Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

The Response to Exploitation of the Los Humeros (México) Geothermal Reservoir

Víctor Manuel Arellano[1], Rosa María Barragán[1], Miguel Ramírez[2], Siomara López[1], Adriana Paredes[1], Alfonso Aragón[1], Rigoberto Tovar[2]

[1]Instituto de Investigaciones Eléctricas, Gerencia de Geotermia, Cuernavaca, Morelos, México

[2]Comisión Federal de Electricidad, Gerencia de Proyectos Geotermoeléctricos, Morelia, Mich., México

rmb@iie.org.mx

Keywords: Los Humeros geothermal field, reservoir processes, reservoir engineering, well simulation, fluid geochemistry, reservoir exploitation

ABSTRACT

In this work, the response to exploitation of the Los Humeros geothermal reservoir was inferred through the study of the changes in production of wells, the thermodynamic conditions of reservoir fluids, and the chemical compositions of fluids over time. Up to 2012, almost 123 million tons of fluids had been extracted from the reservoir. Well bottom conditions (pressure and enthalpy) were calculated using heat and flow simulation. The changes in the composition of fluids seem to be related to boiling. In high-enthalpy wells, condensation in the well or in the reservoir was inferred to occur. Results also showed a decreasing trend in fluid salinity due to increasing boiling and condensation. The average reservoir liquid saturation for the field has a decreasing trend over time. Analysis of gas data suggested that the number of wells produce either a steam phase or condensed reinjection returns. According to the results, five main processes were identified: (a) pressure decrease and enthalpy increase that produces a moderate boiling process with steam gain; (b) iSignificant boiling and steam condensation; (c) production of returns from reinjection; (d) interaction with deep fluids, and (e) decrease in reservoir liquid saturation due to insufficient recharge.

1. INTRODUCTION

The Los Humeros geothermal field is located in the eastern portion of the Mexican Volcanic Belt, approximately 200 km from Mexico city (Figure 1) at an elevation of approximately 3,000 m. The first deep well was drilled in 1982, and the commercial exploitation of the resource began with the installation of the first 5 MWe unit in 1990. From 1990 to 2012, more than 40 wells were drilled (Figure 2) and 7 units totaling 5 MWe were installed (Quijano and Torres, 1995). Currently, the Los Humeros II project, which includes two 25 MW plants, has increased the capacity of the field to a net value of 68.4 MW (installed capacity of the field was 40 MW) after removing 5 power plants with 5 MW each (Gutiérrez-Negrín, 2014). In general, most of the wells produce high enthalpy, two-phase discharges, while a few wells such as the H-1 and H1D produced a relatively high fraction of water at separator conditions. The relatively low salinity water produced by wells, which is classified mainly as bicarbonate or sulfate type rather than chloride type, seems to be a condensate. The changes in chemical compositions of fluids and in thermodynamic conditions of the reservoir due to exploitation from the beginning of exploitation to 2006 have been documented (Barragán et al., 2008; Arellano et al., 2008). In order to delineate better production strategies for the field and considering additional requirements according to increased capacity, a project was developed by the Comisión Federal de Electricidad (CFE) the electrical company that operates the field, and the Instituto de Investigaciones Eléctricas (IIE) in 2013, to estimate the response of the reservoir to exploitation for the 2007-2012 time period, through the analysis of chemical and production data (Arellano et al., 2013).

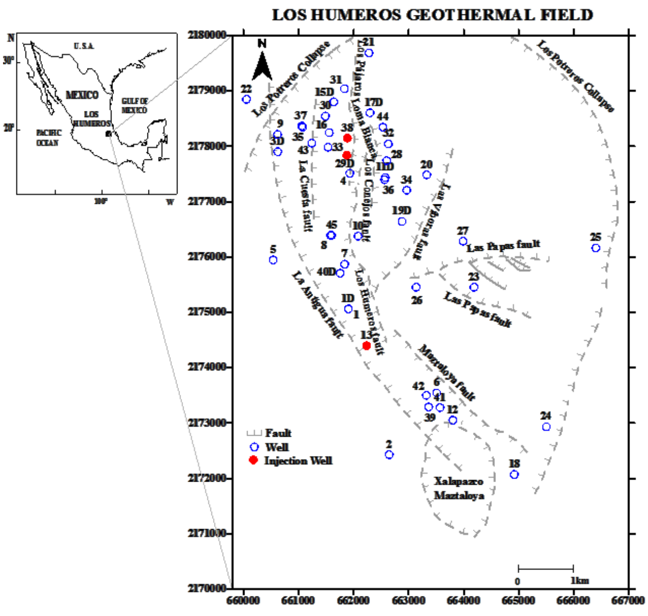

Figure 1: Location of the Los Humeros geothermal field and location of wells.

