COBEM 99
XV Congresso Brasileiro de Engenharia Mecânica
15th Brazilian Congress of Mechanical Engineering
22 - 26 de Novembro de 1999 / November 22 - 26, 1999 Águas de Lindóia, São Paulo,

HYDRAULIC FRACTURING PHYSICAL SIMULATION: AN EXPERIENCE

Paulo R. Ribeiro
Universidade Estadual de Campinas, Departamento de Engenharia de Petróleo
DEP/FEM/UNICAMP Cx. P. 6122- Campinas -13083-970, SP, Brasil
José L. A. de Oliveira e Sousa
Universidade Estadual de Campinas, Departamento de Estruturas
DES/FEC/UNICAMP Cx. P. 6021 - Campinas - 13083-970, SP, Brasil
Paulo D. Fernandes,
CENPES/PETROBRAS
Rio de Janeiro, RJ
Vanessa L. Caldas Leite
Universidade Estadual de Campinas, Departamento de Engenharia de Petróleo
DEP/FEM/UNICAMP Cx. P. 6122- Campinas -13083-970, SP, Brasil

***Abstract**. Hydraulic Fracturing has become one of the most important stimulation techniques since its first treatment back in 1947. Considering that about 40% of the wells drilled around the world are hydraulically fractured, a great deal of attention has been given to the improvement and cost-effectiveness of such treatments. Due to the difficulties associated with the prediction of fracture orientation and geometry, mathematical simulation of the process has been performed by various researchers, and results have been compared to field observations by indirect methods. The limitations of mathematical modeling associated with the difficulties of direct measurements of fracture geometrical parameters has motivated the development of various hydraulic fracturing apparatuses, in order to understand and control the physical process. Due to the remarkable contribution of various researchers in this area, the main objective of this article is to present the state-of-the-art of the subject and to report a experience of designing a hydraulic fracturing apparatus and conducting experiments using the system. The system basically consists of a polyaxial frame for the application of the in situ stress state in (0.1x0.1x0.1)*m^3 *gypsum samples, and a virtual instrumentation system to monitor pressure signals during the propagation and closure of the fracture that was initiated by fracturing fluid injection. Typical curves (fluid injection pressure versus time) obtained in field treatments have been observed in the laboratory and penny-shaped fractures have been generated during the experiments.*

***Keywords:** Hydraulic Fracturing, Petroleum, Laboratory, Polyaxial Frame, Reduced Models, Rock, Reservoir.*

1. INTRODUCTION

Hydraulic Fracturing is largely applied in the petroleum exploitation with the main purpose of increasing the productivity of oil and gas wells or the injectivity of injection wells for disposal or secondary recovery. Due to the high costs associated with the operation and the inherent difficulties of the prediction of the fracture behavior in the formation, the usage of physical simulators in the laboratory has become an interesting option. The physical simulation comprises the confinement of a rock sample in a load cell, for the application of the in situ stress field. The treatment consists in the injection of a fracturing fluid inside the pre-stressed sample in order to generate the fracture.

2. PREVIOUS STUDIES

Daneshy (1973) performed hydraulic fracturing simulations in three different types of material samples. The confining stresses applied to the face of the samples ranged from 1.4MPa to 17.2MPa without any pore pressure. The 6.3mm hole drilled in the $(0.15x0.15x0.25)m^3$ sample for the injection of the fracturing fluid was oriented with azimuths of 0^o and 75^o with inclinations of 24^o and 32^o. The author identified three types of fracture geometries: axial, normal and inclined to the hole axis. The objective of the author was to identify the rock failure mechanism according to the topology of the fracture surface generated.

Blanton (1982) studied the interaction between the hydraulically generated fracture and the natural fractures of Devonian Shale. The (0.3x0.3x0.38) m3 samples were positioned inside a pressure vessel with a 21MPa confining stress capacity in each direction and a fracturing fluid injection rate of 0.8ml/s. The results showed that there exist three mechanisms of interaction between the generated and the existing fractures: the opening of pre-existing fractures, the imprisonment of the hydraulic fracture by the natural fractures and the crossing of the natural fracture system. The occurrence of a determined type of interaction was associated with horizontal confining stress contrast and the average angle between the hydraulically generated and the pre-existing fracture system.

