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Reservoir Engineering Analysis Applied to Low Permeability Formations and High Temperature

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ABSTRACT

It was found a zone in a Mexican geothermal field whose producers' wells gradually are changing from two phase flow (mixture water-steam) to one phase (steam). From analysis carried out it was found that normally this behavior is related, among other factors, to unbalance between production mass flow rate and the recharge water entrance. Additionally some relations were found between formation thickness of low permeability and the evolution presented by reservoir. From the evidences found in the analyzed zone, the main conditions prevailing are: existence of high temperature (about 360 °C); and a lack of fluid in the reservoir. Temperature logged is an index of existence a heat source. The analyzed wells were studied in order to carry out their thermodynamic characterization and through correlation between them, a thermal evaluation of the zone. Pressure and temperature profiles measured during drilling stops at different depths were selected as closest conditions to undisturbed state. Were calculated the profiles of thermal gradient along the analyzed wells in the study zone and their corresponding heat flow profiles. The proposed technique in this work allows carry out an integral characterization of the reservoir in order to define the feasibility for using its stored heat for commercial exploitation. The methodology can be applied in geothermal fields with high temperature, but low or null permeability and, low or null recharge water entrance.

1. INTRODUCTION

Most of the energy currently used comes from fossil-fuel resources such as coal, oil, and gas. However these traditional fossil-fuel resources are finite. The increasing world population and the continued spread of industrialization will result in increased energy demands. A great advantage is that geothermal energy is far cleaner than any of the fossil fuels that now dominate the energy supply around the world.

As with other types of energy resources, geothermal energy should be developed using methods that minimize environmental impacts. Compared with most other forms of power production, geothermal is environmentally benign. A typical geothermal plant using hot water and steam to generate electricity emits about 1 percent of the sulfur dioxide (SO_2), less than 1 percent of the nitrous oxides (N_2O), and 5 percent of the carbon dioxide (CO_2) emitted by a coal-fired plant of equal size.

The exploratory phases of a geothermal project are marked by not only high capital costs but also a high percent of failure, when high fluid temperatures and flow rates are not located (DOE, 2012). The combination of high risk and high capital costs can make financing geothermal projects difficult and expensive.

An important issue is the disposal of cooled geothermal water left after heat extraction or steam separation during the energy-production cycle. In the earliest geothermal developments, such "waste" water was disposed of in surface ponds or rivers. Now, in almost every geothermal development worldwide, this water is injected through wells back into the subsurface. This now common practice not only minimizes the chance of contaminating surface waters, but it also provides replenishing water to help sustain a hydrothermal system, thereby increasing the total amount of heat that can be extracted over its productive life.

Many rocks at cost-effective drilling depths are too hot to provide large amounts of potentially usable thermal energy, however they are not enough permeable to form a natural hydrothermal reservoir. By increasing permeability, additional thermal energy can be recovered. In some cases this has been accomplished by creating new fractures through injection of water at high pressure. Some reservoirs have been considered uneconomic because of low permeability. Tapping into the vast store of thermal energy in hot, low-permeability rock may release much more of the Earth's abundant natural heat. However it is necessary to carry out tests of enhancement technologies, for demonstrating the commercial viability of heat extraction (Duffield and Sass, 2003).

The ordinary concept of an Enhanced Geothermal System (EGS) is the creation or the support of a geothermal reservoir. The basic assumption in an EGS is the low formation permeability, scarce or null liquid and without a recharge source. These problems can be solved by operations to rock formation fracturing, and water recharge through injection wells.

Reservoir characterization involves: Identify sources, resource knowledge and database development, electricity capacity calculation, estimation of the various development component and operating costs and construction of graphical curves including costs vs cumulative capacity. The main technical tools in this stage are: Database creation; temperature and pressure profiles; depth; aerial extent; use of simulator programs; batch process, among others (Petty and Porro, 2007).

One of the methods of evaluating the potential for HDR development in a region is to examine its geothermal gradient (Duchane and Brown, 2002). The geothermal gradient varies widely from place to place, being much higher in tectonically active regions and in areas of volcanic activity.

To date a lack of technological research and development constrains the deployment of EGS power plants. Most technologies used in EGS, such as drilling and geologic imagery techniques, are not yet adapted for specific use in EGS development. The development of EGS consistently is greatly limited due to a lack of understanding of how geothermal reservoirs occur in nature. So researching the geological characteristics of natural geothermal resources is essential for such systems development. Additionally the most promising EGS sites often occur great distances from regions of large electricity consumption, or load centers. Therefore, its use is focused mainly to little communities.

2. BACKGROUND

Los Alamos National laboratory was actively engaged in field testing and demonstration the hot dry rock geothermal energy concept during the period from 1974 through 1995. The tests were carried out in the Fenton Hill hot dry rock site in the Jemez Mountains of north-central New México (Brown, 1995). However after this project ended, a vast amount of information was obtained concerning the characteristics and performance of confined hot dry rock reservoirs, some of them could be applied in new projects. The use of the reservoir heat for power generation represents a great advantage in the solution of global warming by avoiding combustion of fossil fuels, which increases atmospheric CO2. Another advantage is the possibility of power availability in marginal regions (Brown, 2000).

In geothermal engineering had been applied different methodologies in order to improve the wells productivity and retard their decline trend. The final goal is to rescue the production including no-producer wells. The most used techniques, among others, are: Chemical stimulations which influence on the rock matrix (Katagiri et al., 1980), Fracturing by thermal shock (Bodvarsson and Tsang, 2012), Hydraulic fracturing (Keiiti et al., 2012). Under controlled conditions the thermal shock has shown successful results through opening fractures near of injection wells (Bodvarsson and Tsang, 2012). However in geothermal systems the successful of all the operations to improve productivity depends from the feeding characteristics to the reservoir.