2. METHODOLOGY

In order to obtain the thermodynamic characteristics of reservoir fluids and to investigate the dominant processes occurring with exploitation, a method based on the analysis of the following patterns of behavior was used (Arellano et al., 2005): (a) well mass flow-rate, well-bottom pressure, enthalpy and temperature; (b) chloride concentration in separated water and total discharge fluid; (c) the comparison of the total discharge enthalpy and those corresponding to the reservoir temperature estimated by both the "slow-response" cationic (Nieva and Nieva, 1987) and the "fast-response" silica (Fournier and Potter II, 1982) geothermometers (Truesdell et al., 1995); (d) fraction of steam entering the well; (e) total discharge and reservoir chlorides; (f) total discharge and reservoir CO_2 ;(g) liquid saturation; and (h) $\delta^{18}O$ and δD in total discharge. Well-bottom thermodynamic conditions were obtained using WELLSIM simulator, (Gunn and Freeston, 1991). Input data consisted of wellhead production data and well geometry. Chemical, isotopic and production data were provided by the Residencia Los Humeros, CFE. The study included 27 wells (Figure 1): H1, 1D, 3D, 6, 7, 8, 9, 11D, 12, 15D, 16, 17D, 19D, 20, 30, 31, 32, 33, 34, 35, 36, 37, 39, 41, 42, 44 and 45.

3. FLUIDS PRODUCTION/INJECTION

Fluid extraction in Los Humeros started in 1982 (Figure 2), the amount of fluids produced up to December 2012 was 122,934,290 tonnes, including 103,678,826 tonnes of steam (84.3 %) and 19,255,464 tonnes of liquid (15.7 %). Some of the fluids were injected back to the reservoir in order to minimize environmental impacts and also to provide recharge to the aquifer. From 1995 to December 2012, the amount of fluids reinjected to the reservoir was 6,301,863 tonnes (5.1%).

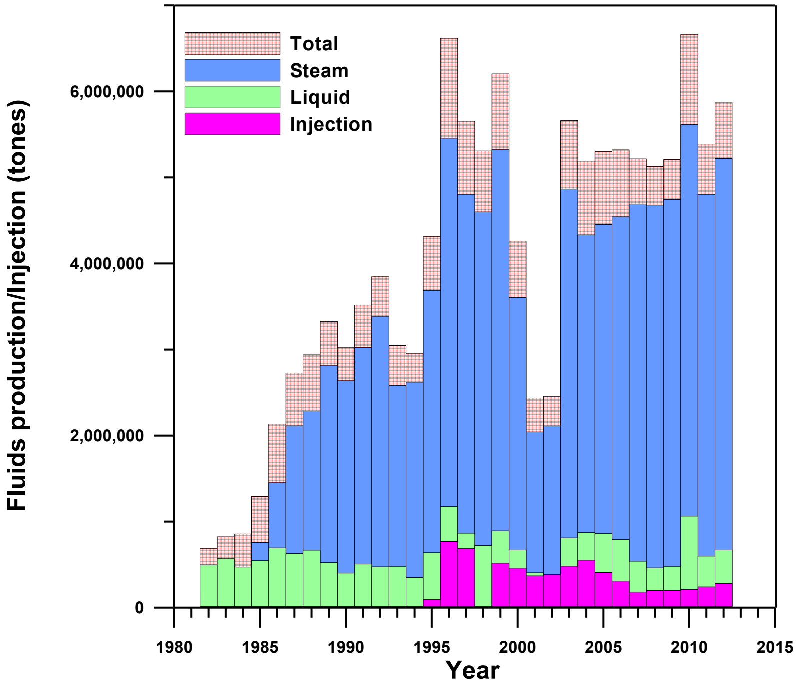

Figure 2: Fluids produced and injected in Los Humeros geothermal field.

