

# Finite Element Simulation of Wireline Formation Tester Applied in Fractured Reservoir

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**Abstract:** This paper used finite element method to simulate the pressure response of wireline formation tester applied in fractured reservoir. At first, the interval pressure transient tests (IPTT) are used to test the pressure response for both crossing well bore and non-crossing fractures in low permeability formation. The simulation results indicate that the fractures crossing the well bore can have dramatic effect on pressure response depending on fractures conductivity, but non-crossing fractures in the vicinity of the well bore have negligible effect. Then the paper used numerical simulation to analyze the feasibility that evaluates the fractures non-crossed well bore with the method of harmonic pulse testing, the results indicate both harmonic amplitude and phase shift are sensitive to the conductivity of fractures in the vicinity of well bore and certify the method can be used to evaluate the fractures efficiently.

**Keywords:** Finite element method, Wireline formation tester, Interval pressure transient tests, Harmonic pulse testing, Fracture seepage.

## 1. INTRODUCTION

Fractures play an important role in both reservoir fluid flow and well productivity. Fractures and faults can behave as barriers, baffles, or open channels to fluid flow in the reservoir and often cause early water breakthrough, gas channeling, etc, which are costly [1]. A good understanding of the fracture characteristics is essential for a successful development of a tight, heavily fractured reservoir. Fracture conductivity is an important parameter to evaluate the fractured reservoir, because it affects the management of fractured reservoir and well productivity. An efficient fracture characterization is required to understand the recovery mechanism, which is critical for field development and optimal production strategy decisions [2, 3].

Micro porosity, as well as fractures, commonly present in carbonate reservoirs, therefore, in contrast to well-sorted sandstone, it is difficult to relate porosity and lithofacies directly to permeability for a carbonate reservoir. Furthermore, the zone's permeability of the faulted deformation bands can be significantly less than that of the formation or infinite if they are open. Although fractures and faults conductivities can be indirectly inferred from formation micro-resistivity images and seismic techniques, these methods are not very reliable. In addition, fractured and faulted zone permeability cannot be obtained from cores because it is almost impossible to capture unaltered cores from these zones [4, 5].

The discrete spatial distribution of fracture and fault conductivities can be estimated from transient pressure

measurements that are spatially distributed [6]. The dual packer module of wireline formation tester (interval pressure transient tests) provides pressure measurements in the near well bore, which can be about 10 ft to 30 ft depending on reservoir permeability [7]. The dual-packer module for an interval test straddles a fracture, a set of fractures, or a fault zone and makes direct measurements of effective conductivities. The pressure response across a set of fractures or faults can immediately indicate if they have high conductivity or are impermeable as was shown by Kuchuk *et al.*, [8, 9]. The fractures intersecting the well bore can have dramatic effect on pressure response depending on the fractures conductivity. Hence the quantitative fracture characterization is possible with interval pressure transient tests. As has been said, non-crossing fractures in the vicinity of the well bore have negligible effect.

A new pressure-pulse test analysis technique has also been introduced by Proett [10, 11]. This method then has been improved [12]. Harmonic pulse testing uses an oscillatory displacement source at the piston face, and the phase delay of the pressure pulse between the probes is used to determine permeability and anisotropic index. This technique is particularly useful when the second monitoring probe is weak or where there is large spacing between the probes. Pulse timing can usually be detected more accurately than its magnitude, thus extending the range of permeability and anisotropic measurements. In addition, the fractures are the main factors to generate the anisotropy in the reservoir.

In order to research the effects that evaluate the fractures in the reservoir with wireline formation tester, we used finite element method to simulate the pressure response of fractured reservoir with the method of interval pressure transient tests and harmonic pulse testing. At first, we

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simulated the pressure response of different fracture parameters with Interval pressure transient tests and analyzed the different effects that evaluated the fractures crossed and non-crossed well bore. Then we analyzed the feasibility that evaluated the fractures non-crossed well bore with the harmonic pulse testing. The pressure response of different pulse frequencies and different dual probe spacings were simulated and we compared the simulation results of different fracture parameters. At last, we got the conclusions that the interval pressures transient tests could evaluate the fractures crossed well bore efficiently and the harmonic pulse testing could be used to detect the fractures non-crossed well bore.

**2. NUMERICAL MODEL METHOD**

**2.1. Mathematical modeling**

In order to research the pressure response of wireline formation tester applied in fractured reservoir, some synthetic fracture examples are considered. The finite element model for this analysis is based on the simulation software of wireline formation testing, which has been developed by our laboratory [13, 14]. The model was established using Darcy’s law that adds the fractures between the two adjacent blocks Fig. (1). Darcy’s law governs velocities in the matrix blocks, while setting up flow in the fractures on boundaries by accounting for the fracture aperture [15, 16]. Representing the fracture as an interior boundary is especially efficient, because it eliminates the need to create the geometry with high aspect ratio.

