LINEAR IMPERMEABLE BOUNDARY IN GEOTHERMAL PRESSURE TRANSIENT ANALYSIS: A RESERVOIR MODELLING ASSESSMENT

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ABSTRACT

There are several analytical models available in oil and gas theory for application to well tests. These include the standard homogenous infinite reservoir model as well as various boundary models. This includes a linear impermeable boundary model which is commonly used to represent an impermeable fault near the well. While all these models are of interest to the geothermal reservoir engineer, commonly they do not fit geothermal well test data. The models are based on analytical solutions with many assumptions that do not fully hold in the geothermal reservoir environment.

Advances are being made in modelling geothermal well tests using the TOUGH2 reservoir simulator rather than analytical models. A standard design for setting up TOUGH2 models has been developed and so to accompany this, an equivalent to the linear impermeable boundary model has been developed. This is achieved by modifying the block volumes of the radial grid as if they are cut by a planar feature at a specified distance from the well. Using these modified volumes to simulate the results of geothermal pressure transients yields derivative plot results which are similar in shape to the equivalent analytical model. The proximity of the boundary to the well is varied in order to investigate how proximal the boundary must be in order to affect the model results.

1. INTRODUCTION

A standard model design for simulating geothermal pressure transients has been developed (McLean and Zarrouk, 2015). This basic model produces a uniform reservoir response. A wide variety of reservoir and boundary models are available in analytical oil and gas pressure transient analysis theory, including a linear impermeable boundary model. A numerical equivalent to this model has been developed and is demonstrated in this paper.

2. BACKGROUND

2.1 Analytical linear impermeable boundary model

A linear impermeable boundary is one of a catalogue of boundary models available in analytical well test analysis (Horne, 1995). It is commonly referred to as a fault boundary. Caution must be exercised when referring to the boundary as a fault, to make it explicitly clear that this is a case of a completely impermeable fault. In some cases, especially in seismically active geothermal reservoirs, faults can be permeable targets for drilling rather than impermeable boundaries, and confusion can easily arise.

The characteristic of an analytical linear impermeable boundary model in a semilog plot is a doubling of the slope of the infinite acting response at the time the boundary starts to affect the measured pressure. The time at which the slope doubles is used to estimate the distance from the well to the fault. This response is seen in a derivative plot as a second flat region (Horne, 1995).

3. MODEL SETUP

3.1 General setup

A numerical model was set up for an injection test into a well in Ohaaki geothermal field, New Zealand, following the standard guidelines outlined by McLean and Zarrouk (2015). A schematic of this model is shown in Figure 1 and key model parameters are given in Table 1. The block volumes and connection areas were then modified as if cut by a linear feature at a specified distance from the well (Figure 2).

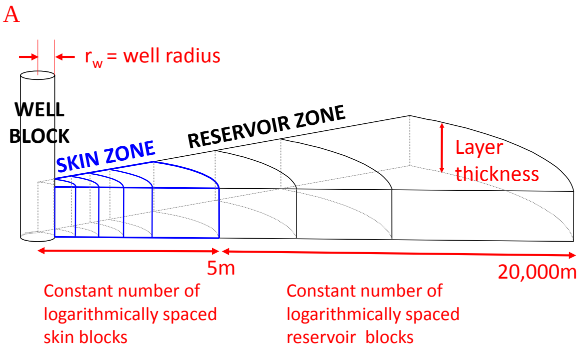

Figure 1: Schematic of standard model setup using TOUGH2 and PyTOUGH (McLean and Zarrouk, 2015).

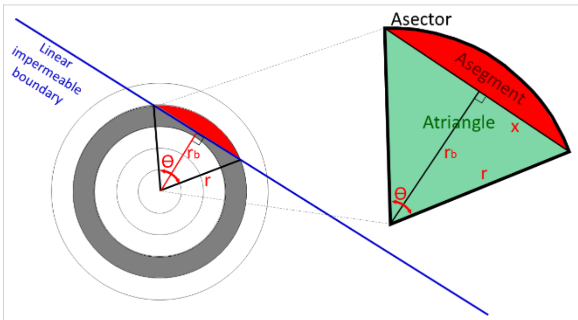

Figure 2: Schematic of top view of model grid with definition of geometry elements to be used in calculations.

