ACID PLACEMENT AND COVERAGE IN THE ACID JETTING PROCESS

A Thesis

by

MIROSLAV I. MIKHAILOV

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2007

Major Subject: Petroleum Engineering

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Approved by:

Chair of Committee,	A. Daniel Hill
Committee Members,	Ding Zhu
	Kumbakonam Rajagopal
Head of Department,	Stephen A. Holditch

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ABSTRACT

Acid Placement and Coverage in the Acid Jetting Process. (August 2007)
Miroslav I. Mikhailov, B.S., Tver State Technical University
Chair of Advisory Committee: Dr. A. Daniel Hill

Many open-hole acid treatments are being conducted by pumping acid through jetting ports placed at the end of coiled tubing or drill pipe. The filter-cake on the bore-hole is broken by the jet; the acid-soluble material is dissolved, creating wormholes in the formation. This combination of two acting factors creates more stimulation beyond the jetting action area.

Existing papers have mentioned the advantages of using jetting both for damage removal and as the preliminary stage before further acidizing. Many papers discuss theory and practical implementation of wormholing during acid jobs and the resulting injectivity enhancement, too. However, there is no complete research regarding jetting efficiency with regards to permeability restoration due to filter-cake disruption, and therefore, no data exists for efficient filter-cake removal by acid jetting just prior to wormholing. My project objective is to conduct experiments of acid jetting, defining the parameters that aid to restore injectivity. Based on the parameters obtained from the experiments, I developed a set of recommendations for acid jetting design and optimization.

DEDICATION

This thesis is dedicated to my family

ACKNOWLEDGMENTS

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CHAPTER I

INTRODUCTION

1.1 Background

Acid jetting plays more the important role among wellbore cleanup and injectivity restoration techniques. It has advantages over conventional acidizing, since it is less time consuming, more accurate in placement, and does not spend too much acid, and therefore, is cheaper.

When acid is being pumped into carbonate formation, its etching action creates highly conductive paths in the formation, referred to as wormholes. Several companies and research institutions have developed different models of wormholing, predicting permeability and injectivity enhancement due to wormhole propagation.

Filter-cake removal and wormhole formation are closely related to each other; once the filter-cake is broken, the formation soaked with acid starts to react, and highly conductive paths (wormholes) are created. As result of such actions injectivity is enhanced; however, no company so far has conducted any experiments or research to find out the best set of parameters to efficiently remove filter cake prior to wormhole initiation during jetting.

No series of experiments using 4 (four) inch cores and stating optimal parameters for dynamic filter-cake removal, were previously conducted. It is important, therefore, to conduct these experiments, and to give a set of recommendations to enhance formation treatment, linking the relevant parameters together.

This thesis follows the style of *SPE Journal.*

1.2 Objectives of the Research Work

The present research has the following objectives:

1) Conduct a series of experiments with the existing modified equipment to obtain experimental data for ascertaining the efficiency of filter-cake removal before wormhole initiation. The filter-cake on the core is initially deposited dynamically by drill-in fluid flowing parallel to and across to the core face. The exposure time of drill-in fluid for the cores is 16-18 hours to provide sufficient deposition and build-up of sized $CaCO_3$ and drilling cuttings on the core face.

2) Identify the parameters and their values, most relevant for successful filter-cake removal just before wormhole initiation. According to the previous research conducted, the most important parameters are:

   - Standoff distance, or the distance between core surface and the jet orifice (rule of thumb: the optimal is 8 of orifice diameter), beyond that distance, the impact force decreases.

   - Jet velocity (should be above 200 ft/sec, according to the previous research). Related to this is orifice size and number of jets.

   - Jet stream profile (refers to the dispersion of the jet stream after leaving the orifice, larger dispersion of the fluid reduces the effectiveness of the jet stream).

   - Rotation of jets (shows better result because of 360 degrees coverage and pulsation effect as compared to stationary jets).

   - Duration of jetting or exposure time. Increasing the time the formation is being subject to acid jet treatment, a better filter cake removal is achieved.

   - Number of jets.

3) Give a set of guidelines to improve the efficiency of the treatment. I discuss the results, conclusions of the experimental work, and give the guidelines to improve acid jetting design.

1.3 Procedure

To validate parameters influencing the efficiency of the jetting process, a series of laboratory experiment were conducted. The procedure is as follows:

- Cut the 4 (four) inch cores using core press; and measure their size.
- Measure core porosity and nitrogen permeability.
- Put the core into the saturator filled with water for at least 24 hours under vacuum to get rid of any trapped air inside the core.
- After putting the core into the acidizing apparatus, connect the lines, apply overburden and back pressure, and flow the core with water, determining the initial (non-damaged) permeability to water.
- Prepare drill-in fluid as per predetermined recipe with sized $CaCO_3$ grains and stipulated amount of Rev Dust added to imitate drilling damage.
- Hook up the mud pump and the mud line to the coreflood equipment.
- Place the carbonate core into the coreholder and circulate the drilling mud at 500 psi pressure and 0.2-0.5 GPM flowrate for at least 16 hours; make the leakoff rate measurement and construct a q vs. t, q vs. $\sqrt{t}$ plots.
- Disconnect the pump; disassemble the coreholder and lines, aiming not to disturb the filter cake.

- Fit jetting nozzle to the coreholder and hook up acid flow lines.
- Prepare acid and charge it into the container. Charge water to the water container in the same fashion; pump water into the core first, establish the flow and measure the damaged permeability.
- Start to inject the acid at high rate for several dozen seconds (initiate jetting); record the pressure profile vs. time, check the flowrate, and volume injected using Lab View software.
- After the exposure time is reached, reduce the flow rate, switching to water injection; continue recording the pressure vs. time profile.
- For some of the experiment where reverse flow is required, bleed off the pressures, disconnect the coreholder turn it 180 degrees and connect it so the inlet becomes the outlet and vise versa.
- Switch to the normal rate, continue to read out data and observe the pressure decline.
- Stop the experiment, lay down the equipment, and clean it up.
- Calculate the parameters necessary (permeability, pressure at the nozzle).

For the experiments:

- I used the flow rate (fluid velocity) as the most important variable.
- I considered the industry recommended optimal standoff distance.
- I investigated jetting duration time influence.
- I used simple drill-in fluid composition with sized calcium carbonate and Rev Dust to imitate drilling damage. I acid jetted cores of 4 inches diameter with

lengths 14 to 18 inches.

- I compared performance of acid jetting vs. water jetting to make the judgment on which process has more impact: mechanical or chemical.

1.4 Outline of the Chapters

This work addresses optimal parameter for successful filter-cake removal. Chapter II discusses existing wellbore cleanup technologies including jetting, and gives formation damage and filter-cake buildup mechanism and background. Chapter III describes matrix acidizing and filter-cake buildup apparatus, drill-in fluid composition and conditioning, parameter for filter-cake deposition and acid jetting experiments. Chapter IV explains results of the experiments conducted and defines the variables for the successful acid jet treatment. Chapter V gives conclusions and recommendations for optimization of acid jetting treatment; it also addresses future work considerations.

CHAPTER II

ACIDIZING, ACID JETTING, AND FORMATION DAMAGE MECHANISMS FUNDAMENTALS

2.1 Overview of Modern Cleanup Techniques

- Coiled Tubing Acid Wash. A coiled tubing string with a jetting tool having jets with a spiral shape covering 360 degree is run to total depth and acid is pumped through the whole open-hole section. Acid is first pumped through the interval which is then filled with Foam while reciprocating coil tubing across the treated zone. Then it is moved to the next interval; the process is repeated to cover the entire open-hole section. Pumping rates on average are 5-6 barrels per minute for 2 inches coil tubing, and 3-4 barrels per minute for 1 ¾ inch coil tubing at ± 4000 psi pumping pressure. This technique is limited to ±6000 ft of open-hole due to the limited reach of coil tubing (Aslam, and Al-Salat[1]).

- Drill Pipe Acid Wash. It is commonly applied when open hole is too long for coil tubing reach. The advantage of drill pipe acid wash is the possibility to pump acid at higher rates, for instance, 15 to 25 barrels per minute. The jetting action at such rate is very effective for removing the filter cake and the drilling fluid damage. Additionally, good worm-holing action is expected due to higher fluid velocity of the treatment fluids. The disadvantage is the drill pipe has to be pulled one-stand at a time which increases the job time; the other problem is that the well has to be killed before running the completion, which can cause some new formation damage (Aslam, and Al-Salat[1]).

- Bull-Heading. Sometimes when it is not possible to run the coiled tubing into the open hole due to restrictions or when the open-hole is too long for coil tubing reach, there is only one option possible: to pump all the acid by bull heading. The major disadvantage of this technique is the acid takes the path of least resistance, and only a small part of the long open- hole may consume all the acid, leaving the rest of the hole untreated. (Aslam, and Al-Salat[1]).

- Coiled Tubing with Bull-heading. It is a combination of the two methods i.e. coil tubing acid wash and bull-heading. A coil tubing string is run to total depth and acid is pumped through the coil tubing while moving it according to the acid dosage. Simultaneously the acid is pumped from the coiled tubing X Tubing annulus at higher rates. Often the acid is allowed to soak in the open hole; later the remaining acid is pumped from both sides: coiled tubing and the coil tubing X Tubing.1 annulus. The advantage is the possibility to achieve higher rates and therefore decrease the total job time (Aslam, and Al-Salat[1]).

2.1.1 Comparison of the Existing Stimulation Techniques

It is very difficult to perform a comparison of the various stimulation techniques because the reservoir conditions are different in any of the two wells. It is also difficult to verify the contribution from a successful stimulation to the final well productivity inasmuch as the same stimulation treatments often give different results on different wells in the same field. There are some uncertain factors about the evaluation process to quantify the degree of success by the current stimulation techniques requiring additional study. However, there are two major issues that are common to all the stimulation techniques applicable to horizontal open holes. These are: a) cost and b) stimulation fluid efficiency.

a) Cost. The first and foremost issue attributed to stimulation of horizontal open-holes is the excessive amounts of acid required and consequently the associated costs are very high. Usually, vertical or deviated wells are acidized with 50 to 300 gallons per foot of hydrochloric acid, as well as the dosage for the horizontal wells has been reduced to 10-50 gals/ft due to economic reasons. The total cost of the stimulation depends on the pricing structure in an area, type of additives, and the dosage of acid used. However, there is a need to develop more cost effective methods of stimulation.

b) Stimulation Fluid Efficiency. Although the wells show considerable improvement after acidizing, the question of efficiency remains unanswered as the productivity increase calculations show an improvement; however they do not show whether the entire open hole was treated or only some sections of the hole received the entire treatment. Post job production logging is the only way to determine whether the lower permeability sections have been treated. In many cases, it is not possible to re-enter a particular lateral due to completion restrictions. The production logging in the open holes is an expensive option, and the results are difficult to interpret due to many variables i.e. angle or deviation at a point, density effects and the changes in the hole size.

2.2 Acid Jetting Fundamentals

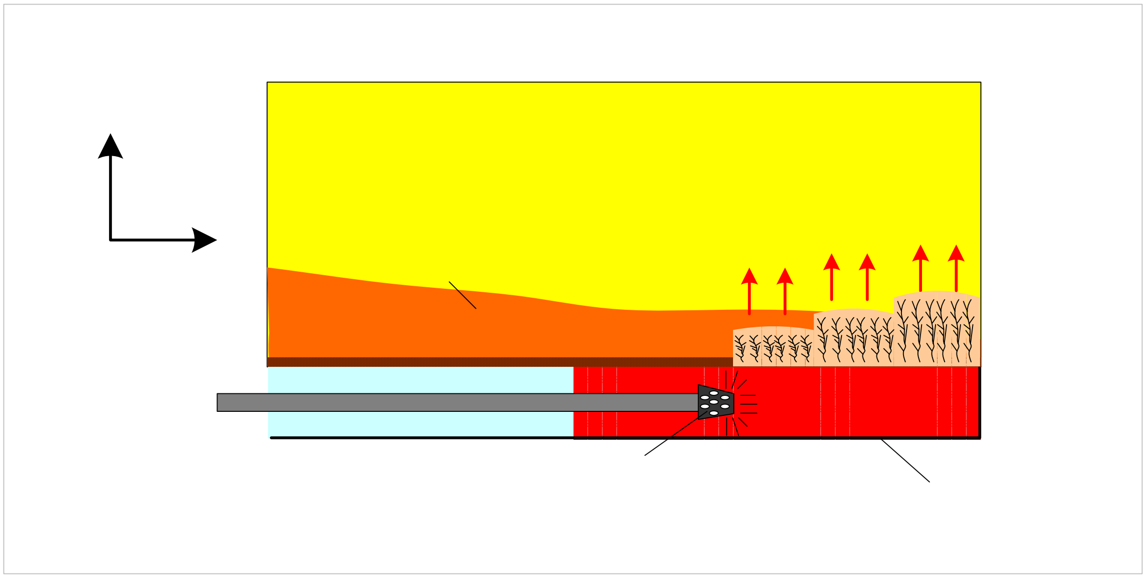


Figure 2.1: Acid Jetting Process Model Schematic (Courtesy of Dr. K. Furui[2])

Jetting was used in many applications, mainly for cleaning different surfaces and cutting different materials. Water is forced through a small orifice by high pressure, causing a high velocity jet. The kinetic energy then is focused at the target surface to achieve the desired outcome. The recent advances in oil and gas technology use open-hole completions with many feet of damaged formation. The damage removal requires large amounts of acid.

