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PRESSURE PROFILES IN TWO-PHASE GEOTHERMAL WELLS: COMPARISON OF FIELD DATA AND MODEL CALCULATIONS

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Abstract

Increased confidence in the predictive power of two-phase correlations is a vital part of wellbore deliverability and deposition studies for geothermal wells. Previously, the Orkiszewski (1967) set of correlations has been recommended by many investigators to analyze geothermal wellbore performance. In this study, we use measured flowing pressure profile data from ten geothermal wells around the world, covering a wide range of flowrate, fluid enthalpy, wellhead pressure and well depth. We compare measured and calculated pressure profiles using the Orkiszewski (1967) correlations.

Introduction

Two-phase steam/water flow occurs in geothermal reservoirs, wellbores, and surface pipelines. The production of steam/water mixtures depends on how the reservoir, wellbore, and surface facilities operate in series. It means that the overall performance of the system can be dominated by poor performance by any of its components. Improved understanding of the system components, therefore, may lead to better production methods for geothermal resources of the liquid- and boiling-dominated type. In this paper we consider the wellbore part of the system.

A feature common to previous studies of geothermal wellbore flow, is that several two-phase flow correlations are compared to a single or few data sets, and the best-fit correlation identified. A limitation of this approach is that a particular correlation can be matched to a single set of flowing data by adjusting a number of parameters. This leaves open the question of generalizability; that is, the application of the best-fit wellbore model to other geothermal wells. It may also not be clear what wellbore correlations to use for predictive purposes. Furthermore, the several-models and single-data-set approach may hide what aspects of modeling and measurements would benefit from research and development. In this paper we address the issue of generalizability by adopting an approach of a single-model and several-data-sets.

The Orkiszewski (1967) wellbore correlations and simulator used in our work are discussed in a companion paper (Ambastha and Gudmundsson, 1986). A related paper is that of Gudmundsson *et al.* (1984).

Field Data

Flowing pressure and temperature profiles from 10 geothermal wells were collected for the purpose of our study. The wells are in 6 countries: the United States, Mexico, New Zealand, the Philippines, Iceland, and Italy. The discharge data for these wells are shown in Table 1. The total flowrate ranges from 12.9 kg/s to 68.6 kg/s; the mixture enthalpy from 965 kJ/kg to 1966 kJ/kg (corresponding to liquid water at 225°C and up); wellhead pressure from 2.3 bar-g to 56.5 bar-g (245 kPa to 6027 kPa); well depth from 913 m to 2600 m. The wellbore diameter is also given in Table 1, the nominal casing size near the surface ranging from 7-5/8" to 9-5/8". We were not able to compile the chemical data (dissolved solids and non-condensible gas content) for the wells.

Flowing data for wells Cerro Prieto 90, East Mesa 6-1, and Utah State 14-2 are given by Ortiz-R. (1983), who in turn obtained the data from Castaneda (1983), Fandriana *et al.* (1981), and Butz and Plooster (1979), respectively. The different sources of the same data sets are listed here to assist investigators in further studies. The data for well East Mesa 6-1 has been used in several studies; for example, Gould (1974), Nathenson (1974), and Juprasert and Sanyal (1977). The original East Mesa reference is that of Lundberg (1973). A reference for the Roosevelt Hot Springs well Utah State 14-2 data is that of Butz and Mickley (1982). Flowing data for well Cerro Prieto 91 was obtained from Ryley and Parker (1982), who in turn used a paper by Goyal *et al.* (1980). The Ryley and Parker (1982) paper was also the source for the data for Krafla 9 in Iceland. The data for well Okoy 7 in the Philippines were taken from a report by Catigtig (1983). A paper authored by Chierici *et al.* (1981) provided the data for the Italian well Mofete 2. Information on well HGP-A in Hawaii was taken from Kihara *et al.* (1977) and Yuen *et al.* (1978). The New Zealand data on well Ngawha 11 was provided by Bixley (1984); the Mexican data on well Los Azufres 18 was provided by Molinar (1985). More wellbore profile data are found in Upadhyay *et al.* (1977), Barelli *et al.* (1982), Butz and Mickley (1982), and Wilson (1984).

