FLOW AND DEPOSITION OF DIFFERENT PROPPANTS CARRIED BY FLUIDS IN A SCALED VERTICAL FRACTURE

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Hydraulic fracturing is a technique used to stimulate the production of conventional and unconventional hydrocarbons, being this type of resource a strategic part of Argentina's energy reserve. The procedure consists in injecting fluids at high pressure into the wellbore to create fractures in the formation that later act as highly conductive paths through which hydrocarbons can flow. Since releasing the pressure of fracturing fluids causes the fracture to close, proppant (granular materials) is pumped together with fracturing fluids. For that reason, the way proppant is transported and deposited into the formation determines the future conductivity of the fracture.

We present experimental results on the transport and settling of particles carried by water in a narrow vertical fracture scaled from typical field conditions. We discuss some basic features of the dynamics of the settlement of the proppant dune and the final placement for different types of proppant. The effect of the chosen material on the proppant transport is significant, yielding a much deeper placement of the dune when in lower density materials are used.

Keywords: hydraulic fracture, proppant transport, fluids.

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I. INTRODUCTION

In recent years, many oil companies have directed their efforts towards developing unconventional reservoirs. The challenges encountered to guarantee a profitable operation in these reservoirs lead the industry to devote a significant amount resources to optimize processes such as hydraulic fracturing, a vital technique stimulating production. Hydraulic fracturing consist in the injection of fluids, along with granular materials (called proppants), into the formation to induce or enhance existing fractures and open high conductivity channels connecting the formation and the wellbore [1].

Proppants fill the fracture and support the closing pressure, guaranteeing the fracture conductivity during production. Although fracturing techniques have evolved, there is still opportunities to increase efficiency. Many of these opportunities are related with the way in which proppants are transported and deposited into the fracture.

There are a number of experimental studies that have considered laboratory scale slots to model the transport of proppant in a planar fracture. Kern *et al.* [2] performed some of the first slot flow experiments using vertical Plexiglass walls. In their work, a fracturing fluid (water and 20/40 mesh sand) was pumped at a flow rate that allowed to reach fluid velocities as high as 1.5 m/s inside the scaled fracture. Among other conclusions, these authors found that: (1) at high pumping rates the proppant is fully washed out from the cell and (2) at lower pumping rates the proppant settles and a dune grows in the cell. However, this work did not specify the exact configuration used for the fluid to drain from the fracture. One may speculate that the end section of the cell was a fully open slot as high as the cell itself, connected to the drain system.

After Kern *et al.* pioneering study, there were several authors who used the same methodology to study the transport of proppant [3-5]. In all cases, low fluid velocities in the cell were used (below 0.1 m/s). In general, all these studies reported the formation of a dune inside the cell. Liu [6] and Fernández [7, 8] presented devices designed to match the fluid velocities (and Reynolds numbers) attained in the field, which requires large positive displacement pumps. These experiments, designed following a scaling, are closer than previous setups to field fractures. An important conclusion from these studies is that the flow develops large eddies that erode the proppant from the initial part of the cell, leaving the propped region disconnected from the wellbore [6]. In all cases, experiments were conducted by leaving the end of the fracture open to a drainage tank or by allowing the fluid to exit though a number of orifices that later connect to the drainage via a set of collectors. In general, a section of a few centimeters at the bottom part of the draining side of the slot was left sealed to create a small barrier that helps the to stabilize a proppant dune inside the cell.

In this work, we use a scaled laboratory slot [7]. The slot is placed vertically and it has smooth walls. The main goal of this work is to elucidate whether the characteristics of the material have an influence on the way proppant deposit. The proppant pack is of vital importance for the future conductivity of the well. We consider a number of different proppant materials and analyze the effect on the final dune

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settled after treatment.

Section II presents our experimental setup for the scaled vertical slot. The results on the final area propped by the settled proppant for different types are detailed in section III. We draw our conclusions in section IV.

II. EXPERIMENTAL SETUP

The experimental setup has been described in detail in Fernandez *et al.* [7]. Here we only describe the main features. The cell that mimics a fracture is made of a stainless steal frame 1.6 m long and 0.8 m high. Two acrylic plates fit in the frame leaving a 6.0 mm gap between them. In the current study, we have used a smooth and tortuous slot. An elastomer band is used as gasket to seal the contact between the frame and the acrylic plates to prevent leakages. Two metal matrices with bolts and nuts are used to press the two acrylic plates against the frame and deform the elastomeric seal. Moreover, these matrices provide additional support to prevent the cell from deforming under pressure during the experiments. Two perforations (6.0 mm in diameter) on one side of the frame (right side in all images and plots) act as inlets for the fluid. On the opposite side the frame has 49 perforations of 6.0 mm distributed along the entire height of the cell to act as fluid outlets. For each group of seven consecutive outlet perforations a prismatic collector welded to the stainless steal frame collects the fluid that exists from the cell to direct it into the treatment and drainage system. These collectors can be opened or closed at will by manual valves installed after each collector. The inlet side of the stainless steel frame is welded to a 2.0 in (50.8 mm) stainless steel tube that serves as casing of the simulated wellbore. Fig. 1 shows the experimental setup.

