Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Geophysical thermal studies applied to petroleum and geothermal Mexican fields: Conductive surface heat flow, thermal models and geothermal potential estimations

Orlando Miguel Espinoza-Ojeda[a]*, Elizabeth Rivera-Calderón[b], David Báez-Magaña[b] and Alberto Beltrán-Morales[c]

[a] CONACyT - Instituto de Investigaciones en Ciencias de la Tierra, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán 58060, México – Centro Mexicano de Innovación en Energía Geotérmica.

[b] Posgrado - Instituto de Investigaciones en Ciencias de la Tierra, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán 58060, México.

[c] Instituto de Investigaciones en Materiales, Unidad Morelia, Universidad Nacional Autónoma de México, Antigua Carretera a Pátzcuaro No. 8701, Col. Ex Hacienda de San José de la Huerta, C.P. 58190, Morelia, Michoacán, México.

*Corresponding author: omespinozaoj@conacyt.mx

Keywords: Geothermal energy; Geothermal boreholes; Petroleum boreholes; Thermal profiles; heat flow, fluid flow; heat exchanger; Mexico.

ABSTRACT

Currently, México has a great geothermal potential of high enthalpy under exploitation for power generation. According to several published scientific works, exist a large number of thermal manifestations sites considered as low and medium enthalpy, but some of these sites are poorly studied or explored. Alongside, México has very large continental petroleum zones with hundreds of drilled boreholes, which are abandoned due that petroleum resources have been exhausted. Those abandoned petroleum boreholes can be proposed for a geothermal project, that might reduce the project investment costs more than 50%. This option is considerably attractive when it could be applied to a very large network of abandoned boreholes or complete hydrocarbons fields. The scientific evidence confirms that the majority of petroleum boreholes were drilled in areas with high geothermal gradient, which makes them a possible renewable source of geothermal energy.

To define the geothermal potential resources from Geothermal and Petroleum Systems, a reliable knowledge from all the involved geological, geophysical and geochemical parameters is required. One of the most important stages of geophysical exploration is the studying the thermal regime caused by the heat transfer that occurs in the formation or reservoir. The thermal regime is defined by the formation temperature profiles and its specific geological characteristics.

In this context, conductive surface heat flow data were calculated through drilling logs [Borehole Transient Temperature (TBT) and/or Bottom-Hole Temperature (BHT), and stratigraphic profiles] from geothermal and petroleum boreholes. Therefore, a numerical simulator was developed to compute the conductive steady state thermal model from Geothermal and Petroleum Systems. And finally, to estimate the geothermal potential of an abandoned petroleum borehole, a numerical-analytical model was developed to simulate the heat and fluid transport process occurring inside the borehole. This model comprise the following processes: (a) the heat transfer between the interface wellbore-formation; (b) the heat transfer in the heat exchanger placed inside the wellbore; (c) the injected fluid flow as heat transport inside the heat exchanger; and (d) the extracted fluid temperature calculation according to the injected fluid temperature, fluid flow velocity and the heat transfer from the formation-wellbore interface.

1. INTRODUCTION

Nowadays, due to the high energy demand in Mexico, it is important to exploit most of the renewable natural resources, both for its positive environmental impact and for the long-term benefit of providing energy and economic savings. The energy sector in Mexico is undergoing a process of changes which has the objective of reducing carbon emissions, diversify the energy mix and attract international investment. Geothermal energy is inexhaustible and very abundant natural resource in Mexico. Even so, it has not been possible to exploit them to the maximum and in a sustainable manner, existing a quite considerable number of zones throughout the national territory with great energy potential without being exploited.

According to the Secretary of Energy (SENER), at the end of 2017, the capacity for generating electricity through renewable sources represented 25% of the total generation capacity. Among all the forms of renewable energy produced in the country, geothermal is one that has kept a constant capacity along the past years and was the only form of renewables from Mexico that decreased its output from 2017-2018 by 13.92% (SENER, 2018). From the total generation capacity, geothermal had a 1% involvement. In the same way, it was reported that the gross generation of electricity through renewable sources was 18% of total generation. Of this percentage, only 2% corresponds to geothermal energy. Although it is known that the main geothermal fields for electricity production have a very high energy potential, they have not been exploited to the maximum, e.g. Gutiérrez-Negrín et al (2015).

