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MODELING STUDIES OF PRESSURE CYCLING ASSOCIATED WITH SEISMICITY IN MUTNOVSKY GEOTHERMAL FIELD, KAMCHATKA, RUSSIA

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ABSTRACT

Two alternative models are presented to explain pressure cycling in the Mutnovsky high temperature two-phase hydrothermal system. A non-linear well-fracture (W-F) model describes an open observation well in terms of a lumped parameter model, with well discharge specified as a function of liquid saturation. Two conditions were found necessary to create cycling: 1. a hysteretic saturation switch for well discharge ("well off" liquid saturation less than "well on" liquid saturation), 2. heat exchange between the well and surrounding rock (to maintain a pressure gradient from the recharge area to the well). The sensitivity of cycling parameters (cycling period and pressure amplitude) was determined from model parameters. Cycling parameter estimations were found in reasonable agreement with pressure data from an observation well at the high temperature Mutnovsky geothermal field, Kamchatka, Russia. An alternative model considering a wellbore intersected by two fractures was also shown capable of generating cyclic behavior, due to an interplay between the different time scales for pressure and thermal equilibration.

1.INTRODUCTION

Unstable and cyclic pressure behavior is common for non-linear systems such as high temperature geothermal wells, hydrothermal convection systems, and magmatic fluid systems of volcanoes. Geothermal wells are especially prone to instabilities when flowing in two-phase conditions with multiple feed zones (Grant et al., 1982). Conditions that have been suggested as providing possible mechanisms for cyclic internal flows in the wellbore include presence of multiple feeds that differ with respect to fluid enthalpies and reservoir transmissivity (Grant et al., 1979; Haukwa and O'Sullivan, 1982), and transient heat losses from the flowing well to the surrounding formation (Michels, 1991). Pressure instabilities in geothermal systems have attracted special interest in connection with the magnitude 7.3 earthquake of June 28, 1992 in Landers, California, which triggered seismicity at distances of up to 1250 km, with particularly strong responses in geothermally active regions, including Coso, Long Valley, The Geysers, Lassen, and Yellowstone (Hill et al., 1993). As possible mechanism for such triggering, Sturtevant et al. (1996) suggested "rectified diffusion," a process of runaway exsolution of non-condensible gas in which large bubbles grow at the expense of small ones.

This paper presents and evaluates pressure observations at the Mutnovsky geothermal field, which is located in southeastern Kamchatka. Mutnovsky is a liquid-dominated reservoir with fluid temperatures from 235 - 270 °C. Reservoir fluids contain approximately 1% non-condensible gas, mostly CO_2, pressure conditions are close to two-phase, and permeability is fracture-dominated. Continuous high-resolution pressure monitoring with a capillary tubing system installed at a depth of 950 m has been carried out in observation well #30 at Mutnovsky since September 1995 (as a part of IV-GSJ collaboration project) . This well is maintained on "bleed" with a small steam discharge rate of approximately 0.01 - 0.03 kg/s.

2.PRESSURE AND DISCHARGE CYCLING

Four instances of quasi-periodic pressure excursions were observed that correlate with seismic events with magnitude from 3.9 to 4.5 at approximately 100 km distance (Kiryukhin et al , 1998). As an example, Fig. 1 shows the pressure record obtained in the period from December 21 - 24, 1996. A 4.5 magnitude earthquake occurred on December 21st at 91 km distance from the Mutnovsky field. The earthquake disrupted recharge of the battery system for the pressure recorder. For two hours following the earthquake pressures were still recorded from the internal battery charge; then a six hour break occurred in the data until power could be restored. During the next 20 hours, strong quasi-periodic pressure cycling was observed with an amplitude of up to 0.9 bars and time periods from 60 - 90 minutes. Wellhead discharge of well # 30 was found to cycle with the same period as downhole pressures. It is believed that fluid entering well # 30 partially discharges at the well head, and partially is returned to the reservoir at another feed point.

We hypothesize that the quasi-periodic pressure excursions observed at Mutnovsky were triggered by an "initiation event" that is related to the observed seismic activity. The seismicity itself may furnish the initiation event, or some other process may be active that triggers both the seismicity and the pressure excursions. In the following sections we propose and partially evaluate hypothetical scenarios and mechanisms that could explain the field observations.