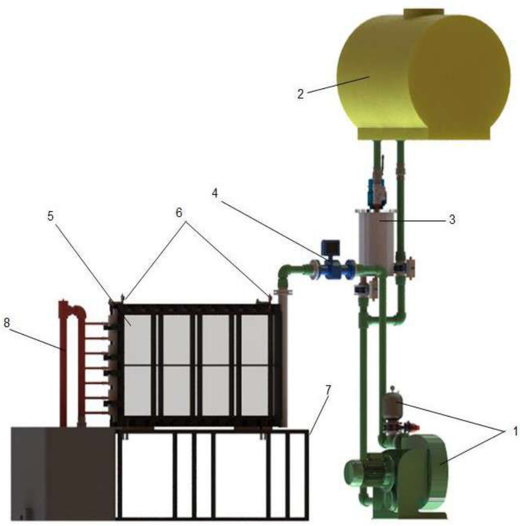

FIG. 1: Experimental setup: (1) Peristaltic pump and flow damper, (2) fresh water tank, (3) blender, (4) flow meter, (5) cell, (6) pressure gages (and purge valves), (7) supporting table, (8) drainage.

The full dimensional analysis used to scale these experiments to a reference field fracture is detailed in Fernandez *et al.* [7]. Briefly, we consider a reference a vertical field fracture with a half wing length of 80 m , an height of 40 m and and a thickness of 6 mm. A closed fracture after completion is typically narrower, however, during pumping, the fracture is open and 6 mm is a reasonable estimation [3]. Since the sand used in the experiments is similar to the one used in real operations, the width of the scaled fracture cannot be different from the field fracture to avoid clogging. Therefore, the cell is 6 mm wide. The other two dimensions are scaled by 1/50, which leads to a cell 1.6 m long and 0.8 m height. We assume that this fracture is connected to a vertical wellbore at two active perforation clusters. Each cluster is represented by a single injection point in the laboratory cell. For a pumping rate of 60 BPM[1] each half wing takes 30 BPM, and each cluster takes 15 BPM. Inside the field fracture the average speed of the fluid is 0.33 m/s. We set our laboratory pumping rate in the range 60 to 100 l/min. This yields a mean velocity in the cell in the range of 0.2 to 0.34 m/s, compatible with the field operation ($\approx 35-60$ BPM). This scaling ensures that the Reynolds number for the proppant particles and for the fracture itself is conserved (see Fernandez et al. [7]). The Reynolds number for the perforations is not conserved, however, both field and laboratory perforations remain in the highly turbulent regime. The dimensional scaling also implies that times are reduced also by a factor 50 in the laboratory cell.

The mixture (proppant + water) is injected into the cell through the casing and inlet perforations using a peristaltic pump (Verderflex, Dura 45). Due to the high flow rate required to pump through the small perforations, the pressure in the casing increases up to 12 kg/cm^2. We use a flow damper after the pump to deliver a more continuous flow rate. The pressure inside the acrylic cell is always below 0.2 kg/cm^2. The fluid is prepared in a mixer that stirs continuously fresh water and proppant. We use proppant according to API standard [9]: (a) premium sand, 30/70 mesh - 0.40 mm , bulk density 1600 kg/m^3;(b) glass spheres, 18 mesh - 1 mm, bulk density 1500 kg/m^3 and (c) ceramic, 20/40 mesh - 0.63 mm, bulk density 1800 kg/m^3 at a concentration of 0.5 kg/l. The flow rate is measured by a flow meter installed just before the casing. A pressure transducer provides a measure of the pressure inside the cell.

To obtain rough walls in the cell, another set of acrylic plates was machined as described in Basiuk et al. [10]. Due to the grooves machined on the fracture walls the cell looses transparency. However, the refractive index of the acrylic is close to the refractive index of water. As a result, the proppant inside the cell can be observed clearly when the cell is filled with water. The cell is recorded during each experiment via a digital camera (Optronix CR3000). The frame rate is set to 120 fps with Full HD resolution. After pumping is stopped and proppant has fully settled, an image is taken at 4032×3024 pixel resolution. To illuminate the cell we used two LED reflectors (22500 lumens) and light diffusers to achieve a uniform illumination on the entire surface of the cell.

We have carried out experiments for three types of proppant, being compatible with field operations: premium sand, glass spheres and ceramic. In all cases we use the same concentration (0.5 Kg/l) and flow rate (61 l/min). The tests were repeated giving the same dune profile in both cases.

