Current Journal of Applied Science and Technology

39(19): 91-111, 2020; Article no.CJAST.58802
ISSN: 2457-1024
(Past name: British Journal of Applied Science & Technology, Past ISSN: 2231-0843,
NLM ID: 101664541)

Methodology Applied for Thickness Selection and Stored Heat Evaluation in Non-producer Geothermal Wells in Order to Its Investment Rescue

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/CJAST/2020/v39i1930796
Editor(s):
(1) Dr. Chien-Jen Wang, National University of Tainan, Taiwan.
Reviewers:
(1) J. Venkatesu Naik, Sri Padmavati Mahila Visvavidyalayam, India.
(2) D. K. Chaturvedi, Dayalbagh Educational Institute, India.
Complete Peer review History: http://www.sdiarticle4.com/review-history/58802

Original Research Article

Received 08 May 2020
Accepted 14 July 2020
Published 22 July 2020

ABSTRACT

An assessment methodology of stored heat in rock formation surrounding to wellbore in geothermal systems is shown. Due to geothermal systems generally are nested in volcanic rock, it is characteristic its heterogeneous behavior. Proposed methodology starts since zone selection with possibilities of heat store. This methodology is focused to be applied in geothermal reservoirs with tendency to production decline, due to low permeability and unbalance between exploitation and water recharge. Because the high costs of drilling geothermal wells, methodology shown in this work is proposed to be applied in those with production decline or non-producers, in order to rescue its investment. The objective is to select the thickness with heat, evaluate its storage, design the appropriate instrumentation for its recovery, its energy conversion and rescue its investment done. The different designs for energy recovery using non-conventional methods to those, used habitually are reviewed. Each one of the variables for stored heat calculation was determined using technical tools of reservoir engineering. A parametric analysis about variables sensitivity (porosity and

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drainage radius) for determining thermal energy and corresponding electric energy of analyzed rock volume is done. Practical application of this methodology was carried out using data of one of wells of Los Humeros Mexican geothermal field.

Keywords: Los Humeros Geothermal Field (LHGF); low permeability; thickness evaluation; heat storage; high temperature; thermal energy; electricity generation.

1. INTRODUCTION

Optimal geothermal energy extraction requires an understanding of both the thermodynamic, fluid dynamical properties; rock properties and thickness of the geothermal reservoir and its relation with heat feed and recharge water entrance. These thermophysical properties depend not only on temperature, but also on fluid composition, which typically varies from site to site. These may also change over time as a result of different operations related with exploitation. Among others, can be mention the introduction of fluids into the geothermal reservoir (injection), geochemical reactions between fluid species and rock minerals, and temperature variation as the fluid flows through the reservoir [1]. It is, therefore, important to understand the extent and manner in which fluid composition affects the efficiency of geothermal energy production and its associated power (i.e. electricity) generation of geothermal power plants.

The conventional exploitation way of geothermal energy to date, mainly is from hydrothermal sources, which besides heat contain fluids at saturation conditions (pressure, temperature, density, enthalpy, etc.). Under such conditions fluid is discharged to the turbine coupled to electricity generator. This technique uses the geothermal fluid (a mixture of water and steam) as transport mean for energy extraction to surface. Even though, the hydrothermal reservoirs contain appropriate conditions for heat energy extraction they need a support of recharge entrance equivalent to mass extracted in order to maintain equilibrium in the reservoir. The reservoir operation under equilibrium conditions leads to that geothermal energy be a renewable source. However the unbalanced between exploitation and recharge would produce, that geothermal fluid changes from fluid phase to two phase (water-steam). If the unbalanced continues, changes from two phases to one phase (steam) and in critical cases until dry steam.

Along the world, different geothermal zones have identified which contain heat but lacking of water recharge. Normally the lack of recharge is associated with low permeability of rock formation which makes difficult the underground fluid flow. So these fields are not hydrothermal and cannot be exploited by conventional techniques. These system geothermal types are known as hot dry rock (HDR) and are characterized by high temperature, low permeability and null or low recharge entrance. Another term used for these systems type is also as, "petrothermal systems" [2]. Majority of these HDR systems are located in zones still without exploitation. However through the use of available geotechnical information it can be determined its stored energy capacity from the stored heat in rock volume.

More than 80 percentage of thermal sources in the Earth are of HDR type but its exploitation by conventional techniques is of low efficiency due to lack of water which works as transport vehicle. Motivation of such circumstances was the base for Alamos National laboratory actively engaged in field testing and demonstration the HDR geothermal energy extraction concept during the period between 1974 and 1995 [3]. The tests were carried out in the Fenton Hill hot dry rock site in the Jemez Mountains of north-central New México [4,5]. Lessons of this project was focused to amount of information obtained concerning the characteristics and performance of confined hot dry rock reservoirs, originating the technique known as Enhanced Geothermal Systems (EGS) [5,6,7].

EGS concept projects creation of an artificially permeable reservoir, through rock formation fracturing, in order to achieve connection between two wells, one of them, injector and other one producer. The objective is that injected water increase its temperature by contact with reservoir hot rock and in this way would acquire thermodynamic conditions for flowing to surface. Heat transfer to injected fluid gives it appropriate energy for surface discharge with enough pressure for moving a turbine coupled to a electricity generator. Initially EGS was projected for artificially created reservoirs, so that extract economical amounts of heat from low permeability and/or porosity geothermal resources [6,8]. The advantage of geothermal energy besides its renewability is its persistence, avoiding operations be stop by external factor, such as lacking of sun, wind, etc., among others.

The objective of this work is focused to show a heat stored evaluation methodology, using wells data located in a section of Los Humeros geothermal field (LHGF). This is classified as a geothermal field with high temperature but low permeability [9]. Even though the LHGF is the third producer field of electric generation in Mexico, heterogeneity of its rock formation, influences in production performance. In this way some wells showed evolution to dry steam after have started to produce a mixture with two phases (steam/water).

2. BACKGROUND REVIEW

In previous studies [9,10], it has been annotated the heterogeneous behavior of LHGF, where each of its zones tend to the compartmentation. It can be found that while some wells are producers, some others, located in the near vicinity are non-producers. In spite of lacking of productive characteristics of some of the LHGF wells, highlights high temperature in the majority of these. According to these conditions (high temperature, production lack, low permeability) it is appropriate evaluate the heat store in reservoir rock for its extraction using some technique different to the conventional.

Due to in this work the study is related to a section of LHGF with high temperature but production lack, it can be treated as a HDR system and its stored heat could be extracted using alternate methodologies to that for hydrothermal system. The first alternative for heat recovery, initially proposed for these systems type is the application of EGS technique.

As mentioned before, initial design of a EGS system was conceptualized for connect two wells by artificially created reservoir by using fracture techniques. However besides be of high cost the fracturing job, would exhibit uncertainties related with the guarantee that wells be connected through created fractures net.

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 [11]. The tests were carried out in the Fenton Hill hot dry rock site in the Jemez Mountains of north-central New México [12,13]. 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. However, one of the main lessons from this project is the low possibility in the practice to connect two wells through the creation of a hydraulic fracture between both. A scheme of EGS methodology which involves both, the injector and the producer well, with the corresponding facilities for electric generation, is shown in Fig. 1 [14].