Cheung (1990) performed hydraulic fracturing simulations in intact and naturally fractured Niagara dolomite samples, with the intent of determining the *in situ* stress field as a function of the breakdown, reopening and closure pressures as well as the strength of the sample. The tests were conducted with a pressure cell of 90MPa horizontal and 140MPa confining stress capacity.

Behrman and Elbel (1990) studied the effect of perforation geometry as well as perforation and fracturing procedure in the initiation of the fracture in horizontal and vertical wells of sandstone samples. The $(0.71x0.71x0.82)m^3$ samples were confined in a polyaxial cell with pore pressure monitoring and control and a 55MPa confining stress capacity per axis. The results showed that the fracture initiation depends, basically, on three factors: local pore pressure surge, micro-annular pressurization and perforation orientation.

Abass et al. (1992) developed an experimental study about the fracture propagation in horizontal wells with different orientation in relation to the horizontal stress field, in order to prevent excessive treatment pressures and premature screenouts. The results showed three types of non-planar fractures, according to the wellbore azimuth: parallel multiple fractures, reoriented fractures and T-shaped fractures. They used $(0.15x0.15x0.25)m^3$ gypsum samples with a load cell of 21MPa confining stress capacity per axis.

Abass et al (1995) studied the effect of the perforation orientation in the initiation and propagation of fractures in vertical and horizontal boreholes. Three kinds of experiments were conducted: vertical wells with 180^o phased perforations variably oriented in the horizontal plane, horizontal wells with vertical perforations along the preferential direction of fracturing, and horizontal wells with clustered perforations in the vertical direction.

Ong (1994) performed a comprehensive research in deviated wellbore stability. Besides a semi-analytical modeling of wellbore stability in an anysotropic nonlinear elastic medium, he conducted hydraulic fracturing experiments in $(0.42\text{x}0.42\text{x}0.44)\text{m}^3$ concrete samples in a load cell of 21MPa confining stress capacity per axis. The results concerned the viability of applying the linear elastic theory to predict rock failure in hydraulic fracturing of inclined wellbores.

3. EXPERIMENTAL APPARATUS

The system was composed, basically, of the load cell, stress confinement and fluid injection system and the data monitoring and acquisition system, as shown in Fig. 1.

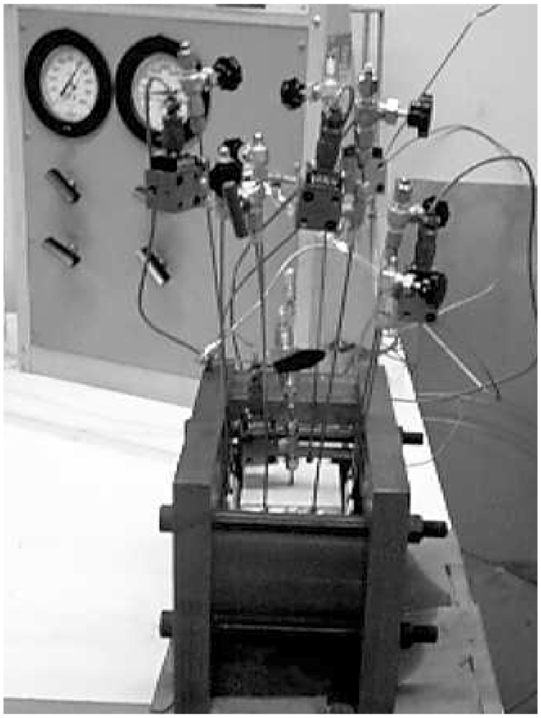

Figure 1: Experimental apparatus

3.1 Load Cell

The $(0.1\text{x}0.1\text{x}0.1)\text{m}^3$ samples were confined in a steel load cell with 21MPa confining stress capacity per axis with a maximum horizontal stress contrast of 10.5MPa. The cell was not equipped with pore pressure monitoring or control.

3.2 Confining Stresses and Fluid Injection System

The 3D confining stress field was applied by stainless steel flat jacks, which were positioned together with shim plates against the six faces of the sample. The flat jacks were manufactured by welding (tungsten inert gas - TIG) two sheets of metal, which were carefully checked against leakage before any testing. A 42MPa capacity positive displacement pump was applied for the stress confinement and fracturing fluid injection, according to Fig. 2.