Table 1: Key model parameters for test model

PARAMETER	VALUE
Reservoir permeability (mD)	10
Reservoir temperature (°C)	310
Skin factor	0
Number of blocks in skin zone	50
Number of blocks in reservoir zone	100
Skin zone width (m)	5
Model radial extent (km)	20
Layer thickness (m)	600
Well radius (m)	0.1
Well porosity	0.9
Well volume (m^3)	81.4
Well compressibility (Pa^{-1})	6×10^{-8}

3.2 Calculate modified volumes

The geometry elements illustrated in Figure 2 are:

- r_b = well-to-boundary distance (m)
- r = radius of the current block (m).
- x = distance along the boundary line from perpendicular bisector to the intersection with the block radius (m).
- h = block thickness (m).
- θ = angle formed at the grid centre by a triangle defined by: the grid centre, and the two points at which the boundary line intersects the outer radius of the block (radians).
- A_{sector} = area of pie-shaped wedge defined by θ and block radius (m^2).
- $A_{triangle}$ = area of triangle defined by θ and block radius (m^2).
- A_{sector} = area of arc-shaped sector defined by θ and block radius (m^2).

These elements are then used to calculate the modified block volume with basic geometry equations. The area of the segment (red area in Figure 2) is needed as this represents the portion of the block that is being excluded.

$$A_{segment} = A_{sector} - A_{triangle} \qquad (1)$$

The law for the area of triangles gives:

$$A_{triangle} = x\, r_b \qquad (2)$$

The sector area is a fraction of the area of the circle of the same radius:

$$A_{sector} = \frac{\theta}{2\pi}\pi r^2 \qquad (3)$$

Equation 2 and 3 merge into Equation 1 to give:

$$A_{segment} = \frac{\theta}{2\pi}\pi r^2 - x\, r_b \qquad (4)$$

The distance x is given by trigonometry:

$$x = r.\sin\left(\frac{\theta}{2}\right) \qquad (5)$$

Equation 5 merge into Equation 4:

$$A_{segment} = \frac{\theta}{2\pi}\pi r^2 - r_b\, r\, \sin\left(\frac{\theta}{2}\right) \qquad (6)$$

Equation 6 allows the calculation of the segment area if block radius (r), well-to-boundary distance (r_b) and angle (θ) are known.

Angle (θ) can be defined in terms of r and r_b using trigonometry:

$$\theta = 2\cos^{-1}\left(\frac{r_b}{r}\right) \qquad (7)$$

Merging Equation 7 into Equation 6 eliminates the angle (θ) and leaves only the known terms which are block radius (r) and well-to-boundary distance (r_b). Multiplication by the layer thickness (h) converts this to a volume:

$$V_{segment} = h\left(\frac{2\cos^{-1}\left(\frac{r_b}{r}\right)}{2\pi}\pi r^2 - r_b\, r\, \sin\left(\frac{2\cos^{-1}\left(\frac{r_b}{r}\right)}{2}\right)\right) \qquad (8)$$

The modified volume of any block is then equal to its original volume minus the volume of the segment, if the block radius is greater than the well-to-boundary distance.

3.3 Calculate modified connection areas

An unmodified connection area between two blocks is equal to the circumference of the inner block multiplied by the thickness:

$$Area = 2\,\pi\, r\, h \qquad (9)$$

The portion of the connection area that is "lost" behind the boundary is a fraction of the whole and defined by the angle (θ). Subtracting this from the original area gives the modified connection area:

$$Area_{mod} = 2\,\pi\, r\, h\left(1 - \frac{\theta}{2\pi}\right) \qquad (10)$$

Merging Equation 7 into 10 gives the modified area in terms of r, r_b and h:

$$Area_{mod} = 2\,\pi\, r\, h\left(1 - \frac{2\cos^{-1}\left(\frac{r_b}{r}\right)}{2\pi}\right) \qquad (11)$$

THESE CALCULATIONS CAN BE DONE AUTOMATICALLY USING STANDARD PYTHON

COMMANDS, AND UPDATED IN THE INPUT FILE FOR TOUGH2. THE USER HAS ONLY TO ENTER A VALUE FOR THE WELL-TO-BOUNDARY DISTANCE (R_B) AS THE BLOCK RADII AND LAYER THICKNESS ARE ALREADY DEFINED IN THE MODEL SETUP. 4. RESULTS AND DISCUSSION

4.1 Derivative and semilog plot behaviour

The model produces results which have characteristics very similar to those of the equivalent analytical model (Section 2.1). These are demonstrated with an example model with an impermeable fault boundary at 50m from the well which is compared to a model with no boundary (Figure 3 and 4).

