Geothermal Inflow Performance Relationhips with Well Damage Effect and Their Applications

A. A. Aragón[1], S. L. Moya[2], M. G. Izquierdo[1], and G. V. Arellano[1]

[1]Instituto de Investigaciones Electricas, Gerencia de Geotermia, Morelos, México
[2]Centro Nacional de Investigación y Desarrollo Tecnológico (CENIDET-SEP), Morelos, México

Keywords

Output curves, inflow performance relationships, damage effect, geothermal type-curves

ABSTRACT

In this work a review of Inflow Performance Relationships (IPR), their development in petroleum reservoir engineering and the innovations made to incorporate the damage effects are presented. In analogous manner the Inflow Performance Relationships for geothermal reservoir are shown. The Inflow Performance Relationship and their corresponding type-curve with damage effect for geothermal reservoirs is proposed. In this paper for the first time, a methodology to determine the value of damage in a well, from its production test data, is established. The applicability of this innovative method using data from three production tests carried out in well M-110 at the Cerro Prieto geothermal field is demonstrated. Such tests were performed in the well at different stages of its productive life; therefore it is possible to identify the variation of the damage value.

Introduction

The inflow performance relationships are characteristic curves of production at bottom-hole conditions. The inflow curves (and the characteristic curves) are specific to each well and vary according to the stage of their productive life. These types of curves began to be used at the hydrocarbon exploitation, in order to establish useful approaches in the exploitation designs.

The development, analysis and application of the first relationships of theoretical curves of the inflow behavior, known as "Inflow Performance Relationships" or "IPR", were made by Vogel (1968), who analyzed production data of wells from different reservoirs and obtained a dimensionless expression known as "Vogel's equation" or "reference curve of Vogel":

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

where p_e is the static reservoir pressure, p_{wf} is the bottomhole flowing pressure, Q_o is the oil flow rate and $(Q_o)_{max}$ is the maximum oil flow rate. Klins and Majcher (1992) and Klins and Clark (1993) improved the predictive capability of Vogel's equation. The improved expression is:

$$\frac{Q_o}{(Q_o)_{max}} = 1 - 0.295\left(\frac{p_{wf}}{p_e}\right) - 0.705\left(\frac{p_{wf}}{p_e}\right)^n \quad (2)$$

where n is denominated as the decline factor:

$$n = \left[0.28 + 0.72\left(\frac{p_e}{p_b}\right)\right](1.24 + 0.001p_b) \quad (3)$$

In this expression p_b is the boiling pressure of the fluid in the reservoir.

The Damage Effect on the Inflow Curves for Oil Reservoirs

Klins and Majcher (1992), Klins and Clark (1993) were the first authors which investigated the damage effect on the inflow relationships by incorporating a coefficient M in Eq. (2). The resulting expression is:

$$\frac{Q_o}{(Q_o)_{max}} = M\left[1.0 - 0.295\left(\frac{p_{wf}}{p_e}\right) - 0.705\left(\frac{p_{wf}}{p_e}\right)^n\right] \quad (4)$$

Variable M involves the damage effect (s), defined as the relationship between the radius of the reservoir drainage area r_e, and the radius of the well r_w. Considering the typical values of r_e and of r_w for oil systems, the expression of M is:

$$M = \left(\frac{6.835}{6.835 + s}\right) \quad (5)$$

Eq. (4) includes simultaneously the damage effect in the well and its decline. This one is presently used in different productivity diagnoses and to estimate the damage in oil wells (Al Qahtani, 2001; Gallice and Wiggins, 2004). Using variables of p and Q in its dimensionless form:

$$p_D = \frac{p_{wf}}{p_e} \tag{6}$$

$$Q_D = \frac{Q_o}{(Q_o)_{max}} \tag{7}$$

where Q_o is the volumetric rate of production determined for a pressure p_{wf} at bottom conditions, the static pressure of the reservoir in the feeding area is p_e, the maximum volumetric rate is $(Q_o)_{max}$. Figure 1 shows the graphics of the dimensionless inflow curves calculated from the relationship proposed by Klins and Majcher (1992), Eq. (4).

