DOE/MC/29077-94/C0288

Fracturing Fluid Characterization Facility (FFCF)

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Contract Number:

DE-FC21-92MC29077

Conference Title:

Fuels Technology Contractors Review Meeting

Conference Location:

Morgantown, West Virginia

Conference Dates:

November 16-18, 1993

Conference Sponsor:

U.S. Department of Energy, Morgantown Energy Technology Center

MASTER

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FRACTURING FLUID CHARACTERIZATION FACILITY (FFCF)

Contract Number

DOE Cooperative Agreement
#DE-FC21-92MC29077

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Period of Performance

September 1, 1993 to June 30, 1995

Schedule and Milestones

FFCF PROGRAM SCHEDULE

MAJOR TASKS		1993	1994	1995
		S O N D	J F M A M J J A S O N D	J F M A M J
I.	Design Modifications for High Pressure Simulator	_____		
II.	Design, Fabrication and Installation of the Mechanical/Hydraulic Systems for the Low Pressure Simulator (LPS)	_____	_____	
III.	Design, Fabrication and Installation of the Computational/Instrumentation/Data Acquisition and Control Hardware and Software for the LPS	_____	_____	
IV.	Interim Research and Development Activities			
	A. Rheological Studies	_____	_____	_____
	B. Instrumentation and Experimental Support.	_____	_____	_____
V.	Development of a Strategy/Plan for Soliciting On-Going Support for FFCF.	_____ -	- - - - -	_____
VI.	FFCF Building Construction	_____	_____	
	A. Site preparation, utilities and construction			
	B. Drill, case, cement, test and equip a 4500 feet well.			
VII.	Develop a Systematic Plan for Relocating High Pressure Simulator to New Building.		_____	
VIII.	Verification and Testing of Low Pressure Simulator			_____
IX.	Reporting and Documentation			

OBJECTIVES

The objectives of this project are:

1. Design and fabricate a large scale experimental apparatus for characterizing proppant laden fracturing fluids.
2. Investigate rheological properties and proppant transport characteristics of various fracturing fluids used for stimulating oil and gas bearing formations.
3. Develop new information for characterizing the behavior of fracturing fluids under conditions more representative of the behavior in actual fractures.

BACKGROUND INFORMATION

Many numerical simulators have been developed to simulate hydraulic fracturing treatments.¹ Although these simulators usually have sound theoretical bases, out of necessity they must incorporate assumptions and approximations to allow solutions to be generated or to account for unavailable data.² Evaluation of the consequences of the assumptions and approximations has not yet been conclusive because controlled experiments on a scale necessary for the evaluation have not been possible. In addition, most fundamental data relating to fluid behavior and proppant transport in fractures have been obtained from laboratory-scale studies, and there is uncertainty about scaling data from such tests to field-scale applications.³ To attempt to resolve these issues, the Gas Research Institute, (GRI) and the U.S. Department of Energy (DOE) are jointly supporting construction and operation of a large slot flow apparatus at the University of Oklahoma.^{4,5} This paper discusses the capabilities of this apparatus and presents results from initial measurements with the apparatus.

PROJECT DESCRIPTION

The FFCF Project has as its main focus the design, fabrication, and construction of a high pressure simulator (HPS) and a low pressure simulator (LPS) to be used to experimentally investigate the rheological properties and transport characteristics of proppant laden fracturing fluids. A discussion of each apparatus is provided as well as the auxiliary equipment, and data acquisition and control systems associated with the simulators.

The High Pressure Slot Flow Apparatus (HPS)

Figure 1 shows the apparatus installed at the University of Oklahoma. The apparatus is designed to operate at pressures to 1200 psi and temperatures to 250°F, and has an instrumented slot flow channel that is 7 ft high by 9.3 ft long and is adjustable to any gap width to 1.25 in. One wall of the flow channel consists of 12 separate, movable steel platens which are 28 in. square and are laid out in a 3 by 4 matrix. The opposite wall is a continuous, 6 in. thick steel slab. The position of each of the movable platens is controlled by hydraulic actuators so that the gap between each platen and the opposite wall can be individually adjusted. This arrangement minimizes variations in the width of the flow channel that might be caused by deformation of the supporting structure at high pressures and high temperatures.

