

Comparison of measured and simulated pressure and temperature profiles in geothermal wells

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RESUMEN

La correcta aplicación de los simuladores de flujo en pozos geotérmicos representa una herramienta útil para la práctica de la Ingeniería de Yacimientos ya que su apropiada calibración y uso a menudo evita la necesidad de correr costosos registros experimentales PTQ dentro de los pozos geotérmicos. En este sentido, se emplearon dos simuladores existentes de flujo en pozos, GEOPOZO Y WELFLO, para obtener perfiles de presión y temperatura, y estos resultados se compararon con perfiles PT medidos en el pozo Az-19 del campo geotérmico de los Azufres, México. Los perfiles PT experimentales se corrieron empleando un equipo electrónico de alta precisión. La comparación entre los perfiles PT experimentales y los obtenidos por simulación muestran que la desviación máxima es de 3.2 % y corresponde al perfil de presión obtenido con el simulador WELFLO.

PALABRAS CLAVE: Pozo geotérmico, simuladores de flujo en pozo, presión, temperatura, campo geotérmico Los Azufres.

ABSTRACT

The correct application of geothermal wellbore flow simulators is a useful tool since their adequate calibration and use often avoids the need to perform costly experimental PTQ logs inside geothermal wells. Two existing wellbore flow simulators, GEOPOZO and WELFLO, were used to obtain pressure and temperature profiles and the results were compared with experimentally measured PT logs in well Az-19 from the Los Azufres, Mexico, geothermal field. PT logs were run using high-precision electronic logging equipment. Comparison of experimentally measured and computed PT profiles shows a maximum error of 3.2% for the pressure profile obtained with the WELFLO simulator.

KEY WORDS: Geothermal well, wellbore simulators, pressure, temperature, Los Azufres geothermal field.

BACKGROUND

The equations that govern the flow of a mixture of water and steam in a geothermal well are mass, momentum and energy conservation (Gould, 1974). When these are complemented with closure equations to completely describe two-phase pipe flow, numerical simulations of wellbore flow are possible.

Research on two-phase fluid flow in non isothermal pipes has produced empirical correlations which describe the flow at essentially adiabatic and steady-state conditions. These correlations have been combined with the conservation equations with the aim of simulating fluid and heat flow in geothermal wells. In this way, it is possible to obtain an estimate of the pressure, temperature, enthalpy, steam quality and velocity profiles in geothermal wells when the detailed well geometry, pressure, enthalpy and flowrate at one extreme of the well are known.

Several flow regimes may occur in a geothermal well

under production conditions (Gould, 1972; Intercomp, 1981, Palacio, 1990):

- Bubble flow: Small bubbles of different diameter and velocity are present. In this case, pressure drop is controlled by the liquid phase.
- Slug flow: The gaseous phase increases, the small bubbles collide with each other and form larger bubbles which separate from the liquid phase. The continuous phase is still the liquid phase. The bubble velocity is greater than the liquid phase velocity. Both the gaseous and the liquid phases affect the pressure drop.
- Transition flow: In this regime, dominance and continuity of the liquid phase changes to the gaseous phase. Even though the liquid phase is still significant, the gas phase predominates.

- Annular flow: The gaseous phase is now the continuous phase. The liquid is completely embedded and transported by the gaseous phase. Although a liquid film wets the pipe walls, its effect is secondary. The pressure gradient is controlled by the gaseous phase.

Numerical simulation of fluid and heat flow in a geothermal well may be used instead of the experimental measurements of PT logs. If the simulator results are proven to be reliable, they can be used in specialized studies on the geothermal reservoir. Among the relevant areas where numerical simulators can be successfully applied are: (a) determination of the bottomhole flow conditions from wellhead data and viceversa; (b) definition of criteria for determination of optimum well operating conditions, subject to the restrictions imposed by the pressure and steam requirements set out by the turbine and related power equipment, and (c) as an auxiliary in determining some reservoir parameters (transmissivity, productivity index, etc.) from wellhead data. Examples of wellbore flow simulations and applications are described in García (1994) and García *et al.* (1995).