4. RESULTS

The methodology described was applied to individual wells in the field to estimate the dominant processes in them. Then by grouping wells with approximately same characteristics, the main processes occurring in different zones of the field were identified. The results obtained allowed the identification of the main processes that have occurred and are occurring in different zones of the Los Humeros reservoir. Reservoir temperatures were estimated using a cationic geothermometer (Nieva and Nieva, 1987) for two-phase wells and using the FT-HSH2 gas equilibrium method (Siega et al., 1999; Arellano et al, 2003) for the steam wells. According to the results, five main processes were identified: (a) pressure decrease and enthalpy increase that produces a moderate boiling process with steam gain; (b) significant boiling and steam condensation; (c) production of returns from reinjection; (d) interaction with deep fluids, and (e) decrease in reservoir liquid saturation due to insufficient recharge.

4.1 Reservoir Processes

4.1.1 Pressure decrease and enthalpy increase that produces a moderate boiling process with steam gain

This process was identified to occur in wells that initially produced from the compressed liquid or two-phase liquid dominated zones of the reservoir, such as H-1 and H-1D (Arellano et al., 2006; 2008). The well H-1 was initially 1,458.6 m deep with 297 m of slotted liner (1153 – 1450 m) and was producing from June 1982 to December 1993. Subsequently, this well was deviated, becoming H-1D, being then 1,850 m deep with 599 m of slotted liner (1245 – 1844 m). It was producing from November 1995 to September 2011. The wells H-1 and H-1D produced two-phase fluids at wellhead, with a relatively high liquid fraction (~0.73 % by mass). In order to illustrate the moderate boiling process with steam gain through the analysis of chemical and production data, time series of (A) well bottom pressure; (B) well bottom enthalpy; (C) chlorides; (D) comparison of total discharge enthalpy and enthalpy estimations by geothermometers; (E) CO_2 and (F) reservoir liquid saturation and excess steam for wells H-1 and H-1D are given in Figure 3. As seen in Figure 3 A and B, due to boiling, pressure decreases and enthalpy increases. As boiling progresses, the steam in the entrance of the well increases, causing excess enthalpy discharges (Figure 3F). Because of the boiling process, a trend of chloride decrease (Figure 3 C and CO_2 increase (Figure 3 E) is noticed in the total discharge of fluids. According to the enthalpy pattern observed (Figure 3 D) in which T_{SiO2} is slightly higher than T_{CCG}, it seems that the well receives lower temperature waters in its production zone. However in Figure 4, where the relative N_2-H_2O-CO_2 compositions (Magro et al., 2013) of produced fluids is given, it is seen that such waters apparently do not contain N_2 from atmospheric origin, but rather a deep CO_2 –enriched component from the roots of the system where volcanic-hydrothermal interactions occur, which seems to be the source for the fluids produced from this well. The liquid saturations of these wells are usually very high (up to 100%), as shown in Figure 3 F. However, decreases are seen when enthalpy and excess steam show intermittent increases after 2000. Besides, the isotopic compositions of discharge fluids become relatively δD-enrichment but δ^{18}O-depleted over time, due to boiling and convection.

