INVESTIGATING THE EFFECTS OF NON-ISOTHERMAL RESERVOIR CONDITIONS ON PRESSURE TRANSIENT ANALYSIS OF AN INJECTION/FALL-OFF TEST USING NUMERICAL MODELLING

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ABSTRACT

Injection/Fall-off tests are commonly performed in geothermal wells to derive reservoir permeability and a skin factor using pressure transient analysis (PTA). Pressure transient data are commonly interpreted using analytical models which usually assume that fluid flow in the reservoir is isothermal. However, for geothermal reservoirs analysis of pressure transient data is complicated by non-isothermal reservoir conditions. The challenge in pressure transient analysis from non-isothermal reservoirs is determining the effects on the pressure response of the fluid and rock temperature-dependent properties.

Using the numerical reservoir simulator TOUGH2, the non-isothermal effects during injection/fall-off tests can be simulated. Different test scenarios were designed to examine the effects of varying reservoir and injectate parameters on the derivative plot and on the analytical PTA derived reservoir permeability (k) and skin factor (S). Six test cases were used, representing different types of geothermal reservoirs, such as homogeneous reservoirs, fissured or fractured reservoirs, and layered reservoirs. Pressure transient data, generated by the numerically modelling the different cases, were analyzed using analytical PTA software SAPHIR™. Results showed that the non-isothermal effects can influence the SAPHIR™ derived values of k and S. Non-isothermal effects on the derived k are less significant at low temperatures than at high temperatures. Non-isothermal effects on the derived S resemble a positive skin effect. The derived S is more sensitive to change at a high ΔT (difference between reservoir and injectate fluid temperature). All SAPHIR™ derived k and S values generated from different models are higher than the specified model values under non-isothermal condition. Analytical model also incorrectly introduced a reservoir boundary effect to match pressure data from some model cases.

1. INTRODUCTION

Injection/Fall-off tests are commonly performed in geothermal well testing after the completion of drilling. The test is performed by injecting cold water at varying rates into the wellbore. The objective of the test is to obtain pressure transient data from which the reservoir permeability and skin factor of the well can be calculated (Benson and Bodvarsson, 1982). These parameters are important for assessing whether the well will produce at commercial levels. During injection/fall-off tests, the temperature of the injected fluid or injectate is invariably different from the temperature of the in situ reservoir fluid (Sigurdsson et al., 1983). The difference in the fluid temperature between the injectate and the reservoir results in non-isothermal reservoir conditions. Under non-isothermal reservoir conditions, there are variations in fluid and rock temperature-dependent properties such as density, viscosity, and compressibility (Cox and Bodvarsson, 1985). These variations in fluid properties affect the pressure gradient between the wellbore fluid pressure and reservoir pressure (Grant and Bixley, 2011). The pressure response during injection/fall-off tests is therefore affected by the non-isothermal state of the reservoir (Mangold et al., 1979).

The pressure response in the well is used as a representation of the actual reservoir response (Horne, 1995). Changes in pressure response over time or pressure transients are usually analyzed using pressure transient analysis (PTA). Current PTA uses analytical models, which usually assume that fluid flow in the reservoir is isothermal (Cox and Bodvarsson, 1985). Analytical PTA models were developed mainly for groundwater, and oil and gas which only allow specification of one set of fluid properties (McLean and Zarrouk, 2015a). Grant and Bixley (2011) demonstrate that is it better to use the reservoir fluid properties rather than the injectate fluid properties, but also recognized that this is an imperfect solution. The challenge in pressure transient analysis for non-isothermal reservoirs is in determining the effect of fluid and rock temperature-dependent properties on the pressure response (Mangold et al., 1979). To interpret pressure transient data correctly, the effect of non-isothermal reservoir conditions must be understood.