Fluids in fractured porous media move quickly through the fractures but also migrate, albeit relatively slowly, through the tiny pores within the surrounding matrix blocks. Some fluid transfers between the fractures and the matrix blocks, so fluid pressure is continuous across the fracture from block to block. Then the mathematical model of the whole course of seepage flow can be derived from the continuity equation, state equation and equation of motion.

The equation of motion can be derived from Darcy’s Law:

$$v = -\frac{K}{\mu} \nabla P \dots \tag{1}$$

Where  $v$  is the velocity of fluid,  $\mu$  is the viscosity of fluid,  $P$  is the pressure of formation,  $K$  is the formation permeability.

The state equation of micro-compressible fluid is:

$$\rho = \rho_0 e^{C_f(P-P_0)} \dots \tag{2}$$

Where  $\rho$  is the density of fluid,  $\rho_0$  is the density of fluid under the pressure of  $P_0$ ,  $C_f$  is the fluid coefficient of compression,  $P_0$  is the initial formation pressure.

The state equation of porosity media is:

$$\phi = \phi_0 e^{C_\phi(P-P_0)} \dots \tag{3}$$

Where  $\phi$  is formation porosity,  $\phi_0$  is the porosity under the pressure  $P_0$ ,  $C_\phi$  is the rock coefficient of compression.

$$C_t = \phi * C_f + (1-\phi) * C_\phi \dots \tag{4}$$

$C_t$  is the total compression of fluid and rock.

The continuity equation, namely mass conservation equation, is:

$$\nabla \cdot (\rho v) + \frac{\partial(\phi\rho)}{\partial t} = 0 \dots \tag{5}$$

Where  $\phi$  is formation porosity,  $t$  is the time.

Substituting equation (1)~(4) into equation (5), the seepage equation of matrix block is derived:

$$\nabla \cdot (-\rho \frac{K}{\mu} \nabla P) + \rho C_t \frac{\partial P}{\partial t} = 0 \dots \tag{6}$$

According to the same principle, the seepage equation of fractures is:

$$\nabla \cdot (-\rho \frac{K_f}{\mu} d_f \nabla P) + \rho d_f C_t \frac{\partial P}{\partial t} = 0 \dots \tag{7}$$

Where  $K_f$  is fractures permeability,  $d_f$  is fracture aperture.

When fractures intersect with the well bore, the interval pressure transient tests was used, the edge that fracture intersecting the well bore is defined as flow boundary:

$$(-\rho \frac{K_f}{\mu} \cdot d_f \cdot \nabla P) \cdot L|_{fracture} = q_f \dots \tag{8}$$

Where  $L$  is the length of fractures which intersect the well bore,

When fractures do not intersect the well bore, the area between dual-packer or probe area (harmonic pulse testing) is defined as flow boundary:

$$(-\rho \frac{K}{\mu} \nabla P) \cdot S|_{matrix} = q \dots \tag{9}$$

Where  $S$  is flow area between dual-packer or probe area.

According to above equations, the mathematical model of wireline formation tester applied in fractured reservoir can be derived:

$$\begin{aligned} \nabla \cdot (-\rho \frac{K}{\mu} \nabla P) + \rho C_t \frac{\partial P}{\partial t} &= 0 \text{ In matrix domain} \\ \nabla \cdot (-\rho \frac{K_f}{\mu} d_f \nabla P) + \rho d_f C_t \frac{\partial P}{\partial t} &= 0 \text{ In fracture domain} \\ P|_{t=0} = P|_{r=\infty} = P_0 & \text{ Boundary conditions ...} \end{aligned} \tag{10}$$

$$(-\rho \frac{K}{\mu} \nabla P) \cdot S = q \text{ Matrix is defined as flow boundary}$$

$$(-\rho \frac{K_f}{\mu} \cdot d_f \cdot \nabla P) \cdot L = q_f \text{ Fracture is defined as flow boundary}$$

**2.2. Finite Element Modeling**

According to the Galerkin method of weighted residual method, the equation (6) can be transformed into finite element style:

$$\iiint_{\Omega} (\nabla \cdot (-\rho \frac{K}{\mu} \nabla P) + \rho C_t \frac{\partial P}{\partial t}) \cdot N_{pi} = 0 \dots \tag{11}$$

Where  $N_{pi}$  is shape function of pressure.

