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 flowing pressure profile data from ten geothermal wells and deposition studies for geothermal wells. Previously, phase correlations is a vital part of wellbore deliverability 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 68.5 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-condensable 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 Krafta 9 in Iceland. The data for well Okoy 7 in the Philippines were taken from a report by Catigtig (1983). A paper authored by Chierrici 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

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

* --- Based on measured bottom-hole temperature

Figure 1. Measured pressure profiles.

Figure 2. Measured temperature profiles.
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:

\[ e_i = p_{calc} - p_{meas} \]  
\[ d_i = \frac{p_{calc} - p_{meas}}{p_{meas}} \times 100 \]

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

\[ \bar{e} = \frac{\sum e_i}{n} \]  
\[ \sigma_{e} = \left( \frac{\sum (e_i - \bar{e})^2}{n - 1} \right)^{1/2} \]  
\[ \bar{d} = \frac{\sum d_i}{n} \]  
\[ \sigma_{d} = \left( \frac{\sum (d_i - \bar{d})^2}{n - 1} \right)^{1/2} \]

where \( e_i \) is the error, \( \bar{e} \) is arithmetic mean error, \( \sigma_e \) 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 \( \sigma_d \) 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 columns of mean percent error and standard deviation of percent 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 4. Pressure profile match for well Ngawha 11.

Figure 5. Pressure profile match for Krafla 9.

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

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

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·m².

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...
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-m².
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