Each of the movable platens is covered by a 1 in. thick, replaceable facing, and the opposite wall is covered by a matching 3 by 4 matrix of identical, replaceable facings. These facings simulate rock surfaces and can be made with desired permeabilities. Therefore, by changing the facings different permeabilities and different surface properties, such as roughness, and topology, can be investigated for their effects on flow behavior and proppant transport. Behind each facing is a system of fluid collection

channels which route fluid loss to a measuring point outside the apparatus, so that when permeable facings are installed on the walls the effects of fluid leakoff can also be investigated.

The flow path through the apparatus is shown schematically in Figure 2. Fluid inlet is through an inlet manifold into 22 equally-spaced inlet tubes, which are 3 in. long by 0.5 in. diameter. These tubes can be used to simulate flow entering a fracture through perforations. Bored plugs can be inserted into the inlet tubes to reduce the ID of the inlets to any desired diameter, and solid plugs can be inserted to prevent flow through any desired inlet. Thus a wide range of inlet configurations can be obtained. Fluid outlet from the apparatus is through 22 outlet tubes into an outlet manifold.

The Low Pressure Slot Flow Apparatus (LPS)

In order to investigate convective settling and proppant/fluid encapsulation in a quantitative manner a much larger (slot height and length) experimental apparatus is currently being designed. This experimental apparatus will contain many of the features of the HPS but will operate at a much lower pressure (300psig). The dimensions of the slot (fracture) will be approximately 15 feet in height, 40 feet in length with a variable slot width of 0.10 in - 1.25 in. A design schematic of the LPS is shown in Figure 3. The control system architecture of the LPS is shown in Figure 4.

Auxiliary Equipment

Auxiliary equipment for each apparatus consists of equipment for mixing fluids and slurries, equipment of pumping the fluids and slurries through the apparatus, and equipment for heating fluids and the apparatus. (See Figure 5)

Pumping equipment consists of a model 6P10 Moyno® pump and a model 5M Deming®

centrifugal pump. The Moyno pump has an infinitely variable speed drive and can deliver up to approximately 140 gal/min at 600 psi. The centrifugal pump serves to boost the suction of the Moyno pump, as an aid in fluid preparation, and as an injection point for crosslinker during tests with crosslinked and proppant-laden crosslinked fluids. Two model 260D ISCO metering pumps (not shown) can be used to inject crosslinker into the suction of the centrifugal pump.

Fluid mixing and storage vessels include a 55 gal stainless steel tank equipped with a three-bladed Lightnin® air mixer, a 200 gal ribbon blender, and a 1000 gal polyethylene storage tank (not shown). Fracturing fluids and slurries are prepared either in the 55 gal tank or in the 200 gal ribbon blender. The 1000 gal storage tank serves as a large volume source of linear gel for continuous, single-pass crosslink tests. The double-pipe heat exchanger can be used for temperature control of the test fluids.

Figure 6 shows a schematic layout of the auxiliary equipment used for tests at high pressures. Pumping equipment consists of a triplex plunger pump and a Galigher 4 x 6 centrifugal pump. The triplex pump can deliver 200 gal/min at the 1200 psi maximum operating pressure of the apparatus. The trifugal pump is used to boost the suction of the triplex pump, as an aid in fluid mixing, and as an injection point for crosslinker.

Two 50-bbl fluid-mixing and storage tanks are located on a trailer unit. Each tank is equipped with an individually-controlled, hydraulically-driven agitator. Two 330-sack bulk-sand storage tanks are located on a second trailer. Sand can be transferred pneumatically from these tanks to prepare slurries for investigating the properties and behavior of proppant-laden fluids.

Instrumentation

Characterization of flow through the apparatus requires measurement of pressure drops,

flow rates, gap widths and temperatures. Instrumentation to accomplish these measurements is:

1. Honeywell model STD 120 differential pressure transducers which are accurate to better than 0.1%.
2. A Micro Motion® model DL200 mass flowmeter that measures volumetric flow rates to 0.2%.
3. Linear voltage displacement transducer (LVDTs) that measure the displacements of the pistons in the hydraulic actuators and thus measure platen displacements and the gap width. Displacements are measured from an initial gap width that is set by gage blocks. The accuracy of these measurements is estimated to be on the order of the accuracy of the LVDTs which are accurate to 0.002 in. To confirm the accuracy of the gap width measurements, two LVDTs that span the gap, and thus measure the gap width directly have been installed.
4. Thermistors located in the flow channel (intrusive), and mounted at the facing/fluid interface, 0.25 in. back from the interface, and 0.50 in. back from the interface in each wall facing, so that the fluid temperature and the heat flux to the fluid can be measured.