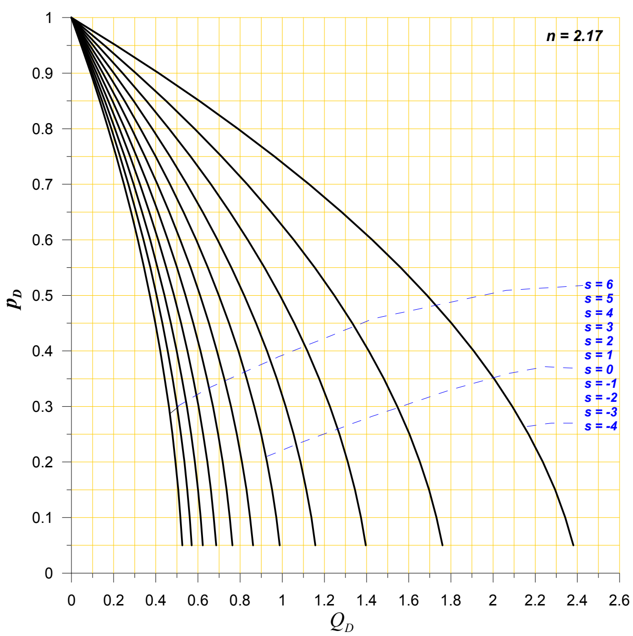

Figure 1. Dimensionless inflow performance curves for different damage values, calculated using the inflow relationship of Klins and Majcher (1992) with damage effect.

Inflow Performance Relationships for Geothermal Reservoir

Geothermal reservoir engineering frequently uses correlations and methodologies from oil reservoirs, in its analysis. Goyal et al. (1980); Grant et al. (1982); James (1989), among others, found that the outflow curves provided a solid tool for the analysis of wells and reservoir characterization.

The particular concavity of the outflow curves of each well is discussed by Grant et al. (1982) who described the form of each curve with respect to the different behavior of these wells. The techniques outlined by Fetkovich (1973) and Jones et al. (1976) are used by Chu (1988) finding applicability in the diagnosis of well conditions.

Iglesias and Moya (1990) formulated the first dimensionless inflow curve for geothermal reservoirs, considering pure water as the geothermal fluid. Subsequently, Moya (1994) obtained the corresponding dimensionless inflow curves for a binary mixture H_2O-CO_2, the expression of the mass productivity being as follows:

$$\frac{W}{W_{max}} = 1.0 - 0.256\left(\frac{p_{wf}}{p_e}\right) - 0.525\left(\frac{p_{wf}}{p_e}\right)^2 + -0.057\left(\frac{p_{wf}}{p_e}\right)^3 - 0.162\left(\frac{p_{wf}}{p_e}\right)^4 \tag{8}$$

To introduce the effect of dissolved salts, Montoya (2003) proposed an inflow curve that considers the geothermal fluid to be a ternary mixture H_2O-CO_2-$NaCl$. This expression assumes low salt content (up to 5% of mass fraction in the liquid phase) and its form is:

$$\frac{W}{W_{max}} = 0.999 - 0.436\left(\frac{p_{wf}}{p_e}\right) - 0.537\left(\frac{p_{wf}}{p_e}\right)^2 + 0.694\left(\frac{p_{wf}}{p_e}\right)^3 - 0.715\left(\frac{p_{wf}}{p_e}\right)^4 \tag{9}$$

For high salt content (greater than 5 % of mass fraction in the liquid phase) including precipitation conditions, Meza (2005) proposes the following expression:

$$\frac{p_{wf}}{p_e} = 1.0 - 0.619\left(\frac{W}{W_{max}}\right) + 1.45\left(\frac{W}{W_{max}}\right)^2 + -5.476\left(\frac{W}{W_{max}}\right)^3 + 7.605\left(\frac{W}{W_{max}}\right)^4 - 3.955\left(\frac{W}{W_{max}}\right)^5 \tag{10}$$

The same expression can be written as a function of p_D in the next form:

$$\frac{W}{W_{max}} = 1.0 - 0.4399\left(\frac{p_{wf}}{p_e}\right) + 1.1658\left(\frac{p_{wf}}{p_e}\right)^2 + -4.0372\left(\frac{p_{wf}}{p_e}\right)^3 + 3.6697\left(\frac{p_{wf}}{p_e}\right)^4 - 1.3782\left(\frac{p_{wf}}{p_e}\right)^5 \tag{11}$$