Wellbore Simulation

The pressure and temperature profiles for the 10 wells, respectively, are shown in Figure 1 and Figure 2. However, well Utah State 14-2 had no temperature profile data. Using the data in Table 1, we used the Orkiszewski-based simulator discussed in the companion paper (Ambastha and Gudmundsson, 1986), to calculate the flowing profiles. All calculations were done from the surface to well bottom. The matches we obtained with the measured profiles ranged from good to not-so-good. It is not possible to show all the matches in this paper. Instead, we determined the average pressure gradient in the first 500 m

Table 1. Data used to calculate pressure and temperature profiles from wellhead to bottom

Well	Total Flowrate kg/s	Mixture Enthalpy kJ/kg	Wellhead Pressure bar-g	Wellbore String Design	Total Depth m
A-- Cerro Prieto 90	45	1343	40.7	0.5808 ft from 0-bottom	1299
B--Los Azufres 18	26.7	1607	30.0	0.7296 ft from 0-959 m 0.5153 ft from 959 m-bottom	1324
C--Ngawha 11	68.6	965	19.8	0.652 ft from 0-673.5 m 0.4934 ft from 673.5 m-bottom	950
D--Okoy 7	13.2	1403	46.5	0.7251 ft from 0-1308 m 0.523 ft from 1308 m-bottom	2600
E--Cerro Prieto 91	34.2	1372	56.5	0.5361 ft from 0-1942 m 0.3370 ft from 1942 m-bottom	2294
F--Mofete 2	16.4	1834	3.5	0.7283 ft from 0.1272 m 0.5118 ft from 1272 m-bottom	1989
G--HGP-A	13.9	1966	3.2	0.802 ft from 0-680 m 0.5833 ft from 680 m-bottom	1966
H--East Mesa 6-1	12.9	1197*	2.3	0.7267 ft from 0-bottom	2134
I--Krafla 9	25	1532*	16.3	0.7297 ft from 0-1053 m 0.5856 ft from 1053 m-bottom	1251
J--Utah State 14-2	40.9	1648*	26.7	0.7433 ft from 0-bottom	913

* --- Based on measured bottom-hole temperature

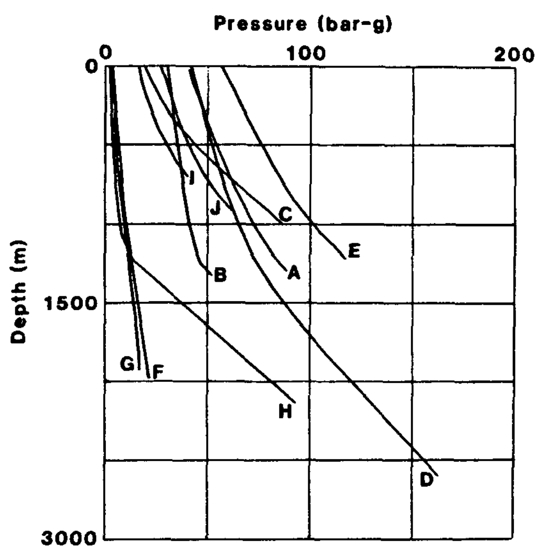

Figure 1. Measured pressure profiles.

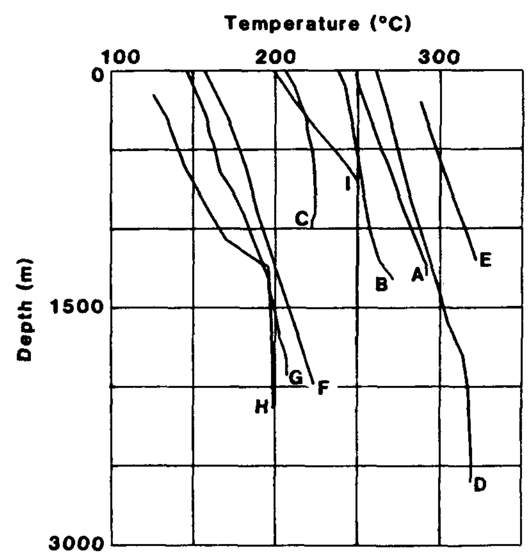

Figure 2. Measured temperature profiles.