Opening the equation (11) and take the integration by part to the first part of equation (11):

$$\iiint_{\Omega} \nabla \cdot \left( -\rho \frac{K}{\mu} \nabla P \cdot N_{pi} \right) d\Omega + \iiint_{\Omega} \rho \frac{K}{\mu} \nabla P \cdot \nabla N_{pi} + \iiint_{\Omega} \rho C_t \frac{\partial P}{\partial t} \cdot N_{pi} = 0 \quad (12)$$

According to Green theory, the equation (12) can be transformed as:

$$\iiint_{\Omega} \left( \rho \frac{K}{\mu} \nabla P \cdot \nabla N_{pi} \right) d\Omega + \iint_{\Gamma} -\rho \frac{K}{\mu} \nabla P \cdot N_{pi} d\Gamma + \iiint_{\Omega} \rho C_t \frac{\partial P}{\partial t} \cdot N_{pi} = 0 \quad (13)$$

According to the same principle, the finite element style of fractures is

$$\iiint_{\Omega} \left( \rho \frac{K_f}{\mu} d_f \nabla P \cdot \nabla N_{pi} \right) d\Omega + \iint_{\Gamma} -\rho \frac{K_f}{\mu} d_f \nabla P \cdot N_{pi} d\Gamma + \iiint_{\Omega} \rho C_t \frac{\partial P}{\partial t} d_f \cdot N_{pi} = 0 \quad (14)$$

When fractures intersect with well bore, substituting boundary condition equation (8) into equation (14):

$$\iiint_{\Omega} \left( -\rho \frac{K_f}{\mu} d_f \nabla P_f \cdot \nabla N_{pi} \right) d\Omega + \iint_{\Gamma} \frac{q_f}{L} \cdot N_{pi} d\Gamma + \iiint_{\Omega} \rho S \frac{\partial P}{\partial t} d_f \cdot N_{pi} = 0 \quad (15)$$

When fractures do not intersect with the well bore, substituting boundary condition equation (9) into equation (13):

$$\iiint_{\Omega} \left( -\rho \frac{K}{\mu} \nabla P \cdot \nabla N_{pi} \right) d\Omega + \iint_{\Gamma} \frac{q}{S} \cdot N_{pi} d\Gamma + \iiint_{\Omega} \rho S \frac{\partial P}{\partial t} \cdot N_{pi} = 0 \quad (16)$$

A coarse mesh was used for the rock matrix, and an extra-fine mesh for the fracture itself, the reason for this is that we are primarily interested in the fluid behavior within the fracture itself. The permeability of the rock matrix is extremely low, and thus any matrix flow is virtually negligible. As such, the use of a relative coarse mesh in this part of the model helps to conserve memory and computing power for the more important calculations; a dense mesh is used around the fracture to simulate the flow geometry accurately.

### 3. INTERVAL PRESSURE TRANSIENT TESTS

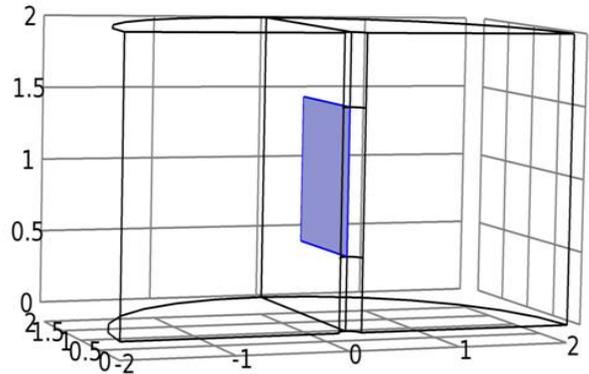
Interval pressure transient tests are conducted using the wireline conveyed dual packer. Each interval is about one meter and envelops a matrix, fracture or fault zone and sets against the borehole to isolate the tested section from the rest of the well bore. The formation fluid is produced through the isolated packers by moving the pretest piston at a constant rate.

**Table 1. Parameters of matrix and fracture.**

Parameters	Matrix	Fracture
Porosity	0.15	0.5
Permeability	10mD	10D~1000D
Fluid Density	0.8g/cm <sup>3</sup>	0.8g/cm <sup>3</sup>
Fluid Viscosity	1cp	1cp
Total Compressibility	3e-6 (1/psi)	3e-6 (1/psi)
Fracture aperture	—	0.01~1mm
Fracture length	—	0.5m~1.5m

In the first example, the geometry in Fig. (1) is a half of cylinder, whose radius and thickness are 2 meters each. It is established as an oil reservoir. A well bore was designed in the middle of cylinder, with a radius of 0.1m. A vertical fracture of square area was designed to intersect the well bore in the middle of the reservoir, where the parameters of matrix and fracture are shown in Table 1. The initial pressure in reservoir and boundary pressure in the geometry are both 10000psi .

