DoubletCalc 2D: a free geothermal flow simulator

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ABSTRACT

The need for better tools to predict flow and temperature behaviour of geothermal reservoirs has led to the development of the freely available software tool DoubletCalc2D. The software tool is capable of handling complex well designs of geothermal projects with more than 2 wells, and spatial heterogeneity of reservoir properties. Among other things, pressure and temperature development during (and after) the lifetime of the aquifer can be simulated in limited calculation time. DoubletCalc2D results were validated by benchmarking to other software. Through DoubletCalc 2D, we aim to bridge the gap between simple 1D prediction tools and sophisticated 2D and 3D reservoir simulators like Eclipse.

1. INTRODUCTION

Geothermal exploration and production activities have increased considerably in the Netherlands in the past decade, and have resulted in the development of many successful doublet systems in clastic reservoirs for direct heat production. Instrumental to the success of geothermal development has been the capability to assess and limit subsurface risk of geothermal systems, through publicly available information of relevant subsurface data from hydrocarbon exploration (www.thermogis.nl) through standardized methods and tools to assess the performance of doublet systems under uncertainty (DoubletCalc, available at nlog.nl).

The current methodology for assessing performance and risk is based on a 1D analytical approach for reservoir flow, whereas it has become more and more apparent that performance can be significantly enhanced and risk reduced through well layouts adapted to specific reservoir conditions, which cannot be analysed and optimised by means of a simplified 1D approach. A complex well design can include more than 2 wells. Furthermore, interference of closely spaced geothermal installations, and spatial heterogeneity of reservoir properties needs to be taken into account. This raised the need for better reservoir simulation tools to predict flow and temperature behaviour of geothermal reservoirs, which are easy to use and available at low cost.

With the development of DoubletCalc 2D, a software tool is now freely available that can address these issues. It enables to calculate the temperature and pressure development around two or more geothermal wells in two dimensions over time. It can handle high resolution spatial variations in reservoir properties, discontinuities like faults, cooling of host rock and spatial and temporal development of pressure, temperature and viscosity in the reservoir. The output graphs show pressure, flow rate and temperature at both producer and injector against time. Additional 2D output grids of pressure and temperature per time step, and optionally viscosity, flow velocity and subsidence at surface (c.f. Fokker et al., 2015) are available.

In this paper we describe the implemented simulation model, and compare the simulation results to other flow simulators. Additionally, we discuss how results for complex well systems and reservoir structures can be incorporated in DoubletCalc for probabilistic risk assessment.

2. SIMULATION MODEL

2.1 Model limitations

DoubletCalc results are calculated at reservoir depth level. Therefore a detailed doublet configuration above reservoir level is not part of the model. Pressure and temperature losses in the production and injection pipes are not taken into account. This means that the results represent bottom hole pressures and temperatures.

2.2 Theoretical background

In DoubletCalc2D the pressures are solved according to a steady solution of the pressure field based on flow or pressure boundary conditions in the wells for yearly time increments. The temperatures are resolved based on a transient solution (cf. hydrological reactive transport model approaches such as MODFLOW, Harbaugh, 2005).

In an Eulerian reference framework, the heat equation, which is solved in a transient mode with constant velocities:

$$\rho c_t \frac{\partial T}{\partial t} = \nabla.(k_t \nabla T) - \vec{v}.\nabla T \qquad [1]$$

With:

T temperature [K or C°]

t time [sec]

ρ density [m^3 kg^{-1}]

c_t specific heat capacity [J kg^{-1} K^{-1}]

k_t thermal conductivity [W m^{-1} K^{-1}]

A radiogenic heat production [W m^{-3}]

∇ nabla operator $\left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)^T$

. dot product

$\vec{v}$ advective velocity

The advective velocity accounts for the effect of fluid flow inside pores or fractures which can strongly affect the thermal distribution (e.g. Cherubini et al. 2014). The fluid velocity is updated on a yearly basis from a steady state solution of the Darcy flow equation:

$$\nabla.\left(\frac{k_f}{\mu_f}\left(\nabla P + \frac{(\rho_f - \rho_0)}{\rho_0} g \nabla z\right)\right) + Q = 0 \qquad [2]$$

With:

P pressure [Pa]

k_f bulk permeability [m^2]

μ_f fluid viscosity [Pa s]

Q source term [m^3 s^{-1}]

ρ_f fluid density

ρ_0 reference density of the fluid, which can be arbitrarily chosen

$\frac{(\rho_f - \rho_0)}{\rho_0} g \nabla z$ relates to density driven source terms.

