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Feasibility Study of Hydraulic Fracture Operations (A Case Study of an Oil Reservoir in the Southwest of Iran)

Hajnajafi Reza[1]*, Amid Arman[2], Nematollahi Sepehr[3], Mehran Esfehanian[1] and Hajnajafi Ghazal[4]

[1]Department of Petroleum Engineering, University of New South Wales, Sydney, Australia
[2]Department of Environmental Management HSE, Tehran North branch of Islamic Azad University, Tehran, Iran
[3]Department of Petroleum Engineering, University of Science and Research of Islamic Azad University, Tehran, Iran
[4]Department of Geology, University of Science and Research of Islamic Azad University, Tehran, Iran

Abstract

Hydraulic fracture is one of the most important and best methods of enhancement recovery in oil and gas wells. Hydraulic fracture operations refer to a process in which fluid is pumped into well with a relatively high injection rate. Pumping operations are continued till the pressure reaches to a level which causes the creation and expansion a crack in the well wall. In the present study, with respect to the status of rock mechanics status in an oil reservoir in southwest of Iran, we attempts to numerically analyze a geo-mechanical model to find a background in line with the way of stress distribution against depth as well as rock resistance. We also tend to investigate each layer based on the data obtained from logging and analyze parameters such as porosity, water saturation and stress in each layer and neighboring layers. Finally, we compute the layer appropriate for fracture creation as well as onset, propagation and closure pressures to fulfill a successful hydraulic fracture operation.

Keywords: Hydraulic fracture; Geo-mechanical model; Water saturation; In-situ-stresses; Porosity

Introduction

Simply, in oil engineering, rock mechanics or geomechanics deals with the impact of stress and resistance of rock on the behavior of formations as a result of oil activities. In all periods of hydrocarbon fields' development, i.e. from the primary stages of exploration when basic questions such as predicting pore pressure before drilling are propounded to the stages of evaluation, development and extraction of fieldwhere operator faces some problems such as optimizing well stability for drilling and predicting the closure of faults and crack permeability, geomechanics-related issues are appeared. In addition to the high importance of geomechanics in reservoir management and some issues such as well stability, sand production, hydraulic fracture, and land subsidence, recently, an increasing interest in developing the relation between fluid flow simulators and geo-mechanical models has been also observed [1].

Oil and gas reservoirs production is accompanied with some change in geo-mechanical properties. These changes influence the status and amount of stress under the surface. As reported by previous studies, this phenomenon involves many problems and challenges in developing and producing non-rigid, chalk, fractured, and highly compact reservoirs of the world. Geo-mechanical changes can strongly influence formation compaction, land subsidence, reservoir permeability, and sweep efficiency in flooding, water breakthrough, and faults reactivation. Geo-mechanical changes due to production methods in reservoir and its overburden with complex field geology can influence wells' stability and cause casing collapse and sand production in the field. Moreover, changes in stress (horizontal) status of region can cause change in the behavior and reaction of reservoir rock to hydraulic fracture operations. In gas storing reservoirs, the frequency of injection, production and change in temperature cause many problems in the reservoir and even the cap rock. In thermal enhanced oil recovery (EOR) methods, steam assisted gravity drainage and increase in temperature and pressure cause change in rock stresses, leading to its fracture. Increasing porosity, permeability and water transfer power increases the acceleration of the process. Further, these changes cause changes in steam movement pattern [2].

Drilling in reservoir layers and deeper layers of discharged fields is followed by some problems. In stress-sensitive reservoirs, in well tests, pressure reaction of the tested well is different to production or injection and in interpreting these data, geo-mechanical behavior of the rock should be considered. Therefore, for optimal decision making during drilling, completing and stimulating well, it is necessary to interpret the information of production, well test, formulating optimal strategy of production, constructing appropriate geo-mechanical model, and studying the behavior of reservoir and environment formations on upper, lateral and lower layers during production period. During production period, the sooner the model is constructed, the fewer problems will be caused [2].

Hydraulic fracture is one of the most important activities which are performed to increase oil and gas production from wells. During this process, for rock fracture, fluid is injected to the formation with adequate pressure. After creating fracture, continuing injection, the fracture created in the formation is expanded and finally, the created fracture is kept open by adding sand (Proppant) to the injected fluid. A successful strategy in reservoir development inevitably requires performing geo-mechanical studies and modeling of reservoir. A comprehensive geo-mechanical model includes stress status as a function of depth (direction and amount), physical properties of reservoir rock and its side-burdens (rock's resistance and elastic

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***Corresponding author:** Hajnajafi Reza, Department of Petroleum Engineering, University of New South Wales, Sydney, Australia; E-mail: rezahajnajafi@gmail.com

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modules), pore pressure estimation, faults and cracks' description and distribution. Achieving such complete information is always difficult and it is necessary to find important geomechancial model elements for problem solving. It should be noted that there is always uncertainty in various elements of geomechanic model.