3.MODEL 1: CYCLING IN A WELL - FRACTURE (W-F) SYSTEM

This model considers a wellbore connected to a single horizontal fracture (Fig. 2). The fracture is modeled as a disk of H = 0.01 m thickness and R = 100 m radius, with constant pressure and temperature conditions maintained at the R = 100 m boundary. A 1-D radial grid is used in the fracture, and the wellbore is modeled as a single "lumped" grid block, as the central element in the 1-D radial grid. The well element is specified so that wellbore volume and surface area are preserved. Heat exchange with the formation is considered for the well element only, where temperature changes from production-induced boiling are most significant. Detailed parameter specifications are shown in Table 1.

Based on flow tests and wellbore flow modeling for the four main production wells at Mutnovsky (Kiryukhin, 1998), the following model was adopted for the well discharge rate

$$(1) \qquad Q = PI * S_w * \rho_w/\mu_w$$

Here, Q is the discharge rate, PI the productivity index, S_w water saturation, ρ_w water density, and μ_w water viscosity. A hysteretic discharge model is used, as follows. At initial reservoir conditions of $S_w = 0.9$ the well is "on." When ,as a consequence of production-induced boiling , the water saturation in the well block drops below a first threshold value S_{w1} ,the well is turned off. Then water saturation increases from recharge, and the well is turned on again when it reaches a second threshold value $S_{w0} > S_{w1}$. In the simulations we use $S_{w0} = 0.8$, while S_{w1} is in the range of $0.635 < S_{w1} < 0.789$, see Table 1. A hysteretic saturation switch for well discharge ("well off" liquid saturation less than "well on" liquid saturation) may be explained by well well-element emptying due to eruption of two-phase fluid from the well , while "no flow" conditions in fracture due to sharp flowrate decline because of critical flow conditions (Fig.3).

Numerical simulations showed cycling behavior of W-F system described above. Fig. 4 presents the cycling behavior of pressures, saturations, well discharge, and recharge data for the base case scenario. Below we discuss the sensitivity of cycling parameters (time period c and pressure amplitude A) to model parameters.

The key parameters determining the cycling behavior of the model are the S_{w0} - S_{w1} switch (the saturation difference S_{w0} - S_{w1} between well discharge being "on" and being "off"), and the T_f - T_r switch (difference between temperature T_f on exterior boundary of the fracture and ambient rock temperature T_r outside the well block). No cycling is observed when these switches are turned off ($S_{w0} = S_{w1}$ and $T_f = T_r$). Other model parameters such as permeability-thickness (kH), heat exchange coefficient (θ) and productivity index (PI) also have important impacts on the period c and amplitude A of cycling (Table 2).

As seen from Table 2 : increase in the difference Sw1-Sw0 causes c and A to increase ; T_f - T_r difference increase causes c to decrease with no effect on A ; kH increase first causes monotonic A decrease, with c decrease to cmin , followed by c increase; PI coefficient increase causes c to decrease and A to increase.

The increase in co-seismic pressure cycling parameters (see above, Fig. 1), i.e., time period increase (from 7.5- 10 min. up to 60-90 min.) and pressure amplitude increase (from 0.15 bars up to 0.9 - 0.95 bars) may be explained from the value of the S_{w1}-S_{w0}-switch increasing from 0.04 to 0.13-0.15 (see Table 2).

4.MODEL 2: CYCLIC FLOW BETWEEN TWO FEED ZONES

Mutnovsky well # 30 intercepts two high-angle fractures that could give rise to cyclic internal flows in the wellbore between the two feeds, accompanied by cyclic variations of downhole pressures. In order to facilitate numerical simulation of this process we adopt a number of simplifications and approximations. The basic fracture-well-fracture (F-W-F) system to be modeled is illustrated in Fig. 5, and typical model parameters are given in Table 3. Corey curves are chosen for relative permeabilities, with irreducible saturations of S_{lr} = .30, S_{gr} = .05. The two fractures are modeled as horizontal, so that 1-D radial grids could be used in the simulations. Flow in the wellbore is approximated as porous flow with very large permeability, using a multi-phase version of Darcy's law. The gravity body force term is modeled using a homogeneous mixture density to improve the representation of wellbore flow. It was assumed that the only permeable features are the fractures and the wellbore. In addition to fluid flow, we also model conductive heat exchange between fracture and wellbore fluids and surrounding formations. For the fractures, this is accomplished by attaching semi-infinite conductive half-spaces to both fracture walls, and using the semi-analytical method of Vinsome and Westerveld (1980). Heat exchange between the wellbore and the formations is treated numerically, by surrounding the wellbore with a 2-D axisymmetric grid. Grid spacing near the wellbore is very small (3 cm), to be able to resolve early-time transients. The heat conduction grid is extended to a sufficiently large distance (50 m) to be infinite-acting for the duration of the simulations.