A schematic of an acid jetting is shown in Figure 2.1. An assumption is made that the filter cake is impermeable, and the injected acid will not flow back into the annulus. An acid is injected and the pipe moved a distance of one stand (90 feet), the filter cake is degraded over this length by the mechanical action of the jets, and injectivity into the formation at this location is restored. Meanwhile, the entire well bore between the nozzle location and the toe of the well can also receive additional acid injection. After this stand of pipe is moved, acid injection is stopped while a stand is removed to the surface. This cycle is repeated many times until the treatment is accomplished.

The use of jetting offers less expensive alternative to usual methods. Many service and operator companies use the process for cutting the casing and micro-fracturing, and cleaning both the damage and scales. They developed some theories that can be applied to acid jetting in particular.

The jetting process is based on the Bernoulli equation:

$$\frac{U^2}{2}+\frac{P}{\rho}+gz=C \tag{2.1}$$

We can neglect the third term since it is high pressure high velocity and highly deviated (or even horizontal) application.

$$\frac{U^2}{2}+\frac{P}{\rho}=C \tag{2.2}$$

If the jet is flaring at a distance r from the wellbore then we can predict local pressures, coupling the Bernoulli equation with a momentum conservation equation:

$$\frac{Q_{in}r}{2}U_{in} + P_{in}A_{n} = \frac{Q_{out}r}{2}U_{out} + P_{out}A_{out} \tag{2.3}$$

Where: **Q_{in}** is flowrate before jetting the jetting tool, **Q_{out}**- flowrate reaching the fracture (usually less due to fluid loss), **U_{in}**- fluid velocity before jetting out, **U_{out}**- fluid velocity coming back out of fracture, **A_{in}** is area of jetting tool, **A_{out}** is area of fracture, **ρ**- fluid density, **P_{in}**, **P_{out}**-pressures in the jetting tool and in the fracture.

We have to check if the Bernoulli equation is valid for our jetting tool. For this we calculate Reynolds numbers for our jetting flowrates. For oilfield units, the formula is:

$$N_{\mathrm{Re}} = \frac{1.48\rho}{D\mu} \tag{2.4}$$

Table 2.1: Experiment data for Reynolds numbers calculation

Jetting orifice internal diameter D, in	0.05
Viscosity μ of 15% HCl, cp	1.28
Density ρ of 15% HCl, lbm/ft^3	67.11

Table 2.2: Calculated Reynolds numbers for experiments

q, cc/min	Q, bbl/day	N_{Re}
100	0.906173	1406.307
140	1.269457	1970.094

The calculated N_{Re} values are shown in the Table 2.1 and 2.2. They are lower then 2100 which means that flow is laminar and the Bernoulli equation is valid for acid jetting experiment parameters.

Surjaatmadja *et al.*[3] stated, that if a jet is flaring at a distance from the wellbore, then we can predict local pressures, coupling the Bernoulli equation with the momentum conservation equation. Pressure, flow rate in the annulus and orifice size have large influence on jet impact force.

The jetting method is simple and cost-effective as compared to other damage removal methods. Pumping equipment used is available on the rig site (Mud Pumps) and the major consumable item is acid. Friction reducing additives are being introduced as an option in accordance to well conditions, drill pipe or coiled tubing dimensions.

The process of jetting has been the topic of many research projects for many possible applications. Aslam and Al-Salat[4] stated that the cake removal effectiveness depends on the following factors:

1) Standoff Distance: The laboratory tests proved that the impact force decreases with the increase in stand-off. A rule of thumb for removal moderate to hard deposits being submerged in a liquid environment is eight times of the orifice diameter.

2) Fluid Velocity: Another important parameter is fluid velocity and / or the pressure drop across the orifice. Long and tapered nozzle entry profiles produce higher fluid velocities. Laboratory studies have stated that fluid velocities above 200 ft/sec are necessary for hard deposit removal.

3) Jet Stream Profile: Jet stream profile is the dispersion of the jet stream after leaving the orifice. Dispersion of the fluid reduces the effectiveness of the jet-stream. The shape of nozzles and the friction force reducing additives enhance the jet stream profile.

4) Rotation: Laboratory studies have stated that the rotating type jetting nozzles

yield better results in comparison to stationary ones. The rotational jets benefit from the pulsation effects. The other advantage provides 360 degree coverage. The disadvantage is that it tends to jam during long treatments due to the corrosive environment of the open holes.

5) Number of jets: Obviously larger numbers of jets increase the efficiency of jetting; however, excessive jet number leads to extra acid spent.

Also the following factors have to be considered when designing a jetting job:

- Well bore fluids. Drilling mud additives as well as drilling cuttings and formation fluid can react with acid and have impact on job efficiency.
- Jetting fluid composition. Water with or without abrasive content, or hydrochloric acid should be selected depending on formation hardness and composition and filter-cake constituents; different acid strength and concentration also have a large impact on the removal efficiency.
- Filter-cake characteristics. All modern drill-in fluid fluids have complex composition. Their physical and chemical properties determine filter-cake features and therefore dictate the particular jetting job design to remove it.

Aslam and Al-Salat[4] made a field case study of water jetting treatments; they pointed out, that high pressure jetting may be efficiently used prior to conventional acidizing. They also mentioned that in high permeability formations, jetting alone proved to suffice to restore well performance without conventional acidizing, and showed limited further improvement after acid treatment.

Dahroug, Brown, and Shaheen[5] mentioned that jetting is dependent upon tool standoff, fluid velocity, jet-stream profile, and rotation. Their field experiments proved the efficiency of jetting and further formation injectivity improvement using acid treatments.

Johnson, Eslinger, and Larsen[6] conducted research on abrasive jetting scale removal system. They found out, that performance of the jet under atmospheric pressure was significantly greater (the groove was about 4 times deeper) than under the downhole pressure conditions. They explained the reason that at atmospheric back pressure bubbles form in the jet by cavitations, then implode on the target with considerable destructive force; however under down hole conditions the formation of these cavitations bubbles are suppressed and the performance of the jet to erode is reduced. The significance is that jetting system can be built and tested under atmospheric conditions and may perform very well, but in a situation with a significant back pressure the performance will be greatly reduced and the jetting system may not work. They also made significant observation that the use of pure water jets or of sand laden slurry jets is not commercially effective or acceptable as a cleanout service. The other finding is that in a water jetting system, if the jet is held stationary for a significant length of time, the jet can break behind the scale and peel it away from the surface in large chunks. Particles of this size may cause severe problems, they are difficult to carry out of the well, and they can become trapped between the tool and the wall of the well, and therefore preventing it from being circulated out to the surface.

2.3 Carbonates Acidizing Fundamentals

Matrix acidizing is one of the most frequently used stimulations for near wellbore damage removal. Initially applied in carbonates it has evolved to embrace more complex mineral composition.

During matrix acid jobs the acid is pumped down at pressures below the formation parting pressure, hence avoiding fracturing the formation while performing the treatment, aiming for restoring the permeability near wellbore, not affecting the reservoir in-depth; usually the acid dissolves the rock up to several feet beyond wellbore for carbonates (Economides, Hill, and Ehlig-Economides[7]).

The HCl-soluble minerals are calcite, dolomite, and siderite, they do not generate precipitates. The reactions are as follows:

Calcite $2HCl + CaCO_3$ ------- $CaCl_2 + H_2O + CO_2$

Dolomite $4HCl + CaMg(CO_3)_2$ ------- $CaCl_2 + MgCl_2 + 2H_2O +2CO_2$

Siderite $2HCl + FeCO_3$ ------- $FeCl_2 + H_2O + CO_2$

2.4 Filter-Cake Buildup Background and Mechanism

As we can see, the drilling damage is very complex. The extent of damage depends on many factors i.e. formation rock type, drilling fluids type and composition, the filtrates chemical composition, and the amounts and types of cuttings in the hole. The number chemical and physical aspects of the drilling damage can be simplified into two main categories: Surface Damage and Deeper Damage.

- Surface Damage: The main objective of the drilling mud is to form a filter-cake at the face of the reservoir rock thus avoiding leak-off and minimize the mud losses. To the contrary, the same filter-cake blocks the production or injection of the fluids. The filter cake must be removed to restore the productivity or injectivity of the well. The mud filter-cake consists of mud solids, rock cuttings, debris and the 'glue', which keeps the solids tied together in the form of a cake. The ‘glue’ type material comes from the residue of polymers used in the drilling fluids as viscosifiers.

- Deeper Damage: The formation damage occurs in matrix of the reservoir rock; it is usually caused by the invasion of mud filtrate. This damage is mainly chemical in nature and only a few solids are squeezed into the rock-matrix. In the case of fractures, the mud solids can invade and plug the entire fracture systems connecting the wellbore to the reservoir rock. The surface damage removal appears to be easier with the use of acids or other chemical treatments. Some filter cakes can not be completely soluble in the acid depending on the type of acid- additives used and the type of filter cake. Also, deeper damage is difficult to remove and in most cases, the well treatments are designed to by-pass the damaged zone by creating ‘wormholes’ or inducing new fractures.

The acid jetting technology seems to successfully solve the problem, removing both surface and deeper formation damage.

When a well put back onto production, it usually has an external filter-cake on the wellbore face and an internal filter-cake (invaded solids and polymers) in the rock. Internal filter-cake forms during some initial time. As more particles are trapped on the surface of the rock, a point where very few particles can invade the rock is reached, and an external cake begins to build. The time at which no more particles invade the rock is the time at which the initial layer of external is completely formed. Jiao and Sharma[8] reported this time as a transition time. If the conditions under which particles form external and internal filter-cakes, and the time required to form the initial layer of external filter-cake, then the entire process of filtration can be approximated by applying the model of internal filter for times less then transition time; and external filter cake for times more then transition time. Figure 2.2 represents filter-cake before and after acid treatment.

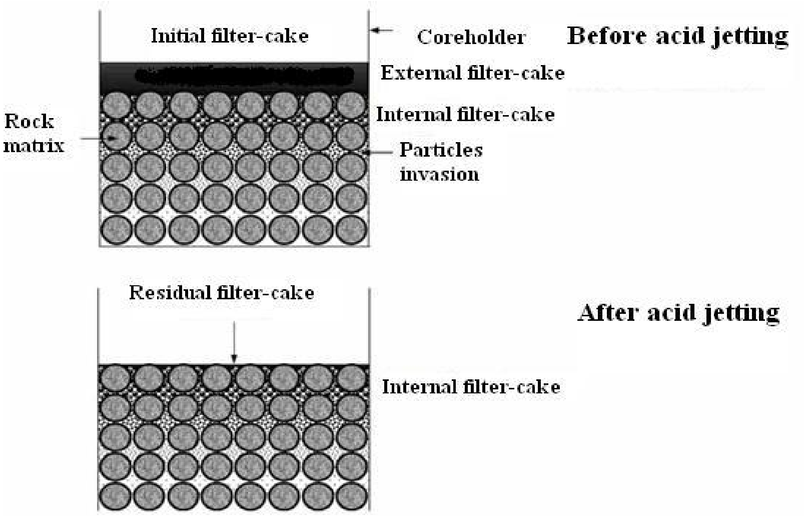


Figure 2.2: Filter cakes (external and internal) before and after acid jetting treatment

It is known, that particle size less than 1/3 or pore throat diameter cause bridging of the porous media, and more than 1/3 pore throat diameter cause its plugging. Internal filter-cake forms first and after the particles bridged up enough, external filter-cake starts to build up. By the making dynamic loss graph, measuring filtrate volume vs. time and then plotting it vs. square root of time aids to determine when we start external filter-cake buildup.

Jiao and Sharma[8] conduced experiments to find out mechanisms of damage due to static and dynamic filtration of drilling mud. They discovered that mud particle invasion usually occurs during initial spurt loss before external mud cake is formed; therefore to reduce formation damage mud should rapidly form a stable external cake and salinity of the mud should be above the critical salt concentration of the rock.

Thomas and Sharma[9] investigated formation damage and mud cake around horizontal wells. They have informed that a stable filter cake formed during the first hour of circulation.

Zain and Sharma[10] pointed out that mud cake lift-off is a function of rock mineralogy and permeability, high flow velocity results in more efficient cleanup, and mud cake removal is harder for rocks with large internal damage.

In one of the research of drilling fluid composition Suri and Sharma[11] concluded that the main factors influencing damage due to particle invasion are:

1. Particle size distribution in the mud;
2. Formation permeability / pore size distribution;
3. Concentration of mud solids;
4. Over-balance pressure;
5. Mud circulation rate and rheology.

The latest work of Suri and Sharma[12, 13] stated once again that both internal and external cakes are key factors for determining the flow initiation pressure and return permeability ratio. Also, they introduced new methodology for calculating the flowback differential pressure.

Ryan, Browne, and Burnham[14] in their major joint study of different mud cleanup techniques stated there is no single best technique for the cleanup of open horizontal wells. Also their conclusions were:

1) Complete external filter-cake removal is not necessary to throughout -cake oil production;
2) High solids content in the mud system has not adverse effect to effective oil production throughout filter-cake;
3) Aggressive breakers (acid) are effective for wellbore cleanup but generate increase in fluid losses;
4) Most breakers reduce damage levels; however, some mud breakers increase damage.