Another method of embedding geomechanic in simulator is to simultaneously solve flow equations and deformation. This method is more precise but it needs more time. However, this method is still under investigation [3,4]. On the other hand, developing fracture mechanics knowledge have been able to increase our understanding about the way of materials' destruction and fracture, leading to the decrease of resulted dangers and damages. Since the discussed issues in industry and engineering are complex issues, analytical solving methods cannot respond the existing need; accordingly, numerical methods are considered as a desirable alternative to investigate complex engineering problems. As the most efficient and popular methods, we can refer to finite element method and recently, developed finite element method. Generally, depending the way of modeling the behavior of crack, various behavioral models can be considered for modeling crack. As an instance, we can refer to linear elastic failure mechanics model and cohesive crack model [5,6].

The concept of cohesive crack was propounded by Barenblatt and Dugdale to describe non-linear fracture processes of crack tip in fragile materials [7-9]. Hillerborg generalized the concept of cohesive crack to simulate crack growth in concrete [10].

Chandre investigated the effect of the law of cohesion on the behavior of cracks [11]. As they revealed, the shape of detachment-cohesion force equation has a high effect on the microscopic behavior of the system. Needleman was one of the pioneers who selected polynominal an exponential type for detachment-cohesion force equation [12]. Espinosaand Zavattieri also defined a tow-line cohesion law to remove the artifact softness created in cohesive region through a primary adjustable slope [13]. Song showed that cohesion law effectively decrease the additional artifact softness created in the cohesive area [14].

To validate and ensure about the accurate performance of developed finite element method, Saberhoseeini computed stress intensity factor for an edge-crack and compare them using analytical method [15]. The obtained results showed an error percentage less than 1%. Given to the aforementioned, the purpose of the present study is to study the feasibility of hydraulic fracture operations in simulating one of the southwest oil reservoirs of Iran.

Methods

Well's characteristics

Kopal oil field has been located at a distance of 60 km of east of Ahwaz City. The presence of carbohydrate in Bangestan reservoir of Kopal field was proved in 1970 through well No. 3. Kopal has an area of 32 × 5 km^2. The reservoir has been consisted of frequent porous and hard layers of limestone. Kopal has a mild wrinkle; principally, fractures are very limited in these wrinkles. According to the obtained data, it was revealed that fractures in Bangestan reservoir have a very weak development and the possibility of open regional fractures is very low. This reservoir has under saturate oil whose production mechanism relates to fluid expansion, reservoir rock and gravity drainage.

Constructing geo-mechanical model

There are various methods to determine geo-mechanical model which indicates mechanical behavior change of reservoir rock in a well and there is a need of a wide range of data in various oil engineering branches such as exploration, drilling and exploitation. However, the best method is to achieve continuous data from the surface to the bed of reservoir rock.

Elastic properties of reservoir rock

Elastic substance refers to a substance which returns to its primary status after tolerating a loading and unloading cycle. To determine elastic coefficients, density and wave transfer time data in shear and compaction states are used.

$$\vartheta = \frac{\frac{1}{2}\left[\frac{\vartriangle t_c}{\vartriangle t_s}\right]^2 - 1}{\left[\frac{\vartriangle t_c}{\vartriangle t_s}\right]^2 - 1}$$

$$E_{dynamic} = \frac{\tilde{n}_b\left[3 - 4\left[\frac{\vartriangle t_s}{\vartriangle t_c}\right]^2\right]}{\vartriangle {t_s}^2 - \vartriangle {t_c}^2}$$

Since dynamic data cannot be used in geomechnic model, the following empirical relation is used to change data into static status:

$$E_{static} = 0.4145 E_{Dynamic} - 1.0593$$

Notably, in the above mentioned equations, Poisson coefficient value equals in both dynamic and static states.