[1] barrels per minute

III. RESULTS

The flow rate used was 61.0 l/min, corresponding to 40 BPM in a field operation [7]. The total duration of the pumping is from 83 s, which corresponds to 69 min in the field. Once the mixture has been pumped into the cell, the pumping is stopped and the proppant that still remains in the cell is allowed to settle down. The photograph of each final dune is used to extract the profile of the dune.

Fig. 2 shows the final deposited dune. The lower right panel of Fig. 2 shows the extracted dune profiles for comparison. As we can see, the higher the density of the material, the larger the final deposited dune in the cell. The large vortices in the cell tend to wash the first half of the cell length in the case of glass spheres, leaving only a small heap next to the casing thanks to a low velocity region in the lower right side of the cell. In the case of sand, the surface covered by the material is greater than that in the case of glass spheres. This is due to the higher material density. The final deposition occurs evenly forming a layer throughout the length of the cell. Lastly, when ceramic proppant is used the dune has a greater amount of settled material, again due to its higher density. In all cases we can see that a similar dune height is obtained close to the casing of the slot. It is important to mention that the small heap (approximately 20 cm high) observed for all materials corresponds to a height of 10 m in the field.

To quantify the dune shape and position, we have measured the dune high (x) every 5 cm distance from the fracture. Table 1 summarizes the results. The data confirm that the mean dune heights for sand and glass are essentially the same. The same goes for the maximum dune heights X. Regarding the distribution of the mean and maximum dune heights, it does not seem to be any pattern of similarities. In the case of ceramic proppant, the maximum dune height is around 23 % higher than that the one obtained with glass and sand. For the mean dune height, the average is 37 % higher than the corresponding mean dune height for glass and sand. It is important to mention that the distribution profile of sand and ceramic are similar, corresponding the latter to slightly higher dune heights all across the cell length, which is a consequence of the higher material density that allows a larger portion of the inyected material to remain into the cell.

Despite the different dune shapes and positions observed in the experiments, one key parameter to assess the quality of an operation is the total area of the fracture effectively covered by the deposited dune. As it can be expected, the lower the density of the material, the lower the area of the dune. The ceramic agent lead to a dune area 34 % greater than the one obtained with sand and glass proppant, which are similar. However, we need to mention that the proppant that left the cell through the exit perforations is effectively covering deeper parts of the fracture in a real operation. The values reported here are in fact an indication of the area covered in the first 80m of the fracture length. When looking the propant distribution along the cell, we can observe that in the first third of its length, the glass proppant has an accumulated area greater than the corresponding for sand. This trend is reversed in the second third of the cell and then equalized in the last third. This is consistent with the strong vortices that are generated in the center of the fracture and prevent a deposition of the material [8].

TABLE 1: The columns show the partial height data of the sand, glass and ceramic proppants respectively.

fracture length [cm]	mean parcial dune height [cm]		
	Sand	Glass	Ceramic
5	21,64	22,532	27,091
10	19,49	22,326	24,443
15	16,72	22,222	21,489
20	15,08	20,052	19,758
25	13,54	18,191	18,332
30	12,31	16,227	17,008
35	11,69	14,677	16,295
40	11,28	12,713	15,888
45	10,87	12,196	15,582
50	10,67	10,853	15,073
55	10,56	9,819	14,564
60	10,46	8,269	14,055
65	10,36	7,132	13,546
70	10,05	6,098	12,731
75	9,85	5,375	12,323
80	9,44	4,755	12,12
85	9,03	4,858	11,509
90	8,82	5,168	11,407
95	8,51	5,271	11,509
100	8,10	5,478	11,407
105	8,00	5,685	11,509
110	7,80	5,995	11,61
115	7,80	6,408	11,814
120	7,90	7,442	11,916
125	8,21	7,959	11,814
130	8,82	8,579	12,323
135	9,33	8,889	12,833
140	9,74	9,406	13,444
145	10,26	10,026	13,851
150	10,67	10,543	13,342
155	10,77	10,853	13,953
160	10,97	10,853	14,055
mean dune height[cm]	10,90	10,52656	14,64356

An important characteristic of the experiment that we have mentioned is the vorticity of the fluid. Although it is not the purpose of this work to explain this phenomenon, which is already explained in Fernandez et al. [8], we want to highlight its relevance. Fig. 3 shows the velocity field vector map for a particular frame. In this figure you can see the trajectory of the fluid particles and quantify the value of the velocity components. In this way, the average speed in every region of the cell and for each frame can be obtained. It can be seen that the flow pattern is very complex with flows and counter-flows throughout the entire cell, displaying strong vortexes, particularly close to the inlets. We note that there exist some foci of high fluid velocities rather than a smooth velocity profile across the cell. This is in agreement with recent simulations of a similar system (see Baldini et al. [11]).

IV. CONCLUSIONS

We have observed that the proppant injected into a narrow cell, after an initial sweep with fresh water, settles in