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Productivity Index for GPK2 and GPK4,

Injectivity Index for GPK3

(Test 11jul05)

Interpretation with HEX-B

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1. Aims

On 11th July 2005 the circulation test 11jul05 has been carried out, with GPK3 as the injection borehole and GPK2 and GPK4 as production boreholes. Production was enabled only by buoyancy (thermosyphon). This study interprets the measured values at wellhead/surface for pressure, flow rate and temperature using the PT-profile simulator HEX-B. Specifically:

- Calculation of the pressure at the casing shoe to determine the productivity index PI [l/s/MPa] for GPK2 and GPK4
- Calculation of the injectivity index II [l/s/MPa] for GPK3
- Sensitivity of the measured wellhead temperature, the density (NaCl-molality) of the produced fluid and the initial downhole pressure to the determination of the productivity index PI.

2. Test data

Figure 1 shows the test data from the circulation test.

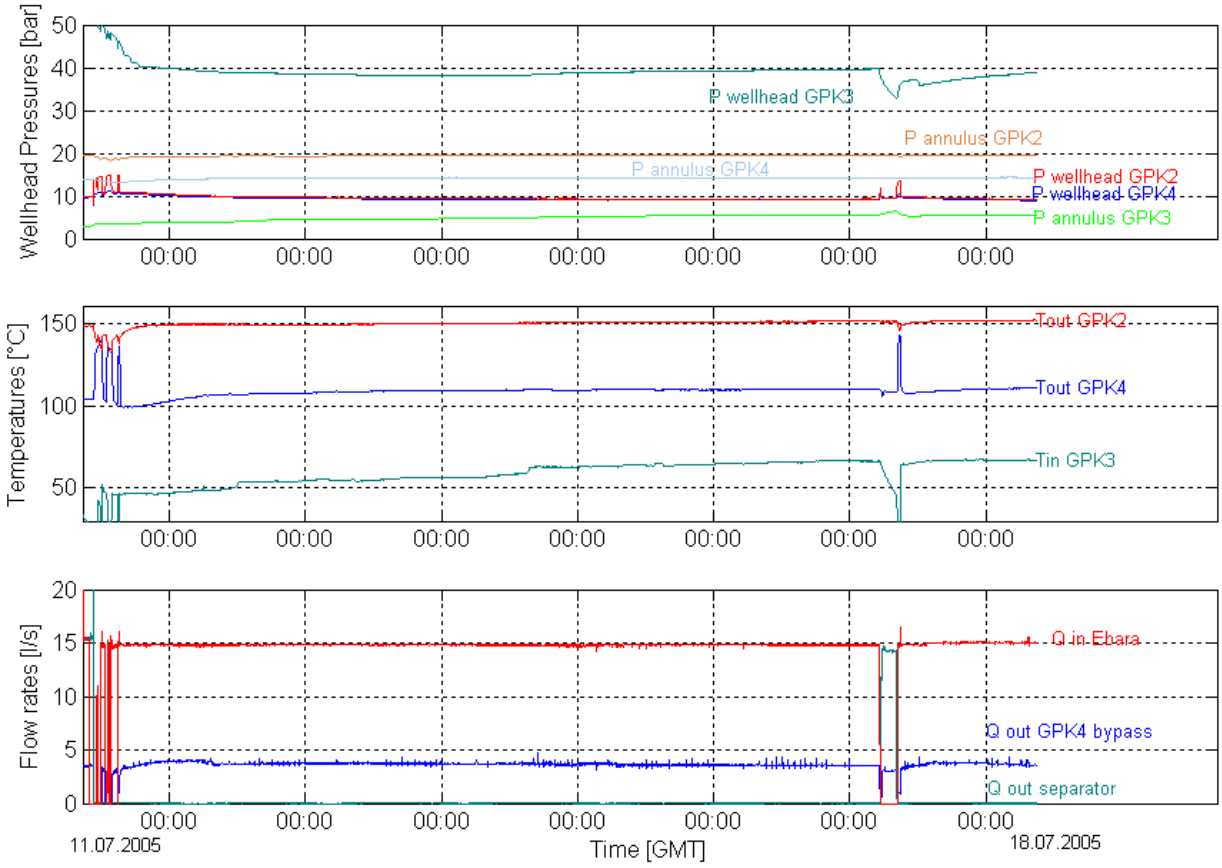

Figure 1: Measured data of circulation test 11jul05.

3. Productivity Index GPK2

3.1. HEX-B model and initial fluid parameters in the well

For the calculation of the conditions during circulation test 11jul05 at the production borehole GPK2, a reduced borehole model was used in HEX-B (see Table 1).

Table 1: Borehole/rock model in HEX-B for GPK2 production (Initial model)

Bore hole parameters						Rock mass parameters	
Depth section MD [m]			Inner radius [m]	Flow rate [% of injection rate]	Average wall roughness [mm]	Thermal conductivity [W/m K]	Specific heat capacity [J/m^{3}K]
Nr	from:	to:					
1	0	1500	0.08	100	0.15	3	2.2 10^6
2	1500	3800	0.08	100	0.15	4	2.2 10^6
3	3800	4430	0.08	100	0.15	3	2.2 10^6

So far, HEX-B neglects effects of the open-hole section under production conditions and considers only the processes along the borehole casing, starting at the casing shoe.

The initial p/T/NaCl-mol conditions are approximated using the initial fluid density ρ_0 = 1065 kg/m^3 (at T= 20°C and atmospheric pressure p_{amb} = 0.1 MPa) for which the water table is assumed at surface (P_{wh}=0). The density of ρ_0 = 1065 kg/m^3 corresponds to a NaCl-molality of 1.935. Taking into account the initial temperature profile and a NaCl-molality of 1.935 (Figure 2) a pressure at the casing shoe (MD 4430 m) of $p_{cs,0}$ = 43.29 MPa results.

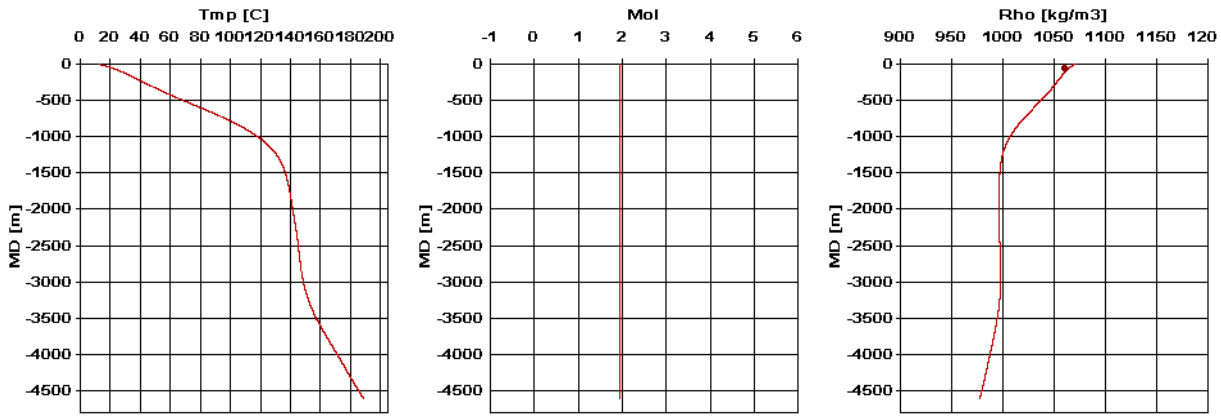

Figure 2: Initial profiles in GPK2 for temperature, NaCl-molality and density.

