A new method of damage determination in geothermal wells from geothermal inflow with application to Los Humeros, Mexico

A. Aragón[1*], S. L Moya[2], A. García-Gutiérrez[1,2], V. Arellano[1]
[1]*Instituto de Investigaciones Eléctricas, Cuernavaca, Morelos, Mexico*
[2]*Centro Nacional de Investigación y Desarrollo Tecnológico, Cuernavaca, Morelos, Mexico*

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Resumen

Se presenta la obtención de curvas-tipo de influjo geotérmico para diferentes valores de daño, y se demuestra su aplicación en los análisis de producción de pozos geotérmicos determinando el daño en trece pozos del campo geotérmico de Los Humeros, Puebla, México. También se hicieron determinaciones de la permeabilidad en las zonas de producción de estos pozos y de sus respectivos índices de productividad. Se compararon los resultados del valor de daño obtenido con la metodología propuesta, con los valores de daño obtenidos a partir de pruebas de presión, encontrando que las diferencias máximas entre ambas técnicas es del orden de 0.7 unidades de daño. La presente metodología permite la caracterización del yacimiento a lo largo de su vida productiva a partir de las mediciones de las pruebas de producción efectuadas en los pozos. La metodología propuesta es innovadora porque anteriormente el daño solamente se podía determinar a partir de los análisis de las mediciones de la pruebas de presión

Palabras clave: Relaciones del comportamiento de influjo, pruebas de producción en pozos, factor de daño, yacimientos geotérmicos, curvas tipo, campo geotérmico Los Humeros.

Abstract

Geothermal inflow type curves were obtained for different values of well damage (i.e., inflow performance relationships). The method was evaluated by diagnosing the damage of thirteen producing wells in the Los Humeros, Puebla, México geothermal field. Permeability determinations were carried out for these wells and their productivity indices were estimated. Comparison of the diagnoses made via damage effects against the results of field pressure tests showed that the maximum difference between both approaches is on the order of 0.7 damage units. The methodology allows reservoir characterization along its productive life, since several production tests are carried out while the reservoir is producing. The data obtained from production tests are used to determine the damage effect and permeability of the rock formation. Previously the damage (skin factor) could only be determined from the analyses of transient pressure tests.

Key words: Inflow performance relationships, well test production, skin damage effect, geothermal reservoir, type curves, Los Humeros geothermal field.

Introduction

Characteristic curves of production at bottom-hole conditions are built from the values of both pressure and flow measured during the production tests of a well, or directly from their characteristic curves of production using a well flow numerical simulator.

The inflow curves (and the characteristic curves) are specific to each well and vary according to the stage of their productive life. They reflect of the thermo- physical characteristics of the formation and of the properties of the fluid in the reservoir. They are used for reservoir characterization.

The goals of this paper are 1) To show the geothermal inflow type-curve with damage effect; 2) To present the methodology determining the damage effect from the production tests data, using geothermal inflow type-curves with damage effect and; 3) To apply the proposed methodology with data production tests carried out in wells of Los Humeros, México geothermal field, obtaining their respective damage values.

The application of the inflow curves was used in hydrocarbon exploitation, in order to establish useful approaches in the exploitation designs (Evinger and Muskat, 1942; Muskat, 1945; Gilbert, 1954). The methods proposed (Fetkovich, 1973; Jones *et al*., 1976; Chu, 1988;

Helmy and Wattenbarger, 1998) were applied to practical field case studies.

The techniques applied for this type of analysis were adapted from the results of the pressure transient analysis (Muskat, 1945; Gilbert, 1954; Van Everdingen and Hurst, 1949; Horner, 1951; Ramey, 1970; Chu *et al.*, 1980).

Weller (1966) established a method to calculate the behavior of the reservoir decline by means of the pressure behavior in the well bottom as a function of production. The above-mentioned technique comprises the determination of well productivity and the implementation of the methodology proposed by Muskat (1945) and Gilbert (1954).

The development, analysis and application of the first relationships of theoretical curves of the inflow behavior, known as "Inflow Performance Relationships" (IPR), were made by Vogel (1968). Later on, Standing (1970), Fetkovich (1973), Klins and Majcher (1992), Klins and Clark (1993) and Wiggins (1994) made improvements to these first inflow curves.

Inflow performance relationships have been used in the petroleum industry for a number of years to determine the productivity of oil wells (Codeon, 2004) from a single dimensionless IPR curve (reference curve), which relates the dimensionless bottom-hole flowing pressure with the respective dimensionless volumetric flow rate. In this sense, the first inflow performance relationship was proposed by Vogel (1968) as follows:

$$\frac{q_o}{(q_o)_{\max}} = 1.0 - 0.2\left(\frac{p_{wf}}{p_e}\right) - 0.8\left(\frac{p_{wf}}{p_e}\right)^2 \quad (1)$$

where p_{wf} is the bottom-hole flowing pressure, q_o is the volumetric flow rate, and the scale parameters are the reservoir pressure (p_e) and the maximum volumetric flow rate $(q_o)_{max}$

Klins and Majcher (1992) modified the above relation by incorporating the decay factor (n) and the skin damage effect (s) after analyzing information of more of 1340 petroleum wells. The final expression is:

$$\frac{q_o}{(q_o)_{\max}} = \mathrm{M}\left[1.0 - 0.295\left(\frac{p_{wf}}{p_e}\right) - 0.705\left(\frac{p_{wf}}{p_e}\right)^n\right] \quad (2)$$

where M is a parameter which incorporates the skin damage effect (s):

$$\mathrm{M} = \frac{\ln\left(\frac{r_e}{r_w}\right) - 0.467}{\ln\left(\frac{r_e}{r_w}\right) - 0.467 + s} = 6.835 \quad (3)$$

where r_e is the reservoir drainage radius and r_w is the wellbore radius.

