

**TNO report**

**TNO 2014 R11396**  
**DoubletCalc 1.4 manual**  
**English version for DoubletCalc 1.4.3**

**Oil and Gas**

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- A Example of the 'base case details' file
- B Sub-layers in an aquifer
- C Explanation of characters and symbols





# 1 Introduction

DoubletCalc v1.4.3 is a software tool that was developed by TNO. It enables to calculate a pre-drill indicative geothermal power of a future geothermal doublet by specifying the key reservoir parameters, the casing scheme and the pump details.

DoubletCalc v1.4 is the successor to DoubletCalc v1.3. The major difference with respect to v1.3 is the possibility to specify the casing scheme of the production and injection wells, and a minimum-median-maximum range for the expected salinity.

DoubletCalc v1.4.3 has largely the same functionality as DoubletCalc v1.4. Both the output to screen and to file has been extended.

This document first explains how the software is used. Next, it describes the way in which a doublet is modelled. Finally, the software implementation is substantiated, including a description of all equations.

The software can be downloaded from:

<http://www.nlog.nl/nl/geothermalEnergy/DoubletCalc.html>

## 2 User manual DoubletCalc v1.4

### 2.1 Installation of the software

The software can be found on the website [www.nlog.nl](http://www.nlog.nl) (<http://www.nlog.nl/nl/geothermalEnergy/DoubletCalc.html>). It is distributed as a compressed (ZIP) file. In order to use the program, the ZIP file needs to be downloaded and saved on the computer. Next, the compressed files need to be unpacked. The user can choose in which folder the files will be stored. In principle a folder named DoubletCalc14 will be created (for example) in which the following files are stored:

- the release notes 'DoubletCalc143 release notes.txt'
- the program files named 'DoubletCalc-143-26092014.jar'.
- the JavaFX 'runtime' folder
- example file of a DoubletCalc scenario 'example.xml'
- the windows executable 'DoubletCalc\_v1\_4\_3.exe'
- the batch file 'start\_doubletcalc.bat' as an alternative executable
- the shell script 'start\_doubletcalc\_osx.sh' for executing on OS X/Linux

#### 2.1.1 Installation on a Windows computer

Java version 6 or newer should be installed. In order to execute DoubletCalc: double click 'DoubletCalc\_v1\_4\_3.exe' in your favourite file manager.

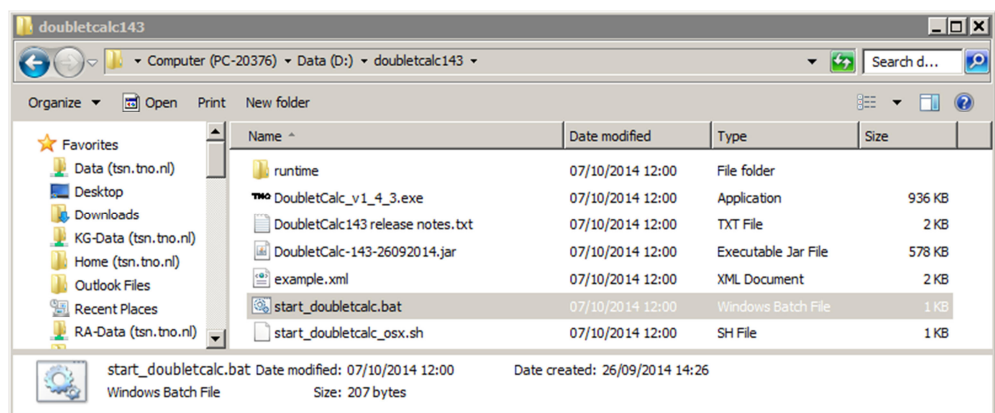


Figure 1 Location of the DoubletCalc files as visible in the Windows default file manager. The file to be executed is named DoubletCalc\_v1\_4\_3.exe

If DoubletCalc does not start, the following check can be performed:

- Was the correct version of Java installed (version 6 or newer). This information can be verified on the website <http://www.java.com/en/download/installed.jsp>. Java can be downloaded from <http://www.java.com/en/download/manual.jsp>
- Alternatively execute the batch file 'start\_doubletcalc.bat' in a command window (run-> cmd.exe)

#### 2.1.2 Installation on Apple computers

Follow the same instructions as for Windows computers, and execute the shell script 'start\_doubletcalc\_osx.sh' from the terminal.

If DoubletCalc does not start, the following check can be performed:

- Assign execute permission to the start script. This can be done in a terminal window by entering: `chmod u+x start_doubletcalc_osx.sh`

## 2.2 Input screen

After the Java installation, the DoubletCalc 1.4.3 input screen appears (Figure 2). The input screen enables the user to specify the essential parameters that are required to calculate the geothermal power estimate. Only the white fields are obligatory. The values in the grey fields are calculated by the software. The min and max values of the aquifer tops are calculated as +/- 10% of the median value. Excessive as this may seem, it also accounts for the uncertainty in the geothermal gradient, which is not user specified. The number of simulation runs and the 'calculation length subdivision' (both in blue) can be entered if desired.

It was deliberately decided to leave as many fields as possible empty after start up, with the exception of those values that in the Netherlands vary the least, like the geothermal gradient and the surface temperature. This was done to prevent that proposed *default* values that are unrepresentative for a scenario are used in that scenario erroneously – the user is now forced to select representative values. Zero-values of the optional parameters (between square brackets) are ignored.

The input screen enables to open an existing scenario ('Open scenario'). In the 'Open scenario' screen the XML-file containing the required scenario can be selected (Figure 3). After opening, the parameters of this scenario are shown.

On the other hand, the user can also start by entering scenario parameters. Once the parameters have been entered, the new scenario can be saved ('Save scenario', Figure 4).

file: d:\doubletcalc143\example.xml

### Geotechnical input

#### A) Aquifer properties

Property	min	median	max	Property	value
aquifer permeability (mD)	150	250	500	aquifer kh/kv ratio (-)	1
aquifer net to gross (-)	0.75	0.80	0.85	surface temperature (°C)	10
aquifer gross thickness (m)	95	105	115	geothermal gradient (°C/m)	0.031
aquifer top at producer (m TVD)	2255.0	2505	2756.0	[mid aquifer temperature producer (°C)]	0
aquifer top at injector (m TVD)	2221.0	2468	2715.0	[initial aquifer pressure at producer (bar)]	0.0
aquifer water salinity (ppm)	100000	120000	140000	[initial aquifer pressure at injector (bar)]	0.0

#### B) Doublet and pump properties

Property	value
exit temperature heat exchanger (°C)	35
distance wells at aquifer level (m)	1460
pump system efficiency (-)	0.61
production pump depth (m)	500
pump pressure difference (bar)	40

#### C) Well properties

calculation length subdivision (m)

Producer					Injector				
Segment	pipe segment sections p (m AH)	pipe segment depth p (m TVD)	pipe inner diameter p (inch)	pipe roughness p (milli-inch)	Segment	pipe segment sections i (m AH)	pipe segment depth i (m TVD)	pipe inner diameter i (inch)	pipe roughness i (milli-inch)
1	500	500	5	1.2	1	50	50	5	1.2
2	1054	1054	12.375	1.2	2	1054	1054	12.375	1.2
3	1930	1833	8.625	1.2	3	1930	1833	8.625	1.2
4	2678	2505	6.625	1.2	4	2645	2468	6.625	1.2
5					5				
6					6				
7					7				
8					8				

[ ] optional

Figure 2 DoubletCalc 1.4.3 input screen (the boxed numbers refer to the text under the casing scheme on the next page).

Open Scenario

Look in: doubletcalc143

runtime  
example.xml

File name: example.xml

Files of type: .xml

Open Cancel

Figure 3 DoubletCalc Open Scenario screen.

Save Scenario

Save in: doubletcalc143

runtime  
example.xml

File name: example.xml

Files of type: .xml

Save Cancel

Figure 4 DoubletCalc Save Scenario screen.

### Casing schedule

In DoubletCalc 1.4.3 the casing scheme has to be specified, including the relevant characteristics of the pipes (inner diameter and roughness), to the top of the aquifer. The Along Hole (AH) and True Vertical Depth (TVD) depth must be specified, according to the same surface reference level as the aquifer depth values (in the Netherlands, NAP or Amsterdam Ordnance Level). Using these parameters, the resistance encountered by the water while flowing through the casing can be calculated. Figure 2, under 'C) Well Properties', shows the essential well input parameters for DoubletCalc 1.4.3:

1. the outer diameter of the producer and injector in the reservoir section. This diameter, specified as inches, determines the areal extent of the surface through which water can enter the wellbore. This is the open hole diameter.
2. the inclination of the well trajectory in the aquifer (in degrees relative to the vertical). In combination with the reservoir gross thickness and net-to-gross ratio, this determines the length of the production interval. DoubletCalc assumes that the entire reservoir section is connected to the well.
3. the top and base of the casing / liner section measured in meters along hole (mAH).
4. the top and base of the casing / liner section measured in meters vertically (true vertical depth, or TVD).
5. the inner diameter of the casing / liner, per section (inch), through which the water is produced.
6. the roughness of the casing (milli-inch). The roughness and inner diameter determine the resistance the water encounters when flowing.

Figure 5, which is the graphical representation of the well design in Figure 2, shows which parameters should be entered. The part of the well inside the reservoir (solid blue in the figure) should not be specified under 'C) Well Properties' if the well is completed using a slotted screen and / or gravel pack in an open hole. In all cases, the drill bit size should be entered as 'outer diameter producer / injector'. If the top part of the casing is unperforated, this will result in extra resistance. This part of the casing must be entered in the scheme.

The detail in the upper right of Figure 5 shows how water will flow towards the perforated section in an inclined well. The area through which water can enter the well is increased by the inclined path of the well through the aquifer. More information can be found in paragraph 3.2 (Penetrating the aquifer) and chapter 8 (The effect of penetrating the reservoir obliquely).

The depth of the top of the aquifer is varied stochastically during calculation of the geothermal power. Therefore the specified architecture of the casing, with a fixed end depth, does not fit the top of the aquifer anymore. To deal with this problem, DoubletCalc will extend or shorten the tubing segment with the largest diameter accordingly.

For reasons of calculation accuracy, DoubletCalc will split the well into segments of equal length during the simulation (the 'calculation length subdivision' under section 'C) Well Properties' in the input screen of Figure 2. A weighted average of the properties is assigned to segments crossing a tubing section boundary (see the 'base case details' file in paragraph 2.3.3). It is advisable to choose the segment length in accordance with the well design. A very small segment length increases the calculation time, whereas a very large length decreases the calculation accuracy.

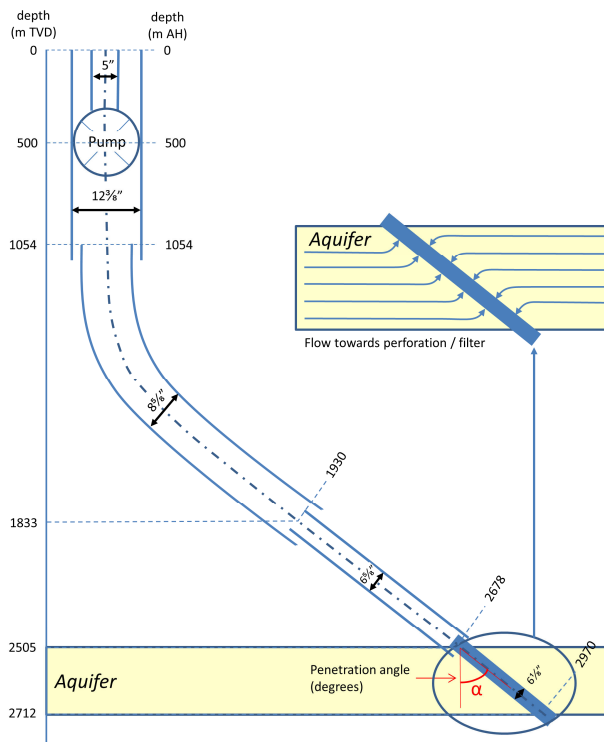


Figure 5 Schematic casing design. The part of the casing located in the reservoir (solid blue) should only be specified under specific circumstances.

The calculation of the geothermal power can be started when all parameters have been entered (button 'Calculate!'). When finished the Doublet Calculator 1.4.3 Result Table (Figure 6) will appear.

### 2.3 Output screen

The output screen shows on the left hand side in the column 'Geotechnics (Input)' the input parameters that were entered in the Input Screen and consequently used during the calculation. The column 'Geotechnics (Output)' on the right hand side shows the results of the calculation. The first block 'Monte Carlo cases' shows the results of the stochastic simulation. The second block 'Base case' shows the results of a calculation in which only the median values were used (in case a range was specified).

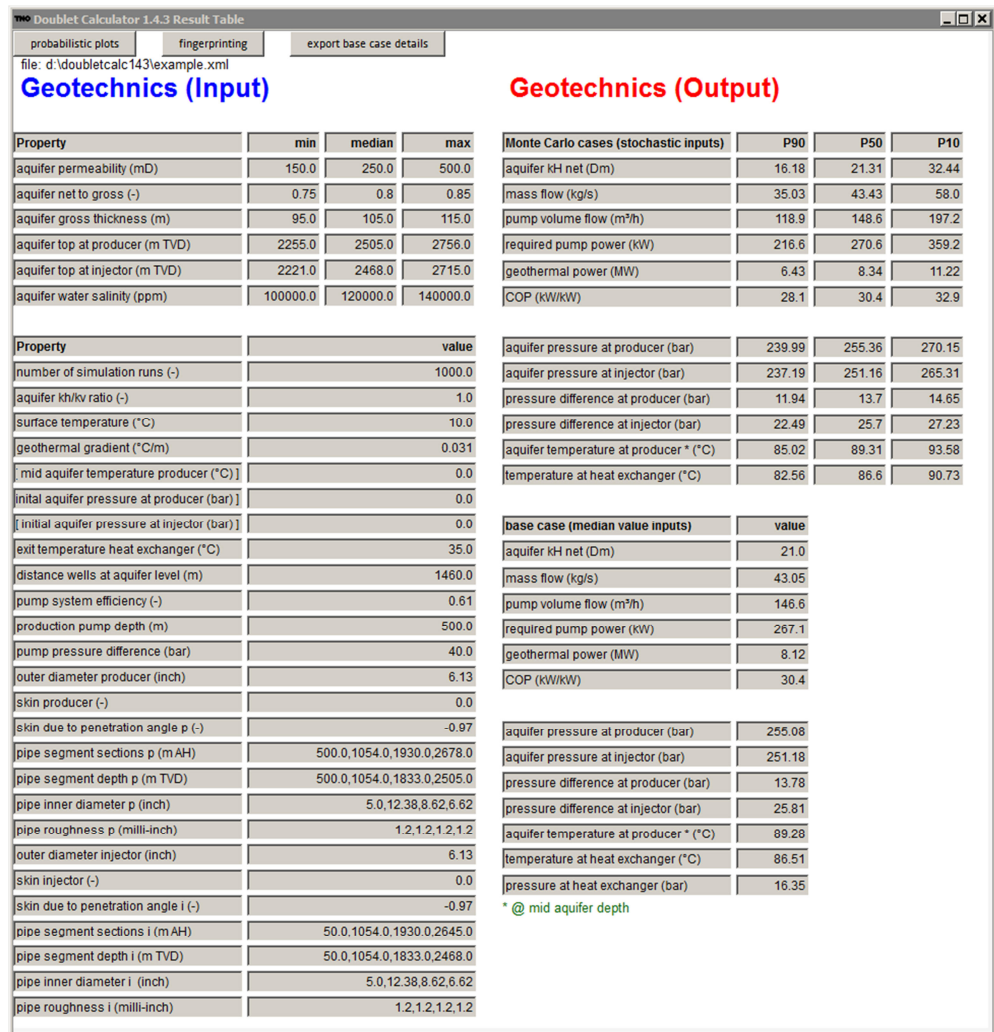


Figure 6 DoubletCalc 1.4.3 output screen.