Note, that the density function ρ (NaCl-mol, T, p) is an approximation (Phillips et al., 1981). The function is subject to possible future recalibration.

3.2. Productivity Index PI

For the determination of the productivity index PI the longterm steady-state pressure at the casing shoe must be known. The simulation with HEX-B used the undisturbed temperature distribution as initial conditions (Figure 3). The density of the produced fluid was measured as ρ_t = 1055 kg/m^3 (at T= 20°C and atmospheric pressure P = 0.1 MPa). This corresponds to a NaCl-molality of 1.525 which has been assumed to be constant in time. A flow of 11.2 l/s and the wellhead pressure (P_wellhead_GPK2 = 0.84 MPa) was measured (Figure 1) which have been used as accurate boundary conditions. Figure 3 shows the profiles at the end of the simulation period (after 500'000 s, green curves) for temperature, NaCl-molality and density.

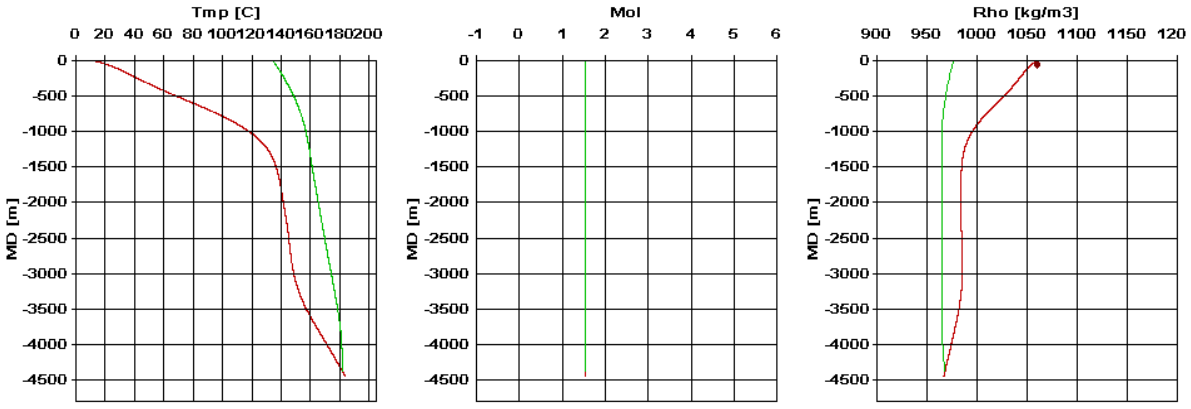

Figure 3: Calculated profiles GPK2 at the end of the simulation period (after 500'000 s, green curves).

Using the initial model (Chapter 3.1) the calculated production temperature T_{out} at GPK2 reaches only 136°C (instead of the measured T_{out} ~150°C, see Figure 1). In order to determine a model for which the calculated value of T_{out} fits the measured value, the borehole model has been varied. Mainly the sensitivity of thermal conductivity of the rock, λ, and the depth of the flow entry in the borehole which increases the production temperature have been tested. Table 2 summarizes the results for a simulation period of nearly 6 days. The downhole pressure at the end of the simulation period p_{cs} is also presented.

The productivity index PI is calculated according to:

$$PI\left[l/s/MPa\right] = \frac{Q}{(p_{cs0} - p_{cs})} \qquad \text{(eq 1)}$$

where:

Flow rate Q	11.2	l/s
Initial downhole pressure at the casing shoe p_{cs0} (4430 m)	43.29	MPa
Pressure at the casing shoe (4430m) at the end of the simulated period p_{cs}	(see Table 2)	

Table 2: Calculated production temperature T_{out} , downhole pressure p_{cs} and productivity index PI for different borehole models

	Fluid Temperature at casing shoe (Equiv. Entry depth [m])	λ [W/mK]	Calculated T_{out}	Calculated p_{cs}	PI [l/s/MPa]
Initial Model	185°C (4430)	3-4-3	136.0	42.13	9.6
Model 1	182°C (4430)	λ_{hom} = 2	148.6	41.92	8.2
Model 2 “standard"	187°C (4600)	λ_{hom} = 2	150.7	42.14	9.8
Model 3	190°C (4700)	λ_{hom} = 2	152.1	42.05	9.1
Model 4	193°C (4800)	λ_{hom} = 2	153.4	41.97	8.5

Model 2 matches the measured T_{out} ~150 °C (Figure 4) best. Hereafter, Model 2 is referenced as “Standard Model” for the following sensitivity tests. It assumes a temperature of 187°C at the casing shoe.

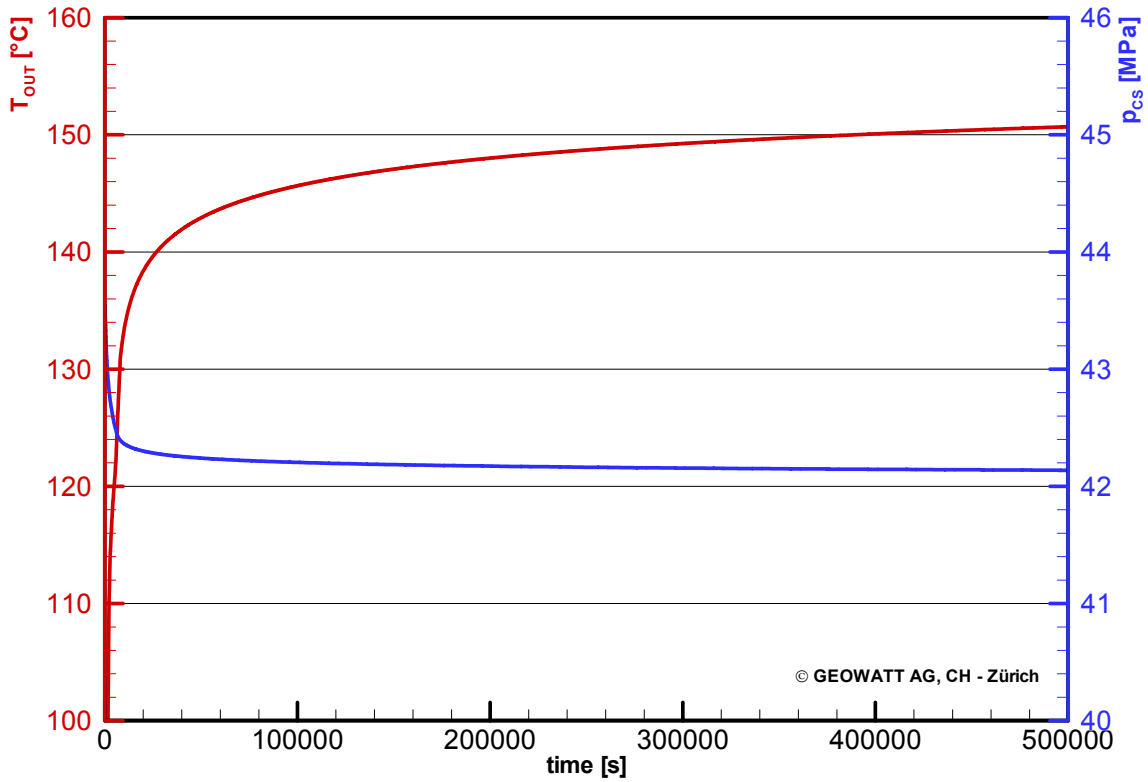

Figure 4: Calculated history of temperature (red line) and downhole pressure p_{cs} @ 4430 m (blue line) for Model 2 (“standard model”) at GPK2.