Through solving the pressure field in eq. [2], the velocities (used for solving the heat equation) can be determined as:

$$\vec{v_f} = \frac{k_f}{\mu_f}\left(\nabla P + \frac{(\rho_f - \rho_0)}{\rho_0} g \nabla z\right) \qquad [3]$$

3. BENCHMARK

Results from DoubletCalc2D were compared to an analytical solution, and solutions from the ECLIPSE reservoir simulator

3.1 Analytical solution

Steady state radial flow in a confined aquifer was described by Thiem (1906). The pressure difference Δp that has to be applied at either the injector (inj) or producer (prod) in order to produce or inject the required flow rate is:

$$\Delta p_{inj} = Q \frac{\mu_{inj}\left(ln\left(\frac{L}{r_w}\right) + S_{inj}\right)}{2\pi k H} \qquad [4]$$

$$\Delta p_{prod} = -Q \frac{\mu_{prod}\left(ln\left(\frac{L}{r_w}\right) + S_{prod}\right)}{2\pi k H} \qquad [5]$$

When entered in Thiems equation with reservoir parameters of Table 1, the pressure difference at the injector is 18.4 bar (-18.4 at the producer). The DoubletCalc2D solution is very similar: 18.6 bar at the injector and -18.4 bar at the producer.

Table 1: Reservoir parameters for analytical solution.

parameter		value	unit
permeability	k	3.76E-13	m^2
thickness	H	100	m
viscosity	μ	0.0008	Pa.s
well radius	r_w	0.0508	m
well rate	Q	0.0556	m^3/s
well distance	L	900	m

3.2 Eclipse

A benchmark was carried out using the Eclipse reservoir simulator (Schlumberger). Eclipse is considered to be the industry reference simulator. The definition of the model used for the benchmark, the assumptions, and the results are described in this section.

Table 2: Reservoir simulation parameters.

Parameter	value	unit
grid cell	200x200x1	-
grid cell size	75x75x25	m
depth	1500	m
permeability	3.76E-13	m^2
porosity	0.14	-
net-to-gross	1	-
viscosity	0.0008	Pa.s
well diameter	0.1016	m
well rate	0.0556	m^3/s
well distance	900	m
reservoir temperature	65	°C
injection temperature	30	°C

The modelled area measures 15x15 km in Eclipse. The initial pressure is 150 bar (hydrostatic). Note that the grids shown in Figure 5 all represent a 3x3 km cut-out of the total modelled area.

In order to maintain a constant head at the area boundaries, additional pseudo wells were used to model the 'open' boundary: 9 producers on the injector side, and 9 injectors on the producer side (Figure 1). The permeability on the boundary was set to 100D (9.87E-11 m^2). The effect of the open boundaries on the outflow from / inflow to the modelled area is some 300 m³/d.

Figure 2 through Figure 5 show that the grid block pressures, actual water velocities and temperature development in Eclipse and DoubletCalc2D are very similar, provided the boundary conditions are specified correctly.

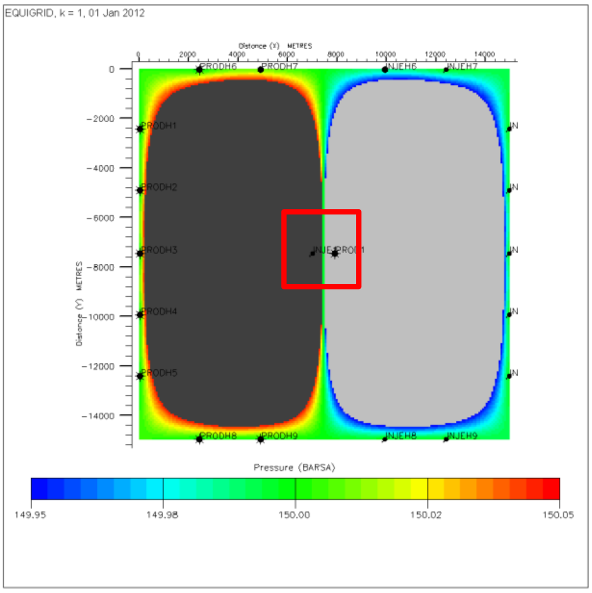

Figure 1: T Locations of producer (PROD1) and injector (INJE) in the model area, and locations of additional producers and injectors along the boundary. The red square represents the 3x3 km area shown Figure 5.

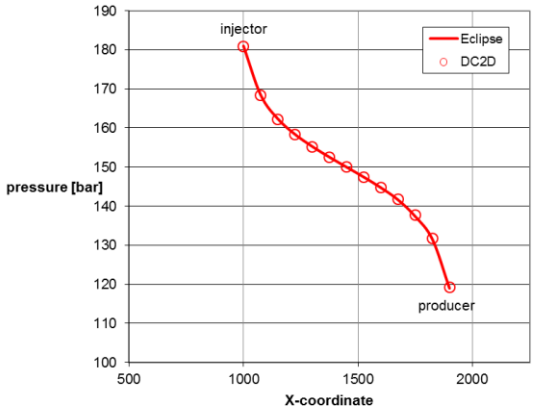

Figure 2: Calculated grid block pressures (in bar) between wells (note shift in X-coordinates w.r.t. Figure 1

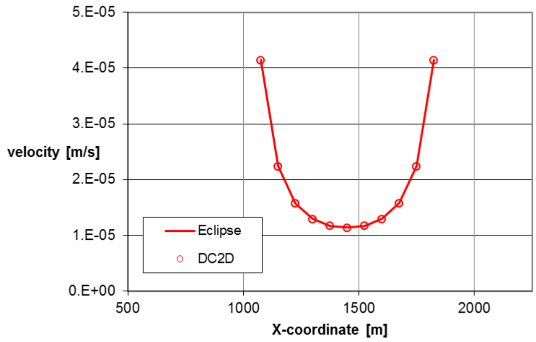

Figure 3: Actual water velocities in the grid block centres.