Incorporating the parameter M in the geothermal inflow relationships and considering a fluid $H_2O - CO_2 - NaCl$ mixture at low salinity (Eq. 9) and high salinity (Eq. 11), one has:

$$\frac{W}{W_{max}} = M\{(0.999 - 0.436\left(\frac{p_{wf}}{p_e}\right) - 0.537\left(\frac{p_{wf}}{p_e}\right)^2 + 0.694\left(\frac{p_{wf}}{p_e}\right)^3 - 0.715\left(\frac{p_{wf}}{p_e}\right)^4\} \tag{12}$$

$$\frac{W}{W_{max}} = M\{1.0 - 0.4399\left(\frac{p_{wf}}{p_e}\right) + 1.1658\left(\frac{p_{wf}}{p_e}\right)^2 + -4.0372\left(\frac{p_{wf}}{p_e}\right)^3 + 3.6697\left(\frac{p_{wf}}{p_e}\right)^4 - 1.3782\left(\frac{p_{wf}}{p_e}\right)^5\} \tag{13}$$

here M for geothermal conditions has the next expression:

$$M = \frac{7.75}{7.75 + s} \tag{14}$$

Fundamentally, the damage in a well is manifested as a decrease in its productivity. However the generalized concept of damage implies that the original conditions of the well are modified. Consistent with this, the damage can be positive, nil or negative.

Positive damage values indicate a decrease in productivity; while negative values indicate improvement in productivity. It is important to emphasize that a negative value of damage in a well, also is related with the presence of fractures that it has intersected and which are naturally existing ones. Also a negative damage values appears in washed, stimulated or fractured wells. In accordance with Eq. (14) damage effect (s) is an inverse function of the parameter M.

Figure 2 represents Eq. (13) for different values of damage and is designated as *geothermal inflow type-curves with damage effect.* Their utility resides in the determination of the damage value in wells, starting with the dimensionless values of inflow from their production tests.

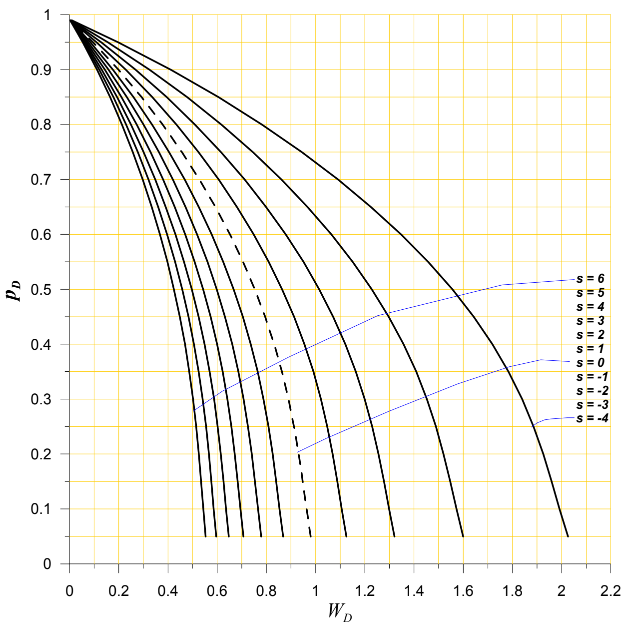

Figure 2. Type-curves for different damage effect (s), for geothermal reservoirs with H_2O-CO_2– $NaCl$.

These inflow type-curves utilized assume that the fluid is a H_2O-CO_2-$NaCl$ mixture. This composition is the one most similar to a geothermal fluid, because it considers gases and salts.

Example of the Use of Geothermal Inflow Type-Curves

In order to show the validity of the type-curves with damage effect [Eq. (13)], data were used from three production tests of well M-110 (Ribó, 1989) located at the Cerro Prieto, México, geothermal field.

The data were obtained from three production tests performed in the well in 1979, 1985 and 1987. The tests were made under initial conditions in the exploitation of the well for the first case, after 6 years of exploitation for the second case, and after 8 years of exploitation for the third case.

The characteristic set of production curves were built with data measured at surface conditions. As shown in Figure 3, one can observe the decline in the productive characteristics of the well. For each test their corresponding values of W_D and p_D were obtained. Such values were graphed into the type-curves with damage effect such as shown in Figure 4 and the damage value in the well was obtained for each case.