The geographical position of Mexico is privileged in relation to geothermal energy of low and medium enthalpy. In the country exist more than 2000 thermal manifestations throughout the territory, as well as its 5 existing geothermal fields (Cerro Prieto, Los Azufres, Los Humeros, Tres Vírgenes and Domo de San Pedro). From the total of known manifestations, there are only enough data to estimate the potential of 1,637 that constitute 927 geothermal systems located throughout 26 of the 32 states of the country, e.g. Iglesias et al (2015, 2016). This potential has mostly been proposed for exploitation as direct use, for example, heat pumps, e.g. García Gutiérrez and Martínez Estrella (2012), however, the use of direct use in Mexico is almost null, e.g. Lund and Boyd (2015).

Despite the negligible negative impact on the environment through the exploitation of geothermal resources in the world, e.g. Martín-Gamboa et al (2015), Aliyu and Garba (2019), this activity continues to present various technological challenges, scientific and economic studies. From this last and of high importance, one of the great problems faced by companies that want to exploit geothermal resources, is the high cost of drilling wellbores, whether exploration or exploitation, this cost corresponds to 40 to 50% of the investment total for the construction of a geothermal field, e.g. Lukawski et al (2014), Kipsang (2015), Yost et al (2015). Perhaps this will slow the expansion of the current Mexican geothermal fields, and also the exploitation of low and medium enthalpy resources for direct uses or the cogeneration of electric power.

On the other hand, when oil resources have been exhausted to an economically unviable point, the wellbores are abandoned or simply cease to be used. In some countries such as Albania, China, Croatia, Hungary, Israel, New Zealand, Poland, Russia and the United States of America have supported economically research and work on the reuse of abandoned oil wellbores as sources of geothermal energy, e.g. Davis and Michaelides (2009), Cheng et al (2013), Templeton et al (2014), Noorollahi et al (2015), Toth et al (2018). The abandoned oil wellbores present an interesting opportunity to be modernized as a geothermal system, since they are generally very deep to access very high temperatures of the surface layers of the Earth's crust. Proposing an abandoned oil wellbore for a geothermal project can reduce the investment costs of the project to more than 50%, even contemplating the idea of being re-addressed would be cheaper than drilling a new one. Another important aspect of the modernization of abandoned wellbores is the availability of a large amount of thermophysical data that has been recorded. These data can be used to determine which wellbores will provide the highest temperatures.

Through the National Hydrocarbon Commission (CNH) it is known that in the national territory (continental area) there are thousands of oil wellbores, which were drilled for the exploration and exploitation of hydrocarbons. In the continental zone, drilled oil wellbores are concentrated mainly in the north and east of the country. From this large number of wellbores, many are already abandoned or not used by the oil industry. Although it is not known exactly the number of these wellbores, it is estimated that hundreds of them are distributed throughout the country, considering that several are more than 50-60 years old since they were drilled and exploited, and that today the oil industry are still drilling hundreds every year.

In this context, this work proposes to evaluate for the first time in Mexico the geothermal resources of the abandoned oil wellbores through the analysis of the geophysical (thermophysical) and geological data of each site under study. Hence, two numerical simulators were developed: (i) to compute the conductive steady state thermal model from Geothermal and Petroleum Systems; (ii) to estimate the geothermal potential of an abandoned petroleum borehole, a numerical-analytical heat exchanger model was developed to simulate the heat and fluid transport process occurring inside the borehole.

2. METHODOLOGY

The methodology proposed in this research work consisted of a set of tasks that are described below:

2.1 Database

In order to create a database, first, it was carried out an exhaustive and detailed review of research works and technical reports related to the proposed study areas. With the purpose of a better knowledge in detail, as well as what kind of studies have been carried out in the geothermal and petroleum areas.

In the case of the geothermal wellbores, a review of technical reports provided by Comision Federal de Electricidad (CFE) was carried out. While for the abandoned oil wellbores, the information was revised and compiled from technical reports of Petroleos Mexicanos (PEMEX), and the complementation with published works related to these areas, i.e. Smith (1974), Smith et al (1979), Reiter and Tovar (1982). Therefore, the compiled information consists of wellbore geology data, formation temperature logs, location data and supplementary data (i.e. thermophysical properties of rock formation, wellbore total depth, elevation, etc.). As example, Figure 1 shows two temperature profiles from oil wellbores.

