

EXPERIMENTAL AND NUMERICAL INVESTIGATION OF SINUSOIDAL PRESSURE TEST

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ABSTRACT

Pressure controlled well test using periodically changing production and injection flow rate is experimentally being applied to geothermal reservoir characterization in Japan. Sinusoidal test is one of the standard periodical function methods. A laboratory experimental apparatus for pressure controlled well test was made, and numerical simulation for designing test rock was done. The numerical simulation was aimed for estimating the range of rock parameters effective for the experiments. Influence of permeability and porosity on amplitude attenuation and phase shift of sinusoidal pressure responses in the test rock was calculated for porous medium and MINC type fractured rock.

Numerical calculations were also done to study the pressure responses of air injection well tests, in which the feed point flow rate is not a simple function of the air injection rate. The experimental and reservoir parameter ranges for use of practical air injection tests were estimated.

INTRODUCTION

Well test is used to evaluate parameters related to the productivity or injectivity of geothermal reservoirs. Conventional well tests consist of injection of water or production of steam at constant flow rate, pressure measurements, pressure transient analysis by graphical method including semi-log plot or type-curve matching .

Improvement of analytical methods based on the developments of modern inversion programs (McLaughlin *et al.*, 1995 or Finsterle *et al.*, 1997) and reservoir simulators (Pritchett, 1995 or Pruess, 1991) have brought about new possibilities of more progressed well test schemes.

NEDO (New Energy and Industrial Technology Development Organization) is developing a new technology for reservoir characterization (Ide *et al.*, in this proceedings) including a new well test system. In this project, NEDO is doing field experiments of pressure controlled well tests, including sinusoidal

test and air injection test. In order to acquire high quality data and to apply them to the new analytical system and derive complicated reservoir parameters, designing of experiments is the most important part.

GSJ is promoting a research program whose purpose is to evaluate and analyze NEDO's project and its data. For the practical use of the new well test system, estimation or prediction of observed signals in geothermal fields should be very important. Ideally, before a well test, a reservoir model which incorporates reservoir parameters estimated from other explorations or experiences should be used as a pre-test reservoir model, for the designing of the well test. Investigation of reservoir responses using the pre-test reservoir models leads to effective use of facilities. The purpose of this study is to expand our experience on new types of well tests, and to evaluate the availability of them.

RESERVOIR PARAMETERS OBTAINED FROM SINUSOIDAL TESTS

Constant production or injection flow rate is usually used in a conventional well test. Multiple flow rate test is also used, which is essentially a superposition of constant flow rate tests. On the other hand, periodical functions can be used for the flow rate.

The merits of using periodical functions for flow rate are, 1) periodical functions can be easily detected and be separated from observed pressure data, 2) fluid flow in the reservoir goes back and forth, so that cold injection water does not damage the reservoir, 3) the same pressure change is observed in each period so that pressure can be monitored at different depths separated by packers in a observed well, 4) analysis of data can possibly be used to depict complicated reservoir parameters such as fractures and three dimensional structures .

On the other hand, the demerits of using periodical functions are, 1) because of the short equilibrium time, pressure signals cannot transmit very far, 2) in order to control the source pressure, elaborated and complicated equipment is necessary, 3) analysis of observed data is not straightforward.

Sinusoidal test uses sine function as the source pressure. Fig.1 shows the source and observed

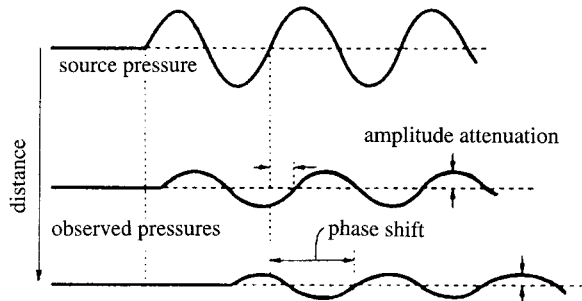


Figure. 1. Source and observed pressures of a sinusoidal test.

pressures. Amplitude attenuation and phase shift of the observed pressures contains reservoir parameter information. Theoretical description of sinusoidal pressure responses for point source cases and line source cases are discussed in Black and Kipp (1981).