Studies on the effects of non-isothermal reservoir condition have been conducted since the 1970's. One of the early studies was conducted by Tsang and Tsang (1978), who developed an analytical model of the pressure response in a non-isothermal reservoir during cold water injection. Benson and Tsang (1980) and Mangold et al. (1979) considered the behavior of non-isothermal pressure transients in a geothermal reservoir, and discussed the effect of the temperature-dependent fluid properties on pressure transient data. Benson and Bodvarsson (1982) used a numerical simulator PT (pressure-temperature) to simulate the non-isothermal effects during injection/fall-off tests. Similar studies that discussed the interpretation of pressure transient during cold water injection into a hot reservoir were conducted by Sigurdsson et al. (1983). Cox and Bodvarsson (1985) extended the analysis of non-isothermal pressure transient data to a fractured reservoir using the numerical simulator PT. Nakao and Ishido (1998) studied the pressure transient behavior during cold water injection into geothermal wells using data from Yatsubo geothermal field in Kyushu, Japan. The most recent study of the non-isothermal effects on pressure transient data was conducted by McLean and Zarrouk (2015a). A standard model set-up (McLean and Zarrouk, 2015b) for geothermal PTA using TOUGH2 (Pruess, 1991) and PyTOUGH (Croucher, 2011) was used to generate pressure transient data to examine an injection test of cold water into a hot reservoir. The model set-up was based on an injection test in Ohaaki geothermal field in New Zealand. The pressure transient data generated from the model was analyzed using analytical models from the software SAPHIR™.

Most of the studies investigating the effects of non-isothermal reservoir conditions have used numerical models to simulate injection/fall-off tests and to generate pressure transient data. Recent studies that utilized numerical modelling have used TOUGH2 (Pruess, 1991), a numerical simulator for non-isothermal flows that is specifically designed for geothermal reservoir engineering. Currently, there are limited numbers of model used for investigating the non-isothermal effects to pressure transient analysis.

2. INJECTION/FALL-OFF TEST AFTER DRILLING COMPLETION

After drilling is completed, the well is tested to gather baseline well test data such as temperature and pressure profiles, potential feed zones, injectivity index, reservoir permeability (k), and skin factor (S). A completion test is considered as one of the most important tests to be conducted to characterize the well and to determined how the well will be utilized. In this research, injection/fall-off tests are discussed as part of the completion test. A completion test will include a water-loss survey, an injectivity test, and a pressure fall-off test. Pressure transient data can be obtained during the pressure fall-off test.

2.1 Pressure Fall-off Test (PFO)

A PFO is usually carried-out by incrementally increasing the injection rate and then reducing it from the maximum rate to zero (single-rate PFO) or a minimum allowed rate (two-rate PFO) and maintaining it there for several hours until a relative stable pressure is measured by the pressure-temperature-spinner (PTS) tool. A sample history plot of an injection/fall-off test is shown in Figure 1. This PFO test was carried-out by reducing the injection rate from 20 bpm to 5 bpm.

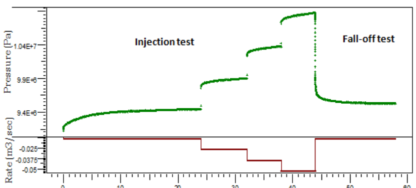

Figure 1: History plot of an injection/fall-off test

The objective of the test is to determine reservoir properties such as permeability thickness (kh), permeability (k), skin factor (S), wellbore storage, reservoir boundary, and formation fracture pressure. The recovery of pressure to its initial pre-test value or pressure stabilization is usually observed in PFO test (Villacorte & O'Sullivan, 2012). The stable pressure reflects the actual pressure response from the reservoir and is analyzed using pressure transient analysis.

3. PRESSURE TRANSIENT ANALYSIS (PTA) OF AN INJECTION/FALL-OFF TEST

PTA, also known as well test analysis, is the analysis of pressure changes over time resulting from a change in the rate of production or injection. The measured pressure response from the well is used as a representation of the actual reservoir response and hence we treat the flow rate transient as input and pressure transient as output (Horne, 1995). The pressure response characterizes the ability of the fluid to flow through the reservoir to the well, which provides a description of the reservoir under dynamic conditions. From the PTA, it is possible to determine the following properties: reservoir permeability, reservoir heterogeneities (fractures, layering), reservoir boundaries, reservoir pressure, production potential (productivity index, skin factor), and well geometry (Bourdet, 2001). The basic idea is to monitor the pressure response during an injection and fall-off test, plot the pressure response versus time, and analyze the plots to deduce reservoir and well properties. PTA methods have developed over time, starting from conventional type curve matching to modern PTA utilizing sophisticated computer-based software.