The output screen has three options for presenting the results in different ways:

- probabilistic plots
- fingerprinting
- export of the 'base case' details

The detailed output is described in the following paragraphs.

### 2.3.1 Probabilistic plots

The button 'probabilistic plots' generates a new window graphically showing the probability distribution of the pump volume flow. In the upper left corner of the window there is an option to show similar graphs for the geothermal power and the coefficient of performance (COP) (Figure 7). Choosing the button 'Export CSV file' will export the graphs numerical data to a text file (Figure 8).

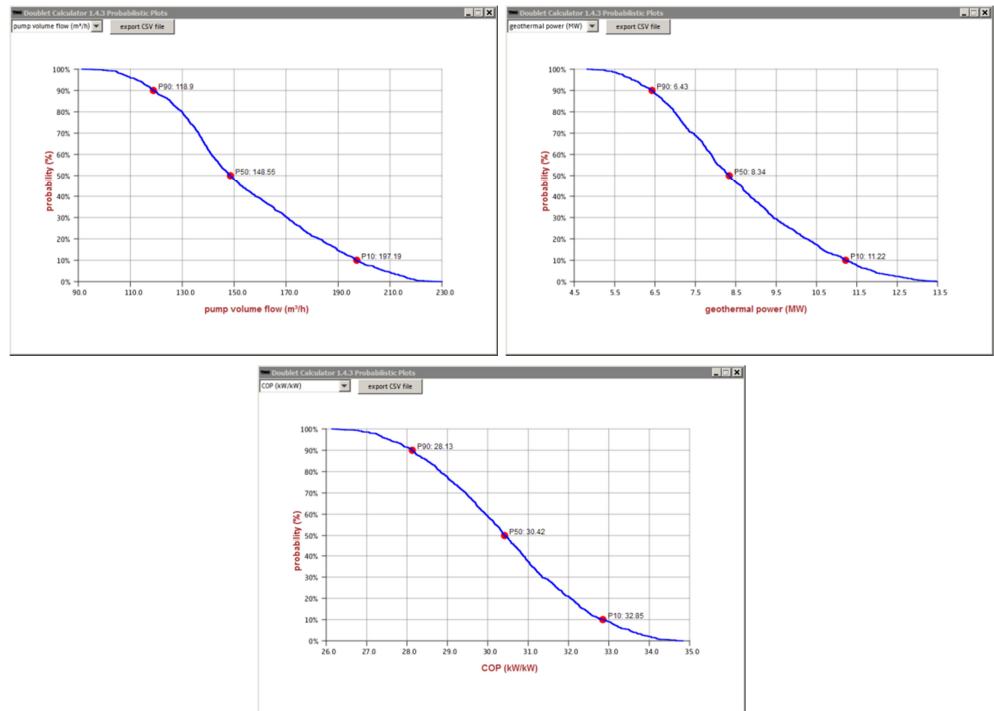


Figure 7 Probabilistic plots for pump volume, geothermal power and COP.

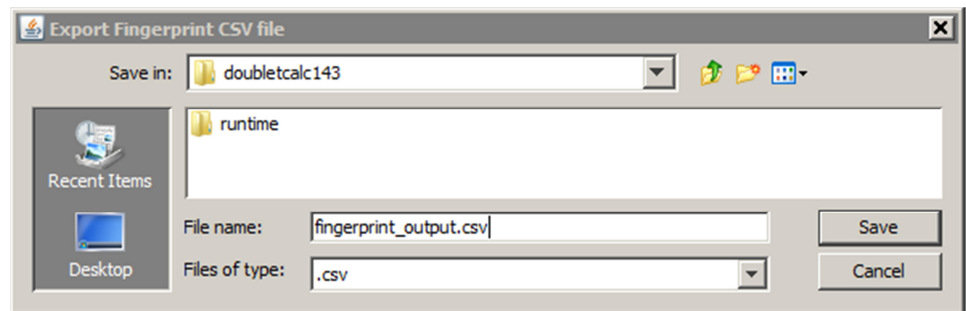


Figure 8 DoubletCalc 1.4.3 Export Fingerprint to file screen

### 2.3.2 Fingerprinting graph

Figure 9 shows the graph that is generated using the Fingerprinting button. DoubletCalc will calculate the geothermal power (green curve), COP (purple), flow rate (red) and the required pump energy (blue) for varying pump pressure differences that are around the specified pump pressure difference. The calculation of these graphs uses the median values from the input screen.



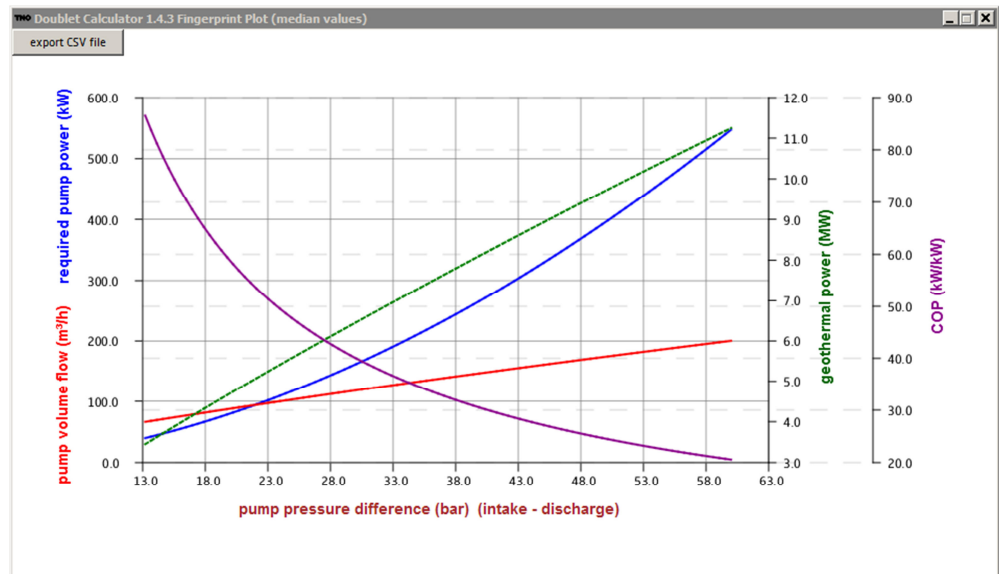


Figure 9 DoubletCalc Fingerprint graph.

2.3.3 Base case details

The button 'export base case details' in the output screen writes the following information to a CSV-file:

- hydrostatic aquifer properties at the producer and injector, calculated along the well path per section (as specified in the 'calculation length subdivision'): pressure, temperature, salinity, density and viscosity (Table 1)
- 'base case' details at the producer and injector, calculated along the well path per section (as specified in the 'calculation length subdivision') (Table 2)
- 'base case' pressure and temperature at a number of key doublet nodes (Table 3)
- 'base case' results calculated for the doublet as a whole (Table 4)
- stochastic results (P90, P50 and P10) for a number of parameters calculated for the doublet as a whole (Table 5).

Appendix 1 shows an example of the base case details file.

parameter	unit	description
Z	m	top depth of calculation segment
P	bar	pressure
T	°C	temperature
S	ppm	salinity
density	kg/m <sup>3</sup>	density
viscosity	Pa.s	viscosity

Table 1 Base case details file parts 1 and 2: initial hydrostatic aquifer properties at producer and injector, calculated per section ('calculation length subdivision').

parameter	unit	description
iN	-	calculation length section number
segment	-	tubing section number
L	m	depth (along borehole)
Z	m	depth (true vertical)
angle	°	modelled inclination
inner diameter	Inch	casing inner diameter
roughness	milli-inch	absolute casing roughness
P	bar	pressure
T	°C	temperature
S	Ppm	salinity (Total Dissolved Solids, NaCl equivalent)
density	kg/m <sup>3</sup>	fluid density
viscosity	Pa s	fluid viscosity
Qvol	m <sup>3</sup> /h	volume flow
dPGrav	bar	pressure difference as a result of gravity operating on the density of the water
dPVisc	bar	pressure difference as a result of varying viscosity
dPpump	bar	pressure difference as a result of pump (input screen)

Table 2 Base case details file parts 3 and 4: parameters calculated per section ('calculation length subdivision') for the production and injection well.

== DOUBLET NODES ==				
node nr.	node name	P (bar)	T (°C)	location
1	Aquifer_Prod	255.08	89.28	static aquifer pressure and temperature near the producer
2	Aquifer/Prod_Bottom	241.30	89.28	bottomhole flowing pressure and temperature at the producer
5 & 6	Prod_Top/Entry_HE	16.35	86.51	wellhead pressure and temperature at the producer
7 & 9	Exit_HE/Inj_Top	16.35	35.00	wellhead pressure and temperature at the injector
10	Inj_Bottom/Aquifer	276.99	35.99	bottomhole flowing pressure and temperature at the injector
11	Aquifer_Inj	251.18	89.28	static aquifer pressure and temperature near the injector

Table 3 Base case details file part 5: pressure and temperature at specific locations in the doublet schedule. The numbers refer to the doublet nodes shown in Figure 18. Node 8 is only relevant if a separate injector pump is installed. The pressure and temperature values in this table result from the example scenario.

=== BASE CASE RESULTS ===		
aquifer kH net (Dm)	21.00	transmissivity
mass flow (kg/s)	43.05	
pump volume flow (m <sup>3</sup> /hr)	146.60	
required pump power (kW)	267.10	
geothermal power (MW)	8.12	indicative geothermal power
COP (kW/kW)	30.40	Coefficient Of Performance
aquifer pressure at producer (bar)	255.08	
aquifer pressure at injector (bar)	251.18	
pressure difference at producer (bar)	13.78	pressure difference between well face and aquifer in the production well
pressure difference at injector (bar)	25.81	pressure difference between well face and aquifer in the production well
aquifer temperature at producer (°C)	89.28	
temperature at heat exchanger (°C)	86.51	
pressure at heat exchanger (bar)	16.35	

Table 4 Base case details file part 6: base case calculation results as observed in the output screen (right hand side column, third and fourth blocks from above). The values result from a single calculation in which only the median parameter values are used. The values in this table result from the example scenario.

=== STOCHASTIC RESULTS ===			
	P90	P50	P10
aquifer kH net (Dm)	16.31	21.26	32.72
mass flow (kg/s)	35.15	43.51	57.93
pump volume flow (m <sup>3</sup> /h)	119.70	148.50	197.00
required pump power (kW)	218.00	270.40	358.80
geothermal power (MW)	6.36	8.33	11.12
COP (kW/kW)	28.10	30.50	32.80
aquifer pressure at producer (bar)	239.98	255.12	270.19
aquifer pressure at injector (bar)	237.12	251.24	265.32
pressure difference at producer (bar)	11.97	13.68	14.63
pressure difference at injector (bar)	22.37	25.70	27.23
aquifer temperature at producer * (°C)	84.98	89.28	93.64
temperature at heat exchanger (°C)	82.54	86.58	90.75

Table 5 Base case details file part 7: stochastic results for the doublet calculation as observed in the output screen (right hand side column, first and second blocks from above). The values result from a large number of simulation runs in which per run parameter values are drawn from a triangular distribution defined by the user specified min-median-max values. The values in this table result from the example scenario.

## 2.4 Error messages

DoubletCalc can generate the following error messages:

**Erratic input:** erratic input was specified in the input. This can for example be:

- a median value smaller than the min value,
- a depth value that is not corresponding to other depth values, like a pump depth deeper than the total depth of the well,
- a non-numerical value where a numerical value is expected,
- for some fields, a value of zero is not allowed, like for instance anisotropy, geo-thermal gradient, pump pressure and tubing inner diameter,
- a field that was left empty.

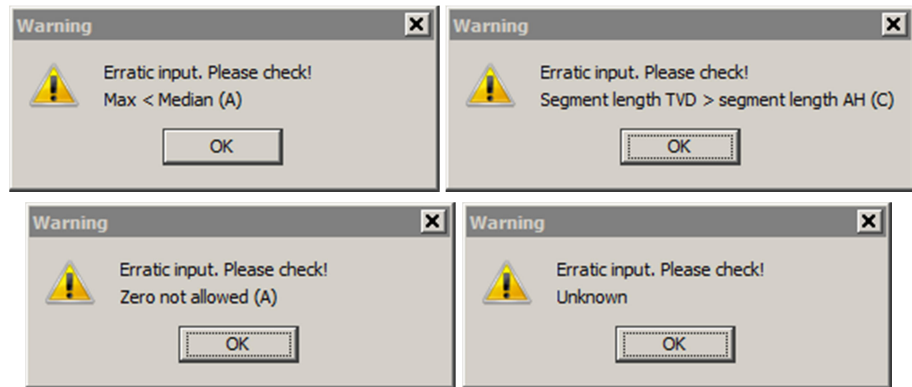


Figure 10 DoubletCalc error message input parameters.

**Data is not converging:** this error message originates from proper input values that, in combination with other input resulting from stochastically obtained values of for instance depth and thickness, results in an impossible configuration between well and aquifer. Examples are extreme values for the skin, or negative permeabilities and depth values.

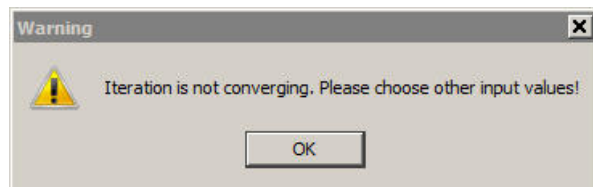


Figure 11 DoubletCalc error message for an incorrect combination of (stochastically drawn) parameter values.

**Well segments must reach top aquifer:** the TVD depth of the last segment specified under 'Well properties' must be at least equal to the value specified as aquifer top under the 'Aquifer properties'.