The values of the damage effect obtained from these three production tests are shown in the Table 1, overleaf. The value of the damage determined in each test corresponds to the stage of the well during its production test. It can be observed that this

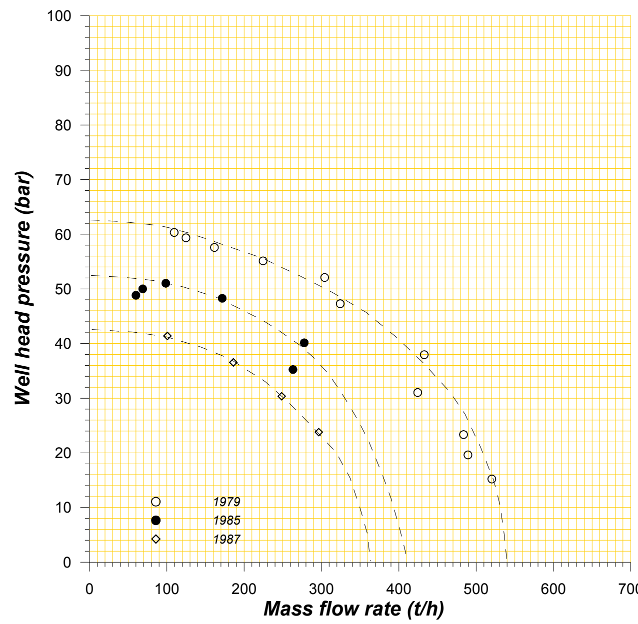

Figure 3. Characteristic production curves of well M-110 obtained from the data published by Ribó (1989).

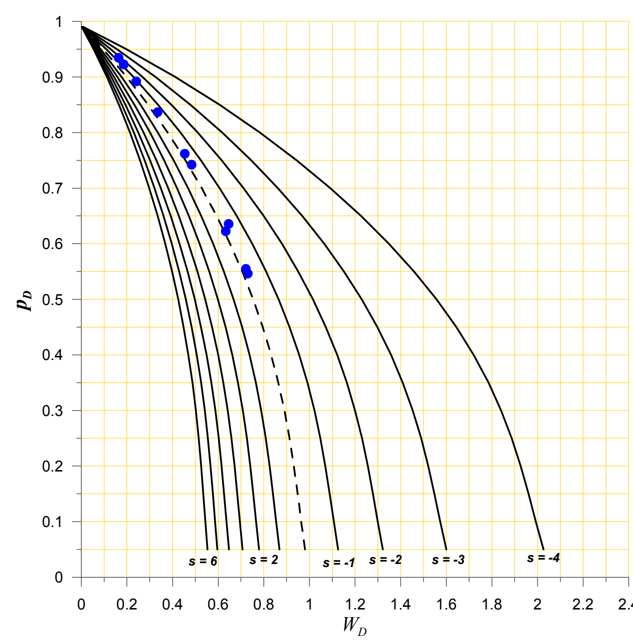

Figure 4. Overlapping of the inflow curve of well M-110 obtained in 1979 with the type-curves. The diagnosed value of damage is s = -0.2.

Table 1. Damage values determined in well M-110 from production tests, over its operating life.

Year	Damage Effect (*s*)	Wmax (*t/h*)
1979	-0.2	540
1985	-0.1	390
1987	0.0	350

value changes with the time of exploitation. The behavior of the damage is a function of the characteristics of the reservoir and, for the same reason, is an indicator of its decline.

Conclusions

From the results obtained in this research, the main conclusions are:

- A review of relevant bibliography on Inflow Performance Relationships was made. The research covers oil and geothermal systems.
- As a result of this analysis we propose the first inflow type-curves with damage effect for geothermal reservoirs, for both low and high salinities.
- A methodology is established to determine the value of damage in a well applying the inflow type-curves with damage effect.
- The methodology is innovative because previously the skin factor could only be determined from the analyses of transient pressure tests. On the other hand, with the proposed methodology it is possible to determine the damage in a well from the measurements of its production parameters.
- The methodology was validated by applying this technique to data from production tests of well M-110 at the Cerro Prieto México, geothermal field.

The usefulness of the proposed methodology is manifested in monitoring the behavior of wells subjected to continuous exploitation and whose production cannot be suspended.