3.3. Sensitivity of the determination of PI for GPK2

The most critical value for the determination of the PI is the downhole pressure which is directly related to the density profile in the well. The density in the well depends strongly on the profile for temperature and NaCl-molality. Therefore the following assumptions are made:

a) Accurate values:
- Production rate Q
- Wellhead pressures p_{wh}

b) Inaccurate values:
- Wellhead temperature T_{out}
- NaCl-molality
- Initial pressure at the casing shoe $p_{cs,0}$

The uncertainties (of the inaccurate values mentioned above) have been evaluated in the following:

- The sensitivity of the **wellhead temperature T_{out}** is analysed by varying the temperature T_{cs} of the fluid entering at the casing shoe. 4 different initial temperature profiles are assumed for each production borehole, GPK2 and GPK4. The temperature at the casing shoe T_{cs} are 160, 170, 180 and 190 °C (profiles for GPK2 shown in Figure 5).

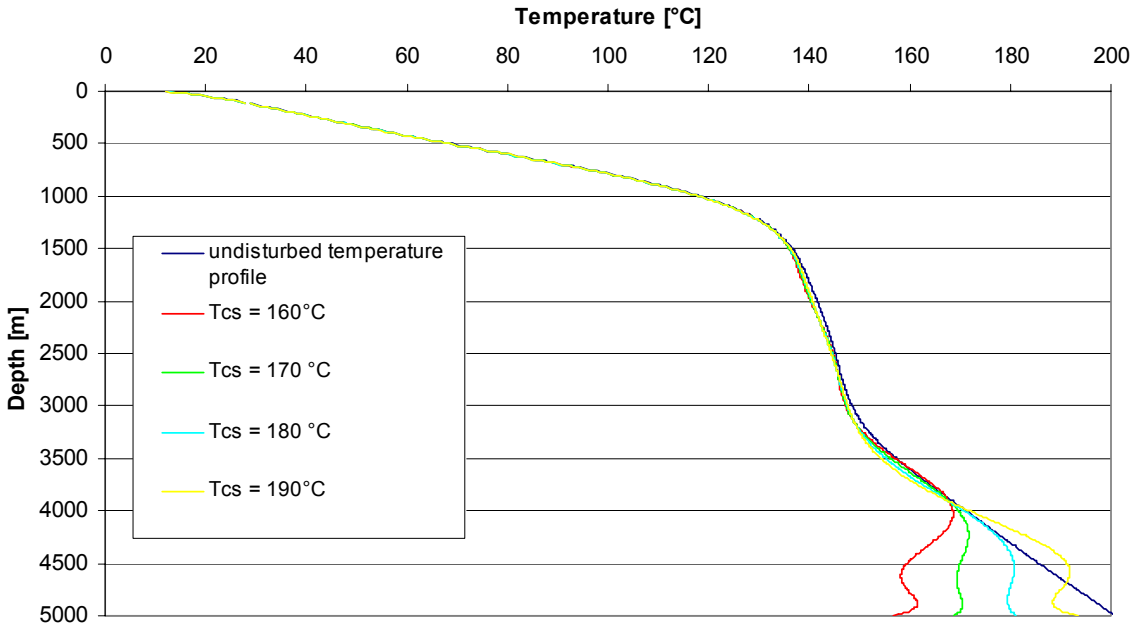

Figure 5: Different initial temperature profiles at the start of circulation

Remarks/Results:

1. A variation of the temperature of the entering fluid by 30 K (160°-190°C) leads to a change in the produced temperature by only 14 K (Figure 6, left),
2. The effect of the temperature to the productivity index PI is eminent (Figure 6 right, Figure 7).
3. This concludes that the accuracy of the temperature measurement at the wellhead is significant.

- The range of the uncertainty of the **NaCl-molality** entering at the casing shoe is chosen ±10%.

  Remarks/Results:

  1. A variation of the NaCl-molality entering at the casing shoe has not a significant effect on the temperature profile in the well (Figure 6, left).
  2. Since the effect of the NaCl-molality to density - and therefore also to the pressure in the well – is eminent, and the difference to the initial pressure in the well is small, the productivity index PI reacts very sensitively (Figure 6 right).

- The range of the uncertainty of **initial pressure at the casing shoe $p_{cs,0}$** is chosen ±1%.

  Remarks/Results:

  1. During a thermosyphon test the change of the downhole pressures are usually small compared to the initial state.
  2. As can be derived from the eq1 the page before small variations in the absolute downhole pressure have strong impacts to the PI. To show this effect, the initial downhole pressure has been varied by ±1% (Figure 7).

The sensitivity of the productivity index PI for GPK2 is summarized in Table 3:

Table 3: Summary of calculated productivity indices for GPK2

PI [l/s/MPa]		**Δmol**		
		0	**+10%**	**-10 %**
T_{cs} [°C]	**undisturbed T-profile**	9.7	12.1	8.1
	160	25.3	48.1	17.0
	170	15.8	22.6	12.0
	180	11.4	14.6	9.2
	190	8.8	10.8	7.4

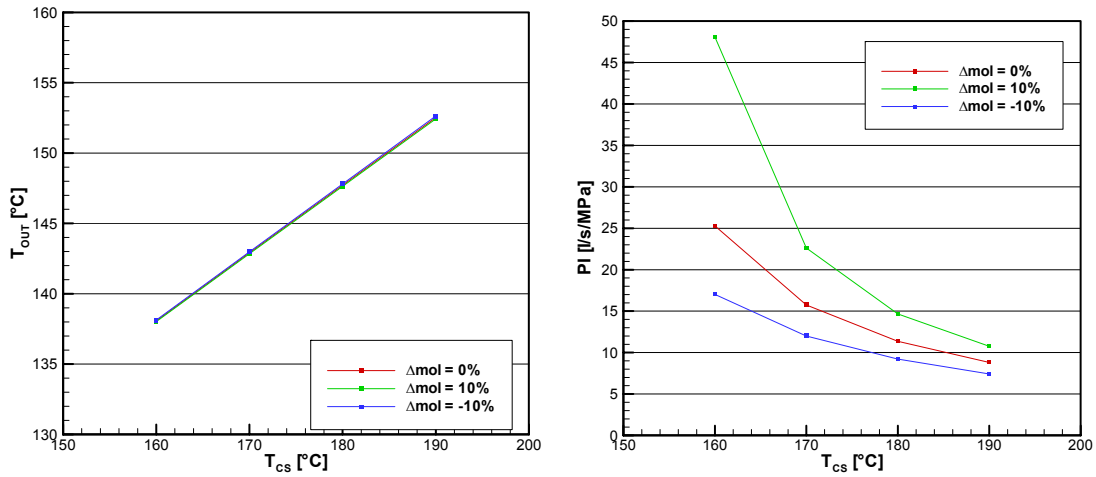

Figure 6: Impact of temperature/NaCl-molality variation on produced temperature (left) and productivity index PI at GPK2