Klins and Majcher (1992) established the mean characteristics of the wellbore radius and the drainage of the reservoir in order to determine the value of M. According with the last thing, they used a value of 247 ft as a drainage radius (r_e) and 2 inches as wellbore radius (r_w). They applied these values in original expression of M and the result is the value of the constants appearing in Eq. (3).

The exponent n of Eq. (2) is a function of the reservoir pressure p_e and the bubble point pressure (p_b), and is given by:

$$n = \left(0.28 + 0.72\right)\frac{p_e}{p_b}(1.235 + 0.001p_b) \quad (4)$$

In the geothermal engineering Iglesias and Moya (1990) formulated the first dimensionless inflow curve for geothermal reservoirs, considering the geothermal fluid as only pure water. The expression is:

$$\frac{W}{W_{\max}} = 1.0 - 0.6\left(\frac{p_{wf}}{p_e}\right)^2 - 0.4\left(\frac{p_{wf}}{p_e}\right)^4 \quad (5)$$

where W is the produced mass flow, W_{max} is the maximum mass flow (theoretically for $p_{wf} = 0$). The flowing bottom pressure is p_{wf} and the reservoir pressure is p_e.

The same authors presented the corresponding inflow curve for thermal productivity (they also call it as thermal power):

$$\left(\frac{Pot}{Pot_{\max}}\right) = 0.7\left(\frac{W}{W_{max}}\right) + 0.3\left(\frac{W}{W_{max}}\right)^4 \quad (6)$$

where Pot is the thermal *power* = (W) (h), and h is flowing enthalpy.

Subsequently, Moya (1994) obtained the respective dimensionless inflow curves for a binary system H_2O-CO_2, being the expression of the mass productivity as follows:

$$\frac{W}{W_{\max}} = 1.0 - 0.256\left(\frac{p_{wf}}{p_e}\right) - 0.525\left(\frac{p_{wf}}{p_e}\right)^2 - 0.057\left(\frac{p_{wf}}{p_e}\right)^3 - 0.162\left(\frac{p_{wf}}{p_e}\right)^4 \quad (7)$$

Applications of the binary model to field case studies of Mexican geothermal reservoirs were made (Moya *et al.*, 1995; 1997; 1998), obtaining outflow curves and comparing them to field data. Iglesias and Moya (1998) validated the inflow curves, comparing their results with bottom-hole data. Moya *et al.* (2001, 2003) extended the application of this methodology to estimate the permeability of rock formations by means of a computation system (Moya and Uribe, 2000) that applies the methodology in automated form.

To introduce the effect of salts, Montoya (2003) proposed an inflow curve that considers the geothermal fluid to be a ternary mixture H_2O-CO_2-$NaCl$. This expression is a result of use the TOUGH program (Pruess, *et al.*, 1999) applied to geothermal reservoirs for different flow values, using diverse salt (*NaCl*) concentrations, up to 5 % of mass fraction in the liquid phase and its form is:

$$\frac{W}{W_{max}} = 0.99 - 0.436\left(\frac{p_{wf}}{p_e}\right) - 0.537\left(\frac{p_{wf}}{p_e}\right)^2 + 0.694\left(\frac{p_{wf}}{p_e}\right)^3 - 0.715\left(\frac{p_{wf}}{p_e}\right)^4 \quad (8)$$

where W is the well mass flow rate and W_{max} is the well maximum possible mass flow rate.

In order to incorporate the damage effect to the reference curve of Eq. (8), it is appropriate to mention the proposed by Klins and Majcher (1992). So, in order to determine the values of the constants applicable to geothermal systems, was done a research about the characteristics of the pipes production and mean dimensions of the different geothermal reservoir of the world. The obtained results helped to establish the value of r_w of 2 inches and r_e of 750 ft. According with the last thing, the equation to determine the value of M is given by the next expression:

$$M = \frac{7.75}{7.75 + s} \quad (9)$$

This factor affects the reference curve given by Eq. (8), which is function of p_{wf} and p_e relation, skin damage and of gas and salt concentration.

$$\frac{W}{W_{max}} = f\left[s, \frac{p_{wf}}{p_e}, NCl, CO_2\right] \quad (10)$$

$$\frac{W}{W_{max}} = M\left[0.99 - 0.436\left(\frac{p_{wf}}{p_e}\right) - 0.537\left(\frac{p_{wf}}{p_e}\right)^2 + 0.694\left(\frac{p_{wf}}{p_e}\right)^3 - 0.715\left(\frac{p_{wf}}{p_e}\right)^4\right]$$

Eq. (10) is the proposed reference curve for geothermal reservoirs with damage effects.