Jetting acting and wormhole forming improve the injectivity; they reduce the damage of the formation by combining scouring of filter-cake by acid and dissolving the carbonates with creation of highly conductive wormholes. In the project I took into account both mechanisms to come up with recommendations and improvements.

CHAPTER III

MATRIX ACIDIZING, FILTER-CAKE BUILDUP APPARATUS, AND EXPERIMENTAL PARAMETERS

3.1 Matrix Acidizing Apparatus

The components and specifications of the setup necessary to perform the experiment must be capable to deal with the required conditions for experimentation on different length core samples at flow rates and temperatures similar to those at field conditions[15]. Figure 3.1 is a schematic of the apparatus.

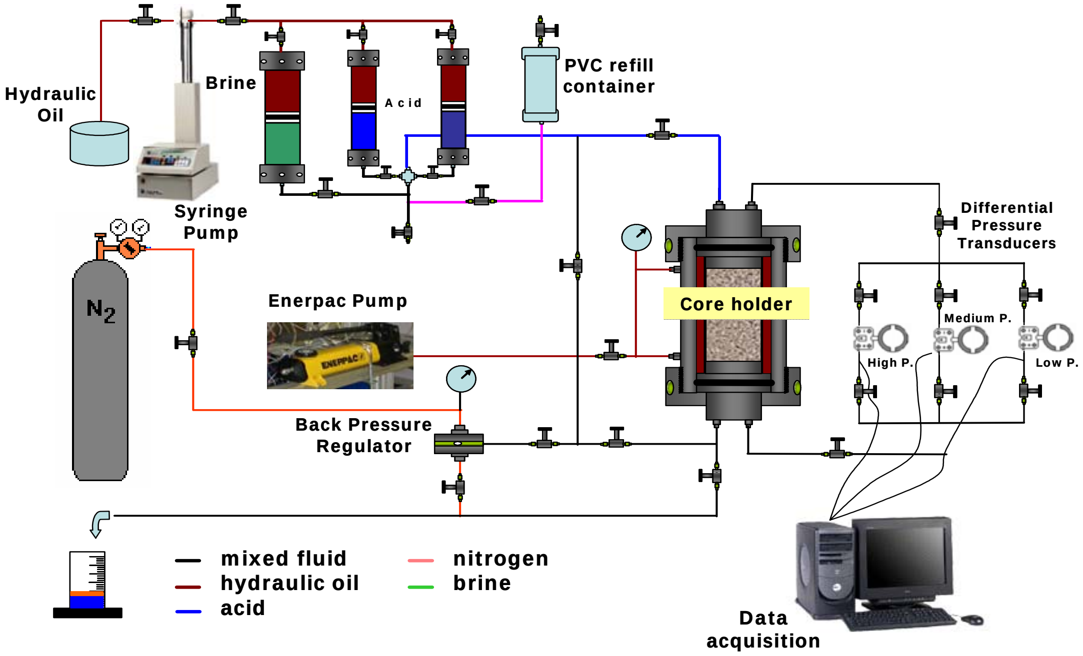


Figure 3.1: Schematic of matrix acidizing setup (Courtesy of J. Nevito[15])

As shown in Figure 3.1, brine and acid prepared beforehand and held in the accumulators, are pumped and heated up, according to the test procedure and particular conditions, via the tubing and manifold system and flows through the cores samples confined inside the core holder. The core sample is confined inside the core holder with a Viton sleeve by a hydraulic oil pressure created by a hydraulic pump. The acid effluent is gathered and measured in the beaker at the end of the experiment. The back pressure supplied via the Teflon diaphragm back pressure regulator maintains the CO_2 in solution.

During the experiments, the flow rate, temperature, confining or overburden pressure, and back pressure are set and kept constant; the differential pressure across the core during the process is measured by analog pressure transducers and recorded by the LABVIEW software to construct and analyze the acid response curve. All the equipment is located inside a laboratory exhaust system to vent the acid fume.

3.1.1 Pumps

In acidizing experimentation, the most important condition for the pump is the flow rate at which the fluids are to be displaced; in the experiment this flow rate must be constant during the process to determine the pressure profile in the rock while the fluids are passing through the core. The pump used is a syringe precision type which is capable of a wide range of chemical feed applications requiring flow rates up to 200 cc/min at pressures up to 3,750 psig; its 500 cc cylinder capacity allows delivering a precise 1 cc/min for over 8 hours on a single fill[15].

The ISCO D500 has a "Smart Key" controller operating up to three pump modules, either independently or together. Operating modes include both single/dual pump independent constant flow or pressure and it additionally comes with a RS-232 serial interface for computer control or monitoring of operating parameters using commercial Lab VIEW software.

The specifications of the pumps are following (J. Nevito[15]):

- Capacity: 507 cc
- Flow Range: 0. 001 – 204 cc/min
- Flow Accuracy: 0.5% of set point
- Displacement Resolution: 31.7 nl
- Motor Stability: ± 0.001% per year
- Pressure Range: 0- 3,750 psi
- Standard Pressure Accuracy: 0.5% FS
- Optional Pressure Accuracy: 0.1% FS
- Wetted Materials (standard): Nitronic 50, PTFE, Hastelloy C-276
- Plumbing Ports: 1/8" NPT
- Operating Temperature: 0 - 40° C Ambient
- Power required: 100 Vac, 117 Vac, 234 Vac, 50/60 Hz
- Dimensions (HxWxD, cm): 103 x 27 x 45
- Weight: Pump module - 33 kg; controller - 3 kg

The set-up has two pumps utilized in parallel; they use hydraulic oil as a driving fluid to exclude direct contact with corrosive conditions during testing. Inlet and outlet ports, that make the refill and dispense lines, are 1/8" NPT female threads connected to 1/8” stainless steel tubing forming the discharge manifold which further on are connected using “Gyrolok” type compression fittings.

Each pump cylinder must be filled prior to any use; discharge and refill lines are independent, and the valves in the manifold are operated carefully during any operation being performed. Once the cylinder is empty after running the pump through a test, the discharge valve shall be closed and the refill valve shall be open; select the pump in the controller and push the refill button. The recommended refill flow rate is between 30 and 40 cc/min. After refill is complete, the refill valves should be closed and while discharge valve is closed, the pump shall be started at 5 to 10 cc/min until reaching the discharge pressure, then open the valve and equalize the pressure (J. Nevito[15]).

3.1.2 Core holder

The core holder is a very important part of the system for matrix acidizing and jetting purposes; Manufactured by Phoenix Instruments, these are just the cells where the core samples are confined to circulate the fluids through them.

Because of the aggressive nature of fluids used, hydrochloric and hydrofluoric acids with different concentration and temperatures, the core holders are made of special corrosion-resistant alloy material. The core holders were manufactured by Phoenix Instruments, made of Hastelloy C276, a corrosion resistant material that is capable to withstand a working pressure of 3000 psi and temperatures of 300^{o} F. Figure 3.2 shows the core holder put aside of the experimental apparatus.

Figure 3.2: 4” diameter by 20” long Core Holder

The core holder is equipped with the regular inlet and outlet tip with ports 1/4” and 1/8”, and the distribution pattern to contact the total face area of the core; inside the cylinder a special rubber Viton sleeve, temperature resistant, has been utilized to confine the core during experiments. The core holder allows the recirculation of mud and conduct different type of experiments on jetting acidizing; the additional set of jetting tips with spacer rings with predetermined stand-offs were made to comply with the necessity to create a certain filter-cake on the face of the core sample, and then break it with high pressure and velocity acid jet.

To allow for specific standoff between the core face and jet nozzle, a set of special spacer ring was designed. They have the same 4 inch external diameter and 3.8 inch internal diameter, with thicknesses varying from 0.2 inch to 2 inches. The standoff rings are shown on Figure 3.3.

Figure 3.3: Spacer rings, providing standoff between core face and jet nozzle

3.1.3 Accumulator

The accumulators were manufactured by Phoenix Instruments. They are piston type. They are the vessels where the products to be displaced through the cores during the acidizing experimentation are contained.

These accumulators (Figure 3.4) were designed to be corrosion resistant (special alloy material, Hastelloy C-276), with capacities of 1000 cc and 2000 cc; there is also one stainless steel accumulator made for brine containment with capacity of 1500 cc. All of the accumulators have inlet/outlet ports of 1/8” NPT.

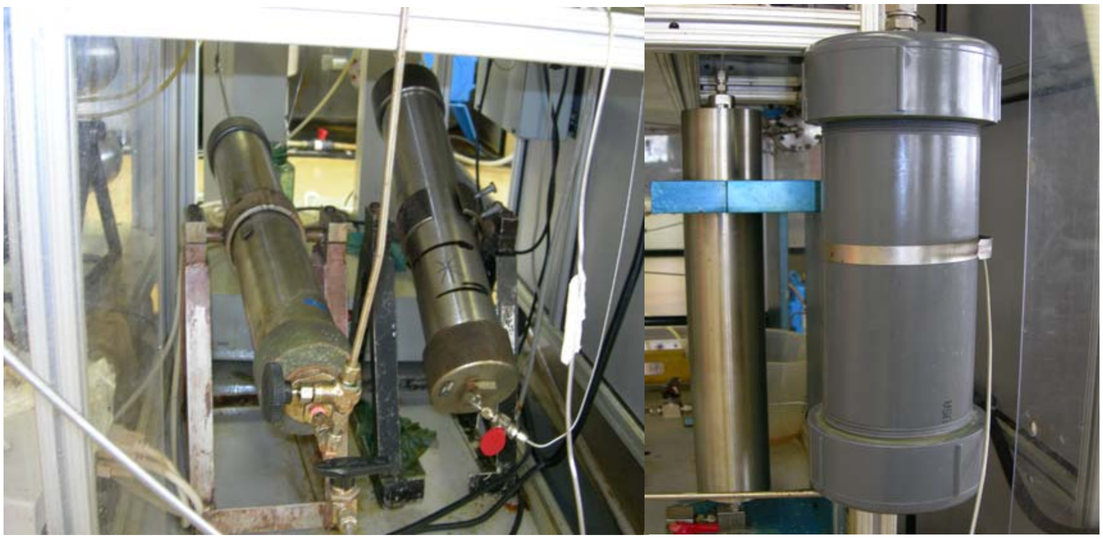


Figure 3.4: Brine accumulators, acid accumulator, and PVC refill container

The displacement of the acid and brine is accomplished by the syringe pumps pumping the hydraulic oil which in turn acts on the Teflon piston pushing either the acid or brine out at necessary pressure and flow rate, carrying them to the core via set of tubing until it hits the core face in the core holder.

To refill the accumulators with acid or brine, a PVC container (Figure 3.4) is filled first; then air at 100 psi from the laboratory air system pushes it into the accumulators. It is necessary to vent the oil line on top of the accumulator to allow either the acid or brine to be entered into the accumulators as the oil inside them is removed. This operation is done independently for each accumulator.

3.1.4 Back pressure regulator

Back pressure is necessary during the experiments at the core outflow to simulate down-hole conditions, and to avoid the presence of free CO_2 gas bubbles, which leads to undesirable two-phase effects. The back pressure must be constant and it needs to be 300 - 400 psi less than the overburden pressure.

A Mity-Mite back pressure regulator model S91-W is fitted on the downstream line. The pressure in the line controls the effluent flow and exerts a resistance, maintaining constant pressure upstream of the core.

The connections to the flow lines are 1/4" NPT female threads and the connection to the charging line is 1/8" NPT female thread. The front panel of the acidizing/jetting setup has a gauge to control the back pressure. The pressure range may vary between 100 and 2000 psi, and temperature -65 ^{o} F and 200 ^{o} F; the material of body and dome is stainless steel and the diaphragm is Teflon. The maximum C_v is 0.38 and it weighs 4 lbs.

The type of back pressure regulator is externally dome loaded; it must be charged from an external source of gas pressure; the dome pressure is supplied by a nitrogen bottle with its regulators. Figure 3.5 shows the regulator installed in the setup[15].