According to the seepage principle of dual porosity and dual permeability in the reservoir, the fluid primarily flows to the borehole from the fracture when fracture intersects with well bore, then the fluid flows from matrix to the fracture when a pressure gradient is generated between matrix and fracture. The walls of the well are therefore designed to be impermeable, except where the fracture intersects the well bore. In order to simulate the process of pressure response during drawdown and buildup, the fluid was drawn at a constant flow rate of 12.5cm<sup>3</sup>/s for 30s, then the drawing stopped and the pressure buildup began for 30s to observe the pressure response at the position of dual packer interval.



**Fig. (1).** Geometry of the fracture intersects with well bore.

In order to investigate the effect of the fracture conductivity on the interval test behavior, at first, we changed the fracture permeability in the range from 10D, 100D to 500D. The pressure response is shown in Fig. (2). The simulation results indicate that pressure drawdown is faster and buildup occurs slower as the fracture permeability decreases. The pressure differential is 259.61psi, 288.61psi and 481.51psi between initial pressure and flow pressure at 30 second, which responds the fracture permeabilities ranging from 10D, 100D to 500D. The pressure differential of different fracture permeabilities can be distinguished easily from a pressure gauge. It presents that the fracture permeability can be evaluated by the interval pressure transient tests efficiently.

The fracture length was then varied from 0.5m, 1m to 1.5m, Fig. (3) shows the simulation results. The pressure drawdown is faster and pressure buildup occurs slower as the fracture length is decreased. In addition, the pressure differential and the time of pressure buildup change dramatically for different fracture lengths. It indicates that the fracture length strongly affects the pressure response.

Finally, we simulated the pressure response of different fracture apertures. The simulation results are shown in

Fig. (4). Changes in pressure aperture have a dramatic effect on the pressure drawdown and buildup. In addition, the pressure drawdown is faster and buildup occurs slower as the fracture aperture is decreased.

Because the fractures do not intersect the well bore, the surface of well bore between the dual packers was designed as a mass flux. At the beginning, the packer interval drew fluid at a constant flow rate of 40cm<sup>3</sup>/s for 30 seconds, then the fluid flow was stopped and the pressure was allowed to build up for 30 seconds.

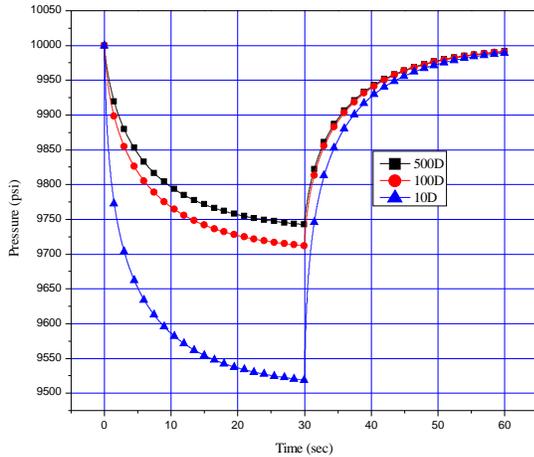


Fig. (2). Pressure response of different fracture permeabilities.

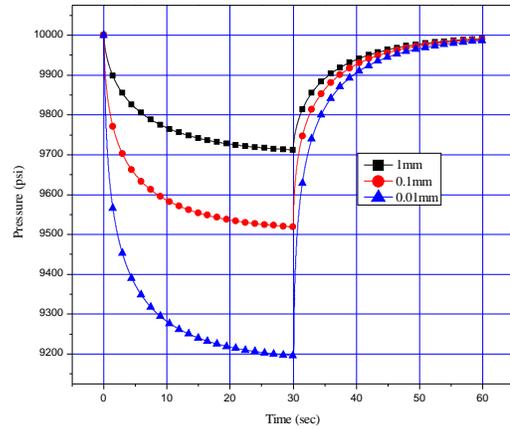


Fig. (4). Pressure response of different fracture apertures.

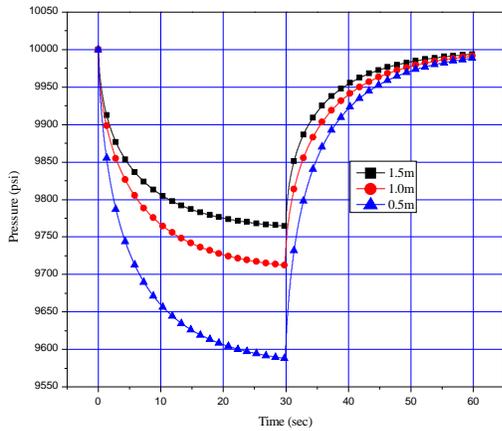


Fig. (3). Pressure response of different fracture lengths.

In the second case, the geometry is shown in Fig. (5) and the parameters of reservoir are the same as the first case, except that the fractures do not intersect with the well bore. The vertical fractures were constructed with three identical elliptical areas, whose long semi-axis is 0.5m and short semi-axis is 0.05m, the distance from center of three facturs to the well bore is 30cm, 50cm and 70cm respectively.