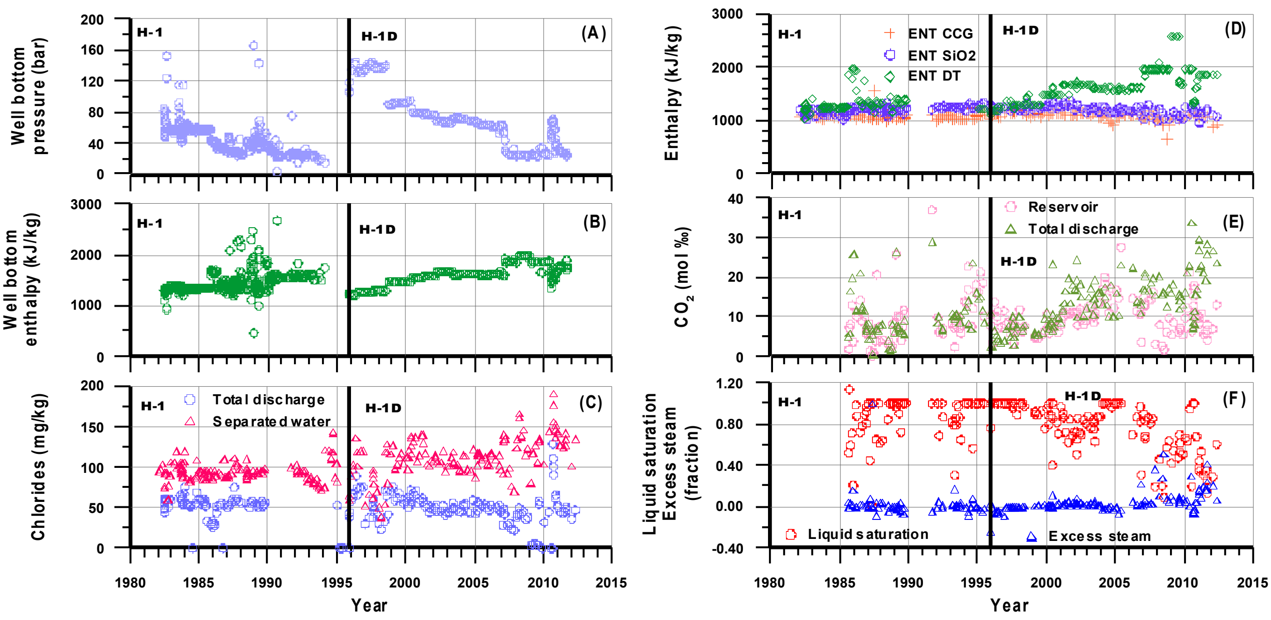

Figure 3: Time series of (A) well bottom pressure; (B) well bottom enthalpy; (C) chlorides; (D) comparison of total discharge enthalpy and enthalpy estimations by geothermometers; (E) CO_2 and (F) reservoir liquid saturation and excess steam of wells H-1 and H-1D, taken as representative of moderate boiling process with gaining steam.

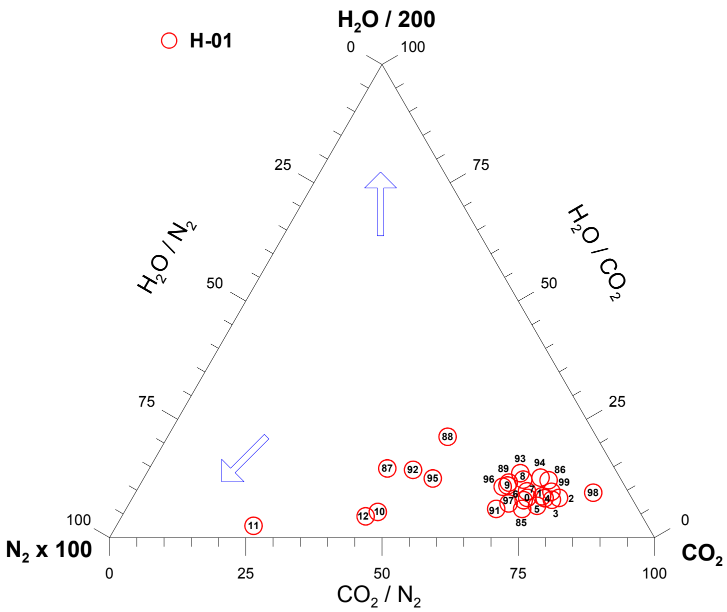

Figure 4: H_2O-CO_2-N_2 ternary diagram for the wells H-1 and H-1D.

4.1.2 Significant boiling and steam condensation

In contrast to the process of moderate boiling with steam gain that was identified to occur only in wells H-1 and H-1D, the process of significant boiling and steam condensation has been identified in a number of wells such as H-3D, H-7, H-9, H-11, H-12, H-15D, H-17D, H-19D, H-20, H-30, H-31, H-32, H-33, H-34 and H-35. This process is developed when boiling becomes important and recharge is limited in the wells. This process is illustrated by the behavior of well H-12 in Figure 5 A-D. This well is 3104 m deep with 113 m of slotted liner (1463.5-1576.6 m). Production data are available from July 1986 to December 2012. The well discharges two-phase fluids, with enthalpies higher than 2,500 kJ/kg and high steam fraction at separation conditions (>0.9), since the beginning of production as seen in In Figure 5 A. It is also seen that the dilution of the fluid with the condensed steam causes relatively low silica temperature estimations from cationic geothermometers (sometimes temperature estimations are lower than 200 ºC). Dilution also causes very low chloride concentrations in the water produced, as can be seen in Figure 5 B. The process of significant boiling with steam condensation also produces relatively high and variable CO_2 concentrations in the discharges (usually between 5 and 30 mol %) as seen in Figure 5 C. In Figure 5 D it is noticed that the reservoir liquid saturation shows an irregular behavior, decreasing from roughly 0.8 to 0.4. In Figure 6, the relative N_2-H_2O-CO_2 compositions of fluids indicate that well H-12, as wells H-1 and H-1D, apparently do not contain N_2 from atmospheric origin, but rather a deep CO_2 –enriched component from the roots of the system where volcanic-hydrothermal interactions occur, which seems to be the source for the fluids.