Fig. 2 shows amplitude attenuation for combinations of frequency, distance, and diffusivity (ditto).

Considering a typical reservoir parameters, as k (permeability) = 10^{-14}m^2 , ϕ (porosity) = 0.2, and liquid water at temperature of $20 \square 200 \square$, κ (hydraulic diffusivity) is $5 \times 10^{-2} \square 10^{-1} \text{m}^2/\text{s}$ ($5 \times 10^3 \square 10^4 \text{m}^2/\text{day}$). This range is shown by the two vertical broken lines added to the figure of Black and Kipp (Fig.2). Assuming a distance between the source and the observation well to be 100m, and the frequency to be one cycle/2 hours (10 cycles/day), it is shown in the figure that the amplitude ratio (observed amplitude/near source amplitude) becomes less than 10^{-4} in this diffusivity range.

Because of the large attenuation like this example, the most important thing in designing a sinusoidal well test in a geothermal reservoir is to "obtain a detectable pressure signal". In this case, using a long cycle period such as 0.1 cycle/day makes the amplitude ratio to be 3×10^{-3} .

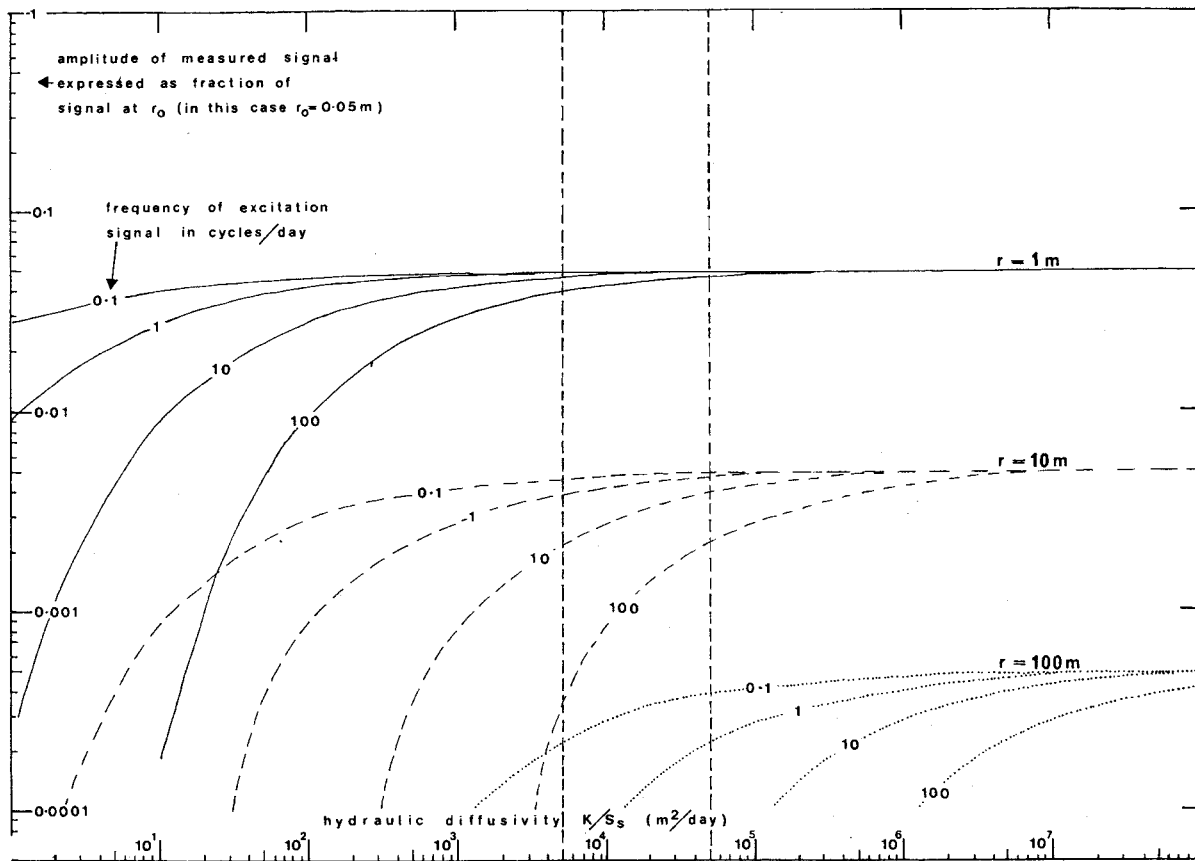


Figure. 2. Dependence of amplitude attenuation on signal frequency, distance, and hydraulic diffusivity for point source case (Black and Kipp, 1981). The vertical broken lines are added to show a range of hydraulic diffusivity explained in the text.