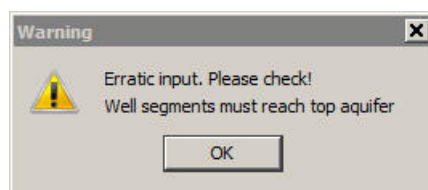


Figure 12 DoubletCalc error message for an incorrect specification of the well segments.

**Segment length TVD > segment length AH:** the 'true vertical' depth must always be smaller than or equal to the 'along hole' depth.

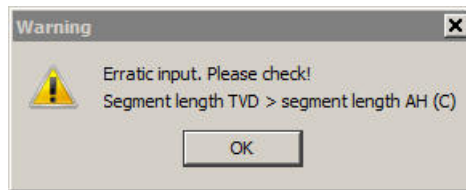


Figure 13 DoubletCalc error message for an incorrect combination of AH and TVD depths.

**Negative pressures:** if the pump pressure is set too low, or if the depth of the pump is chosen very shallow, negative pressures may result (see paragraph 12.4)

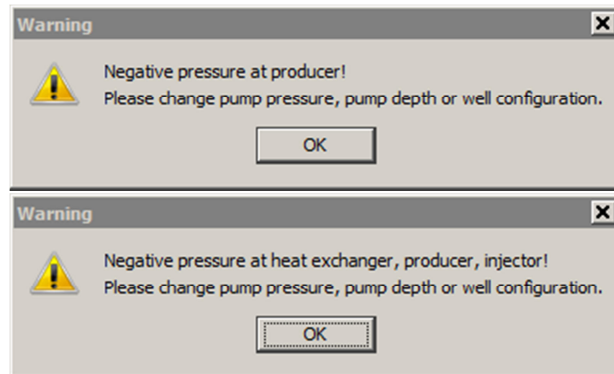


Figure 14 DoubletCalc error messages resulting from negative pressures

### 3 The DoubletCalc model

The objective in the design of DoubletCalc is to be able to calculate the indicative geothermal power on the basis of a model of a geothermal doublet, taking into account the geological aquifer uncertainties. Aquifer- and installation parameters are required in order to calculate the geothermal power. The modelling assumes that the installation parameters are known, and that the uncertainties of the system are a consequence of uncertainties in the (estimation of the) aquifer characteristics. The following tables list the parameters that are required for the operation of DoubletCalc.

parameter	min	median	max	dimension
permeability				mD
gross thickness				m
net/gross fraction				-
brine salinity (Total Dissolved Solids, NaCl equivalent)				ppm
depth top aquifer at production well	-		-	m
depth top aquifer at injection well	-		-	m

Table 6 DoubletCalc input geological parameters (with uncertainty range). The uncertainty imposed on the depth is 10% (see paragraph 2.2).

parameter	value	dimension
geothermal gradient		°C/m
average surface temperature		°C
$k_h/k_v$ ratio of the aquifer (anisotropy)		-

Table 7 DoubletCalc input geological parameters (without uncertainty range)

parameter	value	dimension
casing scheme production well		m
casing scheme injection well		m
inner diameter production casing		inch
absolute roughness production casing		milli-inch
borehole diameter production well at aquifer level		inch
borehole diameter injection well at aquifer level		inch
skin (resistance around well in reservoir section) production well, fixed value	0	-
skin (resistance around well in reservoir section) injection well, fixed value	0	-
inclination between production well trajectory and reservoir		degrees
inclination between injection well trajectory and reservoir		degrees

Table 8 DoubletCalc well specification input

parameter	value	dimension
injection temperature		°C
distance between production and injection well at aquifer level		m
pump efficiency		Fraction
pump depth in production well		M
pump pressure difference		Bar

Table 9 DoubletCalc input for pump and doublet

### Flow

The theoretical flow rate is calculated from the variables in Table 6 to Table 9, and an imposed pressure drop at the boundary between aquifer and well.

The calculation of the geothermal power takes the following into account:

- pressure loss caused by flow in the aquifer to the production well and from the injection well;
- pressure loss around production and / or injection well caused by 'skin';
- pressure loss in the production and injection wells as a result of friction by flow;
- pressure difference caused by gravity;
- pressure difference caused by the pump in the production well;
- heat loss in the production and injection wells as a result of the release of heat to the environment.

Correlations have been used to determine the relevant water properties density, viscosity and heat capacity. Density is a function of pressure, temperature and salinity. Viscosity and heat capacity are a function of temperature and salinity. A detailed theoretical description of the calculation is presented in chapter 4.

### 3.1 Remarks regarding the model

Figure 5 shows that the well is split into a number of sections with varying properties. A new segment should be specified in the DoubletCalc input where a change in well diameter is foreseen. The inclination of the section is calculated from the 'along hole' and 'true vertical' depths. This results in a stepwise deviation trajectory which closely approaches the true deviation and therefore is fit for purpose. The flow resistance and the heat loss on the way up (producer) or heat gain on the way down (injector) can be calculated from the deviation, and the specified casing diameter and roughness. This is described in detail in chapter 4.

The aquifer is modelled as homogeneous, with a uniform thickness, net-to-gross ratio, permeability, anisotropy and salinity. An inclined aquifer can be modelled by entering different TVD values for the top aquifer at producer and injector.

There is no direct relation between aquifer and well in the model. It is implicitly assumed that the entire aquifer or aquifer interval has been drilled and completed. The model also assumes, in principle, that the aquifer is drilled vertically. The improved flow towards the well as a result of drilling an inclined well (like the example shown in Figure 5) is accounted for by entering a penetration angle for producer and / or injector ( $\alpha$  in Figure 5). The 'skin due to penetration angle', shown in the input screen, is calculated automatically (see paragraph 3.2: Penetrating the aquifer).

The reservoir temperature that is used in the model is calculated by multiplying the depth of the middle of the aquifer by the geothermal gradient, increased by the average surface temperature. The middle of the aquifer is calculated for each simulation by adding the stochastically drawn value of the top of the aquifer and the drawn half aquifer thickness.

### 3.2 Penetrating the aquifer obliquely

The intersection of well and aquifer is modelled as a vertical transect. In reality, the production and/or injection wells are rarely perpendicular to the aquifer. Inclined wells have an effect on:

- the distance between the wells in the aquifer
- flow to and from the well.

These effects are discussed below.

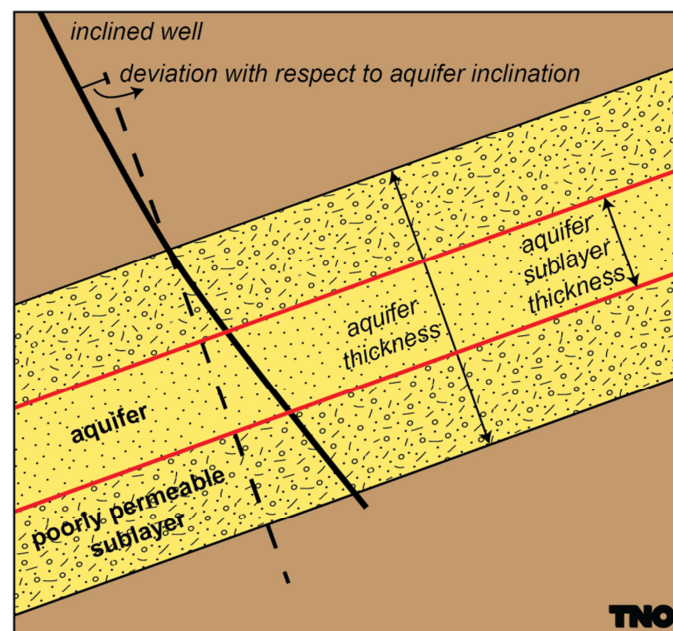


Figure 15 Inclined penetration of the aquifer.

#### Distance between production and injection well

The result of having an inclined well is that the distance between the production and injection wells depends on the well trajectory. The distance between the wells is used for the calculation of the well productivity (chapter 8). When calculating the distance between the wells the inclination is accounted for by using the distance between the wells at the centre of the aquifer.

#### Effect on flow

The inclination has consequences for the flow direction in the reservoir. As a result of the inclined perforation, the length of the intersection of wellbore and reservoir generally exceeds the thickness of the aquifer. Consequently, the flow will be larger for an inclined than for a perpendicular well. This effect can be accounted for by introduction of an extra skin. For an inclined well the sign of the skin is negative. Choi et al. (2008) and Rogers & Economides (1996) present an overview of the



relation between skin and deviation angle, anisotropy, thickness of the aquifer and well diameter.

DoubletCalc accounts for the positive effect on the influx of water by using the skin. The software calculates the skin using the equations presented in chapter 8.

Figure 16 shows the skin as a function of the deviation angle, for varying values of the aquifer thickness ( $H$  or  $h_d$ ) and anisotropy ( $I_{ani}$ ). The (negative) skin as a result of the inclined well increases with increasing deviation angle, and decreasing aquifer thickness (see paragraph 0).

As an example, the skin due to the penetration angle will be calculated for two combinations of the aquifer thickness and anisotropy, and a common well diameter:

$H$  = 20 or 100 meter  
 $I_{ani}$  = 1 or 2  
 $r_w$  = 0.10 meter (corresponding to a well diameter of 8")  
 $h_d$  = 200 or 1000 (=  $H / r_w$ )

Figure 16 shows the skin as a function of the deviation angle for a well distance of 1600 meter and a 0.10 m well diameter. Similarly, Figure 17 shows the deviation against the productivity index ratio, which is the ratio between the productivity index for a deviated well and that for a vertical well. It is clear that for deviation angles less than about  $40^\circ$  the effect on the productivity index is negligible, about 10% for  $I_{ani}=1$  and  $h_d = 1000$ .

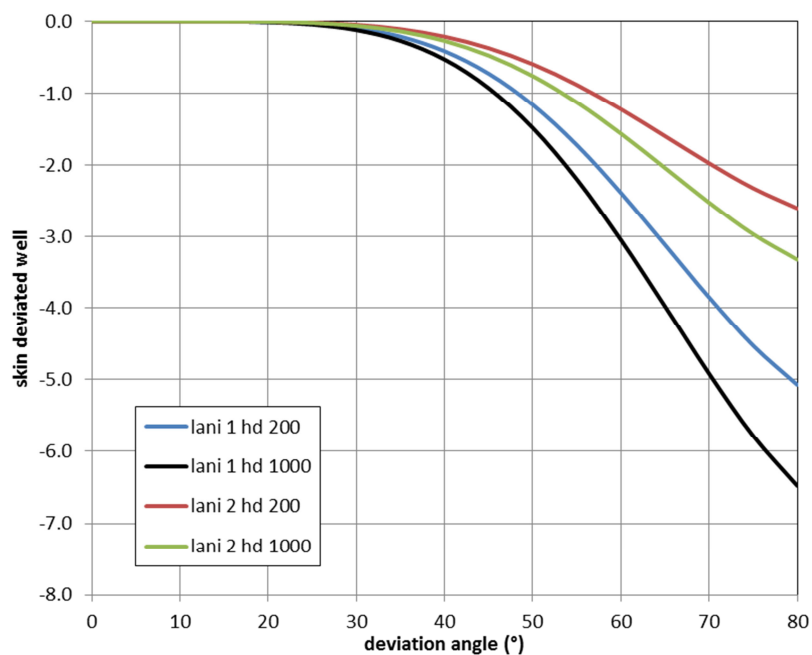


Figure 16 Skin due to penetration angle as a function of angle.

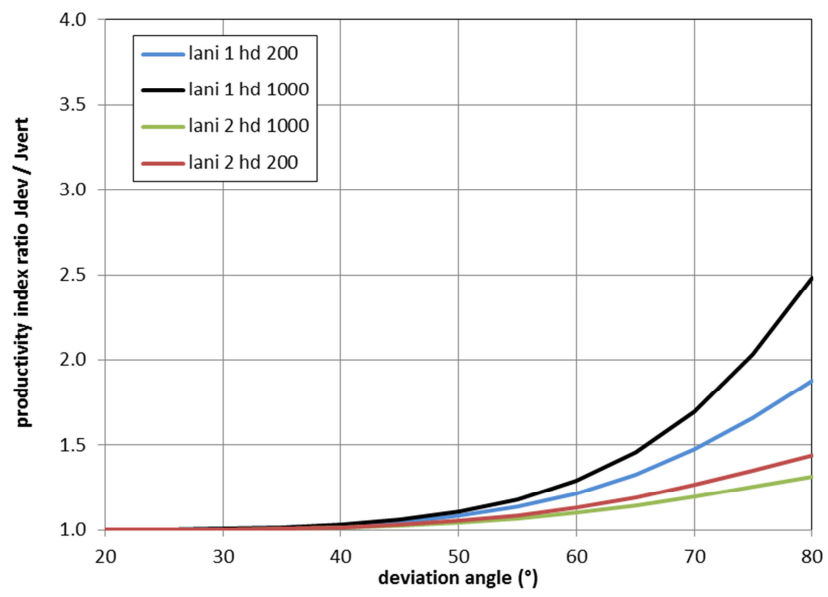


Figure 17 Ratio of the productivity indices for a deviated and a vertical well as a function of deviation angle.

## 4 Theoretical background of the DoubletCalc model

The premises for the calculation of the geothermal energy, given the aquifer, wells and heat exchanger characteristics are:

- Mass balance: the mass flow (kg/s) is constant in the doublet system from the intake in the production well until the injection in the aquifer.
- Impulse balance (pressure balance): this is valid for the entire doublet system and for all of the elements within the system. The sum of the pressure differences over all element in the system is zero. The pressure balance determines the mass flow at a given pump pressure.
- Energy balance: this is valid for all elements within the system. Release of heat to the immediate surroundings of the well and temperature drop in the heat exchanger are taken into account.

Figure 18 is a schematic representation of the doublet system. The numbered nodes, listed in Table 10 and Table 11, are used to describe the components of the pressure and energy balances.