The upper fracture is initialized in single-phase liquid conditions, while single- as well as two-phase conditions with higher temperatures are used for the lower fracture. The system is first run to a steady-state temperature profile, with hydrostatic pressure equilibrium in the wellbore column. These stable initial conditions are then perturbed by introducing a small instantaneous pressure change of typically 0.5 bar either in the upper or lower fracture.

Qualitatively, the model system is expected to behave as follows. In response to a step increase in pressure in the upper zone, downflow through the wellbore into the lower zone is initiated. This causes fluid pressures to decrease in the upper and increase in the lower zone, so that flow rates will decline with time to very small values. On a slower time scale the cooler fluid introduced into the wellbore and the lower zone will be heated conductively, reducing fluid density and increasing fluid pressure until eventually flow in the reverse direction (up the wellbore) will be initiated. As the wellbore fluid is replaced with hotter less dense fluid from the lower fracture, the magnitude of the gravity body force term is reduced, so that upflow occurs at rapidly increasing rates. Pressurization in the upper and depressurization in the lower fracture will cause flow rates to decline with time, and when rates of upflow have become very small, conductive cooling of wellbore fluid will exceed advective heat supply. Then fluid temperature in the wellbore will decline, and fluid density will increase, until again downflow is initiated, starting a new cycle. Once downflow starts the wellbore fluid is replaced with cooler denser fluid from the upper fracture, causing rapid increase of downflow rates.

Our simulations confirmed that the F-W-F system indeed produces cycling behavior, as expected. Results for liquid phase flow rates are shown in Fig. 6, while Fig. 7 presents the time dependence of wellbore fluid pressures at the upper and lower feedzones, respectively. The amplitude of pressure cycling associated with wellbore flow reversals is approximately 0.7 bars at the upper and 0.5 bars at the lower feed, which is comparable in magnitude to observations at Mutnovsky well #30. However, the time period of the cycles obtained in the simulations is of order 3×10^6 sec, which is about 3 orders of magnitude slower than seen in the field. Limited sensitivity studies were done to try and obtain more rapid cycling. Using linear relative permeabilities as opposed to Corey curves for the wellbore flow gave very similar results. Reducing formation compressibilities by an order of magnitude, from 10^{-8} to 10^{-9} Pa^{-1}, indeed accelerated the time scale for cycling, by approximately a factor of 5, but with strongly reduced amplitude. It is not clear whether or not the conceptual model studied here is capable of generating much more rapid cyclic pressure variations, as observed in the field.

5.DISCUSSION AND CONCLUSIONS

Two possible models for pressure cycling at the Mutnovsky field triggered by seismicity have been proposed and explored by numerical simulation. A non-linear well-fracture (W-F) model produces cyclic behavior by means of a saturation switch for well discharge, coupled with conductive heat exchange between the wellbore and the surrounding rock. Sensivity studies were carried out to determine the dependence of cycling period and amplitude to model parameters. Cycling periods obtained in the model ranged from 3.5 - 277 min, pressure amplitudes of cycling ranged from 0.06 - 1.045 bars. These parameters are in reasonable agreement with pressure data from well # 30 in the Mutnovsky high temperature field.

An alternative model of a wellbore intersected by two fractures (F-W-F) was also shown to produce cyclic pressure and flow behavior following an initial perturbation. In the F-W-F model no non-linear switches are used; instead, cyclic behavior arises from the interplay of different time scales for pressure and thermal equilibration. Pressure amplitudes in the F-W-F model agreed with observations at Mutnovsky, but cycling periods were slower than seen in the field by 2-3 orders of magnitude. It is not known whether the F-W-F could generate much more rapid cycling.

The present study has neglected effects of non-condensible gas. Exsolution and dissolution effects may play a significant role in pressure cycling and should be investigated. We also simply assumed that seismic activity at a distance is capable of generating pressure perturbations in the reservoir which may initiate flows that may or may not show cyclic behavior. The actual triggering mechanism remains unknown. Possible candidate mechanisms include "rectified diffusion" (Sturtevant et al., 1996), and dynamic strain changes (Hill et al., 1993).