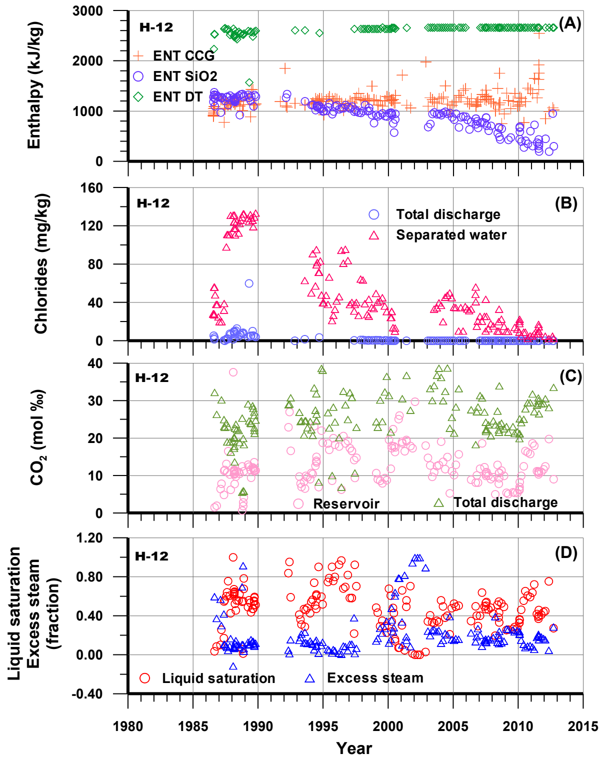

Figure 5: Time series of (A) comparison of total discharge enthalpy and enthalpy estimations by geothermometers; (B) chlorides; (C) CO_2, (D) reservoir liquid saturation and excess steam of well H-12, taken as representative of significant boiling with steam condensation process.

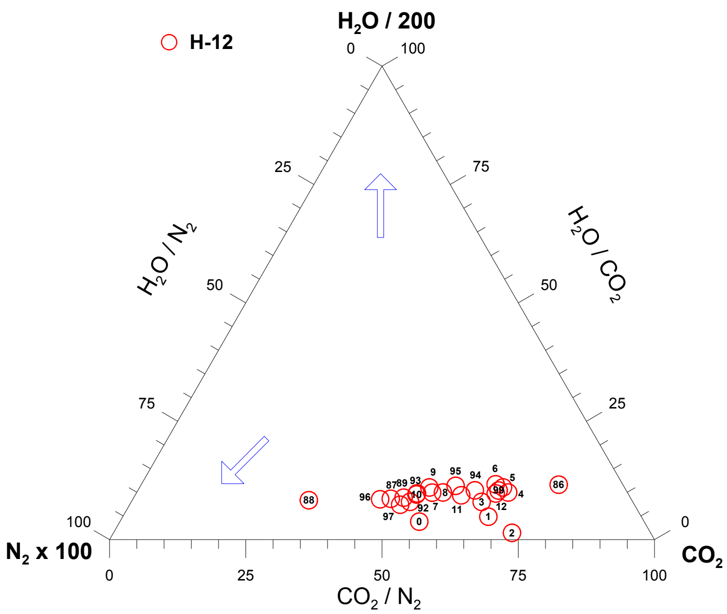

Figure 6: H_2O-CO_2-N_2 ternary diagram for the well H-12.