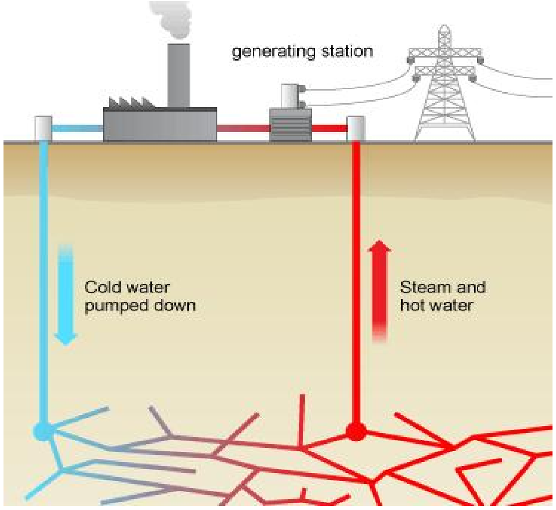

Fig. 1. Scheme of traditional operation of EGS through creation of an artificial reservoir (taken from [14])

As a first analysis in order to improve efficiency system it would be recommended generating a fracture using a defined well and identify their characteristics (fracture length, direction, depth, capacity, thickness, permeability). After knowing the fracture parameters; locate and to drill a second well for intercept it and by this way achieve connection between both wells [15,16]. Different studies have carried out, related to heat recovery from geothermal reservoirs with low permeability and recharge [4,5,17,18,19,20].

Numerical simulation about feasible electric energy generation which can be extracted from a unitary rock volume was carried out by [21]. The study assumes uniform reservoir rock properties including permeability and one of among others obtained results suggest an efficiency volume factor of 26 MWe/km^3. The study adds that taking into account this correlation would be necessary 0.19 km^3 of rock formation volume for generating 5 MWe [15].

Through numerical modeling [22] influence of natural convection on the sustainable rate of heat extraction from a geothermal source is analyzed and interpreted. A project for evaluating the feasibility of coupling capture and storage in saline aquifer of dissolved CO_2, and geothermal heat recovery was carried out [23]. The proposed system basically relies on the integration of a patented water-based in well CO_2 capture facility in a classical low-enthalpy geothermal doublet. Due to problems found through application EGS methodology (before mentioned) for heat recovery, it has been carried out studies for connect two wells through a horizontal drilling, using it as heat exchanger [24]. This same author developed mathematical model to predict the heat extraction from a closed-loop geothermal system which consists of two vertical wells (one for injection and the other one for production), both connected by one horizontal. Analysis focused to heat extraction stored in abandoned petroleum wells was carried out [25,26].

Considering that concept of two vertical wells connected by one horizontal would constitute a methodology for heat extraction in geothermal systems and besides non hydro thermal, an operative scheme is shown in Fig. 2 [14].

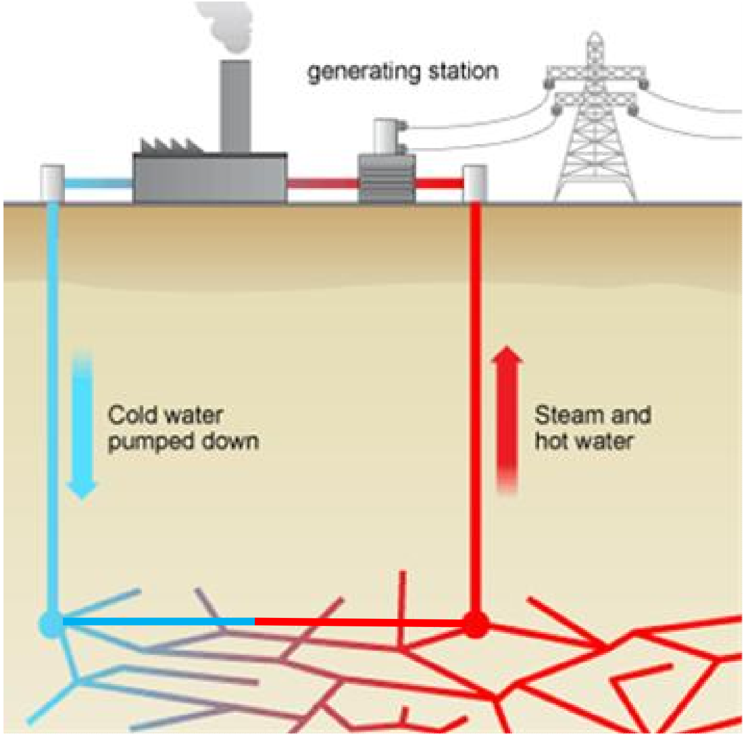

Fig. 2. Scheme of doublet system, including two vertical wells, connected by a horizontal drilling (modified from [14])

A new concept as methodology for heat recovery stored in the rock formation with high temperature but lacking geothermal production or with deficient conditions is considered for its conventional exploitation is proposed in this work. This alternate methodology involves basically a heat exchanger at bottom which extracts stored heat in the rock through a work-fluid with low boiling point. As a general concept, the system implies an injection pump, a work-fluid which flows through a "U" tube inside the well and a turbine coupled to an electricity generator. For selecting the appropriate working fluid, is recommended carry out a tests design for behavior analysis of each fluid at reservoir conditions. Between them would be considered those of low boiling point, such as He, H, Ne, N, Ar, O. Study of CO_2 as work fluid was carried out by [27]. However, this theme is out of scope of this study and would be exposed in another work. A feasible design be used in practical case of wells is shown in Fig. 3. This design would be applied in both type geothermal and petroleum wells and the objective would be the economic rescue of those, as mentioned before, lacking or have a deficient production. In petroleum wells the methodology could be applied in those abandoned and mainly would be useful for those located insulating offshore.

To date, the heat recovery, in this systems type, has been carried out by original EGS technology through creation of artificial system and two wells connected (injector and producer) by fracturing. The heat exchange occurs at bottom between the hot rock and the injected fluid which with new thermodynamic conditions flows up for discharging in a turbine coupled to electricity generator.

The new proposed methodologies for heat recovery use a closed heat exchanger composed by: a) a horizontal well which connects two vertical wells (one injector with another one producer) or b) a "U" tube inside a well. In all the cases the rock formation properties, besides the hot resource plays an important role, which influence in the heat store capacity.

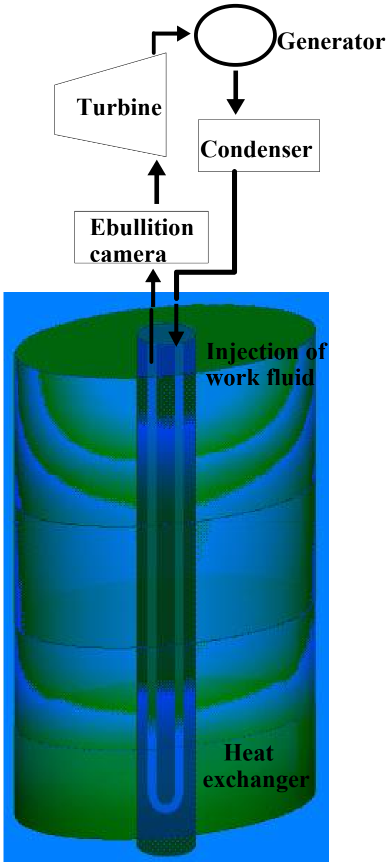

Fig. 3. Schematic diagram of heat exchanger with "U" tube inside the well, coupled to turbine and generator, using a work fluid of low ebullition point

Both last designs induce to have the heat exchange in a defined volume in the reservoir at wellbore, therefore it is of main importance to have knowledge about the rock type for determining its thermal properties. The necessary information involving lithology is recovered during wells drilling. The thermodynamic profiles data can be constructed from measurements carried out in wells during drilling and at their completion stage. Therefore, through correlation of geologic, lithological, thermal properties information with the distribution of isotherms and isobars can be defined useful thickness feasible for heat storing. Correlation of the whole characteristics is the base for evaluating the stored heat volume.

