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Subject
Modelling horizontal wells in DoubletCalc

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Our reference
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Introduction

Geothermal wells penetrating a reservoir can be either vertical, slanted or horizontal. In principle, the longer the penetrated and completed reservoir section, the more water can enter the well per second and per bar drawdown (expressed in the productivity index J [m³/Pa.s]). The improved productivity of a slant well with respect to a vertical well can be expressed in terms of a skin factor. For a slanted well, DoubletCalc automatically calculates the skin factor according to Choi et al. (2008) [6] and Rogers and Economides (1996) [7]. The method is described in the DoubletCalc v1.43 User Manual. This document can be found on the www.nlog.nl website. The equations used in this approach are only valid for deviation angles up to about 85°. Hence, horizontal wells cannot be modelled in DoubletCalc in this way.

In this document a method is proposed to calculate the negative skin that can be applied to an equivalent vertical well fully penetrating the aquifer in order to achieve the productivity of a horizontal well. This skin value, related to the virtual horizontal well, can be used in DoubletCalc to approximate the productivity increase of a horizontal well. Using this method the anisotropy becomes irrelevant and can be assigned “1” in the DoubletCalc input screen.

There are several ways of calculating the productivity improvement of a horizontal well with respect to the productivity of a (fully penetrating) vertical well. The productivity index J_v of a vertical well with skin S is given by the equation

$$J_V = \frac{2\pi kH/\mu}{\ln\left(\frac{R}{r_w}\right)+S} \qquad \text{Eq. 1}$$

having:

k: permeability [m²]

H: reservoir thickness [m]
r_w: well radius[m]
R: reservoir radius [m]
μ: viscosity [Pa.s]

The equation for J_v is valid for steady state flow with a constant pressure p_r at distance R and a constant well pressure p_w. The flow rate Q is equal to J_h (p_r – p_w). A productivity index for a horizontal well does not have the simple and exact analytical expression like a vertical well has, because of the three-dimensional character of the fluid flow (the problem for a vertical well can easily be reduced to a one-dimensional problem). There are various analytical expressions that approach J_h. A number of them have been compared:

1. **3D-2D** (developed by TNO [1])
2. **Giger** ([1] and references therein)
3. **Joshi** (see [2] eq. 6 and [3] eq. 1, including a suggestion for enhancement by **Economides**)
4. **Babu & Odeh** (see [4] case I)

These methods were validated using:

5. a semi-analytical method **AEM** (Analytic Element Method).

The AEM is more accurate than the above mentioned methods, but does not have a closed analytical expression. In order to complete the validation, the above mentioned methods were compared to

6. a Numerical Reservoir Simulator (**NRS**).

J_h is a function of k_h, k_v, H, R, r_w, L and μ:

$$J_H = J_H(k_h, k_v, H, R, r_w, L, \mu) \qquad \text{Eq. 2}$$

having:

L: length of the horizontal well [m]

The productivity improvement of the horizontal well can be expressed in a (usually negative) skin factor for a vertical well. From J_h = J_v follows that

$$S = \frac{2\pi k_h H}{\mu J_H} - \ln\left(\frac{R}{r_w}\right) \qquad \text{Eq. 3}$$

Note that the skin factor and the productivity index ratio do not depend on viscosity. Hence, the productivity of a horizontal well can be expressed as the productivity of a (fully penetrating) vertical well plus a skin factor.

Results

The data used for the benchmark are the expected values based on a largely hypothetical case which is considered roughly relevant for an average reservoir:

r_w = 0.078 m (3.065 inch)
k_h = 480 mD
k_h / k_v = 10 - 60
H = 30 m
R = 1600 m
L = 5 - 1000 m

Figure 1 shows the results of the benchmark for various horizontal well lengths. Short horizontal well lengths (<100 meter) are less efficient than a vertical well for the given reservoir parameters ($J_h < J_v$), whereas long horizontal drains have a higher productivity index than equivalent vertical wells ($J_h > J_v$). 3D-2D, AEM and NRS are in good correspondence over the entire range of modelled horizontal well lengths. Given the observation that AEM is accurate based on theoretical considerations, it follows that 3D-2D and NRS are generally more accurate than Giger, Joshi and Babu & Odeh. For short horizontal well lengths (<100 meter), Giger, Joshi and Babu & Odeh underestimate J_h. For longer horizontal well lengths Babu & Odeh overestimate J_h, while Giger and Joshi correspond to 3D-2D, AEM and NRS. Figure 2 shows the corresponding skin factors. Joshi generally underestimates the negative skin, while Babu & Odeh overestimate it. The difference can be up to about 1 point. Figure 3 shows the skin factors that should be applied to a vertical well in order to have a similar production as a horizontal drain having a length of 500 meter, for various anisotropy ratios.