Table 2. Values representing two-phase nature of flow at/near wellhead

Well	Total Mass Flux $kg/s\text{-}m^2$	Quality at Wellhead	Steam Mass Flux $kg/s\text{-}m^2$	Wellhead Pressure bar-g	Measured Pressure Gradient bar/m	Calculated Pressure Gradient bar/m	Ratio
A--Cerro Prieto 90	1830	0.15	275	40.7	0.0275	0.0275	1.00
B--Los Azufres 18	687	0.33	227	30.0	0.0104	0.0088	0.85
C--Ngawha 11	2211	0.025	55	19.0	0.0494	0.0770	1.56
D--Okoy 7	344	0.16	55	46.5	0.0207	0.0220	1.06
E--Cerro Prieto 91	1630	0.11	179	56.5	0.0398	0.0333	0.84
F--Mofete 2	424	0.57	242	3.5	0.0064	0.0071	1.11
G--HGP-A	296	0.63	187	3.2	0.0042	0.0049	1.17
H--East Mesa 6-1	335	0.14	47	1.5	0.0030	0.0060	2.00
I--Krafla 9	644	0.08	52	20.9	0.0274	0.0117	0.42
J--Utah State 14-2	1015	0.08	83	30.6	0.0275	0.0192	0.70

of each well (from the wellhead and 500 m down) and compared the measured and calculated values. These values are shown in Table 2 for the 10 wells. Also given is the ratio of the calculated and measured pressure gradients. A pressure gradient ratio of unity indicates a good match; a gradient ratio less than unity means that the measured is greater than the calculated; a gradient ratio greater than unity means that the calculated pressure gradient is greater. Our visual inspection of the measured and calculated profiles suggested that the matches were reasonable when the calculated pressure gradient was within about 20 percent of the measured gradient. This means that not-so-good matches were obtained for wells Ngawha 11, East Mesa 6-1, Utah State 14-2 and Krafla 9. Well Cerro Prieto 90 gave a good match, and other wells reasonable matches. Well Okoy 7 was a special case. The calculated and measured pressure gradients near the wellhead were similar, but diverged with depth.

We looked at the quality of matches by estimating mean and standard deviation of error and percent error, as follows:

$$e_i = p_{calc} - p_{meas} \tag{1}$$

$$d_i = \frac{p_{calc} - p_{meas}}{p_{meas}} \times 100 \tag{2}$$

where p_{calc} and p_{meas} are calculated and measured pressures at any point respectively.

$$\bar{e} = \frac{\sum_{i=1}^{n} e_i}{n} \tag{3}$$

$$\sigma_e = \left[\frac{\sum_{i=1}^{n} (e_i - \bar{e})^2}{n-1} \right]^{1/2} \tag{4}$$

$$\bar{d} = \frac{\sum_{i=1}^{n} d_i}{n} \tag{5}$$

$$\sigma_d = \left[\frac{\sum_{i=1}^{n} (d_i - \bar{d})^2}{n-1} \right]^{1/2} \tag{6}$$

where e_i is the error, $\bar{e}$ is arithmetic mean error, σ_e is the standard deviation about $\bar{e}$, and n is the number of data points. Similarly, d_i is the percent error, $\bar{d}$ is mean percent error, and σ_d is the standard deviation about $\bar{d}$. Such statistical parameters have been used before to evaluate the accuracies of two-phase correlations (Vohra *et al.*, 1975). Results of our calculations are summarized in Table 3. For a good match, we should have a low mean and standard deviation. Looking at the mean and standard deviation of error, we find that Ngawha 11, Okoy 7, East Mesa 6-1, Krafla 9 and Utah State 14-2 fall in the category of not-so-good matches. Similar conclusion is drawn by looking at the columns of mean percent error and standard deviation of percent error, except that now it seems that Mofete 2 and HGP-A are also not-so-good matches. But these two wells are low pressure wells and hence small deviation in calculated pressure gets magnified when we calculate percent error. So mean and standard deviation of percent error is not necessarily a good way to determine the quality of matches in low pressure cases. Thus three different criteria to determine the quality of matches suggest that we have not-so-good matches for 5 wells.