Different studies have carried out, related to heat recovery from geothermal reservoirs with low permeability and recharge (Kruger et al., 2000, Buttner and Huenges, 2003; Erdlac et al., 2007; DiPippo, 2004; Fridleifsson et al., 2005; Sanyal and Butler, 2009). However the geothermal reservoirs characteristics are the influence factors for taking decisions about field´s development.

It was observed that unbalance between the recharge and flow rate extraction produces contrasting results influencing productivity decline. If the recharge water entrance is greater than produced mass flow rate, could be that the fluid does not extract all the heat from rock formation, resulting in a gradually decrease in production enthalpy and decline in production parameters.

In some cases the recharge water entrance is too low compared with the produced mass flow resulting fluid evolution to a single phase (steam). The observed effects are increases in the steam quality fraction and fluid enthalpy, decreasing the mass flow rate. The critical condition of such behavior is that the producer wells arrive to operative conditions of their economic limit. However into the rock formation even remains stored heat which could be extracted through others non conventional methods. Some sections of Mexican geothermal fields were identified with these characteristics showing increasing steam flow rate and enthalpy.

3. NUMERICAL EVALUATION

The heat conduction equation, which can be applied to geothermal systems, has next expression (Rybach et al., 1981):

$$q = K_T \left(\frac{\Delta T}{z}\right) \tag{1}$$

Where q (W/m^2) is the heat flow in a squared meter, ΔT (°C) is the temperature difference between two levels, z (m) is the longitude between two depths and K_T (W/m °C) is the thermal conductivity of the rock.

As can be seen in Equation (1), [ΔT/z] is referred to the rock formation thermal gradient. The thermal conductivity is equivalent to heat flow by a second which crosses an area of 1 m^2, under a thermal gradient of 1 (°C/m) in the flow direction.

The above equation represents commonly the called volumetric method, used for geothermal reserves estimation. The advantage of this method is a quickly application for the generality of geologic resources. The used parameters can be measured or estimated however the probable errors could be compensated at least partially.

4. METHODOLOGY

Three crucial factors are needed for properly function of EGS which are: water, permeability of the rock formation and heat. However in some systems the water is not enough for maintain a continuous operation and the recharge water entrance is low or null. The present analysis starts from the assumption that in the field, there are some wells with productivity decline and also there are no-producer wells. However in all the cases the common characteristic is high temperature and low permeability.

Different methodologies for evaluating EGS have been proposed by several authors (Duchane and Brown, 2002; Petty and Porro, 2007; Sanyal and Butler, 2009; among others), all of these focused to create a reservoir feeded by water. However the main objective is the stored heat evaluation for apply appropriate techniques for its recovery. The basic technical tool for heat evaluation stored in the rock formation is through reservoir characterization, which involves next tasks:

Identify the parameters behavior in production wells neighboring to the study zone (mass flow rate, pressure, enthalpy, steam fraction).

Acquire, select and create a database with the information needed of the wells in the study area. The information needed involves hydrogeology study of the area, wells location, measured characteristics during wells drilling, mechanical characteristics of the wells in the study zone, changes in chemical composition of drilling fluids, circulation losses fluid during drilling, profiles pressure and temperature measured in wells, etc., among others. In the case of producer wells the required information is the production history with all the related parameters, such as mass flow rate, pressure, enthalpy, mass fraction, chemical composition, etc., among others.

Determine the temperatures distribution in the study section, which are used for defining the area with possibility for store heat.

If it is possible determine the fluid chemical composition behavior of production wells in the study zone, (Ca, Cl, B, Na, SiO_2, etc., among others). These chemical components are indicative of thermal environment.

Determine the thicknesses permeability conditions along profile of producers and no-producer wells. This parameter is useful in the traditional EGS, due to represent the fluid transfer ability.

Using temperature measurements, determine the thermal gradient, heating index and the bottom estimated temperature. The thermal gradient is used for identify useful depths with probable stored heat. The heating index along profile of the well is used for identify the zone with heat feed. The bottom temperature is used for defining the reservoir temperature.

Determine the thicknesses in each analyzed well, using the temperature profiles along the depth.

Determine the probable area for heat store using petrophysical and thermodynamic reservoir characteristics.

From the established bounds of temperatures working for the system, determine the volume of rock formation with capability for heat storage.

Using all the information about reservoir petrophysical characteristics and measured parameters in wells located in study area, calculate the stored heat in the determined rock volume.

In this study only are described the needed requirements related with reservoir characterization as a first stage of EGS. After evaluating heat stored in a rock volume, it is recommended to carry out feasibility economic analysis for install a power plant. However in some cases not all the information is available, therefore it will be necessary to use only the available for carry out the best possible analysis.

5. ANALYSIS OF A FIELD CASE

From historical behavior of some wells of Mexican geothermal fields it was observed their gradual trends to change from a two phase mixture (water–steam) to only one phase (steam). Through the production analysis, it was found that this typical behavior is related with an unbalanced between mass flow production and the recharge water entrance to the system. Additionally to this behavior it was observed lack of permeability in the production thicknesses of the wells.

