WELLBORE FLOW SIMULATION: STUDY CASES OF SEVERAL MEXICAN WELLS

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ABSTRACT

In this work, a description is given of several wellbore flow simulation cases. These include prediction and match with measured pressure and temperature profiles of well H-17 from the Los Humeros GF after repair and deviation of 22° from the vertical; calculation of the productivity index of well Az-45 from the Los Azufres GF; prediction of production characteristics of well M-201 of Cerro Prieto Geothermal Field (CPGF); explanation of the sudden death of well M-202 of CPGF. Simulation was performed using GEOPOZO, a general purpose wellbore flow simulator developed jointly by the Instituto de Investigaciones Eléctricas (IIE) and the Comision Federal de Electricidad of Mexico (CFE) as a tool for everyday routinary use. GEOPOZO assumes homogeneous flow and is quite versatile, fast and easy to use. GEOPOZO has found wide application in the Mexican geothermal fields and experience gained through its use has proven its reliability in a wide range of applications.

Key words: wellbore; flow simulation; geothermal wells; Mexican geothermal fields

1. INTRODUCTION

Recently, IIE and CFE developed jointly the wellbore flow simulator called **GEOPOZO** as a tool to study normal and unconventional flow cases in Mexican production wells. GEOPOZO became a general purpose wellbore simulator after several versions and can perform calculations both from top to bottom or viceversa under one or two-phase flow. It can handle steady and quasi-steady flows under almost any thermodynamic condition likely to occur in a geothermal field: compressed liquid, full 2-phase region and superheated steam. It can handle variable diameter and several feedzones.

Also, since GEOPOZO was designed to provide for a tool for engineering purposes, it was developed under the assumption of homogeneous flow leaving aside the detailed flow description that phase slip or drift flux approaches can provide. Modem correlations for heat transfer and accurate thermodynamic and formation properties allow fast and reliable calculations. With these characteristics, GEOPOZO is widely used in every-day wellbore flow engineering calculation

Simulation of heat and momentum in geothermal wells has been extensively studied as summarized by Garcia and Frías (1994). Codes exist for one and two-phase flow under homogeneous or phase slip assumptions, with or without corrections for salts and gases, multi-feedzones, etc. The first two-phase flow simulator is due to Gould (1974), while transient flow was first considered by Miller (1980). Some examples of simulators developed include WELFLO (Goyal et *al.*, 1980), VSTEAM (Intercomp, 1981), the code by Ortiz (1983), HOLA (Bjomsson, 1987), Palacio's model (1990), SIMU89 (Sánchez, 1990), GEOPOZO (Garcia and Santoyo, 1991; Garcia *et al.*, 1993) and WELLSIMv2 (Freeston and Gunn, 1993), among others. In this work, flow studies in four wells are described:

* prediction and comparison with measured pressure and temperature profiles of well H-17 from the Los Humeros GF after repair and deviation of 22°.
* determination of the productivity index of well AZ-45 from the Los Azufres GF.
* prediction of the expected production characteristics of well M-201 (3820 m total depth) from the Cerro Prieto GF.
* explanation of the "sudden death" of well M-202 from the Cerro Prieto GF.

2. FOUNDATIONS OF GEOPOZO

The GEOPOZO computer model solves the equations describing mass, momentum and energy conservation to simulate the one-dimensional, one- and two-phase steady flow processes in geothermal wells (Wallis, 1969). These are respectively:

$$\left(\frac{dw}{dz}\right) = 0 \qquad (1)$$

$$\left(\frac{dP}{dz}\right) - \left[\left(\frac{dP}{dz}\right)_f + \left(\frac{dP}{dz}\right)_{ac} + \left(\frac{dP}{dz}\right)_g\right] = 0 \qquad (2)$$

$$\left(\frac{dE_t}{dz}\right) - q = 0 \qquad (3)$$

The definition of the various terms is given by Wallis (1969). If a secondary feedzone exists, the mixing process is assumed to occur at the pressure of that point in the well,

$$P_j = P_{sec} \qquad (4)$$

where P_{sec} is the pressure of the secondary flow. Total flowrate is then the sum of the two feedzones:

$$w_{tot} = w + w_{sec} \qquad (5)$$

The heat transfer term appearing in eq. 3 is obtained from

$$Q = U\,A\,\Delta T \qquad (6)$$

The definition of U is given elsewhere (Willhite, 1967). The temperature in the surrounding formation is obtained from:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_r}{\partial r}\right) = \frac{1}{\alpha}\frac{\partial T_r}{\partial r} \qquad (7)$$

