Review History for “Experimental and numerical investigation of the unclogging process within propped fractures using dynamic stimulation”

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Summary (optional)

The paper was sent to two reviewers — Prof. Derek Elsworth (Reviewer A) and another reviewer who preferred to remain anonymous (Reviewer B). The reviewers remained anonymous during the entire review process and the authors were anonymous for the reviewers. After the reviewing process was complete, one reviewer agreed to disclose their identity. In Review Round 1, the reviewers provided a series of comments for the authors and required a revision of the manuscript. In Review Round 2, the reviewers recommended the manuscript for publication.

Review Round 1

Reviewer A (Derek Elsworth)

The authors complete and report an experimental program to investigate the role of total/effective stress oscillations on permeability evoluton in comminuting proppant systems. They present a clever setup to allow the investigation of both water and gas flows in axisymmetric form and for a variety of conditions of oscillation frequencies, amplitudes and proppant psds. These conditions are quite well controlled and are an interesting range of properties - but omit using pore pressure oscillations in preference for solid stresses, only.

The study is nicely presented and is quite thoughtful (range of parameters and experimental matrix) and completed.

However, the paper lacks any meaningful conclusions of outcomes and mechanistic understanding that the experiments give. The results and trends are reported but no mechanisms are advanced or explanations of why the observed behavior resulted. This leaves the reader (this reviewer) disappointed. Any reader would be dsappointed by the Abstract and Conclusions, that give no mention of any physical insight gained from the experiments.

For example, ... what are the postulated mechanisms that result in the observed behavior? Is the time dependent response resulting from transport of, or decrease in production of fines varying with time? What will be the role of length scale in this - It seems as though the response merely results from the removal of fines - increasing over time - but if the sample diameter is doubled, how will this affect the results? As the fines must migrate and will not be removed from the sample. Is there a mass balance of fines measured with time, to attempt to constrain the results?

These comments may seem harsh, but for this to grab a readers interest, the Abstract (especially) and the Conclusions should have some important (mechanistic) conclusions that will catch someone's attention.

Reviewer B

An experimental study of permeability enhancement in propped fractures upon oscillatory loading of rocks is reported. The manuscript expands on a previous publication on the subject (Fawaz et al, 2021, J Pet Sci Eng), where the overall permeability enhancement method, along with some key findings and analysis of the experiment design parameters were previously enumerated. Therefore, the contribution of the currently submitted manuscript is limited to parametric study of a previously reported work.

Presentation of the content simply relies on observation. That is, running the tests, measuring an experiment variable, and reporting the results. A discussion of the underlying mechanism of fines migration and consequent fracture unclogging because of the applied oscillatory loading would bolster the manuscript content. A suggested format of such discussion could be presentation of a clear hypothesis or hypotheses for the observed behavior, along with a design of experiment to test the hypothesis. A theoretical rationale to support such discussion would further enhance the content. The current manuscript lacks these three components [mechanistic explanation of observed behavior, a method to test such hypothesis, and a theoretical ground to support the same].

Few additional comments are provided, as follows.

1/ The effect of loading frequency and amplitude on the fracture permeability enhancement could go beyond simple repeat of experiments at two or three selected values of these operational parameters. On which other parameters would the cutoff frequency or amplitude depend? would these cutoff values be a function of proppant sizes? fines sizes? their mechanical properties? or rock properties?

2/ The particle size distribution of fines would likely alter the results. This is not discussed in the manuscript.

3/ Appears that all experiments are executed at the same flow rate. It is not clear whether changing the flow rate would alter any of the stated conclusions although intuitively speaking, such changes are expected.

4/ The presumed radial geometry of flow could be a source of significant error in the reported values of enhanced permeability. Once the fines migration and unclogging processes is initiated along a certain path between the outer and inner radii of the fractures, an asymmetric flow for the rest of the experiment would be inevitable. A discussion as to whether the collected data/observations would confirm or reject this concern seems necessary.

5/ The manuscript lacks a discussion of how oscillatory loading may be applied to the field practice of enhanced oil/gas recovery from the unconventional and stimulated reservoirs. Would a relevant field practice be recommended through a completion or a workover operation? and in either case, how could such workover or completion operation be implemented in a wellbore?

Author Response

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Response to the Editor:

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The reviewers found that the paper lacked fundamental mechanistic interpretations. It was noted that there was non-negligible overlap with a previous publication by the authors. It is recommended to structure the paper around clear hypotheses. If the authors believe that they can address the comments provided below, they should provide a point-by-point response to all the questions/points raised, including the more minor comments on the role of particle size distribution and loading flow rate.

First of all, we are very grateful to the editor for his patience. Shortly after receiving the reviewers' comments, the corresponding author left our university and it turned out that he could not invest sufficient time aside his new job to perform the revisions. This is why the corresponding authorship had to be transferred, and also why we are so late.