DESIGN OF LABORATORY EXPERIMENT

Experimental apparatus

In order to study pressure-controlled well test, a laboratory experimental apparatus in Fig.3 was made. It consists of a pump, a flow meter, a pressure gauge, and a control unit which controls the pumping rate depending on the pressure measured. Maximum pumping pressure and flow rate are 3kg/cm^2 and $0.01\text{m}^3/\text{min}$. It can create sinusoidal pressures with cycle period from 10 to 1000 sec.

The apparatus has just been tested to make the sinusoidal pressure signal. It is being planned to

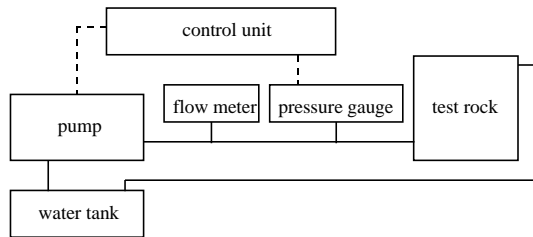


Figure. 3. Configuration of the apparatus for pressure-controlled water injection experiment.

make a vertical two-dimensional test rock piece shown in Fig.4. Pressure gauges and also electrodes will be distributed within the rock piece. Response behaviors of pressure and electrical potential within the rock to the sinusoidal water injection will be monitored to obtain rock parameters.

Simulation study for designing test rock piece

In order to obtain effective signals by the apparatus, preliminary study on the relationship between rock

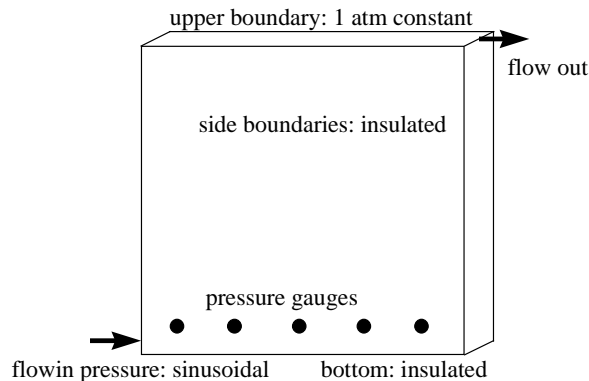


Figure. 4. A vertical two-dimensional rock model.

parameters and the predicted pressure response has been done using numerical simulation. For the simulation, we used the STAR general-purpose geothermal reservoir simulator (Pritchett,1995).

Using a numerical model which simulates a rock shown in Fig.4, pressure changes at the pressure gauges in the figure were plotted. Boundary conditions and the mass source are shown in the figure. Initial condition within the rock is hydrostatic pressure, and temperature is 20°C constant.

Fig.5a shows the pressure changes in a porous rock with $k = 10^{-13}\text{m}^2$ and $\phi = 0.2$. The size of the rock is $2\text{m} \times 2\text{m}$. One cycle period is 100 sec. The largest amplitude shows the source pressure amplitude, and amplitude becomes smaller exponentially as the distance becomes larger. Little phase shift is observed in this case.