3.1 Comments on the Conventional and Modern PTA

Well test interpretation using conventional methods has poor resolution and accuracy due to the fact that the results rely mostly on interpretation by an engineer (matching by eye) and may be subjective, depending on the engineer's perspective. In addition, manual computation is prone to human error and takes a long time to perform. Modern PTA, using computer software, is normally based on analytical models which have mainly been developed for the oil and gas industry, which means that they only work well in a low temperature environment and for simple reservoir structures. It becomes problematic when someone use this software for geothermal PTA as these models do not account for many geothermal factors, some of which violate some of the assumptions behind the analytical models (McLean and Zarrouk, 2015b). One major flaw of analytical models for geothermal PTA is that they only allow the specification of constant fluid properties. Thus the use of an analytical model for geothermal PTA does not account for the non-isothermal effects during injection/fall-off test where the injectate temperature is colder than the hot reservoir fluid.

The use of a numerical simulator is becoming common for modelling pressure transients in geothermal reservoir as it allows both the temperature and fluid properties of the reservoir and injectate to be specified. Thus by using a numerical model to represent a geothermal reservoir and a numerical simulator to simulate injection/fall-off tests, the effect of non-isothermal reservoir conditions to pressure transient analysis can be investigated.

4. INJECTION/FALL-OFF TESTS USING NUMERICAL MODELLING

The issue of non-isothermal effects during an injection/fall-off tests can be addressed with a numerical reservoir simulator by allowing both the temperature and fluid properties of the reservoir and injectate to be specified (McLean and Zarrouk, 2015a). In order to examine the effect of non-isothermal reservoir conditions on PTA, test models are set-up based on injection/fall-off tests with different reservoir and injectate parameters. In each case the tests are simulated with a numerical model and used to generate a model pressure response. In this research, an injection/fall-off test program is simulated with a numerical model by injecting water at different injection rates. The program is based on a completion test of a production well in Leyte Geothermal Field in the Philippines. It utilized the following injection rates: 5 bpm, 10 bpm, 15 bpm, and 20 bpm. A two-rate PFO test was carried out by reducing injection rate from 20 bpm to 5 bpm.

4.1 Model Test Design

Parametric test and different test scenarios were designed to examine the effects of varying reservoir and injectate parameters on the derivative plots and on the analytical PTA derived permeability (k) and skin factor (S).

Three test models have been developed namely: an isothermal test, injectate temperature test, and permeability and skin test. The isothermal test uses a scenario where the difference between the reservoir and injectate temperature is zero ($\Delta T = 0$) which represents isothermal conditions. The non-isothermal test makes use of various injectate temperatures (T_{INJ}) and a constant reservoir temperature (T_{RES}). The permeability and skin test uses different combinations of model k and S to investigate the effect of varying these parameters on the analytical PTA derived k and S under non-isothermal conditions.

Different numerical models were used to simulate the test, ranging from a simple to a complex reservoir model. This process determines how well the analytical PTA handles model complexity that represents actual geothermal reservoirs, such as homogeneous reservoirs, fissured or fractured reservoirs, and layered reservoirs. The following numerical models were used to represent the different types of geothermal reservoirs mentioned:

Case 1: Single-layer single porosity model (SLSP)
Case 2: Single-layer dual porosity model (SLDP)
Case 3: Multi-layer single porosity model w/ impermeable layers (MLSP-IMP)
Case 4: Multi-layer dual porosity model w/ impermeable layers (MLDP-IMP)
Case 5: Multi-layer single porosity model w/ permeable layers (MLSP-P)
Case 6: Multi-layer dual porosity w/ permeable layers (MLDP-P)

A multi-layer model with impermeable layers means that other layers besides the feed zone have a very low permeability, i.e. they are almost impermeable. Multi-layer model with permeable layers means that others layers have moderate to high vertical permeability which can accept fluid from the feed zone during the injection test and can contribute to fluid discharge or pressure support to the feed zone during the fall-off test.