Using variables in dimensionless form:

$$W_D = \frac{W}{W_{max}} \quad (11)$$

$$P_D = \frac{p_{wf}}{p_e} \quad (12)$$

Thus, the dimensionless form of Eq. (10) is as follows:

$$W_D = M\left[0.99 - 0.436(P_D) - 0.537(P_D)^2 + 0.694(P_D)^3 - 0.715(P_D)^4\right] \quad (13)$$

A plot of Eq. (13) is shown graphically in Fig. 1 for skin damage values between -4 and +6.

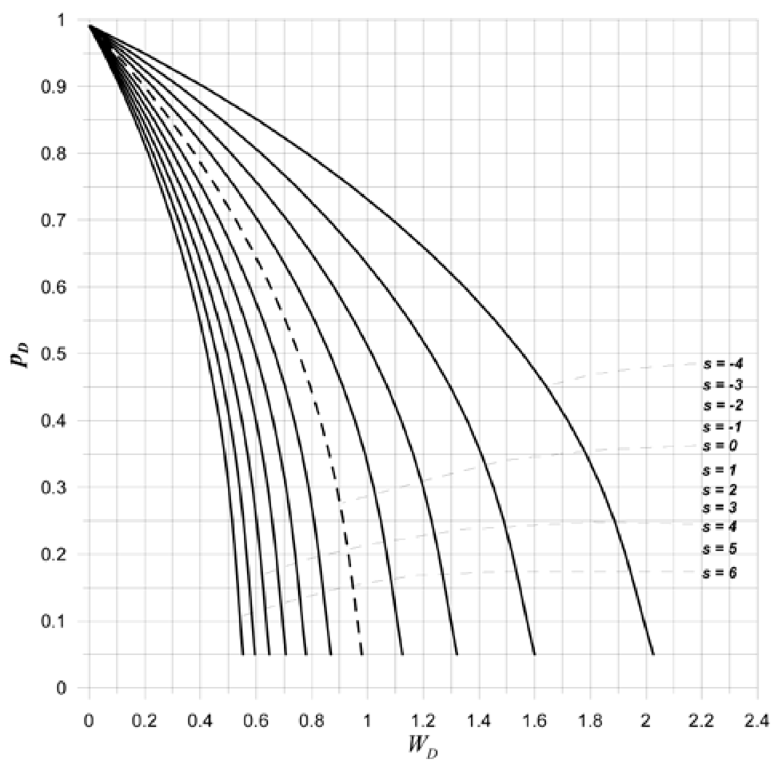

Fig. 1. Type-curve for different skin damage values (*s*) obtained from Eq. (13).

The presence of skin damage (*s*) in the rock formation is manifested by an additional drop in reservoir pressure caused by obstructions or plugging of the rock flow channels, yielding a reduced formation permeability and positive values of the skin damage effect. When the rock formation is artificially treated with a cleaning, stimulation or fracturing job to increase well/formation productivity, then negative values of the damage effect are obtained, which is a beneficial event.

It is common to find beneficial situations in wells (negative values of damage effect) during production tests performed at the end of the well drilling and completion. This occurs because the well discharge induces dragging of the drilling fluid residues that would have lodged in the walls of the well, thus causing a cleaning operation of the well.

Methodology

The proposed general methodology to determine skin damage in a well through the use of the geothermal type-curves with damage effects given by Eqs. (10) and (13) is shown schematically in Fig. 2:

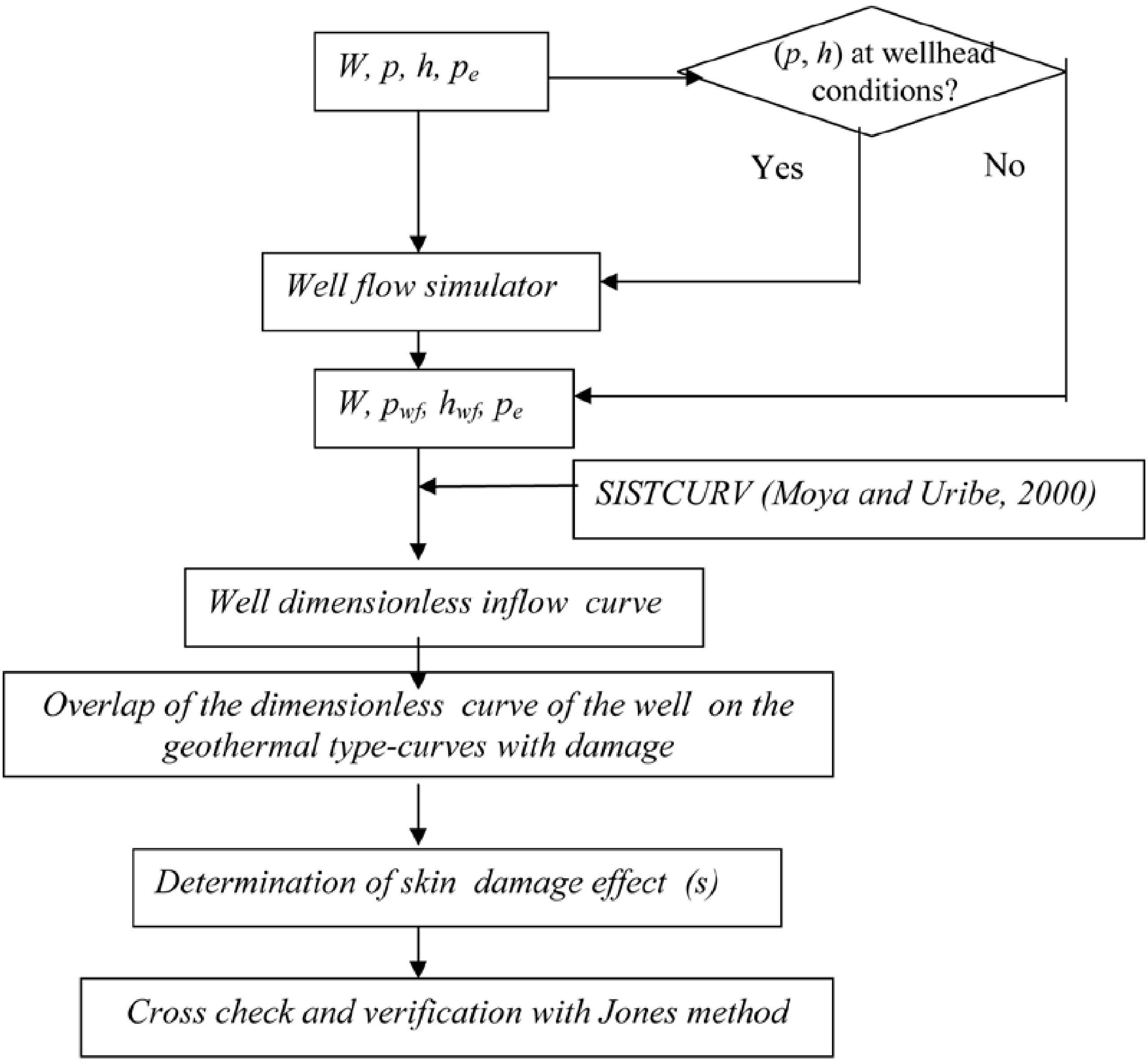

Fig. 2. General methodology employed to determine the damage effec in a geothermal well using the proposed geothermal type-curve with damage.

The proposed methodology establishes the use of the SISTCURV (Moya and Uribe, 2000; Moya *et al.*, 2003), which is a computer program that uses measures data (pressure, flow) of a production test in a geothermal well. This computer program uses the well flow simulator VSTEAM (INTERCOMP, 1981) to determine the bottomhole conditions. So, it reproduces all output curves of the well, and determines the maximum possible flow of the well. The correlations for pressure drops that this program uses, are: Hagedorn-Brown, Orkiszewski, Azis-Govier, Beggs-Brill and Mukherjee-Brill. In this work the correlation of Hagedorn-Brown is used, because the good results for reproduce well conditions.

According to Fig. 2, the methodology employed in this study can be briefly described as follows:

1. The input data correspond to the data of a production test and include the mass flow rate (W), the flowing pressure and enthalpy (p, h), and the static reservoir pressure (p_e).

2. If the available data are at wellhead conditions (p, h), then a well flow simulator is used to obtain the bottomhole flowing conditions.

3. The dimensionless inflow curve of the well is determined from the reference curve (Eq. 5) employing the computational system SISTCURV (Moya and Uribe, 2000; Moya *et al.*, 2003).

4. The dimensionless inflow curve of the well is overlapped on the geothermal type-curve with damage effects shown in Fig. 1. The skin damage effect (s) corresponding to the best overlap of both curves, gives the required skin damage effect value.

5. The method proposed by Jones *et al.* (1976) is used to corroborate the skin damage effect determined using the proposed methodology.

This method is used to determine the skin damage existence in petroleum rock formations at the completion stage of a well using the data of a production test (Chu, 1988). It is a qualitative method and requires a minimum of three pairs of mass flow and pressure data.

The Jones *et al.* (1976) method is used to diagnose the mean conditions of the formation, as at stage of well completion as during any stage of the well operative life. The method was designed mainly to be applied in petroleum wells, but at the date, its application still is not common in geothermal wells. The method is useful to identify the pressure losses, originated by turbulent flow, related with the restrictions in the feed zone, which can indicate presence of damage.

In the present work the method is used as a tool to verify the proposed methodology, under the following procedure:

a) Determine the value $[(p_e-p_{wf})/q]$ for each volumetric flow q. This is equivalent to obtaining the inverse value of the productivity index J.

b) Plot $[(p_e-p_{wf})/q]$ vs. q

c) Fit a straight line to the data points and determine the values of its ordinate b and slope m such that:

$$\frac{p_e - p_{wf}}{q} = mq + b \qquad (14)$$

The criterion of the Jones method used for the diagnosis establishes that if the ordinate value b is less than 0.05, then the rock formation does not have damage, but for values of b greater than 0.05, there is skin damage in the formation.

