THE STUDY OF CROSSLINKED FLUID LEAKOFF IN HYDRAULIC FRACTURING PHYSICAL SIMULATIONS

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***Abstract**. The fluid loss plays an important role in the design and execution of hydraulic fracturing treatments. The main objectives of this work were: the study of the fluid loss associated with the propagation of hydraulic fractures generated at laboratory; and the comparison of two distinct methods for estimating leakoff coefficients – Nolte analysis and the filtrate volume vs. square root of time plot. Synthetic rock samples were used as well as crosslinked hydroxypropyl guar (HPG) fluids in different polymer concentrations. The physical simulations comprised the confinement of (0.1x0.1x0.1) m^3 rock samples in a load cell for the application of an in situ stress field. Different flow rates were employed in order to investigate shear effects on the overall leakoff coefficient. Horizontal radial fractures were hydraulically induced with approximate diameters, what was accomplished by controlling the injection time. Leakoff coefficients determined by means of the pressure decline analysis were compared to coefficients obtained from static filtration tests, considering similar experimental conditions. The research results indicated that the physical simulation of hydraulic fracturing may be regarded as an useful tool for evaluating the effectiveness of fracturing fluids and that it can supply reliable estimates of fluid loss coefficients.*

***Keywords:** Hydraulic, Fracturing, Fracture, Leakoff, Fluid loss, Crosslinked, Pressure Decline, Filter cake, Petroleum, Stimulation, Completion*

1. INTRODUCTION

In most of the hydraulic fracturing operations, a polymer based fluid is pumped down the wellbore to create and propagate a fracture. A certain fraction of the fluid leaks into the formation through the fracture faces, leaving a skin layer (deposition of polymers and other particulate solids) at the rock surface. The fluid lost to the formation does not contribute to the creation of fracture volume.

Basically, the fluid loss process takes place in two stages: the initial invasion of the fracturing fluid into the formation, often referred to as spurt loss; and the buildup of a filter cake on the surface of the porous medium. The after-spurt filtration is controlled by the filter cake, where most of the resistance to leakoff occurs. In high permeability reservoirs, the fluid may also invade the rock matrix, causing polymers to clog the pore throats nearby the fracture surface and, consequently, to form an internal filter cake.[1,2]

In static conditions, the leakoff rate is gradually reduced as the filter cake grows up and the filtrate volume is proportional to the square root of time. On the other hand, in dynamic conditions, the thickness of the external filter cake is limited by the shear stress exerted by the flow, so that the growth of the cake reaches an equilibrium point at a certain shear rate. After the establishment of the equilibrium thickness, the leakoff rate remains constant and the cumulative filtrate volume becomes proportional to time. Comprehensive literature reviews on this subject were published by Penny and Conway[3], Nolte and Economides[4], and McGowen and Vitthal.[5,6]

Due to several reasons ranging from the need to minimize fluid and pumping costs to preventing formation damage, it is critical to use the least amount of fracturing fluid to achieve the designed fracture. Excessive fluid loss to the formation may affect fracture geometry and proppant scheduling or even lead to a premature job termination, caused by screenout. Thus, the success of a fracturing treatment strongly depends on an adequate leakoff control strategy.

Over the years, oil companies have been continuously improving the fracturing fluids properties against fluid loss. The more efficient the fluid, the lower the leakoff rate. Laboratory testing enables the optimization of fluid performance as well as the prediction of the relationship between leakoff coefficients and fracturing fluids or formation properties. Nowadays, both static and dynamic filtration tests are employed for evaluating the fluid loss of fracturing fluids; dynamic tests, however, are considered to be more realistic.

Field measurements of *in situ* fluid loss are required before hydraulic fracturing treatments. A calibration test known as *minifrac* is usually applied to obtain estimates of leakoff coefficients, what is accomplished via the pressure decline analysis, firstly presented by Nolte[7], in 1979. Since then, the method has been continuously improved and extended in applications by various researchers, such as Nolte[8,9], Castillo[10], Lee[11], Mayerhofer *et al*[12], Nolte *et al*[13], Fan[14], and others.

This study focused on the study of fluid loss of crosslinked hydroxypropyl guar (HPG) fluids associated with the propagation of hydraulic fractures generated at laboratory. The effects of polymer concentration and injection flow rate were investigated. Leakoff coefficients determined by means of Nolte analysis were compared to coefficients obtained from static filtration tests. The physical simulations of fracturing comprised the confinement of low permeability synthetic rock samples in a load cell, for the application of the *in situ* stress field.