3. HEAT EVALUATION METHODOLOGY

During drilling stage of each well it is a common activity recover cuttings from rock formation, which are used for identifying the lithology type. Each rock type has single characteristics (density, thermal conductivity, specific heat, thermal diffusivity and specific volumetric heat) which are useful in thermal evaluation [28]. The thickness and its respective temperatures are determined from measured temperature profiles.

Ordinarily some of the rock properties (density, thermal conductivity and specific heat) can be determined through core test carry out in laboratory and by lack of these measurements values can be assumed from published general values. However thermal diffusivity (α) and specific volumetric heat (C_v) can be determined from basic thermal properties.

Thermal diffusivity (a) measures the rate of transfer of heat of a material from the hot end to the cold end. It is determined by the fraction between thermal conductivity and the product of density and specific heat capacity at constant pressure [29], *whose* expression is as follows:

$$a = \frac{K}{\rho * Cp} \tag{1}$$

Where,

K is thermal conductivity, ρ is the rock density and C_p is specific heat. Due to that these properties vary as temperature function, α will vary directly with K and inversely respect to product (ρ C_p). The thermal conductivity is equivalent to heat flow per second which crosses an area of 1 m^2, under a thermal gradient of 1 (°C/m) in the flow direction. Another variable dependent of basic thermal properties is the specific volumetric heat (C_v), which is direct function of the product (ρ C_p), whose expression is:

$$C_v = \rho * C_p \tag{2}$$

In a similar way, C_v is variable which varies as temperature function. The heat conduction at different levels is calculated from next expression:

$$q = K \frac{\Delta T}{z} \tag{3}$$

Where,

q is the heat flow, ΔT is the temperature difference between two levels, z is the depth interval and K defined previously. The term [$\Delta T/z$], is referred to the rock formation thermal gradient. The volumetric method for reservoir thermal energy estimation, whose advantage is a quick applicability for any type of geologic resources, is as following expression:

$$q_R = Ah\,(\varphi \rho_w c_w + \rho_r C_r (1 - \emptyset))(T_{res} - T_{ref}) \tag{4}$$

Where,

q_R is reservoir thermal energy, A is the area estimated from drainage radius of the analyzed well, h is the thickness hot interval, determined from measured temperatures at different depths in the well, ϕ is the porosity in the formation interval, ρ is the density, c is the specific heat, T_{res} is the average reservoir temperature, T_{ref} is the average surface temperature. The subindex w refers to water meanwhile r refers to rock material.

In this work a methodology for stored heat determination is shown in order to rescue existing wells whose production declined or are non-producers, but with high temperature. The advantage of using existing wells data is focused to apply them in the thermal energy determination. Between used data are; lithology and measured temperature profiles. From lithology are defined thermal properties used in Equations (3) and (4). Temperature profiles data are used for determining useful thickness for different isotherm values. Besides are used results of transient pressure tests for defining the area surrounding well with store heat capacity. The calculated stored heat is determined using rock thermal properties, measured thermodynamic data in the well and its drainage radius.

One of the analysis methods, among others, for determining porosity and permeability from transient pressure tests is type curve technique [30]. One of the tools of solid information regarding permeability, are the down hole measurements [31] during transient pressure tests [32]. Under this concept different authors [33] have carried out applications of the transient pressure tests technology. Applying [30] methodology, are calculated; rock permeability (k), porosity (ϕ) and drainage radius (r_e), according next expressions:

For permeability (k):

$$\mathrm{k} = 141.2\ \frac{Q\mu B}{h}\left(\frac{p_{DM}}{\Delta p_M}\right) \tag{5}$$

Where,

Q is volumetric flow rate, μ is fluid viscosity, B is volume factor by change from bottom to surface conditions, h thickness of the reservoir and ($p_{DM}/\Delta p_M$) is the match point between graphs of measured data with type curve.

For porosity (ϕ):

$$\phi = \frac{0.0002637\,k}{\mu c_t r_w^2}\left(\frac{t_M}{t_{DM}}\right) \tag{6}$$

Where,

C_t is total system compressibility; r_w is the well radius and (t_M/t_{DM}) is the match point between graphs of measured data with type curve.

For the drainage radius (r_e) determination:

$$r_e = \ 0.029\sqrt{\frac{kt_s}{\varphi\mu c_t}} \tag{7}$$

Where,

t_s is the time before disturb provoked in the well.

After recoverable thermal energy was calculated, two variables are incorporated for determining the electric energy, which are recovery factor (R_g) and efficiency conversion (η). Recovery factor is the ratio of geothermal energy recovered at wellhead q_{WH}, to the geothermal energy originally in the reservoir, q_R, it is:

$$R_g = \frac{q_{WH}}{q_R} \tag{8}$$

Due to conditions changes between reservoir depth and Surface, extraction factor (R_g), varies between 0.01 and 0.05; however, efficiency conversion factor (η), varies between 0.10 and 0.25 [6].

4. STUDY FIELD

In order to illustrate the study zone, it is appropriate show an overview on geothermal resources in México concerning that had been identified more than 4000 hot springs along the country [34]. To date, electric installed capacity in México from geothermal resources is 957 MW [35]. For achieving this status of electric capacity, Comisión Federal de Electricidad (CFE) carried out geoscientific studies in different geothermal zones, selecting those with major probabilities for having successful. This fact resulted in startup, at different dates, four geothermal fields which are in continuous operation. These fields (operated by CFE) are: “Cerro Prieto B. C.” (CPGF) (570 MW), “Los Azufres, Mich.” (LAGF) (247 MW), LHGF (95 MW) and “Las Tres Vírgenes B.C.S. (LTVGF)” (10 MW).

Forty four power plants of several types (condensing, back pressure and binary cycle) between 1.5 and 110 MW operate in these fields, fed by 229 geothermal wells. The production wells have depths [35] between 600 and 4400 meters and global water-steam ratio is about 1.2. Brine produced with steam, is injected through 28 injection wells (18 in CPGF, 6 in LAGF, 3 in LHGF and 1 in LTVGF), besides CPGF uses a solar evaporation pond of 14 km^2. Besides, recently a private investor (Grupo Dragon) started to generate electricity in “Domo de San Pedro” geothermal field with 35 MW.

In Fig. 4, maps locations of Mexican geothermal fields operating to date, highlighting wells distribution and geologic structures of the study field (LHGF) of this work, are shown. Details of each field, such as, name and project location, electric generation installed capacity, mass flow extracted, their corresponding operator and startup date, are shown in Table 1 [36,37].

LTVGF, LAGF and LHGF are located in formations of volcanic rocks. Due to this rock type of these fields it has been identified behavior different to those in sandy formations. Additionally, in neighboring zones of LHGF, especially high variation in formation characteristics and their parameters, both petrophysical as thermodynamic, has been found [38]. This behavior is characteristic of compartmented reservoirs. However, its thermodynamic characteristics are one of the arguments to be classified as a "super-hot" geothermal system.

LHGF is located at the border between the states of Puebla and Veracruz at central-eastern México (Fig. 4) at about 220 km to east of México City. The field is inside the Los Humeros volcanic caldera which lies at the eastern end of the Mexican Volcanic Belt [39]. LHGF is located near the limit with the Sierra Madre Occidental province, according to [40]. This field is typified as a reservoir of high enthalpy in its production [41], but low permeability and low mass flow production [42].