In addition, laser Doppler velocimeters (LDVs) are located at nine platens so that the fluid velocity can be measured at nine locations. Three of these LDVs are mounted on translating stages so that velocity profiles across the gap can also be measured. The LDVs are TSI SUREPOINT™ Laser Probes which operate at 780 nm with 30 mW power. A more complete discussion of LDVs can be found in reference 6.

In the HPS, a system of transmitting fiber

optic bundles mounted in the facings on one side of the apparatus, combined with receiving fibers on the other side of the apparatus provides a "vision system" for monitoring proppant concentration in the apparatus and for monitoring bed formation. Additional information about the HPS vision system can be found elsewhere.^{5,7} In the LPS the fiber optics bundles will be replaced with instrumentation strips which will be used to illuminate the slot.

Data Acquisition

Figure 7 is a flow diagram for data acquisition. The system can acquire up to 30 channels of temperature data and 7 channels of differential-pressure data. Data from the temperature and differential-pressure transducers are conditioned and converted to digital signals by an analog/digital (A/D) conversion array, then sent to a personal computer (PC) where temperatures and pressures are calculated. Filtering and calculation of moving averages in the PC reduce signal noise. Data are then processed for display and logged by the main computer. The display shows temperature and pressure surfaces in the apparatus, and thus provides a visual image of the progress of a test. A signal processor (PC) validates

signals from the LDV's, and converts the signals to velocities that are displayed on a monitor and logged by the main computer. Data from the mass flowmeter are interfaced to still another PC and logged by the main computer.

Experimental Considerations

To verify operations of the apparatus with the associated control systems and auxiliary equipment, and to evaluate the measuring systems, a series of verification tests with fluids having known properties were conducted. Comparison of the results of these tests with the known properties

allows evaluation of the operation of the apparatus and subsystems. This section presents results from the first of the verification tests. A corn syrup solution (a Newtonian fluid), and a 60 lb/Mgal HPG solution (a non-Newtonian fluid) were used for these tests. Some of the results presented in this paper have been previously reported in reference 8.

Procedures

1. **Newtonian Fluid.** A solution of nominally three volumes of corn syrup in one volume of water was mixed, and the low pressure pumping system (Figure 5) was used to recirculate the solution through the apparatus at a series of flow rates for each of several different gap widths. There was no attempt to control the fluid temperature during these measurements, so, because of fluid heating caused by pumping, the fluid temperature increased during the measurements. Pressure drops, flow rates, fluid velocities, and temperatures were continuously measured and logged. Samples of the solution were taken from the mixing tank and subsequently run on a model 50 Fann viscometer to determine the viscosity-temperature behavior of the solution.
2. **Non-Newtonian Fluid.** A solution of nominally 60 lb of HPG/Mgal of water was mixed, and the low pressure pumping system (Figure 5) was used to recirculate the solution through the apparatus at a series of flow rates for each of several different gap widths. Cooling fluid circulating through the double pipe heat exchanger kept the test fluid nominally at constant temperature. Pressure drops, flow rates, fluid velocities, and temperatures were continuously measured and logged. Samples of the solution were taken from the mixing tank and subsequently run on a

Fann 50 viscometer to determine the viscosity-shear rate behavior of the solution.

Results

1. **Newtonian Fluid.** Figure 8 shows the flow rate schedule and resulting pressure drops for the measurements at a gap width of 0.75 in. Similar results were obtained for gap widths of 0.50 in. and 0.25 in. From the measured pressure drops, flow rates, and gap widths, viscosities for each gap width were calculated according to the relations

$$\tau_w = \Delta PB/L \quad (1)$$

$$\gamma_a = 3Q/2HB^2 \quad (2)$$

$$\eta = \tau_w/\gamma_a \quad (3)$$

Figure 9 compares viscosities obtained at all gap widths with the apparatus to viscosities obtained from a sample of the solution with a Fann 50 viscometer. An average temperature measured by the mass flowmeter is used to correlate data from the large apparatus. This average temperature is expected to be accurate to within $\pm 1^\circ\text{F}$. As shown in Figure 9, agreement between viscosities from the apparatus and viscosities from the Fann 50 is generally within $\pm 10\%$. The cause for the few discrepancies is not known. However, the most probable cause is an error in measuring the gap width, with an error of 0.01 in. being sufficient to account

for the discrepancies. Confirmation of the gap width by direct measurement in future tests should reduce the uncertainty of gap width measurements, so more reliable results can be expected from future tests.