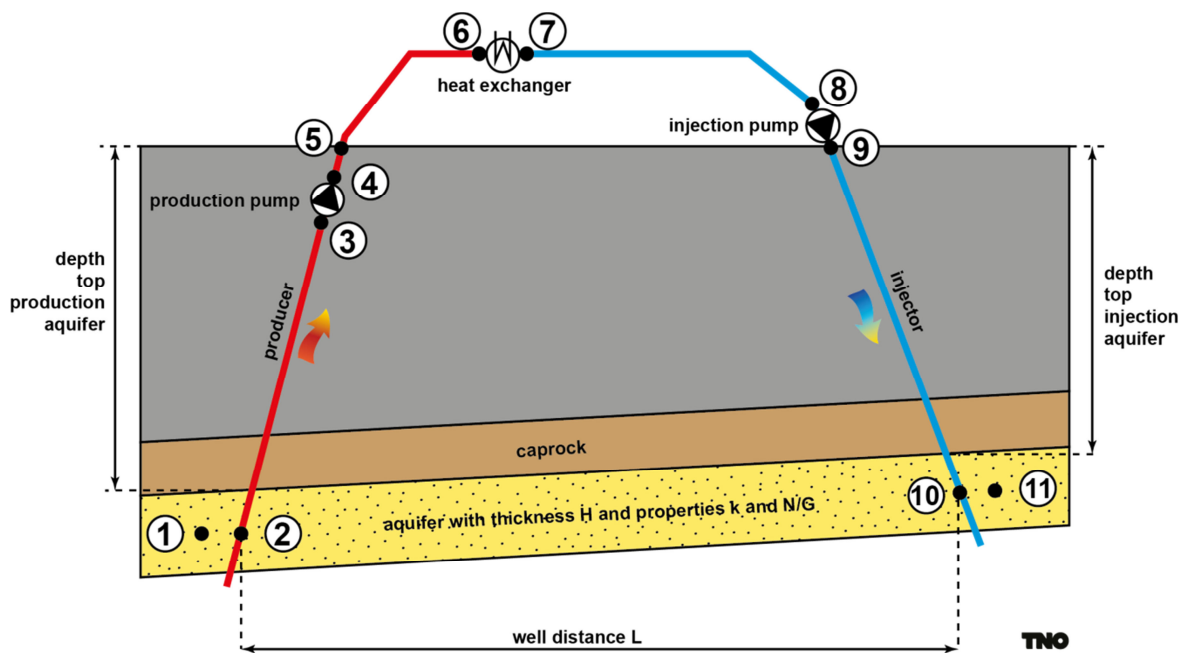


Figure 18 Schematic overview of a geothermal doublet with reference to the nodes used in Table 10 and Table 11.

from node		to node		element	cause of pressure difference	equation
1	static aquifer pressure at production well	2	bottom production well	aquifer	viscous forces	7
2	bottom production well	3	inlet production pump	tubing / casing	viscous forces and gravity	9
3	inlet production pump	4	outlet production pump	pump	pressure increase by pump	13
4	outlet production pump	5	top production well	tubing / casing	viscous forces and gravity	4
5	top production well	6	inlet heat exchanger	casing	viscous forces and gravity. ignored.	-
6	inlet heat exchanger	7	outlet heat exchanger	heat exchanger	viscous forces and gravity. ignored.	-
7	outlet heat exchanger	8	inlet injection pump	casing	viscous forces and gravity. ignored.	-
8	inlet injection pump	9	outlet injection pump	pump	not modelled separately (see §5.6)	-
9	outlet injection pump	10	top injection well	casing	viscous forces and gravity. ignored.	-
10	top injection well	11	bottom injection well	tubing / casing	viscous forces and gravity.	9
11	bottom injection well	12	static aquifer pressure at injection well	aquifer	viscous forces	7

Table 10 Pressure balance

from node		to node		element	nature heat exchange	equation
1	middle aquifer at production well	2	bottom production well	aquifer	none	-
2	bottom production well	3	inlet production pump	tubing/pipe	with surroundings	20
3	inlet production pump	4	outlet production pump	pump	with surroundings - ignored	-
4	outlet production pump	5	top production well	tubing/pipe	with surroundings	20
5	top production well	6	inlet heat exchanger	pipe	with surroundings - ignored.	-
6	inlet heat exchanger	7	outlet heat exchanger	heat exchanger	heat loss to heat exchanger	21
7	outlet heat exchanger	8	inlet injection pump	pipe	with surroundings. ignored.	-
8	inlet injection pump	9	outlet injection pump	pump	not modelled separately (§5.6)	-
9	outlet injection pump	10	top injection well	pipe	with surroundings – ignored	-
10	top injection well	11	bottom injection well	tubing/pipe	with surroundings	20
11	bottom injection well	12	middle aquifer at injection well	aquifer	water warmed by heat exchange with reservoir rock - ignored (paragraph 11.2).	-

Table 11 Energy balance

The equations listed in Table 10 and Table 11 are described in chapter 5. The letters and symbols used in the equations is given at the end of this chapter.

Because the doublet is a closed system, the mass balance dictates that the mass flow  $Q_m$  (kg/s) is equal in all elements of the system.

In the dynamic system the salinity is constant and equal to the salinity of the aquifer water. For the calculation of the hydrostatic pressure it is assumed that the salinity increases linearly with depth from zero at surface level to the specified median value at target reservoir level (see paragraph 7.4).

The pressure and energy balances are solved simultaneously for a given pump pressure or mass flow. This results in a value of pressure and temperature at each node in the doublet system. The resulting geothermal power and the electrical power required to operate the pump are easily calculated.

The calculation of pressure and temperature starts in the aquifer at the production well (node 1). From this node onward, the pressure and temperature at each node are calculated on the basis of the calculated pressure and temperature differences over each element.

## 5 Mass balance

### 5.1 Mass flow

The doublet system is a closed system, as was already remarked in chapter 3 (The DoubletCalc model). Consequently, following the mass balance, the mass flow  $Q_m$  (kg/s) is equal in all elements of the doublet system:

$$Q_m = \text{constant} \dots\dots\dots(\text{eq. 1})$$

### 5.2 Volume flow

The volume flow  $Q_v$  (m<sup>3</sup>/s) is required for the calculation of the pressure loss caused by viscous forces. This follows from:

$$Q_v = \frac{Q_m}{\rho} \dots\dots\dots(\text{eq. 2})$$

The water density  $\rho$  (kg/m<sup>3</sup>) is a function of pressure, temperature and salinity. Pressure and temperature are difference at each location in the doublet system.

### 5.3 Impulse balance

The impulse balance (pressure balance) is given by:

$$\sum_{k=1}^{N-1} \Delta p_{k+1,k} + \Delta p_{1,N} = 0 \dots\dots\dots(\text{eq. 3})$$

in which  $N$  is the number of nodes in the doublet system (Figure 18, Table 10) and

$$\Delta p_{k+1,k} = p_{k+1} - p_k \dots\dots\dots(\text{eq. 4})$$

and specifically:

$$\Delta p_{1,N} = p_{stat,p} - p_{stat,i} \dots\dots\dots(\text{eq. 5})$$

$p_{stat,p}$  and  $p_{stat,i}$  are the initial hydrostatic pressures at the production and injection wells respectively (see paragraph 5.7: Initial hydrostatic aquifer pressure near the production and injection well).

Substitution of 5 in 3 gives:

$$p_{stat,p} + \sum_{k=1}^{N-1} \Delta p_{k+1,k} - p_{stat,i} = 0 \dots\dots\dots(\text{eq. 6})$$

Each of the elements of the above listed equations is described in the following paragraphs. Pressure losses in the surface pipes and the heat exchanger are ignored, like mentioned in Table 10.

#### 5.4 Pressure development in the aquifer from or towards a well

The pressure development in the production well, and the pressure increase in the injection well for a doublet is (Verruijt 1970, equation 6.5 and Dake 1978):

$$\Delta p_{w,aq} = p_w - p_{aq} = Q_v \frac{\mu}{2\pi k H R_{ntg}} \left( \ln \left( \frac{L}{r_{out,w}} \right) + S \right) \dots\dots\dots (eq. 7)$$

with:

- $p_w$  = pressure in well at aquifer (bottom hole pressure)
- $p_{aq}$  = initial hydrostatic pressure in the aquifer at well
- $Q_v$  =  $Q_m / \rho$  = flow, positive for flow from well to aquifer
- $\mu$  = water viscosity (function of temperature and salinity)
- $k$  = permeability of the aquifer
- $H$  = thickness of the aquifer
- $R_{ntg}$  = net-to-gross ratio
- $L$  = distance between production and injection well at aquifer level
- $r_{out,w}$  = outer diameter of the well (filter diameter)
- $S$  = skin factor

This equation is valid for stationary flow to vertical wells and a homogeneous aquifer.

The initial pressure and temperature in the aquifer at the production well are used for the calculation of  $\rho$  and  $\mu$ . The pressure in the bottom of the well and the outlet temperature of the heat exchanger are used for the injection well. The salinity is considered to remain constant, as described in paragraph 7.4.

The right hand side of equation 7 depends on pressure and temperature, because  $\rho$  depends on temperature and pressure, and  $\mu$  on temperature.

The first term of equation 7 gives the pressure loss caused by flow in a homogeneous aquifer. However, the aquifer characteristics in the direct surroundings of the well usually differ from those in the rest of the aquifer as a result of the drilling process and / or special treatment of the well. This effect is called 'skin'. Skin reflects the difference in pressure drop from the aquifer to the well for the original (homogeneous aquifer) and current situation (after drilling, completion, etc.).

Skin is usually caused by wellbore damage, like drilling mud that hasn't been flushed (Figure 19). Constipation of pores by fines (very fine grained components of the aquifer rock like clay) can also contribute progressively to the skin in the course of water production and injection. Treatment of the well (stimulation) has as objective to decrease the pressure drop around the well.

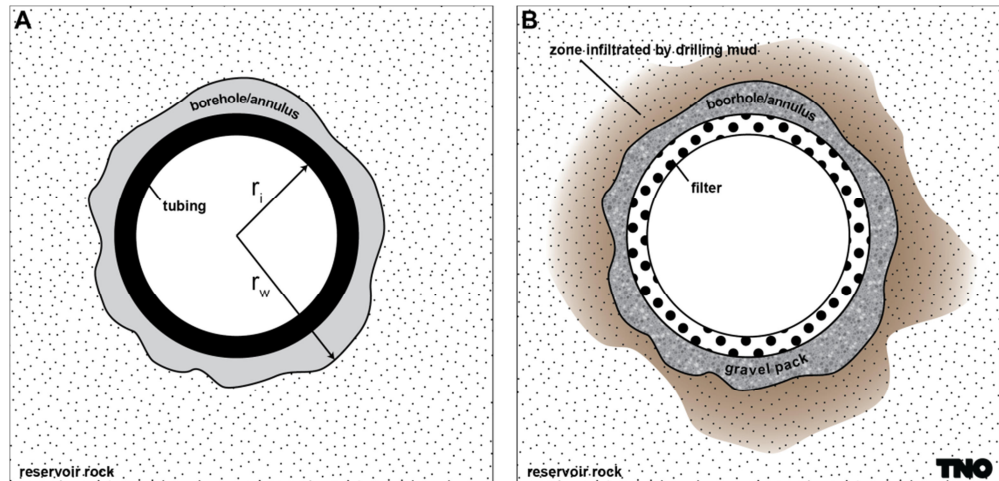


Figure 19 Horizontal sketch of the wellbore showing casing, annulus and reservoir (A), and drilling mud infiltration into the aquifer (B).

The difference in pressure drop is represented by the second term of equation 8:

$$\Delta p_{skin} = Q_v \frac{\mu}{2\pi k H} S \dots\dots\dots (eq. 8)$$

Skin is a dimensionless figure. A positive skin value indicates wellbore damage and extra pressure loss. A negative skin value is representative for a well that has been stimulated (cleaned, acidized, fractured, ..), and a reduced pressure drop.

**5.5 Pressure development in a casing**

Casings and other pipes are present at numerous locations in the doublet system. Because the pipes belonging to the surface system are relatively short in comparison with the underground casing, and have a relatively large diameter, their resistance is ignored (Table 10). The pressure differences in the casing of the production and injection wells are important for the pressure balance. Three factors contribute to pressure difference during flow in a tubing:

- gravity
- friction / viscous forces
- inertia (acceleration) forces

The latter two result from flow. However, the inertial forces can be ignored because water is hardly compressible. Consequently, the pressure development in a pipe is given by the Darcy Weissbach or Fanning equation (Beggs and Brill, 1985):

$$\frac{dp}{dl} = - \frac{f \rho v^2}{2 D_{in}} - g \rho \frac{dz}{dl} \dots\dots\dots (eq. 9)$$

The first term results from viscous forces, the second from gravity, with:

- l* = length (distance) along pipe
- z* = height of pipe
- D<sub>in</sub>* = inner diameter of pipe
- g* = gravitational acceleration (9.80665 m/s<sup>2</sup>)



- $\rho$  = fluid density
- $f$  = friction number
- $v$  = the section average velocity:

$$v = \frac{4Q_v}{\pi D_{in}^2} \dots\dots\dots (eq. 10)$$

Given common flow rates and inner tubing diameters of doublet systems, the flow is probably non-laminar flow ( $R_e > 5000$ , see below for the definition of  $R_e$ ). Therefore an adequate approximation of  $f$  is (Beggs and Brill, 1985, p99):

$$f = \left[ 1.14 - 2 \log \left( \frac{\varepsilon}{D_{in}} + \frac{21.25}{R_e^{0.9}} \right) \right]^{-2} \dots\dots\dots (eq. 11)$$

with

- $\varepsilon$  = inner tubing roughness
- $\varepsilon/D_{in}$  = inner tubing relative roughness
- $R_e$  = Reynolds number for flow in pipes:

$$R_e = \frac{\rho v D_{in}}{\mu} \dots\dots\dots (eq. 12)$$

Farshad and Rieke (2006), among many others, have published reference values for common pipe wall surface roughness.

**5.6 Pressure development in the pump**

The pressure development in the pump is a constant that is specified by the DoubletCalc user:

$$\Delta p_{pump} = constant \dots\dots\dots (eq. 13)$$

Currently the software ignores a possible relationship between  $\Delta p_{pump}$  and  $Q_v$ .

On account of the pressure development in the production well, the presence and location of a pump in the production well is essential. Otherwise, at any location, starting from the aquifer, underpressure will result. The use of an injection pump is not strictly necessary. However, for technical reasons it may be more efficient to do so, rather than having only a pump in the production well.

The model does not model a potential injection pump separately. This results in a negligible difference in the density of the water in the trajectory from the outlet of the production pump to the inlet of the injection pump. The production pump pressure difference that is specified by the user in the DoubletCalc input screen is, in case an injection pump is used, the sum of the pressures of the production and injection pumps. The pump efficiency is the effective efficiency of both pumps.

## 5.7 Initial hydrostatic aquifer pressure near the production and injection wells

The initial static pressure follows from equation 9, where  $v=0$  and  $dz/dl = 1$ :

$$\frac{dp}{dz} = -g\rho \dots\dots\dots(\text{eq. 14})$$

with the precondition  $p = p_{atmospheric} = 1$  bar at the surface.

$g$  is the gravitational acceleration. The water density  $\rho$  is a function of pressure, temperature and salinity.

The temperature at any location in the well is determined by the geothermal gradient, which is described in paragraph 6.1. The salinity at any location in the well is determined by the static salinity profile described in paragraph 7.4.

Equation 9 becomes implicit in pressure once temperature and salinity are given. This equation is solved numerically for the hydrostatic pressures  $p_{stat,p}$  and  $p_{stat,i}$  at the production and injection wells respectively.

The initial hydrostatic pressures are reported in the 'base case details file' (see Table 1).