Friction factors for one-phase turbulent flow are obtained from the Moody-Colebrook-Whitecorrelation (e.g., Sanchez, 1990), while film heat transfer coefficients are taken from the Gnielinsky correlation (Garcia, 1985) which has proven to be superior to most correlations and covers flows where Re$\geq$2300. Formation properties are taken for the particular well from the IIE rock property files. Thermodynamic properties are obtained from well proven correlations (IFC, 1967; Meyer *et al*, 1968; Mercer and Faust, 1976; haver, 1984). The resulting code covers the liquid region from 1 to 45.0 MPa; the **full** two-phase region and the vapor region under 16.5MPa and an enthalpy of 2565 kJ/kg. Min/max enthalpies are 109 and 3174 kJ/kg.

3. RESULTS

CASE 1: pressure and temperature profiles of well H-17 from the Los Humeros GF after repair and deviation of 22".

This well was drilled in 1986 and completed with 0.220m (9-5/8") casing to 1401 m and 0.157m (7") liner from 1350 to 2261 m. Later on, it was opened to production and an attempt to obtain its output curves was performed. Continuous flow oscillation was observed at production conditions without ever completely stabilizing. However, it produced 42T/h of steam and 2.4T/h of water at separation pressure of **0.8MPa**, with wellhead pressures of 1.5MPa. In 1992, the well was closed and repaired with an inclination of 22° from 1102 to 1223m, with total depth of 1700m, Fig. 1. Static pressure and temperature logs were then taken before opening it for initial production. Finally, output curves using 2", 2-1/2" and 3" diameter orifices were determined. Results of the latter development are discussed. Static pressures indicated a liquid column with water level at 87m. Static temperature profiles showed a convective feedzone in the 1500-1600m interval, with average pressure of 12.73MPa. Bottomhole static temperatures were about 300°C, dropping to about 228°C when flowing through a 2" orifice. This temperature drop is associated with the pressure drop occurring in the formation since the fluid enters the well at saturated conditions. Average flowing pressure in the 1500-1600m interval was 2.6MPa. Overall pressure drop (reservoir to wellhead) was 11.23MPa of which 10.07 occur in the formation.

Simulation results. Flow simulation was performed from wellhead to bottom using the GEOPOZO code. To validate the simulation, calculated and measured pressure and temperature profiles were compared. For a 2" orifice, wellhead pressure measured with a manometer was 1.44MPa and logged pressure was 1.42MPa. Measured wellhead enthalpy was 2595kJ/kg while total mass flowrate was 16.3T/h. Figure 1 shows the well completion after repair and the comparison between calculated and measured pressure and temperature profiles. The measured profile was better calibrated (1.4% relative error at wellhead) than the corresponding temperature profile (9.4% relative error). It is seen from Fig. 1 that the calculated pressure profile adjusts quite well with slight overprediction of bottomhole flowing pressure while the temperature profile is fairly well adjusted.

CASE 2: determination of the productivity index of well AZ-45 from the Los Azufres GF.

A second case where GEOPOZO was used is calculation of the productivity index of well Az-45 prior *to* its connection to the stem supply pipe network at Los Azufres GF. The well was completed with 0.2224 m (9-5/8") diameter casing from 0 *to* 1501m, 0.157m (7") casing from 1394 to 1541m and 0.157m (7") liner to 1697m. The well was drilled between December 1983 and March 1984. The results from this simulation were compared with the results obtained using the simulator developed by Ortiz (1983) employing the phase-slip approach. The experimental data used for the simulation are shown on Table 1. Table 2 shows results for