The paper has been thoroughly revised, taking into account the reviewers' comments: the overlap with the previous publication has been decreased, mainly by referring the reader to the previous article. Each subsection of the parametric study is concluded by clear hypotheses about the phenomena at stake. A new section presenting the numerical model has been added, allowing to conclude on the two basic mechanisms that control, in our opinion, the unclogging process.

Revisions are marked in red in the new manuscript.

In the following, our answers to the reviewers' comments are detailed.

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Responses to the Reviewer A:

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The authors complete and report an experimental program to investigate the role of total/effective stress oscillations on permeability evolution in comminuting proppant systems. They present a clever setup to allow the investigation of both water and gas flows in axisymmetric form and for a variety of conditions of oscillation frequencies, amplitudes and proppant psds. These conditions are quite well controlled and are an interesting range of properties - but omit using pore pressure oscillations in preference for solid stresses, only.

The study is nicely presented and is quite thoughtful (range of parameters and experimental matrix) and completed.

However, the paper lacks any meaningful conclusions of outcomes and mechanistic understanding that the experiments give. The results and trends are reported but no mechanisms are advanced or explanations of why the observed behavior resulted. This leaves the reader (this reviewer) disappointed. Any reader would be disappointed by the Abstract and Conclusions, that give no mention of any physical insight gained from the experiments.

Thanks for this nice comment.

First, each subsection in the experimental result part is concluded by comments on the mechanistic understanding of the experiments:

- The influence of the size distribution of the proppant is related to the porosity and hydraulic diameter with respect to the size of the fine particles. See lines 279-300.
- The influence of the frequency is related to the occurrence of clusters, depending on the amount of fines. At low amount of fines, pressure oscillations break clusters and fines are evacuated. The influential parameter is the number of pulses. At high amount of clusters, high frequency helps better at destabilizing these clusters due to the oscillation of drag forces. See lines 337-351.
- The influence of the amplitude relates to the motion of proppant particles in addition to fine particles. See lines 379-385.

It is this last assumption (possibility of motion of proppant particles) that is verified in section 4 that presents the computational model.

We have also added a new section which presents a prototype computational model based on coupled DEM/finite volume analysis. This is standard in PFC3D, but the permeability model had to be changed to allow an increase of permeability in a cell when solid particles are in motion (compared to Kozeny-Carman formula). It is the original part of this section. Lines 386-524.

We hope that the reviewer, with these revisions and additions will be less disappointed as insights from the basic phenomena at stake are better provided.

For example, ... what are the postulated mechanisms that result in the observed behavior?

Is the time dependent response resulting from transport of, or decrease in production of fines varying with time?

What will be the role of length scale in this - It seems as though the response merely results from the removal of fines - increasing over time - but if the sample diameter is doubled, how will this affect the results? As the fines must migrate and will not be removed from the sample. Is there a mass balance of fines measured with time, to attempt to constrain the results?

The basic mechanisms are the fluid-particles interactions (drag forces and local variation of permeability) that induce particle motion. This is presented in the computational model in section 4 (lines 386-524).

Unfortunately, it was not possible experimentally to investigate the evolution during stimulation of the production of fines. The authors agree that it would have been quite informative.

Thanks for the remark. The issue of the sample size and of the geometry of the fluid flow is indeed very important. This is mentioned in line 224 (about scattering), and in lines 212-219. The geometry of the fluid flow controls the shape of the pressure distribution and in larger specimens, clusters may form nearby the fluid outlet with little influence on the unclogging compared to small specimens.

Only the amount of particles flushed out of the specimen could be recorded at the end of the test. This information is provided for each series of test results.

These comments may seem harsh, but for this to grab a readers interest, the Abstract (especially) and the Conclusions should have some important (mechanistic) conclusions that will catch someone's attention.

We are very thankful to the reviewer for this remark. The conclusion has been rewritten almost totally. It provides hopefully clear conclusions from the experiments, with some assumed mechanisms. In this study, only those related to the influence of the proppant size distribution acting on the pore size compared to the size of fine particles could be checked, along with the assumption that proppant particles are indeed moving during the stimulation. To us, these are the two most important mechanisms at stake.

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Responses to the Reviewer B:

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An experimental study of permeability enhancement in propped fractures upon oscillatory loading of rocks is reported. The manuscript expands on a previous publication on the subject (Fawaz et al, 2021, J Pet Sci Eng), where the overall permeability enhancement method, along with some key findings and analysis of the experiment design parameters were previously enumerated. Therefore, the contribution of the currently submitted manuscript is limited to parametric study of a previously reported work.

Presentation of the content simply relies on observation. That is, running the tests, measuring an experiment variable, and reporting the results. A discussion of the underlying mechanism of fines migration and consequent fracture unclogging because of the applied oscillatory loading would bolster the manuscript content. A suggested format of such discussion could be presentation of a clear hypothesis or hypotheses for the observed behavior, along with a design of experiment to test the hypothesis. A theoretical rationale to support such discussion would further enhance the content. The current manuscript lacks these three components [mechanistic explanation of observed behavior, a method to test such hypothesis, and a theoretical ground to support the same].