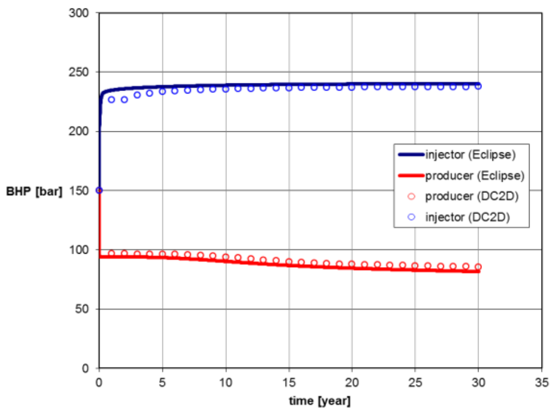

Figure 4: Bottom hole pressures for producer and injector.

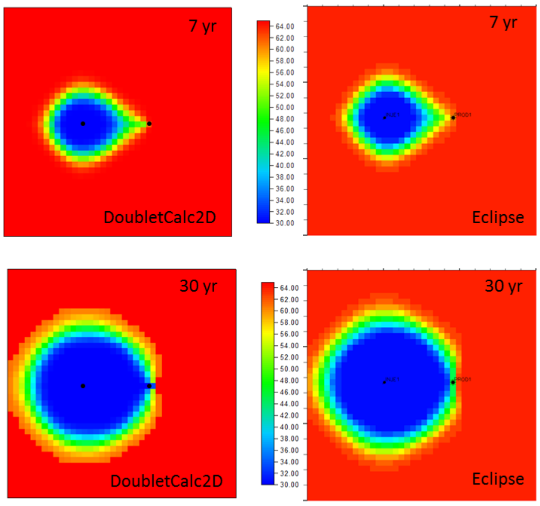

Figure 5: Temperature after respectively 7 and 30 years of operation (left: DoubletCalc, right: Eclipse).

3.3 DoubletCalc

DoubletCalc is a software tool that enables to calculate a pre-drill indicative geothermal power of a planned geothermal doublet by specifying the key reservoir parameters, the casing scheme and the pump details (Mijnlieff et al. 2014). It is therefore distinctly different from DoubletCalc2D. However, it is useful to be able to generate a DoubletCalc scenario that is compatible with a DoubletCalc2D scenario. For that purpose, first a DoubletCalc scenario should be set up according to the planned or realised doublet and reservoir properties. Next, a DoubletCalc2D scenario must be set up with equal input parameters, note that the viscosity should be calculated from the salinity, temperature and pressure.

Please take into account that all well input values in DoubletCalc2D represent values at reservoir level. As stated before a detailed doublet configuration is not part of the model. Temperature and pressure losses due to friction are ignored.

Table 3: Reservoir simulation parameters. The DC2D column marks parameters for DoubletCalc2D only.

Parameter	value	unit	DC2D
grid cell	200x200x1	-	x
grid cell size	75x75x100	m	x
depth	2000	m	
permeability	1.97E-13	m^2	
porosity	0.12	-	x
net-to-gross	1	-	
thickness	100	m	
salinity	70000	ppm	
well diameter	0.1778	m	
well skin	-0.94	-	
well rate	0.0304	m^3/s	
well distance	1500	m	
reservoir temperature	71.5	°C	
injection temperature	35	°C	

To compare the results, DoubletCalc gives a pressure difference at the producer and injector of respectively 11.7 bar and 18.4 bar, constraining the flow to 0.0304 m^3/s (110 m^3/h). Well pressures as result from DoubletCalc2D are comparable respectively 11.8 and 18.8 bar.

4. CONCLUSIONS

Overall it can be concluded that DoubletCalc2D produces similar results compared to analytical solutions, simplified prediction tools like DoubletCalc (1D), and full reservoir simulation (Eclipse). Therefore it is well suited to bridge the gap between simple 1D prediction tools and sophisticated 2D and 3D reservoir simulators like Eclipse.

The anticipated users of DoubletCalc2D are consultants and doublet operators interested in the analysis of the lifetime and performance of geothermal systems for direct heat production in heterogeneous aquifers, risk assessment and interference issues with neighbouring doublets.

The DoubletCalc2D software can be downloaded free of charge from www.thermogis.nl under the GNU Lesser General Public License.

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