The shown characteristics by the analyzed system are a good feeding of heat from a deep source (Ferriz and Mahood, 1984) but a lack of transport vehicle for its extraction to the surface. In the analyzed area there are producers as no-producer wells but the producer wells are changing their productive characteristics to a decline. A highlight is that in the study area is common to find a non-producer too close of a production well. It seems that the heterogeneous characteristics of this field are the reason for the existence too near of both type of wells, as can be seen in Figure 1. In the map of last figure, the producer wells (P) are marked with red, while no-producer wells (NP) are marked with yellow. This found behavior is a technical base to carry out a study of the zone conditions and to evaluate the feasibility of heat storage in it. The correlation of parameters between the analyzed wells was used for determining their distribution along the zone. The formation conditions chosen as nearby to unperturbed state, were the temperature and pressure measured with standby times (at least 24 hrs) during drilling.

Due to a lack of transient pressure data analysis, only a qualitative idea about permeability was obtained from the circulation fluid losses during drilling. Because this work is to define an area of the field for analysis about the possibility of heat storage, data of producer wells P1, P2 and P3 and unproductive wells NP1, NP2 and NP3 are used.

In this particular section, the producer wells are grouped to West side, although it can be found nearby no-producer wells. The production behavior through exploitation time in the producer wells is being monitored by measurements at surface conditions. From observations in produced mass flow rate by the wells, highlights the changes in the steam-water ratio, which results in a decrease of the liquid fraction. In order to analyze production parameters at reservoir conditions, it was necessary to transform the parameters at bottom hole conditions. It was used the WELLSIM simulator program (Freeston and Calum, 1993) with production measurements carried out at surface conditions for obtain these parameters at reservoir conditions. Figures 2, 3 and 4 show the behavior of pressure-enthalpy of the producer wells P1, P2 and P3 with their corresponding saturation state into the phase's diagram.

Figure 1: Study area and well´s locations, showing the producers (P) with red marks and non-producers (NP) with yellow marks.

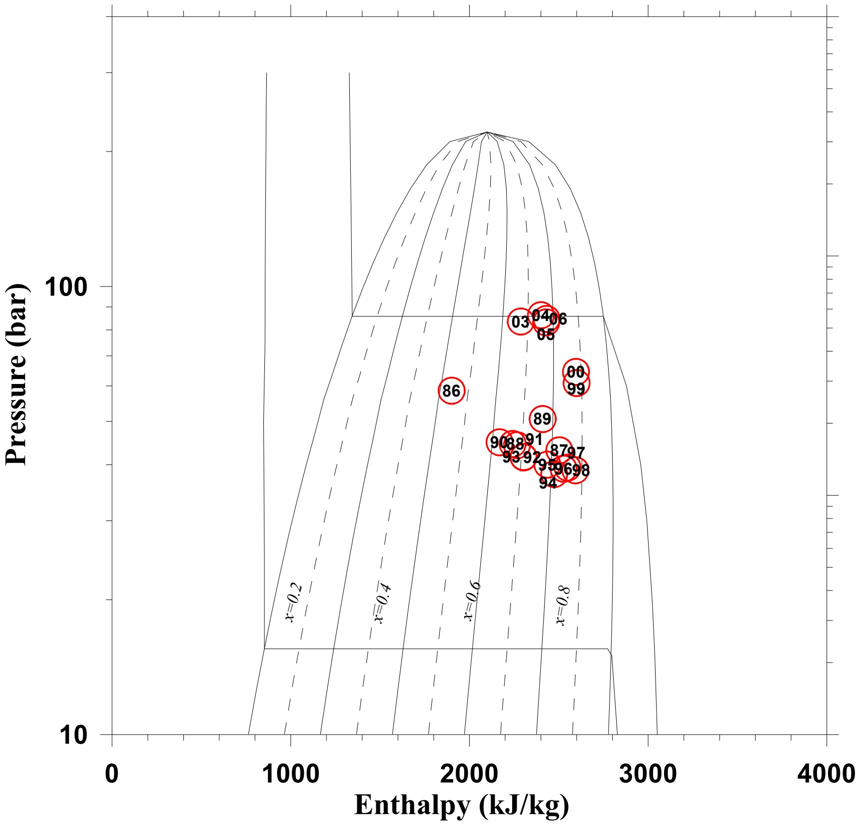

Figure 2: Behavior of bottom pressure and enthalpy of the well P1, through its exploitation time.