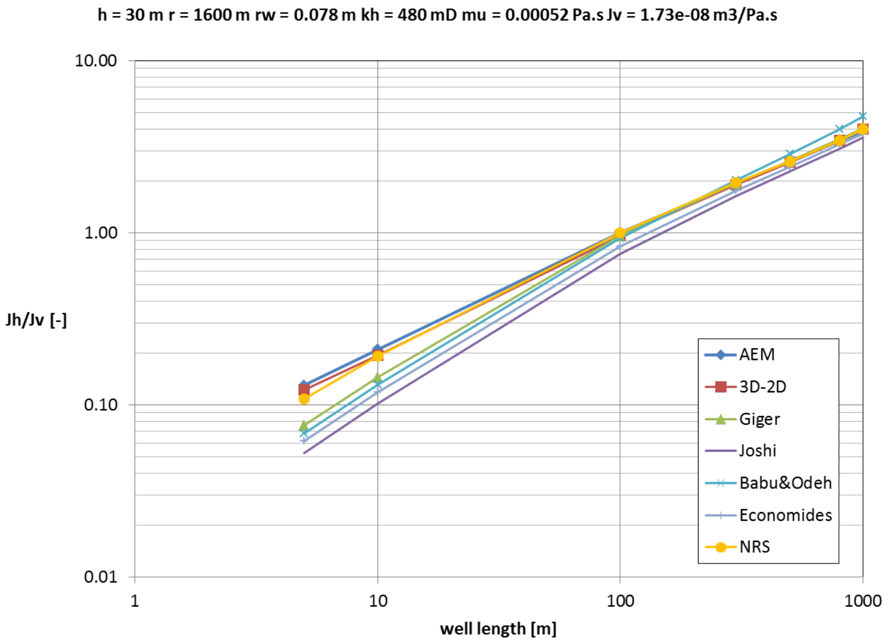

Figure 1 Productivity index ratio as function of horizontal well length, according to the various methods and having k_h/k_v = 20.

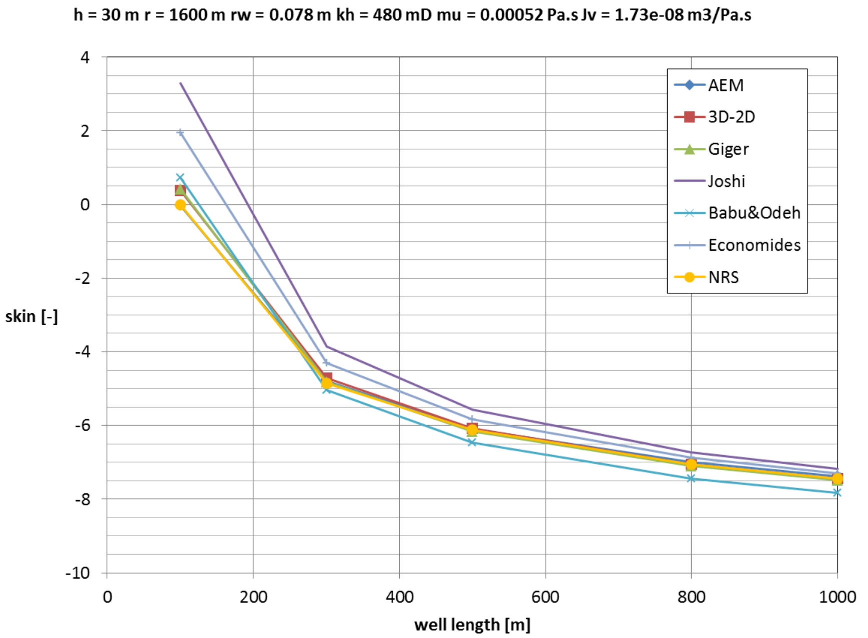

Figure 2 Skin as function of horizontal well length, according to the various methods and having k_h/k_v = 20.