In the diagnosis of the well conditions, the method proposes to determine b' from the next expression:

$$b' = b + m\,Q_{max} \qquad (14)$$

where Q_{max} is obtained from the inflow relationship (Eqs. 10 and 11).

If the ratio of b'/b, is less than 2.0 then, in the interface wellbore-formation, the turbulence is small or there is not.

For values of b less than 0.05 and b'/b greater than 2, the poor productivity could be originated because the area for the flow is not enough. In the last situation, the resulting solution is to improve the exploitation zone by making deeper the well.

Study cases

The methodology described above was applied to data of thirteen wells from the Los Humeros, Puebla, México geothermal field which is located approximately 200 km east of México City. Fig. 3 shows the location of the wells in the field. The wells considered in the present study appear in Fig. 3 with a different symbol and are listed in Table 1. Wellhead production test data for these wells were taken from Arellano *et al.*, (1998).

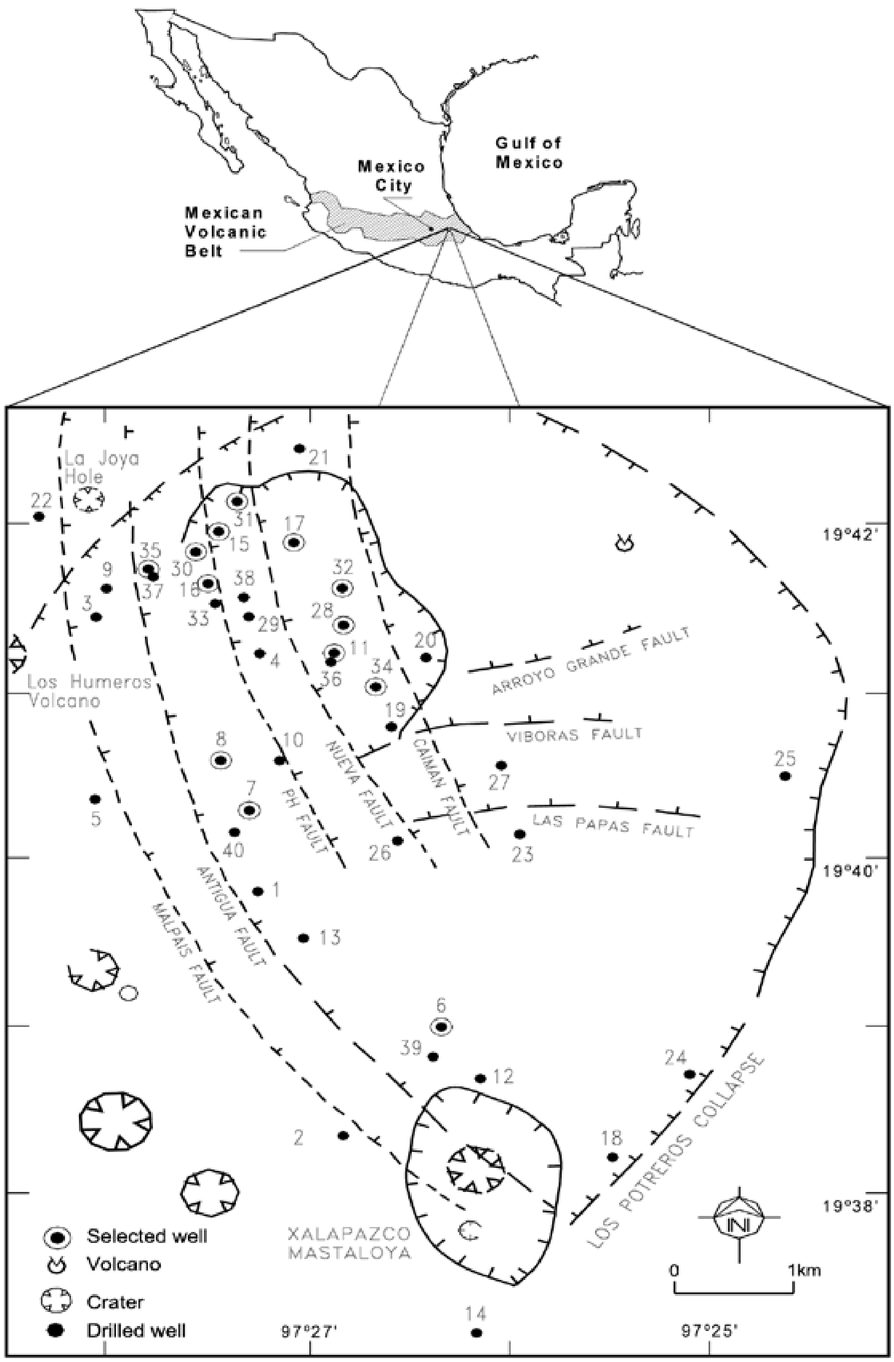

Fig. 3. Schematic diagram of the Los Humeros, México, geothermal field (taken from Rodríguez, 1997).