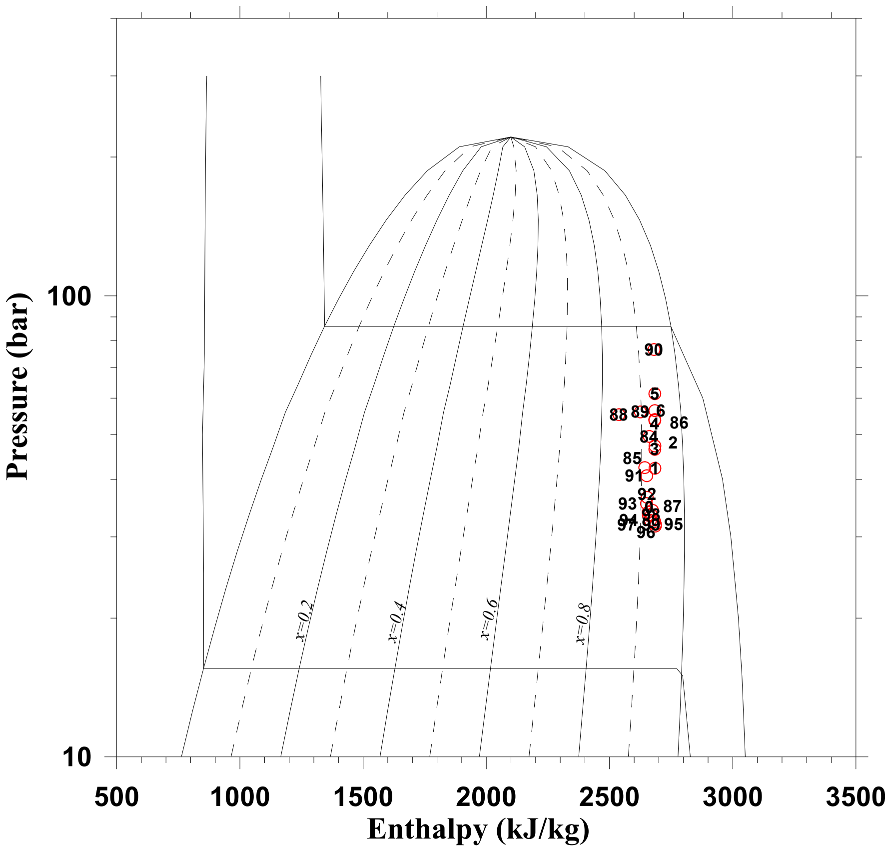

Figure 3: Behavior of bottom pressure and enthalpy of the well P2, through its exploitation time.

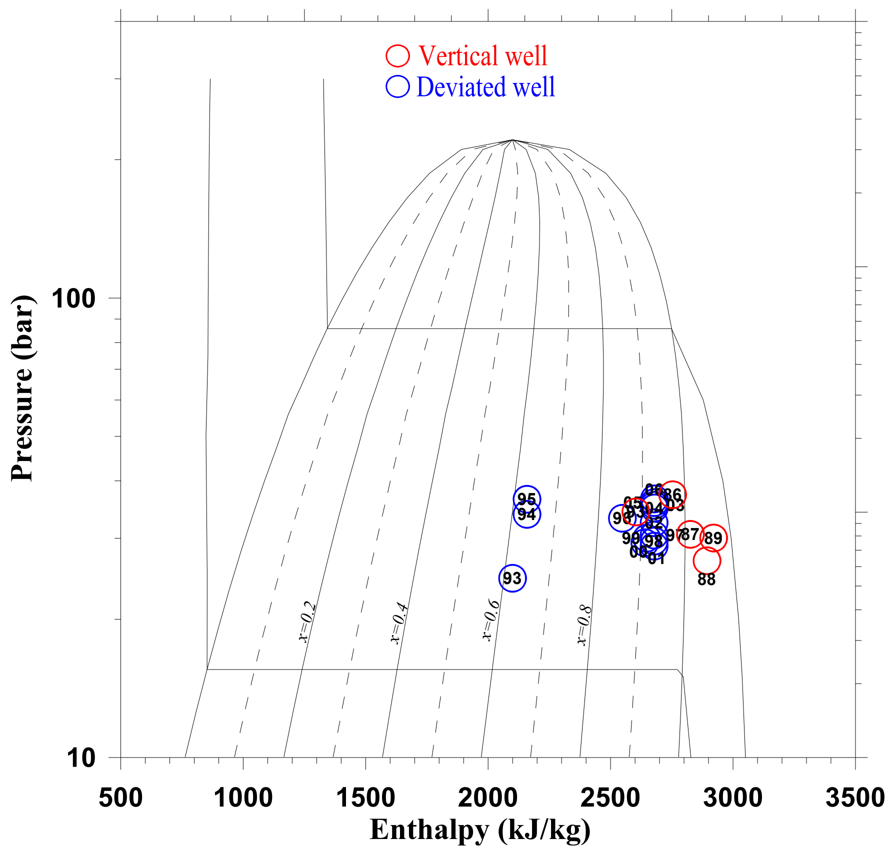

Figure 4: Behavior of bottom pressure and enthalpy of the wells P3, through its exploitation time (red circles indicate the original well, blue circles correspond to deviated well).

According to behavior shown by the three production wells of this analyzed area it can be observed evolution in the steam fraction with trend to achieve dry conditions.

In relation with permeability of rock formation in the study zone the only available information was the report of circulation fluid losses during drilling of the wells. Were constructed graphs of fluid lost volumes along the profiles of each well, which are shown in Figure 5. One of the main characteristics identified in this field during the wells drilling is that the field in general showed low volumes of circulation losses during drilling. The major volumes of fluid circulation losses were found at shallow depths in each well as can be seen in these graphs. But in all the wells studied it was found similar behavior in volumes of fluid circulation losses during drilling. It is important to emphasize that the major volumes identified at shallow depths were in some cases greater to 50 m^3/hr. This type of behavior is found in both producers as in non-producer wells. Which is the base of assuming that at shallow depths, the losses fluid circulation are not related with geothermal reservoir.