The Cerro Prieto 90 , Ngawha 11 (ratio greater than unity), and Krafla 9 (ratio less than unity) pressure profiles are shown in Figures 3, 4, and 5, respectively. They demonstrate the range of results obtained in our work. All the wellbore calculations reported here were done assuming no heat transfer to/from the formation; the absolute casing

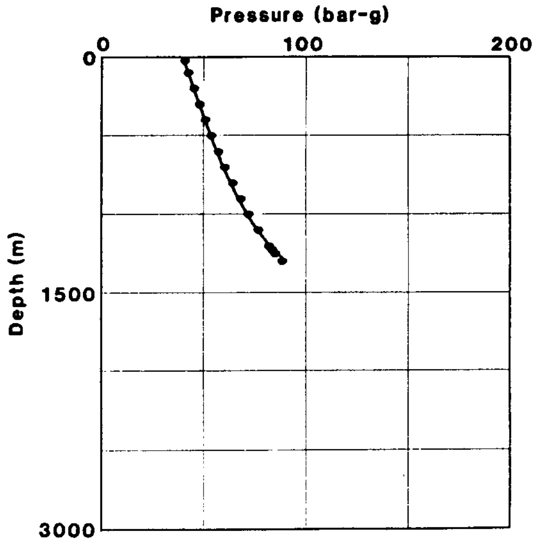

Figure 3. Pressure profile match for well Cerro Prieto 90.

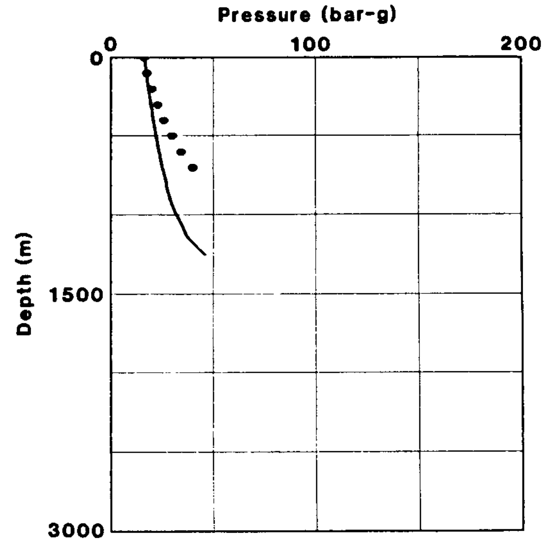

Figure 5. Pressure profile match for Krafla 9.

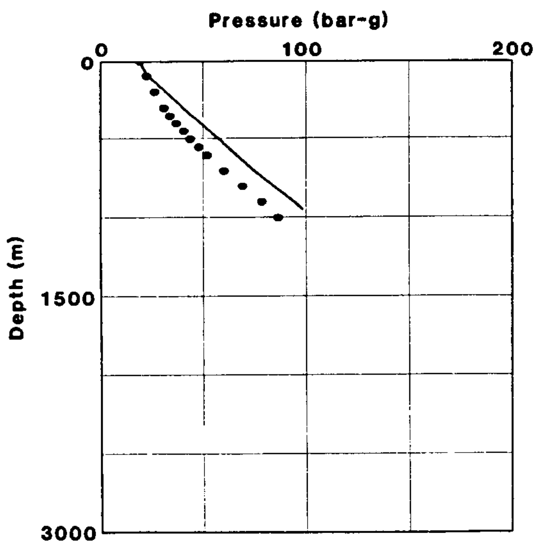

Figure 4. Pressure profile match for well Ngawha 11.

