AGH DRILLING, OIL, GAS • Vol. 34 • No. 2 • 2017

http://dx.doi.org/10.7494/drill.2017.34.2.411

Dariusz Knez*, Jan Ziaja*, Monika Piwońska*

COMPUTER SIMULATION OF THE INFLUENCE OF PROPPANT HIGH DIAMETER GRAINS DAMAGE ON HYDRAULIC FRACTURING EFFICIENCY**

1. INTRODUCTION

Hydraulic fracturing technology originates in the late forties. Since then, its popularity grew, that by the end of 1955 made more than 100 thousand treatments [1]. Currently, it is the most common method of stimulation of oil and gas wells in unconventional reservoirs. The point of the fracturing treatment is to create a propped fracture, which has good conductivity and permeability after the fracturing fluid is flowed back. In practice, the key parameter in determining the permeability of proppant pack is its porosity. Small changes in the porosity of proppant pack result in significant changes in the permeability of the pack and the fracture conductivity. Rapid loss of fracture conductivity after hydraulic fracturing treatment is often considered to be the result of particle formation migration in proppant pack or form the particles resulting from crushing of the proppant [6]. Forming of minerals may occur in the proppant pack because of chemical differences between the formation and the proppant. As a result of these reactions, proppant pack porosity may decrease.

2. THE CHEMICAL COMPOSITION OF THE PRODUCED RESERVOIR WATER

One of the factors that affect the damage of proppant pack is interaction with the components contained in the produced water. The chemical composition of the

---

* AGH University of Science and Technology, Faculty of Drilling, Oil and Gas, Krakow, Poland

** This work was supported by research project number 11.11.190.555

produced water is very variable and depends on the conditions under which deposits were formed. The content of dissolved chemical compounds varies widely. They include: sodium, potassium, magnesium, calcium, chloride ions, sulphate and carbonate, as well as trace amounts of ions such as radium, strontium, iodine, bromine, copper, manganese, iron, mercury, lead, etc. [3]. The most toxic chemicals, found in the produced water include: BTEX (benzene, toluene, ethylbenzene, xylene), polycyclic aromatic hydrocarbons (PAHs), radioactive elements (such as radium, uranium, actinium, plutonium), and heavy metals [2].

During production the liquid equilibrium at the reservoir is disrupted, what is resulting in supersaturation of the solution and lead to precipitate the scales. Precipitated during operation scales may cause some inconvenience. The greatest difficulties cause scales that are difficult to dissolve in water, e.g. carbonates of calcium, magnesium, and iron, iron sulfide and sulfates of calcium and barium. On the other hand, when the produced water is injected that cause mixing it with water of different physicochemical parameters. If there are changes in physical and chemical parameters of water, it may cause their aggressiveness (water unstable with corrosive properties). Contact with water containing aggressive ions may lead to a reduction in mechanical strength of proppant. Therefore, it may reduce the fracture conductivity and consequently reduce production.

3. PROPPANT DIAGENESIS

The term diagenesis usually concerns post-depositional modifications and/or reactions that arise as a result of physical, chemical and biological processes, which leads to structural changes in sedimentary rocks and their primary mineralogy [6]. These changes may begin to appear at relatively low temperatures and pressures. The increase in pressure and temperature favour dissolving minerals, therefore, changes occur faster. Diagenetic reactions appear in the geological time. In the case of newly created hydraulic fractures, which are filled with proppant, the time required for diagenesis depends on the geochemical reaction rate at reservoir temperature and current rock stress. In this case, the time diagenesis may be less than a year.

Taking into consideration above processes, the result of their actions is to reduce the porosity of proppant pack that fills the fracture, and thus increasing the flow resistance and reduce the conductivity. The decrease in the conductivity led to the development and introduction of the concept that when proppant is located in hydraulic fracture where are conditions of high temperature and stress, diagenetic reactions can occur rapidly and significantly reduce its conductivity. In 2003, Hideaki Yasuhara et al. reported work suggesting that effective stress with a value of 34.47 MPa, at temperatures ranging from 348 K to 573 K, causing a reduction in porosity of the proppant pack. The ultimate porosities asymptote reached 15% for the 573 K to 25% for the 348 K of their original porosity [7]. In the contact points of proppant are very high stresses between the grains in propped fracture. This stress causes an increase in the solubility of the proppant, by entering the greater amount of material to the solution between the grains. As dissolved mineral diffuses into the pore space, its concentration is above the level of solubility and consequently precipitates. Therefore, the material is moved from the region of high stress in the area of low stress and thereby reduces the total stress system.