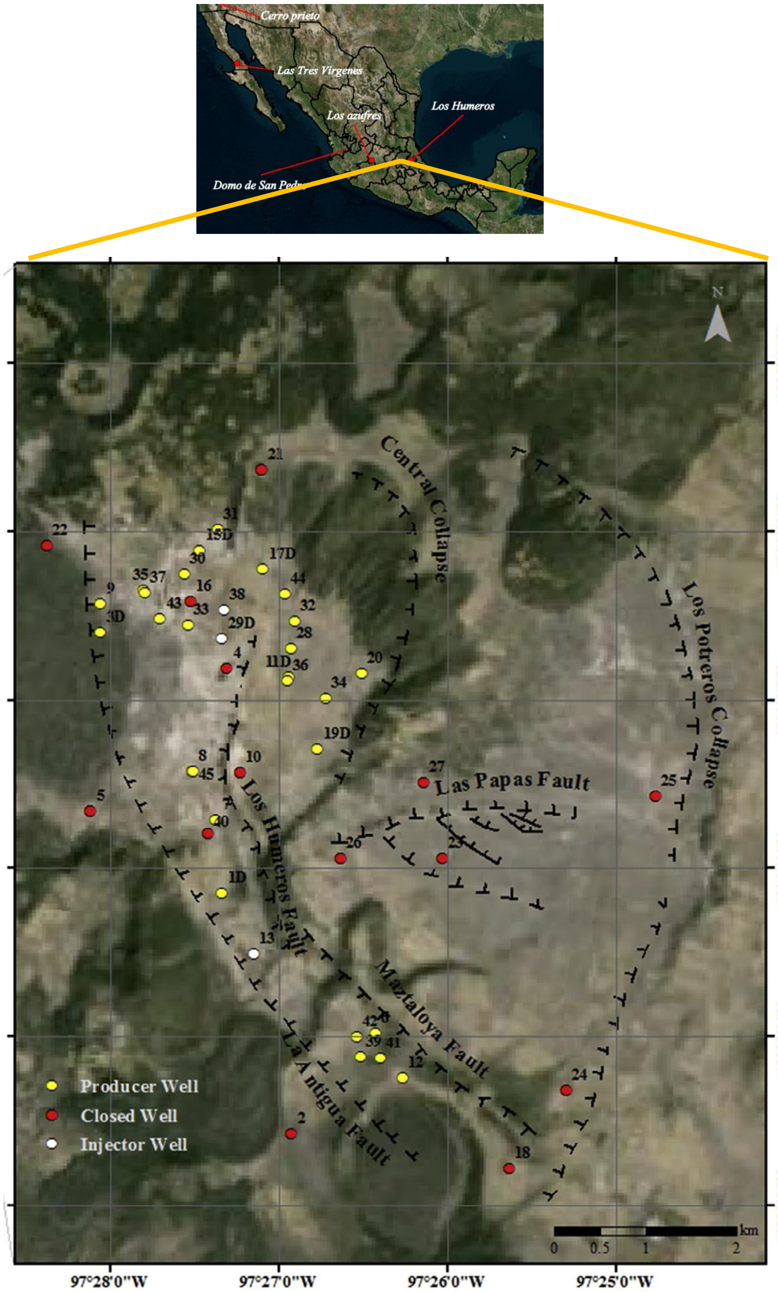

Fig. 4. Maps showing geothermal fields locations operating to date in Mexico and a close up of LHGF with wells and geologic structures

A section of LHGF has been identified existing with no-producer wells but with high temperature, which could be considered appropriate for applying the study for stored heat estimation. In LHGF have been identified three zones each one with single behavior and performance. Even though not all this field wells are producers majority of them start producing two phase flow and after, change its mixture quality, increasing produced steam fraction even, in some cases, reaching to dry steam. The production parameters diminish in some of these wells and provoke that fall below the economic limits. These characteristic are the cause that wells do not sustain the operation conditions and get out from operation system. Nevertheless at bottom the wells maintain high temperatures. The main lecture of this behavior is the existence of an unbalance between the mass extracted and that which acts as recharge.

Besides in each zone of the field have encountered non-producer wells but with high temperature measurements along their profile. Determinations from transient pressure tests analysis allow assume low permeability at bottom. This is corroborated from scarce fluid circulation losses during drilling stage. Through correlation of this whole behavior, the main presumption is focused that structures domain underground flow. Additionally, from thermodynamic measurements done at different stages of the wells operative life the high temperatures are signal of heating and therefore heat feed of a deep source. Geothermal reservoir would have ideal behavior if the owner developer achieves equilibrium between the mass extracted and that which enters to reservoir as recharge, so by this manner geothermal energy would demonstrates its property of renewable.

Due to existence of geothermal wells without use in different sectors of LHGF, the proposal for taking advantage of their capacity for heat store could help for recovering investment done by its exploration and drilling. In order to determine heat stored capacity in the wellbore and its neighboring area in the reservoir, it is applied Equation (4) using values of the different associated variables.

5. APPLICATION TO FIELD CASE

The evaluation methodology of stored heat is focused to a specific zone of LHGF Mexico. The field is characterized by high temperature and low permeability, measured temperature in wells of studied section of the field resulted in the rank of 300°C, however are non-producers [43]. Methodology for stored heat evaluation was applied to each stratum bounded by the defined isotherms, taking into account thermal properties of rock according to lithology found during the well drilling. The used data correspond to well H26 of LHGF, located at its central eastern as can be seen in Fig. 4. At this stage of each well were recovered cuttings from rock formation, which were used for identifying the lithology type and consequently thermal properties of its nearby adjacent volume.

After selecting zone and the well for analyzing, it is identified the thermal properties of rock taking into account found lithology distribution along profile of the well. In order to define an interest thickness limit along well profile is used thermodynamic (pressure-temperature) measurements, taking as lower limit 200°C temperature. Through isotherms correlation in wells located in the study zone it was found that temperature goes deeper toward eastern direction. Maximum measured temperature in this eastern sector was of 350°C in well H26 even though at 2500 m depth (about 350 masl). From data analysis of well H26 it was found that losses circulation only were found at shallow depth and that the well has a long thickness between isotherms of 200 and 350°C, even though at deeper.

With exception well H1 all the wells of cross section of Fig. 5 are non-producers. It can be seen that isotherms go to more depth toward west direction, where is located well H25, this behavior leads to considered this well as a one of bounds of LHGF. Well H26 shows an interesting thermal gradient in last 500 m with values in rank of 0.3°C/m which influences in a speedy heating.

Using data of well H26 were constructed temperature and pressure profiles at 24 hours of static conditions, both correlated with circulation losses during drilling, temperature gradient profile and lithology which are shown in Fig. 6. Due to thickness of thermal interest and its heating speed, was selected well H26 for apply methodology of stored heat evaluation and its respective rescue for converting it as operative. Characteristics of low permeability and lack of hydrothermal resource found in the well would support for application of technical different to that conventional for energy extraction and its corresponding financial rescue.