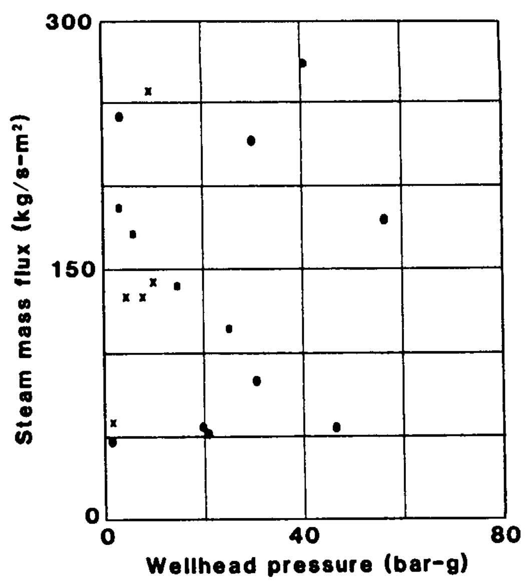

Figure 6. Steam mass flux vs. wellhead pressure

roughness used throughout was 0.0006 feet; the wellbore was divided into about 50 segments in most cases. The effects of noncondensible gases and dissolved solids were not considered.

We think that the Orkiszewski (1967) method performs as well as any other method for geothermal wellbore flow; that is, the method seems to have general applicability. What we would like to know also, is under what conditions it performs best, and under what conditions it should not be expected to give good results. We looked at the 10 matches of calculated and measured profiles, and tried to group the good and not-so-good wells using two-phase flow related criteria such as mass flux, void fraction, and pressure. We found that by plotting the "steam mass flux at the wellhead" against "wellhead pressure," the wells exhibiting not-so-good matches formed a group away from the better matched wells. This result is shown in Figure 6. The values used to draw this figure are given in Table 2. The rationale for Figure 6 are these: (1) the steam mass flux represents the dryness or void fraction of the flow, arbitrarily taken at the wellhead; (2) the wellhead pressure correlates the physical properties of steam and water.

There are more points in Figure 6 than are given in Table 2. Nine of the wells in Table 2 are represented by circles in Figure 6. The well not shown by a circle is HGP-A in Hawaii; it is represented by stars. There are four stars in Figure 6. The highest flowrate one is that given in Table 2. The other three are lower flowrate profiles that we also matched using the wellbore simulator. The five crosses in Figure 6 are data points from a paper by Upadhyay *et al.* (1977), from wells in the Philippines

Table 3. Comparison of measured and calculated pressure profiles

Well	Data Points	Measured Pressure Range, bar-g	Mean Error bar-g	Standard Deviation of Error, bar-g	Mean Percent Error	Standard Deviation of Percent Error
A--Cerro Prieto 90	16	40.9-88.5	-0.3	0.8	-0.6	1.1
B--Los Azufres 18	18	30.0-52.1	-1.1	1.2	-2.65	2.2
C--Ngawha 11	14	19.0-86.3	10.8	5.1	22.8	10.4
D--Okoy 7	14	41.7-162.9	5.3	4.1	5.1	3.9
E--Cerro Prieto 91	13	56.5-117.0	-0.15	2.6	-0.66	2.9
F--Mofete 2	5	3.5-21.5	0.4	0.4	4.9	5.7
G--HGP-A	17	3.2-16.7	0.6	0.4	6.1	2.7
H--East Mesa 6-1	15	2.3-92.9	11.0	9.4	59.5	53.2
I--Krafla 9	8	16.3-40.0	-5.5	5.4	-17.5	13.8
J--Utah State 14-2	30	27.0-61.6	-6.7	4.6	-13.6	6.9

and the United States. Upadhyay *et al.* (1977) stated that reasonable matches were obtained when comparing measured profiles to calculated profiles using a wellbore simulator based on Orkiszewski's (1967) correlations. The total flowrate of these two-phase wells ranged from 3 kg/s to 11 kg/s. It appears from Figure 6 that the Orkiszewski (1967) correlations do not work as well when the steam mass flux is below 100 kg/s-m^2.