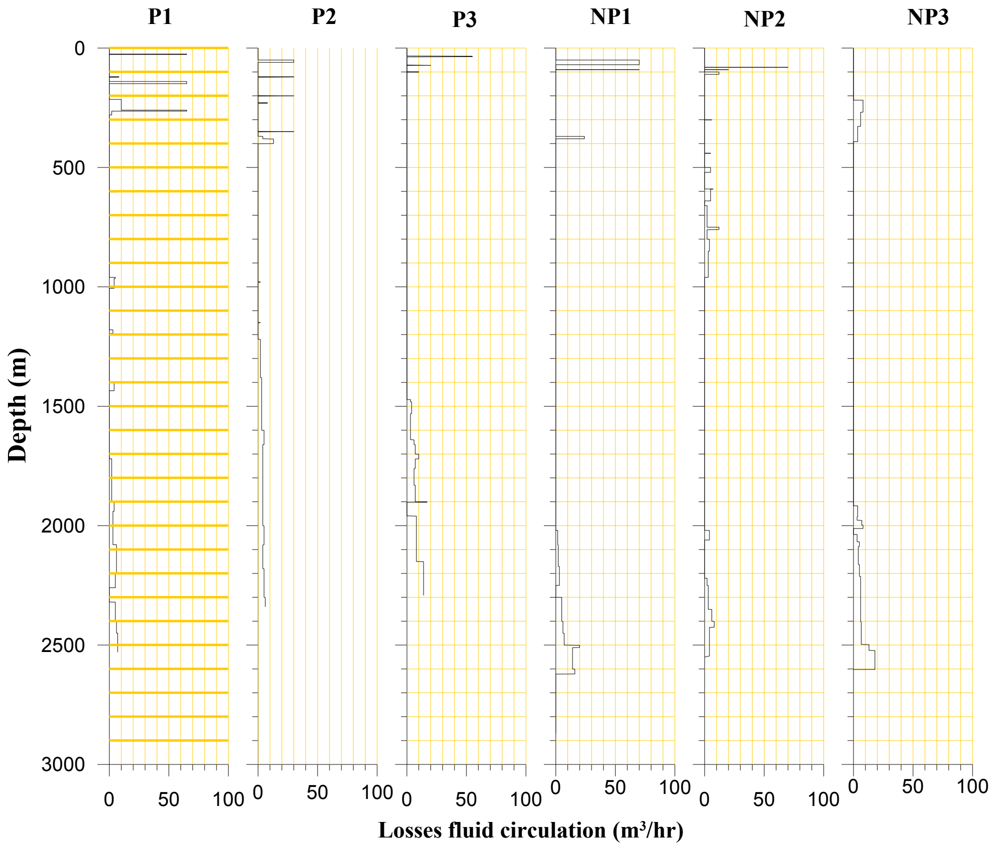

Figure 5: Schemes profiles of losses fluid circulation during drilling of the six wells analyzed in this work.

The fluid circulation losses measured at deep zones of the analyzed wells have been small, in the majority of cases; the variation never was more than m^3/hr. Even in some cases were found greater volumes of fluid circulation losses in non-producer wells than in producers. However it can be assumed that this behavior could be related with that permeability decreases with increase of the depth.

It can be seen from Figure 5, that losses fluid circulation in non-producer wells are higher than those in producing wells.

In order to analyze temperature behavior in the study zone were used temperature logs taken at 24 hrs of standby in the well at their total depth before completion stage. These conditions were selected due to information availability and for consistency conserving in the comparison of measured temperatures with all the wells. The desirable would have been take long times possible toward achieve steady state. The graphs of Figure 6 show the temperature profiles of the six analyzed wells, identifying with red the producer wells and with blue, the no-producer wells.

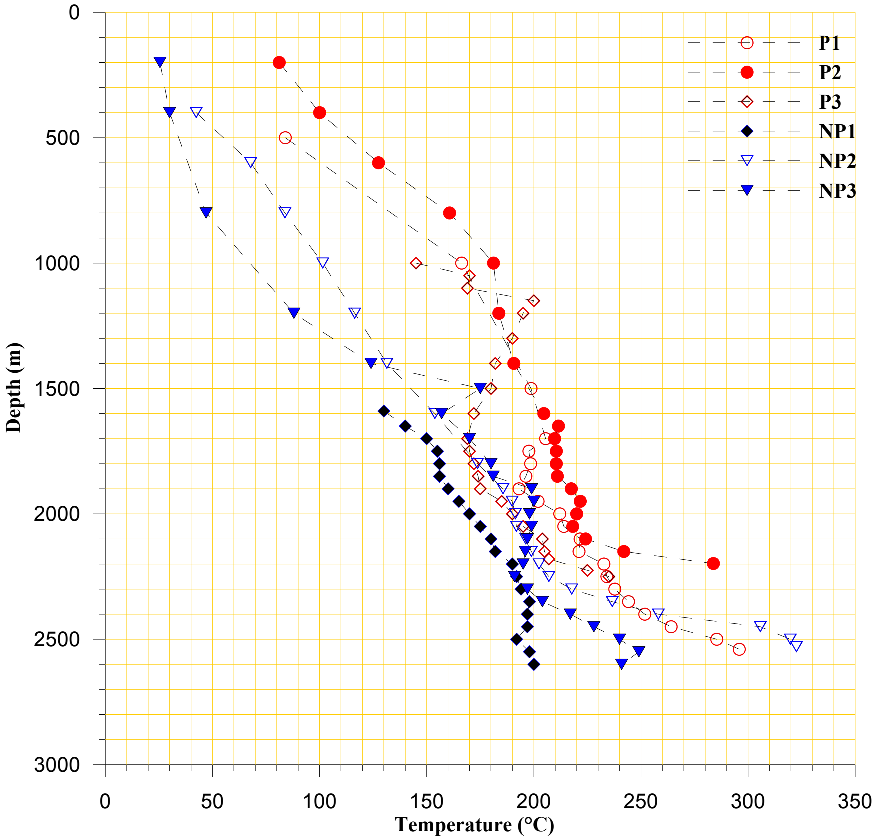

Figure 6: Temperature profiles in the analyzed wells, measured at 24 hrs. of standby after drilling stop.