Table 1. Description of the five geothermal fields existing and operating to date, in Mexican Republic, including their location, project name, starting year, electricity generation capacity and mass flow extracted [35,36]

State	Location	Project	Developer	Starting year	Installed capacity (MWe)	Extracted mass (t/h)
Baja California	Mexicali	Cerro Prieto	CFE	1973	570	8500
Michoacán	Cd. Hidalgo	Los Azufres	CFE	1982	247	3600
Puebla	Chignautla	Los Humeros	CFE	1995	95	1200
Baja California Sur	Mulege	Las Tres Vírgenes	CFE	2001	10	420
Nayarit	San Pedro Lagunillas	Domo de San Pedro	Geotérmica para el Desarrollo	2015	35	580

Table 2. General lithological characteristics found in Los Humeros wells; related with lithological groups, its Unit, rock type and formation age [45, 46]

Lithologic group	Lithologic unit	Description	Age	Geological Era
I. Post Caldera Volcanism	1. pyroclasts	Tuffs, pumices, some alluvion	< 0.003 Ma	Quaternary (< 0.06 Ma)
	2. Post caldera lava flows	Rhyodacites, andesites, basaltic andesites, olivine basalts lava flows	0.05 - 0.003 Ma	
II. Caldera volcanism	3. Los Potreros caldera volcanism	Zaragoza ignimbrites, rhyodacitic flows (0.069 Ma)	0.069 Ma	Quaternary
	4. Intercalderas volcanism	Rhyolitic and obsidian domes, Faby tuff and andesitic-dacitic lava flows	0.074 - 0.07 Ma	Quaternary
	5. Los Humeros caldera volcanism	Xaltipan ignimbrite, andesitic, rhyolitic lavas	0.164 Ma	Quaternary
III. Pre-caldera volcanism	6. Upper precaldera volcanism	Rhyolites, dacites, andesites, tuffs and basalts	0.693-0.155 Ma	Quaternary
	7. Intermediate pre-caldera volcanism	Pyroxene andesites, mafic andesites, dacites	2.61 Ma - 1.46 Ma	Pliocene-Early Quaternary
	8. Basal pre-caldera volcanism	Hornblende andesites, dacites	10.5 - 8.9 Ma	Miocene
IV. Basement	9. Basement	Granites and schists, limestones and shales, granitic intrusions	15.1 - 190 Ma	Paleozoic to midle Miocene

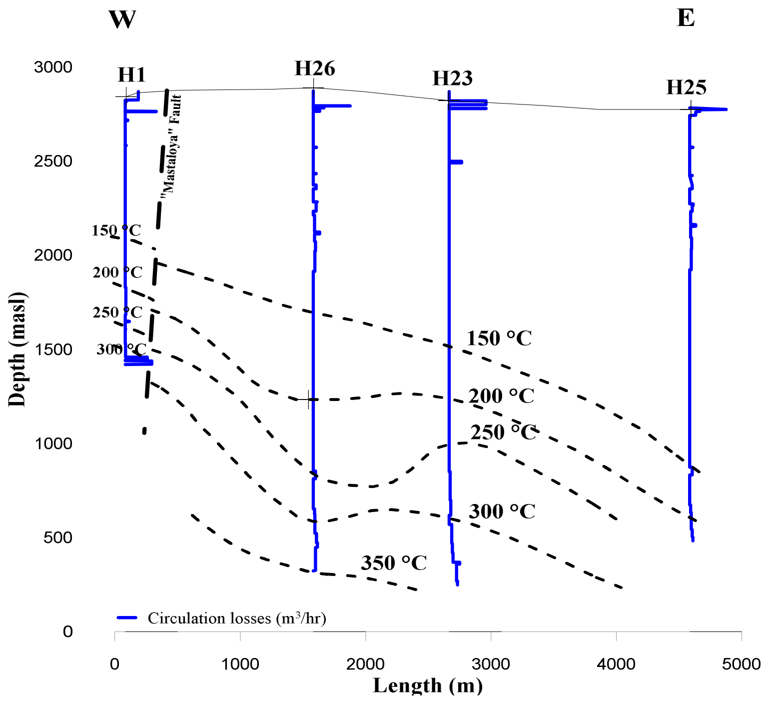

Fig. 5. Cross section (E-W) of wells located at central zone of LHGF, showing intervals of circulation losses during drilling and isotherms distribution determined from temperature measurements

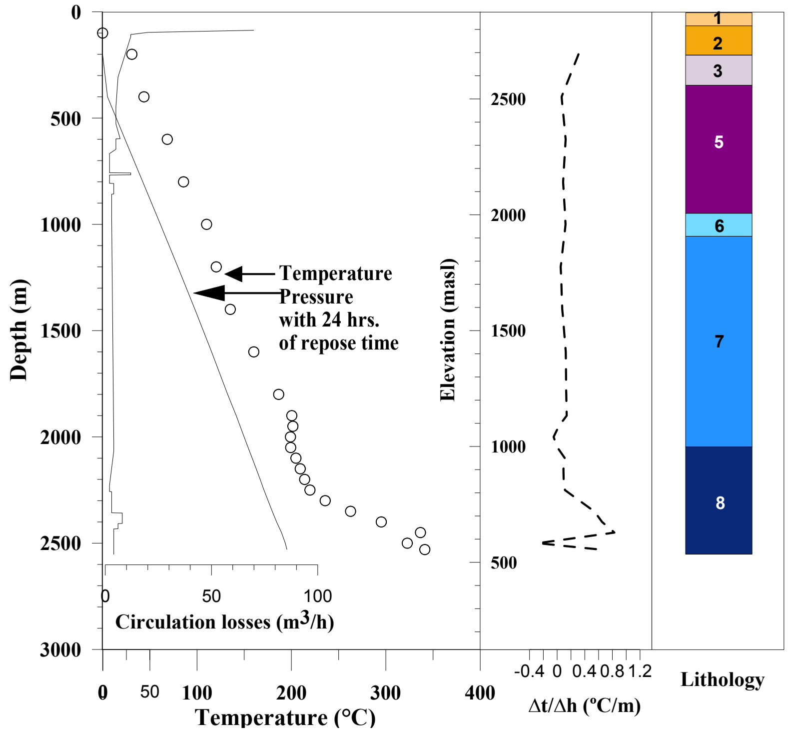

Fig. 6. Profiles of temperature and pressure at 24 hours of static conditions in the well H26 of LHGF, correlated with circulation losses during drilling, temperature gradient profile and lithology

Table 3. Depths of tops and bottom of thicknesses for each isotherm, determined in well H26, from measured data

Isotherm (°C)	Depth (m)		Thickness (m)	Elevation (masl)	
	Top (m)	Bottom (m)		Top (masl)	Bottom (masl)
200	1690	1996	306	1186	880
250	1996	2246	250	880	630
300	2246	2458	211	630	418
350	2458	2641	183	418	235

As mentioned above, in this analysis was used the lithological column defined from cuttings obtained during drilling of each well [44]. Due to reservoir heterogeneity, each well has a single lithological column and its thermal properties were defined from the reservoir rock formation taking into account lithological Group and its Unit, according to its identification. According field studies and cutting samples analysis, main lithological Units of LHGF initially were identified [45]. However, a last update and description of litohological groups and corresponding Units was carried out by [46], showing in Table 2.

Due to that this study is related with heat evaluation, thermodynamic conditions are the main control parameters, therefore thicknesses determination of rock was based on measurements carried out in the well. Using temperature data were constructed isotherms for 200, 250, 300 and 350°C, whose depths (top and bottom) are shown in Table 3.

Taking into account isotherms in the interval between 200 and 350°C it was defined lithological distribution at these depth ranges and according to the rock type was defined its thermal properties. So, in Table 4 appear the rock type (according found lithology) and their respective thermal properties values obtained from different information sources [47-52].

Thermal diffusivity (α) and Specific volumetric heat (C_v) were determined by using Equations (1) and (2) respectively.

The heat stored determination technique was applied in the geometry around the analyzed well (H26) using estimated values of the required variables, obtained from measurements, and tests. A scheme of the geometrical model developed using information above mentioned, is shown in Fig. 7.