Discussion

In general, the Orkiszewski (1967) correlations work well for different geothermal wellbore flow situations. The mean percent errors for Ngawha 11, East Mesa 6-1, Krafla 9 and Utah State 14-2, however, were larger than 10%. Ngawha 11 has 1.4% of noncondensible gas in the total flow. This may be the reason for the bad match, because the wellbore simulator does not consider the effect of noncondensible gases.

Krafla 9 is said to have wellbore deposition problems which reduces the effective area open to flow in the wellbore and this could be the reason for the bad match. If we reduce the wellbore string diameter, we will have larger pressure drop and can match the measured pressure profile. We are not aware of any problems with well Utah State 14-2, so we can not propose a reason for the not-so-good match in this case.

East Mesa 6-1 is a special case. The mean percent error and standard deviation about mean percent error for East Mesa 6-1 were unusually large. This match is shown in Figure 7. We see that calculated pressure profile is displaced away from the measured pressure profile by a constant positive pressure in single-phase section of the wellbore. This means that the predicted depth of flashing is higher up in the wellbore than the actual depth of flashing. The calculated depth of flashing is highly dependent on the fluid enthalpy value used. Thus fluid enthalpy is an important parameter which determines the depth of flashing and hence the quality of match.

Conclusions

The Orkiszewski (1967) correlations have been used to compare the measured and calculated pressure profiles from ten wells that cover a wide range of flowrate, fluid enthalpy, wellhead pressure and well depth. We conclude

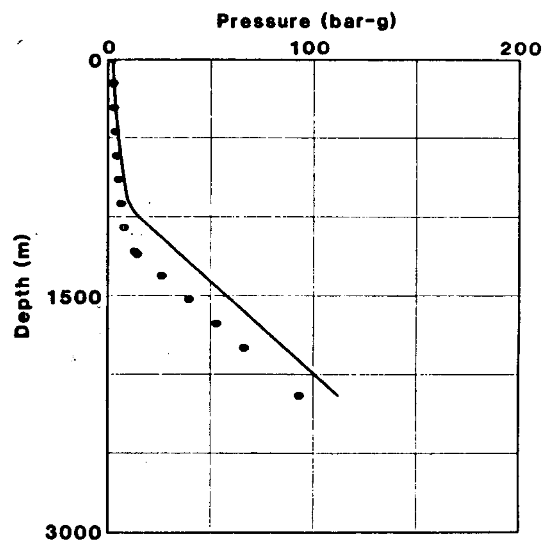

Figure 7. Pressure profile match for well East Mesa 6-1.

the following:

1. The Orkiszewski (1967) correlations seem to have general applicability for geothermal wellbore flow, and work well under a variety of situations.
2. Good matches between the calculated and measured pressure profiles were obtained using the correlations if the steam mass flux is larger than 100 kg/s-m^2.
3. Gas content and fluid enthalpy are important parameters in determining the depth of flashing and hence the agreement between calculated and measured pressure profiles.

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References

Ambastha, A.K. and Gudmundsson, J.S.:"Geothermal Two-Phase Wellbore Flow: Preesure Drop Correlations and Flow Pattern Transitions," Proc., 11th Workshop on Geothermal Reservoir Engineering, Stanford Univ., Stanford, CA (Jan. 21-23, 1986).

Barelli, A., Corsi, R., Delpizzo, G. and Scali, C.:"A Two-Phase Flow Model for Geothermal Wells in Presence of Non-condensable Gases," Geothermics, Vol. 11, No. 3 (1982) 175-191.

Bixley, P.F.:"Personal Communication" (1984).

Butz, J. and Mickley, M.C.:"Theoritical and Experimental Research on Two-Phase Flow in Geothermal Wells," Denver Research Institute, Report DOE/ET/27141-3 (DE82011702), U. of Denver, Denver, CO, (1982).

Butz, J. and Plooster, M.:"Subsurface Investigations at the Roosevelt Hot Springs, Utah, KGRA," Report DOE/ET/28389-1 (Oct. 1979).

Castaneda, M.:"Personal Communication" (1983).