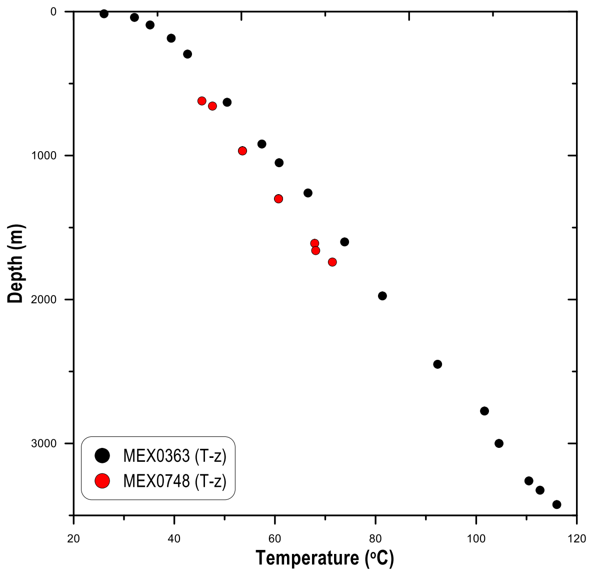

Figure 1: Temperature-depth profile from two petroleum wellbores.

2.2 2D Thermal model

The heat transfer processes with predominant conduction are based on the Law of Heat Conduction or Fourier's Law, that can be expressed from its general form:

$$q = -k\nabla T \tag{1}$$

where q is the conductive heat flow, k the thermal conductivity and T the temperature.

In the development of the numerical simulation code, the equations were computed using Fortran as a programming language, which a conductive regime in a steady state was considered. It was idealized a scenario which the conduction dominates in solid rock without intervention of any type of fluid flow. The characteristics of the reservoir include variable thermal conductivities of the formation. The stabilized temperature records from each wellbore were used to validate the 2D model temperature calculations. Once the particular characteristics and conditions of the model are stablished, the domain/geometry of the model was designed.

Hence, it was defined a two dimensions (2D) geometric configuration of the model, developing a rectangular mesh to cover the calculation surface, where the lateral boundaries are defined by the wellbores and the upper limit is in contact with the topography. In this work the topography of the surface is negligible, which simplify the developing of a rectangular geometry.

The limits of the model are named as Northern Boundary (T_N), Southern Boundary (TS), Eastern Boundary (T_E) and Western Boundary (TW), as illustrated in Figure 2. The specific boundary conditions were assigned by means of numerical subroutines included in the 2D model, to calculate the temperatures.

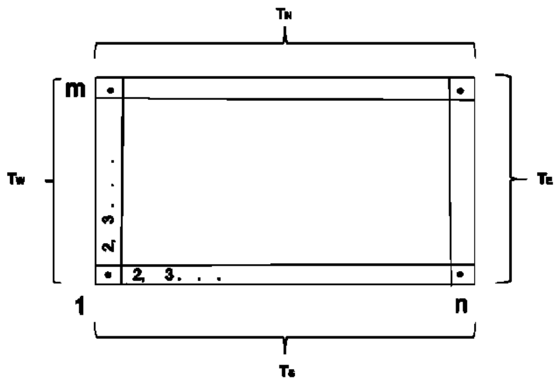

Figure 2: Geometric configuration of the 2D model for computational calculation.

The Numerical Method of Control Volume was used in the computer code to solve the differential equations and, in this manner, to obtain the temperature values from each point of the medium. This numerical method is based on the replacement of differential equations, by a set of algebraic equations that represent the unknown temperatures at the selected points in the model space. After the discretization of each control volume, a system of algebraic equations is obtained. These are distributed in a matrix that can be easily solved by the algorithm of Tridiagonal Matrix Algorithm (TDMA), which is based on Gaussian elimination.

2.3 Heat exchanger model

The main objective of this numerical tool is to estimate the outlet temperature from petroleum wellbores, therefore, to determine the possible geothermal potential. Hence, a dual tube heat exchanger design is proposed, which is located inside the petroleum wellbore with "U" shaped geometry (see Figure 3). Whose physical-mathematical model is represented by a system of equations that describe the phenomenon of heat transfer through the wellbore, the velocity and initial injection pressure of the working fluid and the geothermal gradient.

The heat exchanger procedure consists of the heat transported by fluid flow, described as follows: the injected working fluid (isobutane) through the annular section of the tube at an initial temperature T_1, it flows from the surface point to the bottom of the wellbore where it is reached the maximum temperature T_2. During this stage, information is obtained on the heat transfer between the formation rock and the oil wellbore pipe. Then, at the bottomhole, the isobutane reverses its path (T_3), now it flows through the inner pipe and initiates the exit stage, which theoretically will have a final temperature T_4. Figure 3 represents the phenomenon of heat and fluid transport.

The heat and fluid transfer process are given by the equations of mass, moment and energy conservation, which are described below:

Continuity equation. The mass flow can be described as follows:

$$m = \rho vA = \text{constant} \tag{2}$$

where ρ is the density of the fluid, v is the velocity of the fluid and A is the area of the conduit which the fluid travels.