In the present work it was shown that physical simulations of hydraulic fracturing allow the comparison of field-used fluids with different efficiencies related to leakoff control and also that this type of experiments can supply reliable values of fluid loss coefficients, according to laboratory results.

2. EXPERIMENTAL ASPECTS

This section comprises the basic description of the hydraulic fracturing physical simulation and the static filtration tests which were performed.

2.1 Hydraulic fracturing physical simulations

The hydraulic fracturing physical simulator is composed, basically, by three systems: (i) confinement vessel; (ii) fracturing fluid injection and confining pressure application; and (iii) data monitoring and acquisition. A detailed description of the overall experimental apparatus was decribed by Ribeiro *et al*.[15]

Synthetic rock samples. The (0.1x0.1x0.1) m^3 blocks were made of gypsum (in a mixture of water, alcohol and salt), with a curing period of about two weeks in a controlled humidity environment. The average mechanical and petrophysical properties of the gypsum blocks are shown in Table 1.

Table 1: Properties of the synthetic rock samples

Poisson´s Ratio	0.2
Young´s Modulus	1.3 GPa
Permeability	6 mD
Porosity	40 %

Fracturing fluids. Titanate-crosslinked hydroxypropyl guar fluids were used in different polymer concentrations, and a proppposed nomenclature for the fluids, according to polymer concentration (Gel 20 through Gel 60), was applied in the remaining sections of the article. Additives were not introduced, except for buffers, and the final pH of the gelled fluids was 7.5. A water-soluble dye was added to the fracturing fluids, what enabled the visualization of the fracture faces after the conclusion of the tests and did not affect either the fluid leakoff process or rheological properties of the gels.

Testing procedure. Experiments applying four injection flow rates (1, 2, 3 and 4 ml/min) were performed with each one of the five fracturing gels. The *in situ* stress field and properties of rock samples were the same for the whole set of tests (no vertical stress and equal horizontal stresses of 3.45MPa). No pore pressure was applied and all the experiments were run at room temperature.

Each physical simulation was conducted in two steps: (1) the dyed fracturing fluid was pumped to initiate and propagate the fracture inside the sample; (2) after fracture closure, the gel without dye was pumped to reopen the fracture and extend it towards the block boundaries. Pressure data acquired from step 1 was used for pressure decline analysis. The procedure applied in step 2 proved to be adequate for breaking apart the gypsum sample and also for subsequent analysis of fracture geometry and orientation.

A critical aspect of the testing procedure was the control of propagation time. The objective consisted in the generation of fractures with approximate diameters (4,9 to 5,4 cm), regardless of the flow rate or gel properties. This task was accomplished by adopting a trial-and-error method. Since fractures pursued diameters sufficiently close to each other, a straightforward analysis of polymer concentration and injection rate effects became possible.

2.2 Static filtration tests

The experiments were conducted in a Baroid static cell and the gels were tested with 2.07 and 3.45 MPa pressure differentials at room temperature (24°C). The pressure differential during the tests was held constant. Wall-building coefficients (C_w) were determined by plotting accumulated filtrate volume *versus* the square root of time.

2.3 Experimental variables

A critical matter in this work referred to the establishment of similar experimental conditions between the fracturing simulations and filtration tests, in order to allow comparisons of fluid loss coefficients obtained from these distinct experiments.

The rheological parameters (K and n) of the gelled fluids, represented by the Ostwald de - Waale model, were found to be constant throughout a period of 3 hours after the end of manufacturing, according to Table 2. Moreover, due to the short pipe length and low residence times of the fracturing fluids inside the injection system, there had been no polymer degradation caused by shear effects; this was proved to be true by means of rheological measurements of fluid samples. Within the fractures, significant viscosity changes were not expected in most fracturing simulations because of relatively low propagation times.