There are codes for one and two-phase flow which use formulations of the homogeneous or phase-slip types, with or without fluid property correction for salt and gas content, multiple feedzones, etc. (García and Frías, 1994); Gould (1974) developed a two-phase geothermal wellbore flow simulator. Nonsteady-state conditions were considered by Miller (1980). Other simulators include WELFLO (Goyal *et al.*, 1980), VSTEAM (Intercomp, 1981), Ortiz (1983), HOLA (Bjornsson, 1987), Palacio (1990), SIMU89 (Sánchez, 1990), GEOPOZO (García and Santoyo, 1991; García *et al.*, 1993) and WELLSIM (Hadgu and Freeston, 1993).

It is necessary to monitor periodically the behavior of the well under continuous exploitation, by direct measurement of the thermodynamic parameters of the flow in the well. However, this is not always possible due to the limited availability of wells for testing. In order to avoid having to shut down a producing well, it is common practice to employ a wellbore flow simulator to estimate its bottomhole operating characteristics from wellhead measured data. However, it is necessary to perform a previous analysis about the conditions under which simulation is to be applied.

We present the results from wellbore flow simulators (GEOPOZO and WELFLO) and a comparison with logged profiles by direct measurement of the parameters in a geothermal well. Measurements were performed using a high precision electronic logging equipment. Consideration was given to the calibration of the simulators in order to extend

their application in reliable form to wells with similar characteristics.

DESCRIPTION OF THE WELL USED FOR PT MEASUREMENTS

The well selected for this study is well Az-19, in the northern zone of the Los Azufres geothermal field, Michoacán, México. The field (Figure 1) is located in the western part of the Mexican Volcanic Belt at an average elevation of 2800 meters above sea level (m.a.s.l.).

The geothermal reservoir was initially explored in 1972, and well drilling began in 1977. Commercial power generation started in 1982 using several 5-MWe wellhead power units. Other power plants were later installed in different parts of the field, totalling at present 95 MWe of installed capacity. In 1988, a 50 MWe power plant was installed in the southern part of Los Azufres. This plant is known as Tejamaniles and is fed with steam from wells in this part of the field.