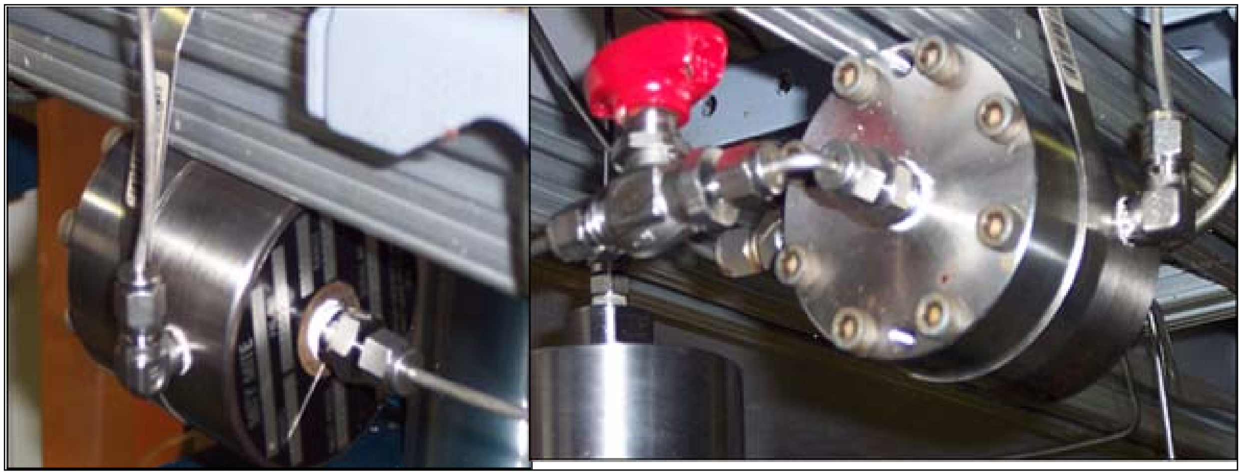


Figure 3.5: Mity-Mite model S91-W back pressure regulator

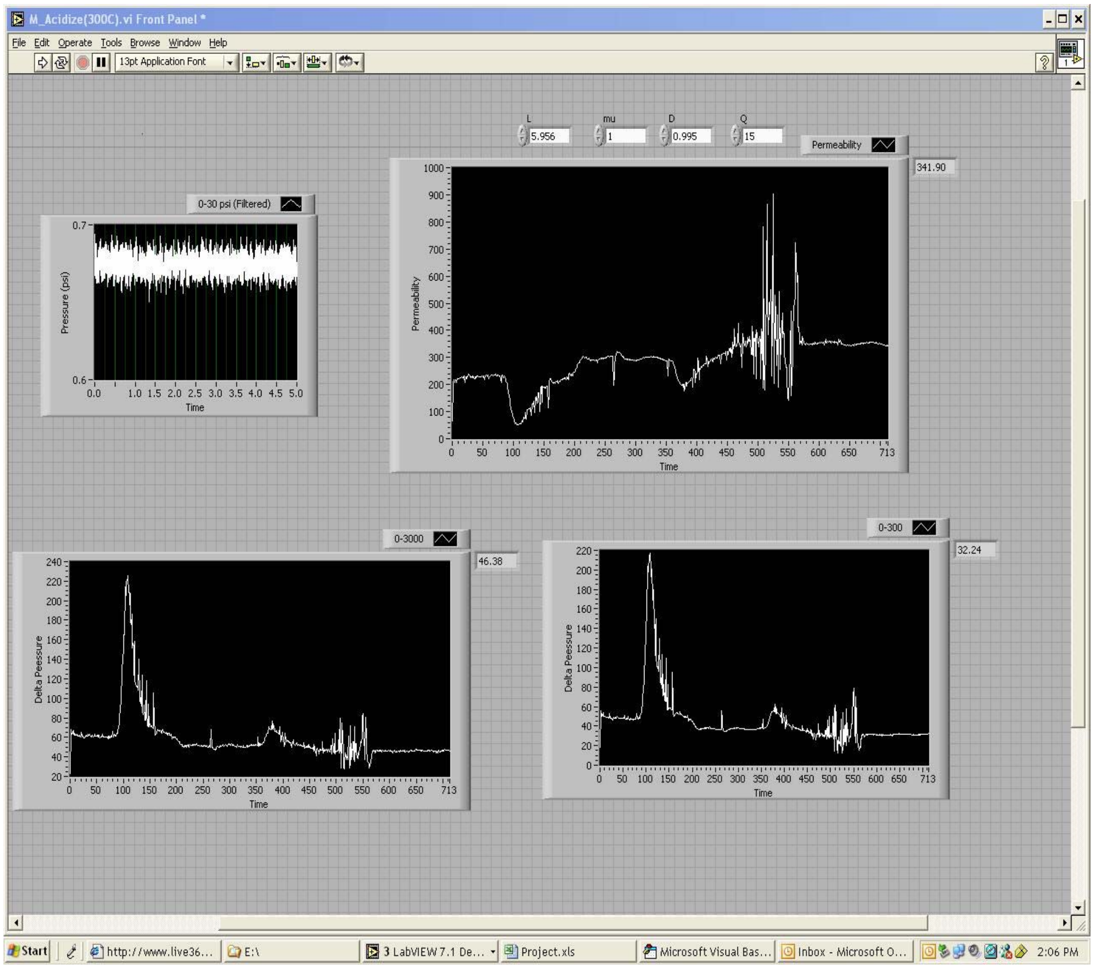
The principle of acting the dome type back pressure regulator is following. The dome pressure acts over the exposed area of the diaphragm to seat it on the nozzle; when upstream pressure exceeds the desired level, it pushes the diaphragm up off the nozzle. The flow of fluid through the regulator relieves the pressure in the upstream system; as the upstream pressure drops off, the diaphragm moves down to reduce or shut off the flow, so that upstream line pressure is held constant.

3.1.5 Data acquisition

The flow rate is directly set and controlled by the ISCO syringe pumps controller. Because the experimentation is mostly carried out at constant flow rate the variable that changes during process is the discharge pump pressure, determining the pressure at the inlet face of the core. The pressure drop across the core is read with a set of FOXBORO differential pressure gauges model IDP10-T26(C-D-E) 21F-M2L1; they measure the difference between two pressures and transmit a proportional or square root (Flow) electrical Signal. The differential pressure gages are powered by a 30 volt single DC power supply and display pressure data on LCD screens and output 4~20 mA DC current signals that are transmitted to hardware via grade 16AWG electric cable. There are three different gages installed with ranges 0-30 psi, 0-300 psi, and 0-3000 psi; which permits choosing the most suitable one according to the expected pressure drop, related to the rock permeability. The sensor of these devices is made of Hastelloy C276 and silicone fill fluid. The connections of the transmitters are with 1/8” Hastelloy C276 tubing and Gyrolok compression fitting. Figure 3.6 illustrates the pressure transmitter setup and Figure 3.7 shows the connection mode to receive the electric signals and transmit to PC based data acquisition system[15].

Figure 3.6: FOXBORO pressure transducers

There are three pressure signals actually installed in the set up, using independent analog channels in the interface board; these signals are then distributed and directed to the main board installed inside a desktop computer. The signals are then processed by the Lab VIEW software, automatically recognizing and displaying them on a wave chart in the front panel as shown in Figure 3.8.



L 5.956

mu 1

D 0.995

Q 15

Permeability 341.90

0-3000 46.38

0-300 32.24

Figure 3.7: Data Acquisition System Lab VIEW program front panel

The software works with specific commands for each task and easily links the pressure signals with the workflow to calculate the variable permeability, which was previously formulated in the specific command. The pressure drop and permeability readings are finally sent to be saved in a file in a time sequence determined as optimum depending on the duration of the test. The frequency of data acquisition must be set and normally one reading every two, five, or ten seconds is the standard.

The file can be extracted as a excel spread sheet to represent the differential pressure and permeability data. Figure 3.8 shows the block diagram of the Lab VIEW with the program to acquiring and writing the data.

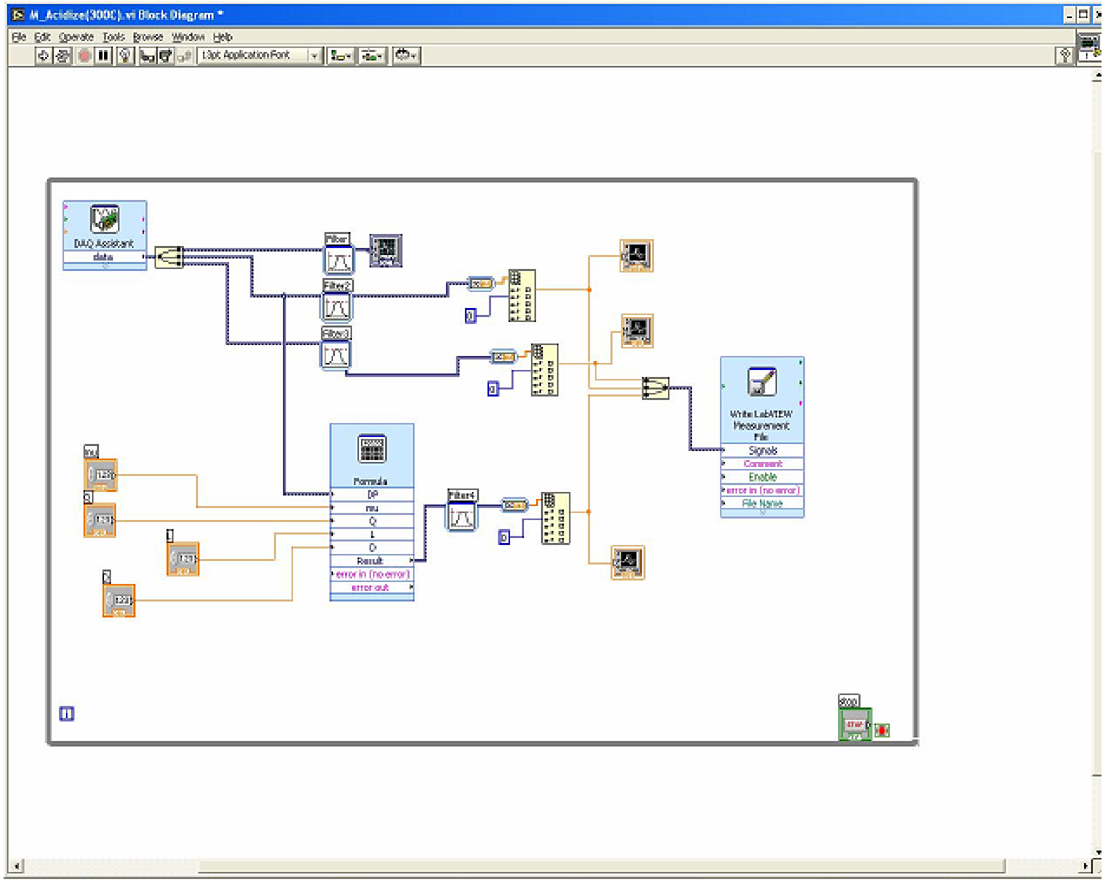


Figure 3.8: Data acquisition Lab VIEW program block diagram

3.1.6 Hydraulic pump for overburden pressure

This pump is an ENERPAC hydraulic model P392 that provides the necessary pressure to confine the core sample inside the core holder to simulate the overburden pressure. Pressure, commonly 1,000-1,200 psi, acts on the rubber Viton sleeve; which in turn contact the core sample. It should be 300-400 psi greater than backpressure. Figure 3.9 shows the ENERPAC hydraulic pump.

Figure 3.9: ENERPAC model P392 hydraulic pump (J. Nevito[15])

3.1.7 Pipe work, valves, and fittings

The tubing pipe installed in the set up to serve as flow line to displace the acids and brine during the experiments was designed to be 1/8 inch diameter with a wall thickness of 0.03 inch. Its effective inner diameter allows to flow at the maximum rates provided by the ISCO D500 pumps that is 204 cc/min; the burst pressure is greater than 7500 psi. Due to the nature of the fluid we deal with, the tubing is made of Hastelloy C276 to resist the corrosive environment of HCl-HF mixtures. Regular stainless steel tubing 1/8 inch is used in tubing in which hydraulic oil is the fluid.

Two types of valves are installed in the piping network of the set up; needle valves with HiP taper seal made of Hastelloy and ball valves. The needle valves are used for flow lines with acid; their fittings seal metal to metal as a compression fitting by a sliding sleeve fastened to the tubing. These valves are designed to withstand pressures up to 15,000 psi and temperatures of 450 ^{o} F. The ball valves are made of stainless steel and are used in lines with either no dynamic flow as those for detecting pressure signals or hydraulic oil lines; they withstand up to 6000 psi and 300 ^{o} F.

3.2 Filter-Cake Buildup Apparatus

To create a proper filter-cake imitating conditions after drilling operations, a special apparatus was designed. After surveys and feedback gathered from the industry we decided to use a piston pump with variable pump rate and pressure, regulated by a stroke length adjusting mechanism. The pump is capable of maintaining a flow rate from 0.1 to 4 gallon per minute with pressures to 2000 psi. This pump was chosen due to its ability to handle high solids content (RevDust, sized calcium carbonate, other drill-in fluid additives) and variable pump rate with high pressure rating. The pump rate was kept in the range of 0.2-0.5 gallon per minute which enabled dynamic filter-cake deposition across the core face. The pulsation dampener installed into the discharge line before connection to the coreholder smoothes out the pressure jumps and aids to stabilize the flow. The pump suction and discharge lines are metal-wire braided half-inch rubber hoses, which allow more flexibility in the system layout and component placement. Special requirements for power and water supply require that this apparatus be in a laboratory with the necessary plugs/outlets.

The drill-in fluid is mixed beforehand and stored in a 10 gallon LabWare plastic barrel with a cover. A port located at the bottom of the barrel connects via rubber hose to the pump suction. From the line at the pump discharge, after the pulsation dampener, drill-in fluid flows to the coreholder inlet, and pressure readings are taken from the inlet pressure gauge. A back pressure regulator is fitted into the coreholder outlet at the same side of the coreholder to maintain back pressure around 500 psi. The drill-in fluid passing throughout the back pressure regulator plate then goes to the barrel port at the top. The drill-in fluid flow-out pressure is read by the outlet pressure gauge. The overburden pressure imposed on the core is exerted by the same ENERPAC hydraulic pump model P392. It is kept 300-500 psi higher then back pressure. The coreholder is positioned vertically to minimize gravitational effect on filter cake deposition process.