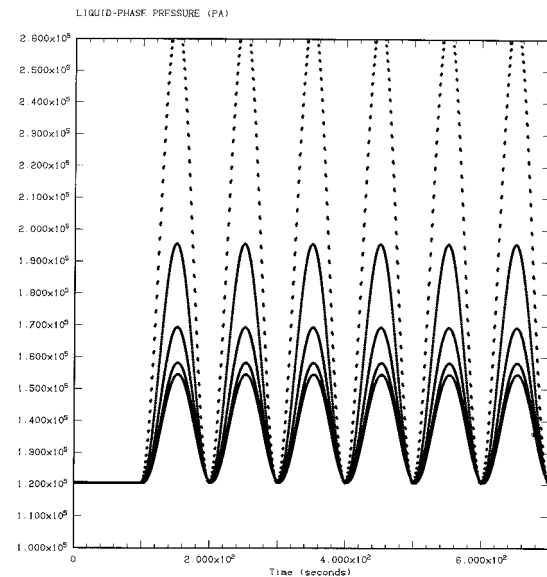


Figure. 5a. Simulated pressures in a test rock of $k = 10^{-13}\text{m}^2$.

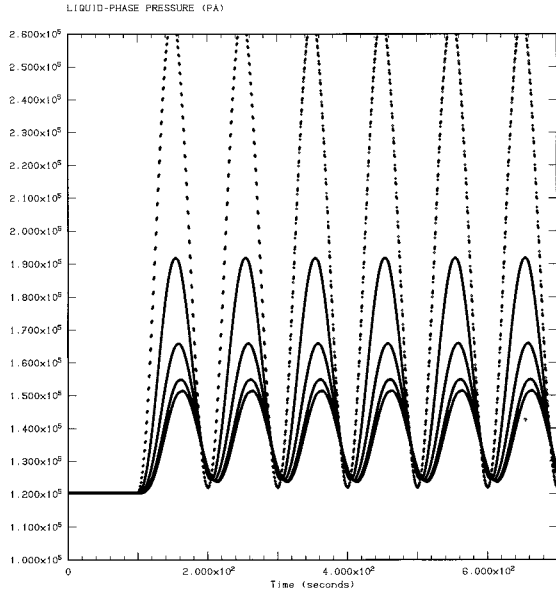


Figure 5b. Simulated pressures in a test rock of $k = 10^{-14} \text{ m}^2$.

Models shown in Figures 5b and 5c use smaller

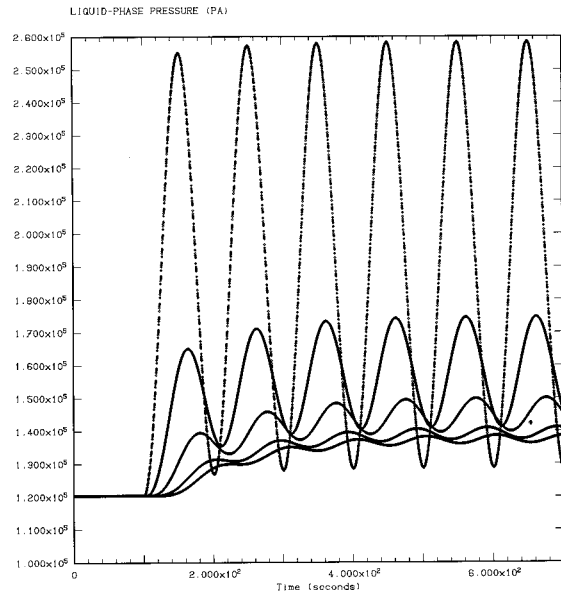


Figure 5c. Simulated pressures in a test rock of $k = 10^{-15} \text{ m}^2$.

permeabilities than Fig. 5a case. In Fig. 5b ($k = 10^{-14} \text{ m}^2$), phase shifts are observed. In Fig. 5c ($k = 10^{-15} \text{ m}^2$), phase shifts are more eminent. In the last case, steady state is not reached within 3 or 4 cycles, due to the very small permeability.

Figures 6a and 6b compare the effect of porosity on the observed phase shifts. Here, the size of rock is

