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Dry Steam Feed Zones and Silica Scaling as Major Controls of Total Flow Enthalpy at Cerro Prieto, Mexico

Joseph J. Beall¹, Andres Pelayo Ledesma² and Juan de Dios Ocampo²
¹Calpine Corporation, Santa Rosa, California
²Constructora y Perforadora Latina S.A.
Campo Cerro Prieto, Baja California, Mexico

ABSTRACT

Enthalpy and chloride data for Cerro Prieto well fluids define a mixing line between original reservoir liquid (1,300-1,500 J/g, 9,000-11,000 ppm Cl) and superheated steam (2,870 J/g, 0 ppm Cl). The mixing relationship establishes that dry steam feed zones contribute to the total fluid flow of many wells. Fluids produced from newly completed or worked over wells often show rapid movement in either direction along the enthalpy-chloride mixing line. The direction of movement along the enthalpy-chloride mixing line depends upon whether increased formation boiling (increasing the dry steam flow to the well) or silica scaling in the formation and on the surface of the well bore (which inhibits the flow of dry steam) is the dominant process.

Introduction

Approximately 135 wells produce steam to the three geothermal power plants at Cerro Prieto. Twenty-eight of these wells were drilled and are operated and maintained by Constructora y Perforadora Latina (Latina). Since late 1995 Calpine Corporation has been a partner with Latina in this endeavor.

The Cerro Prieto geothermal field produces from the shallow "alpha" reservoir in the western part of the field and the deeper "beta" reservoir which underlies the entire field (Halfman et al., 1984, 1986; Lippmann et al., 1991). Most beta reservoir wells eventually produce “excess steam”, or steam quantities greater than would result from separator flashing of reservoir liquid produced to the surface (Truesdell et al., 1992). Excess steam therefore represents flashing in the subsurface within the formation. Gutiérrez-Puente and Mendoza (1995) have noted that silica scaling in the formation and wellbore (a consequence of subsurface boiling) is the primary cause at Cerro Prieto of accelerated production and wellhead pressure decline, resulting in numerous well workovers.

An analysis of chemical and enthalpy data for fluids produced from Latina wells provides insights into reservoir boiling and the relationship between formation and wellbore silica scaling and short term changes (often of large magnitude) in the chloride and enthalpy values of produced fluids. Current chemical monitoring of most Latina wells (all of which produce from the beta reservoir) includes periodic Na, K and Ca analyses for the purpose of calculating geothermometer temperatures. These analyses are performed by the Comisión Federal de Electricidad (CFE) in their laboratory at Cerro Prieto. In addition, samples are taken and analyzed by Latina for chloride and silica, using a titrometer and colorimeter, respectively.

These data are compatible with a model of the reservoir in which initially single phase water or two phase feed zones flow to the wellbores. Original beta reservoir fluids are best represented by single phase water with about 9,000 to 11,000 ppm chloride and a temperature range of 300°C to 330°C (Truesdell et al., 1989). Because of the very high temperatures in the reservoir, boiling within the formation begins or expands soon after production begins in all except the deepest (southeastern) part of the reservoir.

As the steam fraction of the fluid entering the wellbore increases, the enthalpy of the produced fluids increases commensurately. High temperature water, saturated in silica, becomes supersaturated during boiling, resulting in silica deposition in the wellbore and formation. As the boiling front, which is the locus of silica deposition, moves into the formation (away from the wellbore), permeability is reduced. This is schematically shown in Figure 1 along with the distribution of fluid phases around the wellbore. Consequently, shallow feed zones may
produce only steam while deeper zones produce two phase flow or single phase water. Where water or two phase flow in the wellbore mixes with dry, superheated steam, accelerated boiling causes an increase in the silica deposition rate. This impedes flow from the steam zone, causing a decrease in the enthalpy of the produced fluids.