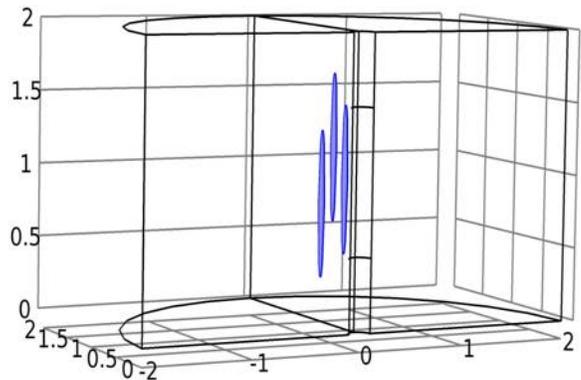


Fig. (5). Geometry of the fractures non-crossing with well bore.

For the second case, the fracture permeability was varied from 10mD, 1D, 10D to 1000D. The formation is homogeneous and none fracture exists in formation when the fracture permeability is defined as 10mD, because the reservoir permeability is 10mD. Fig. (6) shows the pressure response for the four cases. The simulation results show that pressure response have a small change when the fracture permeability is varied. As is shown in Table 2, the pressure differential between initial pressure and flow pressure at 30

Table 2. The pressure differential for different fracture parameters after 30 seconds.

Fracture permeability (Darcy)	Pressure differential (psi)	Fracture length (m)	Pressure differential (psi)	Fracture distance (cm)	Pressure differential (psi)
0.01	299.16	0	299.16	20cm	311.71
1	296.77	0.5	298.22	30cm	318.57
10	293.67	1	293.67	50cm	322.56
1000	291.35	1.5	287.13	70cm	323.48
				100cm	323.81

second was calculated. Although the value of different pressure differentials can be distinguished by a quartz gauge, the effect to pressure response is negligible.

Then the pressure response of different fracture lengths along vertical direction was simulated. As is shown in Fig. (7), the fracture length varies from 0.0m, 0.5m, 1m to 1.5m. However, the effect of pressure response is negligible. Only when the fracture length increases to 1.5m, the effect is noticeable.

Finally, we simulated the pressure response for different radial depths for one fracture. The distances from fracture to well bore are 20cm, 30cm, 50cm, 70cm and 100cm respectively. Fig. (8) shows the pressure response at the interval packer. From these simulation results, as have been shown in the figures, the pressure responses are relatively little affected by the different radial depth of fractures. Only when the fracture gets much closer the well bore does the effect becomes noticeable. Table 2 shows the pressure differential of different fracture permeabilities, different fracture lengths and different fracture radial depths at 30 second. It indicates that the interval pressure transient tests are not able to detect and evaluate the non-crossing fractures with well bore.

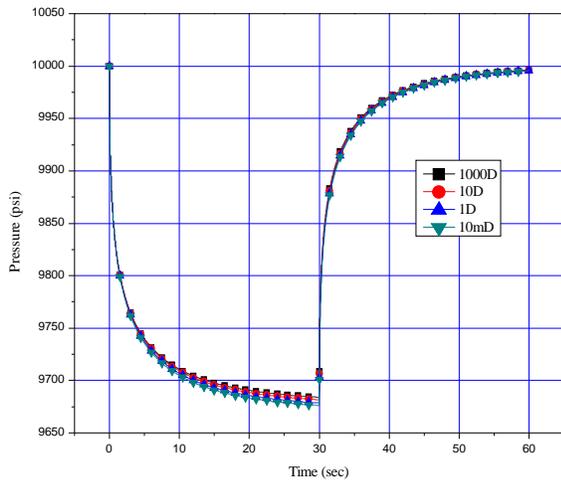


Fig. (6). Pressure response of different fracture permeabilities.

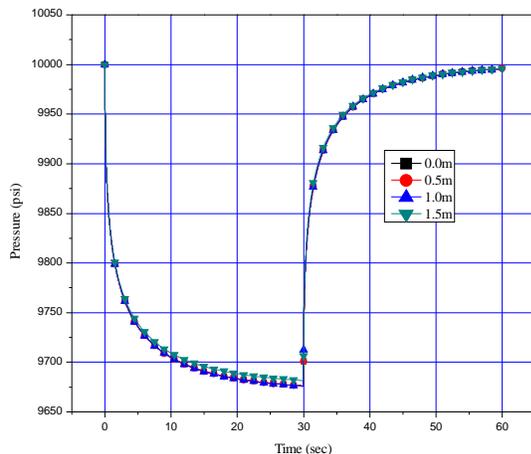


Fig. (7). Pressure response of different fracture lengths.