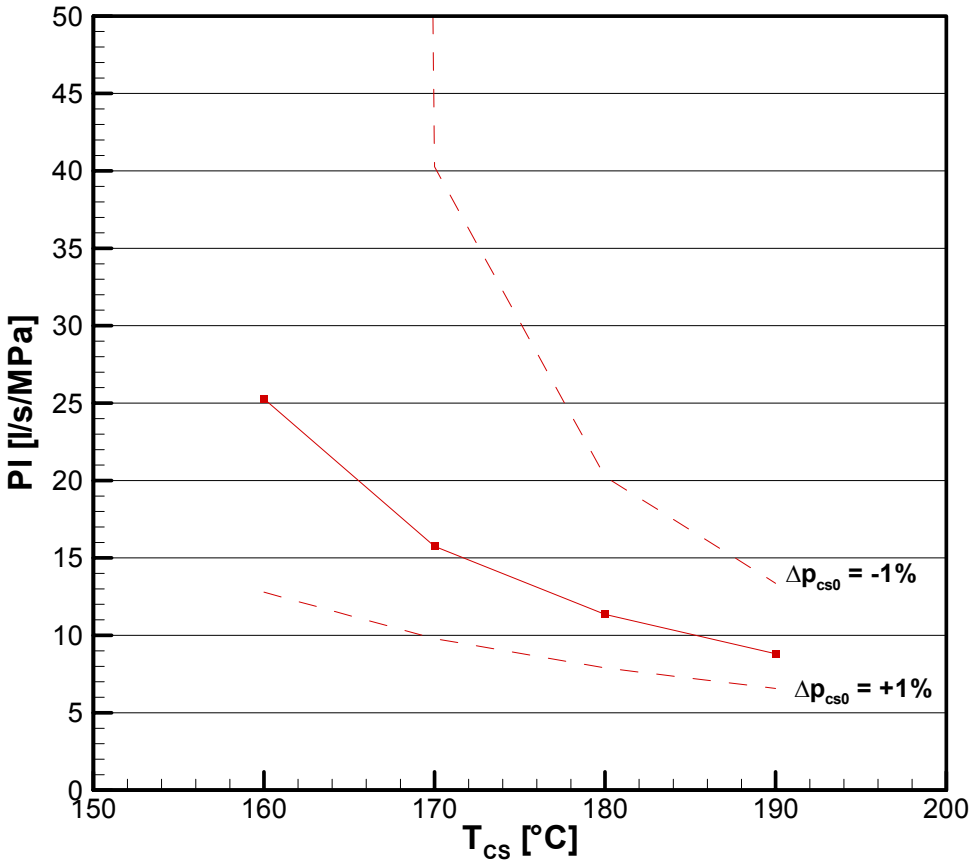

Figure 7: Impact of Δp_{cs0} on productivity index PI at GPK2 compared to Standard Model.

4. Productivity Index GPK4

4.1. HEX-B model and initial fluid parameters in the well

The same procedure as for GPK2 was applied to GPK4. The calculation started with an initial model for the production borehole GPK4 using a reduced borehole geometry ending at the casing shoe (see Table 4).

Table 4: Borehole/rock model in HEX-B for GPK4 production

Bore hole parameters						Rock mass parameters	
Depth section MD [m]			Inner radius [m]	Flow rate [% of injection rate]	Average wall roughness [mm]	Thermal conductivity [W/m K]	Specific heat capacity [J/m^{3}K]
Nr	from:	to:					
1	0	1500	0.11	100	0.15	3	2.2 10^6
2	1500	3800	0.11	100	0.15	4	2.2 10^6
3	3800	4756	0.11	100	0.15	3	2.2 10^6

Again, the initial density of ρ_0 = 1065 kg/m^3 (at 20 °C / 0.1 MPa) and the corresponding NaCl-molality mol_0 = 1.935 were used (Figure 8). An initial downhole pressure at casing shoe p_{cs0} = 44.36 MPa is obtained for GPK4.

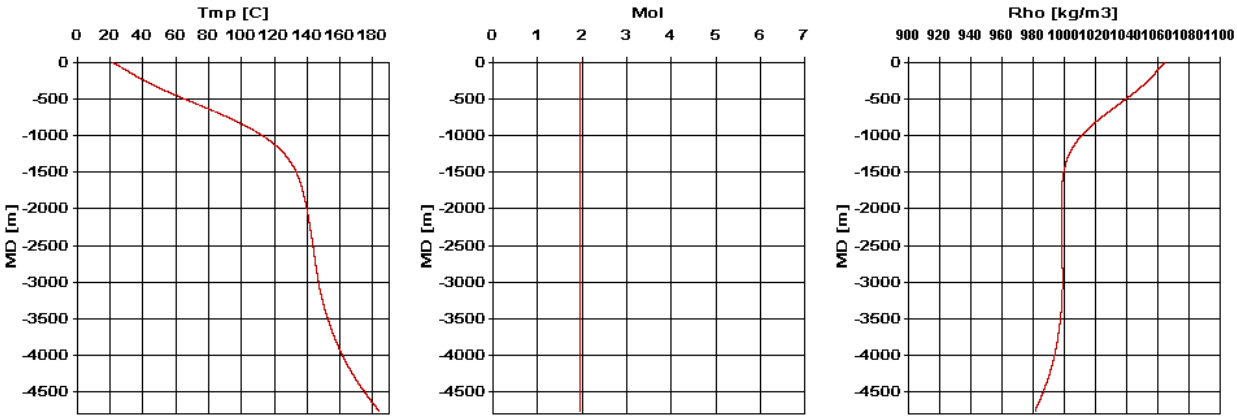

Figure 8: Initial profiles GPK4 for temperature and NaCl-molality and for the corresponding density.

4.2. Productivity Index PI

The density during the circulation was measured as ρ_t = 1042 kg/m^3 (at 20 °C / 0.1 MPa), which corresponds to a NaCl-molality mol_t = 0.998. The dynamic simulation with HEX-B assumes initially an undisturbed temperature field and an entering of fluid with mol_t = 0.998 at the casing shoe. A flow of 3.8 l/s and the measured wellhead pressure (P_wellhead_GPK4 = 0.84 MPa) shown in Figure 1 have been applied. Figure 9 shows the profiles at the end of the simulation period (after 500'000 s) for temperature, NaCl-molality and density. Figure 10 shows the simulated production temperature and downhole pressure at the casing shoe with time.