Truesdell et al. (1992) showed that the chemistry of some Cerro Prieto wells is influenced by the intrusion of colder water or the production of steam condensate. Those authors, using analyses of 1990 well fluid samples, presented a Na/K geothermometer temperature contour map (using the equation of Fournier, 1979). The map shows that, at the time of sampling, most of the field (i.e., the beta reservoir) was producing fluids with geothermometer temperatures above 325°C. September 1996 analyses from 23 Latina wells distributed areally over most of the field yield a maximum geothermometer temperature (same equation as above) of 320°C and an average of 310°C. The geothermometer data therefore suggest a gradual field-wide decrease in the average temperature of water entering wellbores. The magnitude of this change is in the range of 15°C to 20°C over a six year period. While this process appears to be long term and ongoing, the dominant and much shorter term effect on the chemistry and enthalpy of produced fluids is the addition or reduction of dry steam flow to the wellbore. In this paper, chloride and enthalpy data for Latina well fluids are shown to define a mixing line (Figure 2) between original reservoir liquid and dry steam. New or recompleted wells produce fluids which may initially evolve in either direction along the mixing line. The direction depends upon whether increased formation boiling (which increases the dry steam flow to the well) or silica scaling (which inhibits the flow of dry steam) is the dominant process.

Chloride vs. Enthalpy

In Figure 2 enthalpy versus chloride is plotted for the combined water and steam at the Latina wellhead separators. The data are for fluids sampled from Latina wells in September and November 1996 and March 1997. The data points fall along a mixing line connecting typical beta reservoir liquid (9000 to 11,000 ppm Cl and 1300 to 1500 J/g) with single phase steam at 2,870 J/g and 0 ppm Cl. The X axis intercept of 2,870 J/g is greater than the maximum enthalpy of saturated steam (2,803 J/g) suggesting that after separation, the steam becomes superheated en route to the wellbore.

Below about 1,530 J/g, the samples represent primarily liquid dominated reservoir flow. At higher enthalpies, progressively greater contributions from dry steam feed zones are required. The addition within the wellbore of two phase flow to typical reservoir liquid will not generate the mixing line shown in Figure 2. During boiling, essentially all of the chlorine is concentrated in the remaining liquid fraction. Consequently, if any residual liquid fraction accompanies the steam to the wellbore (i.e., two phase flow), the chloride contribution of the original (unboiled) liquid will be essentially conserved. The result would be an approximately constant chloride, increasing enthalpy trend (horizontal arrow of Figure 2). The mixing relationship shown in Figure 2 therefore requires the dilution of original reservoir liquid (plus or minus a small component of two phase flow) with dry steam. Some two phase mixing with reservoir liquid undoubtedly occurs in the wellbore and adds to the data scatter of low enthalpy points. The amount of this mixing is not sufficient, however, to generate an identifiable trend on Figure 2.

Figure 3 shows the chloride-enthalpy history of fluids produced from Latina wells 605 and 613 since May 1996, when the current geochemical monitoring program began. Both wells initially showed increasing steam components (i.e., shifted along the mixing line toward steam). After July 1996 and November 1996, fluids produced from wells 605 and 613, respectively, reversed direction along the mixing line. This is interpreted to indicate that the dry steam zones feeding those wells have been sufficiently sealed off by scaling to reverse the dilution effect of adding steam to reservoir liquid. The development of dry steam feed zones therefore alters the initial chloride-enthalpy character of the produced fluids in the dire-
tion of superheated steam. Silica scaling reverses this trend and chloride-enthalpy of produced fluids migrate back toward their original values.

Most Latina wells, after workovers or initial completion, follow all or part of the cycle described above. For some wells, falling enthalpies accompanied by increasing production decline rates raised concern that cooler fluids than those initially produced could be entering the wellbore. This process was documented for the shallow alpha reservoir using enthalpy-chloride relationships (Grant et al., 1984). Some of the scatter in the data plotted in Figure 2, especially in the low enthalpy, high chloride area of the mixing line could be the result of mixing with cooler, lower chloride waters. The amount of such mixing must be minor, however, as no clear mixing trend with a cooler, lower chloride end member is evident. Moreover, most wells showing 'substantial short term enthalpy losses have time frame.

