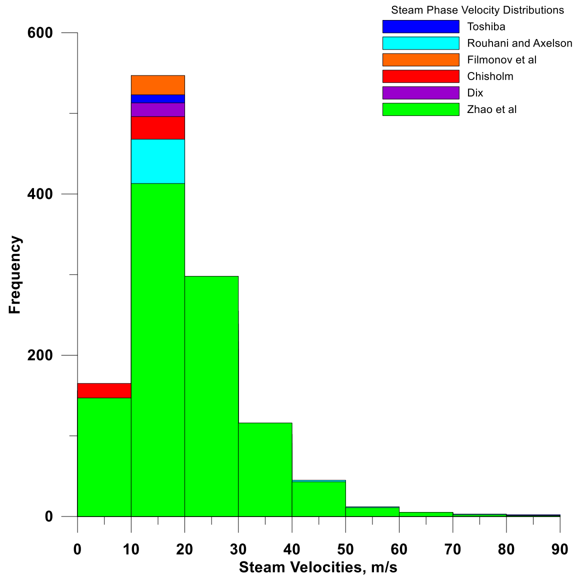

Figure 19. Histograms of the calculated steam velocities using the different slip ratio/void fraction correlations.

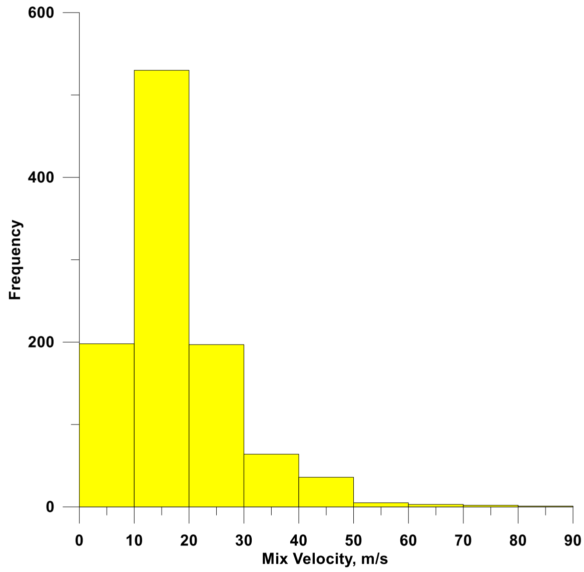

Figure 20. Distribution of the calculated mix velocity of the two-phase flow based on TFT/BOM data.

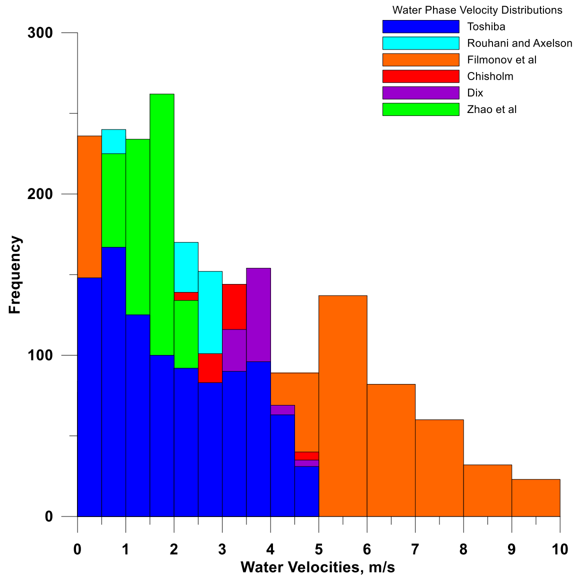

Figure 21. Distributions of calculated water phase velocities using the different correlations.

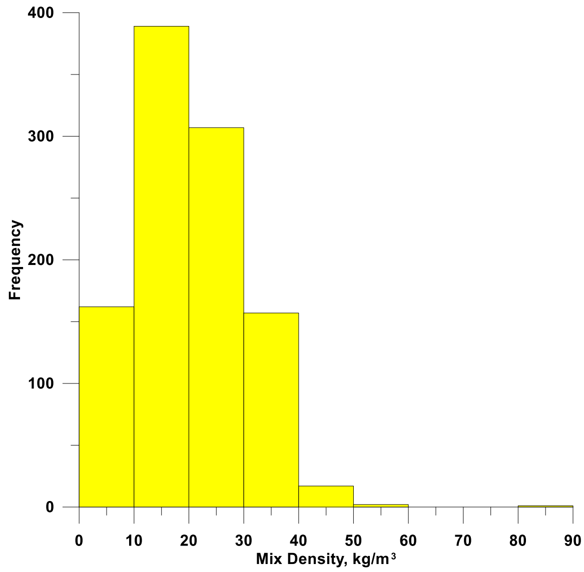

Figure 22. Fluid mix density of two-phase water-steam flow based on TFT/BOM data using homogeneous model.