The core inside the coreholder is given the two inch standoff by the stainless steel spacer ring inside; it provides essential room for mud circulation and filter-cake deposition. The opposite side of the core holder has another outlet line; this line leads to the measuring beaker with scale. During the filter-cake deposition, the line drains brine which was displaced by the invading drill-in fluid filtrate; its volume versus time measurement gives understanding of how the filter-cake deposition process is evolving. Figure 3.10 shows the mud pump and the mud tank with mixer.

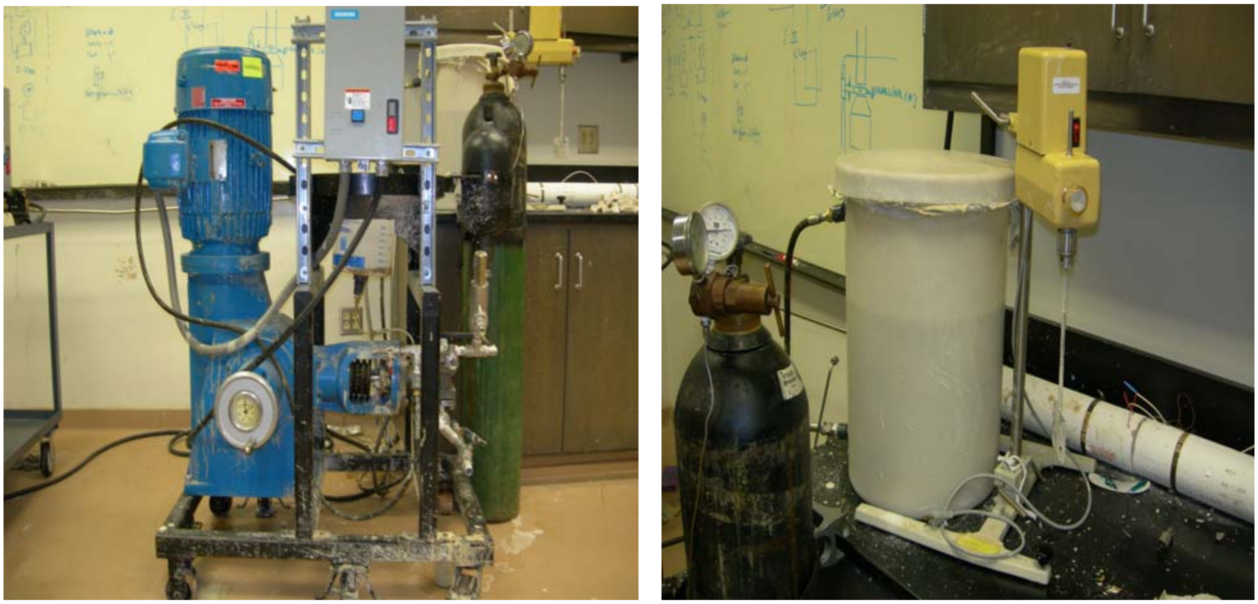


Figure 3.10: Mud pump with backpressure nitrogen vessel; mud tank with mud mixer

3.3 Core Cutting

Core samples used in jetting experiments are carbonates (mostly Cream Chalk). These cores are cut using the HILTI model DD200, a heavy duty and portable core cutter. The cutting is made by 4 inch special design core bit required for use with the core holder. A special frame was built to install the machine and provide rigidity and stability because of the lengths of cores used. Also, the cutting process required special power and water supply to cool the bit and transport the cuttings. The frame with the core drill is built and installed in the laboratory which had to be specially prepared for meeting these demands beforehand. The core press and the bit are shown on Figure 3.11.

Figure 3.11: Heavy duty HILTI DD200 Core Press and Core Bit (J. Nevito[15])

Core bits specially designed for HILTI are used in our application in a non-standard length 4” diameter by 20” long. Figure 3.12 shows the cores obtained from Cream Chalk. The time spent for cutting the cores is approximately 45 minutes per core. The cores are saturated in the vacuum facility already existing in the Department. This pre-saturation process assures the initial permeability is measured at 100% saturation.

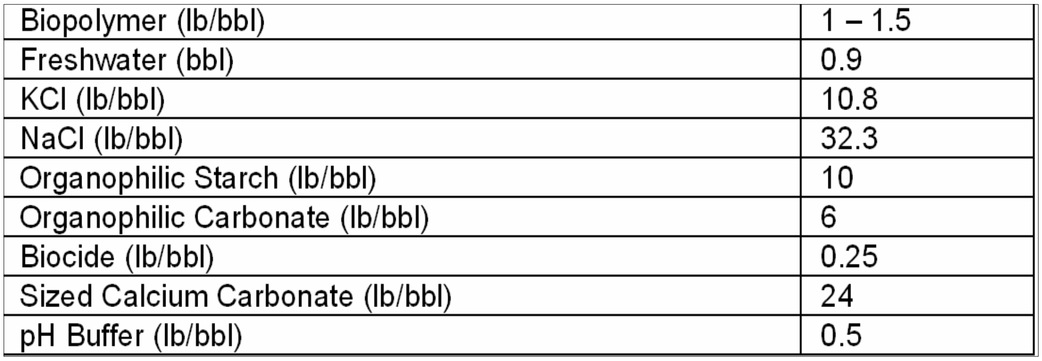
Figure 3.12: Chalk 4” in diameter, 20” length core cut by 'HILTI' Core Press

3.4 Drill-In Fluid Composition and Conditioning

A drill-in fluid of a simple composition was selected for the experiment. The main concern was simplicity to make it in the laboratory conditions and its closeness to the actual drill-in fluids used for the drilling operations in the Middle East for carbonate reservoir. The M-I Swaco (Ravitz *et al.*[16]) drill-in fluid was selected and prepared after several trials.

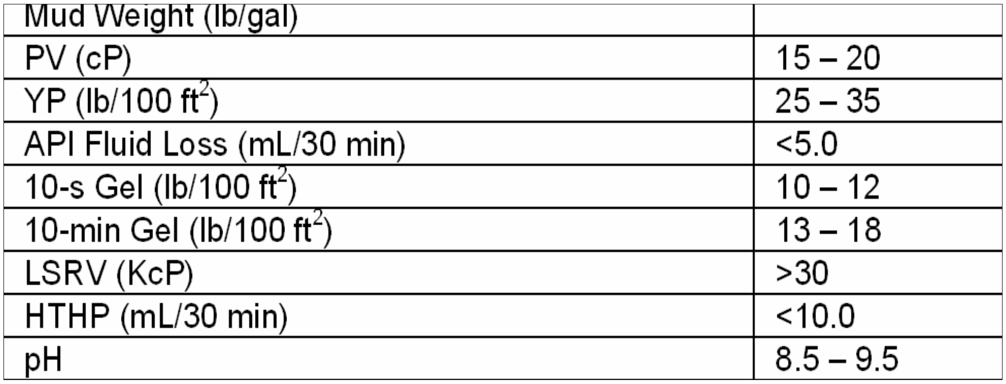
The composition and rheological properties of the drill-in fluid for experiment series are shown in Tables 3.1 and 3.2:

Table 3.1: Drill-in fluid composition by MI-Swaco (Ravitz *et al.*[16])



Biopolymer (lb/bbl)	1 – 1.5
Freshwater (bbl)	0.9
KCl (lb/bbl)	10.8
NaCl (lb/bbl)	32.3
Organophilic Starch (lb/bbl)	10
Organophilic Carbonate (lb/bbl)	6
Biocide (lb/bbl)	0.25
Sized Calcium Carbonate (lb/bbl)	24
pH Buffer (lb/bbl)	0.5

Table 3.2: Drill-in fluid properties by MI-Swaco (Ravitz *et al.*[16])



Mud Weight (lb/gal)	
PV (cP)	15 – 20
YP (lb/100 ft^2)	25 – 35
API Fluid Loss (mL/30 min)	<5.0
10-s Gel (lb/100 ft^2)	10 – 12
10-min Gel (lb/100 ft^2)	13 – 18
LSRV (KcP)	>30
HTHP (mL/30 min)	<10.0
pH	8.5 – 9.5

The components for the selected drill-in fluid to control the properties[17] are as follows:

- Brine base. The brine is chemically compatible with the formation. The brine base is KCl and NaCl solution.

- Bridging additive. Sized calcium carbonate was used as the most common bridging agent. It can be dissolved in hydrochloric acid. Since it is available in different median particle sizes which can be used to match the pore throat and minimize permeability impairment. The size was selected following the “1/3 rule” (van Vilet and Hassan[18]): in order to bridge on the outside of a permeable formation, the bridging particles should have a particle size distribution with a median size (slightly) larger than 1/3 of the median formation pore throat size diameter. The reliable pore throat size data of the carbonate reservoir cores was not available; therefore the median pore throat size was estimated according to the following rule of thumb:

$$D_{50} = 0.9\sqrt{k} \tag{3.1}$$

Since the measured cores permeability was within the range of 16-25 mD, the D_{50} ratio is about 4.5. The closest D_{50} ratio is 5 for the Halliburton product Baracarb-5, which was selected as $CaCO_3$ additive. The mean particle size distribution for different grades of Baracarb product is shown on Figure 3.13.

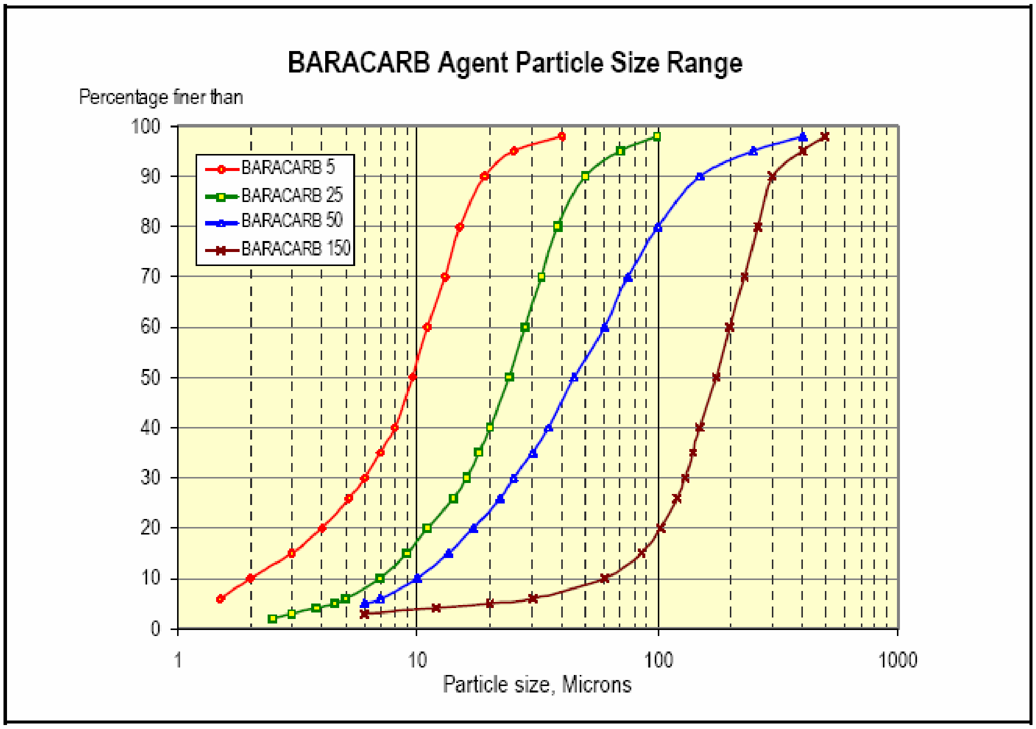


Figure 3.13: Halliburton’s BARACARB agent mean particle size distribution

- Fluid Loss Control Additive. The most common one, starch was used. Its drawback is easy fermentation by microorganisms (yeasts, molds, bacteria). To fight it, the mud was saturated with salt and the pH was kept around 12.

- Rheology Control Agent or Biopolymer. Xanthan Gum polymer was used to control rheological properties such as viscosity and yield point. The effect of pH on viscosity is negligible within range to 11.

- pH buffers. Caustic soda was used in as a source of hydroxyl ions to control pH.

- Bactericide. The bactericide was used, to kill the bacteria, which destroy organic additives such as starch or polymers.

- Rev Dust. To reproduce drilling damage, 30-40 ppg of RevDust was introduced to the active drill-in fluid system. Is did not change rheological properties significantly, but this concentration, advised by previous researchers, was successful to plug and invade the formation pores.

The drill-in fluid was prepared, mixed, and conditioned for the purpose of imitation drilling conditions and drilling damage on carbonate rock reservoir in the Middle East. Control and adjustment on rheological properties was performed in accordance to standard API procedure for rheology and fluid loss.

3.5 Parameters for Filter-Cake Deposition Process

Successful filter-cake deposition is the key to the research. After careful investigation and reference to previous researches, the following parameters were adopted:

- Time of deposition. Previous authors[8-12, 14] achieved good sustained filter-cakes pumping the fluid across the core face during 12 – 16 hours. The maximum reported time 16 hours was selected due to the core dimensions.

- Pressure of deposition. Different researcher reported differential pressure used within range from 300 to 500 psi[19-21] with accordance to permeability. Since the cores we cut, were Austin Cream Chalk having permeability 15-23 mD, a maximum 500 psi pressure rating was used. To verify pressure at the core inlet for drill-in fluid invasion a back pressure of 500 psi was applied to the outlet at the same side of the core holder.