The static pressure data were obtained from transient pressure tests or measurements carried out at the completion stage of the well (Torres-Rodríguez, 1995) for sufficiently long stabilization times (greater than 100 hours). The static temperatures of the wells were determined using the Horner (1951) method (Arellano *et al.*, 1998). The output or discharge measurements correspond to the initial exploitation stage of the wells.

Example of skin damage determination using data of well H-11

In order to show the application of the proposed methodology, the data of well H-11 were considered which is located in the most exploited zone of the field. Fig. 4 shows the complete output curve obtained with SISTCURV and its comparison with the well production test field data.

Table 1

Initial conditions of the wells from the Los Humeros, México geothermal field included in the present study (Arellano *et al*., 1998)

Well	*Depth* (m)	*Elevation* (masl)	*W* (t/h)	p_{wh} (bar)	h_{wh} (kJ/kg)	p_e (bar)	T_e (°C)
H-6	2541	444	46.4	4.6	1998	117(1)	320
H-7	2340	480	39.0	5.9	2723	133(1)	301
H-8	2388	641	39.8	4.4	2140	113(2)	360
H-11	1465	1340	34.0	6.2	2666	100(1)	293
H-15	1913	882	66.8	9.0	2676	109(2)	250
H-16	2048	773	51.6	6.8	2727	140(2)	284
H-17	1661	1152	12.8	6.3	2757	101(1)	250
H-28	2575	289	36.1	4.6	2096	166(2)	360
H-30	1911	878	44.1	6.4	2758	114(1)	268
H-31	1926	881	55.6	8.1	27.08	145(2)	315
H-32	2200	625	42.3	10.7	2736	150(2)	333
H.34	1800	1010	9.0	8.8	2700	133(2)	234
H-35	1690	1151	48.8	22.1	2797	106(2)	293

(1) Determined from transient pressure tests
(2) Measurement performed at the completion stage of the well with sufficiently long stabilization times (>100 hours).

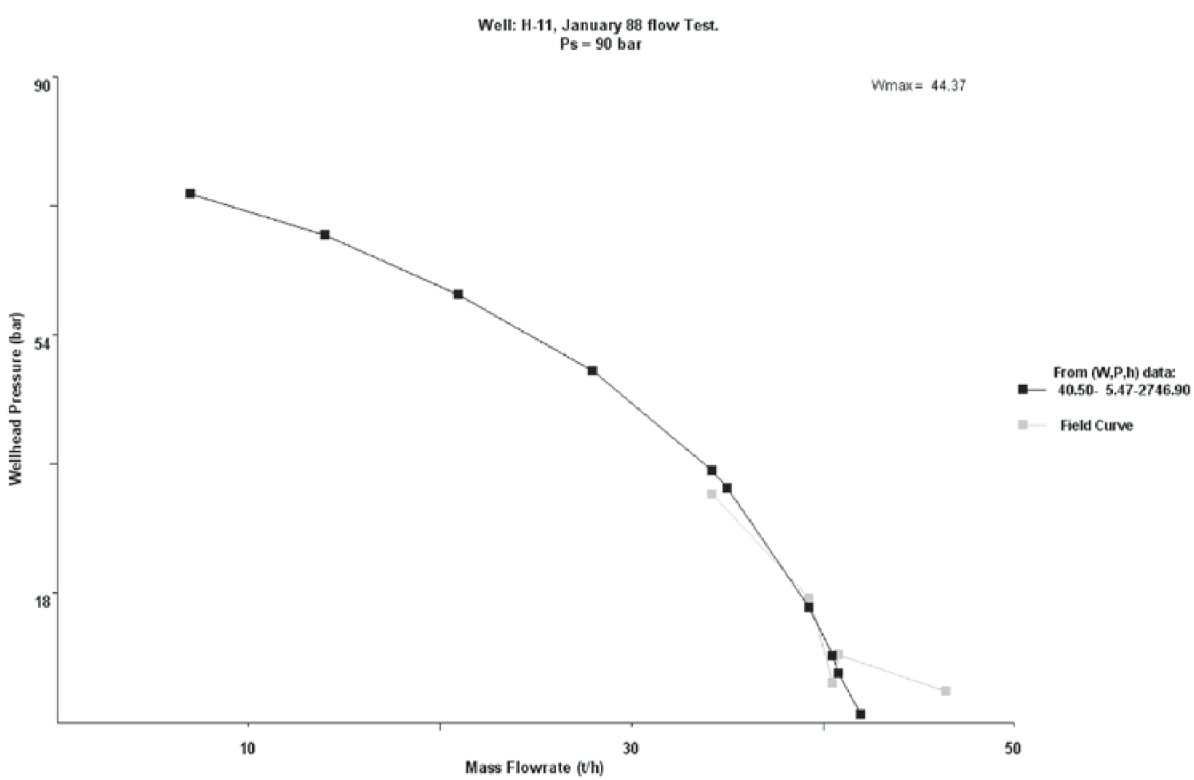

Fig. 4. Output curve of well H-11 obtained with SISTCURV and comparison with its own production test data.