As noted previously, Na/K geothermometer calculations indicate, over a six year period, a possible 15°C to 20°C decline in the average temperature of water flowing to wellbores. A reservoir water temperature decrease of this magnitude can, at most, lower the enthalpy of the produced fluids by 100 J/g to 125 J/g. Enthalpy changes of much greater magnitude and shorter time frame are common for Cerro Prieto well fluids (e.g. Figure 3) and are best explained by the dry steam/scaling mechanism described above.

**Subsurface Silica Deposition**

To better understand the role of subsurface silica deposition in affecting enthalpy and production declines, a technique was developed to estimate the rate of subsurface silica deposition. The average temperature of the water entering the wellbore is calculated by Na-K geothermometry. (Na-K geothermometry is preferred over Na-K-Ca geothermometry in this instance because it is not influenced by dilution or concentration of Na or K by the addition or separation of steam. The calculated temperature is only influenced by the ratio of the ionic concentrations. Na-K-Ca geothermometry is not totally independent of the ionic concentrations.) The temperature calculated is then used to obtain the silica average concentration, which is a very reliable function of water temperature. Water samples from the wellhead separator are then analyzed for silica. The separated steam is mathematically added back to the water to get a steam plus water (or total flow) silica concentration. In most wells the concentration of silica in the combined fluid is less than the equilibrium concentration of silica in formation water, determined as described above. This means that the difference represents deposition of silica in the subsurface. Subsurface silica deposition rates for Latina wells range from zero to 120 pounds per hour.

The ratio of subsurface silica deposition to silica produced at the surface (SiO₂ D/P) can also be calculated using the logic described above. Unlike the rate of silica production or deposition, the ratio SiO₂ D/P is not flow rate dependent. Figure 4 illustrates a good correlation on a semi-log plot of enthalpy vs. SiO₂ D/P. For wells with enthalpy less than 1800 J/g, more silica is produced at the surface than is deposited in the formation and wellbore in response to supersaturation due to steam separation. As enthalpy increases above 1800 J/g, the ratio increases from 1 to 10. This is in agreement with experimental data and theoretical calculations showing that silica deposition increases with both the degree of silica supersaturation and the salinity. For reservoir water, both of these parameters increase with an increase in the fraction of steam separated.

Latina wells producing from the deeper (i.e., southeastern) part of the beta reservoir generally have low values of SiO₂ D/P and enthalpies which indicate liquid saturated formation conditions. These wells produce from formation which is not "phase stratified" as shown in Figure 1. Consequently, silica deposition in the formation and wellbore is not a dominant influence on their flow rates, which are much more stable than those which derive some production from dry steam zones.
Conclusions

The chloride-enthalpy data show that for Latina wells with enthalpies greater than about 1600 J/g, dry steam feed zones contribute significantly to production. Chloride and enthalpy of wells plot along a mixing line between typical beta reservoir water and dry steam (zero Cl and H=2870 J/g).

Most Latina wells participate in a reservoir process whereby boiling eventually results in dry steam feed zones in the upper part of the well's productive interval. This is accompanied by increasing enthalpy. Subsurface silica deposition at some point begins to interfere with well flow rates and diminishes the dry steam contribution to well flow. This causes a reversal in the enthalpy trend and values begin to decline. New or redrilled wells may initially produce from reservoir fluids ranging from single phase water (i.e., the left end of the enthalpy-chloride mixing line of Figure 2) to a stratified sequence of fluids as shown in Figure 1 (dry steam, two phase and liquid zones).

Consequently the enthalpy-chloride evolution of a new or re-completed well can initially be in either the direction of dry steam or original reservoir liquid. This is dependent upon whether the early production conditions in the reservoir are more influenced by increased contributions from dry steam zones or by silica scaling sealing off dry steam feed zones.

Further chemical monitoring of Latina wells may allow for development of criteria for determining the optimum timing of well workovers to remove scale from wellbores. Under reaming (enlarging the diameter of the open hole) is currently being evaluated as a means of combating silica scaling in the wellbore and within the "skin" of the wellbore. Formation "washing", whereby steam condensate or other low silica water is slowly pumped into the formation, is being considered as a possible scaling remedy. Producing back the injected water after it has approached equilibrium saturation with silica may help restore permeability lost to scaling. If successful, this process might eliminate the need for some well workovers.

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