- Confining or overburden pressure with ENERPAC pump was kept to reach the desired pressure; it was set 300 psi higher than back pressure.

- Pump rate. At early time, the filtration rate is high. As the cake builds-up, the filtration rate decreases until an equilibrium filtration rate has been attained. During cake build-up under dynamic filtration conditions, the force preventing particle deposition on the surface is proportional to the shear rate. As it was mentioned by previous authors[8-9] external filter-cake starts to build up after bridging is complete. In the case of sized $CaCO_3$, it takes more significant amount of time than it would be for fiber agent. Previous experiments showed that the drilling fluid velocity along the core face does not have serious impact if it is kept within typical wellbore conditions 0.4-1.2 ft/sec. Hence, the pump rate was kept within the range 0.3 to 0.5 gallons per minute to satisfy this.

- Temperature. Temperature was not expected to differ significantly after filter-cake formation.

The core parameters are stated in the Table 3.3:

Table 3.3: Parameters for filter-cake deposition

Core Type	Cream Chalk
Permeability, mD	16-25
Porosity, %	19-22
Core dimensions, (diameter, inch x length, inch)	4 x 18
Saturation fluid	water

3.6 Parameters for Acid Jetting Experiment

To properly conduct the jetting procedure the following parameters are to be set:

- Confining or overburden pressure with ENERPAC pump to reach the desired pressure; it was recommended 1200-1500 psi.

- Back pressure was 300 psi less than overburden pressure; this was the pressure to be applied on the dome of back pressure regulator; was checked in the gauge mounted in the front panel.

- Temperature. The same as for filter-cake deposition, an ambient temperature was used.

- Exposure time. Duration of jetting was the one of variables to be adjusted for determining what values of them were more efficient for the treatment. The duration varied for each experiment.

- Acid concentration. A permanent hydrochloric acid concentration of 15 per cent by volume was used while jetting is applied.

- Syringe pump rate. Initial rate was adjusted to 30-40 cc/min, in order to fill the core with brine first, and having established flow from the outlet, decreased to 2-5 cc/min for measuring permeability. After measuring the permeability to brine, for jetting experiment the higher pump rate (100 or 140 cc/min) was used.

CHAPTER IV

RESULTS AND DISCUSSIONS

4.1 Defining the Jetting Flow Rate

As previously mentioned, the necessary velocity for filter-cake removal is 200 ft/sec. To have efficient removal efficiency we need to be above this magnitude. The 1/8 inch tubing (jet) ID at the outlet is 0.05 inch, and applying simple math, obtain:

$$A = \pi \frac{d_i^{\,2}}{4} \tag{4.1}$$

$$A= 0.00196 \text{ inch}^2=1/35E\text{-}5 \text{ ft}^2 \tag{4.2}$$

$$q = vA \tag{4.3}$$

Where **A** is area in inch^2 or ft^2, **q** fluid flowrate in cc/min or ft^3/sec,
v is fluid velocity in cm/min or ft/sec.

Table 4.1: Flowrate and velocity calculated for the experiment

q, cc/min	100	140
q, ft^3/sec	0.003531	0.004944
v, ft/sec	259.06	362.68

For the experiments the above flowrates are used for both acid and water jetting.

4.2 Filter-Cake Deposition Experimental Results

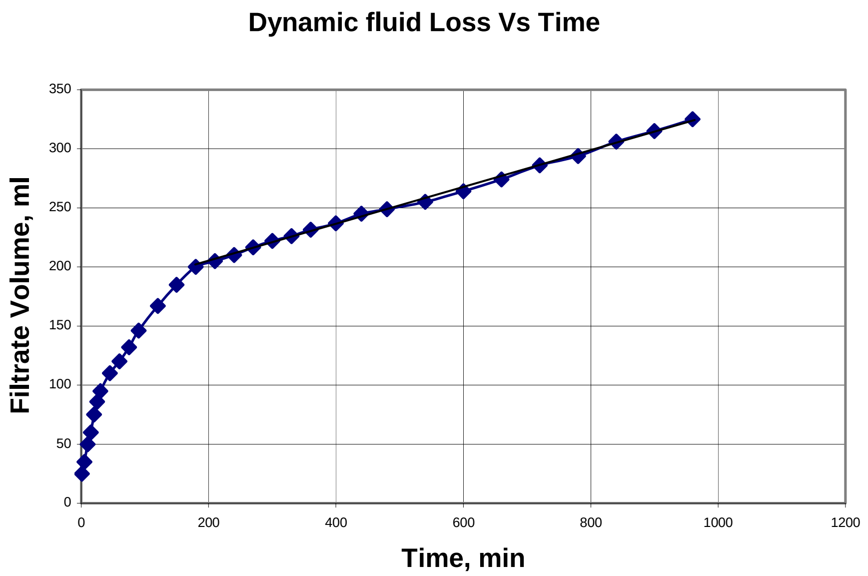


Figure 4.1: Dynamic fluid loss vs. time

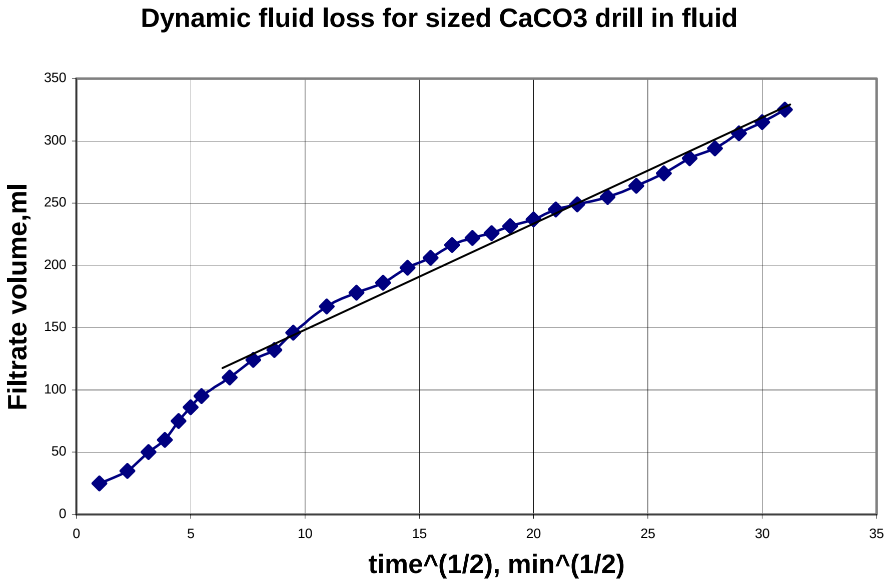


Figure 4.2: Dynamic fluid loss vs. $\sqrt{time}$

Figures 4.1 and 4.2 represent the filtration loss vs. time and vs. square root of time as occurred during the cake buildup experimental series. As you may see from the upper graph an external filter-cake stops to build up after around three hours of mud circulation; since after this time a straight line (constant fluid loss rate with time) it is observed. The lower graph shows the spurt loss is over after about 6 min$^{0.5}$; the slope then changes to linear, which means that an external filter-cake starts to develop.

4.3 Jetting Experimental Results

Overall 36 experiments were conducted some of them were not successful, and therefore their data can not be used.

Table 4.2: Tests and variables

Test #	Fluid	Flow rate q, cc/min	Jetting duration, sec	Acid volume, cc	k_{before}, mD	k_{damage}, mD	k_{after}, mD	R_D	R_S
1	Acid	100	20	33.35	17	12	35	2.917	2.059
2	Acid	100	45	75	17.5	13	46	3.538	2.629
3	Acid	100	60	100	18	13	60	4.615	3.333
4	Acid	100	90	150	17.4	12	72	6.000	4.138
5	Acid	140	20	46.65	19	12	72	6.000	3.789
6	Acid	140	45	105	19	13	82.5	6.346	4.342
7	Acid	140	60	140	19	11	99	9.000	5.211
8	Acid	140	90	210	17	12	118	9.833	6.941
9	Water	100	45	75	20	11	19	1.727	0.950
10	Water	100	90	150	25	12	24	2.000	0.960
11	Water	100	180	300	26	11	28	2.545	1.077
12	Water	140	45	105	26	11	27	2.455	1.038
13	Water	140	90	210	26	12.5	26	2.080	1.000
14	Water	140	180	420	22	10.2	22.5	2.206	1.023

Where: $\mathbf{k_{before}}$ is undamaged (original) core permeability, mD; $\mathbf{k_{damage}}$ is core permeability after filter-cake deposition, mD; $\mathbf{k_{after}}$ is core permeability after jetting, mD

The Table 4.2 shows experimental results and variables with jetting duration and flow rate that were conducted and which data was used for the purpose of this work.

4.4 Variables Influencing Filter-Cake Removal Efficiency

To make proper judgments of the variables influencing filter-cake removal, a couple of new terms are introduced. They can help to characterize numerically the filter-cake removal efficiency and stimulation. These terms are calculated as follows:

$$R_S = \frac{k_{afterjetting}}{k_{undamaged}} \tag{4.4}$$

$$R_D = \frac{k_{afterjetting}}{k_{damaged}} \tag{4.5}$$

The first variable, R_S, is the treated core permeability normalized to undamaged core permeability; it shows how much the permeability increased after jetting as compared to the same core undamaged permeability. One thing should be mentioned about R_S: when R_S is equal to 1, it means we removed the filter-cake damage but did not dissolve any rock and did not create any wormholes; therefore no stimulation was done. If it is larger than 1, it indicates stimulation work beyond just filter-cake removal.

The second one, R_D, is the treated core permeability normalized to damaged core permeability; it gives an understanding of how much the core permeability improved after jetting as compared to that of the same damaged core. These variables are tabulated in the Table 4.2 for each experiment conducted.

The experiments showed that filter-cake removal efficiency depends on several variables. These are:

- Jetting duration. The longer the core was exposed to jetting, the more filter-cake was removed. As a result the restored/stimulated core permeability increased. The experiments showed direct correlation between jetting duration and resulting permeability Figure 4.3 shows R_S as a function of jetting duration for the conducted experiments. As it can be seen, for each flow rate, longer duration time results in higher resulting permeability. Note that in every case R_S is more than 1, so the core is actually stimulated.

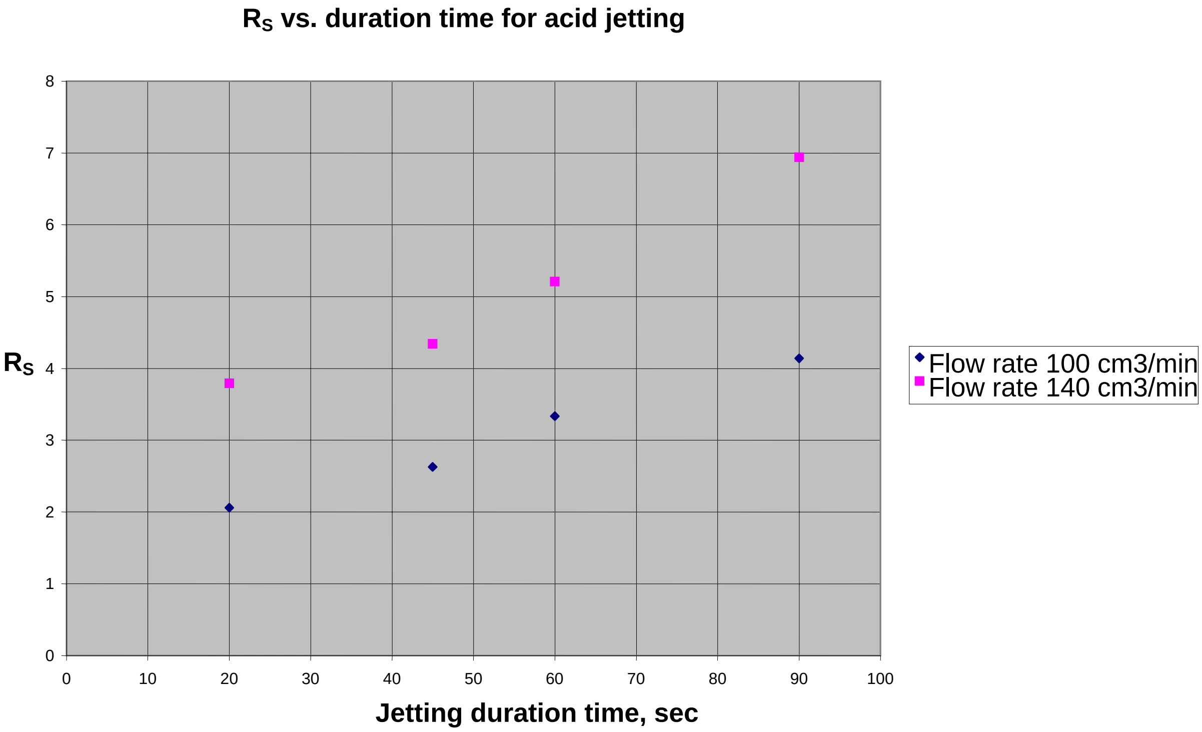


Figure 4.3: Combined experimental data of treated core permeability normalized to original vs. acid jetting duration