## 6 Energy balance

The energy balance is solved for each system element individually using the pressure and temperature at the inlet of each system element. This yields the temperature at the outlet of the system element. Heat is exchanged at only two locations in the system:

- production well
- heat exchanger

Starting point for the calculation is the temperature at the production well, which is calculated from the geothermal gradient (paragraph 6.1). The temperature loss in the production well and the heat exchanger is covered the paragraphs 6.2 and 6.3.

### 6.1 Geothermal gradient

The initial temperature profile  $T_{gt}$  is required for the calculation of the initial aquifer temperature and the heat loss in the production well:

$$T_{gt} = T_{gt}(d) = T_{sur} + \lambda d \dots\dots\dots(\text{eq. 15})$$

With:

$d$  = depth (positive downward)

$T_{sur}$  =  $T_{gt}(d=0)$

yearly average temperature at surface level

For the Netherlands, this is 10.5 °C (Bonté et al., 2012).

$\lambda$  = geothermal gradient.

For the Netherlands, this is 0.031 °C/m on average (Bonté et al., 2012).

The initial aquifer temperature at the injection well is:

$$T_{aquifer} = T_{sur} + \lambda(d_{top,p} + 0.5H) \dots\dots\dots(\text{eq. 16})$$

with:

$d_{top,p}$  = depth top aquifer at production well

$H$  = aquifer thickness

### 6.2 Heat loss in the production well

The hot formation water loses heat to the relatively cold environment on its way up to the surface. The heat loss per unit length follows from Garcia-Gutierrez et al. (2001):

$$q_{w,well} = \frac{4\pi k_{t,g}(T_c - T_{gt})}{\ln\left(\frac{4\alpha_{t,g}t}{\sigma_c^2}\right)} \dots\dots\dots(\text{eq. 17})$$

with:

$q_{w,well}$  = heat loss per unit length (W/m)

- $T_c$  = casing temperature, considered to be equal to the temperature of the water in the well
- $t$  = time since start of heat flow
- $k_{t,g}$  = thermal conductivity of the rocks surrounding the well
- $r_c$  = inner radius of the casing
- $\sigma$  =  $e^\gamma = 1.781072$ , with Euler's constant  $\gamma = 0.577216$
- $\alpha_{t,g}$  = thermal diffusion coefficient of the aquifer rock:

$$\alpha_{t,g} = \frac{k_{t,g}}{\rho_g c_{p,g}} \dots\dots\dots(\text{eq. 18})$$

with:

- $c_{p,g}$  = heat capacity of the aquifer rocks around the well
  - $\rho_g$  = density of the aquifer rocks around the well
- Using empirically derived data,  $k_{t,g} = 3 \text{ W/(m}\cdot\text{K)}$  and  $\alpha_{t,g} = 1.2 \times 10^{-6} \text{ m}^2/\text{s}$  for the calculation.

The calculation of heat loss is executed for time  $t = 1$  year since the start of the production. Following the energy balance, the heat loss to the environment is equal to the heat release of the formation water:

$$q_{w,put} = Q_m c_p \frac{dT_{put}}{dl} \dots\dots\dots(\text{eq. 19})$$

with:

- $T_{well}$  = temperature of the water in the well
- $l$  = length (distance) along the well
- $c_p$  = water heat capacity (paragraph 5.3)

Rewriting equation 17 yields

$$\frac{dT_{well}}{dl} = \frac{q_{w,well}}{Q_m c_p} \dots\dots\dots(\text{eq. 20})$$

The temperature decrease in the production well is 1-3 °C for a typical doublet. Given a temperature difference in the heat exchanger of about 25-40 °C, the loss of geothermal power is about 3-10%.

In the injection well, during injection, the water will first cool (until the temperature of the cooled production water is equal to the ambient temperature), and then, as the ambient temperature keeps on rising, reheat again. The total temperature effect is less than 1 °C. The only effect is on the viscosity of the injected water.

### 6.3 Temperature decrease in the heat exchanger

The temperature decrease in the heat exchanger is:

$$\Delta T_{he} = T_{he,in} - T_{he,out} \dots\dots\dots(\text{eq. 21})$$

$T_{he,in}$  is the temperature at the inlet of the heat exchanger. It is equal to the temperature at the well head, of which the calculation is described in paragraph 6.2.

$T_{he,out}$  is the temperature at the outlet of the heat exchanger. This is an external variable specified by the user in the DoubletCalc input screen:

$$T_{he,out} = constant \dots\dots\dots(eq. 22)$$

## 7 Water properties

### 7.1 Density

The density of water as a function of pressure  $p$ , salinity  $s$  and temperature  $T$  is calculated using the equations of Batzle and Wang (1992):

$$\rho_{fw} = 1 + 10^{-6}(-80T - 3.3T^2 + 0.00175T^3 + 489p - 2Tp + 0.016T^2p - 1.3 \cdot 10^{-5}T^3p - 0.333p^2 - 0.002Tp^2) \dots\dots\dots(\text{eq. 23})$$

$$\rho = \rho_{fw} + s\{0.668 + 0.44s + 10^{-6}[300p - 2400ps + T(80 + 3T - 3300s - 13p + 47ps)]\} \dots\dots\dots(\text{eq. 24})$$

with:

- $\rho_{fw}$  = fresh water density (kg/m<sup>3</sup>)
- $\rho$  = salt water density (kg/m<sup>3</sup>)
- $p$  = pressure (MPa)
- $s$  = salt content (salinity) (ppm/1,000,000 or kg/kg)
- $T$  = temperature (°C)

### 7.2 Viscosity

The water viscosity is calculated using the correlation given by Batzle and Wang (1992):

$$\mu = 0.1 + 0.333s + (1.65 + 91.9s^3) \exp(-[0.42(s^{0.8} - 0.17)^2 + 0.045]T^{0.8}) \dots\dots\dots(\text{eq. 25})$$

with:

- $\mu$  = water viscosity (cP)
- $s$  = salt content (salinity) (ppm/1,000,000 or kg/kg)
- $T$  = temperature (°C)

### 7.3 Heat capacity

The heat capacity  $c_p$  of water depends on temperature, salinity and pressure. The heat capacity of salt formation water can be approximated using the polynomials used by Grunberg (1970). Despite the fact that this is a relatively old publication, it is considered to be reliable because recent publications like Feistel and Marion (2008) refer to Grunberg as a reliable source for heat capacity calculation.

$$c_p = \left( + 5.328 - 9.760 \cdot 10^{-2} s + 4.040 \cdot 10^{-4} s^2 \right) + \left( - 6.913 \cdot 10^{-3} + 7.351 \cdot 10^{-4} s - 3.150 \cdot 10^{-6} s^2 \right) T + \left( + 9.600 \cdot 10^{-6} - 1.927 \cdot 10^{-6} s + 8.230 \cdot 10^{-9} s^2 \right) T^2 + \left( + 2.500 \cdot 10^{-9} + 1.666 \cdot 10^{-9} s - 7.125 \cdot 10^{-12} s^2 \right) T^3 \dots\dots\dots(\text{eq. 26})$$

with:

- $c_p$  = water heat capacity (kJ/(kg·K))
- $s$  = salt content (salinity) of the water (g/kg)
- $T$  = temperature (°K)

Keep in mind that in in Grunberg the sixth coefficient contains an error (+3.15·10<sup>-6</sup> instead of -3.15·10<sup>-6</sup>).

**7.4 Salt content**

Two regimes apply for the salt content (salinity) of the water:

- static: the initial equilibrium in the subsurface
- dynamic: during the production in the doublet system

The salt content  $s$  of the water in its initial equilibrium as a function of depth  $d$  follows from:

$$s(d) = s_{aq} \frac{d}{d_{top,p} + 0.5H} \dots\dots\dots(eq. 27)$$

- $s_{aq}$  = salinity of the aquifer brine (kg/kg or ppm)
- $d_{top,p}$  = depth of the top of the aquifer at the production well (m TVD)
- $H$  = aquifer thickness at the production well (m)

From the formula follows that at surface level, the salinity is 0. The salinity increases linearly with depth to the user specified value at reservoir depth. The production water is circulated during production. The salinity of the production water is assumed to be equal to that of the reservoir brine, everywhere in the doublet system:

$$s = s_{aq} \dots\dots\dots(eq. 28)$$

## 8 The effect of penetrating the reservoir obliquely

The effect of penetrating the reservoir obliquely, i.e., the angle between the reservoir and the wellbore is not 90°, is that the wellbore – reservoir interface can be longer than the reservoir thickness. This has a positive effect on the flow rate.

The extra skin as a result of obliquely drilling the reservoir is calculated as (Rogers and Economides, 1996):

$$s_{\theta} = -2.48 \frac{(\sin \theta)^{5.87} \cdot h_d^{0.152}}{I_{ani}^{0.964}} \text{ for } I_{ani} \geq 1 \dots\dots\dots (\text{eq. 29})$$

with:

- $s_{\theta}$  = skin as a result of obliquely drilling the reservoir (dimensionless)
- $\theta$  = well deviation from the vertical (°)
- $h$  = aquifer (sub)layer thickness (m)
- $r_w$  = wellbore outer diameter (m)
- $h_d$  = dimensionless aquifer (sub)layer thickness =  $\frac{h}{r_w}$
- $k_h$  = horizontal permeability (m<sup>2</sup>)
- $k_v$  = vertical permeability (m<sup>2</sup>)
- $I_{ani}$  = anisotropy index =  $\sqrt{\frac{k_h}{k_v}}$

The layer thickness is measured perpendicularly to the aquifer strata (Figure 15). This is also valid for the deviation angle. The equation is valid for deviation angles up to 85°.

This skin is calculated automatically from the penetration angle of the producer and injector that are specified by the user in the DoubletCalc input screen. It has a negative sign. During the simulation it is added to potential skins resulting from other factors like well damage or stimulation, which can be entered by the user directly.

If impermeable layers occur within the aquifer, the layer thickness is the thickness of the permeable sub-layer. The presence of impermeable layers, or, in other words, increasing anisotropy, decreases the positive effect of the inclined well. Appendix 2 goes into the details of dealing with sub-layers.

The ratio between the productivity index with and without skin due to penetration angle provides a better understanding in the effect of having an oblique penetration angle than the skin. Productivity is calculated as (equation 6.5 from Verruijt (1970) and Dake (1978)):

$$J = \frac{Q}{p_w - p_{aq}} = \frac{2\pi k H R_{ntg}}{\mu \left( \ln \left( \frac{L}{r_w} \right) + S \right)} \dots\dots\dots (\text{eq. 30})$$

with:

- $J$  = well productivity (m<sup>3</sup>/s/Pa)
- $p_w$  = pressure in the well near the aquifer (bottom hole pressure) (Pa)
- $p_{aq}$  = initial hydrostatic pressure in the aquifer near the well (Pa)
- $Q$  =  $Qm / \rho$  = flow, taken positive for flow from the well towards the aquifer (m<sup>3</sup>/s)



- $\mu$  = water viscosity (see paragraph 7.2) (Pa·s)  
 $k$  = aquifer permeability (m<sup>2</sup>)  
 $H$  = aquifer height (m)  
 $R_{ntg}$  = net-to-gross ratio  
 $L$  = distance between the production and injection wells (m)  
 $r_w$  = outer diameter of the well (filter) (m)  
 $S$  = skin (-)

The productivity index ratio for a well with and without skin due to penetration angle, after some rewriting, is:

$$\frac{J_{inclined\ well}}{J_{vertical\ well}} = \frac{\ln\left[\frac{L}{r_w}\right]}{\ln\left[\frac{L}{r_w}\right] + s_\theta} \dots\dots\dots (eq. 31)$$

with:

- $L$  = distance between the production and injection wells (m)  
 $s_\theta$  = skin due to penetration angle (-)  
 $r_w$  = outer diameter of the well (filter) (m)

$L$  is typically between 1500 and 2000 m, and  $r_w$  about 0.1 m. For these values, the productivity improvement is about 10% per unit skin:  $J_{vertical} / J_{horizontal} = 1.1$  for a skin of 1 (also see Figure 16 and Figure 17).

## 9 Solution method

The pressure balance  $f_{db}$  (equation 31), given geological and installation parameters, is a function of pump pressure ( $\Delta p_{\text{pump}}$ ) and mass flow ( $Q_m$ ):

$$f_{db} = p_{stat,p} + \sum_{k=1}^{N-1} \Delta p_{k+1,k} - p_{stat,i} = f_{db}(\Delta p_{\text{pump}}, Q_m) = 0 \dots\dots\dots(\text{eq. 32})$$

At a given pump pressure  $Q_m$  is solved from the pressure balance using the commonly employed secant numerical method.

The pressure balance is build segment after segment, starting at  $p_{stat,p}$ , the static aquifer pressure at the production well. Figure 18 shows the order of segments and nodes.

Pressure and temperature are known in the aquifer at the production well (node 1). From here, pressure and temperature difference are calculated for each subsequent doublet element (Figure 18, Table 10 and Table 11), at given pump pressure  $\Delta p_{\text{pump}}$  and mass flow  $Q_m$ . The pressure and temperature differences over a doublet element can be calculated explicitly for each element, with the exception of the wells (calculation user specified section length), provided the pressure and temperature at the inlet point of the doublet element are known.

The wells are split into a number of segments to increase the accuracy of the calculation of pressure and temperature difference over the well (this is the *segment length* under 'C) Well properties' in Figure 2). It is advisable to choose the segment length neither smaller than the length of the shortest tubing segment (for this will cause uncertainty), nor very small (for this will increase the calculation time). Equations 9 and 19 are solved simultaneously for each segment using the secant method, at given pressure and temperature at the inlet of the well segment. This yields pressure and temperature at the outlet of the well segment. In this way all segments are calculated subsequently.

The result of the calculation is an estimate of pressure, temperature, mass flow and volume flow at each node.

## 10 Parameter range

A number of parameters in the DoubletCalc input screen must be specified in terms of a minimum, median and maximum value (chapter 5):

- Gross thickness and net to gross ratio of the aquifer.  
The range of these parameters can be estimated from the corresponding values in the available wells or maps.
- Aquifer permeability.  
the range the permeability can be estimated from the reservoir average permeabilities of relevant well tests and / or petrophysical analyses.
- Depth to top aquifer.  
Only a median value must be specified for the depth. DoubletCalc automatically calculates the min and max values by subtracting resp. adding 10%. This may seem a large uncertainty for a depth map. The reason for having 10% is that the uncertainty in depth is used to take account for the fact that no uncertainty is allowed for the geothermal gradient.

The above mentioned parameters are considered to be independent of each other. Therefore it is possible to calculate a probability distribution of the geothermal power from the parameter range using stochastic simulation (Monte Carlo). The probability distribution of the parameters is modelled as a double triangle (Figure 20).