Uniaxial compressive strength

One of the basic parameters in geo-mechanical model is uniaxial compressive strength. This strength, in fact, is the maximum strength which is tolerated by rock before being fractured. In the present work, we have made use of the relation between porosity and uniaxial compressive strength

$$\sigma_c = 135.9 \exp(-4.8*\varphi)$$

Tensile strength

Tensile strength of formation is used to evaluate tensile fracture of well due to tension concentration. The value of tensile strength is mainly a percentage of uniaxial compressive strength.

$$T = \frac{1}{10} \times USC$$

Vertical tension

Mathematically, using the following equation, the value of vertical tension can be computed through integration of rocks' density from the surface to the considered depth:

$$\sigma_i = \int_{\tilde{n}}^{z} \rho(z) g dz \cong \bar{\rho} g z$$

Where ρ (z) indicates the density as a function of depth and g indicates gravity acceleration of earth. Also, $\bar{\rho}$ denotes the average density or higher levels' density.

The minimum and maximum horizontal tension

Knowing about the minimum horizontal tension changes against depth is one of the most important parameters in hydraulic fracture operations. Horizontal tensions value is estimated through the following equations:

$$\sigma_H = \frac{\nu}{1-\nu}\sigma_P - \frac{\nu}{1-\nu}{}_{P}\alpha P + \alpha P_x + \frac{E}{1-\nu^2}\varepsilon_y + \frac{\nu E}{1-\nu^2}\varepsilon$$

$$\sigma_h = \frac{v}{1-v}\sigma_v - \frac{v}{1-v}\alpha P_P + \alpha P_P + \frac{E}{1-v^2}\varepsilon_y + \frac{vE}{1-v^2}\varepsilon_x$$

$$\alpha = 1, \qquad \varepsilon_x = 1/5, \qquad \varepsilon_y = 1$$

Where the minimum horizontal pressure, the maximum horizontal pressure, Poisson coefficient, and vertical tension are based on Mpa; Biot coefficient equals 1; and strain in the minimum and maximum horizontal tension are 15 and 1, respectively. Computing the value of minimum and maximum horizontal tension revealed that the dominant tension regime is normal.

The values of physical parameters including density, porosity, compressive and shear sound waves, and pore pressure have been reported by logging operations. The formation density (ρ_b) in various distances has been reported from the depth of 4039.7 m to 4368 m; its maximum value has been 2.83 g/cm^3; the average density of formation has been also 2.65 g/cm^3. The maximum, minimum and average porosity in the well have been also 0.61, 0 and 0.1085, respectively. Using transmission time values of compressive wave (Δ_c) and shear wave (Δ_s), elastic parameters values in dynamic state are computed. In this well, the maximum and minimum as well as Young's dynamic modulus parameters (E_d) are 13.766 and 47 Gpaand Poisson coefficient (v) is 0.44, 0.039 and 0.31, respectively.

Results

Numerical analysis results

To investigate the sensitivity of the model to geomechnical and operational parameters (fracture stiffness, Young' modulus, Poisson ratio, fluid injection rate, fracture tensile strength, and fluid subsidence rate), a sensitivity analysis has been performed on each of the parameters and the amount of pressure necessary for formation fracture at each stage has been computed. At this stage, in each step of sensitivity analysis, only one of the base model parameters are changed and other values are kept constant [16,17].

Investigating the effect of young's modulus on fracture onset pressure

Young's modulus refers to the amount of digging formation rigidity which is of factors involving in the behavior of substance against applying load as well as parameters affecting formation pressure gradient determination. The model results indicate that increasing Young's modulus from 20 Gpa to 50 Gpa leads to the increase of fracture pressure amount from 46.09 Mpa to 51.5 Mpa (Figure 1).

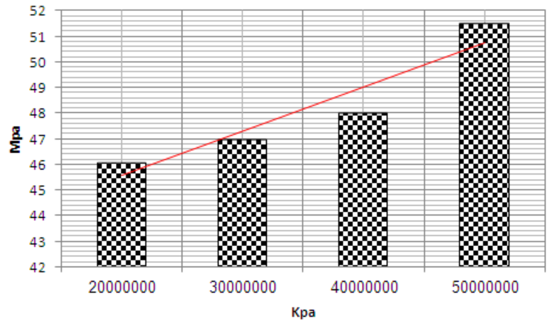

Figure 1: The diagram of formation fracture pressure changes based on Young's modulus.