See first answer to reviewer A:

First, each subsection in the experimental result part is concluded by comments on the mechanistic understanding of the experiments:

- The influence of the size distribution of the proppant is related to the porosity and hydraulic diameter with respect to the size of the fine particles. See lines 279-300.
- The influence of the frequency is related to the occurrence of clusters, depending on the amount of fines. At low amount of fines, pressure oscillations break clusters and fines are evacuated. The influential parameter is the number

of pulses. At high amount of clusters, high frequency helps better at destabilizing these due to the oscillation of drag forces. See lines 337-351.

- The influence of the amplitude relates to the motion of proppant particles in addition to fine particles. See lines 379-385.

It is this last assumption (possibility of motion of proppant particles) that is verified in section 4 that presents the computational model.

We have also added a new section which presents a prototype computational model based on coupled DEM/finite volume analysis. This is standard in PFC3D, but the permeability model had to be changed to allow an increase of permeability in a cell when solid particles are in motion (compared to Kozeny-Carman formula. It is the original part of this section. Lines 386-524.

We did not strictly follow the organization of the manuscript proposed by the reviewer. We started from experimental results, made some mechanistic considerations and then presented a computational model that enables to check these considerations. Still we do hope that in this form, the reviewer will find it acceptable.

The effect of loading frequency and amplitude on the fracture permeability enhancement could go beyond simple repeat of experiments at two or three selected values of these operational parameters. On which other parameters would the cutoff frequency or amplitude depend? would these cutoff values be a function of proppant sizes? fines sizes? their mechanical properties? or rock properties?

A full range of parameters could not be considered in order to achieve the determination of cut off frequencies and amplitude. Most probably, it would be better to use first a computational model in order to predict the ranges at which a possible cut-off is expected, and then run the few required experiments.

The reviewer is correct: the observed cut-off is mainly related on the size of the pore throats in the propped fracture compared to the size of fine particle as discussed in lines 279-300.

In addition, for proppant 40/70, there has been observed a cut off for quantity of fines greater than 15% (line 244-245). This is, in our opinion related to the same effect of relative sizes between pores and fine particles.

The particle size distribution of fines would likely alter the results. This is not discussed in the manuscript.

The reviewer is correct, see answer above.

Appears that all experiments are executed at the same flow rate. It is not clear whether changing the flow rate would alter any of the stated conclusions although intuitively speaking, such changes are expected.

The reviewer is correct. Changes of the flow rate should alter the efficiency of unclogging. See the comment added in lines 165-169.

The presumed radial geometry of flow could be a source of significant error in the reported values of enhanced permeability. Once the fines migration and unclogging processes is initiated along a certain path between the outer and inner radii of the fractures, an asymmetric flow for the rest of the experiment would be inevitable. A discussion as to whether the collected data/observations would confirm or reject this concern seems necessary.

The reviewer is correct. Asymmetric flow should occur and preferential paths are also observed in the numerical model as the flow is certainly not unidirectional (see figure 18 for the distributions of permeability).

This bears several consequences: (i) on the repeatability of the tests at growing content of fine particles (see lines 224-226); (ii) on the meaning of the measured data, i.e. average properties only (see lines 134-137).

The manuscript lacks a discussion of how oscillatory loading may be applied to the field practice of enhanced oil/gas recovery from the unconventional and stimulated reservoirs. Would a relevant field practice be recommended through a completion or a workover operation? and in either case, how could such workover or completion operation be implemented in a wellbore?

This issue which is highly relevant for practice has not been considered. Nevertheless, we mention in the last paragraph of the conclusions some subsequent work presented at URTEC, dealing with a specific illustration of implementation. (Ref. Fensky et al. 2022).

Review Round 2

Reviewer A (Derek Elsworth)

Great. The authors have addressed the review comments - aligned mainly to increase the impact of their article. The new modeling study is above-and-beyond what would have been helpful - so that is great. The Abstract appears unchanged (no red text markup) but it addresses components that were not in the original (the DEM modeling and outcomes) so that is just an editing error. It all looks good to me. And will be an interesting and informative addition to the literature. Thanks

Reviewer B

Attempts have been made to improve the previous version of the manuscript by including a proxy numerical model. The review comments are addressed in most part by sporadic inclusion of notes within the text acknowledging the points that were raised by those comments. Mechanistic explanations are somewhat provided e.g., through consideration of drag forces and discussion of loading frequency effects on fine migration at low and high mass fractions, but still remain minimally conclusive due to limited size of test matrix and rather elementary analysis/modeling. Field implementation would be challenging if at all possible.

Author Response

Great, please publish it.