4. COMPUTER SIMULATION

Many models in the literature connect the permeability of proppant pack with their porosity. Fracpro models the proppant permeability as being damaged, or apparently damaged by the phenomena associated with the flow and not associated with the flow. The effects of these phenomena are represented separately by two damage factors, which are then effectively summed to reach a total damage factor, which is the actual parameter used for the effective in-fracture proppant permeability reduce (that is, hydraulic fracture conductivity). It is calculated using equation (1):

$$D_{total} = 1 - \left(1 - D_{apparent}\right) \cdot \left(1 - D_{proppant}\right) \tag{1}$$

where:

D_{total} – total damage factor,

$D_{apparent}$ – apparent damage factor, it is calculated from the entries describing the non-Darcy and multi-phase flow effects,

$D_{proppant}$ – proppant damage factor resulting from non-flow related phenomena.

A total damage factor of 1 represents the zero proppant permeability. A total damage factor of 0 means no damage, the proppant has a permeability corresponding to the value interpreted from the closure stress vs proppant permeability.

The objective of this study was to evaluate how the proppant pack destruction affects the efficiency of hydraulic fracturing using proppant with higher diameter grains. For this case, a tight oil example was considered. The 30.48 m of pay zone was limited by shales from the top and the bottom. Also at depth of 2560 m was an aquifer, so the fracture height was limited to 2545 m to avoid growth at water bearing zone. The properties of the rock are presented in the Table 1.

Table 1

Rock properties

Rock Type	Permeability [m^2]	Leakoff Coefficient [ft/min$^{1/2}$]	Young's Modulus [MPa]	Poisson's Ratio
Shale	$0.00001 \cdot 10^{-15}$	$6.46 \cdot 10^{-6}$	41.37	0.25
Sandstone	$0.009 \cdot 10^{-15}$	$2 \cdot 10^{-4}$	34.47	0.2

The simulation was performed using the p3D model, example result of proppant concentration is shown on the Figure 1.