4.2 Numerical Model Set-up

Schematics of a single-layer and multi-layer model are shown in Figures 2 and 3. Key model parameters are given in Tables 1 and 2. For the multi-layer models, the temperature and pressure profiles are based on a heat-up survey of a geothermal well in Leyte geothermal field in the Philippines.

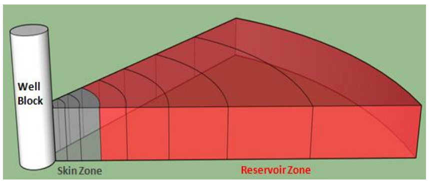

Figure 2: Schematic of a single-layer radial grid model

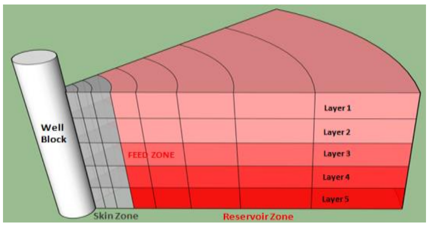

Figure 3: Schematic of a multi-layer radial grid model

Table 1: Single-layer Radial Grid Model Parameter

SECTION	PARAMETER	VALUE
Well Block	well radius	0.10795 m
	volume	81.4 m^3
	compressibility	$6x10^{-8}$ Pa^{-1}
	porosity	0.9
	permeability	*3 orders of magnitude higher than reservoir permeability*
Skin Zone	# of blocks	50
	width	5 m
	porosity	0.1
	permeability	*depending on the value of skin factor*
Reservoir Zone	# of blocks	100
	radial extent	20 km
	porosity	0.1
	permeability	*variable*
	layer thickness	100 m

Table 2: Multi-layer Radial Grid Model Parameter

SECTION	PARAMETER	VALUE
Well Block	well radius	0.10795 m
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	# of layers	5
	permeability	*depending on the value of skin factor*
Reservoir Zone	# of blocks	100
	radial extent	20 km
	porosity	0.1
	permeability	*variable*
	layer thickness	100 m
	# of layers	5
	feed zone	3rd layer

5. PTA OF THE SIMULATED PRESSURE TRANSIENT DATA USING SAPHIR^{TM}

The analytical PTA software SAPHIR^{TM} was used for the analysis of pressure transient data generated by the different model cases. The main objective was to compare the SAPHIR^{TM} derived k and S to the specified model k and S, and to quantify the range of error introduced by using a standard analytical analysis.

5.1 Isothermal Test Results

To check the isothermal assumption used in analytical PTA, an injection/fall-off test was simulated using an injectate temperature (T_{INJ}) similar to the reservoir temperature (T_{RES}). In this test, the model k was 1.0E-13m^2, the model S was 0, and T_{RES} and T_{INJ} were assigned the same values. The temperature was assigned one of the following values: 25°C, 50°C, 100°C, 150°C, 200°C, 250°C, and 300°C.

The derivative plots generated by SAPHIR^{TM} are shown in Figure 4. SAPHIR^{TM} derived values for k and S are shown in Figure 5.

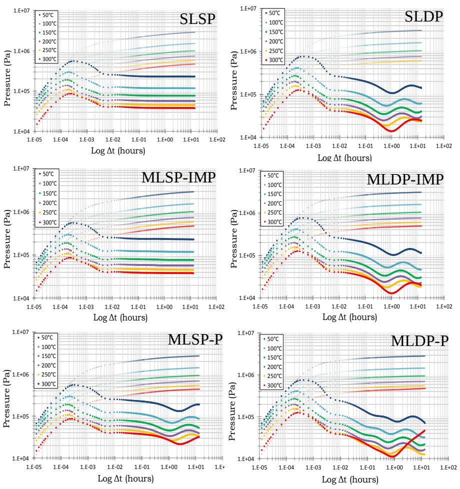

Figure 4: Derivative plot results for the isothermal test

The following features can be observed in the derivative plots shown in Figure 4:

- The derivative plots generated by the different model cases shifts downward as the temperature increases, and are more sensitive to change at low temperature and less at high temperature.
- The size and steepness of the derivative hump which represents skin effect is unaffected by the temperatures.
- The middle time derivative plot of SLDP and MLDP-IMP models shows two humps and one dip (S-curve) which represents dual porosity reservoir model.
- MLSP-P also shows an S-curve similar to dual porosity models but the transitional dip is shallow and takes longer to occur.
- MLDP-P which represents a combination of dual porosity and layered reservoir shows three humps and two dips.
- The late-time derivative plot of some plots shows a decrease in pressure derivative which indicates a boundary effect.

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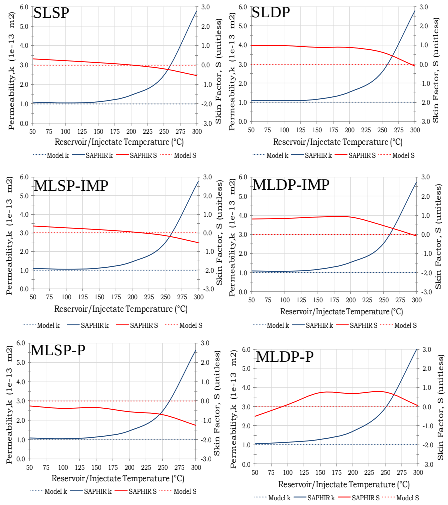

Figure 5: SAPHIR^{TM} derived k and S for the isothermal test

The analytical SAPHIR^{TM} models that are used to fit the simulated pressure response are similar to the model cases specified (e.g. homogeneous, dual porosity, and layered reservoir) except for model cases with a boundary effect that is matched using a circular, no flow boundary instead of the infinite boundary model. The following can be observed in the SAPHIR^{TM} derived k and S plots shown in Figure 5:

- The derived value of k is greatly affected by temperature for the range 150°C to 300°C and less affected at temperatures below 150°C.
- In general, the derived value of k is more sensitive to change at higher temperatures and less at lower temperatures.
- The derived value of S is unaffected by temperature at isothermal conditions as reflected in the slight change in the derived S as the temperature increases.

5.2 Injectate Temperature Test Results

To investigate the effect of non-isothermal reservoir conditions on PTA of an injection/fall-off test, different injectate temperatures were simulated using the model. In this test, the model k was 1.0E-13m^2, the model S was 0, and T_{RES} and T_{INJ} were assigned a range of different values. For each T_{RES} value of 200°C, 225°C, 250°C, 275°C, and 300°C; a T_{INJ} of 25°C, 50°C, 75°C, 100°C, 150°C, 200°C, up to the assigned T_{RES} value were used. For multi-layer models, the reservoir temperature and pressure profiles are based on the heat-up survey of a geothermal well in Leyte geothermal field in the Philippines.

The derivative plots generated by SAPHIR™ at T_{RES} = 300°C at varying injection temperature are shown in Figure 6. Similar derivative plot behavior can be observed for different T_{RES} values. SAPHIR™ derived values for k and S are shown in Figure 7.

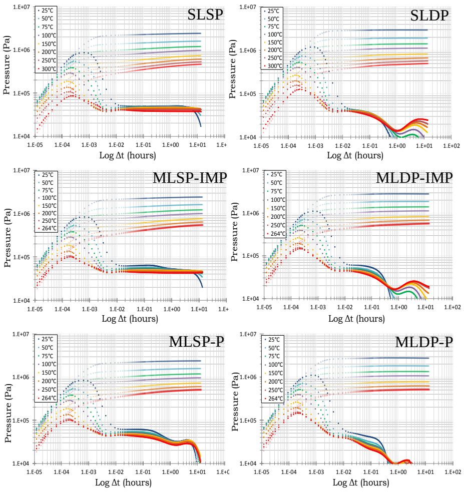

Figure 6: Derivative plot results on injectate temperature test

The following features can be observed in the derivative plots shown in Figure 6:

- The derivative plots generated by the different model cases shifts downward as the temperature increases, and are more sensitive to change at low temperature and less at high temperature.
- The size and steepness of the derivative hump increases as the T_{INJ} decreases which resembles a positive skin effect.
- The derivative hump which represents skin effect is more sensitive to change at lower T_{INJ} and less sensitive at higher T_{INJ}.
- The middle time derivative plot behavior is only slightly affected by T_{INJ} as reflected in the slight increase in k as the T_{INJ} increases.
- The boundary effect is more likely to have to be included to match the data in dual porosity and layered reservoir models.
- The late-time derivative plot of case 6 (MLDP-P) falls below the log-log scale so it is difficult to match the boundary model.

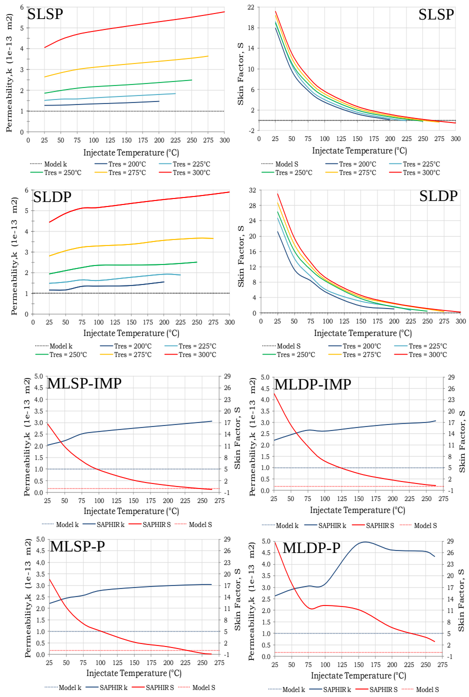

Figure 7: SAPHIR™ derived k and S on injectate temperature test

The analytical SAPHIR™ models that are used to fit the simulated pressure response are similar to the model cases specified (e.g. homogeneous, dual porosity, and layered reservoir) except for model cases with a boundary effect that is matched using a circular, no flow boundary instead of the infinite boundary model. The following can be observed in the SAPHIR™ derived k and S plots shown in Figure 7:

- The derived value of k is greatly affected by T_{RES} and slightly affected by T_{INJ}, but the derived k is more sensitive to T_{INJ} at higher T_{RES} and less sensitive at lower T_{RES}.
- In general, the derived k is more sensitive to change at higher temperature and less at lower temperature.
- As the difference between the T_{RES} and T_{INJ} increases (ΔT), the derived S drastically increases and is more sensitive to change at higher ΔT and less at lower ΔT.

5.3 Permeability and Skin Test Results

To investigate the effect of varying the specified model k and S on the analytical PTA derived k and S under non-isothermal conditions, different combinations of model k and S values were used. In this test, T_{RES} was 264°C, T_{INJ} was 65°C and the model k and S were assigned different values. For each S value of 0, 1, 3, 5, -1, and -3; a k value of 0.1, 0.5, 1, 5, 10, and 50 (x 1.0E-13m^2) were used. The skin value was incorporated into the model by changing the

Commented [MO2]: Explain how skin was included in the model permeability of the skin zone and by using the following equation:

$$S = \left(\frac{k}{k_s} - 1\right) \ln \frac{r_s}{r_w}$$

where:

k_s = skin zone permeability (m^2)

k = reservoir permeability (m^2)

s = skin factor (dimensionless)

r_s = skin zone radius (m)

r_w = well radius (m)

The derivative plots generated by SAPHIR™ at a constant model k of 1.0E-13m^2 at different values of model S are shown in Figure 8. Similar derivative plot behavior can be observed at different model k values. SAPHIR™ derived k and S values are shown in Figure 9.