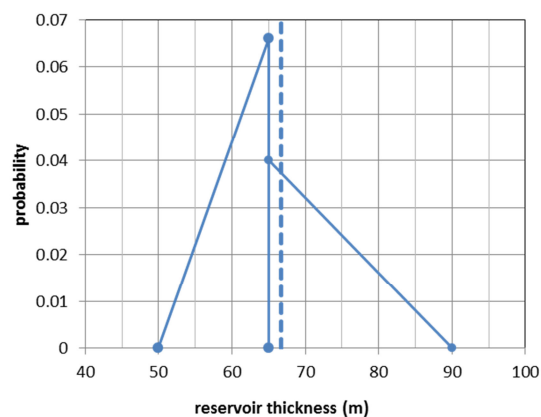


Figure 20 Example of a double triangle probability distribution. The user specified minimum, median and maximum values in this example are 50, 65 and 90. The resulting average is 66.7 (dashed line). The surface under both triangles is equal.

## 11 Calculated characteristics of the geothermal doublet system

After running the Monte Carlo simulation, three characteristics of the doublet system are presented in a probabilistic plot (chapter 10: Parameter range):

- Flow at (the inlet of) the heat exchanger
- Geothermal power
- Coefficient Of Performance (COP)

The following paragraphs explain how these characteristics are calculated.

### 11.1 Geothermal power

Once the mass flow at given pump pressure is calculated, the power issued to the heat exchanger is given by:

$$P_{he} = Q_m c_p \Delta T_{he} \dots\dots\dots (eq. 33)$$

The heat capacity of water  $c_p$  can be calculated because pressure, temperature and salt content at the inlet of the heat exchanger are known.

### 11.2 Required pump power

The net power  $P_{pump,net}$  the pump should supply is:

$$P_{pump,net} = Q_v \Delta p_{pump} = \frac{Q_m}{\rho} \Delta p_{pump} \dots\dots\dots (eq. 34)$$

The gross power is

$$P_{pump,gross} = P_{pump,net} / \eta \dots\dots\dots (eq. 35)$$

with  $\eta$  being the user specified pump efficiency.

### 11.3 Coefficient of performance (COP)

De Coefficient of Performance (COP) is defined as the geothermal power extracted by the heat exchanger from the produced water divided by the power needed for producing and injecting the water:

$$COP = \frac{P_{he}}{P_{pump,gross}} \dots\dots\dots (eq. 36)$$

## 12 Considerations

### 12.1 Power gain by density difference between production and injection well

The temperature of the water is several tens of degrees Celsius lower in the injection well than in the production well. After all, the hot production water has been cooled in the heat exchanger. Therefore, the density of the water is higher in the injection well than in the production well. The resulting difference in hydrostatic pressure  $\Delta p_h$  between the two wells is:

$$\Delta p_h = p_{h,i} - p_{h,p} = g(\bar{\rho}_i - \bar{\rho}_p)\Delta h \dots\dots\dots(\text{eq. 37})$$

with:

$p_{h,i}, p_{h,p}$  = hydrostatic pressure in the injection and production wells, respectively

$\bar{\rho}_i, \bar{\rho}_p$  = average density in the injection and production wells, respectively

$\Delta h$  = average depth (from top to bottom) of injection and production wells

The increased power  $P_h$  is:

$$P_h = \Delta p_h Q_v \dots\dots\dots(\text{eq. 38})$$

For a typical doublet the pressure difference is approximately 1-2 bar. At a typical flow rate  $Q_v$  of 150 m<sup>3</sup>/h the extra power is 4-8 kW. In practice this means that, at a given pump pressure, the flow rate will be higher if the density difference is taken into account. The increased power is calculated by the software.

### 12.2 Difference between produced and injected flow

One of the starting points of the calculation is that the average pressure in the aquifer remains constant during production. This is the case if the volume of the produced water equals the volume of the injected water. However, this is not the case.

The temperature of the water that is being injected into the reservoir is approximately equal to the temperature of the water at the outlet of the heat exchanger. The temperature of the produced water is approximately equal to the initial reservoir temperature. Therefore the density of the injected water is higher than that of the produced water. Because the mass flow is similar in the entire system (paragraph 5.2), the volume of the produced water exceeds the volume of the injected water. This will result in a decrease of the average reservoir pressure.

The total effect is negligible because:

- The density difference caused by the temperature difference is only about 1%.
- The injected water is being reheated by the reservoir rock, which initially has the temperature defined by the geothermal gradient and the average surface temperature. Only about 20-40% of the volume of the injected water remains at the lower injection temperature.

Therefore this effect is ignored.

### 12.3 Viscosity of the injected water

The temperature of the injected water is approximately equal to the temperature of the water at the outlet of the heat exchanger. This low temperature has a considerable effect on the viscosity of the injected water. For example, at a production water temperature of 60 °C the viscosity is about 0.63 cP, whereas the viscosity of the injected water at 30 °C is about 0.94 cP. The 50% increase in viscosity results in a pressure drop from injection well to aquifer of that is 50% higher than at the production well. The choice of the right temperature for the injected water for calculation of the viscosity is therefore important.

There are two opposing effects:

- The injection water reheats quickly like described in paragraph 12.2. This reduces the pressure drop from injection well to aquifer.
- Over time, the aquifer rocks surrounding the well will cool down to the temperature of the injected water. The largest pressure drop will take place around the well ( $\Delta p \approx \ln(r)$ , with  $r$  begin the distance to the well).

This justifies the chosen approximation to use the temperature of the injected water near the bottom of the well for calculating the viscosity.

### 12.4 Depleted reservoir and negative pressures

Negative pressures in the upper part of the (production) well may be observed in the base case details file, and possibly in the result table (lower right hand side 'pressure at heat exchanger'). In most cases this is caused by the difference between the reservoir pressure ( $HP_{res}$ ) and the (static) pressure of the water column in the (production) well at reservoir level (bottom hole pressure BHP). If negative pressures result from a scenario, a popup will be shown (Figure 14), but the calculation will be finished normally.

The density and hence the static pressure of the water column in the well is determined by the salinity of the reservoir brine, which is constant over the entire well trajectory. In the subsurface it is assumed that the salinity increases linearly with depth, from 0 ppm at surface level, to the specified salinity at reservoir level (see equation on page 35). Therefore the reservoir pressure is lower than the static pressure in the water column. In reality, at atmospheric well head pressure, the water will flow back from the producer into the reservoir, and the water level in the producer will drop below surface, if the pump is switched off and the producer is not connected to the injector.

DoubletCalc assumes a closed doublet system with balanced pressures. The software will return negative pressures in case the pump pressure is specified too low to overcome the difference in reservoir pressure and the static pressure in the water column. This may also be the case if the pump depth is set too shallow in the production well. Because a negative pressure is physically impossible, this means that the water cannot be pumped from producer to injector.

In order to prevent negative pressures in the well, it is advised to increase the pump pressure iteratively until the DoubletCalc output shows a well head pressure of at least 1 bar.

For a depleted reservoir, in practice, the pump pressure will have to be increased considerably to prevent negative pressures and to enable the extraction of water from the reservoir. Similarly, the injection pressures can be very low for a depleted reservoir. The flow rates will be high. Another possibility to prevent negative pressures, is to increase the friction in the injector by reducing the casing diameter (pinching).

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## 14 Signature

Utrecht, <datum>

TNO

<naam afdelingshoofd>

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# A Example of the 'base case details' file

Part 1: initial hydrostatic aquifer properties @producer:

Doublet Calculator 1.4 Base Case Details						
=== HYDROSTATIC AQUIFER PROPERTIES @PRODUCER ===						
Z(m)	P(bar)		T(degC)	S(ppm)	Density(k)	Viscosity(Pa s)
	0	1	10	0	998.9188	0.001251
-49.5926	5.861976	11.53737	2375	1000.507	0.001211	
-99.1852	10.73165	13.07474	4751	1002.084	0.001173	
-148.778	15.60896	14.61211	7127	1003.649	0.001138	
-198.37	20.49385	16.14948	9502	1005.202	0.001105	
-247.963	25.38627	17.68685	11878	1006.742	0.001074	
-297.556	30.28615	19.22422	14254	1008.271	0.001045	
-347.148	35.19343	20.76159	16629	1009.787	0.001018	
-396.741	40.10806	22.29896	19005	1011.291	9.93E-04	
-446.333	45.02998	23.83633	21381	1012.783	9.69E-04	
-495.926	49.95911	25.3737	23756	1014.262	9.46E-04	
-545.519	54.89541	26.91107	26132	1015.729	9.25E-04	
-595.111	59.83882	28.44844	28508	1017.183	9.04E-04	
-644.704	64.78926	29.98581	30884	1018.624	8.85E-04	
-694.296	69.74668	31.52318	33259	1020.053	8.66E-04	
-743.889	74.71102	33.06056	35635	1021.469	8.49E-04	
-793.481	79.68222	34.59793	38011	1022.872	8.32E-04	
-843.074	84.66021	36.1353	40386	1024.262	8.16E-04	
-892.667	89.64492	37.67267	42762	1025.64	8.00E-04	
-942.259	94.63631	39.21004	45138	1027.004	7.85E-04	
-991.852	99.6343	40.74741	47513	1028.355	7.71E-04	
-1041.44	104.6388	42.28478	49889	1029.694	7.58E-04	
-1087.95	109.3376	43.7264	52117	1030.937	7.45E-04	
-1132.05	113.7987	45.09354	54229	1032.105	7.34E-04	
-1176.15	118.2649	46.46068	56342	1033.263	7.23E-04	
-1220.25	122.7361	47.82781	58455	1034.411	7.12E-04	
-1264.35	127.2123	49.19495	60567	1035.549	7.02E-04	
-1308.45	131.6933	50.56209	62680	1036.676	6.92E-04	
-1352.56	136.1792	51.92922	64793	1037.793	6.83E-04	
-1396.66	140.6699	53.29636	66905	1038.899	6.73E-04	
-1440.76	145.1653	54.6635	69018	1039.995	6.64E-04	
-1484.86	149.6655	56.03063	71130	1041.081	6.55E-04	
-1528.96	154.1703	57.39777	73243	1042.157	6.47E-04	
-1573.06	158.6798	58.76491	75356	1043.222	6.38E-04	
-1617.16	163.1939	60.13204	77468	1044.277	6.30E-04	
-1661.26	167.7125	61.49918	79581	1045.322	6.22E-04	
-1705.37	172.2356	62.86631	81694	1046.357	6.14E-04	
-1749.47	176.7631	64.23345	83806	1047.381	6.07E-04	
-1793.57	181.2951	65.60059	85919	1048.395	5.99E-04	
-1837.71	185.8353	66.96891	88033	1049.4	5.92E-04	
-1882.26	190.4226	68.35008	90168	1050.404	5.85E-04	
-1926.81	195.0142	69.73124	92302	1051.398	5.78E-04	
-1971.37	199.6102	71.11241	94436	1052.382	5.71E-04	
-2015.92	204.2104	72.49358	96571	1053.356	5.64E-04	
-2060.48	208.8149	73.87474	98705	1054.319	5.58E-04	
-2105.03	213.4235	75.25591	100839	1055.273	5.52E-04	
-2149.58	218.0363	76.63708	102974	1056.216	5.45E-04	
-2194.14	222.6532	78.01824	105108	1057.15	5.39E-04	
-2238.69	227.2741	79.39941	107242	1058.073	5.33E-04	
-2283.24	231.8991	80.78058	109376	1058.987	5.27E-04	
-2327.8	236.528	82.16174	111511	1059.891	5.22E-04	
-2372.35	241.1609	83.54291	113645	1060.785	5.16E-04	
-2416.91	245.7977	84.92408	115779	1061.67	5.10E-04	
-2461.46	250.4383	86.30525	117914	1062.545	5.05E-04	
-2506.01	255.0826	87.68641	120048	1063.411	5.00E-04	

Part 2: initial hydrostatic aquifer properties @injector:

=== HYDROSTATIC AQUIFER PROPERTIES @INJECTOR ===					
Z(m)	P(bar)	T(degC)	S(ppm)	Density(k)	Viscosity(Pa s)
0	1	10	0	998.9188	0.001251
-49.9057	5.892693	11.54708	2390	1000.517	0.001211
-99.8113	10.79318	13.09415	4781	1002.104	0.001172
-149.717	15.7014	14.64123	7172	1003.678	0.001137
-199.623	20.6173	16.1883	9562	1005.241	0.001104
-249.528	25.54082	17.73538	11953	1006.791	0.001073
-299.434	30.47189	19.28245	14344	1008.329	0.001044
-349.34	35.41045	20.82953	16734	1009.854	0.001017
-399.245	40.35646	22.3766	19125	1011.367	9.91E-04
-449.151	45.30983	23.92368	21516	1012.867	9.67E-04
-499.057	50.27052	25.47075	23906	1014.355	9.45E-04
-548.962	55.23846	27.01783	26297	1015.83	9.23E-04
-598.868	60.21358	28.56491	28688	1017.293	9.03E-04
-648.774	65.19584	30.11198	31078	1018.742	8.83E-04
-698.679	70.18515	31.65906	33469	1020.179	8.65E-04
-748.585	75.18146	33.20613	35860	1021.602	8.47E-04
-798.491	80.18471	34.75321	38251	1023.013	8.30E-04
-848.396	85.19483	36.30028	40641	1024.411	8.14E-04
-898.302	90.21176	37.84736	43032	1025.795	7.99E-04
-948.208	95.23543	39.39443	45423	1027.167	7.84E-04
-998.113	100.2658	40.94151	47813	1028.525	7.69E-04
-1048.02	105.3028	42.48858	50204	1029.87	7.56E-04
-1093.63	109.9115	43.90239	52389	1031.088	7.44E-04
-1138	114.4016	45.27815	54515	1032.262	7.32E-04
-1182.38	118.8966	46.65392	56641	1033.426	7.22E-04
-1226.76	123.3968	48.02969	58767	1034.58	7.11E-04
-1271.14	127.9019	49.40545	60893	1035.723	7.01E-04
-1315.52	132.412	50.78122	63019	1036.856	6.91E-04
-1359.9	136.927	52.15699	65145	1037.978	6.81E-04
-1404.28	141.4468	53.53276	67271	1039.089	6.72E-04
-1448.66	145.9715	54.90852	69396	1040.191	6.62E-04
-1493.04	150.501	56.28429	71522	1041.282	6.54E-04
-1537.42	155.0351	57.66006	73648	1042.362	6.45E-04
-1581.8	159.574	59.03582	75774	1043.432	6.37E-04
-1626.18	164.1174	60.41159	77900	1044.492	6.28E-04
-1670.56	168.6655	61.78736	80026	1045.541	6.20E-04
-1714.94	173.2181	63.16312	82152	1046.58	6.13E-04
-1759.32	177.7752	64.53889	84278	1047.608	6.05E-04
-1803.7	182.3368	65.91466	86404	1048.627	5.98E-04
-1848.06	186.9008	67.28984	88529	1049.635	5.90E-04
-1892.38	191.4652	68.66382	90652	1050.631	5.83E-04
-1936.7	196.0339	70.03779	92776	1051.618	5.76E-04
-1981.02	200.6069	71.41177	94899	1052.594	5.70E-04
-2025.35	205.1841	72.78574	97022	1053.56	5.63E-04
-2069.67	209.7654	74.15972	99145	1054.517	5.57E-04
-2113.99	214.3509	75.5337	101268	1055.463	5.50E-04
-2158.31	218.9405	76.90767	103392	1056.4	5.44E-04
-2202.63	223.5341	78.28165	105515	1057.326	5.38E-04
-2246.96	228.1318	79.65562	107638	1058.243	5.32E-04
-2291.28	232.7334	81.0296	109761	1059.151	5.26E-04
-2335.6	237.3389	82.40358	111884	1060.048	5.21E-04
-2379.92	241.9484	83.77755	114008	1060.936	5.15E-04
-2424.24	246.5616	85.15153	116131	1061.815	5.10E-04
-2468.56	251.1787	86.5255	118254	1062.684	5.04E-04