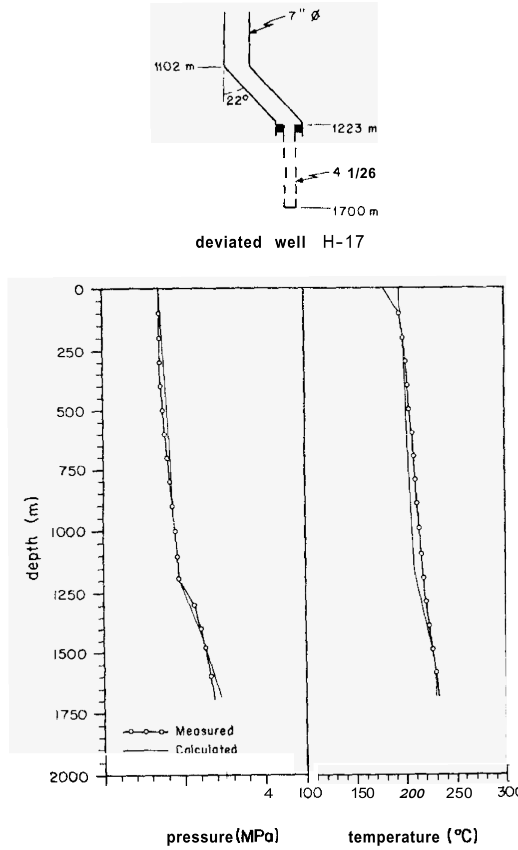

Figure 1 Pressure and temperature profiles of well H-17 after repair; Los Humeros, G. F.

each orifice used.

For a reservoir pressure of 8.2 MPa, the average calculated productivity index was 15.7T/h/MPa. It compares with a value of 13.7T/h/MPa obtained using Ortiz's (1983) simulator. The difference between these two values is 13.9%.

Table 1 Experimental data used to calculate the productivity index of well Az-45 from the Los Azufres geothermal field, México.

EXPERIMENTAL DATA			
Dor. m	**Pwh, MPa**	**Flow, T/h**	**Ent, kJ/kg**
0.051	4.69	42.0	2542
0.064	3.65	51.0	2564
0.076	2.65	57.0	2562
0.102	1.60	62.0	2555
0.127	1.10	64.0	2559
0.279	0.60	68.0	2560

CASE 3: prediction of output curves of well M-201, Cerro Prieto GF.

This is one of the deep exploratory wells (M-200's) drilled at Cerro Prieto GF. It could not sustain production flow when compressed-air was injected. Thus, this well was studied to determine if its inability *to* sustain flow was due to its geometry and depth, the existence of a secondary cold-water feedzone, high heat losses or to the reservoir characteristics.

Table 2 Summary of calculations of productivity index for each mass flowrate obtained during initial production of well Az45.

CALCULATED VALUES					
GEOPOZO			ORTIZ, (1983)		
P_{wf} MPa	ΔP MPa	P.I. T/h/MPa	P_{wf} MPa	ΔP MPa	P.I. T/h/MPa
5.71	2.49	16.87	5.56	2.64	15.93
4.99	3.21	15.89	4.49	3.71	13.74
4.42	3.78	15.08	3.80	4.41	12.94
4.02	4.18	14.83	3.39	4.51	12.88
3.94	4.26	15.02	3.30	4.90	13.06
4.05	4.15	16.39	3.36	4.84	14.05

These wells had been little used in part due to the availability of steam from other shallower wells and due to their particular characteristics: total depth, fishing, stuck-ins or sudden death. It was also assumed that these wells were affected by the existence of shallow aquifers which led to very small temperature gradients (2°C/100m) from surface to some 1500m thus enhancing heat losses to the surrounding formation. In addition, the existence of cold-water secondary feedzones due to mechanical damage could prevent the wells from sustaining production flow.

Well M-201 has a total depth of 3820 m and was completed with 0.2224m (9-518") diameter casing from 0 to 2350m, followed by 0.157m (7") diameter casing down to 3600m and 220m of 0.1 14m (4-1/2") liner. Reservoir characteristics are 350°C and 32.1MPa. The productivity index used to calculate the changes in downhole pressure with flowrate which in turn was used in the simulator was 2.71Ton/hr/bar (Gutierrez, 1991). A reservoir thickness of 300m was assumed. Other data used for this case can be found in Garcia and Santoyo (1991). Fig. 2 shows the expected output (calculated) pressure curve which would be obtained under normal operation, i.e., steady state, negligible heat losses, no secondary feedzone and reservoir characteristics.