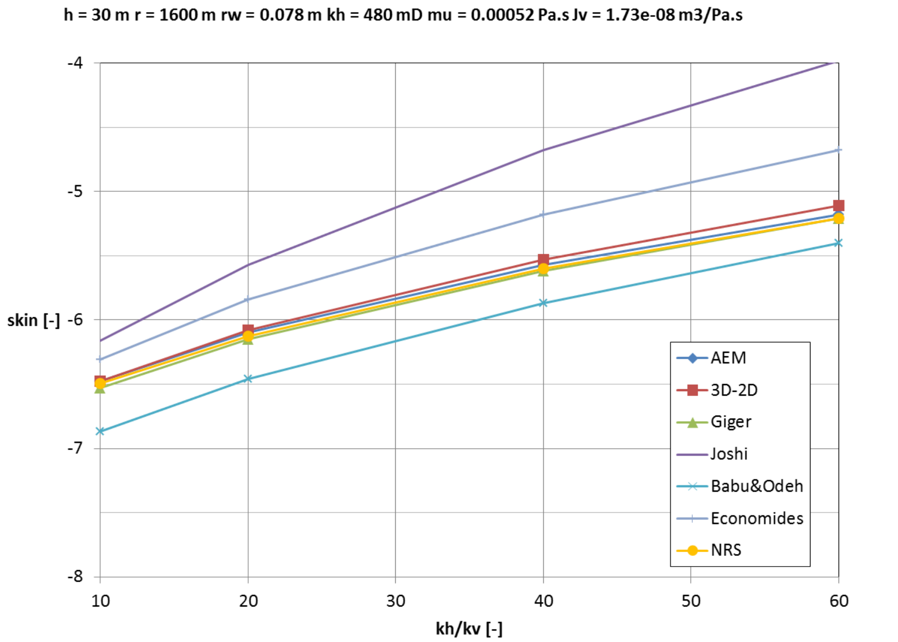

Figure 3 Skin factor as function of k_h / k_v ratio for a horizontal well with length 500m, according to the various methods.

Conclusions

It is possible to simulate a horizontal well in DoubletCalc by defining it as a fully penetrating vertical well in combination with a negative skin. The negative skin can be calculated using the spreadsheet which can be downloaded from www.nlog.nl.

Four analytic methods (3D-2D, Giger, Joshi, and Babu) were implemented in Matlab code, and validated against a semi-analytic method (AEM) and a numerical reservoir simulator (NRS).

The results of the 3D-2D method correspond very well to those of the semi-analytic method (AEM) and the numerical reservoir simulator (NRS).

The 3D-2D method is more accurate for shorter horizontal drains (<100 meter) than the other three analytical methods. The latter underestimate J_h.

The 3D-2D, Giger and Joshi methods correspond well for longer horizontal drains (>100 meter).

Babu & Odeh significantly overestimate J_h for horizontal drains >100 meter (which is confirmed by the findings of [5], Table D-1].)

Joshi underestimates the skin for all horizontal drain lengths. Babu & Odeh overestimate the skin for all horizontal drain lengths.

Remarks

The AE method is more general than the other methods; it can handle deviated and partial or fully penetrating wells, including friction in the well and (finite conductive) fractures.

For the Giger method the formula for an isotrope and homogeneous reservoir was used. The isotropic medium was obtained by 3D scaling of the axes of the anisotropic medium.

References

[1] Egberts, P.J.P. & Fokker, P.F. (2000). New analytic Approximation for the Flow into a Well in a Finite Reservoir. TIPM

[2] Economides, M.J., Delmbacher, F.X., Brand, C.W. and Heinemann, Z.E. (1991). Comprehensive Simulation of Horizontal-Well Performance, SPE FE, SPE 20717.

[3] Economides, M.J. and Frick, T.P. (1994). Optimization of Horizontal-Well Matrix Treatments, SPE PF, SPE 22334.

[4] Babu, D.K. and Odeh, A.S. (1989). Productivity of a Horizontal Well, SPE RE, SPE 18299.

[5] Dietrich J.K. (1995). Discussion of Productivity of a Horizontal Well, SPE RE, SPE 31025

[6] Choi, S.K., Ouyang, L.-B. and Huang,W-S. (2008). A comprehensive comparative study on analytical PI/IPR correlations. SPE conference paper 116580.

[7] Rogers, E.J. and Economides, M.J. (1996): The skin due to slant of deviated wells in permeability-anisotropic reservoirs. SPE conference paper 37068