Momentum equation. This equation is written in terms of two heights z_1 and z_2, and is used for the calculation of the isobutane static pressure and is given by:

$$\frac{P_1}{\rho_1 g} + \frac{v_1^2}{2g} + z_1 = \frac{P_2}{\rho_2 g} + \frac{v_2^2}{2g} + z_2 + h_l \tag{3}$$

where P is the static pressure, z is the height, g is the gravitational acceleration and h_l the pressure drops.

Energy equation. For the following expressions, we refer to Figure 3. The energy equation is essentially the first law of thermodynamics for an open system. The change of external work in the pipe is always zero, and the heat is given by the change of enthalpy, which includes the kinetic and potential energy. The heat transfer rate that is obtained from the rock formation and transported by the isobutane to the exterior pipe is given by:

$$\dot{Q_{12}} = 2\pi Rh(T_w - T_1)\Delta z \tag{4}$$

Where T_w is the rock temperature, T_1 is the initial temperature, Δz is the variation of the depth of the wellbore, the convective coefficient of heat transfer h, and the wellbore radius R. The internal heat transfer 3-4 is given as follows:

$$\dot{Q_{34}} = 2\pi U(T_3 - T_4)\Delta z = \dot{m}(h_3 - h_4) = \dot{m}c_p(T_3 - T_4) \tag{5}$$

Therefore, the total heat can be estimated by the following relationship:

$$Q_{total} = \dot{Q_{12}} + \dot{Q_{34}} \tag{6}$$

After solving the system of equations mentioned above, and before to propose a simulation code, the transport properties of isobutane, such as viscosity and thermal conductivity, as well as thermodynamic properties, such as density, enthalpy and entropy, must be calculated.

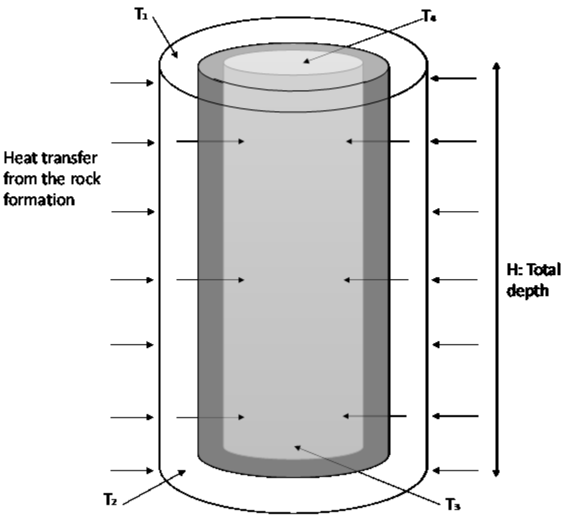

Figure 3: Heat exchanger model with "U" shaped geometry.

3. PRELIMINARY RESULTS

The application of the two numerical tools developed to estimate the possible geothermal potential in petroleum zones and to better know the natural thermal regime in geothermal areas, led to interesting preliminary results.

3.1 Conductive thermal model

In this work, a fraction of northern Mexico was chosen as study area, where about ten of abandoned petroleum wellbores are located. This study area includes four states, Chihuahua, Durango, Baja California and Baja California Sur (Baja California Peninsula), in Figure 4, the location of the wellbores is shown and the states are delimited with white line.