Figure 10 compares velocity profiles across the gap obtained from LDV measurements with the profile

$$v = \frac{3Q}{4BH} [1 - (y/B)^2] \quad (4)$$

predicted for laminar flow through the gap. Agreement between both the shape and magnitude of the measured and predicted profiles is very good at a gap width of 0.75 in. At a gap width of 0.50 in., measured and predicted velocities agree up to the centerline, but beyond the centerline they are offset about 0.08 in. The cause for this discrepancy is not known, but it does not appear in any other measurements, so it may be caused by a systematic error in location for these particular measurements. The good results obtained at the 0.75 in. gap width indicate that detailed information about velocities in the gap can be obtained.

2. Non-Newtonian Fluid. Figure 11 shows the flow rate schedule and resulting pressure drops for the measurements at a gap width of 0.50 in. Similar results were obtained at gap widths of 0.25 in. and 0.75 in. From these results apparent viscosities were calculated from Equations 1 through 3. Figure 12 compares apparent viscosities from the slot flow apparatus and data from the Fann 50 viscometer. Data from the Fann 50 are represented by the power law model

$$\eta_a = \tau_w / \dot{\gamma}_a = K \dot{\gamma}_a^{n-1} \quad (5)$$

and have been corrected from the concentric cylinder geometry of the Fann 50 to the slot flow geometry of the measurements from the apparatus according to

$$K_a = K_v \left(\frac{2n+1}{3nS} \right)^n \quad (6)$$

where

$$S = (1 - \beta^2)/n(1 - \beta^{2n}) \quad (7)$$

and

$$\beta = \tau_{bob} / \dot{\gamma}_{cup} \quad (8)$$

The temperature of these measurements was $70.5 \pm 0.6^\circ\text{F}$. In this case, the agreement is to within $\pm 10\%$ and further indicates satisfactory operation of the equipment and the measuring systems. Figure 13 compares velocity profiles across the gap obtained from LDV measurements with the profile

$$v = \frac{Q(2n+1)}{2BH(n+1)} [1 - (y/B)^{(n+1)/n}] \quad (9)$$

predicted for laminar flow of a power-law fluid through the gap between parallel plates. The power-law parameter, n ,

required for the prediction was obtained from the measurements on a sample of the solution with a Fann 50 viscometer. Agreement in both the shape and magnitude of the measured and predicted profiles is again good (all measured values are within $\pm 10\%$ of predicted values) and gives further evidence that detailed information about velocities in the gap can be obtained.

Figures 14-16 shows a plot of apparent viscosity versus shear rate for a 60lb Titanium crosslinked HPG fluid. Data was obtained at different fracture widths. From the data presented in Figures 14-16 the displacement of the curves of data for different gap (fracture) widths can be interpreted as suggesting wall slip or differences in fluid structure. Investigation of these differences is continuing.

Figures 17-18 show plots of perforation friction as a function of flow rate and variation of perforation coefficient as a function of perforation size for various fracturing fluids. From the data in Figure 18 fluid structure plays an important role in predicting pressure drop through perforations.

FUTURE RESEARCH

Future research will focus upon the following activities:

1. Design, fabricate, and install the Low Pressure Simulator (LPS).
2. Rheological and Proppant Transport Research Using the High Pressure Simulator (HPS)

- Convective settling and encapsulation and their effects upon proppant transport
- Dynamic fluid loss studies and correlation with laboratory scale experiments
- Characterization of crosslinked fluids and crosslinked slurry rheology
- Investigate fluid dynamics through perforations
- Develop a verification test plan for the LPS
- Theoretical modeling of transport of proppant laden non-Newtonian fluids

3. Develop a strategy/plan for soliciting future support for the FFCF.
4. Develop a verification and testing program for the LPS.

In addition to these future research endeavors a building to house the HPS, LPS, and associated equipment will be constructed at the University of Oklahoma. Completion of the building for occupancy is scheduled for the last quarter of 1994. In addition a 4500-5000 ft. vertical shear well is proposed to be drilled, completed and instrumented near the new FFCF building. Although funds are not currently available for such a well it is believed the cost of this well can be raised from industry. Further, efforts will also be directed toward dismantling the HPS, moving and reassembling it in the new building. Some effort will have to be devoted to conducting selected flow tests to insure the HPS is still functioning correctly after its relocation.