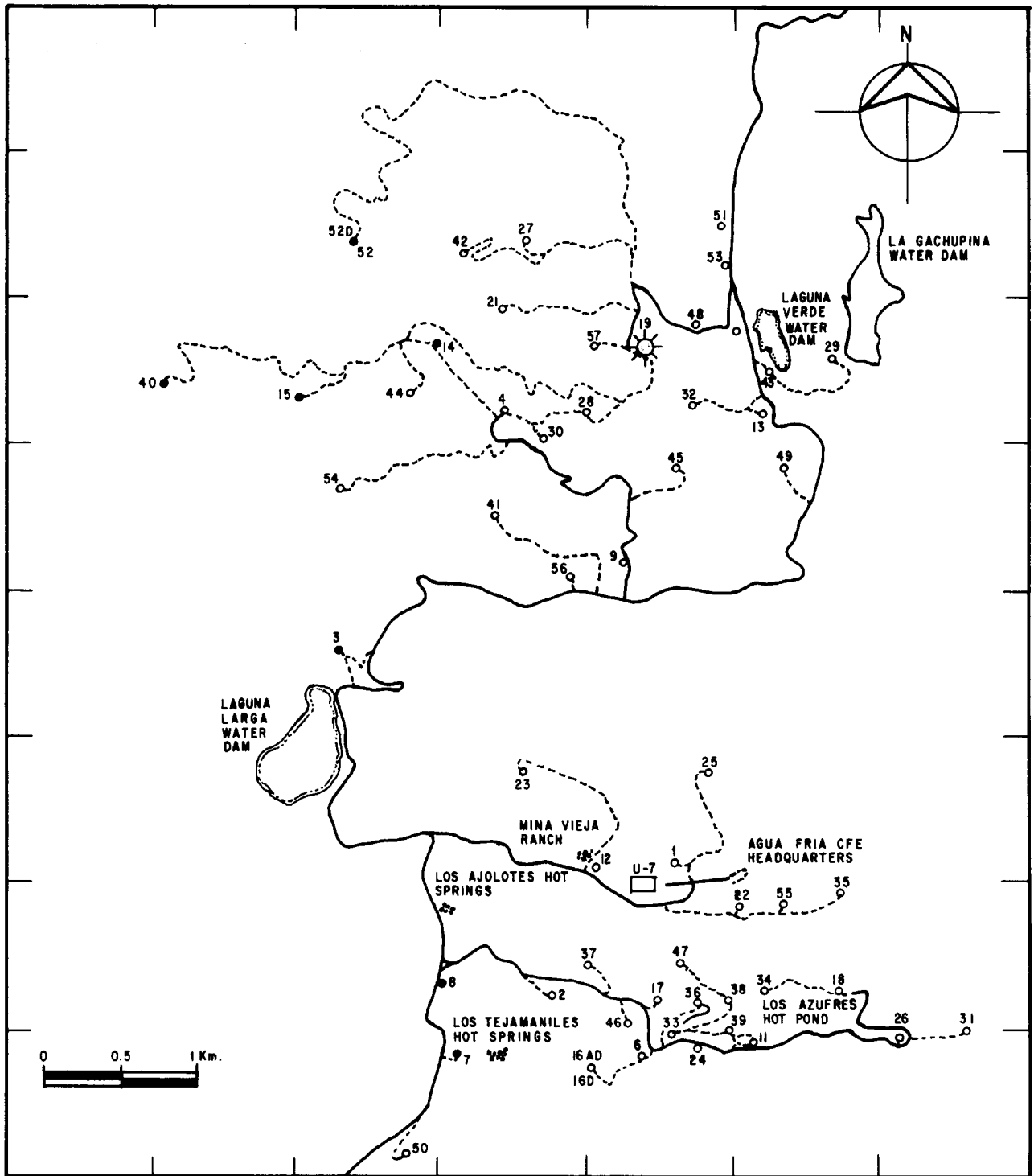
Well Az-19 was coupled to wellhead unit No. 5 (5 MWe capacity) in 1982. Later on it was withdrawn from production because of decrease in its output. It was then subjected to a number of pressure and temperature logging tests with the well flowing at constant rate.

Measurements were performed in the well with state-of-the-art electronic logging equipment. Pressure, temperature and flow velocity precision measurements were made to 0.001 psi, 0.01°C and 0.01 m/sec, respectively. For unidimensional, steady-state systems, measurement response is instantaneous (real-time). The PT profiles were compared with the computed profiles obtained with the two two-phase numerical simulators GEOPOZO and WELFLO and these were fed with thermodynamic wellhead flow data and the geometrical characteristics of well Az-19.

EXPERIMENTAL DETAILS

The calibration test consisted of applying a constant temperature of 100°C to the PT logging system. Then, a gradually increasing pressure was applied to the logging system. The pressure was increased up to 100 bar. This test showed that the pressure recorded by the logging system reproduced satisfactorily the applied pressure.

The second part of the test consisted of applying a constant pressure of 50 bar to the PT logging system and gradually increasing the temperature to 300°C. This test showed that the temperature recorded by the PT logging system was different from the applied temperature. The



Legend

- Main access
 Secondary access
 Studied well
 Production well
- Injection well

Fig. 1. Map of Los Azufres geothermal field.

difference was greater than the accuracy of the PT logging system. Therefore, any PT profiles where this situation occurred were discarded. Only the PT profiles that were taken when the logging system had been properly calibrated were included in this study.