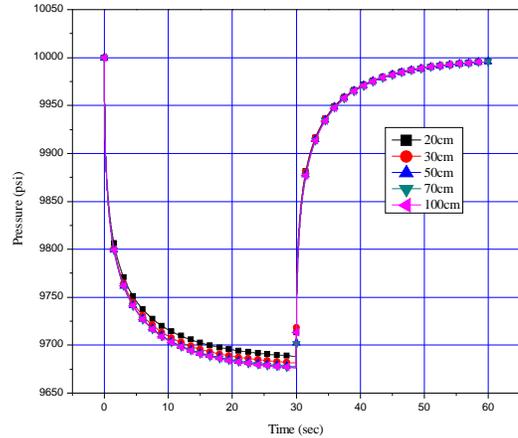


Fig. (8). Pressure response for different fracture radial depths.

#### 4. HARMONIC PULSE TESTING

A convenient method of using the harmonic analysis testing technique is to analyze the pressure pulses generated while pumping a sample. The pressure wave is generated by a reciprocating piston transmitted to the formation by a probe. The pressure is sensed by a high accuracy quartz gauge in the probe. This pressure is compared to the pressure sensed at a spaced probe or to the flow rate of the piston to calculate permeability or other formation properties [17, 18]. The basic relationships for the pressure amplitude and time delays have been developed by Proett and Chin (1999) [19]. The delay time between the source pulse and receive pulse with a frequency of  $f$  Hz can be determined by

$$\Delta t_{phase} = \frac{(r - r_p)}{2\pi f} \sqrt{14,696\phi\mu c\pi f / k} \dots \quad (17)$$

If the transmitter has an amplitude of  $P_0$  and the receiver has an amplitude of  $P(r)$ , then the amplitude ratio is

$$A_r = \frac{P(r)}{P_0} = \left(\frac{r_p}{r}\right) e^{-(r-r_p)\sqrt{14,696\phi\mu c\pi f / k}} \dots \quad (18)$$

According to the simulation results of the second case of interval pressure transient tests, it is difficult to detect and evaluate non-crossing fractures near the well bore with interval pressure transient tests. However, the method of harmonic pulse testing has been employed for detecting the formation permeability and anisotropy successfully. Fractures in the formation are main factors causing formation anisotropy. So in order to test the feasibility of this method, the authors applied it to detect and evaluate the non-crossing fractures near well bore with a detailed finite element method. The geometry and parameters of the reservoir and fractures are the same as the second case above, and the flow rate was defined as  $1.25\text{cm}^3/\text{s}$ . We simulated the pressure response for different fracture permeabilities in the reservoir.

In the first case, the pump pulse frequency was defined as 1Hz and the spacing for the dual probe was equal to 20cm. The fracture permeability varied from 1000D, 100D, 10D to 10mD. We simulated pressure response for 30 seconds, but in order to compare and analyze the data, we only selected

the time interval of 15s to 16s. Fig. (9) shows the pressure response for different fracture permeabilities. From the simulation results, we can see the pressure amplitude and phase delay have not changed significantly for the different fracture permeabilities over the whole time. The pressure differential is less than 0.02 psi at wave trough (15.6s) between fractured reservoir and non-fractured reservoir (the fracture permeability was defined as 10mD). Although the value of pressure differential is greater than the resolution of pressure gauge, interpretation is difficult in the complicated environment of the well bore. In addition, the pressure image is shown in Fig. (10), it indicates the fractures have little effect on pressure testing, because the pressure wave does not reach the radial distance of the fractures. This demonstrates that the parameters of frequency and spacing of dual probe are not appropriate to this model simulation.

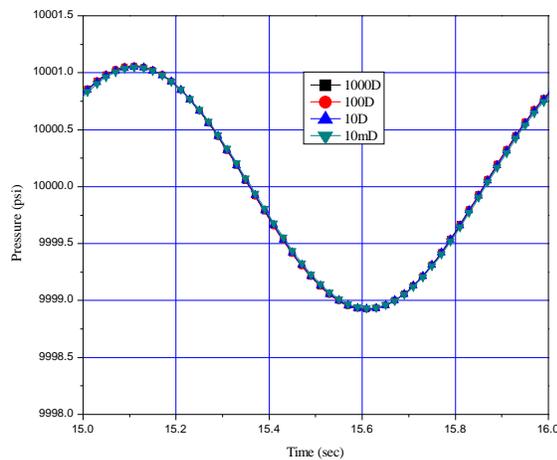


Fig. (9). Pressure response for different fracture permeabilities. (The pulse frequency is 1Hz and spacing of dual probe is 20 cm).