Table 2: Rheological properties (24 °C)

Fluids Nomenclature	***C_{HPG} (kg/m^3)***	***K (Pa s^n)***	***n***
Gel 20	2.4	0.7	0.60
Gel 30	3.6	3.8	0.52
Gel 40	4.8	9.2	0.45
Gel 50	6.0	22.0	0.35
Gel 60	7.2	31.6	0.31

It was necessary to identify a relationship between the injection pressure reading and the actual pressure inside the fracture, which is inherently connected to the driving force of the fluid loss process. Firstly it was assumed that, within the fracture, the pressure nearby the injection pipe could be estimated as the pressure reading and the frictional pressure drop – from the pressure sensor until the extremity of the injection pipe – were known values. An average propagation pressure was calculated according to Eq. 1:

$$\overline{P}_w = \frac{\int P_w(t)dt}{t_p} \qquad (1)$$

Based on the pressure distribution profile in radial fractures and the absence of pore pressure, the $\overline{P}_w$ value was regarded as "representative" of the leakoff driving force. The pressure differentials applied in the filtration tests (2.07 and 3.45 MPa) were chosen on the basis of the determined values of average propagation pressures. $\overline{P}_w$ values obtained from all the fracturing simulations ranged from 2.03 to 3.4 MPa.

3. RESULTS

The tests carried out with the gypsum blocks confirmed the possibility of successfully simulating fracture initiation, extension, closure and reopening in such samples.

3.1 Pressure behavior

An example of the resulting injection pressure *versus* time and G-plot curves is presented in Fig. 1. Other results can be found in the work by Grothe.[16]

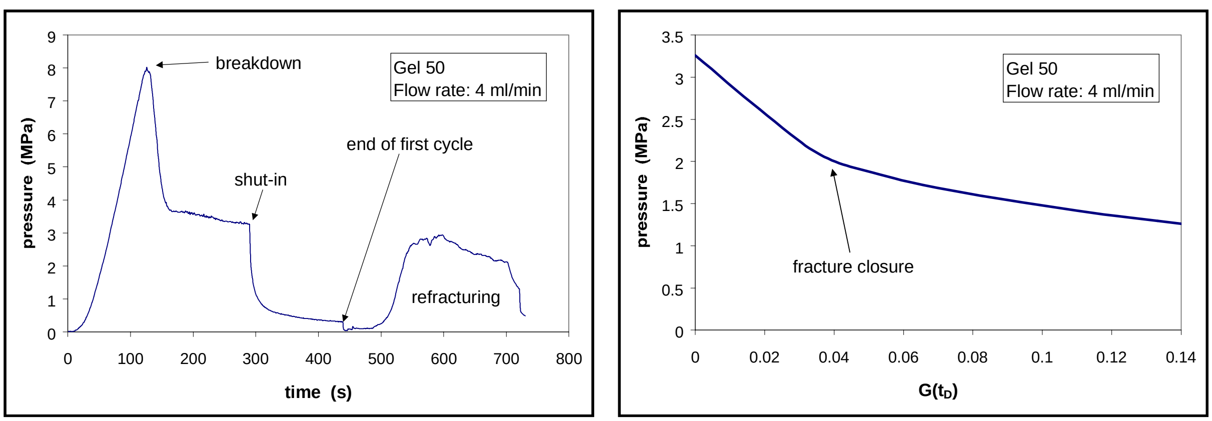

Fig. 1: Injection pressure *versus* time records and G-plot curves for different fluids

A decrease in pressure after breakdown is always expected because the fracture propagation pressures are lower than the pressure necessary to break the formation. A significant relief in pressure took place just after the initiation of the fractures. This salient decrease in pressure is attributed to the flow from the borehole into the incipient fracture, coupled with extremely high leakoff rates (spurt loss). A similar behavior is observed in field treatments, but usually in a weaker intensity. During fracture propagation, the pressure decreased smoothly. Fracture closure was complete because no proppants or particulate solids were added to the fracturing fluid. No fracture extension after shut-in was verified. Pressure records immediately after shut-in were used to adjust the best straight line in the G-plot curve.

At the end of the first fracturing cycle, the injection system was cleaned up in order to allow pumping of the auxiliary fluid (gel 50 with no dye) for reopening the fracture. Pressure response during the second cycle did not follow a repetitive pattern in all experiments; however, pressure behavior in the refracturing cycle will not be discussed in this article.

3.2 Fracture geometry

The radial geometry was verified for all induced fractures, due to the confining stress state imposed to the samples as well as the homogeneity and isotropic characteristics of the material. Examples of test results are presented in Fig. 2.