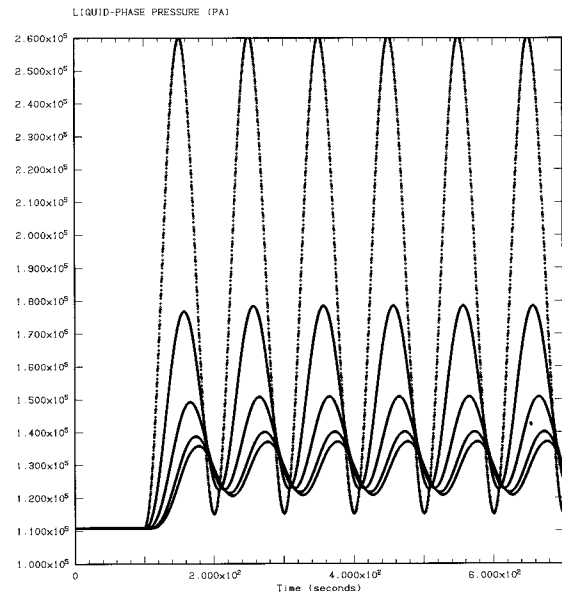


Figure 6a. Simulated pressures in a test rock of $\phi = 0.2$.

$1\text{m} \times 1\text{m}$. Permeability is 10^{-13} m^2 . Phase shift is larger in Fig. 6a where $\phi = 0.2$, and smaller in Fig. 6b where $\phi = 0.05$.

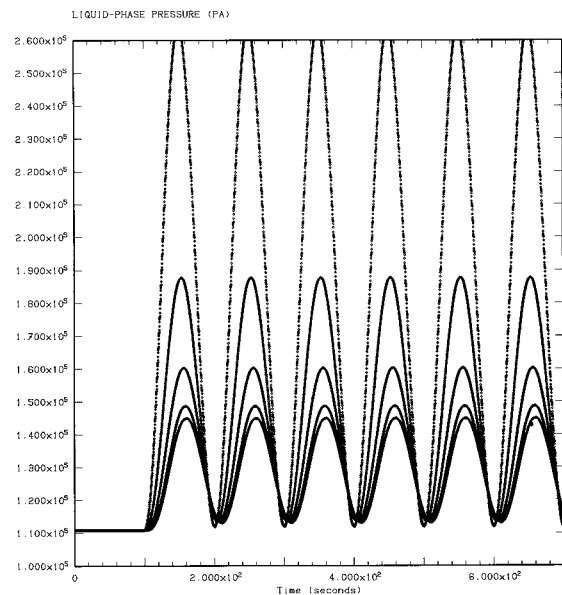


Figure 6b. Simulated pressures in a test rock of $\phi = 0.05$.

In case of fractured porous media, the number of rock parameters becomes larger, including fracture spacing, permeability and porosity of fracture (k_f and ϕ_f), permeability and porosity of rock matrix (k_m and ϕ_m). Figures 7a and 7b show pressure changes in MINC (Pruess and Narasimhan, 1985) type fractured

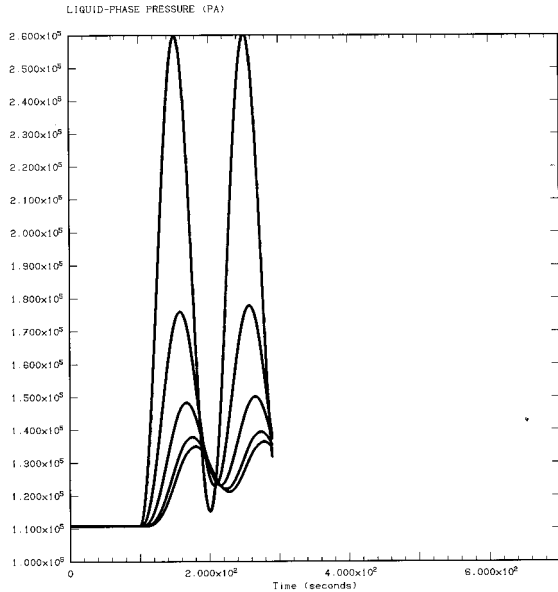


Figure. 7a. Simulated pressures in a fractured test rock of $k_m = 10^{16} m^2$.