To this stage, two useful variables for determining the reservoir thermal energy, appearing in Equation (4), which are porosity (ϕ) and Area (A) are needed; both can be obtained from transient pressure tests. Even though some of the parameters values were determined by transient tests assuming a radial configuration, in order to prevent the uncertainties in its calculation was carried out a parametric evaluation using values in the rank of those calculated. Area was determined using drainage radius (r_e) and in this work were used values of 180, 220 and 260 m. Porosity (ϕ) was used with different values of 1, 2, 3, 4, 5, 8 and 10%. Surface temperature was taken according to geographical field localization in 10°C [53]. Taking into account variables values for each thickness, it was calculated the stored heat in each interval delimited by the isotherms of 200, 250, 300 and 350°C.

The sum of calculated heat in these, corresponds to heat feasible be recovered from the study well under such conditions. Due to heterogeneity of rock formation a parametric evaluation of stored heat in the rock volume adjacent to well was carried out.

Using Equation (4) was determined stored energy in the rock formation in Joules. After determining the heat stored according to each thickness the calculated values are converted to thermal MW in order to later transform these in electric MW.

Examples of obtained evaluations of thermal energy stored in each thickness interval bounded by each isotherm are shown in Tables 5, 6 and 7 in study well. For this calculations were used drainage radius of 180, 220 and 260 m, and porosities between 0.01 and 0.1. For obtaining feasible electric energy of this rock volume from thermal energy must be considered Factor extraction (R_g), which varies between 0.01 and 0.05; Efficiency conversion (η): with variations between 0.10 and 0.25 and a probably operation time (30 years) [6].

Table 4. **Thermal properties, estimated for 300°C of constant temperature in the production thickness, of the study well (H26), using information of the found lithology**

Interval (masl)	(masl)	Lithology	ρ[1]Density 10^3 (Kg/m^3)	K[2] Thermal conductivity (W/m°K)	C_p[3] Specific heat (J/Kg°K)	α Thermal diffusivity(10^{-6} m^2/seg)	C_v Specific volumetric heat 10^3 (KJ/m^3°C)
Top	Bottom						
1450	939	Andesite	2650	1.87	1150	0.61	2740
939	873	Rhyodacite	2630	3	1050	1.08	2483
873	717	Silicified andesite	2650	1.87	1150	0.61	2740
717	579	Dacite	2630	3	1050	1.09	2483
579	493	Andesite	2650	1.87	1150	0.61	2740
493	423	Basalt	2750	2.11	890	0.86	2201
423	333	Intrusive	2750	2.11	890	0.86	2201
333	325	Basalt	2750	2.11	890	0.86	2201

[1][49], [2][47], [3][45]

Table 5. **Thermal energy stored estimation for each thickness bounded by the isotherms in study well used as example, assuming r_e= 180 m for different porosity (ϕ) values**

Rock formation	Thickness length (m)	Temp (°C)	ϕ					
			0.01	**0.02**	**0.03**	**0.04**	**0.05**	**0.1**
			q_R (MWth)					
Andesite	511	200	8.39E+06	8.41E+06	8.43E+06	8.46E+06	8.48E+06	8.55E+06
Rhyodacite	66	250	9.83E+05	9.91E+05	9.97E+05	1.00E+06	1.01E+06	1.03E+06
Silified andesite	156		2.55E+06	2.58E+06	2.59E+06	2.60E+06	2.61E+06	2.70E+06
Dacite	138	300	2.05E+06	2.08E+06	2.09E+06	2.10E+06	2.12E+06	2.19E+06
Andesite	86		1.40E+06	1.42E+06	1.43E+06	1.44E+06	1.45E+06	1.50E+06
Basalt	70	350	9.25E+05	9.35E+05	9.43E+05	9.50E+05	9.58E+05	9.66E+05
Intrusive	90		1.18E+06	1.20E+06	1.21E+06	1.22E+06	1.23E+06	1.27E+06
Basalt	8		1.06E+05	1.07E+05	1.08E+05	1.09E+05	1.09E+05	1.13E+05
Sum			1.76E+07	1.77E+07	1.78E+07	1.79E+07	1.80E+07	1.83E+07

Table 6. Thermal energy stored estimation for each thickness bounded by the isotherms for the study well, used as example, assuming r_e= 220 m for different porosity (ϕ) values

Rock formation	Thickness length (m)	Temp (°C)	ϕ					
			0.01	0.02	0.03	0.04	0.05	0.1
			q_R (MWth)					
Andesite	511	200	1.25E+07	1.26E+07	1.26E+07	1.26E+07	1.27E+07	1.28E+07
Rhyodacite	66	250	1.46E+06	1.48E+06	1.49E+06	1.50E+06	1.51E+06	1.55E+06
Silified andesite	156		3.84E+06	3.85E+06	3.86E+06	3.88E+06	3.90E+06	3.98E+06
Dacite	138	300	3.09E+06	3.10E+06	3.12E+06	3.14E+06	3.16E+06	3.27E+06
Andesite	86		2.10E+06	2.12E+06	2.14E+06	2.15E+06	2.16E+06	2.22E+06
Basalt	70	350	1.39E+06	1.40E+06	1.41E+06	1.42E+06	1.43E+06	1.49E+06
Intrusive	90		1.79E+06	1.80E+06	1.81E+06	1.82E+06	1.84E+06	1.91E+06
Basalt	8		1.59E+05	1.60E+05	1.61E+05	1.62E+05	1.63E+05	1.70E+05
Sum			2.63E+07	2.65E+07	2.66E+07	2.67E+07	2.68E+07	2.74E+07

Table 7. Thermal energy stored estimation for each thickness bounded by the isotherms, using data of the example of studied well, assuming r_e= 260 m for different porosity (ϕ) values

Rock formation	Thickness length (m)	Temp (°C)	ϕ					
			0.01	0.02	0.03	0.04	0.05	0.1
			q_R (MWth)					
Andesite	511	200	1.74E+07	1.75E+07	1.76E+07	1.76E+07	1.77E+07	1.79E+07
Rhyodacite	66	250	2.06E+06	2.07E+06	2.08E+06	2.09E+06	2.10E+06	2.16E+06
Silified andesite	156		5.35E+06	5.37E+06	5.40E+06	5.42E+06	5.45E+06	5.57E+06
Dacite	138	300	4.31E+06	4.33E+06	4.36E+06	4.39E+06	4.42E+06	4.57E+06
Andesite	86		2.96E+06	2.97E+06	2.98E+06	3.00E+06	3.02E+06	3.09E+06
Basalt	70	350	1.93E+06	1.95E+06	1.97E+06	1.98E+06	2.00E+06	2.08E+06
Intrusive	90		2.50E+06	2.51E+06	2.53E+06	2.55E+06	2.57E+06	2.67E+06
Basalt	8		2.21E+05	2.23E+05	2.25E+05	2.26E+05	2.28E+05	2.37E+05
Sum			3.67E+07	3.70E+07	3.71E+07	3.73E+07	3.75E+07	3.83E+07