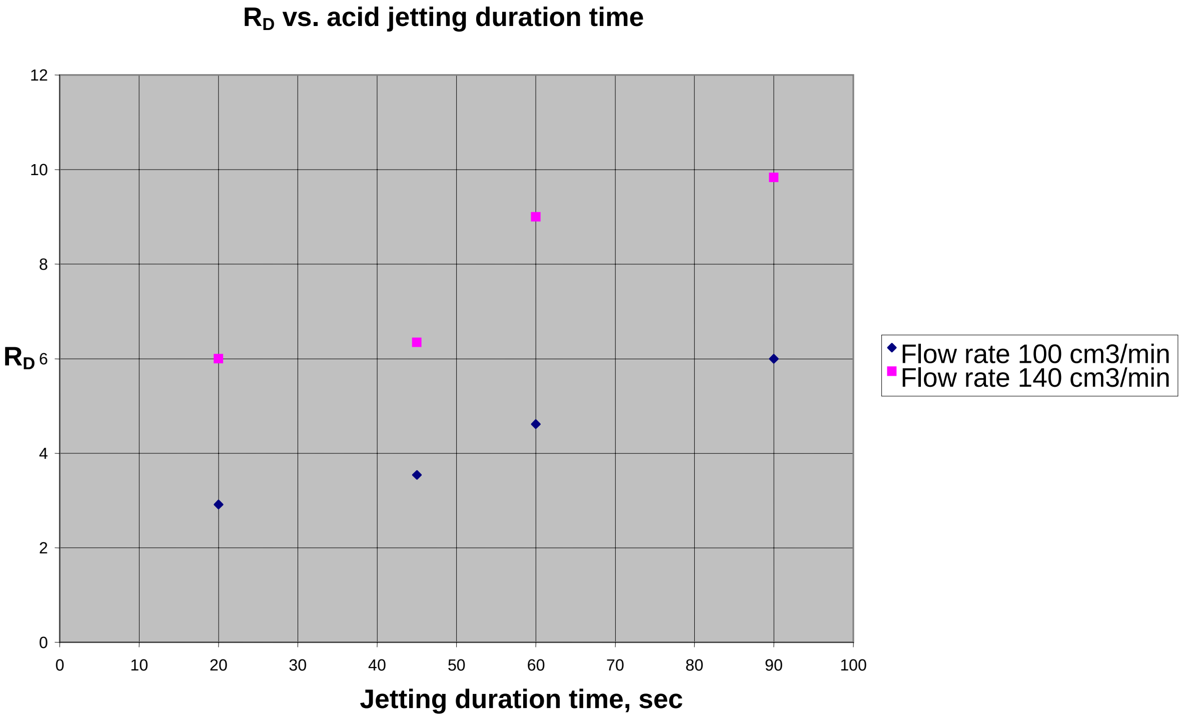


Figure 4.4: Combined experimental data of treated core permeability normalized to damaged vs. acid jetting duration

Figure 4.4 illustrates R_D as a function of jetting duration, and the trend remains identical to R_S on Figure 4.3: more duration enhances permeability greater.

Figure 4.5 illustrates that acid jetting duration has significant effect on filter-cake removal efficiency. It appears for the upper core that a larger portion of the filter-cake was removed and dissolved from its surface than for the lower one with the same acid jetting flow rate.

Figure 4.5: The upper core was subject to acid jetting (q=100 cc/min, duration 60 second), the lower one was subject to acid for 20 second (q is 100 cc/min)

- Jetting flow rate. The experimental data stated that jetting flow rate has direct influence on removal efficiency. The experiments were run with two flow rates: 100 and 140 c/min. The general trend was: higher acid flow rate gave higher removal efficiency and resulted in higher permeability. Figures 4.6-4.7 illustrate this trend for different acid durations; this trend remained valid for every experiment with different jetting duration performed. However, for water jetting the same tendency was not that obvious. Water jetting removal efficiency has different mechanism that is why neither rate nor duration has the same impact as for the acid experiments. Please note that R_S is larger than 1, we stimulated the core.

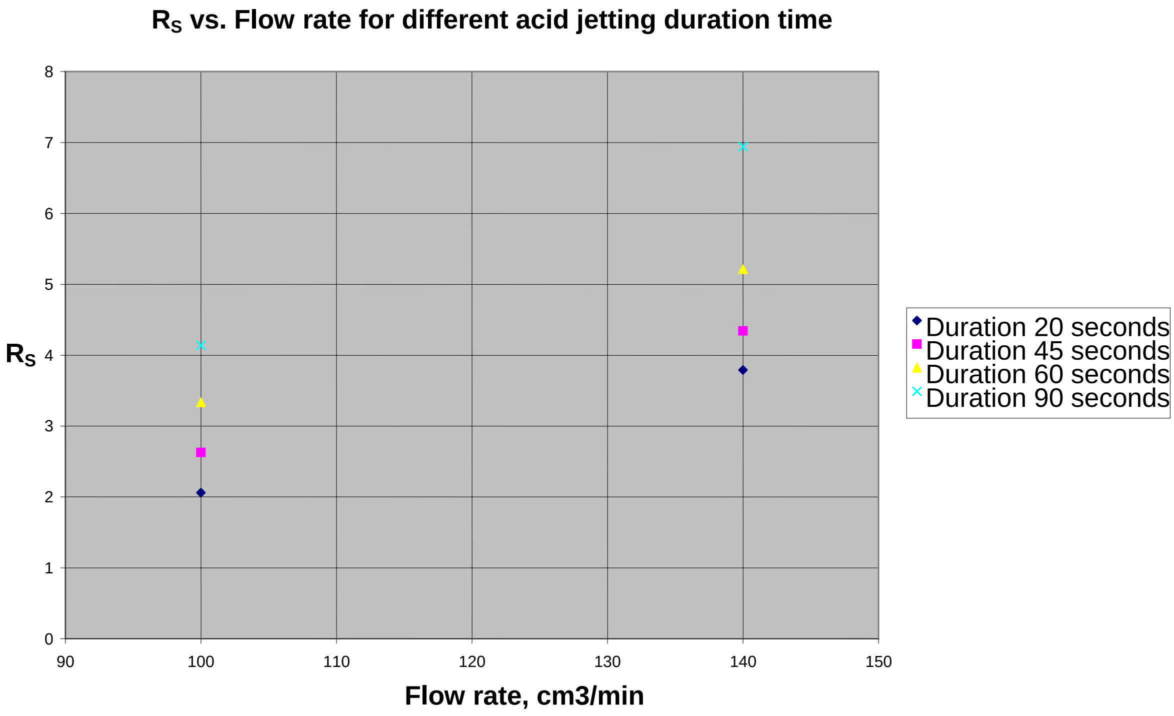


Figure 4.6: Combined experimental data of treated core permeability normalized to original vs. flow rate

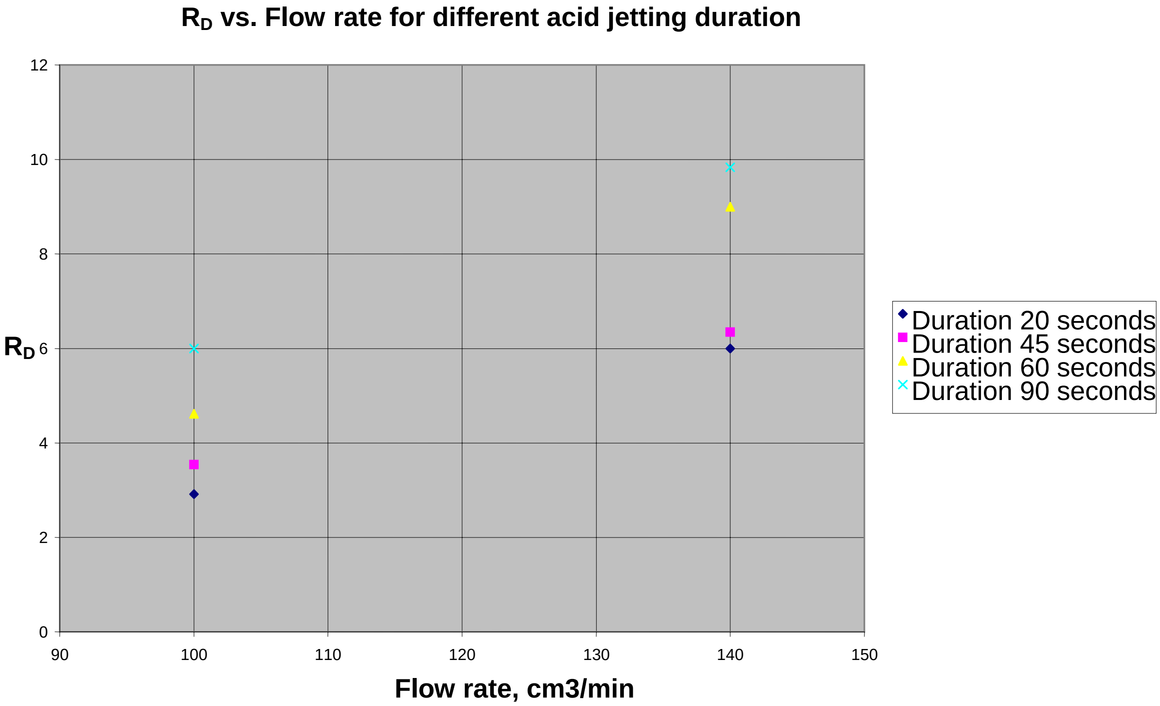


Figure 4.7: Combined experimental data of treated core permeability normalized to damaged vs. flow rate

Figures 4.8-4.9 prove that higher jetting flow rate actually removed larger portion of filter-cake. It can be seen the lower core (Figure 4.9) was subject to higher acid jet and lost more filter-cake than the upper one (Figure 4.8). Note that the central wormhole for the lower core was less developed.

Figure 4.8: Core with mud cake after acid jetting (q=100 cc/min, duration 60 sec)

Figure 4.9: Core with mud cake after acid jetting (q=140 cc/min, duration 60 sec)

- Acid vs. water jetting. As it was inferred from experiments, acid jetting resulted in higher permeability after treatment, as compared with water jetting. Acid jetting has combined chemical and mechanical impact on the core face and damaged zone, while water jetting involves only mechanical scouring action of the high velocity, high pressure fluid jet. Acid removed filter-cake more uniformly and even dissolved some portions of it as compared with water. A further stimulation was achieved due to wormholing and partial carbonate rock dissolution. Water acted less efficient even with jetting duration of three minutes as compared even with twenty seconds of acid jetting. Figures 4.10-4.11 show that acid stimulates the core and dissolves the filter-cake readily while as water in the best case removes only a lesser portion of it. Notice R_S for water is always 1, however it does not signify complete cake removal, and that for the treatments R_S for acid is higher than 2 to7 times than for water.

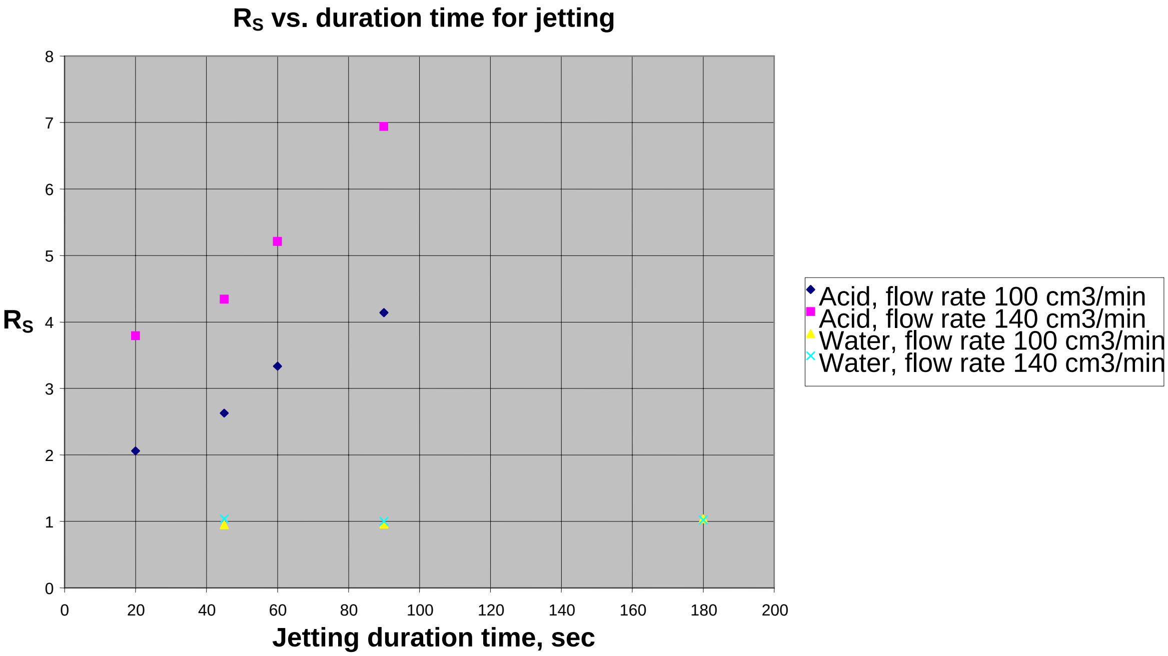


Figure 4.10: Combined experimental data of treated core permeability normalized to original vs. acid or water flow rate