Figure 3 demonstrates a flattening of the pressure derivative followed by a second flat region at a slightly higher level. Figure 4 demonstrates a steepening of the slope of the semilog straight line from 1.3 to 2.0.

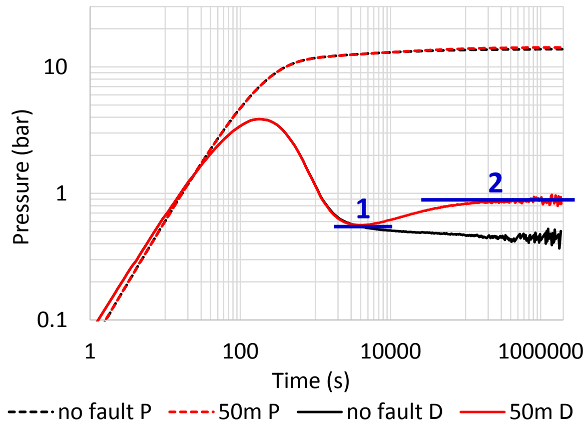

Figure 3: Pressure derivative plot comparing model results for no fault to a fault at 50m. First and second flat derivative regions indicated with blue lines.

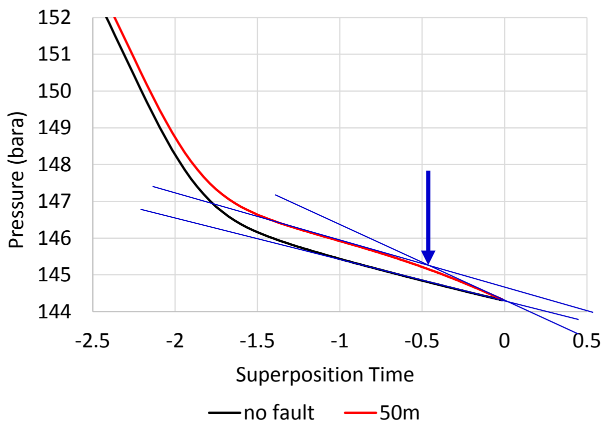

Figure 4: Semilog plot comparing model results for no fault to a fault at 50m. Semilog straight lines indicated with blue lines. Estimated time at which fault influences response indicated with blue arrow.

4.2 Variation of well to boundary distance

The well to boundary distance has been varied from 1m to 5000m. The simulations have been run for 2 million seconds (23 days) to demonstrate the long-term behaviour. The reservoir permeability of the test model is 10mD with no skin effect. The derivative plot results are shown in Figure 5.

It can be seen in Figure 5 that if the fault is very close to the well, then the first flat derivative region cannot be seen as it is masked by the early-time hump related to wellbore storage. For a boundary 10m or closer, the response looks like a standard uniform reservoir response. Therefore the interpretation of the data as a uniform reservoir will result in a significant underestimate of the reservoir permeability.

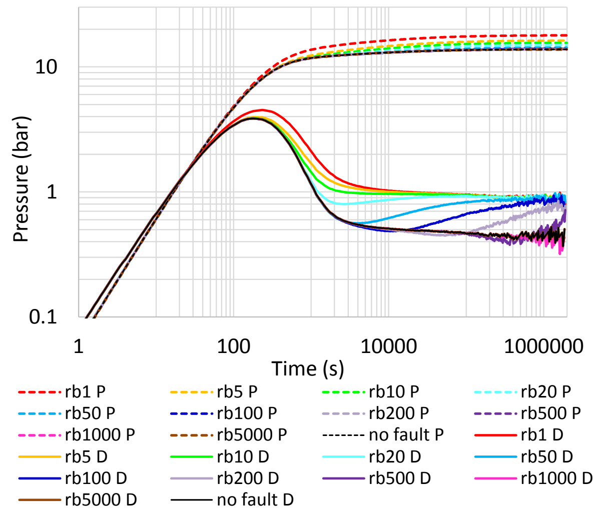

Figure 5: Derivative plot of simulated results for a range of boundary distances 1m to 5000m.

The duration of the simulation is not sufficient to see the effects of a boundary at 1000m or greater. The results for a boundary at 1000m and 5000m are not distinguishable from the results when there is no boundary (Figure 5). In reality it is unlikely the a boundary would be identified at a distance greater than 100m as the effects of this boundary are only seen after 10 hours, and tests of this duration are rare.