Gel 20	Gel 50
Flow rate: 4 ml/min	Flow rate: 4 ml/min
Fracture radius: 2.45 cm	Fracture radius: 2.7 cm
Propagation time: 259 s	Propagation time: 130 s

Figure 2: Photos of fractures hydraulically induced

An examination of the samples after testing revealed the buildup of thin layers of polymeric material covering the fracture surfaces, recognized as filter cakes.

3.3 Overall leakoff coefficients

The experimental results indicated the feasibility of obtaining leakoff coefficients from the physical simulations. The immediately after shut-in portion of the injection pressure curves was used to determine the overall leakoff coefficients regarding the application of Nolte's analysis. G-function plots were used, as shown in Fig. 4 and the estimated values of C_L are presented in Fig. 3.

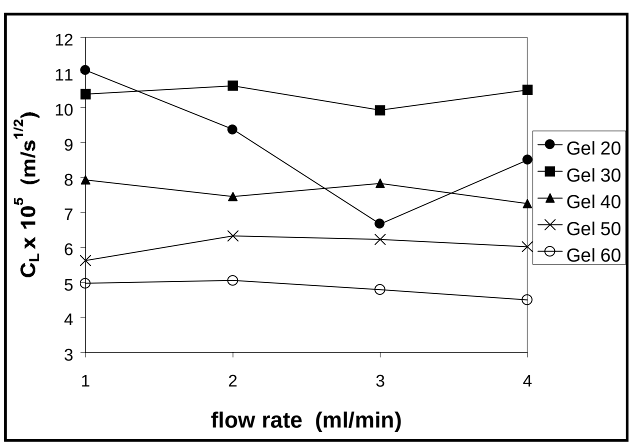

Figure 3: Overall leakoff coefficients obtained from fracturing simulations

Except for Gel 20, it was possible to conclude that: (1) for each gel, the leakoff coefficients tend to a common value, regardless of the injection rate; and (2) for each flow rate, the higher the HPG load, the smaller the value of C_L, which is in fully accordance to filtration theory. No evident relationship between leakoff coefficients and average propagation pressures was realized.

The fluid loss of crosslinked fluids has usually shown to be affected by the shear rate inside the fracture. The application of different flow rates had the purpose of assessing shear effects on the overall leakoff coefficients. In view of the results, it is likely that shear stresses did not affect the leakoff rate. This phenomenon may be understood as a consequence of considerably short propagation times and/or sufficiently low shear rates. Lower propagation times lead to less exposition of the growing filter cake to shear stresses and, therefore, reduced dynamic effects.

The tests carried out with Gel 20 yielded the higher propagation times for every flow rate. Thus, the higher values of C_L should have theoretically been encountered for this gel, as a direct result of lower fluid efficiency. Based on two facts: (1) the systematic behavior of a decreasing propagation time as a function of increasing HPG concentration and increasing injection rate; and (2) the flow rate-independent coefficients trend observed for the other gels (Fig. 3); it was possible to conclude that the pressure decline analysis might not produce accurate C_L values for the Gel 20 cases. Assumptions in the development of the pressure decline analysis[7,8], such as pressure-independent leakoff coefficient and incompressible fluid, may possibly have caused the observed deviations.

3.4 Comparison of fluid loss coefficients (C_L *versus* C_w)

The wall-building coefficients (C_w), obtained from the static filtration tests, followed the classical theory: the filtrate volume is proportional to the square root of time for the two applied pressures. Considering the tendency shown in Fig. 3 (leakoff coefficients independent of flow rate), an arithmetical average of the four C_L values associated to each fluid was calculated. This averaging parameter was referred to as C^*.

Fig. 4 presents a comparative plot of fluid loss coefficients obtained from fracturing simulations and static leakoff tests. This plot permitted a simplified analysis of the experimental data. The C^* value for gel 20 may be analyzed separately, due to the reasons pointed out formerly.

As it can be observed in Fig. 4, coherent values of wall-building coefficients (C_w) were found for Gel 20, in opposition to the results from fracturing simulation. It was also proved to exist a certain dependency between the leakoff coefficients and the pressure differential within the pressure range studied.