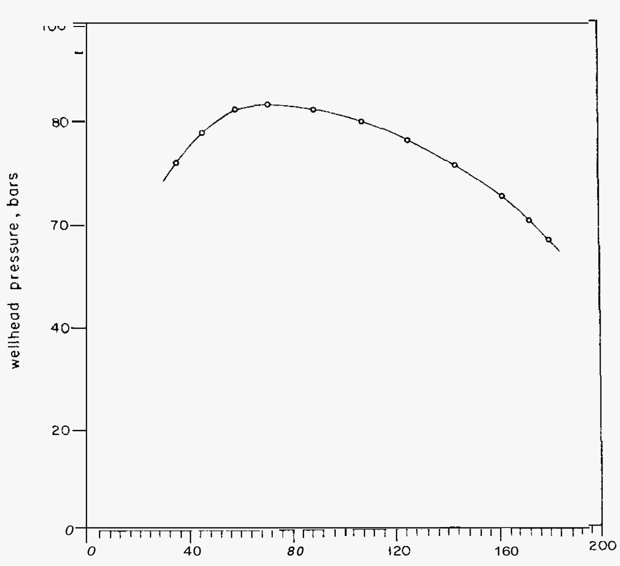

Figure 2 Expected output pressure curve of well M-201 of Cerro Prieto G F.

This curve indicates the under such conditions, the well should sustain production flow with mass flowrates between 40 and 180T/h at least. It was then concluded that the well did not sustain flow due to a secondary feedzone, probably of an enthalpy lower than that of the reservoir fluid, which prevented the flow from reaching the surface. However, the lack of production may also have been due to low permeability or damage to the production **zone** for which a hydraulic conductivity of $7.7x10^{-13}m^3$ was estimated (Gutiérrez, 1991). Thus, further information would be needed to support the existence of a possible secondary feedzone that produced lower enthalpy fluid.

CASE 4: explanation of the sudden death of well M-202, Cerro Prieto GF.

This is also a deep well: 3986m total depth. It was completed with 0.2224m (9-518") diameter casing from 0 to 2432m; 0.157m (7") casing from 2381 to 3483m and 0.114m (4-1/2") liner from 3432 to 3986m. It also exhibits the characteristics of all six deep exploratory wells: low temperature gradient up to 1500m followed by a rapid increase (14°C/100m) in the following 2000m and a third change of gradient above 3500m to reach about 340-350°C at depths of 4000m or more.

This well was studied to investigate the causes of its "sudden death" during its evaluation stage. At that time, sand blockage was reported as the reason of the killing of this well. Upon revising information on this well, temperature measurements indicated that cold water might have entered the well. This was evaluated by analysis of information on the well drilling, induction and development, combined with flow simulation and comparison of calculated and measured data.

Well M-202 was completed in June 1984 and observed during the next 5 months. The water level stabilized at 300m and temperature logs were run which indicated temperatures of 340°C at 3760m. No pressure log was run but a caliper run showed resistance from this depth on, possibly due to mud flocculation. The well was inducted by air injection later in November, the flow was induced and recorded wellhead manometric pressure was 0.1MPa. By December 25, wellhead pressure was 3.97MPa. At the end of heating, development of the well was carried out for the next 9 days and the output curves were determined but when testing with a 0.114m (4-112") orifice, it was reported that the well was blocked with sand and stopped flowing.

A caliper log was immediately run: 0.157m to 2389m; 0.146m (5-3/4") to 3435m and 0.076m (3") to 3735m (250m above total depth and inside the 0.114m liner). No anomalous situation was found. Then, on January 4 & 5, 1985 Two temperature **logs** were run which clearly indicated cold water inlet (150°C) between the 0.2224m casing and the 0.157m hanger, 2350m depth approximately. Repair of the well was attempted with no success due to a 2695m, 0.114m diameter drilling pipe fish and failure to recover it. Since then this well is used for monitoring purposes.