4.1.3 Production of returns from reinjection

Currently, the production of returns from reinjection in the liquid phase have not been clearly identified to occur in wells, but it is suspected that wells H-3D, H-9 and H-35 could have produced some reinjected fluid, since usually their fluids are isotopically enriched regarding the isotopic compositions of reinjection wells. However, the production of steam or condensed steam from boiling of reinjected fluids was identified to occur in a number of wells such as H-15D, H-16, H-17D, H-30, H-32, H-33, H-35, H-37, H-41 and H-44. In these wells, the following characteristics are observed. (a) The data points for well H-37 locate close to the N_2 corner in H_2O-CO_2-N_2 ternary diagrams (Figure 7); (b) N_2/Ar molar ratios are lower than that for air saturated water (38), as seen in Figure 8 for well H-35; (c) relatively low gas contents, $CO_2 < 10$ (mol %), as seen in Figure 9 for well H-33; and in general, (d) relatively depleted isotopic compositions.

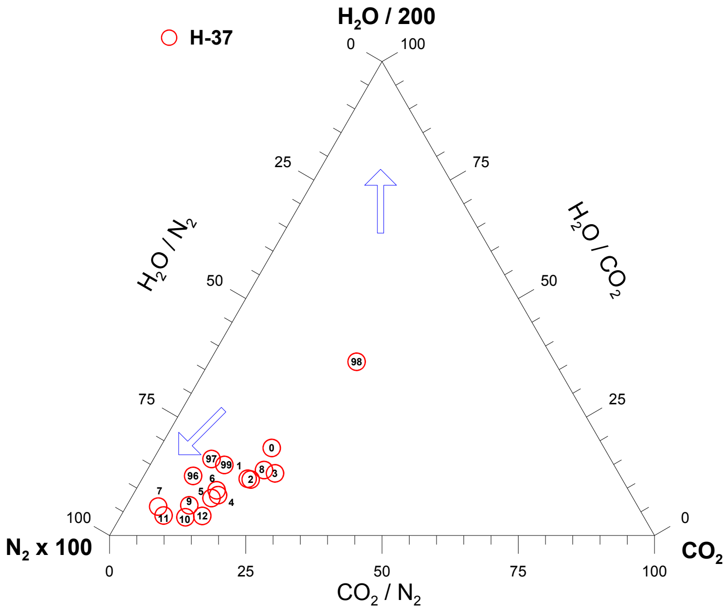

Figure 7: H_2O-CO_2-N_2 ternary diagram for the well H-37.

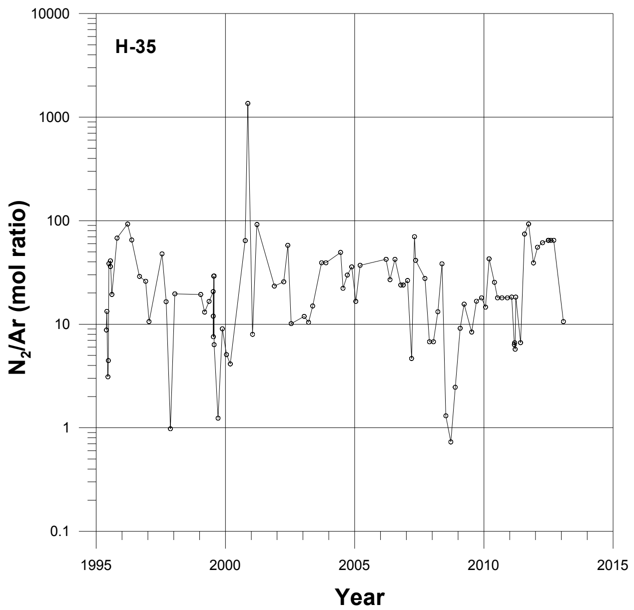

Figure 8: N_2/Ar (mol ratio) for the well H-35.

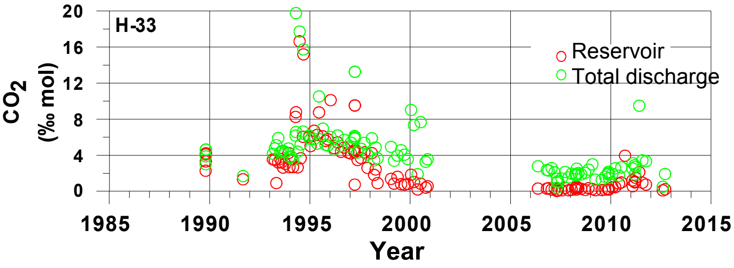

Figure 9: CO_2 of well H-33 over time.