DESCRIPTION OF SIMULATORS

The wellbore simulators employed in the present work are WELFLO (Goyal *et al.*, 1990) and GEOPOZO (García *et al.*, 1993). WELFLO can be applied for modeling one or two-phase flow (liquid or liquid-vapor) in producing geothermal wells. It takes into account phase changes, change of flow regime, phase slip, changes in pipe diameter and heat transfer between the produced fluid and the surrounding formation. It incorporates Orkiszewski's (1967) empirical correlation for pressure drop in the bubble, slug, transition and mist regimes, the slip correlation of Wallis (1969), and the Chisholm (1973) correlation for friction losses. It considers water as a pure fluid. This code has been used to generate pressure and temperature profiles which are then fitted to the corresponding experimental logs. This procedure allows estimation of the bottomhole flowing conditions during pressure tests. It has also been used as a tool in the development of methodologies for the determination of certain reservoir parameters using wellhead data (Iglesias *et al.*, 1993). It has proved to be very accurate when adequately calibrated, i.e., the computed pressure and temperature profiles match the corresponding experimental PT logs, and the wellhead data is of good quality.

GEOPOZO (García *et al.*, 1993) can be applied for modelling one or two-phase flow of pure water with or without corrections for noncondensable gases (liquid, liquid-vapor) in producing geothermal wells. It takes into account phase change, fluid-rock heat transfer and the geometrical characteristics of the well. It can be used for steady-state or transient flow conditions and can run calculations from wellhead to bottomhole and viceversa. The main difference with other simulators is that it uses a homogeneous flow formulation which does not require the use of detailed flow correlations to describe flow regimes, i.e., the liquid water and steam are assumed to flow at the same velocity (no slip) and therefore, closure relations are only needed to calculate friction losses and density changes with pressure and temperature. This code has been successfully applied for the study of deep geothermal wells (over 4000 m deep) fed by liquid water at very high pressure and temperature. It has been used to study wells with secondary feedzones, deviated wells, and for estimating expected output curves and productivity indexes (García *et al.*, 1995).

SIMULATION RUNS

For the simulation study, both WELFLO and GEOPOZO simulators were employed. Both simulators can be fed with

the same set of data. For the present study, the input data includes the well geometry and wellhead parameters. Calculations proceed from wellhead to the bottom of the hole. The data are shown in Table 1.

Table 1

Data of well Az-19 employed for the simulation runs performed with the WELFLO and GEOPOZO simulators. Wellhead pressure and mass flowrate data were measured at the wellhead in July, 1994.

Well Number	Wellhead Pressure	Mass Flowrate	Enthalpy
Az-19	4.25 MPa	30.8 ton/hr	2525 kJ/kg
Length Section 1	Length Section 2	Diameter Section 1	Diameter Section 2
930 m	733 m	0.2224 m	0.1570 m

Results from both simulators are in the form of depth versus pressure, temperature, enthalpy, steam quality, flow velocity and flow regime.

Figure 2 shows the measured and computed pressure profile of well Az-19. The experimental log was obtained using high-precision electronic logging equipment. The temperature profiles are shown in Figure 3. In these figures, open circles represent the experimental pressure or temperature values, while the results obtained with WELFLO are shown as open squares and the results obtained with GEOPOZO are shown as open triangles. The geometric profile of well Az-19 is shown on the left-hand side.

DISCUSSION

The profiles shown in Figure 2 are approximately linear all the way from the bottom to the wellhead, with a marked change in slope at the 930 m depth level. This change in slope corresponds to the change in pipe diameter in the well from 7" to 9-5/8".