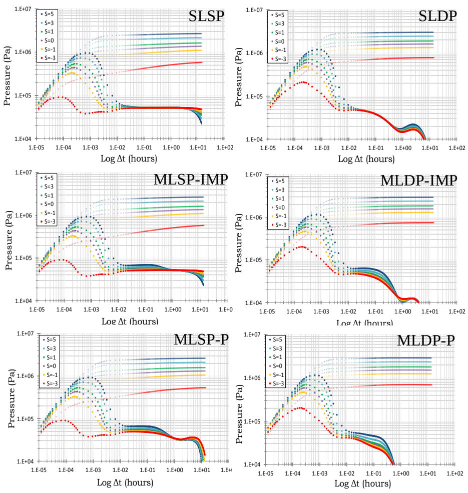

Figure 8: Derivative plot results on permeability and skin test

The following features can be observed in the derivative plots shown in Figure 8:

- The skin effect is very large for a positive model S while moderate effect can be seen on a negative model S as it counters the positive skin effect of T_{INJ}. It is reflected on the steepness of the derivative hump.
- The middle-time derivative plot is unaffected by varying the model S, which is reflected in the slight change in the derived k value.
- The late-time derivative plot shows a boundary effect for all the model cases.

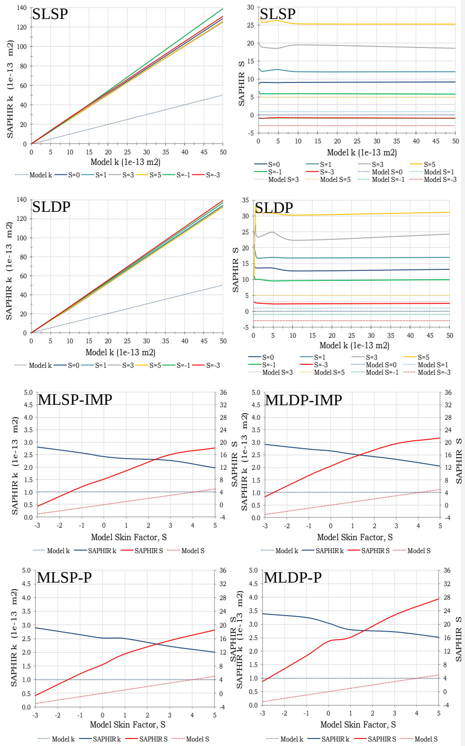

Figure 9: SAPHIR™ derived k and S on permeability and skin test

For multi-layer models, a constant model k value of 1.0E-13 m^2 for the feed zone was used with a range of model S values similar to single layer model. Varying the feed zone k while keeping the value of k in other layers constant can cause complicated PTA matching (e.g. some parts of the pressure transient data cannot be seen on the log-log scale).

The analytical SAPHIR™ models that are used to fit the simulated pressure response are similar to the model cases specified (e.g. homogeneous, dual porosity, and layered reservoir) except for model cases with a boundary effect that is matched using a circular, no flow boundary instead of the infinite boundary model. The following features can be observed in the SAPHIR™ derived k and S plots shown in Figure 9:

- The derived value of k is more sensitive to change at higher model k and less at lower model k; and is unaffected by the value of model S.
- The derived value of S is amplified for a positive model S but was countered by a negative model S; and is unaffected by the value of model k.

6. COMMENTS ON THE SIMULATION RESULTS

Effects of non-isothermal reservoir conditions on the analytical PTA SAPHIR™ results are apparent for k, S, and the reservoir boundary.

6.1 Non-Isothermal Effect on Permeability (k)

Non-isothermal effect on the SAPHIR^{TM} derived k are less significant at lower temperature but more significant at higher temperature. The temperature effect on the estimate of k mirrors the dependence of the dynamic viscosity (μ) on temperature (Figure 10).