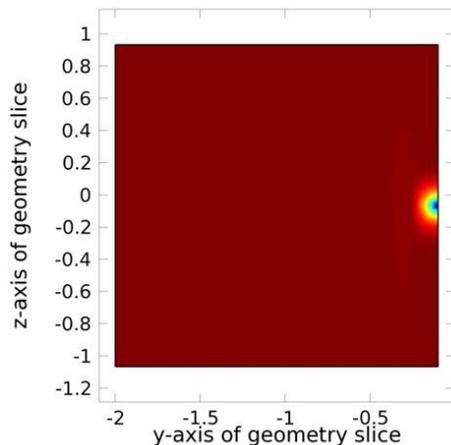


Fig. (10). Pressure image for pulse frequency was defined as 1Hz.

The pulse frequency was then defined as 0.1Hz. Fig. (11) shows pressure amplitude and phase shift for different fracture permeabilities, for which the spacing of dual probe was defined as 20cm. From the simulation results, there is a certain pressure differential and phase shift between fractured reservoir and non-fractured reservoir (pressure differential is more than 0.35 psi at the wave trough). In

addition, the pressure differential and phase shift can be distinguished between different fractures permeability. Fig. (12) shows pressure response when the spacing of dual probe was equal to 50cm, there is evident amplitude differential and phase shift between fractured formation and non-fractured formation. The phase shift between source probe and observation probe is shown in Table 3. The reservoir vertical permeability was calculated according to Eq. 17, it indicates the phase shift decreased and reservoir permeability increased with an increase in fracture permeability. In addition, an opposite phenomenon is observed in that pressure amplitude increases with an increase in fracture permeability, because the higher fracture conductivity reduces the attenuation of pressure wave in the formation. Thus it indicates the long spacing of dual probe can detect those fractures near well bore more efficiently. The pressure image in Fig. (13) shows the pressure wave transmitted into the fractures during the testing, it indicates the pressure wave can transmit further at the lower pulse frequency.

Table 3. Phase shift and reservoir permeability for different fracture permeabilities.

Fracture permeability (Darcy)	Phase shift (sec)	Reservoir Permeability (mD)
0.01	0.9	9.8
10	0.82	11.75
100	0.73	15.18
1000	0.7	15.62

Finally, we simulated the pressure response for different radial depths of fractures to the well bore, for which the pulse frequency was defined as 0.1Hz and the spacing of the dual probe was 50cm. the pressure amplitude and phase shift are shown in Fig. (14). According to the simulation results, the method of harmonic pulse testing can detect the fractures near well bore efficiently. However, it becomes more difficult and probably invalid for detecting those fractures located far away from the well bore.

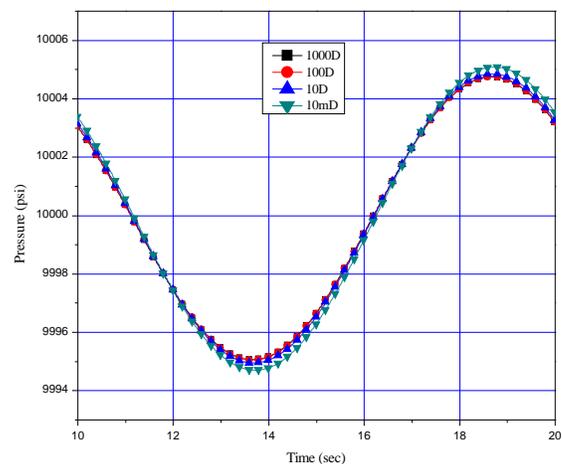


Fig. (11). Pressure response of different fracture permeabilities. (The pulse frequency is 0.1Hz and spacing of dual probe is 20 cm).

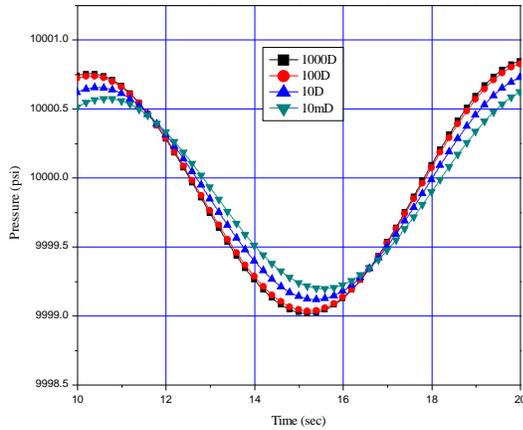


Fig. (12). Pressure response of different fracture permeabilities. (The pulse frequency is 0.1Hz and spacing of dual probe is 50 cm).