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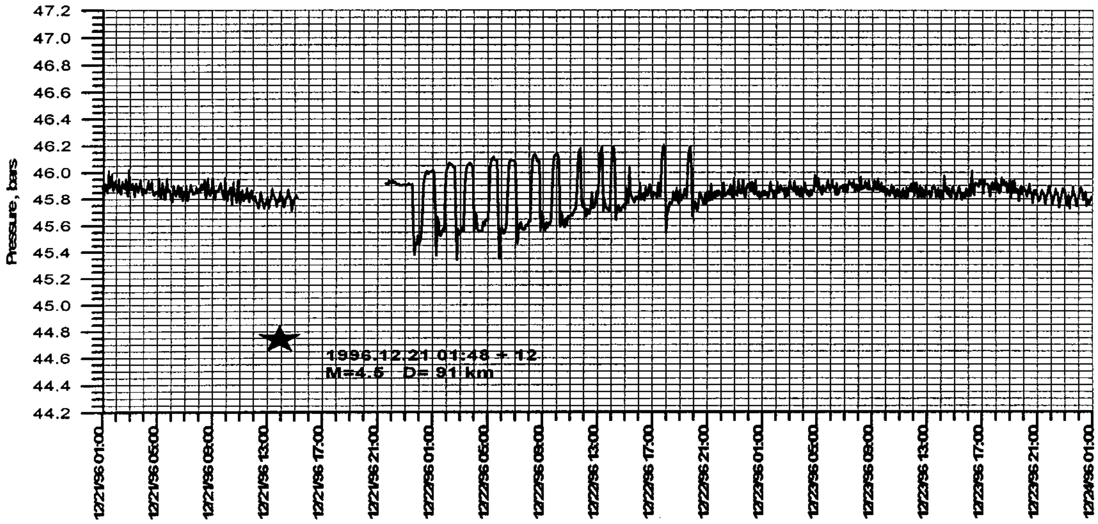

Fig.1 Example of co-seismic cycling in well #30 , Verkhne-Mutnovsky site , Mutnovsky geothermal field. Star denote earthquake event.

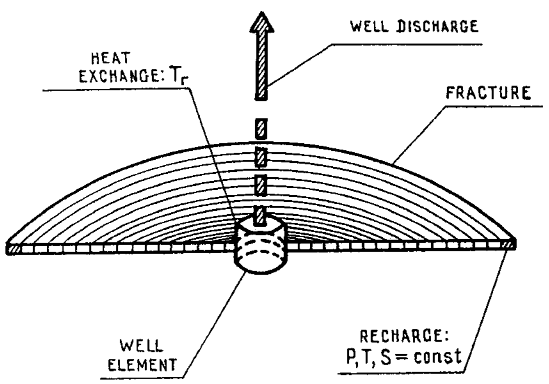

Fig.2 Geometry of "Well-Fracture"(W-F) Model

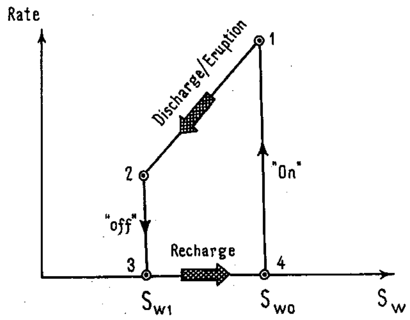

Fig.3 Liquid Saturation-Rate Cycling in W-F system:
1-2 Discharge following by eruption, 2-3 Turn-off the well ,
3-4 Recharge phase , 4-1 Turn-on the well.

Table 1. Parameters for well-fracture (W-F) system.

Fracture	**Base Case**	**Range**	**Well element**	**Base Case**	**Range**
Radius, m	100	100	Porosity	0.95	0.95
Thickness, m	0.01	0.01	Compressibility, Pa^{-1}	0.0	0.0
Permeability , Darcy	1300	13 – 600000	Heat exchange coefficient, W/m^2 °C	21.0	2.1-21000.0
Porosity	0.95	0.95	Water saturation to close discharge S_{w1}	0.7	0.635 - 0.789
Compressibility, Pa^{-1}	0.0	0.0	Water saturation to start discharge S_{w0}	0.8	0.8
Number of elements	200	100-200	PI coefficient, $Pa*m^3$	$2.56*10^{-11}$	$3.2*10^{-13}$ - $2.56*10^{-11}$
Well element			**Initial conditions**		
Volume, m^3	17.17	0.1717- 17.17	Pressure, MPa	4.60	4.60
Heat exchange area, m^2	435.9	4.359 – 435.9	Liquid Saturation	0.9	0.9
Ambient rock temperature T_r ,°C	258.5	252 – 259.5	Temperature, °C	258.75	258.75