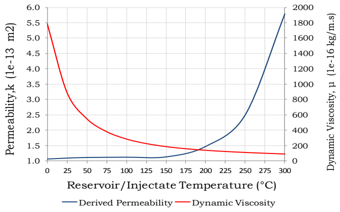

Figure 10: Relationship of k and μ with temperature

At lower temperatures, μ changes rapidly with temperature and less so at higher temperatures. This is the opposite of the temperature dependence of derived k which changes rapidly with high temperatures and less so at lower temperatures. As shown in Figure 10, the derived k seems to be more sensitive at lower μ, and less sensitive at higher μ. These effects demonstrate that the less viscous the fluid is, the faster the formation fluid will react to a local pressure disturbance resulting in high derived values of k.

6.2 Non-isothermal Effect on Skin (S)

The effect of T_{INJ} on the steepness of the derivative hump resembles a positive S. The value of T_{RES} should also be considered because the difference between T_{RES} and T_{INJ} (ΔT) is the main factor in determining how the estimate of S is likely to be sensitive to change. The higher the ΔT, the higher the SAPHIR^{TM} derived S value. The non-isothermal effects at higher ΔT are more pronounced and increase the effect of thermal discontinuity that resembles a permeability boundary. This boundary act as an additional skin for the reservoir; thus, increasing the derived values of S.

6.3 Non-isothermal Effect on Reservoir Boundary

All model cases were set-up with an effectively infinite boundary but the late-time derivative plots of some model cases were matched using a "circular, no flow" boundary as the analytical model in SAPHIR^{TM}. A decrease in pressure on the late-time derivative plot indicates that a reservoir boundary is reached. The circular, no flow boundary model that matched the late-time derivative plots means that the tested well is located at the center of a circular shaped reservoir with a boundary that no fluid will pass through. This boundary effect is caused by the pressure change at zones with different temperatures that resemble a permeability boundary. This is an effect of the thermal discontinuity due to the non-isothermal reservoir condition. The boundary effect under non-isothermal reservoir condition seems to be more apparent in test scenarios where the difference between T_{RES} and T_{INJ} is high and in model cases with dual porosity and layered reservoir models.

6.4 Contrasting SAPHIR^{TM} Results

The derivative plots and SAPHIR^{TM} derived k and S values generated from model case 6 (MLDP-P) differ significantly compared to the behavior and results generated by other model cases. It seems that the dual porosity, layered reservoir model introduced a complex PTA when using analytical models. The storativity of layers and matrix blocks, and the cross flow between layers, the fissure system, and the matrix blocks may add to the complication of deriving the k and S values.

7. CONCLUSION

Based on the results of the experiments performed, the following conclusions are drawn:

1. Numerical modelling is applicable to systematically testing and investigating non-isothermal effects during injection/fall-off tests.
2. Under isothermal conditions, the SAPHIR^{TM} derived k increases rapidly as temperature increases. The temperature effect on the derived k mirrors the dependence of dynamic viscosity on temperature, but with an opposite response.
3. Under isothermal conditions, the SAPHIR^{TM} derived S is unaffected by increasing /decreasing the temperatures.
4. The analytical model introduced boundary effects to match some model cases. It was more apparent in test scenarios where the difference between T_{RES} and T_{INJ} (ΔT) was high; and in model cases that represent fissured/fractured and layered geothermal reservoir.
5. Non-isothermal effects on analytical PTA SAPHIR^{TM} derived k are less significant at lower temperatures but more significant at higher temperatures. Also, the derived k is more sensitive to change at higher temperatures and less on lower temperatures.
6. Non-isothermal effects on analytical PTA SAPHIR^{TM} derived S resembles a positive S. The derived S is more sensitive to change for higher ΔT and less for lower ΔT. Also, the non-isothermal skin effect is amplified using a positive model S but was countered with a negative model S.
7. All the SAPHIR^{TM} derived k values generated from the different model cases are higher than the assigned model values with % difference ranging from 4% to 513%. This was demonstrated under both isothermal and non-isothermal reservoir conditions.
8. The SAPHIR^{TM} derived S values generated from the different model cases is almost the same as the specified model values under isothermal conditions. However, under non-isothermal reservoir conditions, the derived value of S is always higher than the assigned model S.
9. The model case with a combination of dual porosity and layered reservoir model provides contrasting SAPHIR^{TM} results compared to the other model cases.

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