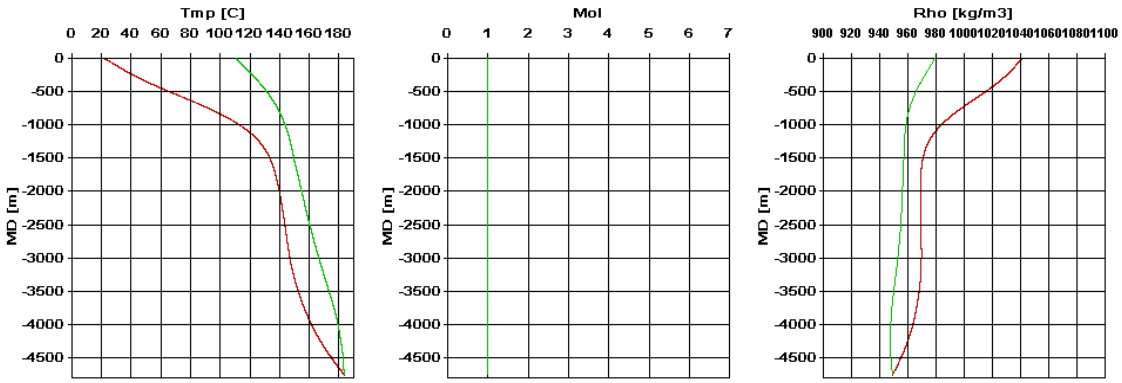

Figure 9: Calculated profiles GPK4 at the end of the simulation period (green curves).

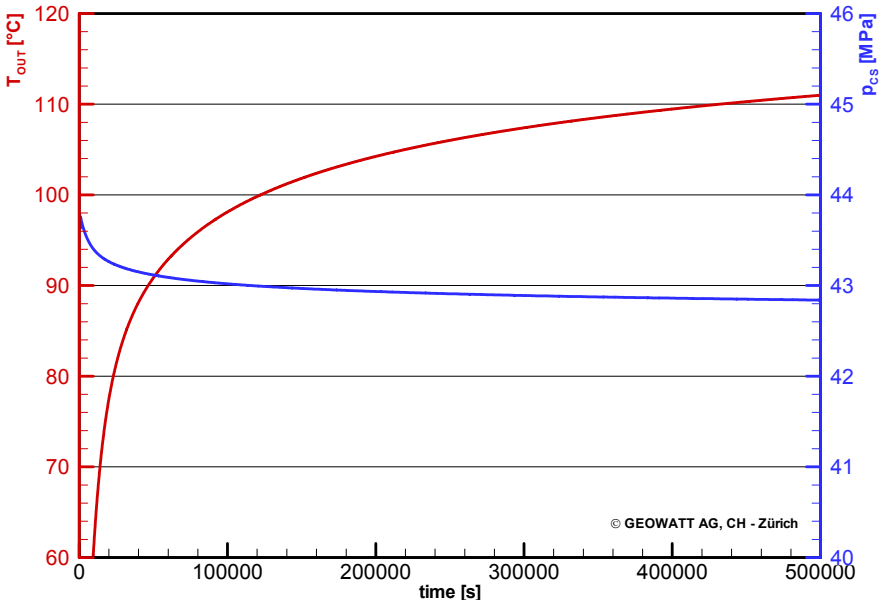

Figure 10: Calculated history of temperature and p_{cs} @ 4756 m MD of circulation test 11jul05 at GPK4.

The calculated production temperature T_{out} agrees well with the measured values shown in Figure 1. The calculated downhole pressure at the end of the simulation period p_{cs} = 42.83 MPa allows to calculate the productivity index PI as

PI = 2.5 [l/(s MPa)]

4.3. Sensitivity of the determination of PI for GPK4

As for GPK2 the sensitivity of different temperature profiles (corresponding to GPK2, shown in Chapter 3.3), NaCl-molalities and initial downhole pressures are analysed. Generally the same comments as for GPK2 in chapter 3.3 can be made. The following additional remarks are made:

- Since the flow rate in GPK4 is only 3.8 l/s the effect different entry temperatures at the casing shoe to the wellhead temperature is significant smaller compared to GPK2 with 11.2 l/s. A variation of the entry temperature T_{cs} by 30 K results only in a change of T_{out} of 3 K. This implies that the determination of T_{cs} using the measured T_{out} is a very critical task and needs very accurate T_{out}-measurements and a very sophisticated borehole model (Figure 11, left).
- Assuming an entry temperature at the casing shoe T_{cs} derived from the undisturbed initial temperature of 180°C we obtain a PI of 2.5 l/s/MPa. However, a quit lower T_{cs} is likely due to the heavy injection of cool water during the stimulation tests. This implies a higher effective PI of 3-4 l/s/MPa (Figure 11, right).

Table 5: Summary of calculated productivity indices for GPK4

PI [l/s/MPa]		**Δmol**		
		0	**+10%**	**-10 %**
T_{cs} [°C]	**undisturbed T-profile**	2.5	2.8	2.3
	160	3.3	3.8	2.9
	170	2.8	3.2	2.5
	180	2.5	2.8	2.3
	190	2.3	2.5	2.1

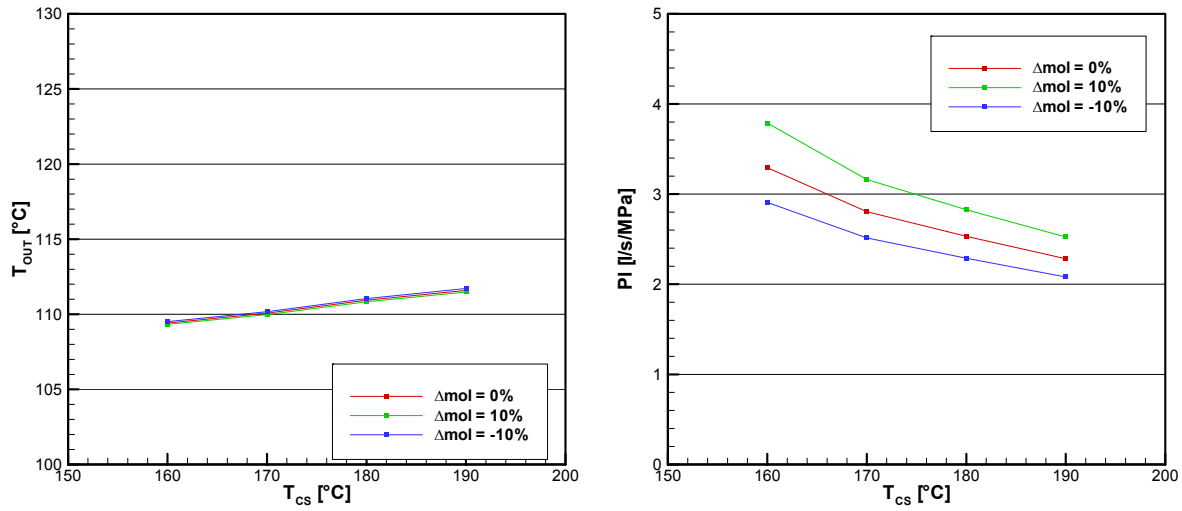

Figure 11: Impact of temperature/NaCl-molality variation on produced temperature (left) and productivity indexPI at GPK4