4.1.4 Interaction with deep fluids

This process was identified in wells H-1D, H-3D, H-9, H-11D, H-12, H-19D, H-31 and H-39. The following characteristics are useful to recognize this process. (a) N_2-CO_2-H_2O relative compositions of discharges plot close to the CO_2 corner, which helps to recognize the presence of a deep CO_2 -enriched component from the roots of the system where volcano-hydrothermal interactions occur. This is seen in Figures 4 and 6 for wells H-1, H-1D and H-12. (b) High gas contents, as seen in Figures 3E and 5 C for wells H-1, H-1D and H-12; but (c) low N_2 concentrations; and (d) relatively enriched isotopic compositions of fluids. The isotopic characteristics of Los Humeros wells with respect to δ D vs δ ^{18}O are shown in Figure 10 (Arellano et al, 2003; Barragán et al., 2010). In this Figure, it is seen that isotopic compositions of wells H-1 and H-12 for 1987 data are found on the mixing line with a relatively enriched composition that identifies their interaction with deep fluids. Considering that well H-18, which showed the most isotopic enrichment, was not productive, the isotopic compositions of wells H-1and H-12 constitute the more isotopically enriched end of the mixing line. Besides, according to 1987, data well H-16 was found to have a relatively enriched isotopic composition with respect to its position after it was repaired in 1988, when it became the most isotopically depleted well of the field. It is evident that after the well was repaired, the interaction with deep fluids was minimized.

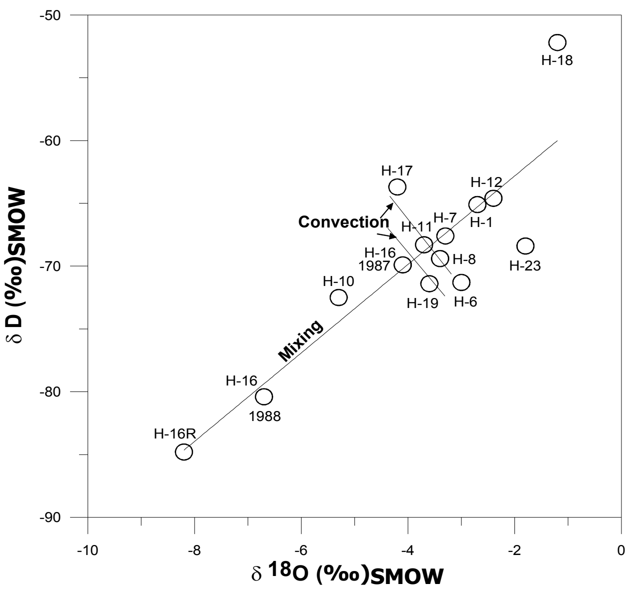

Figure 10: δ D vs δ ^{18}O of Los Humeros wells (Arellano et al, 2003; Barragán et al., 2010).

4.1.5 Decrease in reservoir liquid saturation due to the lack of enough recharge

Liquid saturation in the field has decreased over time. In the beginning of the 1990's the liquid saturation was estimated to be about 90% while in 2012 it was estimated to be about 50%. The wells that showed decreases in liquid saturation were H-3D, H-9, H-12 (shown in Figure 5 D), H-15D, H-31, H-33, H-35, H-36, and H-37.

5. CONCLUSIONS

The analysis of chemical and production data for the Los Humeros geothermal field allowed the response to exploitation of the reservoir to be investigated. According to the results, after 22 years of commercial exploitation of the field, the extraction and reinjection of fluids have induced the occurrence of five physical processes: (a) moderate boiling with gaining steam (b) significant boiling with steam condensation, (c) production of returns from injection, either as liquid or steam, and the production of steam and sometimes condensed steam from boiling of injection fluids, (d) interaction with deep fluids, and (e) decrease in liquid saturation due to insufficient recharge. To overcome this, it is recommended to provide effective artificial recharge to the reservoir to extend the resource lifetime. Reservoir processes can occur for defined time periods and more than one process could be identified in wells. However, the results of this study are useful to support decisions on exploitation strategies.