rocks. The common parameters are k_f (10

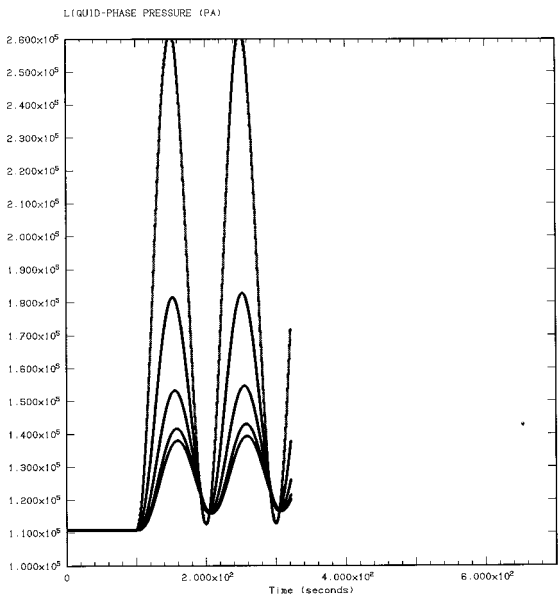


Figure. 7b. Simulated pressures in a fractured test rock of $k_m = 10^{19} m^2$.

$15 m^2$, $\phi_f(0.5)$ and $\phi_m(0.2)$. In Fig.7a, $k_m = 10^{16} m^2$, and $k_m = 10^{19} m^2$ in Fig.7b. It is shown that the difference

of rock matrix permeability brings about the difference of pressure responses.

AIR INJECTION WELL TEST

Air injection well test is another experimental method for geothermal reservoirs. Air can be pumped into or out from a well, so that the test can be periodical. The merits of using air injection instead of water injection are 1) no need of water, 2) no need to put cold water into a production well, 3) easy field operation. On the other hand, the demerits are 1) small feedpoint flow 2) complicated wellbore storage effect which obstructs the reservoir behavior.

In order to study air injection well test, we set up a numerical model shown in Fig.8. It is a cross section view of the radial flow model. Wellbore casing

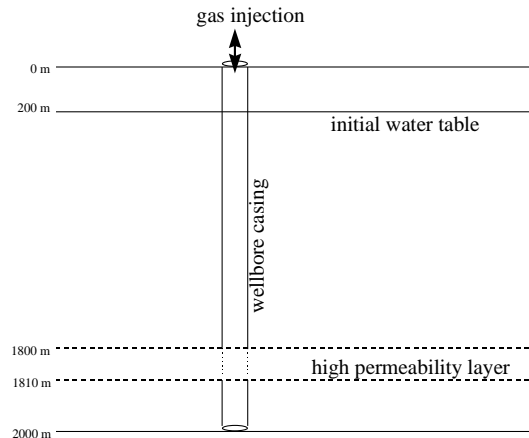


Figure. 8. Gas(air) injection well test.

(radius = 0.1m) is insulated and fluid can only move through the wellbore and the high permeability layer at the depth of 1800m-1810m. At the initial state, water table depth in the well is 200m. Temperature is 20°C (0m-300m), 20°C-150°C (300m-500m), 150°C-250°C (500m-1000m), and 250°C (1000m-2000m). Ideally, the properties of air should be used to simulate air injection model, however, for convenience, we used the default CO₂ properties of BRNGAS equation-of-state package of STAR. Density of CO₂ is about 1.5 times larger than air, but similar well test behavior can be expected.

Fig. 9 shows feedpoint and wellhead pressure transients of gas injection well test, and the change of feedpoint mass flux rate. Note that the pressure scales for feedpoint and wellhead are different. A constant gas injection mass flow rate of 0.1kg/sec was used. The reservoir is porous medium with $k = 10^{13} m^2$ (kh = 1darcy-m) and $\phi = 0.2$. The wellhead pressure increases about 30 bars in 3 hours. On the other hand,

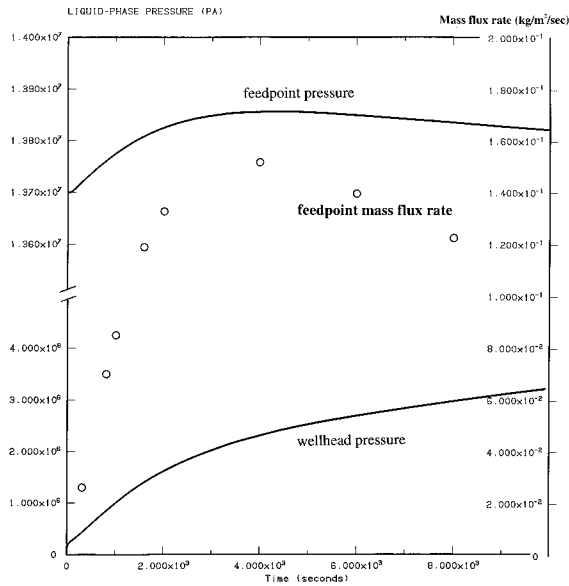


Figure 9. Feedpoint and wellhead pressures (in different scales), and feedpoint mass flux rate of gas injection well test.