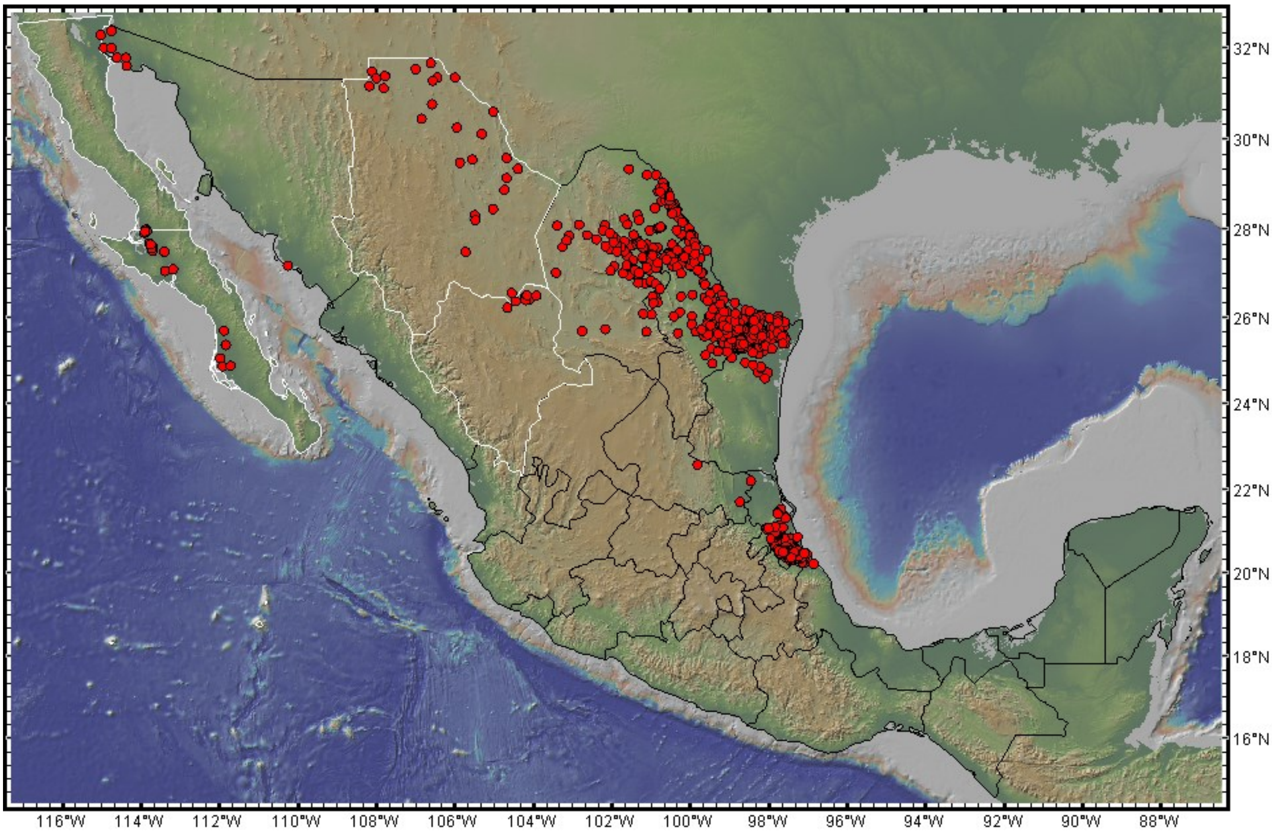

Figure 4: Location of the compiled abandoned petroleum wellbores (red filled circles). States delimited with white line were proposed as study zones in this work.

As illustrative example, Figure 5 shows the 2D thermal model from some sites in the Sedimentary Basin of northern Chihuahua. In order to know their temperature field in conductive regime, according to their stratigraphy, it is necessary to consider the model with thermal anisotropic conductivities.

Northern Chihuahua is located in a large Sedimentary Basin, e.g. Barboza-Gudiño et al (2016), where currently abandoned petroleum wellbores were drilled by PEMEX. Reiter and Tovar (1982) reported geothermal anomalies in some wellbores located in this region.

The few studies about the geothermal potential of the sedimentary basins in Mexico were the main motivation of this work. The objective is to obtain an overview of the heat flow distribution in the abandoned petroleum wellbores.

The anomalies in the sedimentary basins are often attributed to the influence caused by the structural system of extensive type, characterized by normal faults systems and the crustal thinning by the tectonic formation of rifts, e.g. Moeck (2014). The zones of cortical weakness favor the ascent of plutonic bodies that generate thermal manifestations.

Moeck (2014) states that conductive heat transfer predominates in sedimentary basins geothermal systems, although there are exceptions in areas with fluid interference. In the case of abandoned petroleum wellbores, considered in the thermal numerical simulation of this model, no fluids have been reported in the system, i.e. Reiter and Tovar (1982). The 2D model calculates the conductive thermal state, which is the first approximation of the temperature distribution of this kind of system in Mexico.

The area of the abandoned petroleum wellbores covers approximately 44,000 km2. In Figures 5, the thermal profiles from the correlation between the petroleum wellbores MXPUB009-MXPUB015-MEX0127 are shown. And, in Figure 6, the correlation of some computed 2D thermal profiles are illustrated.