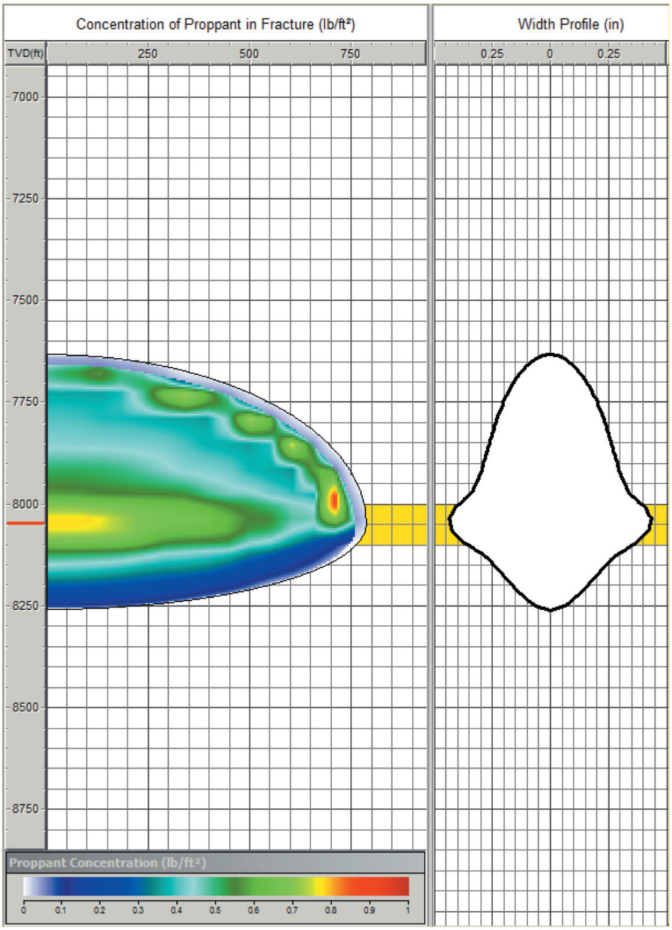

Fig. 1. Proppant concentration in the fracture

For the 12/20 Badger proppant pack, the porosity of 0.408 indicates a random pack and average proppant diameter of 0.0011 [m]. The applied proppant showed good permeability under reservoir conditions, also its price was a critical issue. Production analysis model uses assumption of one mobile phase and two dimensional reservoir flow. The wellbore and fracture are treated same way. Model ignore cleanup effects and damage due to a fracturing fluid invasion in the reservoir. Production constraints include a minimum of bottom hole pressure of 20.68 MPa and maximum oil rate of 953.92 m^3/day. Other data include: reservoir temperature of 372.04 K, initial reservoir pressure of 41.37 MPa, average pay zone permeability of $0.009 \cdot 10^{-15}$ m^2, depth to middle of pay of 2453.59 m, net pay thickness of 30.48 [m] and closure stress gradient of 18 096.48 Pa/m. The maximum proppant pack damage was assumed 0.3 of the initial proppant pack permeability. Next, the Fracpro simulation was performed for the following values of proppant damage factors: 0; 0.1; 0.2; 0.3 and 0 for apparent damage factor. This consequently resulted in the total damage factor equal proppant damage factor.

First step of analysis was looking for the fracture conductivity changes versus time caused by proppant pack damage. The forecast has been made for a period of time amounting to 730 days and four values of the total damage factor of: 0; 0.1; 0.2; 0.3 representing the percentage of damage proppant pack permeability. By analyzing the obtained results, it is noted that in the initial period of production i.e. one day, there is a quick decline of fracture conductivity. After this time, the fracture conductivity decreases much more slowly over a period of approximately 365 days. After that, it is stabilized what shows Table 2. The length of the individual period in fracture conductivity changes depends on the height of the total damage factor. Higher proppant pack damage results in extending each of these periods. Also higher proppant damage factor reduces the fracture conductivity compared with the undamaged state. The factor of 0.3 resulted in decreases in the fracture conductivity by approximately 30%. Another forecast has been made for the oil production. Also, in this case, the parameter was applied for a period of 730 days and different values of total damage factor. The production rate, in the initial period of time, has reached its maximum value. Then, its value decreased with time as shown in Table 3. For 365 days, its value is about 3.2 m^3/day, while for 730 days only 2.3 m^3/day. As in the case of fracture conductivity, proppant damage factor resulted in the achievement of lower rate values. The increase in total damage factor of 0.3 caused decrease initial flow rate only about few percent for first day. On the other hand, the time progress caused that the difference has been changed, so that for 10 days was negligible small and for the time greater than 730 days the difference was constant.

Table 2

Changes of fracture conductivity with time for different values of total damage factor from Fracpro simulation

Time [days]	Fracture conductivity [$m^2 \cdot m$]			
	Total damage factor			
	0	0.1	0.2	0.3
0	5.63E-12	5.07E-12	4.50E-12	3.94E-12
10	3.28E-12	2.96E-12	2.64E-12	2.32E-12
20	3.25E-12	2.94E-12	2.62E-12	2.30E-12
30	3.24E-12	2.92E-12	2.60E-12	2.28E-12
60	3.23E-12	2.91E-12	2.59E-12	2.27E-12
91	3.22E-12	2.90E-12	2.58E-12	2.26E-12
182	3.21E-12	2.89E-12	2.57E-12	2.26E-12
273	3.21E-12	2.89E-12	2.57E-12	2.25E-12
365	3.21E-12	2.89E-12	2.57E-12	2.25E-12
547	3.21E-12	2.89E-12	2.57E-12	2.25E-12
730	3.21E-12	2.89E-12	2.57E-12	2.25E-12

Table 3

Changes in oil production rate with time for different values of total damage factor from Fracpro simulation