A similar result was found in measured and computed temperatures. In this case, the computed profiles generated with WELFLO and GEOPOZO are linear from the well bottom to the 930 m depth level; then a marked change in slope occurs and the profiles are again linear from there onwards. This behavior is also found in the (measured) temperature profile; however, near the wellhead a rapid decrease in temperature is observed while the computed profiles do not show this degree of cooling. This is often found in geothermal wells and is normally caused by turbulence when the well is opened to introduce the logging

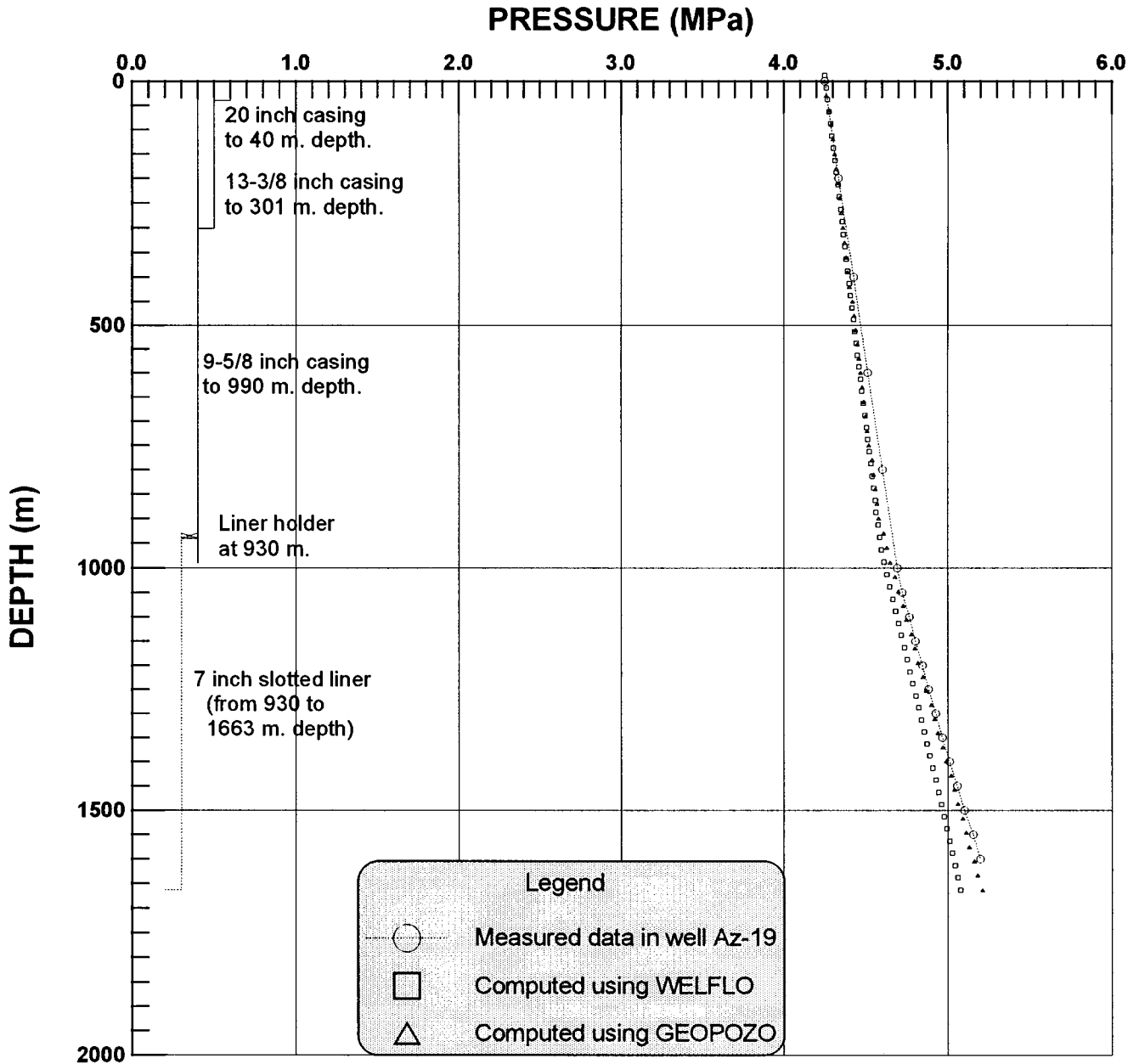


Fig. 2. Comparison of the measured pressure profile in well Az-19 from Los Azufres, Mexico geothermal field with the computed profiles obtained with the WELFLO and GEOPOZO simulators.

tool. The wellhead temperatures predicted by WELFLO and GEOPOZO differ slightly due to the different thermodynamic correlations employed in the simulators.