CONCLUSIONS

From the above descriptions and results it can be concluded that:

1. A slot flow apparatus for investigating hydraulic-fracturing fluid flow, proppant transport, and leakoff, on a scale much larger than previously reported, is now operational at the University of Oklahoma.
2. Initial tests with a Newtonian fluid and with a non-Newtonian fluid show that the apparatus and associated instrumentation are working satisfactorily. Viscosities obtained from the slot flow apparatus for both the Newtonian fluid and the non-Newtonian fluid generally agree to within $\pm 10\%$ of data obtained from a laboratory rotational viscometer.
3. LDV measurements with a Newtonian fluid and with a non-Newtonian fluid show that detailed information about velocities in the slot can also be obtained.
4. A much larger low pressure simulator is being designed which can be used to provide industry with new and valuable information for characterizing the behavior of fracturing fluids under conditions that are more representative of their behavior in fractures than previously possible.

NOMENCLATURE

B = half width of the gap

H = height of the flow channel

K = power law consistency index

K_o = power law consistency index for slot flow

K_v = power law consistency index for concentric cylinders

L = length over which a pressure drop is measured

n = power law flow index

ΔP = pressure drop

Q = volumetric flow rate

r_{bob} = bob radius for concentric cylinder rheometer

r_{cup} = cup radius for concentric cylinder rheometer

S = defined by Equation 7

v = fluid velocity

y = gapwise distance, from centerline

$\beta = r_{bob}/r_{cup}$

γ_a = nominal shear rate

η = shear viscosity

η_a = apparent shear viscosity

T_w = shear stress at the wall

ACKNOWLEDGEMENTS

The authors thank the Gas Research Institute, the U.S. Department of Energy and the University of Oklahoma for funding this project and for permission to publish this work.

MTS Systems Corporation designed, built, and installed the apparatus and has participated in the project since its inception.

Halliburton Services has participated in the project since its inception, has supplied the auxiliary equipment, and its employees have provided many valuable suggestions and much valuable assistance.

RESPEC Corporation has also participated in the project since its inception and has provided valuable suggestions relating to quality assurance and project organization.

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Figure 1. The High Pressure, Slot Flow Apparatus

Figure 2. Schematic of Flow Simulator Showing Fluid Flow Paths

Low Pressure Simulator

Fracture dimensions 14' 8" x 39' 0" x 1.25"
 Maximum pressure 300 psi (100 + 200Δp)
 Actuator spacing 26" grid
 Control channels 18
 Approximate weight 650,000 lbf

TOP VIEW

SIDE VIEW

Figure 3. Design Schematic of Low Pressure Simulator

Figure 4. Control System Architecture for LPS

Figure 5. Low Pressure Fluid Pumping and Mixing Equipment

Figure 6. High Pressure Fluid Pumping and Mixing Equipment

Figure 7. Flow Diagram for the Data Acquisition System

Figure 8. Flow Data for 3:1 Corn Syrup in 0.75 Inch Gap Width

Figure 9. Viscosity vs. Temperature for 3:1 Corn Syrup Solution

Figure 10. Velocity Profiles for a 3:1 Corn Syrup Solution

TEMPERATURE(°F) & RATE(GPM)

Figure 11. Flow Data for 60 lb/Mgal HPG Solution in 0.5 Inch Gap Width

Figure 12. Apparent Viscosity vs. Shear Rate for 60 lb/Mgal HPG

Figure 13. Velocity Profiles for 60 lb/Mgal HPG Solution

Figure 14. Apparent Viscosity vs. Shear Rate for a 60 lb. Crosslinked HPG Fluid with 1/4 Inch Wellbore Perforations

Figure 15. Apparent Viscosity vs. Shear Rate for 60 lb. crosslinked HPG Fluid with 3/8 Inch Wellbore Perforations.

Figure 16. Apparent Viscosity vs. Shear Rate for a Crosslinked HPG Fluid with 1/2 Inch Wellbore Perforations.

**Figure 17. Perforation Friction as a Function of Flow Rate
(0.25" Width & Four 0.25" Perfs)**

Figure 18. Perforation Coefficient vs. Perforation Size

END

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