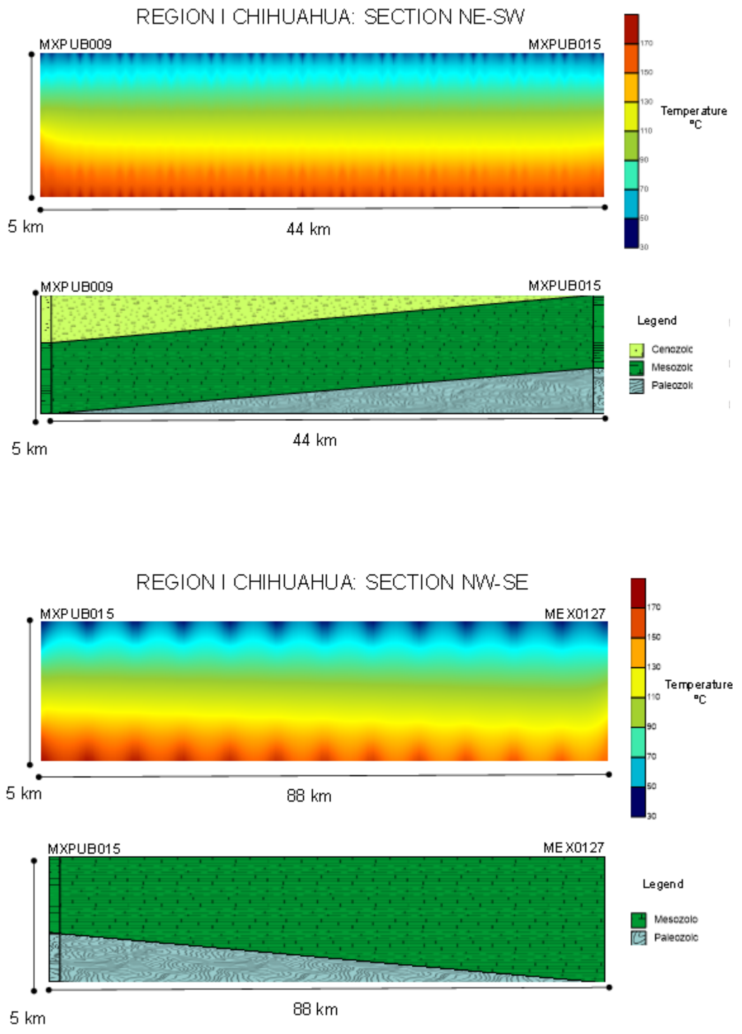

Figure 5: 2D thermal profile from MXPUB009-MXPUB015-MEX0127 petroleum wellbores from the sedimentary basin. Including geological age model.

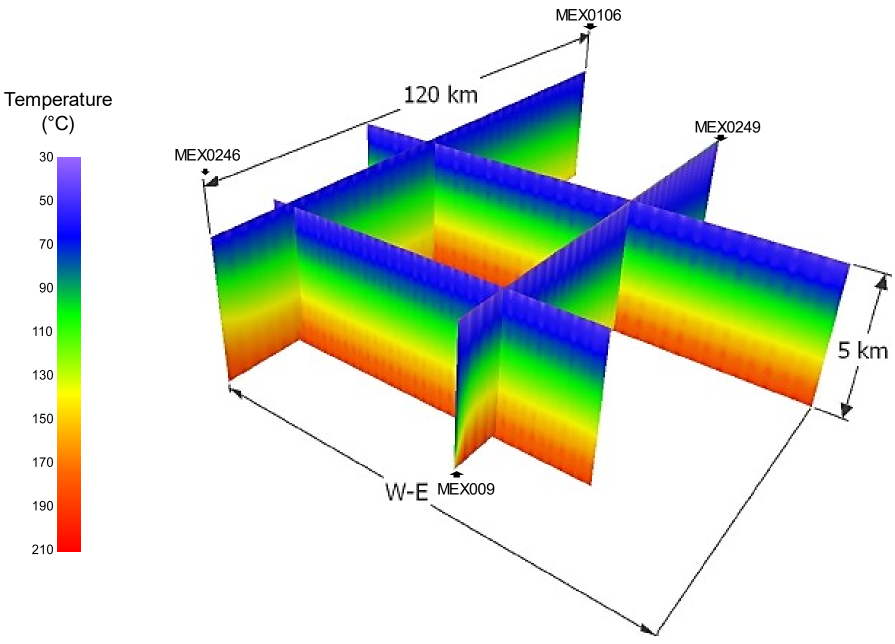

Figure 6: Correlation of 2D thermal profiles from some petroleum wellbores from the sedimentary basin.

3.2 Abandoned petroleum wellbores

According to the thermal profiles obtained from the application of the 2D thermal model, this motivates to analyze each petroleum wellbore involved in this project. A complete and finished heat exchanger simulator is required. During the development of the simulation code, the thermodynamic parameters, as well as the isobutane transport parameters, are described by functions dependent on temperature and pressure. These parameters are the unknown variables of the system equations. Fundamental variables to complete the numerical model.

A suggested numerical adjustment between the thermodynamic and transport parameters with Temperature and Pressure was carried out. This allowed to estimate the change of these parameters in function with temperature and pressure. A database was created according to Younglove and Ely (1987), using the range of values for the temperature from 300 K to 400 K and the pressure from 0 MPa to 3.5 MPa. To support the adjustment functions, the NIST Standard Reference Data was used.