From Figures 2 and 3, the agreement between measured and computed results may be appreciated. For pressure the simulated profile obtained with GEOPOZO matches the logged profile from the well bottom to the wellhead, except for a slight deviation between 900 and 500 m. The agreement

obtained with WELFLO is not as good as that obtained with GEOPOZO between the well bottom and about 600 m depth. Comparison of the measured and computed temperatures shows that the profile generated with GEOPOZO matches well the experimental profile from the bottom of the hole to about 930 m. In the same depth range, the computed profile obtained with WELFLO deviates slightly and the computed temperatures are greater than the measured values. From 930 m to about 250 m depth, the measured temperature profile

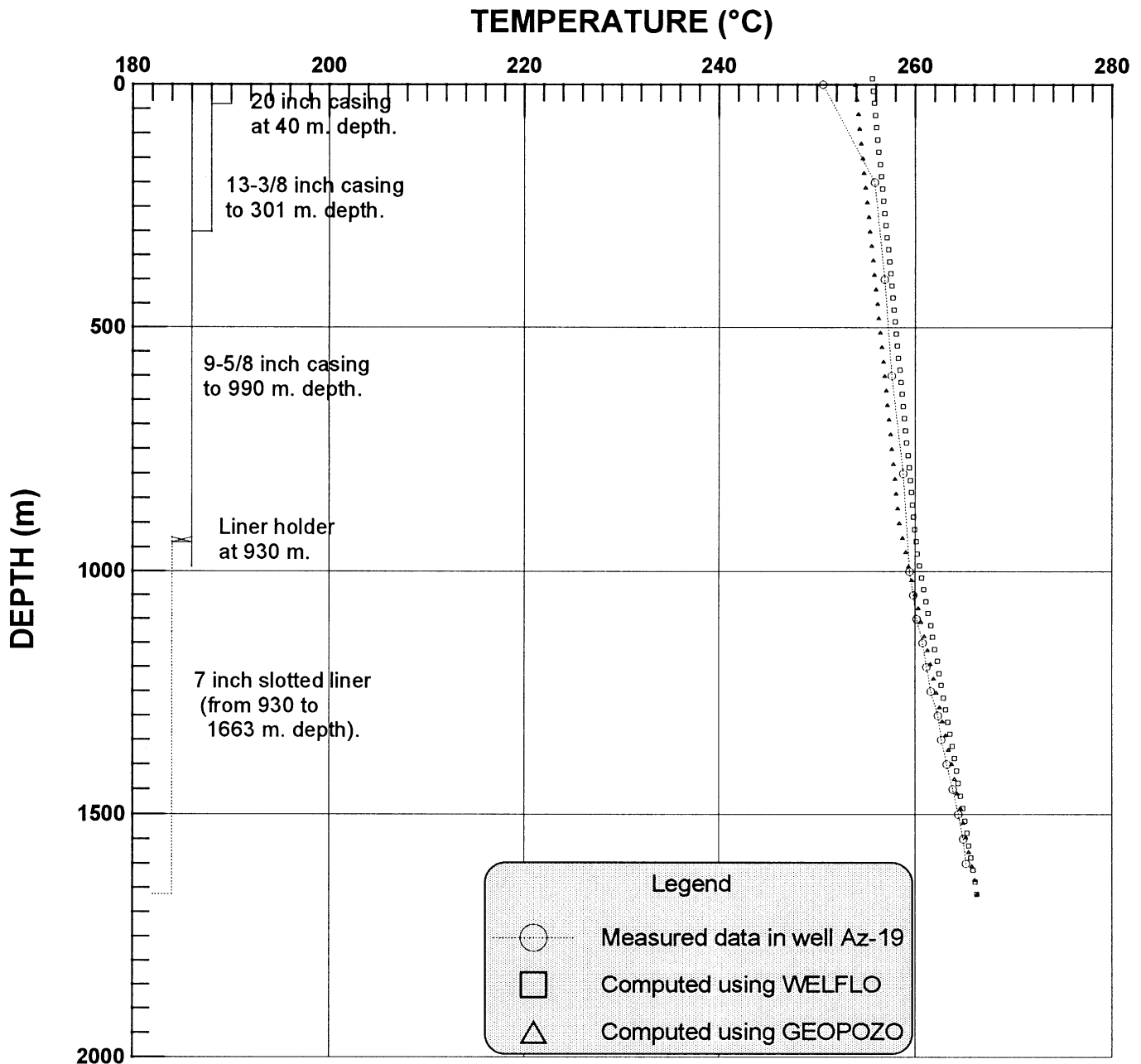


Fig. 3. Comparison of the measured temperature profile in well Az-19 from Los Azufres, Mexico geothermal field with the computed profiles obtained with the WELFLO and GEOPOZO simulators.

stays between the computed temperatures. Again, the temperatures obtained with WELFLO are greater than the measured ones, while the temperatures obtained with GEOPOZO are smaller than the measured results. Finally, from about 250 m to the wellhead, the measured temperatures exhibit a rapid decrease as explained above.

In conclusion, the GEOPOZO program appears to reproduce better the phenomena that occurred in well Az-19.

Bottomhole flowing pressures and temperatures are of interest for well productivity indexes, well output curves, etc. Comparison of the pressure and temperature results measured at bottomhole conditions, i.e., at a depth of 1600 m, with the simulations allows one to determine in quantitative terms the errors of the simulators. These differences are shown in Tables 2 and 3.

The bottomhole pressure result predicted with GEOPOZO is very close to the measured bottomhole pressure

Table 2

Measured and computed bottomhole pressure and temperature results in well Az-19 from the Los Azufres, México, geothermal field at a depth of 1600 m. Simulations were performed using the WELFLO and GEOPOZO simulators.