In general form it can be appreciate a normal behavior of temperature profiles in the analyzed wells, i.e., temperatures in non-producer wells are lower than those in producer wells. However it is appropriate to highlight the behavior of temperature profile of well NP2, which, shows a quickly increase in intervals nearby to its total depth. However an inverse behavior was found in this well, which showed less losses fluid circulation at these depth levels.

Using temperature measurements in the analyzed wells was done a correlation between wells and were obtained isothermal distributions along the study area. In this work it was established as bound of temperatures for the analysis of the heat flow in the zone, those between 200 and 300 °C. By this reason it was emphasized in the isotherms distribution at these two temperatures and Figures 7(A) and 7(B) show both.

Overlapping the two isothermal surfaces was used for obtaining the net thickness of the rock formation with capability for heat storage. Figure 8 shows a general scheme which could be used for volumetric determination of the study area using as temperature boundaries 200 and 300 °C. From this figure it can be appreciated that at eastern section, the temperature distribution, are found at deeper levels.

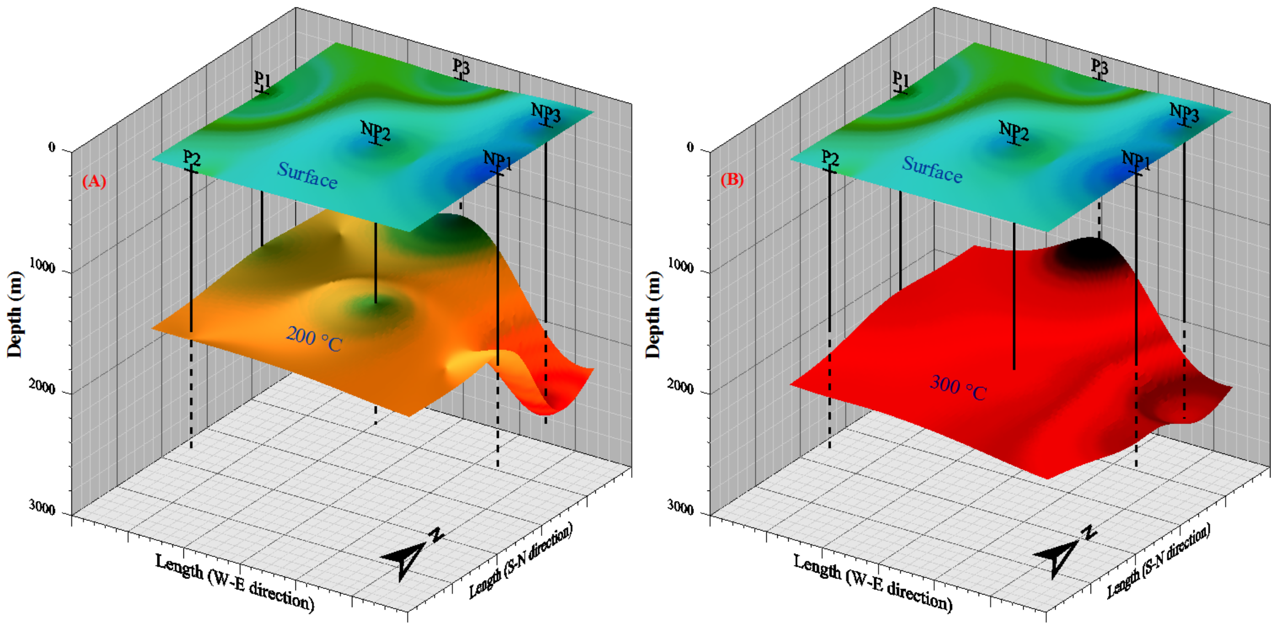

Figure 7: Isothermal distribution in the study area which was determined using temperature measurements of the analyzed wells. 7(A) shows the isothermal configuration of 200 °C, while 7(B) shows the corresponding distribution for 300 °C.