Fig. 5 shows the overlap of the corresponding dimensionless inflow curve of the well with the geothermal type-curves with damage effect (Fig. 1). From this overlap it is obtained a skin damage value (*s*) of -0.8.

In order to verify this determination the qualitative method of Jones *et al*. (1976) is used to confirm the presence or absence of the damage determined with the proposed methodology. Fig. 6 shows the plot of q versus $\Delta p/q$ in the form suggested by the Jones method. It can be seen that the ordinate value is less than 0.05 ($b = 0.0068$); therefore it is verified that there is not damage in the well. Furthermore, the value of the skin damage effect also is verified with that obtained from transient pressure tests of $s = -1$ (Table 2).

Results and discussion

Table 2 shows a summary of the well skin damage determinations performed for thirteen wells from the Los Humeros geothermal field considered herein and their comparison with the skin damage effect results, obtained by Arellano *et al*. (1998) from transient pressure tests. Corroboration of results using the Jones method is also included according to the present methodology. Table 2 also includes the mass flow rate of each well and the respective permeabilities obtained with SISTCURV through the application of the methodology proposed by Moya *et al*. (2001) which are in the interval of mean values for this field. Finally, the corresponding productivity indices which were determined with the values of maximum mass flow are included. These values originate from the application of the SISTCURV procedure, as described before.

It can be seen from Table 2 that all the damage values determined using the present methodology are negative with exception of well H-31, which has a positive skin value of 0.2, and that the interval of damage values varies from -1.3 to 0.2. The presence of negative damage values is related with the fact that the production data correspond to early exploitation stage of the wells. In the initial exploitation stage, the flow from reservoir removes any possible obstruction caused by residues of well drilling, so this results in a cleaning operation of the rock formation yielding favorable beneficial conditions. It is also necessary to emphasize that the conditions close to the natural undisturbed state of the reservoir occur at the initial exploitation stage, so under this situation it is common to find beneficial flow conditions, i.e., negative values of damage effect.

When comparing the damage values from the present diagnosis with those obtained using transient pressure tests (Matthews and Russell, 1967), variations between 0.2 and 0.7 damage units were found. These differences are less than unity and therefore the results are considered reasonably reliable.

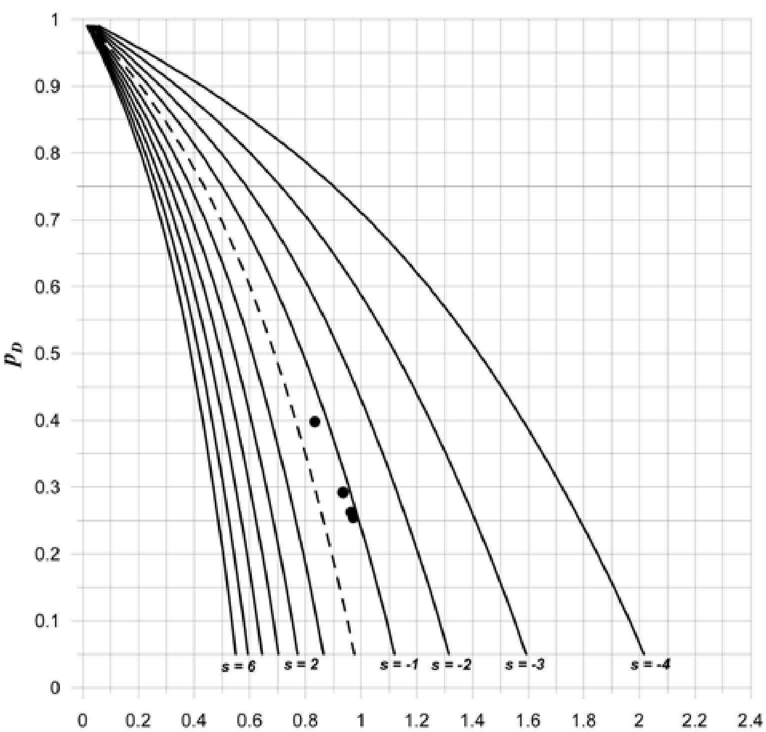

Fig. 5. Determination of the skin damage value (*s*) for the well H-11 using its production test data.

Table 2

Results of damage effect values obtained by applying the proposed methodology to production data of Los Humeros, México geothermal field.

Well	Skin damage value (*s*) This work	Skin damage value (*s*) Pressure tests [1]	Absolute skin damage value difference	Qualitative diagnosis with Jones method	W_{max} (t/h)	K (mD)	Productivity index (t/h)/bar
H-6	-0.9	-0.94	0.04	*b* = 0.02 <0.05 no damage	48	3.7	0.81
H-7	-1.2	-0.7	0.5	*b* = -0.07<0.05 no damage	40	3.35	0.36
H-8	-0.7			*b* = 0.03 <0.05 no damage	32.5	2.7	0.27
H-11	-0.8	-1.0	0.2	*b* = 0.01 <0.05 no damage	45	6.5	0.5
H-15	-0.4			*b* = -0.04<0.05 no damage	72	17	0.93
H-16	-0.7	-0.9	0.2	*b* = -0.03<0.05 no damage	47.2	3.5	0.7
H-17	-1.3	-0.6	0.7	*b* = -0.01<0.05 no damage	55.3	7.9	0.78
H-28	-0.6	0.0	0.6	*b* = -0.01<0.05 no damage	36	2	0.65
H-30	-0.3	0.0	0.3	*b* = 0.04 <0.05 no damage	45.5	6.2	0.65
H-31	0.2			*b* = 0.13 >0.05 damage	55.5	4.25	0.45
H-32	-0.8			*b* = 0.04 <0.05 no damage	44	3.15	0.44
H-34	-0.6			*b* = -2.77<0.05 no damage	12	2.37	0.18
H-35	-0.5			*b* = 0.04 <0.05 no damage	55.5	3.7	0.53

(1)Taken from Arellano *et al*. (1998).