Nomenclature

M	Auxiliary parameter which incorporates the damage effect	
n	Decline factor	(Dimensionless)
p	Pressure	(bar)
Q	Volumetric flow rate	(b/d)
s	Damage effect	(Dimensionless)
r	Radius	(ft)
W	Mass flow rate	(t/h)

Subscripts

D	Dimensionless
e	Static reservoir conditions
max	Maximum value
o	Oil
w	Well
wf	Well flowing

Acknowledgments

The authors want to express their gratitude to the authorities of IIE (México) and Gerencia de Proyectos Geotermoeléctricos (CFE-México) for their support in publishing this work. Also we thank to S. Sanyal by his comments.

References

Al Qahtani, A. M., 2001. "A new technique and field application for determining reservoir characteristics from well performance data". SPE Middle East Oil Show and Conference, SPE 68141, Bahrain, pp. 172 – 179.

Chu, M. H., 1988. "Inflow performance relationships for geopressured geothermal wells". Geothermal Resources Council Transactions, **12**, pp. 437 – 440.

Fetkovich, J. J., 1973. "The isochronal testing of oil wells". SPE 4529, presented at the SPE 48th Annual Fall Meeting, Las Vegas Nevada, U.S.A., pp. 78- 84.

Gallice, F., Wiggins, M., 2004. "A comparison of two-phase inflow performance relationships". Paper SPE 88445, SPE Mid-Continent Operations Symposium, Oklahoma City, U.S.A., pp. 100 - 104.

Goyal, K. P., Miller, C. W., Lippmann, M. J., 1980. "Effect of measured wellhead parameters and well scaling on the computed downhole conditions in Cerro Prieto Wells". Proc. 6th Workshop on Geothermal Reservoir Engineering, Stanford University, California, U.S.A. pp. 130- 138.

Grant, M. A., Donaldson, I. G., Bixley, P. F., 1982. "Geothermal reservoir engineering". Academic Press, New York, U.S.A., 117 p.

Iglesias, E. R., Moya, S. L., 1990. "Geothermal inflow Performance relationships". Geothermal Resources Council Transactions, 14 part II, pp. 1201 – 1205.

James, R., 1989. "One curve fits all". Proc. 14th Workshop on Geothermal Reservoir Engineering, Stanford University, California, U.S.A., pp. 329 – 334.

Jones, L. G., Blount, E. M., Glaze, O. H., 1976. "Use of short term multiple rate flow tests to predict performance of wells having turbulence". SPE 51st Annual Fall Meeting, SPE 6133, New Orleans, LA., U.S.A., pp. 378 – 383.

Klins, M., Majcher, M. W., 1992. "Inflow performance relationships for damaged or improved wells producing under solution-gas drive". Journal Pet. Tech., SPE-AIME, pp. 1357 – 1363.

Klins, M. A., Clark, L. 1993. "An improved method to predict future IPR curves". SPE Reservoir Engineering, pp. 243 – 248.

Meza, C. O., 2005. "Efecto de la precipitación de sales en el diagnóstico de permeabilidades rocosas". Tesis de maestría, CENIDET, (Centro Nacional de Investigación y Desarrollo Tecnológico) SEP, Cuernavaca, Morelos, México, 107 p.

Montoya, D., 2003. "Estimación de permeabilidades de yacimientos geotérmicos mediante la aplicación de curvas tipo de influjo geotérmico". Tesis de maestría, CENIDET, (Centro Nacional de Investigación y Desarrollo Tecnológico) SEP, Cuernavaca, Morelos, México, 112 p.

Moya, S. L., 1994. "Efectos del bióxido de carbono sobre el transporte de masa y energía en yacimientos geotérmicos". Tesis Doctoral, División de Estudios de Posgrado, Facultad de Ingeniería, Universidad Nacional Autónoma de México, 204 p.

Ribó, M. O., 1989. "Análisis de pruebas de presión en pozos de Cerro Prieto". Proceedings Symposium in the field of geothermal energy, Convenio entre Comisión Federal de Electricidad y el Departamento de Energía de los Estados Unidos de Norteamérica, San Diego California, Estados Unidos de Norteamérica, pp. 123 – 129.

Vogel, J. V., 1968. "Inflow performance relationships for solution gas drive wells". Journal Pet. Tech. SPE 1476 Annual Fall Meeting of Society of Petroleum Engineers, Dallas Texas, U.S.A., pp. 66 – 79