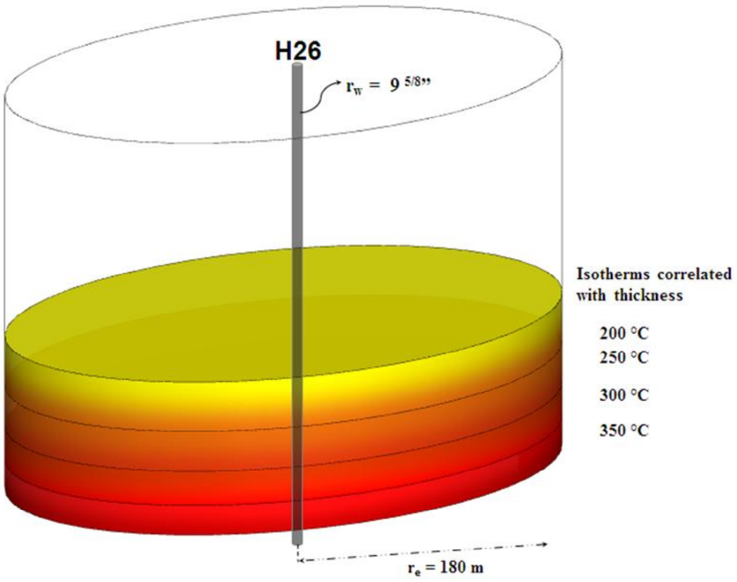

Fig. 7. Scheme of geometrical model in the vicinity of study well H26 developed for this work, using for variables, values obtained from measurements and tests

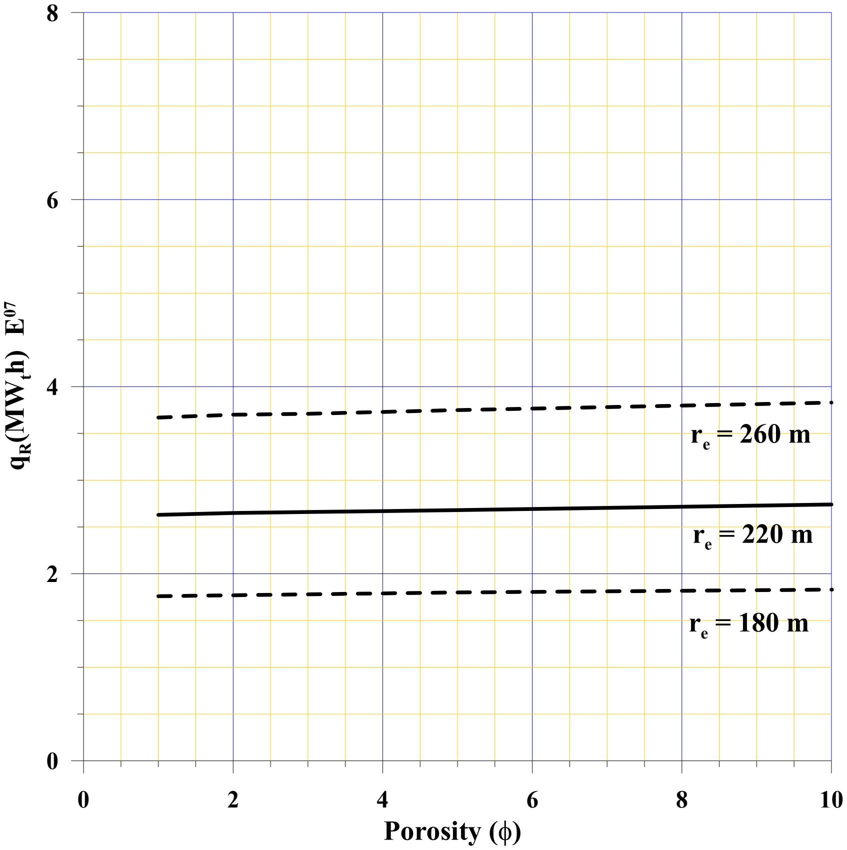

Fig. 8. Graphical representation of recovered thermal energy (MW) as porosity function, according to consideration of different drainage radii values

A graphical representation of obtained results regarding thermal energy can be recovered using data of the rock properties found in the analyzed well is shown in Fig. 8. Using as control parameters porosity for different drainage radii in the well, this figure shows behavior of thermal energy which can be recovered.

Through performing another analysis, it was determined the thermal energy as function of rock temperature for different porosity values of rock formation surrounding study well. Thermal energy which can be recovered as temperature rock function for different porosities is shown through graphs of Fig. 9.

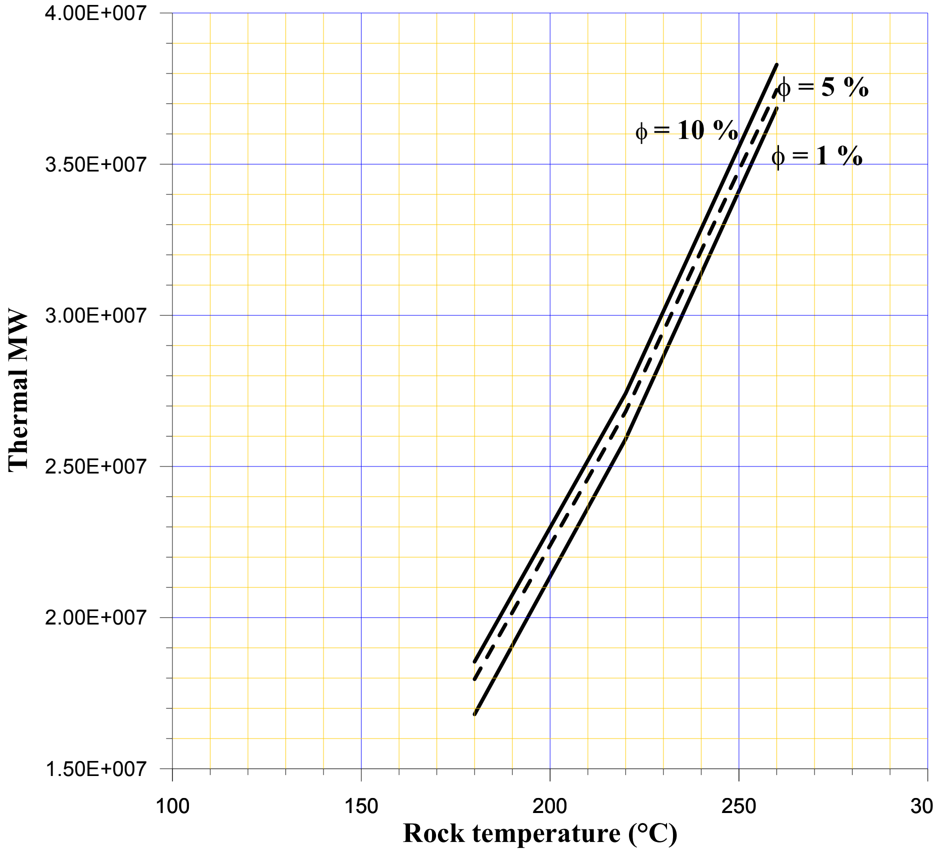

Fig. 9. Graphical representation of recovered thermal energy (MW) as reservoir temperature function, according to consideration of different rock porosity values

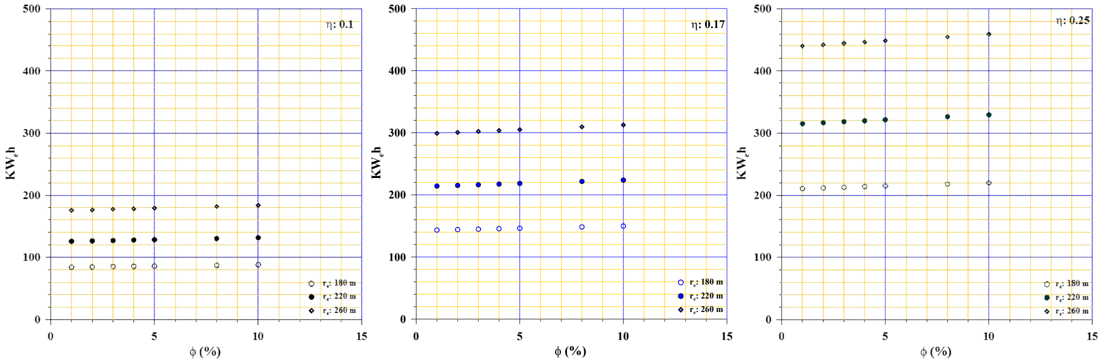

Fig. 10. Graphs showing electric energy estimation that could be obtained from rock volume surrounding to the study well H26, for efficiencies conversion (η) of 0.10, 0.17 and 0.25

In a later stage this thermal energy is transformed in electric energy, taking into account the factor extraction and thermal efficiency. The final result is the determination of electric energy capacity that the rock volume surrounding to the well can be store. Graphical results are shown in Fig. 10, by considering variation of only two of the parameters; porosity (ϕ) and drainage radius (r_e) and for efficiencies conversion (η) of 0.10, 0.17 and 0.25.