An important question that arises at this point is whether the coefficients are representative of a similar phenomenon. The fluid loss of crosslinked gels is controlled by the filter cake; this statement is often valid for static and dynamic leakoff tests. It is widely accepted that the same fluid loss mechanism occurs during the propagation of hydraulic fractures in field operations. In this work, the formation of filter cake could be observed in both filtration tests and fracturing simulations.

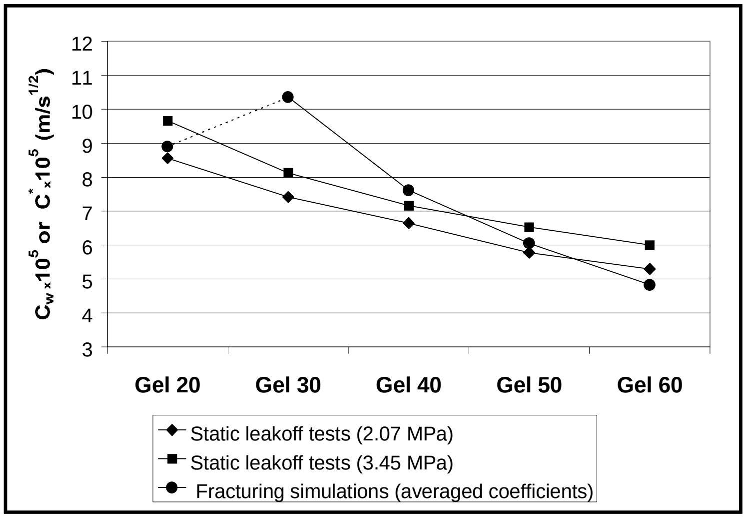

Figure 4: Comparison of coefficients C^* and C_w

Theoretically, a filtration cell is able to simulate the fluid loss of one fracture surface element, since only this areal element is subjected to a defined group of conditions (pressure differential, shear rate, etc.) in a given moment of time. On the other hand, the results from the fracturing simulations are expected to represent the processes involved in the propagation of the fracture, although the pressure decline analysis is an indirect tool to supply estimates of leakoff coefficients.

In view of the distinct experimental methodologies from which the coefficients C^* and C_w were determined, in a general manner it can be seen that, except for Gel 20, the values of C^* and C_w related to each fluid are considerably approximate. This results have also confirmed the reliability in applying Nolte analysis to the experimental data.

4. CONCLUSIONS

1. The experimental results indicated that the hydraulic fracturing physical simulation may be regarded as an useful tool for studying fluid loss performance of fracturing fluids and also that it can supply reliable estimates of leakoff coefficients. The applied testing methodology turned out to be a considerably simple technique for comparing fracturing gels with different properties concerning fluid loss control.

2. Except for the Gel 20, it was possible to conclude that: (i) for each gel, the overall leakoff coefficients (C_L) tend to a common value, regardless of the injection rate; and (ii) for each flow rate, the higher the HPG load, the smaller the value of C_L, which is in fully accordance to filtration theory. No evident relationship between leakoff coefficients and average propagation pressures was realized.

3. It was observed in the hydraulic fracturing experiments, a systematic behavior of a decreasing propagation time as a function of increasing HPG concentration and increasing injection rate. The flow rate-independent trend of the coefficients (C_L) observed for the other gels allowed the conclusion that the pressure decline analysis might not produce accurate C_L values for the Gel 20 cases. Assumptions in the development of the pressure decline

analysis[7,8], such as pressure-independent leakoff coefficient and incompressible fluid, may possibly have caused the observed deviations.

4. In general, the average leakoff coefficients, C^*, and the wall-building coefficients, C_w, showed fair agreement even though they were obtained from totally different experimental methodologies. In both cases, fluid loss of the gelled fracturing fluids was characterized by filter cake buildup. These results also confirmed the feasibility of applying the pressure decline analysis (Nolte) to obtain C_L.

NOMENCLATURE

C_{HPG} = hydroxypropyl guar concentration (kg/m^3)
C_L = overall leakoff coefficient ($m/s^{1/2}$)
C_w = wall-building coefficient ($m/s^{1/2}$)
C^* = arithmetic average of C_L values
K = consistency index (Pa s^n)
n = flow behavior index (dimensionless)
P_w = injection pressure reading (MPa)
$\overline{P}_w$ = average propagation pressure (MPa)
ΔP = filtration pressure differential (MPa)
R = fracture radius (cm)
t = time (s)
t_p = propagation time (s)

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