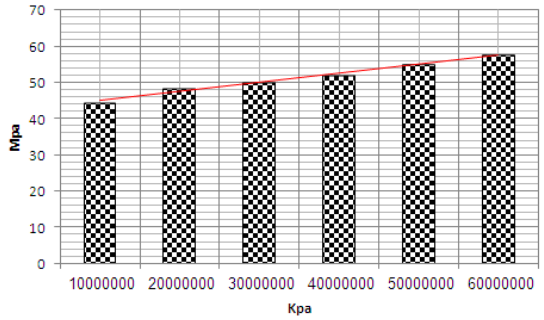

Figure 2: The diagram of formation fracture pressure changes based on fracture stiffness.

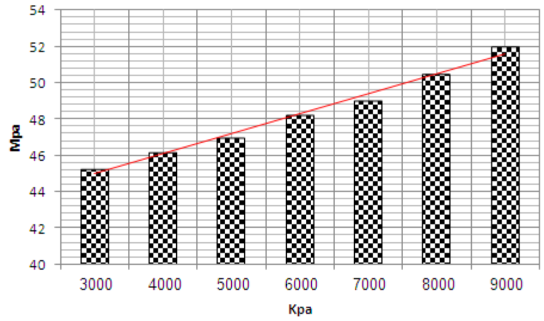

Figure 3: The diagram of fracture pressure changes based on the formation tensile strength.

Investigating the effect of crack stiffness on fracture onset pressure

Stiffness is one of the effective geo-mechanical parameters in fracture onset pressure. Increasing fracture stiffness leads to the increase of the pressure of the fluid needed for fracture onset. Given to Figure 2, we can conclude that approximately, for each unit of increase in stiffness, the pressure necessary for hydraulic fracture onset is linearly increased as much as 0.26 Mpa.

Investigating formation tensile strength effect on fracture onset pressure

Increasing the pressure of injected fluid causes to the increase of tangential tensile stresses imposed on the wall, leading to fracture onset by reaching this value to the formation tensile strength. Given to Figure 3, there is a linear direct relation between the formation tensile strength and fracture pressure such that for each unit of increase n tensile strength, the formation fracture pressure is increased about 1 Mpa as well.

Investigating poisson ratio effect on fracture onset pressure

Poisson ratio is the ratio of latitudinal strain to longitudinal strain. Increasing this ratio causes the decrease of the strength of object against imposed loads. Consequently, the injected fluid pressure necessary for fracture onset is also decreased (Figure 4).

Investigating the effect of injected fluid subsidence rate on fracture onset pressure

Fluid subsidence rate is one of the effective operational parameters

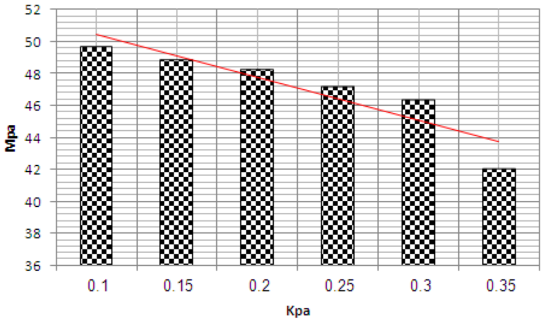

Figure 4: The diagram of fracture pressure changes based on Poisson ratio.

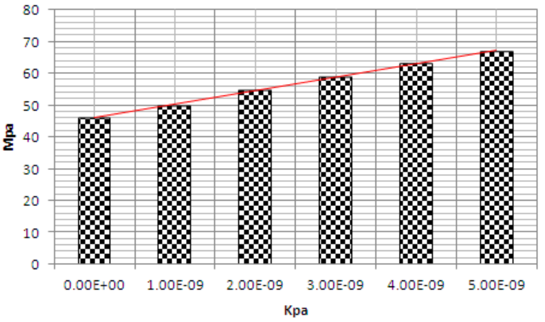

Figure 5: The diagram of fracture pressure changes based on fluid subsidence rate.

in hydraulic fracture process. The most ideal state occurs when there is no fluid subsidence from the inside of fracture to the inside of formation such that it needs less pressure for the formation fracture. Therefore, given to the aforementioned and the results obtained from sensitivity analysis (Figure 5), we can conclude that increasing fluid subsidence leads to wasting the fluid which causes the increase of the formation fracture pressure [18,19].

Investigating the effect of the injected fluid viscosity on fracture onset pressure

To investigate the effects of changing fluid type on hydraulic fracture onset pressure, injected fluid viscosity change is the best alternative. Typically, water is used as an injected fluid to create hydraulic fracture in most of oil reservoirs. Given that sensitivity analysis which was performed to observe the effect of fluid viscosity on fracture pressure, the obtained results revealed that there is no certain relation between these two parameters and increasing viscosity sometimes causes to the decrease and sometimes leads to the increase of fracture pressure.