ACKNOWLEDGEMENTS

The results of this work were part of the project "The Response of the Los Humeros geothermal reservoir to exploitation" conducted in 2013 and funded by the Gerencia de Proyectos Geotermoeléctricos (Comisión Federal de Electricidad, CFE). The authors would like to express their gratitude to the authorities of CFE for authorizing this publication. Recognition is given to the technical staff of the Residencia Los Humeros (CFE) who provided support for this work.

REFERENCES

Arellano, V. M., García, A., Barragán, R. M., Izquierdo, G., Aragón, A., and Nieva, D.: An Updated Conceptual Model of the Los Humeros Geothermal Reservoir (Mexico), *Journal of Volcanology and Geothermal Research*, **124**, (2003), 67-88.

Arellano, V.M., Torres, M.A., and Barragán, R.M.: Thermodynamic Evolution of the Los Azufres, Mexico, Geothermal Reservoir from 1982 to 2002, *Geothermics*, **34**, (2005), 592-616.

Arellano, V.M., Barragán, R.M., Aragón, A., Aguilar, K.M., and García, P.: Respuesta del Yacimiento de Los Humeros a la Explotación. *Final Report,* IIE/11/13121 for the Comisión Federal de Electricidad, Instituto de Investigaciones Eléctricas, Cuernavaca, Morelos, Mexico (2006).

Arellano, V.M., Aragón, A., Barragán, R.M., Flores, M., Ramírez, M., and Tovar, R.: Análisis de Datos de Producción y Condiciones Termodinámicas del Fluido de Alimentación de Pozos de Los Humeros, Pue., *Geotermia, Revista Mexicana de Geoenergía*, **21**, (2008), 21-28.

Arellano, V.M., Barragán, R.M., López, S., Paredes, A., and Aragón, A.: Respuesta del Yacimiento de Los Humeros a la Explotación 2007-2012, *Final Report,* IIE/11/14531/02F, Instituto de Investigaciones Eléctricas for the Comisión Federal de Electricidad, Cuernavaca, Morelos, México (2013).

Barragán, R.M., Arellano, V.M., Flores M., and Tovar R.: Cambios Químicos en Fluidos de Pozos del Campo Geotérmico de Los Humeros (México) (1987-2005). *Geotermia, Revista Mexicana de Geoenergía*, **21**, (2008), 11-20.

Barragán, R. M., Arellano, V. M., Ramírez, M., and Tovar, R.: Geoquímica Isotópica (δ18 O, δD) de Fluidos de Pozos del Campo de Los Humeros, Pue., *Geotermia, Revista Mexicana de Geoenergía*, **23**, (2010), 16-25.

Fournier, R.O., and Potter II, R.W.: A Revised and Expanded Silica (quartz) Geothermometer, *Geothermal Resources Council Bulletin*, (Nov. 1982), 3-12.

Gunn, C., and Freeston, D.: An Integrated Steady-State Wellbore Simulation and Analysis Package, *Proceedings*, 13th Workshop on New Zealand Geothermal, University of Auckland, New Zealand (1991).

Gutiérrez-Negrín, L. C. A., Personal communication, (2014).

Magro, G., Gherardi, F., and Bayon, F.: Noble and Reactive Gases of Palinpinon Geothermal Field (Philippines): Origin, Reservoir Processes and Geodynamic Implications, *Chemical Geology*, **339**, (2013), 4-15.

Nieva, D., and Nieva, R.: Developments in Geothermal Energy in Mexico-Part Twelve: A Cationic Geothermometer for Prospecting of Geothermal Resources, *Heat Recovery Systems & CHP*, **7**, (1987), 243-258.

Quijano, J.L., and Torres, M.: The Los Humeros geothermal reservoir, a case of very high temperature system, *Proceedings,* World Geothermal Congress, Florence, Italy (1995).

Siega, F.L., Salonga, N.D., and D'Amore, F.: Gas Equilibria Controlling H2S in Different Philippine Geothermal Fields, *Proceedings*, 20th Annual PNOC-EDC Geothermal Conference, Manila, Philippines (1999).

Truesdell, A.H., Lippmann, M., Quijano, J.L., and D'Amore, F.: Chemical and Physical Indicators of Reservoir Processes in Exploited High-Temperature, Liquid-Dominated Geothermal Fields, *Proceedings,* World Geothermal Congress, Florence, Italy (1995).