In late-time the derivative calculated from the model results becomes increasingly noisy (Figure 5). In late-time the pressure change becomes less as the pressure fall-off flattens. As the pressure change becomes smaller, the number of significant digits available in TOUGH2 for pressure becomes insufficient to describe the pressure change. The pressure output begins to resemble a step function with increments of 0.001 bar. The overall effect on the derivative is that is becomes increasingly noisy, and eventually starts oscillating between noisy sections and zero. This is a fundamental issue related to the way in which TOUGH2 is setup, and also the manner in which the derivative is calculated. It is possible these issues can be resolved with further work, though this is beyond the scope of this paper.

4.3 What is a believable boundary distance?

During the inverse modelling process of fitting various models to a set of field data, a number of models may fit the same data. It is a matter for the reservoir engineer to establish which of the models is the most reasonable (representative). Sometimes a linear impermeable boundary model will “fit” the data but give an impractically large boundary distance of 1000m or more. When a set of field data is quite short and the boundary distance is very large, it is clear the model can be disregarded. However the question of exactly where to draw this line is not easy to address.

The time required for the boundary to affect the results of the test depends on distance to the boundary and also the permeability of the reservoir. The closer the boundary and the more permeable the reservoir, the shorter the test duration required to "see" the boundary.

In order to investigate this issue a number of simulations have been run using the test model. Three values for reservoir permeability have been investigated, 10mD, 100mD and 1000mD. For each permeability value a range of boundary distances has been investigated, 1m, 5m, 10m, 20m, 50m, 100m, 200m, 500m, 1000m and 5000m. Derivative plots of the simulated results have been visually examined to identify the point at which the boundary starts to affect the results (Table 2). These values are the minimum time required for the effect to start, a much longer time is required to adequately capture this effect.

Table 2: Simulation time required to "see" effects of boundary.

Boundary distance (m)	Time to "see" boundary (sec)		
	10mD	100mD	1000mD
1	Too close	Too close	Too close
5	Too close	Too close	Too close
10	Too close	Too close	Too close
20	4,000 (1.1 hr)	400 (0.1 hr)	70 (0.02 hr)
50	6,000 (1.7 hr)	600 (0.2 hr)	100 (0.03 hr)
100	30,000 (8.3 hr)	2,000 (0.6 hr)	400 (0.1 hr)
200	200,000 (2 days)	10,000 (2.8 hr)	1000 (0.3 hr)
500	2,000,000 (23 days)	100,000 (28 hr)	Noisy
1000	Not seen	Noisy	Noisy
5000	Not seen	Noisy	Noisy

It can be seen in the results presented in Table 2 that:

- For all values of reservoir permeability, a boundary 10m or closer cannot be identified. The response is masked by wellbore storage as discussed in Section 4.2.
- Some late time results are so badly affected by noise for reservoir permeabilities of 100mD and 1000mD that the boundary response cannot be identified.
- The time to "see" the boundary increases exponentially with the boundary distance.
- A 10 hour test will "see" a fault out to 100m if the permeability is quite low at 10mD. It will "see" a fault out to 200m if the permeability is higher at 100mD.
- A 1 hour test is not long enough to "see" any faults when the permeability is low at 10mD. A 1 hour test will "see" a fault out to 100m if the permeability is higher at 100mD.
- A reservoir permeability of 1000mD is impractically high and investigated only for interest. In theory if the permeability is this high, then a fault will be "seen" out past 200m with a test of only 1 hour. The limit cannot be determined due to noise in the results.

5. CONCLUSIONS

- The characteristic response for this TOUGH2 linear impermeable boundary model is very similar to but not identical to the analytical model equivalent.
- Characteristics of this model are a second flat region on the derivative plot, and a semilog straight line which steepens to a second semilog straight line.
- A boundary very close to the well (10m or less) cannot be identified as the characteristic features in the derivative plot are masked by wellbore storage. The derivative plot looks like a standard uniform reservoir response, and will result in a significant underestimate of the reservoir permeability.
- The test duration required to "see" a fault response increases exponentially with fault distance.
- In a low permeability reservoir (10mD) a 10 hour test will only see a fault boundary out to approximately 100m. A much longer test would then be required to capture the entire boundary response.
- In a high permeability reservoir (100mD) a 10 hour test will still only see a fault boundary out to approximately 200m.
- Very long simulations produce derivative results which are noisy in late-time. This is related to the number of significant digits available for pressure in the TOUGH2 simulator.
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