3.3 Data monitoring and acquisition system

The system was equipped with four pressure transducers for monitoring of the three confining stresses (2 horizontal and a vertical) and the fracturing fluid injection pressure. The four conditioned signals were sent to a 16-bit data acquisition board, which was controlled by virtual instrumentation software. That *DAQ* setup allowed onscreen real time reading of the pressure sensors during the tests, as well as pressure *versus* time plotting facilities. In order to monitor the volume of fracturing fluid injected during the test, an analytical scale was hooked up to the serial port of the microcomputer.

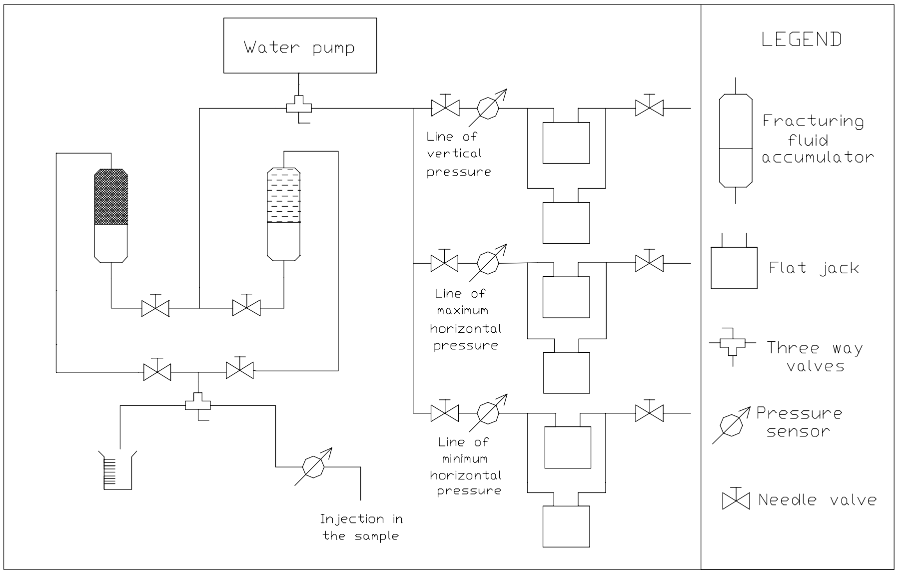

Figure 2: Fluid Injection System

4. TESTING PROCEDURE

The testing procedure involved, basically, the preparation of the sample, the stress confinement of the sample and the fracturing fluid injection.

4.1 Sample Preparation

The $(0.1x0.1x0.1)m^3$ samples were made of gypsum (in a mixture of water, alcohol and salt) with a curing period of about two weeks in controlled humidity environment. Salt was introduced to control the gypsum resistance, allowing reduction of the breakdown and propagation pressures. The use of alcohol increased the time available to manufacture the samples. An important aspect in this matter is the influence of sample aging in the quality of the results of the tests. The homogeneity as well as the reduction of trapped air of the sample was attained by a vibrating probe device.

Fracturing fluid was injected by a 3.2mm stainless steel tube, positioned inside the sample during its casting process. A 10mm long, 1.1mm open hole was created at the end of the injection tube by using a hypodermic needle or a nylon line

4.2 Confining Stresses

The 3D stress state was obtained by applying a hydrostatic stress state with the minimum confining stress, and adding the respective stress contrast at each direction by isolating, sequentially, the three pairs of flat jacks. This pre-stressing procedure was applied by Ong (1994), which is simpler than what was performed by Behrman and Elbel (1990).

4.3 Fracturing Fluid Injection

A silicone-based oil with 5000 cP viscosity was used as fracturing fluid. The test was conducted in two steps: i) the fluid with a purple dye was pumped to initiate and propagate the fracture inside the sample; ii) after fracture closure, the same fluid (with no dye) was used to reopen the fracture and propagate it to the sample boundaries. That technique proved to be very efficient for breaking apart the sample and subsequent analysis of fracture geometry and orientation. Fig. 3 shows a flat jack, gypsum sample and dyed silicone oil applied in the tests.