Catigtig. D.C.:"Boreflow Simulation and its Application to Geothermal Well Analysis and Reservoir Assessment," Report 1983-8, UNU Geothermal Training Programme, Reykjavik, Iceland, (1983).

Chierici, G.L., Giannone, G., Sclocchi, G. and Terzi, L.:"A Wellbore Model for Two-Phase Flow in Geothermal Reservoirs," SPE of AIME, Paper SPE 10315, Presented at 56th Annual Fall Tech. Conf. and Exhibition, San Antonio, TX (Oct. 5-7, 1981).

Fandriana, L., Sanyal, S.K. and Ramey, H.J., Jr.:"A Numerical Simulator for Heat and Fluid Flow in a Geothermal Well," Pet. Eng. Dept., Stanford U., Stanford, CA (1981).

Gould, T.L.:"Vertical Two-Phase Steam-Water Flow in Geothermal Wells," J. Pet. Tech. (Aug. 1974) 833-842.

Goyal, K.P., Miller, C.P. and Lippman, M.J.:"Effect of Measured Wellhead Parameters and Well Scaling on the Computed Downhole Conditions in Cerro Prieto Wells," Proc., Sixth Workshop on Geothermal Reservoir Engineering, Stanford Univ.,Stanford, CA (Dec. 1980) 130-138.

Gudmundsson, J.S., Ortiz-R., J., and Granados, E.E.:"Two-Phase Flow and Calcite Deposition in Geothermal Wells," SPE of AIME, SPE Paper 12741, Presented at California Regional Meeting, Long Beach (April 11-13, 1984).

Juprasert, S. and Sanyal. S.K.:"A Numerical Simulator for Flow in Geothermal Wellbores," Trans., Geothermal Resources Council, Vol. 1 (1977) 159-161.

Kihara, D., Chen, B., Yuen, P. and Takahashi, P.:"Summary of Results of HGP-A Well Testing," Proc., Third Workshop on Geothermal Reservoir Engineering, Stanford Geothermal Program, Report SGP-TR-25, (1977) 138-144.

Lundberg, E.A.:"Geothermal Resource Investigations: Special Report on Test Well Mesa 6-1," U.S. Bureau of Reclamation, (Feb. 1973).

Molinar-C. R.:" Personal Communication" (1985).

Nathenson, M.:"Flashing Flow in Hot-Water Geothermal Wells," J. Research U.S. Geological Survey (Nov.- Dec. 1974) 743-751.

Orkiszewski, J.:"Predicting Two-Phase Pressure Drops in Vertical Pipe," J. Pet. Tech. (June 1967) 829-838.

Ortiz-R., J.: "Two-Phase Flow in Geothermal Wells: Development and Uses of a Computer Code," Stanford Geothermal Program, Report SGP-TR-66 (June 1983).

Ryley, D.J. and Parker, G.J.:"Flowing Geothermal Wells: Cerro Prieto Well M-91 and Krafla Well KJ-9; Computer Analysis Compared with Experimental Data," International Conference on Geothermal Energy, Florence, Italy, Paper C4 (May 11-14, 1982) 187-194.

Upadhyay, R.N., Hartz, J.D., Tomokoria, B.N. and Gulati, M.S.:"Comparison of the Calculated and Observed Pressure Drops in Geothermal Wells Producing Steam-Water Mixtures," SPE of AIME, Paper SPE 6766, 52nd Annual Fall Tech. Conf. and Exhibition, Denver, CO., (Oct. 9-12, 1977).

Vohra, I.R., Hernandez, F., Marcano, N. and Brill, J.P.:"Comparison of Liquid-Holdup and Friction-Factor Correlations for Gas-Liquid Flow," J. Pet. Tech. (May 1975) 564-568.

Wilson, D.J.:"Computer Modeling of Output From Geothermal Wells," Master of Engineering Project Report, Dept. Mech. Eng., University of Canterbury, New Zealand (Feb. 1984).

Yuen, P.C, Chen, B.H., Kihara, D.H., Seki, A.S. and Takahashi, P.K.:"HGP-A Reservoir Engineering," U. of Hawaii, Honolulu, HI (Sept. 1978).