Part 3: parameters calculated per 'calculation length' section in producer:

=== PRODUCER ===															
iN	Segment	L(m)	Z(m)	Angle (de	Inner dia	Roughnes	P(bar)	T(degC)	S(ppm)	Density(k	Viscosity	Qvol(m3/	dPGrav(b	dPVisc(b	dPpump(bar)
0		0	0				16.35055	86.50769	119999	1056.001	5.06E-04	-146.755			
1	1	49.59259	-49.5926	0	5	1.2	21.81337	86.60029	119999	1056.138	5.05E-04	-146.736	5.136058	0.326759	0
2	1	99.18519	-99.1852	0	5	1.2	27.27679	86.69111	119999	1056.276	5.05E-04	-146.717	5.136726	0.326699	0
3	1	148.7778	-148.778	0	5	1.2	32.74083	86.78016	119999	1056.414	5.04E-04	-146.698	5.137397	0.326639	0
4	1	198.3704	-198.37	0	5	1.2	38.20548	86.86744	119999	1056.553	5.04E-04	-146.679	5.138071	0.326579	0
5	1	247.963	-247.963	0	5	1.2	43.67075	86.95294	119999	1056.692	5.03E-04	-146.659	5.138749	0.326519	0
6	1	297.5556	-297.556	0	5	1.2	49.13664	87.03667	119999	1056.833	5.03E-04	-146.64	5.13943	0.326459	0
7	1	347.1481	-347.148	0	5	1.2	54.60315	87.11861	119999	1056.974	5.03E-04	-146.62	5.140114	0.3264	0
8	1	396.7407	-396.741	0	5	1.2	60.07029	87.19877	119999	1057.116	5.02E-04	-146.6	5.140802	0.326341	0
9	1	446.3333	-446.333	0	5	1.2	65.53807	87.27715	119999	1057.258	5.02E-04	-146.581	5.141494	0.326281	0
10	1	495.9259	-495.926	0	5	1.2	71.00648	87.35374	119999	1057.401	5.01E-04	-146.561	5.142188	0.326222	0
11	1	545.5185	-545.519	0	11.76914	1.2	36.15039	87.44253	119999	1056.141	5.01E-04	-146.736	5.139471	0.004441	-40
12	2	595.1111	-595.111	0	12.375	1.2	41.29057	87.53023	119999	1056.268	5.00E-04	-146.718	5.136714	0.003468	0
13	2	644.7037	-644.704	0	12.375	1.2	46.43137	87.6158	119999	1056.395	5.00E-04	-146.7	5.137333	0.003467	0
14	2	694.2963	-694.296	0	12.375	1.2	51.5728	87.69923	119999	1056.524	4.99E-04	-146.683	5.137957	0.003466	0
15	2	743.8889	-743.889	0	12.375	1.2	56.71485	87.78053	119999	1056.654	4.99E-04	-146.665	5.138585	0.003465	0
16	2	793.4815	-793.481	0	12.375	1.2	61.85753	87.85968	119999	1056.784	4.99E-04	-146.646	5.139218	0.003464	0
17	2	843.0741	-843.074	0	12.375	1.2	67.00085	87.9367	119999	1056.916	4.98E-04	-146.628	5.139856	0.003463	0
18	2	892.6667	-892.667	0	12.375	1.2	72.14481	88.01157	119999	1057.049	4.98E-04	-146.61	5.140498	0.003463	0
19	2	942.2593	-942.259	0	12.375	1.2	77.28942	88.08429	119999	1057.182	4.97E-04	-146.591	5.141146	0.003462	0
20	2	991.8519	-991.852	0	12.375	1.2	82.43467	88.15485	119999	1057.317	4.97E-04	-146.573	5.141798	0.003461	0
21	2	1041.444	-1041.44	0	12.375	1.2	87.58059	88.22327	119999	1057.452	4.97E-04	-146.554	5.142454	0.00346	0
22	2	1091.037	-1087.95	20.32742	9.574402	1.2	92.41572	88.28591	119999	1057.58	4.96E-04	-146.536	4.822798	0.012338	0
23	3	1140.63	-1132.05	27.21842	8.625	1.2	97.01063	88.34536	119999	1057.702	4.96E-04	-146.519	4.574137	0.020769	0
24	3	1190.222	-1176.15	27.21842	8.625	1.2	101.6061	88.40305	119999	1057.824	4.96E-04	-146.502	4.574664	0.020765	0
25	3	1239.815	-1220.25	27.21842	8.625	1.2	106.202	88.45895	119999	1057.947	4.95E-04	-146.485	4.575195	0.020761	0
26	3	1289.407	-1264.35	27.21842	8.625	1.2	110.7985	88.51308	119999	1058.071	4.95E-04	-146.468	4.575729	0.020758	0
27	3	1339	-1308.45	27.21842	8.625	1.2	115.3955	88.56543	119999	1058.196	4.95E-04	-146.451	4.576267	0.020754	0
28	3	1388.593	-1352.56	27.21842	8.625	1.2	119.9931	88.61599	119999	1058.322	4.95E-04	-146.433	4.576809	0.02075	0
29	3	1438.185	-1396.66	27.21842	8.625	1.2	124.5912	88.66477	119999	1058.448	4.94E-04	-146.416	4.577354	0.020747	0
30	3	1487.778	-1440.76	27.21842	8.625	1.2	129.1898	88.71176	119999	1058.576	4.94E-04	-146.398	4.577903	0.020743	0
31	3	1537.37	-1484.86	27.21842	8.625	1.2	133.789	88.75697	119999	1058.704	4.94E-04	-146.381	4.578456	0.02074	0
32	3	1586.963	-1528.96	27.21842	8.625	1.2	138.3888	88.80038	119999	1058.833	4.94E-04	-146.363	4.579012	0.020736	0
33	3	1636.556	-1573.06	27.21842	8.625	1.2	142.9891	88.84199	119999	1058.963	4.94E-04	-146.345	4.579572	0.020733	0
34	3	1686.148	-1617.16	27.21842	8.625	1.2	147.5899	88.88181	119999	1059.094	4.93E-04	-146.327	4.580136	0.020729	0
35	3	1735.741	-1661.26	27.21842	8.625	1.2	152.1914	88.91983	119999	1059.225	4.93E-04	-146.309	4.580704	0.020726	0
36	3	1785.333	-1705.37	27.21842	8.625	1.2	156.7934	88.95605	119999	1059.358	4.93E-04	-146.29	4.581275	0.020722	0
37	3	1834.926	-1749.47	27.21842	8.625	1.2	161.3959	88.99047	119999	1059.491	4.93E-04	-146.272	4.58185	0.020719	0
38	3	1884.519	-1793.57	27.21842	8.625	1.2	165.9991	89.02308	119999	1059.626	4.93E-04	-146.253	4.582429	0.020716	0
39	3	1934.111	-1837.71	27.12172	8.459204	1.2	170.6089	89.05376	119999	1059.761	4.92E-04	-146.235	4.586984	0.022824	0
40	4	1983.704	-1882.26	26.05201	6.625	1.2	175.3175	89.08125	119999	1059.902	4.92E-04	-146.215	4.630649	0.077953	0
41	4	2033.296	-1926.81	26.05201	6.625	1.2	180.0267	89.10701	119999	1060.043	4.92E-04	-146.196	4.631265	0.077941	0
42	4	2082.889	-1971.37	26.05201	6.625	1.2	184.7365	89.13102	119999	1060.185	4.92E-04	-146.176	4.631884	0.077929	0
43	4	2132.481	-2015.92	26.05201	6.625	1.2	189.4469	89.15329	119999	1060.328	4.92E-04	-146.156	4.632507	0.077917	0
44	4	2182.074	-2060.48	26.05201	6.625	1.2	194.158	89.17382	119999	1060.472	4.92E-04	-146.137	4.633133	0.077905	0
45	4	2231.667	-2105.03	26.05201	6.625	1.2	198.8696	89.19259	119999	1060.616	4.92E-04	-146.117	4.633763	0.077894	0
46	4	2281.259	-2149.58	26.05201	6.625	1.2	203.5819	89.20962	119999	1060.762	4.92E-04	-146.097	4.634397	0.077882	0
47	4	2330.852	-2194.14	26.05201	6.625	1.2	208.2948	89.22489	119999	1060.908	4.92E-04	-146.076	4.635035	0.07787	0
48	4	2380.444	-2238.69	26.05201	6.625	1.2	213.0084	89.2384	119999	1061.055	4.91E-04	-146.056	4.635676	0.077858	0
49	4	2430.037	-2283.24	26.05201	6.625	1.2	217.7225	89.25016	119999	1061.203	4.91E-04	-146.036	4.636321	0.077847	0
50	4	2479.63	-2327.8	26.05201	6.625	1.2	222.4373	89.26015	119999	1061.352	4.91E-04	-146.015	4.63697	0.077835	0
51	4	2529.222	-2372.35	26.05201	6.625	1.2	227.1528	89.26839	119999	1061.502	4.91E-04	-145.995	4.637623	0.077824	0
52	4	2578.815	-2416.91	26.05201	6.625	1.2	231.8689	89.27486	119999	1061.653	4.91E-04	-145.974	4.638279	0.077812	0
53	4	2628.407	-2461.46	26.05201	6.625	1.2	236.5856	89.27956	119999	1061.804	4.91E-04	-145.953	4.638939	0.077801	0
54	4	2678	-2506.01	26.05201	6.625	1.2	241.303	89.2825	119999	1061.957	4.91E-04	-145.932	4.639603	0.077789	0
total/aver	4	2678	-2506.01	16.18007	8.165329	1.2	224.9524	2.774806	119999	1058.505	4.96E-04	-146.408	260.1134	4.839067	-40

Part 4: parameters calculated per 'calculation length' section in injector:

=== INJECTOR ===															
IN	Segment	L(m)	Z(m)	Angle (de)	Inner dia	Roughnes	P(bar)	T(degC)	S(ppm)	Density(k	Viscosity	Qvol(m3)	dPGrav(b	dPVisc(b	dPpump(bar)
0		0	0				16.35055	35	119999	1079.509	9.73E-04	143.5594			
1	1	49.90566	-49.9057	0	5	1.2	21.29768	34.9699	119999	1079.72	9.74E-04	143.5313	5.283714	-0.33659	0
2	1	99.81132	-99.8113	0	12.36106	1.2	26.57867	34.93612	119999	1079.946	9.74E-04	143.5013	5.284783	-0.00379	0
3	2	149.717	-149.717	0	12.375	1.2	31.86079	34.90469	119999	1080.171	9.75E-04	143.4715	5.285885	-0.00377	0
4	2	199.6226	-199.623	0	12.375	1.2	37.14401	34.87562	119999	1080.395	9.75E-04	143.4417	5.286983	-0.00377	0
5	2	249.5283	-249.528	0	12.375	1.2	42.42832	34.84889	119999	1080.618	9.76E-04	143.4121	5.288076	-0.00376	0
6	2	299.434	-299.434	0	12.375	1.2	47.71372	34.82452	119999	1080.84	9.76E-04	143.3827	5.289165	-0.00376	0
7	2	349.3396	-349.34	0	12.375	1.2	53.00021	34.80248	119999	1081.061	9.76E-04	143.3533	5.29025	-0.00376	0
8	2	399.2453	-399.245	0	12.375	1.2	58.28778	34.78279	119999	1081.281	9.77E-04	143.3241	5.291331	-0.00376	0
9	2	449.1509	-449.151	0	12.375	1.2	63.57642	34.76544	119999	1081.501	9.77E-04	143.295	5.292406	-0.00376	0
10	2	499.0566	-499.057	0	12.375	1.2	68.86614	34.75042	119999	1081.719	9.77E-04	143.2661	5.293478	-0.00376	0
11	2	548.9623	-548.962	0	12.375	1.2	74.15692	34.73773	119999	1081.937	9.77E-04	143.2373	5.294545	-0.00376	0
12	2	598.8679	-598.868	0	12.375	1.2	79.44877	34.72737	119999	1082.153	9.77E-04	143.2086	5.295607	-0.00376	0
13	2	648.7736	-648.774	0	12.375	1.2	84.74168	34.71933	119999	1082.369	9.78E-04	143.1801	5.296665	-0.00376	0
14	2	698.6792	-698.679	0	12.375	1.2	90.03563	34.71361	119999	1082.584	9.78E-04	143.1517	5.297718	-0.00376	0
15	2	748.5849	-748.585	0	12.375	1.2	95.33064	34.7102	119999	1082.797	9.78E-04	143.1234	5.298767	-0.00376	0
16	2	798.4906	-798.491	0	12.375	1.2	100.6267	34.70912	119999	1083.01	9.78E-04	143.0953	5.299811	-0.00376	0
17	2	848.3962	-848.396	0	12.375	1.2	105.9238	34.71033	119999	1083.222	9.78E-04	143.0673	5.30085	-0.00376	0
18	2	898.3019	-898.302	0	12.375	1.2	111.2219	34.71386	119999	1083.433	9.78E-04	143.0394	5.301885	-0.00376	0
19	2	948.2075	-948.208	0	12.375	1.2	116.5211	34.71969	119999	1083.643	9.78E-04	143.0117	5.302915	-0.00376	0
20	2	998.1132	-998.113	0	12.375	1.2	121.8213	34.72782	119999	1083.852	9.77E-04	142.9842	5.30394	-0.00375	0
21	2	1048.019	-1048.02	0	12.375	1.2	127.1225	34.73824	119999	1084.06	9.77E-04	142.9567	5.30496	-0.00375	0
22	2	1097.925	-1093.63	23.95632	9.074433	1.2	131.9541	34.75002	119999	1084.249	9.77E-04	142.9319	4.848853	-0.01718	0
23	3	1147.83	-1138	27.21842	8.625	1.2	136.6513	34.76359	119999	1084.431	9.77E-04	142.9078	4.719209	-0.02207	0
24	3	1197.736	-1182.38	27.21842	8.625	1.2	141.3492	34.77903	119999	1084.613	9.77E-04	142.8839	4.720002	-0.02207	0
25	3	1247.642	-1226.76	27.21842	8.625	1.2	146.0479	34.79634	119999	1084.793	9.76E-04	142.8601	4.72079	-0.02206	0
26	3	1297.547	-1271.14	27.21842	8.625	1.2	150.7475	34.81553	119999	1084.973	9.76E-04	142.8364	4.721575	-0.02206	0
27	3	1347.453	-1315.52	27.21842	8.625	1.2	155.4478	34.83659	119999	1085.153	9.76E-04	142.8128	4.722357	-0.02206	0
28	3	1397.358	-1359.9	27.21842	8.625	1.2	160.1488	34.85951	119999	1085.331	9.76E-04	142.7893	4.723134	-0.02205	0
29	3	1447.264	-1404.28	27.21842	8.625	1.2	164.8507	34.8843	119999	1085.508	9.75E-04	142.766	4.723909	-0.02205	0
30	3	1497.17	-1448.66	27.21842	8.625	1.2	169.5533	34.91096	119999	1085.685	9.75E-04	142.7428	4.724679	-0.02204	0
31	3	1547.075	-1493.04	27.21842	8.625	1.2	174.2567	34.93947	119999	1085.861	9.74E-04	142.7197	4.725446	-0.02204	0
32	3	1596.981	-1537.42	27.21842	8.625	1.2	178.9609	34.96983	119999	1086.036	9.74E-04	142.6967	4.726209	-0.02203	0
33	3	1646.887	-1581.8	27.21842	8.625	1.2	183.6659	35.00206	119999	1086.21	9.73E-04	142.6738	4.726969	-0.02203	0
34	3	1696.792	-1626.18	27.21842	8.625	1.2	188.3716	35.03613	119999	1086.383	9.73E-04	142.6511	4.727724	-0.02202	0
35	3	1746.698	-1670.56	27.21842	8.625	1.2	193.078	35.07205	119999	1086.555	9.72E-04	142.6284	4.728476	-0.02202	0
36	3	1796.604	-1714.94	27.21842	8.625	1.2	197.7852	35.10982	119999	1086.727	9.72E-04	142.6059	4.729224	-0.02201	0
37	3	1846.509	-1759.32	27.21842	8.625	1.2	202.4932	35.14943	119999	1086.897	9.71E-04	142.5835	4.729969	-0.02201	0
38	3	1896.415	-1803.7	27.21842	8.625	1.2	207.2019	35.19089	119999	1087.067	9.71E-04	142.5613	4.730709	-0.022	0
39	3	1946.321	-1848.06	27.26572	7.970936	1.2	211.8989	35.23348	119999	1087.236	9.70E-04	142.5392	4.729434	-0.03249	0
40	4	1996.226	-1892.38	27.36306	6.625	1.2	216.5434	35.27631	119999	1087.402	9.69E-04	142.5174	4.726014	-0.08144	0
41	4	2046.132	-1936.7	27.36306	6.625	1.2	221.1887	35.32087	119999	1087.567	9.69E-04	142.4957	4.726734	-0.08142	0
42	4	2096.038	-1981.02	27.36306	6.625	1.2	225.8348	35.36717	119999	1087.732	9.68E-04	142.4742	4.727451	-0.0814	0
43	4	2145.943	-2025.35	27.36306	6.625	1.2	230.4816	35.4152	119999	1087.895	9.67E-04	142.4528	4.728164	-0.08139	0
44	4	2195.849	-2069.67	27.36306	6.625	1.2	235.1291	35.46497	119999	1088.058	9.67E-04	142.4315	4.728873	-0.08137	0
45	4	2245.755	-2113.99	27.36306	6.625	1.2	239.7773	35.51647	119999	1088.22	9.66E-04	142.4103	4.729579	-0.08135	0
46	4	2295.66	-2158.31	27.36306	6.625	1.2	244.4263	35.5697	119999	1088.381	9.65E-04	142.3892	4.73028	-0.08133	0
47	4	2345.566	-2202.63	27.36306	6.625	1.2	249.0759	35.62465	119999	1088.541	9.64E-04	142.3683	4.730978	-0.08131	0
48	4	2395.472	-2246.96	27.36306	6.625	1.2	253.7263	35.68133	119999	1088.7	9.63E-04	142.3475	4.731672	-0.08129	0
49	4	2445.377	-2291.28	27.36306	6.625	1.2	258.3774	35.73973	119999	1088.858	9.63E-04	142.3268	4.732362	-0.08127	0
50	4	2495.283	-2335.6	27.36306	6.625	1.2	263.0292	35.79986	119999	1089.016	9.62E-04	142.3062	4.733048	-0.08125	0
51	4	2545.189	-2379.92	27.36306	6.625	1.2	267.6817	35.86169	119999	1089.172	9.61E-04	142.2858	4.73373	-0.08123	0
52	4	2595.094	-2424.24	27.36306	6.625	1.2	272.3349	35.92525	119999	1089.328	9.60E-04	142.2654	4.734408	-0.08121	0
53	4	2645	-2468.56	27.36306	6.625	1.2	276.9888	35.99051	119999	1089.482	9.59E-04	142.2452	4.735082	-0.08119	0
total/aver	4	2645	-2468.56	16.41131	9.439272	1.2	260.6382	0.990511	119999	1084.85	9.73E-04	142.8537	262.5908	-1.95255	0

## Part 5: pressures and temperatures at specified doublet nodes

=== DOUBLET NODES ===			
Node		P(bar)	T(degC)
1	Aquifer_Prod	255.0826	89.2825
2	Aquifer/Prod_Bottom	241.303	89.2825
5&6	Prod_Top/Entry_HE	16.35055	86.50769
7&9	Exit_HE/Inj_Top	16.35055	35
10	Inj_Bottom/Aquifer	276.9888	35.99051
11	Aquifer_Inj	251.1787	89.2825

## Part 6: base case results, calculated for the specified median values:

=== BASE CASE RESULTS ===			
aquifer kH net (Dm)		21	
mass flow (kg/s)		43.05	
pump volume flow (m <sup>3</sup> /h)		146.6	
required pump power (kW)		267.1	
geothermal power (MW)		8.12	
COP (kW/kW)		30.4	
aquifer pressure at producer (bar)		255.08	
aquifer pressure at injector (bar)		251.18	
pressure difference at producer (bar)		13.78	
pressure difference at injector (bar)		25.81	
aquifer temperature at producer * (°C)		89.28	
temperature at heat exchanger (°C)		86.51	
pressure at heat exchanger (bar)		16.35	

## Part 7: stochastic results, calculated for the specified median values:

=== STOCHASTIC RESULTS ===				
	P90	P50	P10	
aquifer kH net (Dm)	16.31	21.26	32.72	
mass flow (kg/s)	35.15	43.51	57.93	
pump volume flow (m <sup>3</sup> /h)	119.7	148.5	197	
required pump power (kW)	218	270.4	358.8	
geothermal power (MW)	6.36	8.33	11.12	
COP (kW/kW)	28.1	30.5	32.8	
aquifer pressure at producer (bar)	239.98	255.12	270.19	
aquifer pressure at injector (bar)	237.12	251.24	265.32	
pressure difference at producer (bar)	11.97	13.68	14.63	
pressure difference at injector (bar)	22.37	25.7	27.23	
aquifer temperature at producer * (°C)	84.98	89.28	93.64	
temperature at heat exchanger (°C)	82.54	86.58	90.75	
=== end of file ===				



## B Sub-layers in an aquifer

DoubletCalc assumes that the aquifer consists of a single continuous layer. The input data for DoubletCalc can be calculated using the approximation specified below in case the aquifer consists of various sub-layers. Figure 21 shows an example of a complex reservoir.

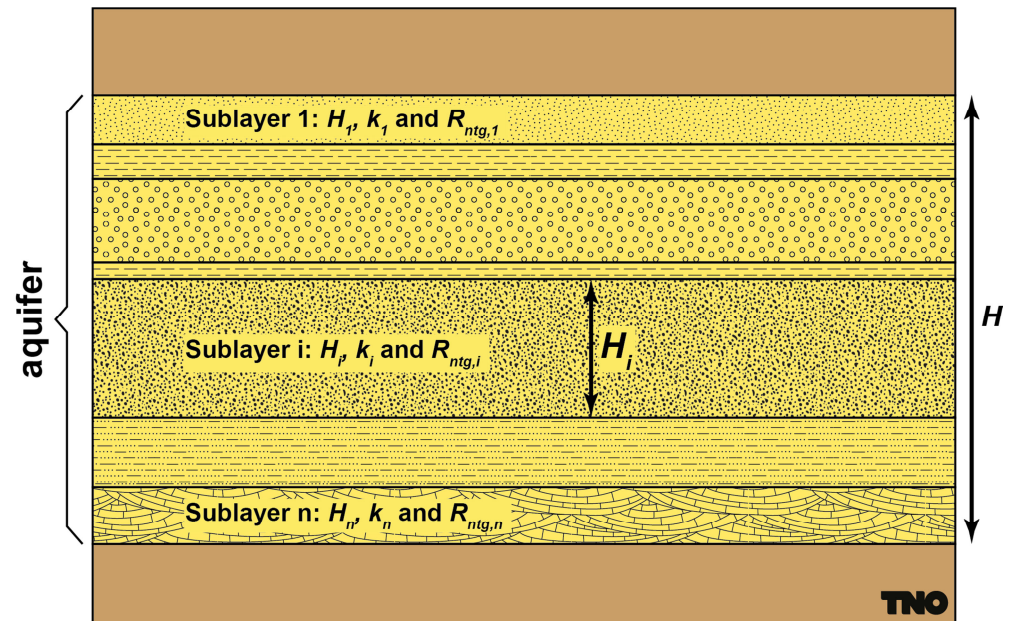


Figure 21 Example of an aquifer consisting of various sub-layers with different characteristics.

The stratification of the aquifer influences the effective average permeability, net height and net-to-gross ratio. These parameters are used for calculating the productivity index  $J$  (see Verruijt 1970, equation 6.5 and Dake 1978):

$$J = \frac{Q}{p_w - p_{aq}} = \frac{2\pi k H R_{ntg}}{\mu \left( \ln \left( \frac{L}{r_w} \right) + S \right)} \dots \dots \dots (1)$$

with:

- $p_w$  = bottom hole pressure
- $p_{aq}$  = initial hydrostatic pressure in the aquifer near the well
- $Q$  =  $Q_m / \rho$  = flow, positive from well to aquifer
- $M$  = water viscosity (function of temperature and salinity)
- $k_{eff}$  = aquifer effective permeability
- $H$  = aquifer gross thickness
- $R_{ntg}$  = aquifer net-to-gross ratio
- $L$  = distance between production and injection well at aquifer level
- $r_w$  = outer diameter of the well in the aquifer (filter)
- $S$  = skin

For a stratified aquifer the factor  $kHR_{ntg}$  in equation 1 should be interpreted as:

$$kHR_{ntg} = \sum_{i=1}^n k_i H_i R_{ntg,i} \dots \dots \dots (2)$$

with  $k_i$ ,  $H_i$ , and  $R_{ntg,i}$  being the permeability, gross thickness and net-to-gross ratio of the individual layers. The assumption is the flow is parallel to the stratification in the

aquifer. The DoubletCalc input parameters  $k$ ,  $H$ , and  $R_{ntg}$  should be chosen in such a way that the product  $kHR_{ntg}$  meet the result of equation 2. The gross aquifer thickness  $H$  is also used for more calculations within the software than just the product of  $k$ ,  $H$  and  $R$ . Therefore the value of  $H$  cannot be changed at will. The parameters net-to-gross and permeability can be changed, as long as the product  $kHR$  remains correct.

The net-to-gross ratio follows from

$$R_{ntg} = \frac{\sum_{i=1}^n H_i R_{ntg,i}}{H} \dots\dots\dots(3)$$

The permeability follows from

$$k = \frac{\sum_{i=1}^n k_i H_i R_{ntg,i}}{H R_{ntg}} \dots\dots\dots(4)$$

The gross thickness  $H$ , the net-to-gross ratio  $R_{ntg}$  (equation 3) and the permeability  $k$  (equation 4) are entered into the DoubletCalc input screen.



## C Explanation of characters and symbols

The units given below are in SI. The parameters in the DoubletCalc input and output screens are entered / reported in 'practical' units, for example milli-Darcy for permeability, ppm for salinity and °C for temperature.

Internally, DoubletCalc uses SI units except for empirical functions which as used as published in literature.

### English

$c_p$	heat capacity (J/(kg·K))
$CoP$	Coefficient of Performance
$d$	depth, positive downward from surface level (m)
$d_{top}$	depth to top aquifer (m)
$D$	tubing / casing diameter (m)
$f$	friction number
$g$	gravitational acceleration 9.80665 m/s <sup>2</sup>
$H$	aquifer thickness, measured perpendicular to the strata (m)
$k$	permeability (m <sup>2</sup> )
$k_t$	thermal conductivity (W/(m·K))
$l$	length along tubing / casing (m)
$L$	distance production – injection well at aquifer level (m)
$p$	pressure (Pa)
$P$	power (W)
$q_w$	heat exchange well - surroundings (W/m)
$Q_v$	(volume) flow (m <sup>3</sup> /s)
$Q_m$	mass flow (kg/s)
$r$	radius of tubing / casing (m)
$R_e$	Reynolds number
$R_{ntg}$	net-to-gross ratio
$s$	salinity (salt content of aquifer brine) (weight fraction, ppm)
$S$	skin
$t$	time (s)
$T$	temperature(°K)
$v$	average water velocity in the tubing (m/s)
$z$	height, measured negative downward from surface level (m)

### Greek

$\alpha_t$	thermal diffusivity (m <sup>2</sup> /s)
$\Delta$	difference
$\varepsilon$	tubing / casing roughness (m)
$\lambda$	geothermal gradient (°K/m)
$\mu$	water viscosity (Pa·s); 1cP = 0.001 Pa·s
$\eta$	pump efficiency (%)
$\rho$	density (kg/m <sup>3</sup> )
$\rho_{fw}$	density fresh water (kg/m <sup>3</sup> )
$\sigma$	$e^\gamma = 1.781072$ , with Euler's constant $\gamma = 0.577216$
$\theta$	well deviation with respect to vertical

### Subscripts

$ani$	anisotropy
$aq$	aquifer
$c$	casing
$db$	pressure balance

<i>g</i>	rock
<i>gt</i>	geothermal
<i>h</i>	hydrostatic
<i>he</i>	heat exchanger
<i>i</i>	injection well
<i>in</i>	(inner-)diameter or radius
<i>k</i>	node number
<i>out</i>	outer-)diameter or radius
<i>p</i>	production well
<i>sur</i>	surface
<i>stat</i>	static (pressure, temperature)
<i>top</i>	top aquifer
<i>w</i>	well