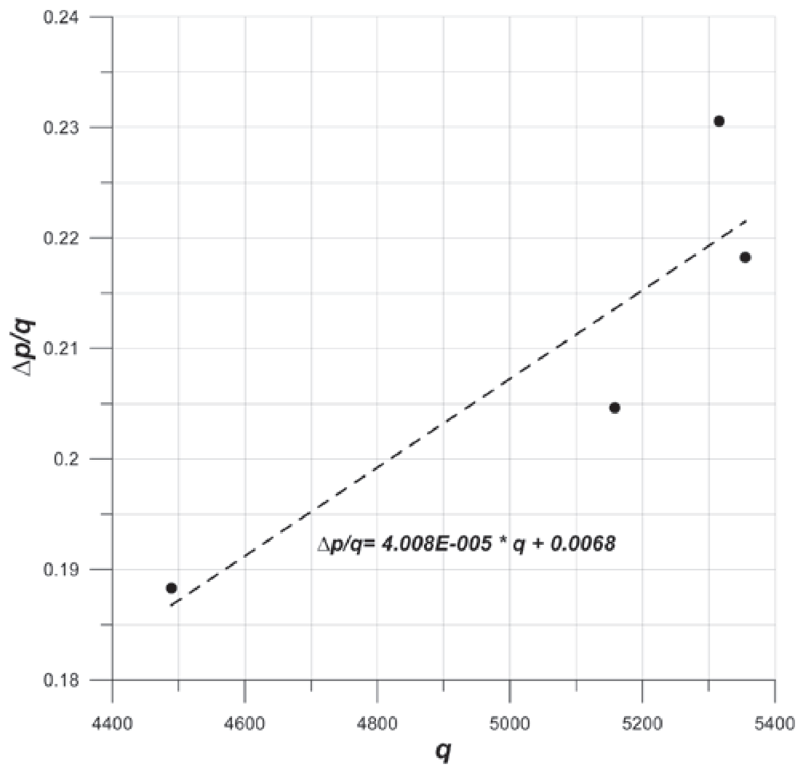

Fig. 6. Jones method applied to data of a production test of well H-11.

Conclusions

From the technical literature reviewed was found that the inflow performance relationships (IPR) are a good tool to characterize a production well, but the skin damage factor still is not included in these relationships.

In this work we presented inflow performance relationships including the skin damage effect (s).

We obtained geothermal inflow type-curves affected with skin damage effect and in this work are presented.

A new methodology to evaluate skin damage effects in geothermal wells using production tests data has been developed and described herein.

This methodology was successfully applied to the analysis and skin damage determinations of thirteen wells from the Los Humeros, México, geothermal field using production tests data.

The results obtained using the methodology proposed in this work were corroborated with the qualitative Jones method and supports the values of the skin damage effect obtained for the wells considered in the analysis, and also confirms the validity of the proposed methodology.

Comparison results of the skin damage obtained using the analysis method of transient pressure and using the proposed methodology, shows good agreement and the maximum difference was of 0.7 damage units.

Nomenclature

b	Value of ordinate in equation of a line	
h	Enthalpy	(kJ/kg)
m	Slope of equation of line	
M	Parameter dependent of re, rw and s	
n	Polynomial exponent	
p	Pressure	(bar)
p_b	Bubblepoint pressure	(bar)
p_e	Reservoir pressure	(bar)
p_{wf}	Bottom flowing pressure	(bar)
p_{wh}	Wellhead pressure	(bar)
q_o	Volumetric flow rate	(STBD)
$(q_o)_{max}$	Maximum volumetric flow rate	(STBD)
r_e	Drainage radius	(ft)
r_w	Well radius	(ft)
s	Skin damage effect	
T_e	Reservoir temperature	(°C)
W	Mass flow rate	(t/h)
W_{max}	Maximum mass flow rate	(t/h)

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A. Aragón[1*], S. L Moya[2], A. García-Gutiérrez[1,2], V. Arellano[1]

[1]*Instituto de Investigaciones Eléctricas, Av. Reforma 113, Col. Palmira, C. P. 62490 Cuernavaca, Morelos, Mexico*

[2]*Centro Nacional de Investigación y Desarrollo Tecnológico, Av. Palmira, Esq. con calle Apatzingan, Col. Palmira, C. P. 62490 Cuernavaca, Morelos, Mexico*

**Corresponding author: aaragon@iie.org.mx*