Evaluating layers

Selecting the most appropriate layer for hydraulic fracture operations is always one of the most important concerns of oil and reservoir engineers. A layer should be selected in such a way that it has the highest efficiency. In the process of selecting appropriate layer, in general, we face with two kinds of target and obstacle layers. According to the findings, all the layers of the considered well are productive. However, according to the existing conditions, the least uniaxial compressive strength and Young's modulus are in layers 5 and 6. So, these layers are more appropriate for hydraulic fracture operations (Figure 6) [20].

Fracture onset pressure, closure and propagation of fracture

During the first cycle, fracture begins with the pressure of P_b and starts to grow with a pressure less than fracture pressure of P_b. When a certain volume of fluid was injected, the pumping is stopped but the fluid is still within pumping line. The created fracture which is not fed by fracture fluid any longer starts to be closed. There are two separated stages in the closing phase of crack. The first stage is immediately after stopping pumping due to which a strong drop occurs in pressure. After sudden pressure drop, depending on rock permeability, pressure drops with a slower rate. When pressure approaches $\sigma_{h,}$ the crack is completely closed and the fluid exists from the crack. On pressure-time curve, obstruction pressure point theoretically equals σ_h. The main difference between the first cycle (detachment cycle)and the second cycle (openness cycle) is that the pressure necessary for the crack openness is less than fracture pressure and it is equals fracture pressure minus the rock tensile strength. However, the crack propagation pressure and obstruction pressure are identical in all the cycles.

Unlike fracture pressure and openness pressure, the crack propagation pressure includes only a stress smaller than σ_h. However, as an advantage, it can be easily determined and shows less dependency to permeability. For long fractures, cohesion factor (ΔP_k) is ignored in the crack propagation and the crack propagation pressure equals:

$P_P= \sigma_h+P_P$

FPP = Pr = Pb-T (Psi)

FCP = Shmin (Psi)

Maximum, minimum and average limits of breakdown, propagation and closure pressures for productive layers of this well have been shown in Figures 7 and 8.

Firstly, we analyzed each layer to perform zoning operations. Based on three factors of porosity, in-situ-stress and water saturation, we divided diagrams into 8 layers and discussed each of them (Figure 9).

Layers 1, 2, 3, 4, and 6: With a high level of stress (about 50 Mpa), a high level of water saturation and an average porosity (about 15%),

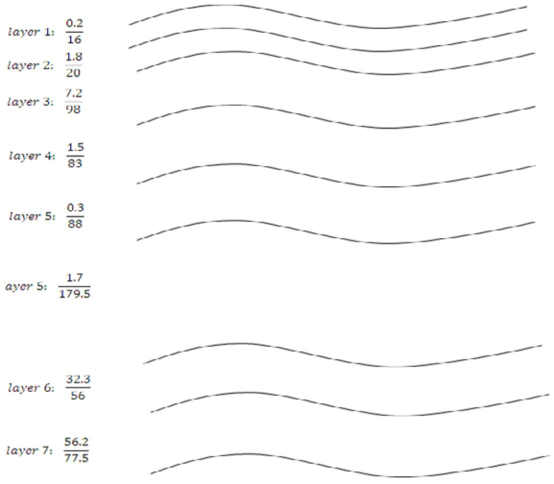

Figure 6: The ratio of Useful thickness to total thickness.

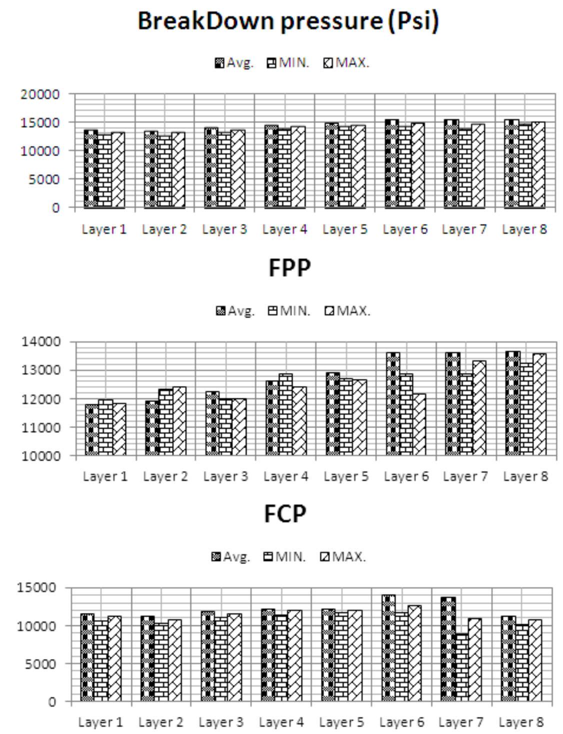

Figure 7: Reference pressures.