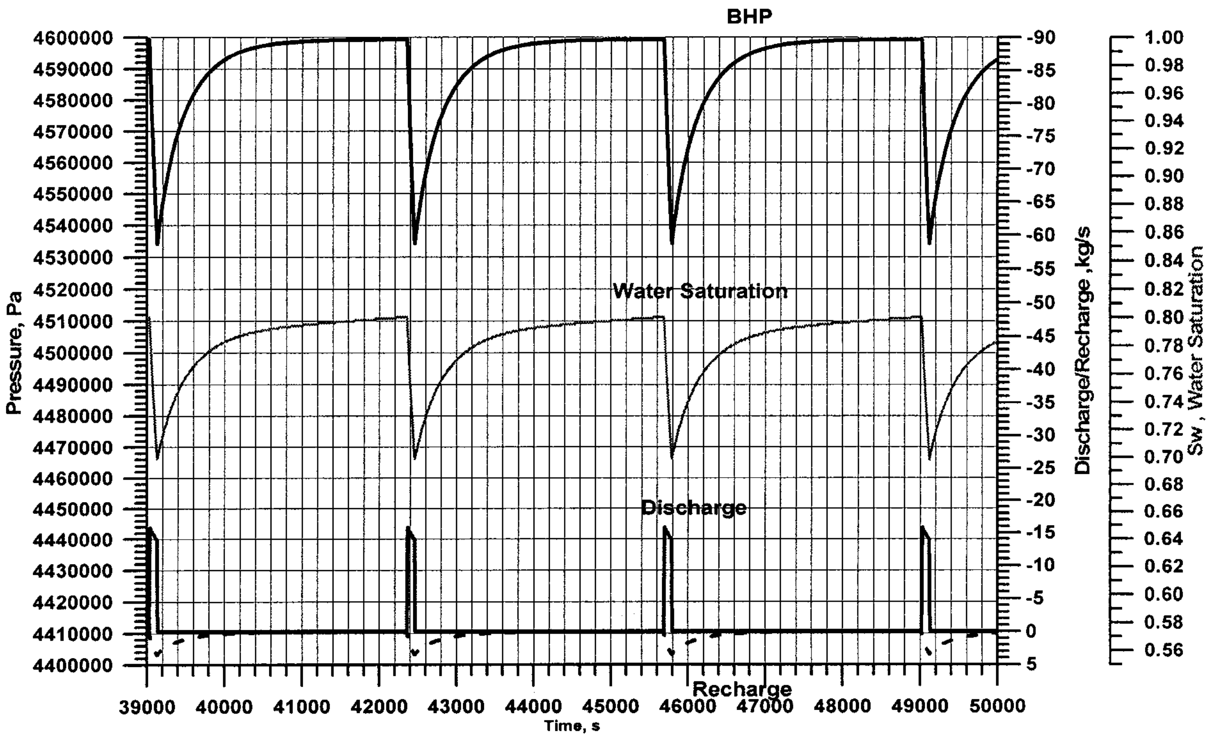

Fig. 4. Cycling of bottom hole pressure (BHP), water saturation, and discharge for W-F system.

Table 2. Cycling parameters obtained for W-F model.

	Time period c of cycling, min	Pressure amplitude A of cycling , bars	# of runs
$S_{0,1}$-switch $S_{0,1} \subset [\,0.011, 0.165\,]$	$c=172.2\Delta S+ 3638.9\Delta S^2$ $c \subset [\,3.5, 129.8\,]$	$A=6.38\ \Delta S$ $A \subset [\,0.069, 1.045\,]$	6
$T_{f,r}$ -switch $T_{f,r} \subset [\,0.0, 7.0\,]$ (°C)	$c = 20.7\Delta T^{-0.694}$ $c \subset [\,6.7, 91.0\,]$	No relation found $A \subset [\,0.618, 0.652\,]$	5
Kh , $Kh \subset [0.13 , 6000\ ]$ Permeability*thickness (D*m)	$c=53.8+(17.5-12.3\ lg(KH))^2$ $c_{min}=53.8$, $KH_{min}=26.5$ $c \subset [\,53.8 , 933.3\,]$	$A=0.72+0.035lg(KH)-0.054lg^2(KH) \approx$ $0.7 - 0.05\ lg^2(Kh)$ if $1 \le KH \le 6000$ $A \subset [\,0.01, 0.694\,]$	10