Figure 3: Flat jack, gypsum sample and dyed silicone oil used in the experiments

5. RESULTS

The main objective of the tests performed was to investigate the feasibility of obtaining useful results from $(0.1x0.1x0.1)m^3$ samples of gypsum or other materials to simulate hydraulic fracturing processes in laboratory. The earlier tests had the objective of checking the possibility of performing fracture initiation and multiple cycles of propagation, closure and reopening in such small samples. The results indicated this possibility after adjusting fluid and sample mechanical parameters (fluid viscosity, gypsum resistance, etc.). The resulting fracture geometry can be observed in Fig. 4. The lack of perpendicularity between fracture surface and sample faces was due to imperfections in positioning the flat jacks, problem that was detected with help of numerical simulations and corrected in the subsequent tests, as shown in Fig. 5. The resulting pressure versus time curve for the sample shown in Fig.5 is presented in Fig. 6.

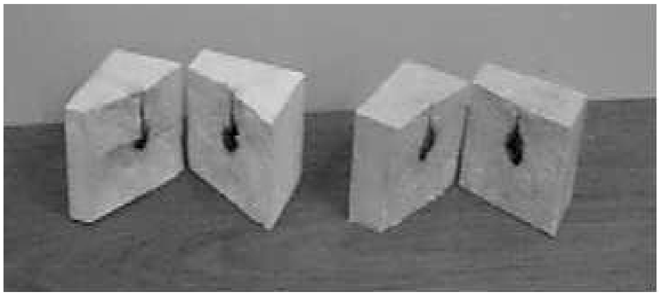

Figure 4: Fracture geometry obtained from (0.1x0.1x0.1)m3 samples

The pressure decline portion of the curves were used to compute leakoff coefficients, according to Carter (1957), which were used for a semi-analytical simulation of fluid induced fracture propagation, resulting in good agreement with the fracture geometries and pressure versus time curves (Fernandes, 1998)