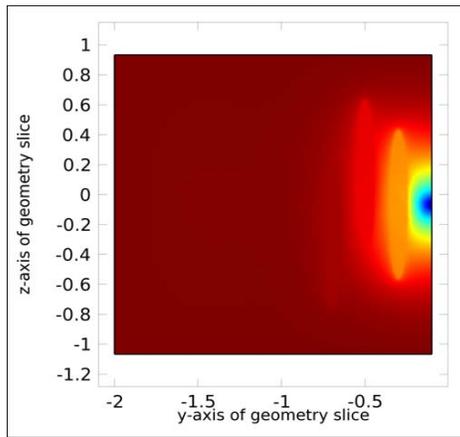


Fig. (13). Pressure image of pulse frequency was defined as 0.1Hz.

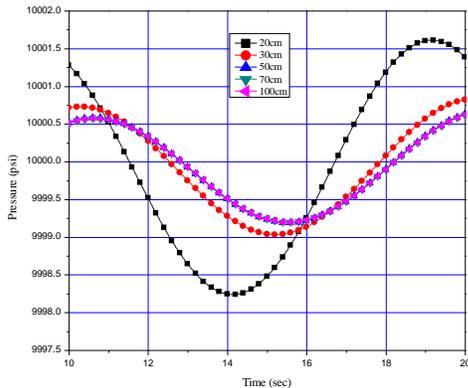


Fig. (14). Pressure response of different fracture radial depth. (The pulse frequency is 0.1Hz and spacing of dual probe is 50 cm).

**RESULTS AND DISCUSSION**

In this paper, we used finite element method to simulate the pressure response of fractures intersecting well bore in the low permeability reservoir. Simulation results show that pressure response is sensitive to fracture parameters, which include permeability, length and aperture, the response can be used to characterize the fracture conductivities and provide the quantitative results. In fact, the fractures along the well bore can be tested individually to obtain a distribution of fracture conductivities. The simulation results are almost the same with the conclusion published by

M.Zeybek and Kuchuk in 2002, they simulated the two dimensional fracture model with a commercial well test simulator and showed that the fractures crossing the well bore have dramatic effect on pressure response and non-crossing fractures in the vicinity of the well bore have negligible effect. However, they have not pointed out how to evaluate the non-crossing fractures with other methods.

In order to investigate the new method to evaluate the fractures non-crossing well bore, we simulated the pressure response with the method of dual probe harmonic pulse testing. The method has been applied for determining reservoir permeability or anisotropy by worldwide oilfield service companies, but has not been used for evaluating fractures around the well bore. Different pulse frequencies and different dual probe spacings have been simulated, the results indicated the method of harmonic pulse testing can be used to detect and evaluate those fractures non-crossed well bore.

In this paper, we only considered the simple synthetic fractures model with finite element method, in order to research the complex fractures around the well bore, we will simulate the pressure response with discrete fracture network model. In addition, the mathematical model of oil water two-phase applied for factures simulation has been investigated, it will make the simulation more accurate and reliable.

**CONCLUSIONS**

The following conclusions result from the numerical simulations with finite element method considered in this paper:

1. The fractures intersecting the well bore can be evaluated efficiently by interval pressure transient tests depending on the fracture conductivities. Non-intersecting fractures in the vicinity of the well bore have negligible effect with the method. However, when the fracture permeabilities and fracture lengths increase, or the fractures get close to well bore, the effect becomes noticeable.
2. The non-intersecting fractures near well bore can be detected and evaluated by the method of harmonic pulse testing through setting appropriate spacing of dual probe and pulse frequency. However, this method becomes much less precise when the fractures are located far away from the well bore.
3. In low permeability formations, decreasing the frequency of pump pulse and increasing the spacing of the dual probe can increase detection distance and improve the detection precision.

**NOMENCLATURE**

- $D$  = Darcy
- $mD$  = milliDarcy
- $\Phi$  = formation porosity, fraction
- $\rho$  = fluid density,  $kg/m^3$
- $d_f$  = fracture aperture, mm
- $C_f$  = fluid compressibility coefficient, 1/psi
- $C_\phi$  = matrix compressibility coefficient, 1/psi

$C$	=	total compressibility, 1/psi
$K$	=	formation matrix permeability, mD
$K_f$	=	fracture permeability, D
$\mu$	=	fluid viscosity, cp
$P$	=	formation pressure, psi
$\Delta t_{\text{phase}}$	=	pulse time delay, sec
$f$	=	pulse frequency, Hz
$r$	=	spherical coordinate, cm
$r_s$	=	spherical source radius, cm
$r_p$	=	probe radius, cm

### SI Metric Conversion Factors

$$\text{cp} \times 1.0 \text{ E-}03 = \text{Pa}\cdot\text{s}$$

$$\text{mD} \times 1.0 \text{ E+}00 = \text{cm}^2$$

$$\text{mD} \times 9.81 \text{ E-}16 = \text{m}^2$$

$$\text{psi} \times 6.894757 \text{ E+}00 = \text{kPa}$$

Conversion factors are exact.

### CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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