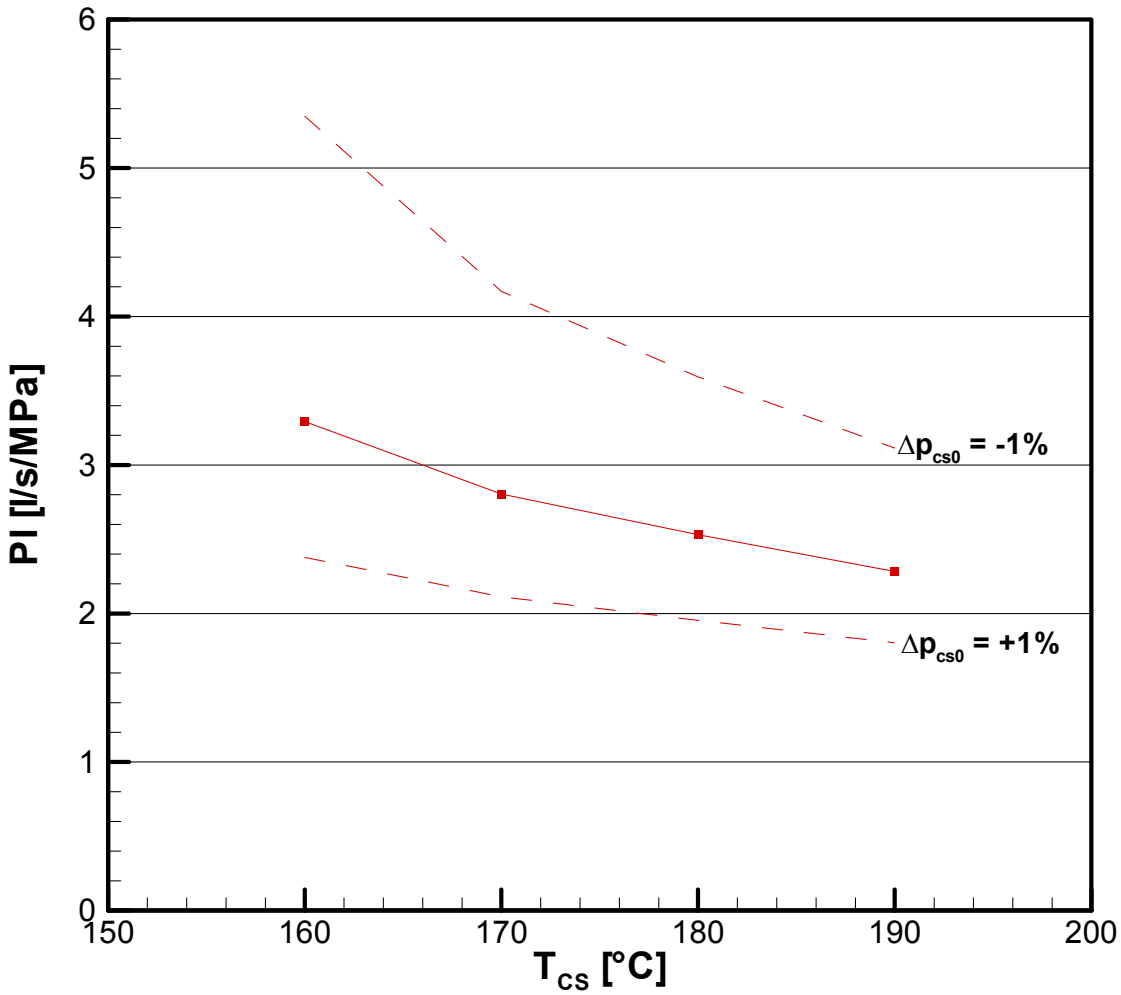

Figure 12: Impact of Δp_{cs0} on productivity index PI at GPK4 compared to Standard Model.

5. Injectivity Index GPK3

5.1. Initial HEX-B Model

The borehole model for the injection well GPK3 includes also the open hole section (Table 6).

Table 6: Borehole/rock model used in HEX-B for GPK3

Bore hole parameters						Rock mass parameters	
Depth section MD [m]			Inner radius [m]	Flow rate [% of injection rate]	Average wall roughness [mm]	Thermal conductivity [W/m K]	Specific heat capacity [J/m^{3}K]
Nr	from:	to:					
1	0	1500	0.11	100	0.15	3	2.2 10^6
2	1500	3800	0.11	100	0.15	4	2.2 10^6
3	3800	4556	0.11	100	0.15	3	2.2 10^6
4	4556	4760	0.108	100	1.00	3	2.2 10^6
5	4760	5100	0.108	30	1.00	3	2.2 10^6

As initial conditions the undisturbed temperature distribution was used (Figure 13). As for GPK2 and GPK4 an initial density of ρ_0 = 1065 kg/m^3 (at 20 °C / 0.1 MPa) and the corresponding initial NaCl-molality mol_0 = 1.935 were applied. Using these values an initial downhole pressure at casing shoe (MD = 4556 m) p_{cs0} = 44.31 MPa is obtained.

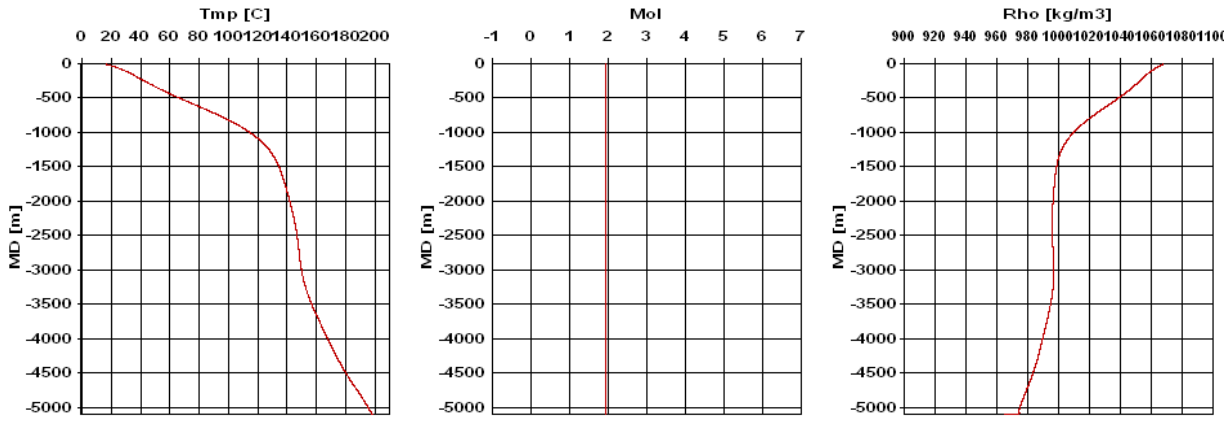

Figure 13: Initial profiles in GPK3 for temperature, NaCl-molality and for the corresponding density.