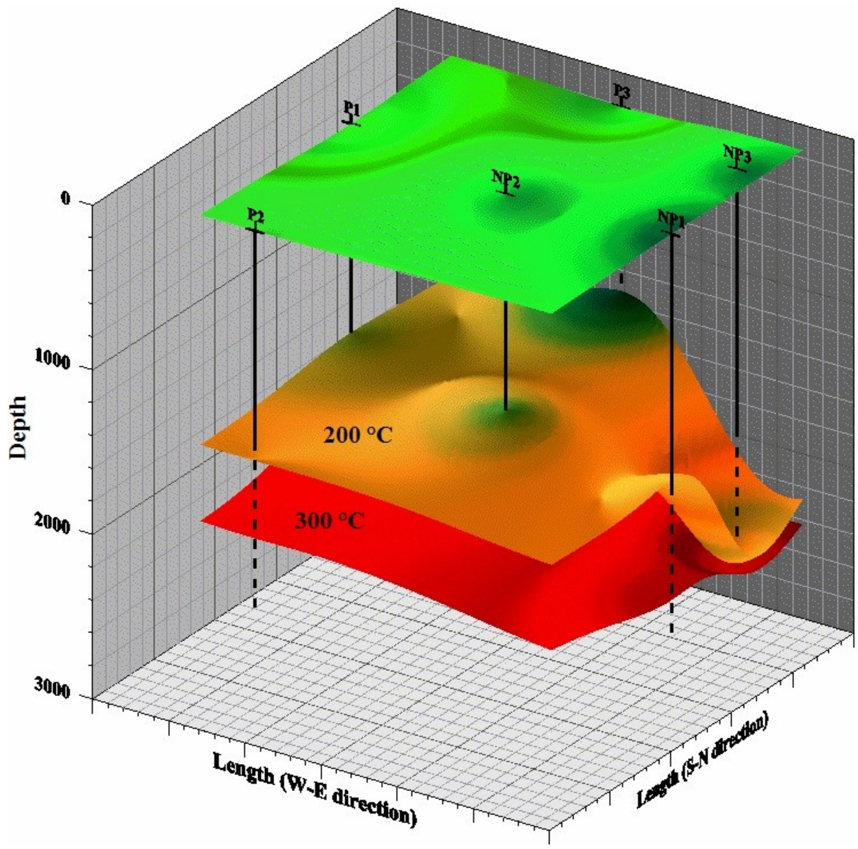

Figure 8: Visualization of the rock formation volume with capacity for heat storage, having established, 200 and 300 °C as boundary temperatures.

Through the use of measurements of temperature profiles in the analyzed wells were calculated the thermal gradients at different depths along each one of these. Were calculated values of thermal gradient at depths since 1500 m to the total depth of each well, whose results are shown in Table 1.

The heat flow occurring along the profiles of the analyzed wells in the study zone was calculated using Equation (1).

Table 1: Calculated thermal gradient profiles along depths of analyzed wells in the study zone.

Depth (m)	ΔT/Δz (°C/m)					
	P1	P2	P3	NP1	NP2	NP3
1500	0.06	0.04	-0.02	0.04	0.11	0.51
1800	0.02	0.01	0.04	0.08	0.10	0.10
2000	0.20	0.08	0.10	0.05	0.03	0.02
2100	0.15	0.12	0.18	0.04	0.08	0.02
2200	0.23	0.87	0.40	0.08	0.07	0.12
2300	0.07		0.40	0.04	0.21	0.12
2400	0.15			0.08	0.65	0.26
2500	0.43			0.12	0.28	0.24
2550	0.26			0.12	0.10	0.18

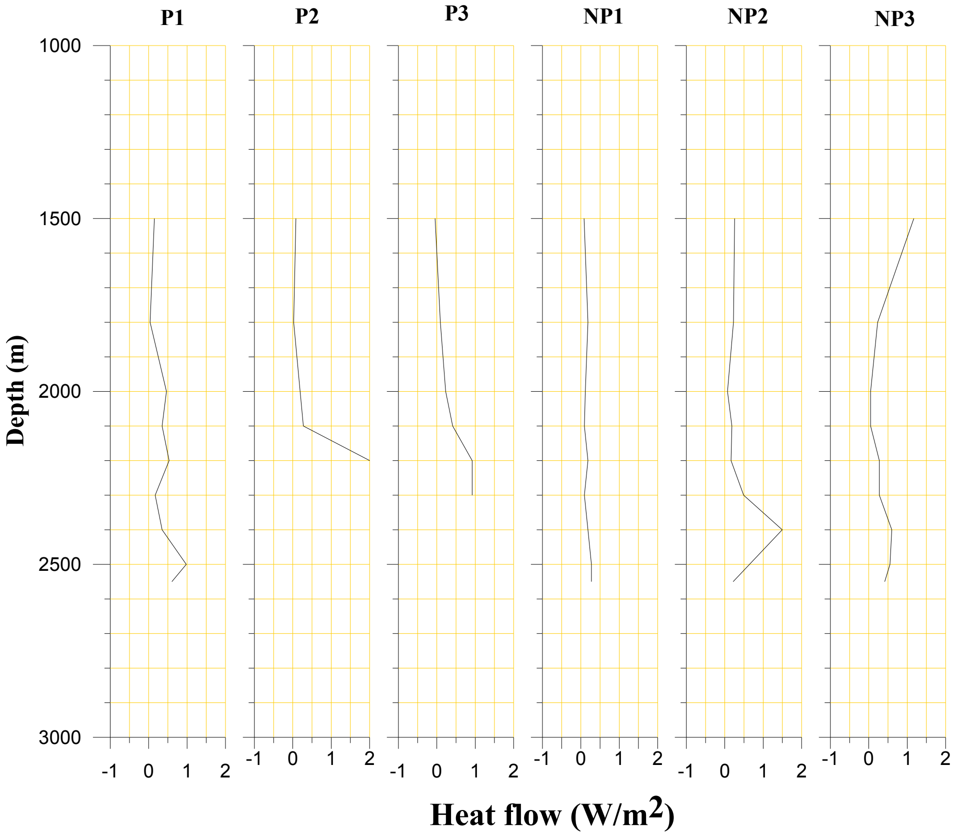

Figure 9: Thermal flow calculated along the profiles of the analyzed wells located in the study zone.

6. DISCUSSION RESULTS

In the producer well P1 it can be see that at its early production stage, the steam fraction is about 0.55 however with exploitation time, steam fraction was increasing to achieve values near of 0.9.

The mass production quality of the well P2 been constant in values about 0.9. The bottom-hole pressures vary in a rank between 30 and 80 bars which can be considered useful for the field operation systems.

The production well P3 originally was vertical drilled, but after five years of operation, its production decreased and the steam fraction increased to values near to 1. The decrease in its performance shown was the technical base for its repair and its deviated drilling. At the early exploitation stage after the well deviation, its produced steam quality started from 0.6, however after again increased to a values of about 0.85. The reservoir calculated pressures with WELLSIM program vary between 25 and 40 bar.