To each numerical adjustment, the percentage error was calculated to estimate the reliability of the adjustment.

$$\% \text{ Error} = \frac{Theoretical\ value - Experimental\ value}{Experimental\ \text{value}} * 100\% \tag{7}$$

As example, Table 1 summarizes the temperature and pressure values used to prove the reliable adjustment of the viscosity. Table 2 summarizes the theoretical, numerical and percental error values.

Finally, with the parameter's adjustments, thermal conductivity, density, viscosity, entropy and enthalpy, the numerical model was finished. Therefore, the output temperature was estimated, see Figure 7.

Table 2: Temperature and pression values used to compute the viscosity.

Temperature (K)	Pression (Mpa)
300	0.36970
305	0.42600
345	1.13100
355	1.39400
360	1.54100
390	2.68500

Table 2: Viscosity values according to Temperature and Pression values from Table 1. Including percental error as comparison between theoretical and numerical values.

Theoretical viscosity value	Numerical viscosity value	Percental Error
148	145	2.02%
140	139	0.7%
91	91	0%
81.2	81.1	0.1%
76.6	76.3	0.3%
50.2	49.6	1.1%

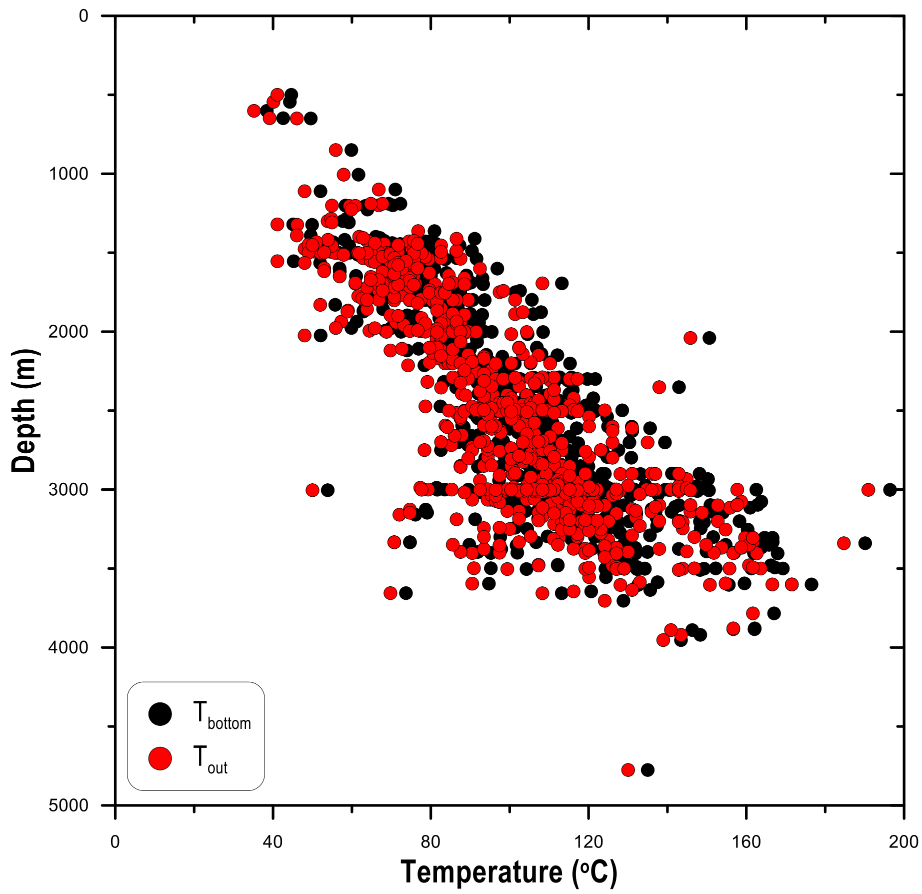

Figure 7: Plot of the bottomhole temperature of different petroleum wellbores and their corresponding output temperature estimated by the heat exchanger borehole model. T_{out} was located next to its corresponding T_{bottom}.

4. CONCLUSIONS

The sedimentary basin, according to the numerical results, could be consider as a low-medium enthalpy geothermal system. Direct uses could be applied to exploit the heat reserves.

The 2D thermal profiles is a useful tool to estimate thermal states from large areas. The more data available, the more accuracy and coverage will be obtained.

The individual analysis to each petroleum wellbore gave as result, most of the abandoned wellbores have medium enthalpy, according to their estimated output temperature. These preliminary results suggest that these wellbores could be geothermal direct uses sources.