θ ,$\theta \subset$ [2.1,21000] Heat exchange coefficient(W/m2 oC)	$c = 75.4(\theta)^{-0.997}$ $c \subset [\,25.2, 261.6\,]$	$A= 0.61+0.131g\theta-0.061g^2\theta \approx 0.7-0.041g^2\theta$ if $21 \le \theta \le 21000$ $A \subset [\,0.057, 0.68]$	9
PI, PI$\subset$[3.2E-7,2.56E-5] Productivity coefficient (Pa*m3)	$d = 6.001g(PI+7.0)^{-4.11}$ $d \subset [\,0.15 ,99.7\,]$ d - time period of discharge	$A=0.7-0.08\ lg(PI+7.0)^{-2.23}$ $A \subset [\,0.33, 0.69\,]$	5

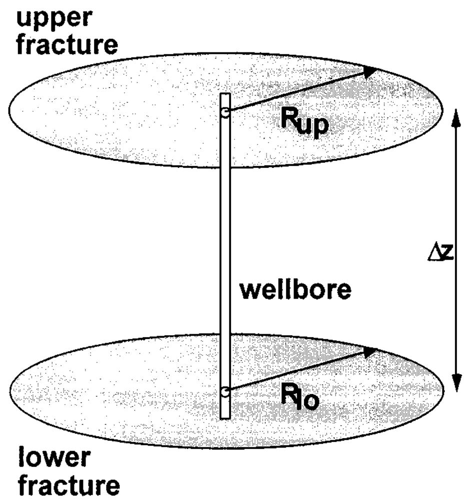

Figure 5. Conceptual model of a system of two fractures intercepted by a wellbore.

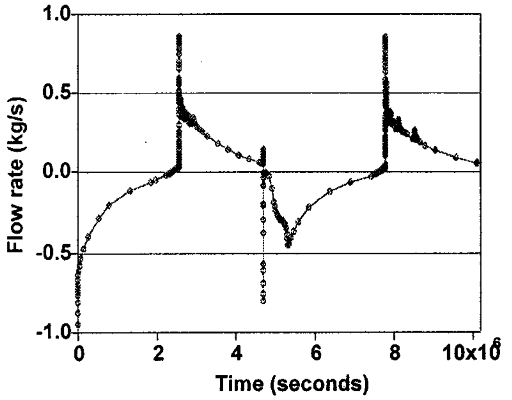

Figure 6. Liquid flow rates in the wellbore. Positive rates indicate upflow.

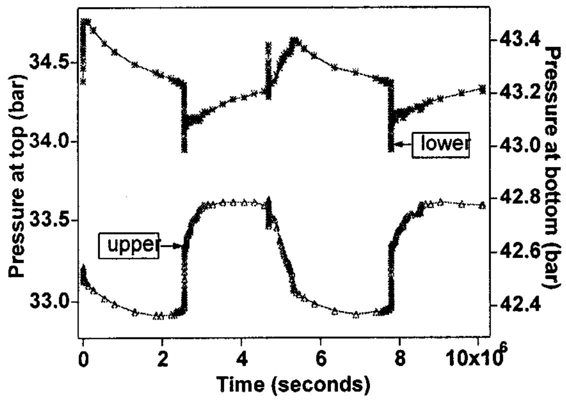

Figure 7. Fluid pressures at upper and lower feedzones.

Table 3. Parameters for fracture-well-fracture system

upper and lower fracture zones	
radius	$R_{up} = R_{lo} = 1000$ m
thickness	$h = 0.25$ m
permeability	$k_f = 10^{-11}$ m^2
porosity	$\phi_f = 0.90$
compressibility	$c = 10^{-8}, 10^{-9}$ Pa^{-1}
vertical distance	$\Delta z = 130$ m
Wellbore	
Radius	$R_w = 70$ mm
Permeability	$k_w = 10^{-7}$ m^2
Porosity	$\phi_w = 0.823$ (*)
thermal parameters	
rock grain density	2650 kg/m^3
rock specific heat	1000 J/kg °C
Thermal conductivity	2.1 W/m °C
Thermodynamic parameters	
Temperature	$T_{up} = 237$ °C
	$T_{lo} = 250 - 255$ °C
	T_{wel} (conductive profile)
pressure	$P_{up} = 32.98$ bar
	$P_{lo} = 43.25$ bar
	P_{wel} (gravity equilib.)
gas saturation	$S_{up} = 0$
	$S_{lo} = 0.1$ %

(*)Chosen to preserve the volume of the5''diameter wellbore.