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Geothermal Inflow Performance Relationships
with Well Damage Effect and Their Applications

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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 the damage effect on the inflow curves (and their corresponding type-curve) are specific to each well and vary according to the stage of their productive life. These types of curves (known as “Vogel’s equation” or “reference curve of Vogel”):  

\[
\frac{Q}{(Q_{o})_{max}} = 1 - 0.295 \left( \frac{P_{e}}{P_{o}} \right) - 0.705 \left( \frac{P_{e}}{P_{o}} \right)^{8} 
\]

where \( P_{o} \) is the static reservoir pressure, \( P_{ef} \) 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:

\[
\frac{Q}{(Q_{o})_{max}} = 1 - 0.295 \left( \frac{P_{e}}{P_{o}} \right) - 0.705 \left( \frac{P_{e}}{P_{o}} \right)^{8} 
\]

where \( n \) is denominated as the decline factor:

\[
n = 0.28 + 0.72 \left( \frac{P_{e}}{P_{o}} \right) (1.24 + 0.001p_{b}) \]

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:

\[
\frac{Q}{(Q_{o})_{max}} = M \left[ 1.0 - 0.295 \left( \frac{P_{e}}{P_{o}} \right) - 0.705 \left( \frac{P_{e}}{P_{o}} \right)^{8} \right] 
\]

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:

\[
M = \left( \frac{6.835}{6.835 + s} \right) 
\]

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:
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:

\[
\text{Inflow Performance Relationships for Geothermal Reservoir}
\]

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.

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

\[
\frac{W}{W_{max}} = 1.0-0.4399\left(\frac{p_{ref}}{p_e}\right)+1.1658\left(\frac{p_{ref}}{p_e}\right)^{8} -4.0372\left(\frac{p_{ref}}{p_e}\right)+3.6697\left(\frac{p_{ref}}{p_e}\right)^{8} -1.3782\left(\frac{p_{ref}}{p_e}\right)^{8}.
\]

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:

\[
\frac{W}{W_{max}} = M\left\{0.999 - 0.436\left(\frac{p_{ref}}{p_e}\right)-0.537\left(\frac{p_{ref}}{p_e}\right)^{8} + 0.694\left(\frac{p_{ref}}{p_e}\right)-0.715\left(\frac{p_{ref}}{p_e}\right)^{8}\right\}.
\]

\[
\frac{W}{W_{max}} = M\left\{1.0-0.4399\left(\frac{p_{ref}}{p_e}\right)+1.1658\left(\frac{p_{ref}}{p_e}\right)^{8} -4.0372\left(\frac{p_{ref}}{p_e}\right)+3.6697\left(\frac{p_{ref}}{p_e}\right)^{8} -1.3782\left(\frac{p_{ref}}{p_e}\right)^{8}\right\}.
\]

where $Q_o$ is the volumetric rate of production determined for a pressure $p_{ref}$ 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).

\[
\begin{align*}
Q_o &= \frac{p_{ref}}{p_e} \\
\frac{Q_o}{(Q_o)_{max}} &= \frac{W}{W_{max}} \tag{6}
\end{align*}
\]

\[
\frac{W}{W_{max}} = 1.0 - 0.256\left(\frac{p_{ref}}{p_e}\right) - 0.525\left(\frac{p_{ref}}{p_e}\right)^{4} - 0.057\left(\frac{p_{ref}}{p_e}\right)^{4} - 0.162\left(\frac{p_{ref}}{p_e}\right)^{4} \tag{7}
\]

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

\[
\begin{align*}
\frac{W}{W_{max}} &= 0.999 - 0.436\left(\frac{p_{ref}}{p_e}\right)-0.537\left(\frac{p_{ref}}{p_e}\right)^{8} + 0.694\left(\frac{p_{ref}}{p_e}\right)-0.715\left(\frac{p_{ref}}{p_e}\right)^{8} \tag{8}
\end{align*}
\]

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:

\[
\frac{W}{W_{max}} = M\left\{0.999 - 0.436\left(\frac{p_{ref}}{p_e}\right)-0.537\left(\frac{p_{ref}}{p_e}\right)^{8} + 0.694\left(\frac{p_{ref}}{p_e}\right)-0.715\left(\frac{p_{ref}}{p_e}\right)^{8}\right\}.
\]

In the geothermal inflow relationship, $M$ being as follows:

\[
M = \frac{7.75}{7.75 + 8} \tag{14}
\]
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 is also related with the presence of fractures that it has intersected and which are naturally existing ones. Also, a negative damage value 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](image1.jpg)

**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...
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 con-
clusions are:
- A review of relevant bibliography on Inflow Performance
  Relationships was made. The research covers oil and geo-
  thermal 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 tran-
sient 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 Mexico, 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

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<table>
<thead>
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<tr>
<td>Year</td>
<td>Damage Effect ((\delta))</td>
</tr>
<tr>
<td>1979</td>
<td>-0.2</td>
</tr>
<tr>
<td>1985</td>
<td>-0.1</td>
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<tr>
<td>1987</td>
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