ACKNOWLEDGEMENTS

The successful development of this work is the result from the scientific project PN2015-01-388 “Aprovechamiento de pozos petroleros abandonados/inoperantes como fuente sustentable de energía para sistemas híbridos Geotermia/Concentrador Solar”, from the national program Proyectos de Desarrollo Científico para Atender Problemas Nacionales 2015 (CONACYT).

REFERENCES

Barboza-Gudiño, J., Torres-Hernández, J., and Villasuso-Martínez, R.: Revisión estratigráfica y estructural de la Sierra Plomosa, Chihuahua, *Revista Mexicana de Ciencias Geológicas*, (2016), 221-238.

Cheng, W.-L., Li T.-T., Nian Y.-L., and Wang C.-L.: Studies on geothermal power generation using abandoned oil wells, *Energy*, **59**, (2013), 248-254. doi: 10.1016/j.energy.2013.07.008.

Davis, A. P., and Michaelides E. E.: Geothermal power production from abandoned oil wells, *Energy*, **34**, (2009), 866-872. doi:10.1016/j.energy.2009.03.017.

García Gutiérrez, A., and Martínez Estrella I.: Status of development of geothermal heat pumps, *Geotermia Revista Mexicana de Geoenergía*, **25**(2), (2012), 58-68.

Gutiérrez-Negrín, L.C., Maya-González R. and Quijano-León J.L.: Present Situation and Perspectives of Geothermal in Mexico, *Proceedings*, World Geothermal Congress 2015, Melbourne, Australia.

Iglesias, E. R., Torres R. J., Martínez-Estrella I., and Reyes-Picasso N.: Summary of the 2014 assessment on medium- to low-temperature Mexican geothermal resources, *Proceedings*, World Geothermal Congress 2015, Melbourne, Australia.

Iglesias, E. R., Torres R. J., Martínez-Estrella J. I., Lira-Argüello V., Paredes-Soberanes A., Reyes-Picasso N., Prol R. M., Espinoza-Ojeda O. M., López-Blanco S., and González-Reyes I.: Potencial teórico SGM en los afloramientos del basamento en México *Geotermia Revista Mexicana de Geoenergía*, **29**(2), (2016), 6-17.

Moeck, I. S.: Catalog of geothermal play types based on geologic controls, *Renewable and Sustainable Energy Reviews*, **37**, (2014), 867-882. http://dx.doi.org/10.1016/j.rser.2014.05.032.

NIST Standard Reference Data (2017). [https://webbook.nist.gov/chemistry/fluid/].

Noorollahi, Y., Pourarshad M., Jalilinasrabady S., and Yousefi H.: Numerical simulation of power production from abandoned oil wellsin Ahwaz oil field in southern Iran, *Geothermics*, **55**, (2015), 16-23. doi: 10.1016/j.geothermics.2015.01.008.

Reiter, M., and Tovar J. C.: Estimates of terrestrial heat flow in northern Chihuahua, Mexico, based upon petroleum bottom-hole temperaturas, *Geological Society of America Bulletin*, **93**(7), (1982), 613-624. doi: 10.1130/0016-7606(1982)93<613:EOTHFI>2.0.CO;2.

Secretaria de Energia (SENER). Informe sobre la participación de las energías renovables en la generación de electricidad en México, al 31 de diciembre de 2014. http://www.gob.mx/cms/uploads/attachment/file/25602/Informe_Renovables_2014-2.pdf. 14 december 2015.

Smith, D. L.: Heat flow, radioactive heat generation, and theoretical tectonics for northwestern Mexico, *Earth and Planetary Science Letters*, **23**, (1974), 43-52. doi:10.1016/0012-821X(74)90028-4.

Smith, D. L., Nuckels C. E. III, Jones R. L., and Cook G. A.: Distribution of heat flow and radioactive heat generation in northern Mexico, *Journal of Geophysical Research*, **84**(B5), (1979), 2371-2379. doi: 10.1029/JB084iB05p02371.

Templeton, J. D., Ghoreishi-Madiseh S. A., Hassani F., and Al-Khawaja M. J.: Abandoned petroleum wells as sustainable sources of geothermal energy, *Energy*, **70**, (2014), 366-373. doi: 10.1016/j.energy.2014.04.006.

Younglove, B. A., and Ely J. F.: Thermophysical properties of fluids. II. Methane, Ethane, Propane, Isobutane, and Normal Butane, *Journal of Physical and Chemical Reference Data*, **16**, (1987), 577-798. https://doi.org/10.1063/1.555785.