5.2. Injectivity Index II

During the dynamic simulation, the injected NaCl-Molality was set to the weighted value of the produced NaCl-molality at GPK2 and GPK4 (mol_t = 1.392). The measured values for flow, injection temperature and wellhead pressure showed in Figure 1 have been used as boundary condition.

Figure 14 shows the profiles at the end of the simulation period of temperature, NaCl-molality and the corresponding density. Figure 15 shows the calculated injectivity index and Figure 16 the calculated temperature and pressure evolution at the casing shoe.

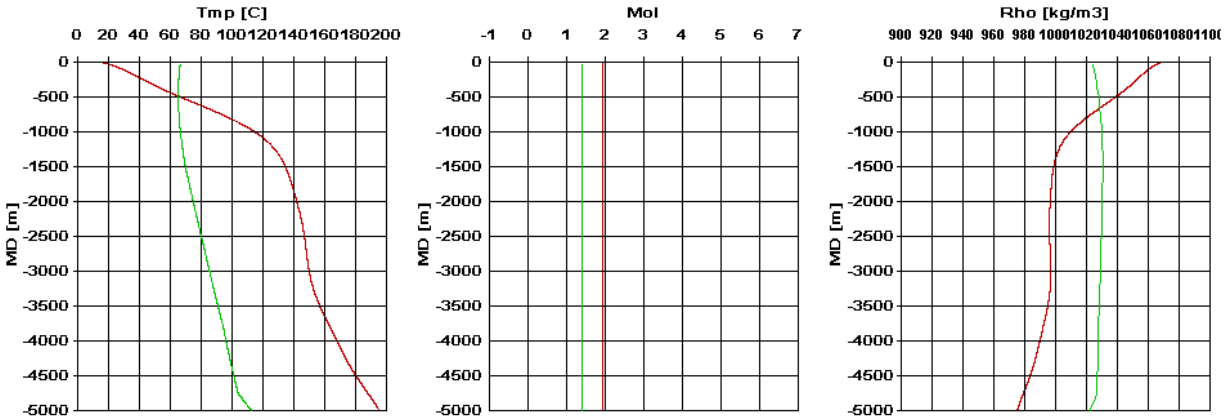

Figure 14: Calculated profiles GPK3 at the end of the simulation period (green curves).

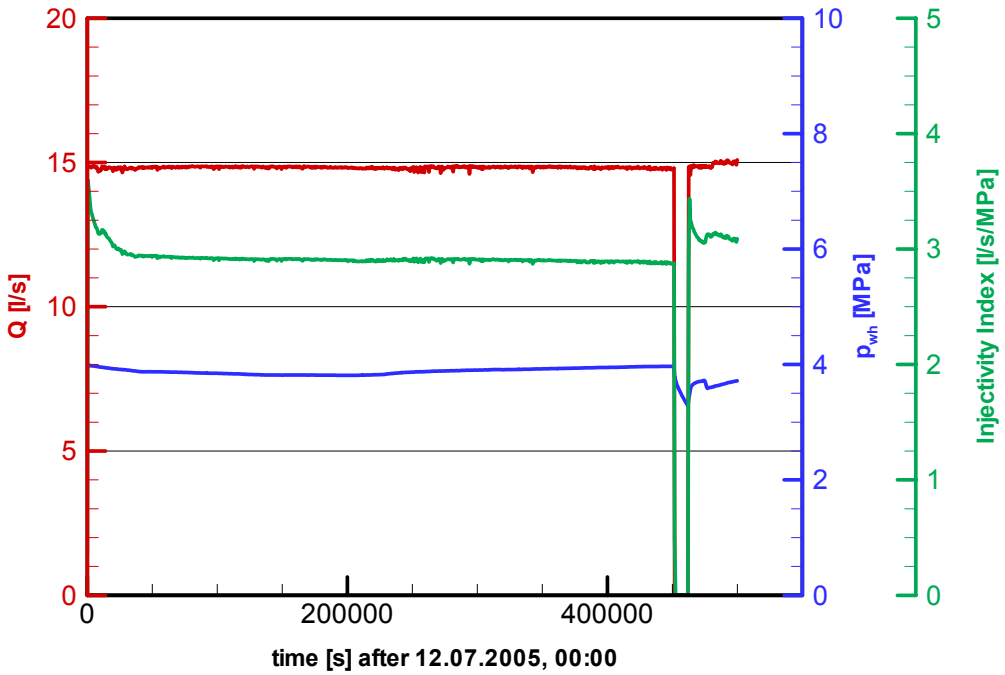

Figure 15: History for flow rate (red), wellhead pressure (blue) and calculated injectivity index (green) at GPK3 during the circulation test 11jul05.

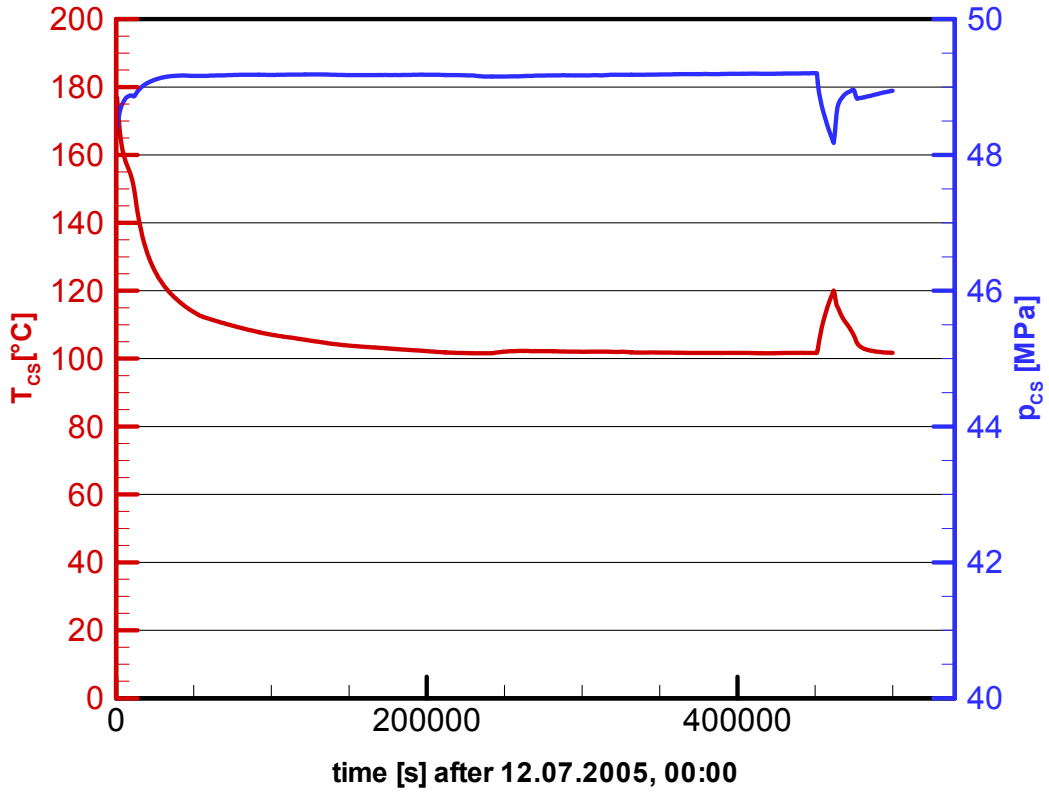

Figure 16: History of calculated temperature (red curve) and downhole pressure (blue curve) at casing shoe (4556 m).