6. DISCUSSION

The characteristic of geothermal energy is its renewal ability. In this study case it is analyzed behavior of one of the wells of LHGF which is non-producer by low permeability, however, its high measured temperatures; indicate that heat remains in the reservoir rock. In LHGF are found cases in which production wells increase its dryness, starting from two phase flow, and gradually changing to only steam phase. This is related with unbalance between mass discharged by exploitation and water recharge entrance. The objective for having a renewable system is to achieve equilibrium between exploitation, recharge and heat feed. However in some wells of the analyzed field the behavior trend is toward dry steam associated with pressure decline which obstructs its incorporation to transportation net to electric generation plant. In these cases still remains heat at bottom of the wells. Therefore, is appropriate to evaluate this stored heat and to carry out economic analysis in order to design schemes for heat extraction to surface, possibly by non-conventional methods. With this, would be feasible, financial recovery of the wells.

Considering that some variables introduce an uncertainty grade due to methods for their measurement and reservoir heterogeneity [54] in this study were used variations in reservoir porosity (ϕ) and in drainage radius (r_e).

The analysis of used variables behavior in Equation (4) for q_R estimation allows identify sensitivity of both in the final evaluation. By this way, for all the cases, from Tables 5, 6 and 7 it can be seen that porosity values influence in lesser percentages that values of drainage radius. Porosity influences in heat transfer, because this process occurs easier through solid rock, so while the rock increases its porosity change its thermal properties. It was found that porosity variations (between 0.01 and 0.1) influence in results in about 4 and 5 percent. However variations in drainage radius (r_e) produce difference in results in percentages with range as far as 50.

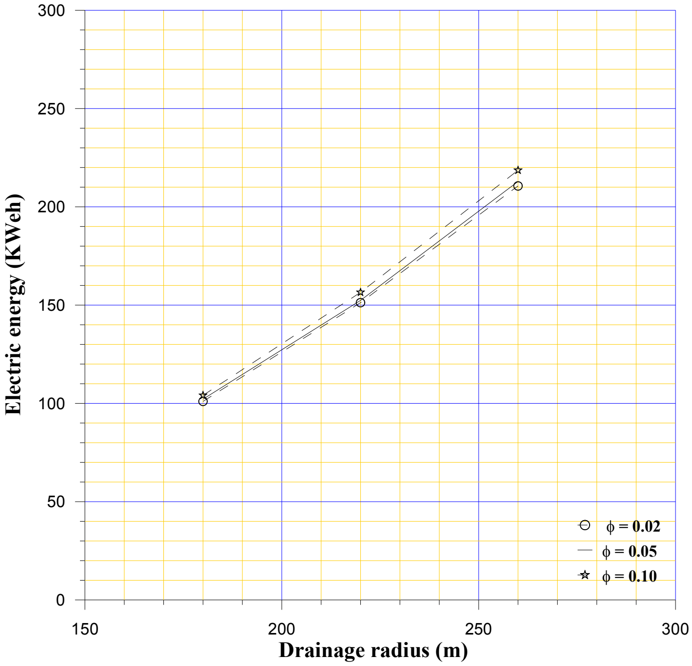

Fig. 11. Sensitivity analysis of variables (porosity and drainage radius) behavior, in electric energy determination, considering different values of efficiency conversion factor (η)

A sensitivity analysis about behavior of variables involved in Equation (4), which show some uncertainty grade, was carried out. Under this view point in graph of Fig. 9 appear the results of electric energy calculated as function of different drainage radii (180, 220 and 260 m), for porosities of 0.02, 0.05 and 0.1. In these determinations was considered extraction factor (R_g) value of 0.01 and different values (0.1, 0.17 and 0.25) of efficiency conversion factor (η). From graph of Fig. 11 it can be seen that drainage radius (r_e) is a variable of more influence than porosity (ϕ).

In the majority of cases this energy is of charge low and this provokes that does not be integrated to net of high voltage. Under such conditions it can be used an integrated system of energy storage batteries for supplying in isolated areas (without energy distribution net).

Due to that objective of this methodology is focused to integral recovery of stored heat and the rescue of well investment it is appropriate to carry out an economic study of instrumentation cost for equipment start up, for electric generation.

7. CONCLUSION

The review carried out on renewable energies allows determine that geothermal energy has advantage over the other clean energies due its persistence, avoiding operations be stop by external factor, such as lacking of sun, wind, etc., among others.

In this work are reviewed and discussed three of the different non-conventional methods for heat extraction in geothermal reservoirs with high temperature, low permeability and scarce or null water recharge.

The analyses carried out allow identify that the use of "U" tube increases efficiency in heat recovery and avoids more drilling of wells. This non-conventional methodology projects heat recovery from non-producer well, with high temperature, is innovative because to date only are applied the traditional techniques for geothermal exploitation.

In this work a methodology for stored heat evaluation in rock volume neighboring to a geothermal well is shown, using representative data of the reservoir.

It was shown that heat in wells with high temperature but low permeability or this remained in those declined after operative life, can be extracted by non-conventional methods and be used for electricity generation.

One of the conclusions of this work is that wells with production decline or trend to dry steam are correlated to a possible unbalanced between exploitation and recharge. However under presence of heat feed in its nearby it can be analyzed conditions for stored heat evaluation for energy extraction applying non-conventional methods.

Production decline of wells normally leads to its retire from operation network, however even though, production conditions would fall to operative limits, in several cases, heat remains in rock, so, the objective of this work is focused to use this energy.

Taking into account the analyses carried out, the proposed methodology could be applied in geothermal reservoirs with single different characteristics two of those conventional, such as: Existence of a heat source, low permeability system and low recharge entrance.

The accurate determination of thermal stored energy in rock volume is an influence factor for researching and application new extraction techniques to surface and its use.

One of the advantages for using the shown methodology is investment recovery by the costs of drilled wells.

Through application of the proposed methodology in this work is possible to determine quantity of thermal and electric energy for any well. Next stage is the economic analysis for defining its operative feasibility.

ACKNOWLEDGEMENTS

The authors wish thank to SENER, CONACYT, CFE and INEEL authorities by support provided for this study. This work was developed under Task 6.4 of GEMex project CONACYT-European Union Number 268074; “GEMex: Cooperación México-Europa para la investigación de sistemas geotérmicos mejorados y sistemas geotérmicos supercalientes”, SENER-CONACYT funds. The authors also thank to Reviewers, whose comments help to improve this work.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sdiarticle4.com/review-history/58802