Time [days]	Flow rate [m^3/day]			
	Total damage factor			
	0	0.1	0.2	0.3
10	19.28	19.27	19.27	19.25
20	13.91	13.91	13.90	13.89
30	11.08	11.08	11.08	11.08
60	8.04	8.04	8.04	8.04
91	6.41	6.41	6.41	6.41
182	4.69	4.69	4.69	4.69
273	3.77	3.77	3.76	3.76
365	3.22	3.22	3.22	3.22
547	2.66	2.66	2.66	2.66
730	2.30	2.30	2.30	2.30

The Table 4 shows the relation between cumulated production per stage and the total damage factor for different production times. The cumulated production increases with time. The total damage factor affects on it what is resulting in small production reduction in the very early period of time. The damage of proppant pack permeability of 0.3 caused a reduction of cumulated production about 2.8% for the initial time of production. With the passage of time, this difference is less reaching for 10 days the value of 1%, and later on difference is negligible small. Large diameter proppant grains provide very high permeability flow path comparing to matrix permeability. Even significant drop in proppant permeability due to damage has almost no influence on oil production from stimulated well in the case considered here.

Table 4

Changes in cumulated production with time for different values
of total damage factor from Fracpro simulation

Time [days]	Cumulated production per stage [m^3]			
	Total damage factor			
	0	0.1	0.2	0.3
10	340.87	339.91	338.80	337.37
20	482.21	481.09	479.98	478.39
30	595.88	594.93	593.66	592.23
60	840.25	839.29	838.18	836.59
91	1 035.48	1 034.53	1 033.26	1 031.67
182	1 463.80	1 462.68	1 461.41	1 459.82
273	1 807.37	1 806.41	1 805.14	1 803.39
365	2 101.18	2 100.22	2 098.95	2 097.20
547	2 586.72	2 585.61	2 584.34	2 582.59
730	3 007.56	3 006.45	3 005.18	3 003.43

5. CONCLUSIONS

1. Proppant cannot be treated as inert material, it become quite reactive under the influence of thermal stress as temperature increases, what should be included in project calculations.
2. Proppant pack damage may be from suspended solids in the reservoir fluid, from scale precipitation or stress crush effect. For this reason laboratory research is necessary to find damage factor used in simulation.

3. Effectiveness of hydraulic fracture stimulation is measured in terms of its conductivity and production. Fracture conductivity decreases with time, at the certain time the fracture conductivity reaches almost a constant value. Although, the production rate is the same for all total damage factors in analysed case.
4. For shorter production time, the changes in the efficiency of hydraulic fracturing treatment, derived from the destruction of the proppant pack, are more significant than in the case of longer times.
5. Proppant pack permeability is a very important property that directly affects productivity of a well, but it could be so high compering to matrix permeability so proppant permeability decrease due to damage factor has almost no influence on cumulative production.

REFERENCES

[1] Economides M.J., Nolte K.G. et al.: *Reservoir Stimulation Second Edition*. Prentice Hall, New Jersey 1989.

[2] Jarzynowska L., Rożek A., Wielicka D.: *Halophilic microorganisms in petroleum produced waters.* Ochrona Środowiska i Zasobów Naturalnych, nr 48/2011.

[3] Kluk D.: *Badania procesu mieszania wód zatłaczanych z wodami złożowymi o zróżnicowanych potencjałach elektrochemicznych.* Nafta i Gaz, nr 2/2011.

[4] Rasika P., Hutchins R., Makarychev-Mikhailov S.: *Evaluating Damage to the Proppant Pack from Fracturing Fluids with Saline Water.* SPE International Conference and Exhibition on Formation Damage Control, Lafayette, Louisiana, USA, 24–26 February 2016.

[5] Weaver J., Parker M., van Batenburg D., Nguyen P. (Halliburton): *Fracture-Related Diagenesis May Impact Conductivity*. SPE Journal, 2007.

[6] Weaver J., Rickman R., Luo H., Loghry R. (Halliburton): *A Study of Proppant--Formation Reactions*. SPE International Symposium on Oilfield Chemistry, The Woodlands, Texas, USA, 20–22 April 2009.

[7] Yasuhara H., Elsworth D., Polak A.: *A mechanistic model for compaction of granular aggregates moderated by pressure solution.* Journal of geophysical research Solid Earth, 2003.