Fig. 3 shows temperature log T/19 run 48 hours after the well went dead. It is seen that a 150°C secondary feedzone appears to exist at about 2350m whose flowrate may be determined using the data obtained in the previous development and with the aid of mass and energy balances. Consider a reservoir contribution with mass flowrate m, and temperature of 340°C and a secondary contribution with mass flowrate m_2 at 150°C, then the flowrate measured at wellhead must be satisfied. From this exercise it is seen that as the well is opened to higher flows, the secondary feedzone flowrate increases. This in turn affects the production enthalpy.

Flow simulation: In order **to** calibrate the GEOPOZO wellbore simulator against measured data, the temperature log T/17, which was run when flowing through a 0.05m (2") purge, was reproduced. Since discharged flowrates were unknown for the purge, different flowrates were used to adjust the measured profile.

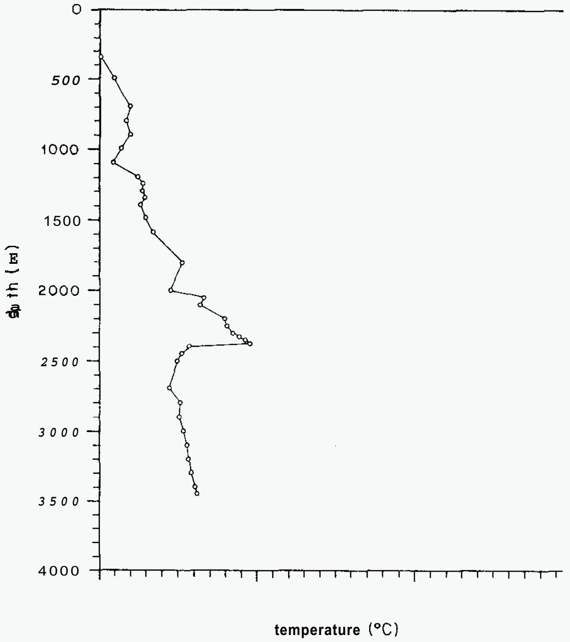

Figure 3 Temperature profile of well M-202 measured 48 hrs. after going dead; Cerro Prieto, G. F.

Fig. 4a illustrates the calculated profile without considering secondary flow. As observed, the measured profile was not reproduced satisfactorily. Then, reservoir (84% of total flow) and secondary flow (16% of total flow) contributions were considered. The calculated and measured profiles agreed well from total depth to about 1400m, Fig. 4b. This was not the case at shallow depths where possibly the homogeneous two-phase flow assumption fails. It is noticed that the calculated curve shows a temperature drop at the secondary inflow zone that is not apparent in the curve measured under flowing conditions. However, the temperature drop is present in the temperature log T/17, Fig. 3, on which other smaller temperature drops are observed at 2000 and 1100m. The latter may be the reason for the poor match at shallow depths seen on Fig. 4.

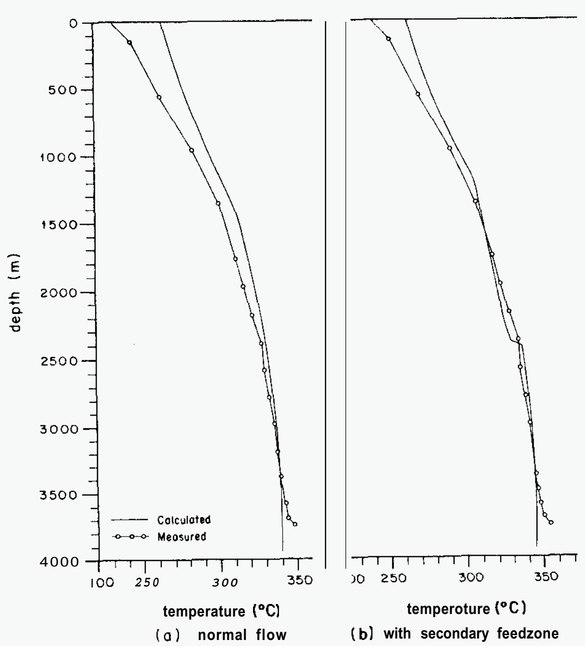

Figure 4 Measured and calculated temperature profiles of well M-202 Cerro Prieto, G. F., when flowing through a 2" orifice.