the feedpoint pressure increases about 1.5 bars in one hour at the beginning, but it gradually decreases after that, while gas is continuously being injected into the well. This shows the complicated wellbore storage effect for gas injection. As gas is being injected into the well, the pressure and the volume of the gas in the well increase, which push the water in the well downward. As long as the water is moving downward and is moving into the reservoir, the feedpoint pressure is larger than the initial pressure (reservoir pressure). However, as the pressure and volume of the gas increase, the rate of the movement of the water in the well starts to decrease at a certain time (in this case, it is about one hour). As is shown in the figure, the water mass flow rate at the feed point increases in the early time, and it decreases subsequently, corresponding to the change of the feedpoint pressure. Note that mass flux rate of $0.1 \text{ kg/m}^2/\text{sec}$ corresponds to 0.628 kg/sec , because the feedpoint flow area is $2\pi r_w^2$.

Fig.10 shows the effect of magnitude of reservoir kh values on the feedpoint pressure transients of gas injection well tests. The case with $kh = 1 \text{ darcy-m}$ is the same in Fig.9. Feedpoint pressure of the case with larger kh (10 darcy-m) shows little increase, while the wellhead pressure increase (which is not shown in the figure) is almost the same as in Fig.9. Inversely, if kh is small (0.1 darcy-m), feedpoint pressure increase is very large (it is shown in two different scales in Fig.10).

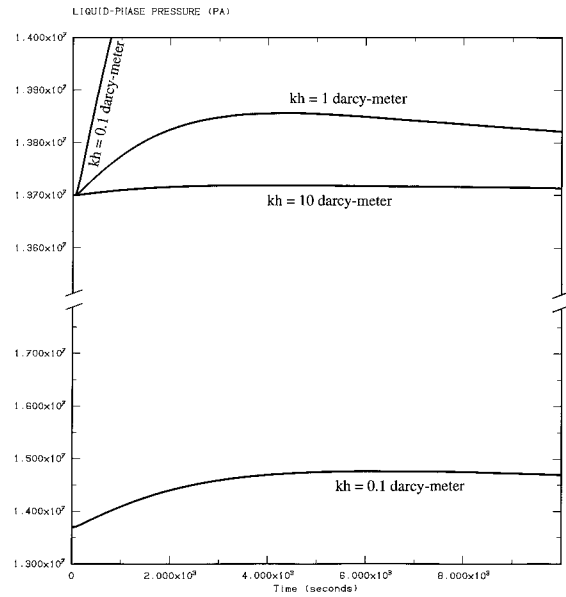


Figure 10. Feedpoint pressures of gas injection well tests for different permeabilities (in two scales for $kh = 0.1 \text{ darcy-meter}$ case).

Fig.11 shows a case of periodical gas

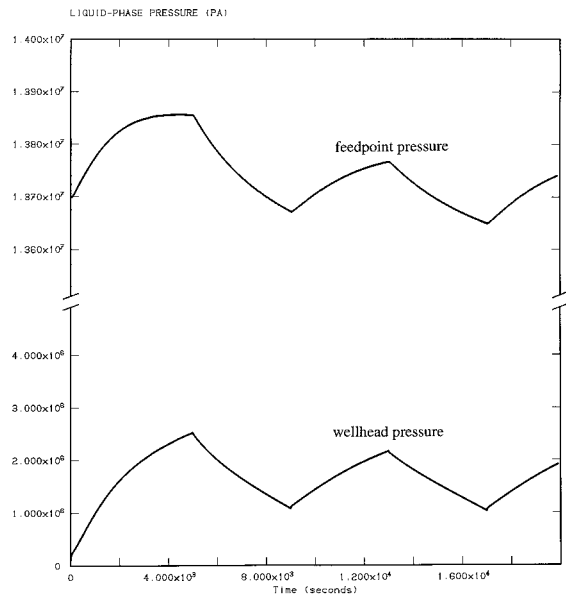


Figure 11. Feedpoint and wellhead pressures of periodical gas injection well test.