	Measured values	WELFLO results	GEOPOZO results
Pressure (Mpa)	5.20	5.04	5.16
Temperature (°C)	265.19	265.77	265.76

Table 3

Percentage deviation with respect to measured values in the calculation of bottomhole pressure and temperature of well Az-19 from the Los Azufres, México, geothermal field at a depth of 1600 m using WELFLO and GEOPOZO.

	WELFLO results	GEOPOZO results
Difference in Pressure (%)	- 3.2	- 0.8
Difference in Temperature (%)	+ 0.2	+ 0.2

(5.16 vs 5.20 MPa), a difference of under 1%. A deviation of -3.2% was found with WELFLO. On the other hand, the bottomhole temperature obtained with GEOPOZO and WELFLO are identical, and differ from the measured value by less than 1°C or 0.2%. At the total depth of 1663 m, the computed pressures obtained from both simulators differ more from each other but the computed temperatures agree better.

CONCLUSIONS

Overall, the results obtained with GEOPOZO show better agreement with measured profiles and bottomhole values. From Table 3, the deviations of computed values with respect to measured values at the well bottom are less than 4% for the worst case. Thus the simulation of heat transfer and fluid flow processes in geothermal wells is suitable for application in reservoir engineering analysis. The degree of uncertainty of the simulated results guarantees their application to wells similar to the well considered in this study. To a great extent, this avoids the need to depend

rigorously on expensive pressure and temperature profile log measurements. Once the feasibility of using a wellbore simulator has been confirmed, care must be taken of avoiding its indiscriminate use. Well behavior changes with time, and periodic calibration should be carried out. The user can determine the model sensitivity due to the varying conditions in the well. The application of the wellbore flow simulators GEOPOZO and WELFLO for reproducing the measured flowing bottomhole and main variable profiles of well Az-19 from the Los Azufres geothermal field is encouraging. Maximum deviations were found to be less than 4%.

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