Next, wellhead flowrates and enthalpy measured during the development of the well were reproduced. Fig. 5 shows the case when well M-202 was flowing through a 0.05m (2") orifice for varying flowrates of the secondary feedzone. It is noted that as cold-water flowrate increases, wellhead pressure decreases and when the secondary flow contributes with 28.5% of total flow (22T/h), the well "goes dead". Similar results were found for all flowrates measured during the well development.

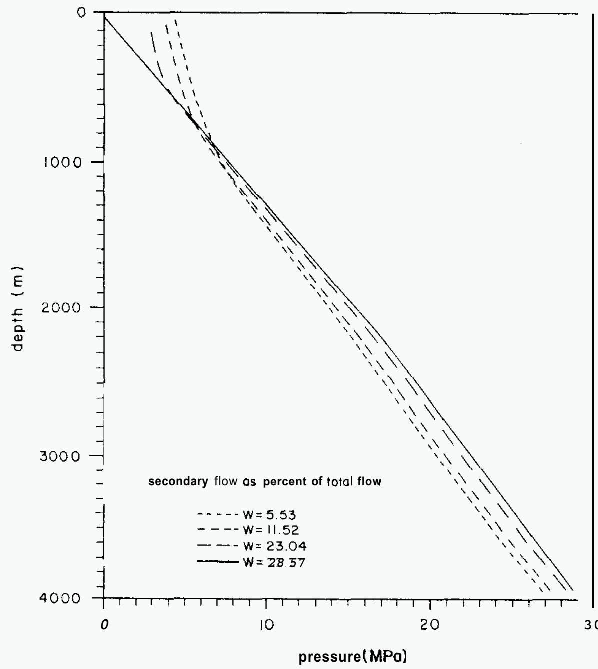

Figure 5 Pressure profiles of well M-202 flowing through a 2"Ø orifice with different secondary flow rates,

The analysis described above allows to think that the reason for the well "sudden death" was the inlet of a secondary cold fluid and not a sand blockage. However, lack of match at shallow depths indicates that the wellhead conditions derived from calculated results differ from measured data. This is important when calculating output curves and, therefore, further analysis and modelling is required to account for the temperature drops probably caused by other secondary feedzones observed on Fig. 3 to properly match observed and estimated curves.

4. DISCUSSION

Numerical simulation of heat and fluid flow continues to be a powerful tool to model typical transport processes of production geothermal wells or to understand not so common processes. In this work, four different cases have been described which include normal applications of wellbore flow simulation and rather uncommon flow situations.

The wellbore flow simulator GEOPOZO used in this work has proven to provide results of sufficient accuracy for engineering purposes and in most cases, these are comparable to those obtained using more sophisticated simulators. The homogeneous formulation, although somewhat limited when compared with other two-phase approach, is of great value if a detailed description of the flow is not needed. The examples described above have clearly demonstrated this fact.

Furthermore, the simulator described above has been developed to an extent which has become of sufficient generality and its wide thermodynamic range of application make it a useful and fast tool for use in almost any geothermal well and for the routinary use of the engineer related with geothermal wells.

5. CONCLUSIONS

Four different cases of flow in geothermal production wells have been analyzed employing the wellbore flow simulator called GEOPOZO. This simulator has become a useful, fast and reliable tool for everyday use in any geothermal well. Its thermodynamic range covers most situations likely to be found in Mexican, or other, geothermal fields. The homogeneous flow approach used has proven to be accurate enough if a detailed flow description is not needed.

The cases described include normal flow situations (estimation of output curves and productivity indices) and not so common situations (deviated wells and modelling of wells with secondary feedzones). All cases were successfully simulated and, in particular, the analysis performed on well M-202 of the Cerro Prieto GF allowed to conclude that the reason for the "sudden death" of the well might have been a secondary inflow of lower enthalpy, as opposed to the sand blockage reason initially argued. This case, however will be further studied to improve the match between measured and calculated results.

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