5.3. Sensitivity of the determination of II for GPK3

Generally the sensitivity of the injectivity index II is less critical than of the productivity index PI, due to the higher pressure differences. The effect of a variation of the initial downhole pressure p_{cs0} = 44.31 MPa up to +10% and –10% is shown in Figure 17.

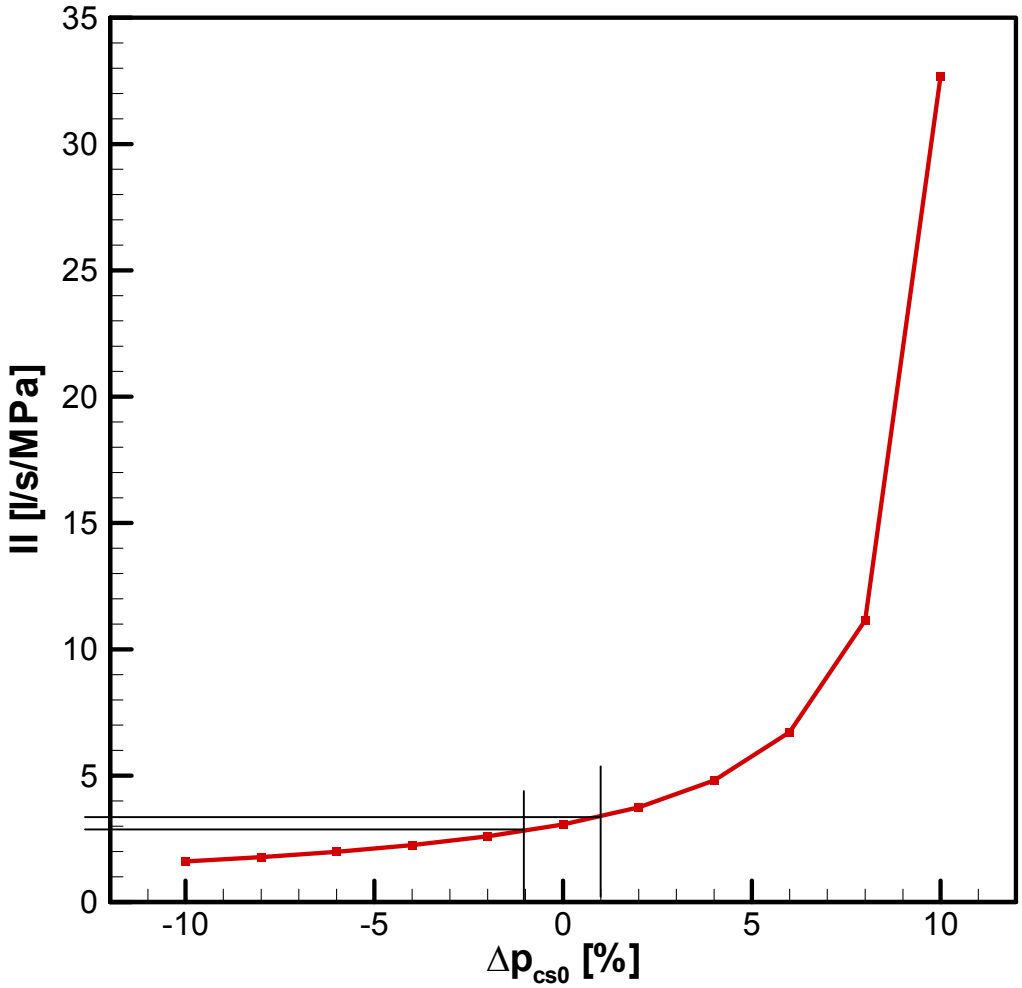

Figure 17: Impact of Δp_{cs0} on injectivity index at GPK3. Δp_{cs0} = 0% corresponds to the initial value p_{cs0} = 44.31 MPa.

Remarks/Results:

The variation of the downhole pressure by ±1% results in a range for II from 2.9 to 3.4 l/s/MPa. This is due to the much higher pressure differences during injection.

6. Summary/Remarks

- The productivity indices PI of GPK2 and GPK4 have been calculated with the data acquired during the thermosyphon production test.
- The productivity index PI of GPK2 is definitely higher than GPK4. The applied standard models in HEX-B provide values of **~10 l/s/MPa** for **GPK2** and ~2.5 l/s/MPa for GPK4. However, for **GPK4** a PI of **3-4 l/s/MPa** is more likely (see below).
- The calculation with HEX-B of the injectivity index of **GPK3** at an injection flow of ~15l/s provides a value of **~3 l/s/MPa**.
- In deep wells like GPK2/3/4 also small variations of the density profile have a significant impact to the downhole pressure whose accuracy is crucial for the determination of the productivity (and also injectivity) index. In addition to NaCl-molality (and pressure) the density itself is also a function of the temperature profile. The temperature profile is calculated in HEX-B using only the wellhead temperature and a borehole model comprising the thermal effects of the vicinity of the borehole. The thermal parameters of the vicinity of the borehole are important and should be therefore calibrated by adequate experiments.
- Specifically with regard to the productivity index PI the simulations highlight the importance of an accurate data acquisition (wellhead temperature, density of the produced fluid, density of the initial fluid in the well, wellhead pressure).
- Larger downhole pressure differences reduce the sensitivity of PI. Therefore, data from a pure thermosyphon tests are not ideally suited for an estimation of PI. Forced flow test conditions would improve the present statements.
- In this technical note the calculation of the production temperature has been carried out assuming an entering of the fluid at the depth of the casing shoe with a temperature corresponding to this depth. To fit the production temperature at GPK2 reasonable results were obtained for a slightly reduced heat exchange of the borehole with the rock matrix in the model must be assumed.
- In contrary to GPK2, the calculated production temperatures at GPK4 are in good agreement with the original borehole model assuming an inflow at the depth of the casing shoe of 180°C. In fact the sensitivity of the wellhead temperature T_{out} is very minor for the low flow rates at GPK4. Since GPK4 has been extensively cooled by the injection fluid during the recent stimulation tests the entry temperature T_{cs} is probably significant lower. This would result in a more favourable productivity index PI for **GPK4 of 3-4 l/s/MPa**.