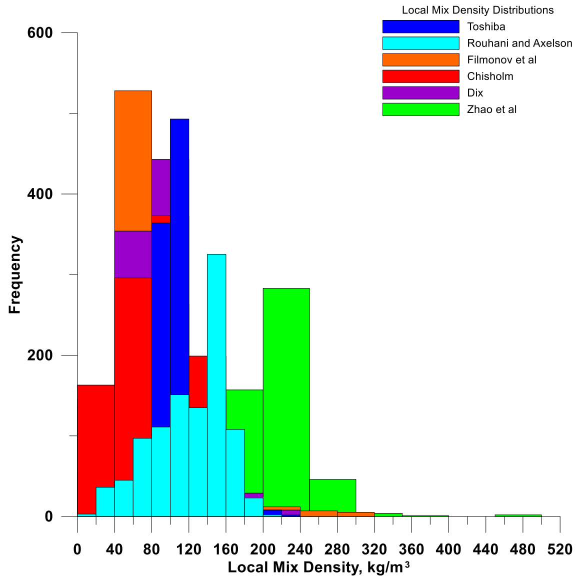

Figure 23. Local mix density distributions based on different correlations.

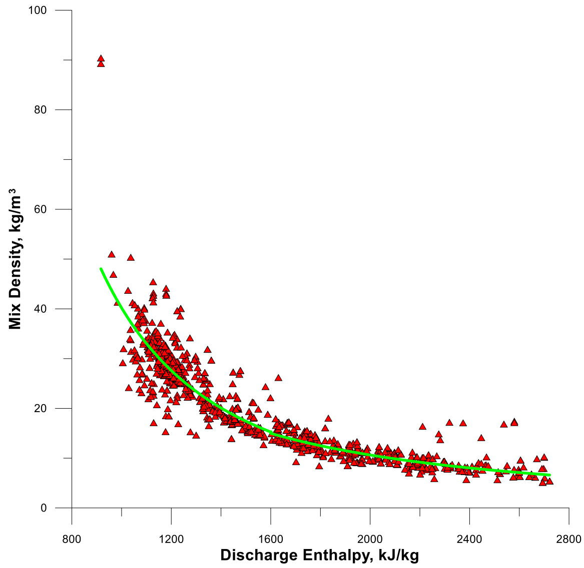

Figure 24. Relationship of Mix density with that of total discharge enthalpy based on TFT/BOM data using the homogeneous model.

3. CONCLUSION, RECOMMENDATION AND FUTURE WORKS

Void fraction values calculated using different correlations and more than a thousand historical TFT/BOM measurements of multiple wells are higher than 0.6. Moreover, calculated void fraction directly from two-phase mass/volume flux definitions, fluid saturation properties, and historical TFT/BOM data showed very high values between 0.9 and 1. The later values implied a homogenous flow model.

The calculated slip ratios based on different correlations range from 2.6 to 12.2 with corresponding steam velocities of 1.4 m/s to 89.6 m/s and average of 19.5 m/s. Similarly, the homogenous model give steam/mix fluid velocities in the range of 1.3 to 82.6 m/s and average of 17.8 m/s. Generally, the flow regime predicted is either annular or fully mixed mist flow.

For fully mixed homogenous two-phase flow, the total mass flow can be measured directly using differential pressure meter (orifice, venture, etc.) assuming mix density is correlated to total discharge enthalpy. In practice, total discharge enthalpy versus wellhead pressure plot/curve is created using BOM data so we can estimate the fluid mix density.

For the separated flow, the two-phase flow equations can be fully solved by determining at least any two of the following parameters: water/steam phase velocities, total mass flow, void fraction, or steam flow quality.

Theoretically, void fraction and/or fluid mix density can be determined using gamma ray attenuation, fluid electrical capacitance/resistivity/inductivity measurements, ultrasonic, and/or vibration frequency. In the future, the use of conditioning orifice plate and gamma attenuation will be used to measure homogenous two-phase flow. In addition, the use of fluid electrical capacitance measurements to measure phase velocities and volume fractions will be deployed to test the separated flow model of the two-phase flow.

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