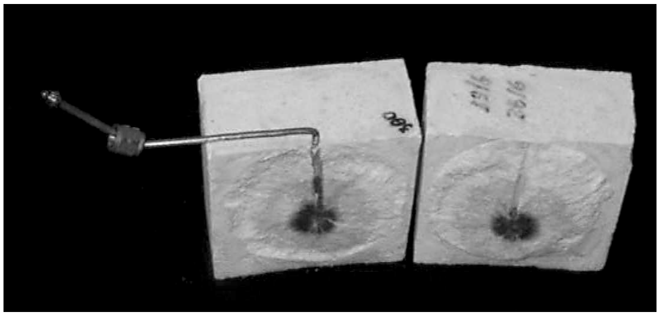

Figure 5: Fracture geometry obtained after correcting flat jacks positioning

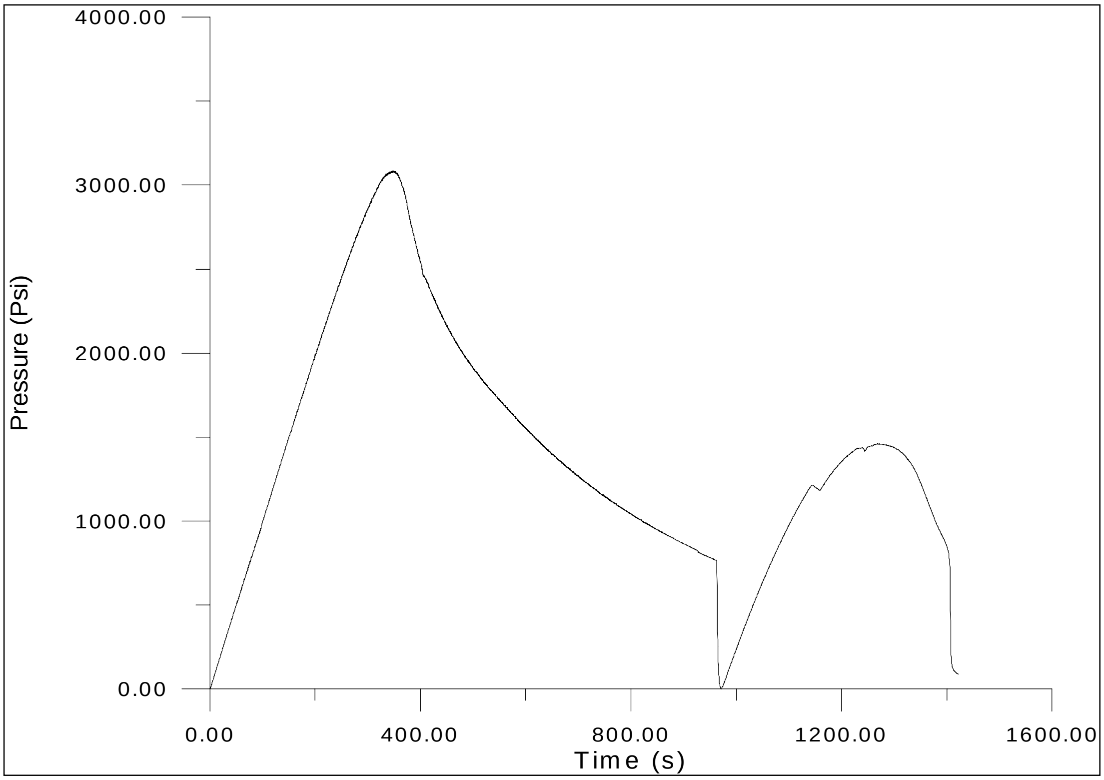

Figure 6: Pressure versus Time curve.

6. CONCLUSIONS

A description of an experimental apparatus for simulation of hydraulic fracturing processes using $(0.1x0.1x0.1)m^3$ samples was presented. The following are the results obtained from this preliminary operation phase of the experimental apparatus:

1. useful results of geometries and pressure records are likely to be obtained from small samples in the experimental investigation of fluid induced fracture behavior;
2. fracture geometries simulated with these samples were compatible with expected results observed in numerical or physical simulations performed with larger samples or observed in field experiments;

3. fluid leakoff to the formation could be successfully obtained with the synthetic samples, allowing pressure decline analysis;
4. the small size of the samples allows the performance of a larger number of experiments to investigate a phenomenon prior to the performance of experiments with larger sample sizes.

ACKNOWLEDGMENTS

The experimental equipment, lab facilities and personnel was provided by the Petroleum Engineering Excellence Center (PRONEX-MCT) and the Department of Petroleum Engineering of the Universidade Estadual de Campinas (UNICAMP), Brazil. The authors would like to thank the Department of Petroleum Engineering of the Commonwealth Scientific and Industrial Research Organisation (DPR-CSIRO), from Melbourne, VIC, Australia, for the technical support that helped the development of this project. The continuous support provided by Petrobras S. A., Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) is also appreciated.

REFERENCES

Abass, H.A., Hedayati, S., and Meadows, D.L., 1992, Nonplanar Fracture Propagation from a Horizontal Wellbore: Experimental Study, SPE 24823, 1992 SPE Annual Tech. Conference and Exhibition, Washington, DC, Oct. 4-7.

Abass, H.A., Brumley, J.L., Hedayati, S., and Gazi, N., 1995, Oriented Perforations - A Rock Mechanics View, SPE 28555, 1995 SPE Middle East Oil Show & Conf., Bahrain, March 11-14.

Blanton, T.L., 1982, An Experimental Study of Interaction Between Hydraulically Induced and Pre-Existing Fractures, paper SPE/DOE 10847, 1982 SPE/DOE Symposium on Unconventional Gas Recovery, Pittsburg, PA, May 16-18.

Behrmann, L.A., and Elbel, J.L., 1990, Effect of Perforations on Fracture Initiation, SPE 20661, 1990 SPE Annual Tech. Conf. and Exhibition, New Orleans, LA, Sep. 23-26.

Carter, R.D., 1957, Apêndice de Optimum Fluid Characteristics for Fracture Extension, de G.C. Howard e C.R. Fast, Drilling and Production Practices, API, 267.

Cheung, L.S., 1990, Laboratory Simulated Hydraulic Fracturing Stress Measurements in Intact and Prefractured Rocks, Ph.D. dissertation, U. of Wisconsin, Madison, WI.

Daneshy, A.A., 1973, A Study of Inclined Hydraulic Fractures, Soc. Petroleum Engineers J. **13**, No. 2, 61-8.

Fernandes, P.D., 1998, Modelagem Semi-Analítica Pseudo Tridimensional de Propagação e Fechamento de Fraturas Induzidas em Rochas, Doctoral dissertation (in Portuguese), Universidade Estadual de Campinas, Campinas, SP, Brasil.

Ong, S.H., 1994, Borehole Stability, Ph.D. dissertation, U. of Oklahoma, Norman, OK