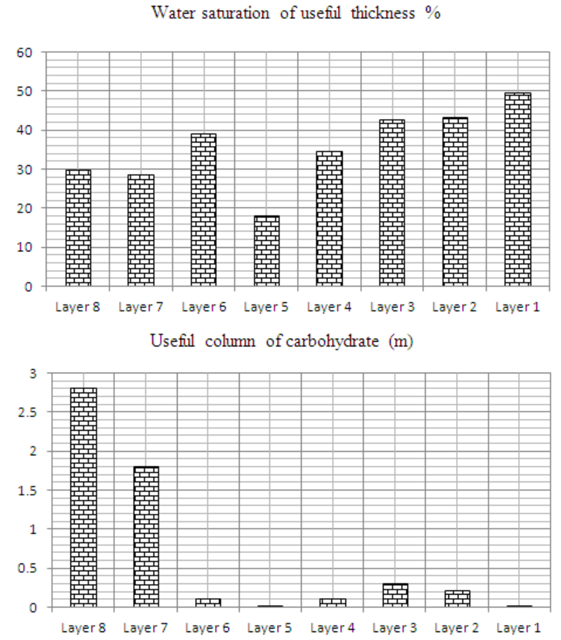

Figure 8: Evaluating petro-physical layers.

these layers are appropriate to be selected as obstacle layer for lower layer. Based on RT log, in this area, the existing fluid is probably sure and there is no hydrocarbon. Additionally, hydraulic fracture in this layers leads to water production; therefore, it is not considered as an appropriate layer for hydraulic fracture.

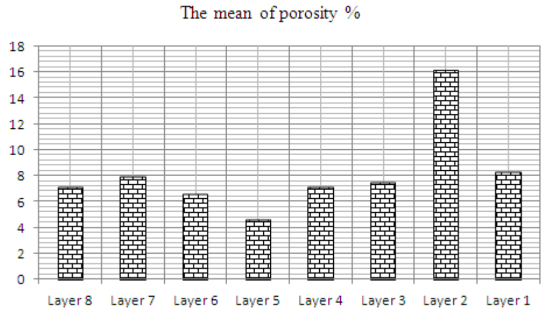

Figure 9: Evaluating porosity layers.

Layer 7: this layer has a porosity of about 17%; based on PEF log, it has lithology of limestone and a stress about 55 Mpa with a very low water saturation; based on RT log, it has a high resistance which indicates the presence of hydrocarbon in this layer. Also, due to low stress in this layer, compared to its two neighboring layers, it is an appropriate alternative for hydraulic fracture. Further, two upper and lower layers, with respect to their conditions, can well play the role of obstacle layer.

Conclusion

The present study was an attempt to analyze formation fracture onset pressure and its effective parameters in hydraulic fracture process through finite element method. To this end, using ABAQUS Software, hydraulic fracture operations conditions was simulated in an oil reservoir and the formation fracture onset pressure was investigated using the theory of cohesive elements with the law of traction-separation law. To investigate the sensitivity of the model to geo-mechanical parameters of the reservoir including the formation Young's modulus, fractures stiffness of the reservoir, Poisson ration, the formation tensile strength, and operational parameters such as the injected fluid viscosity and fluid subsidence rate, sensitivity analysis was performed on each of parameters and the pressure necessary for the formation fracture at each stage was computed. In this work, the mean of fracture onset pressure is about 13785 pam per square inch and 14287 pam per square inch in layers 1 and 2 and in layers 3 to 8, respectively. The average fracture closure pressure is also 11247 pam per square inch and 12456 pam per square inch in layers 1 and 2 and in layers 3 to 8, respectively.

The model results indicate that the formation fracture pressure is increased by increasing Young's modulus, fracture stiffness, rock tensile strength, and fluid subsidence rate. Also, increasing Poisson ratio leads to the decrease of this value. Notably, increasing the injected fluid viscosity leads to uncertain changes in the behavior of the formation fracture pressure.

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