Low volumes of losses fluid circulation during drilling in the well NP2 were measured, which influences in calculated thermal gradient of 0.65 (°C/m) at 2400 m depth. Analyzing the temperature profile of well NP2, shown in Figure 6, it is possible to find some explanation about its high value of calculated thermal gradient. It can be observed that in the last interval depth (100 m), the temperature increases 65 °C, which are enough to achieve the highest value of the majority the analyzed wells.

Due to that there are uncertainties in the knowledge of thermal parameters of rock formation, for calculating heat flow, was assumed constant thermal conductivity along the profiles of analyzed wells. However, similar to behavior thermal gradient, it can observe that calculated curve of heat flow for the well NP2 is the highest of analyzed wells. The curves of heat flow calculated in producer wells (P1, P2 and P3) can be considered under normal behavior, according to the obtained results.

7. CONCLUSIONS

Were applied different technical tools of reservoir engineering, in the several analyses, in order to achieve criteria for making decisions in feasible projects of the field heat recovery.

The different techniques applied in the reservoir engineering allow characterize the overall reservoir or only a section of this.

In the studied section, it was found that analysis of the general system involves petrophysical properties, physicochemical behavior of fluids, mass flow rate, water entrance recharge, among other parameters. The productivity decline is a result of combinations between these variables.

It was identified a zone, in a Mexican geothermal field with high temperature, low permeability besides a quick decline rate in its wells. Evidences found indicate that in this zone, there is an unbalance between produced mass flow and the recharge water entrance.

The heterogeneity of the study zone of the reservoir, is a factor for to find producer wells, too nearby with no-producer wells neighboring.

The analyzed parameters in the studied zone have allowed carry out its characterization for reservoir understanding behavior, and planning its development. The technique used for defining isotherm depths of 200 and 300 °C allows configure thicknesses of the study zone. Using data of losses circulation fluid during drilling was identified qualitatively, relation between depths and the corresponding permeability.

In this research were calculated the profiles of thermal gradient along the analyzed wells in the study zone and their respective heat flow profiles.

The proposed technique in this work allows carry out an integral characterization of the reservoir in order to define the feasibility for using its stored heat for commercial exploitation. The methodology can be applied in geothermal fields with high temperature, but low or null permeability and, low or null recharge water entrance.

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REFERENCES

Bodvarsson G. S., and Tsang C. F.: Injection and thermal breakthrough in fractured geothermal reservoirs, Journal of Geophysical Research: *Solid Earth*, **87** (2), (2012), 1031-1048.

Brown W. D.: The US Hot Dry Rock Program - 20 Years of Experience in Reservoir Testing, *Proceedings*, World Geothermal Congress, Florence, Italy (1995).

Brown W. D.: A hot dry rock geothermal energy concept utilizing supercritical CO_2 instead of water, *Proceedings* 25th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford CA (2000).

Buttner, G. and Huenges E.: The heat transfer in the region of the Mauna Kea (Hawaii)—Constraints from borehole temperature measurements and coupled thermo-hydraulic modeling, *Tectonophysics*, **371**, (2003), 23– 40.

DiPippo R.: Second Law assessment of binary plants generating power from low-temperature geothermal fluids, *Geothermics*, **33**, (2004), 565-586.

DOE, 2012. “Geothermal Technologies Program - EGS Systems Demonstration.” http://www4.eere.energy.gov/geothermal/projects?filter[field_project_area][0]=%2249%22

Duchane D. and Brown D.: Hot dry rock (HDR) geothermal energy research and development at Fenton Hill, New México, *GHC Bulletin* December, (2002), 13 – 19.

Duffield W. A., and Sass J. H.: Geothermal energy clean power from the Earth’s heat, USGS Science for a changing world, U. S. Department of the Interior, Circular 1249, *U. S. Geological Survey*, Reston, Virginia USA, (2003), 43 p.

Erdlac, R.J. Jr., Armour L., Lee R., Snyder S., Sorensen M., Matteucci M., and Horton J.: Ongoing resource assessment of geothermal energy from sedimentary basins in Texas, *Proceeding*s 32th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2007).

Ferriz Dominguez H., and Mahood A.: Eruption rates and compositional trends at Los Humeros Volcanic Center, Puebla., Mexico. *J. Geophys. Res*, **89**, (1984.), 8511-8524.

Freeston D., and Calum G.: Wellbore simulations – Case studies, *Proceedings,* 18th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (1993).

Fridleifsson G. O., Elders W. A., Thorhallsson S., and Albertsson A.: The Iceland Deep Drilling Project –A Search for Unconventional (Supercritical) Geothermal Resources, *Proceedings* World Geothermal Congress, Antalya, Turkey, (2005).

Katagiri K., W., Ott K., and Nutley B. G.: Hydraulic fracturing aids geothermal field development, *World Oil* **191** (Dec.), (1980), 75 – 88.

Keiiti A., M., Fehler, R. L. Aamodt, J. N. Albright, R. M., Potter, J., and Tester W.: Interpretation of seismic data from hydraulic fracturing experiments at the Fenton Hill, New Mexico, hot dry rock geothermal site, Journal of Geophysical Research: *Solid Earth*, **87** (2), (2012), 936 – 944.

Petty S., and Porro G.: Updated U. S. geothermal supply characterization, *Proceedings* 32th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford CA (2007).

Rybach L., Leroy J., and Muffler P.: Geothermal systems: Principles and case histories, Wiley, New York USA, (1981).

Sanyal S. K., and Butler S. J.: Feasibility of geothermal power generation from petroleum wells. Trans. *Geothermal Resources Council*, **33**, (2009), 673 – 680.