injection/suction well test. The reservoir parameters are the same as in Fig. 9. The gas injection rate is 0.1 kg/sec for the first 5000 sec , and -0.07 kg/sec for the next 4000 sec , and then 0.07 kg/sec for the next 4000 sec , and so on. As this periodical gas injection/suction test uses the early times of comparatively large feedpoint flow phase, the feedpoint pressure transient can be periodical.

Simulations of the application of gas injection well test to MINC type reservoirs were also made. However, it was found to be very difficult to see fracture characteristics by gas injection test. As long as the global permeabilities and porosities are the same for a porous reservoir and a fractured reservoir, there is little difference between the feedpoint pressure transients of them, even with a large fracture spacings and small matrix permeability. Fig.12 shows the difference of pressure transients of a porous reservoir and two fractured reservoirs with different fracture spacings, for a “constant” feedpoint

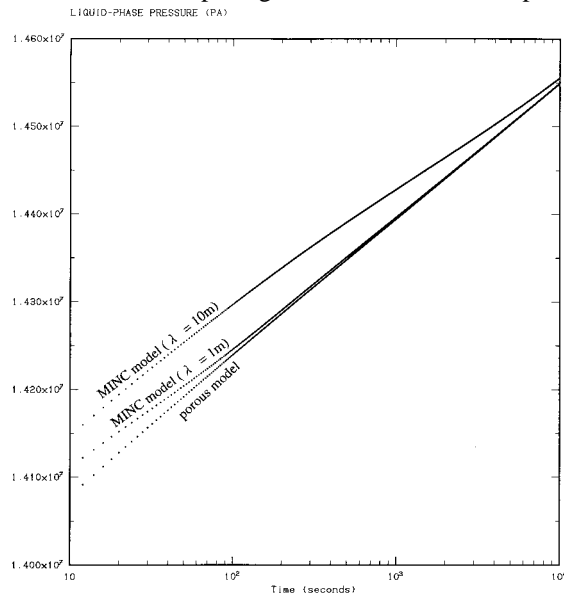


Figure. 12. Feedpoint pressures of water injection into a fractured reservoir

water flow rate (these are not the cases with gas injection). As in the figure, if the feedpoint flow rate are the same and constant, fracture behaviors can be observed. However, in case of gas injection, the complicated wellbore storage effect obstruct the fracture characteristics.

SUMMARY

Considering a typical geothermal reservoir parameters, a large amplitude attenuation may cause difficulty in observing pressures in case of interference test by sinusoidal source pressures. In order to avoid ineffective setup of a testing, prediction of observed signals by pre-test models is important.

A laboratory experimental apparatus was made to investigate sinusoidal test. Observed pressures are fed back into a control unit, which controls the pump to make sinusoidal pressure. Two-dimensional test rock is being considered to be applied to the experiment. Simulation was done for designing the test rock. In

the laboratory scale experiment, it is possible to examine the influence of permeability and porosity on the amplitude attenuation and phase shift. If porosity is small, phase shift is very small. In case of fractured porous medium, larger matrix permeability with a large total porosity makes observable phase shift.

In addition to the sinusoidal water injection test, air injection well test was examined by numerical simulation. Air injection can have merits especially for field operations, but it is quite a trouble for analysis, due to the complicated wellbore storage effect. Even with a constant air injection into a well, feedpoint pressure can only increase in the early time, then it will gradually decrease. The feedpoint pressure transient is sensitive to the reservoir permeability. However, periodical air injection test is possible, using the relatively large early time change of feedpoint pressure. In order to obtain data which can be used to analyze reservoir parameters in a air injection test, it is important to monitor the feedpoint water flow rate. For this, monitoring the water level and the temperature distribution of water column from the water level to the feedpoint by optical fiber system should be one of the practical methods.

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