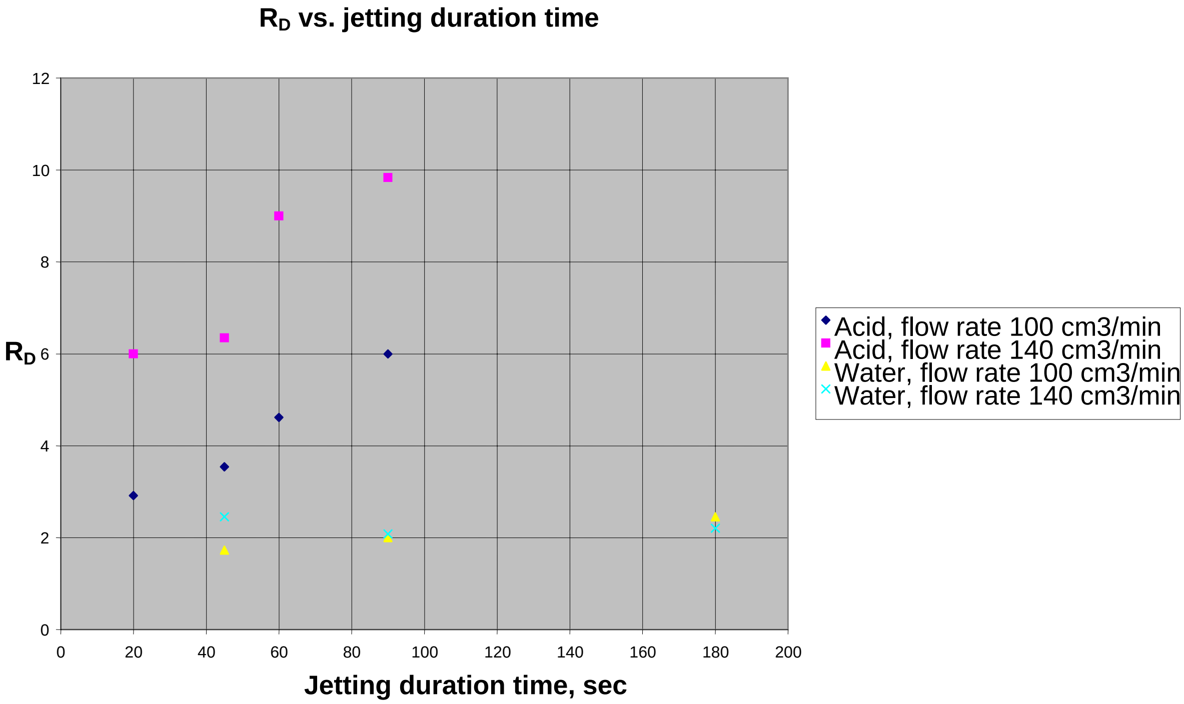


Figure 4.11: Combined experimental data of treated core permeability normalized to damaged vs. acid or water flow rate

On Figure 4.11 one may see that water jetting experiments also showed less resulting permeability. It is important to note that R_D for acid treatment is 1.5-5 times higher than for water. It is achieved by combined chemical and mechanical processes. Figures 4.12-4.13 prove better permeability response to acid experiments than that to water. Figure 4.12 shows filter-cake removed by water q=100 cc/min, jetting duration is 90 sec, and Figure 4.13 shows filter-cake removed by acid with q=100 cc/min, duration of jetting is 20 seconds. It is obvious that filter cake was better removed by acid, despite the job was not thorough.

It is important to add that since water restores the permeability to its undamaged level even without dissolution. In case of absence of severe damage and large internal filter-cake, water jetting proves to be quite efficient and safe.

Figure 4.12: Core with mud cake after water jetting (q=100 cc/min, duration 90 sec)

Figure 4.13: Core with mud cake after acid jetting (q=100 cc/min, duration 20 sec)

- Volumes of jetted acid/water. The acid volume has a direct impact on filter-cake dissolution, wormhole formation and development. Figure 4.14 shows the direct influence of acid volume on R_S: the more acid volume the larger R_S is; it means larger stimulated permeability. Some data scattering may be attributed to cores heterogeneity and some pressure fluctuations due to equipment.

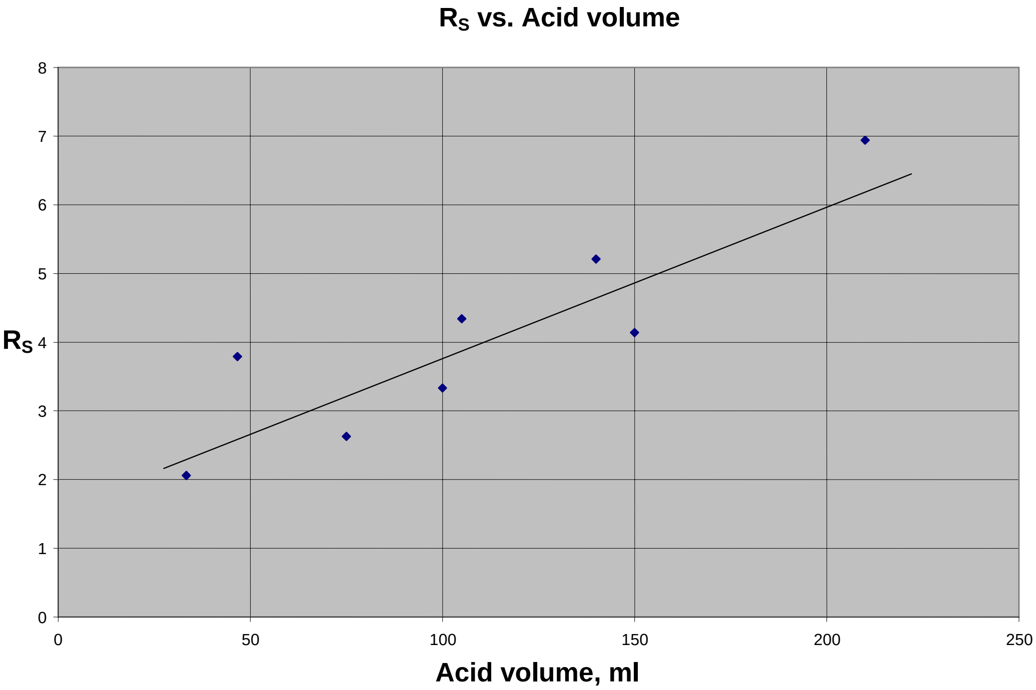


Figure 4.14: Combined experimental data of treated core permeability normalized to original vs. acid volume

Figure 4.15 has the same trend only for R_D and supports the idea of importance of acid volume to acid jetting. The data scattering has the same nature.

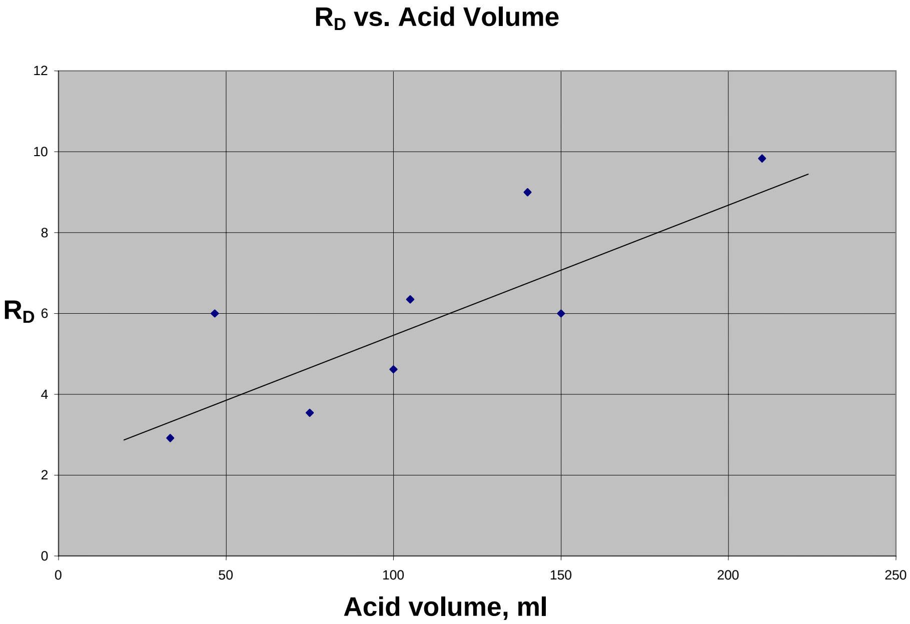


Figure 4.15: Combined experimental data of treated core permeability normalized to damaged vs. acid volume

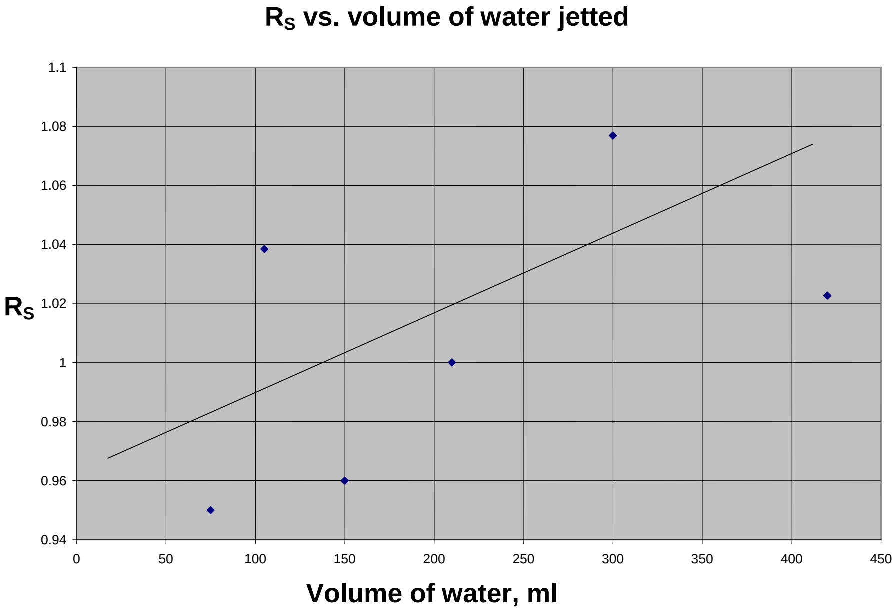


Figure 4.16: Combined experimental data of treated core permeability normalized to stimulated vs. water volume

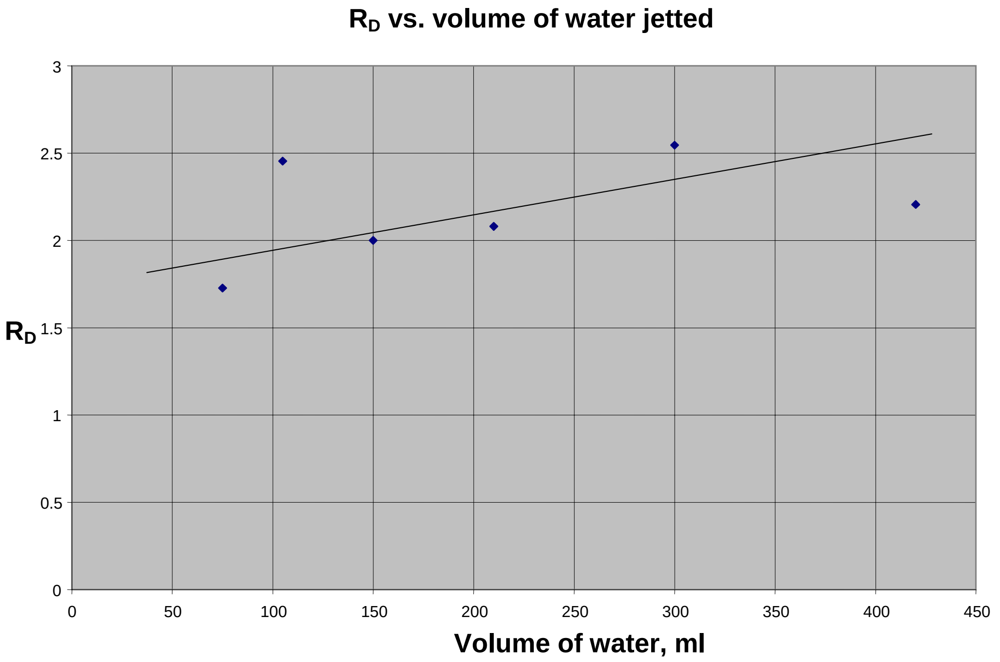


Figure 4.17: Combined experimental data of treated core permeability normalized to damaged vs. water volume

Figures 4.16-4.17 show the trends for water volume. The water volume influence is less pronounced and has less effect. It verifies assumption that for small number of jets and low volume jetting mechanical process is less important than chemical. Our water is not laden with an abrasive substance and its mechanical action is therefore more limited. And it means that for the jetting in these conditions (one jet, relatively small volumes of acid/water injected, not rotating jets), the process is basically chemically dominated.

- Filter-cake strength. When jetting was performed one day (24 hours) after filter-cake deposition procedure, i.e. it had been exposed to the air and became dry; the resulting removal efficiency was less. Figure 4.18 shows dry filter-cake (24 hour of the open air exposure after it was formed).

Figure 4.18: Dry filter-cake (exposed to the open air for 24 hrs after deposition)

Figure 4.19 shows comparison of removal efficiency of the filter-cake prepared by the routine procedure, and the dry one.

Figure 4.19: Two acid jetted cores; one jetted immediately, the other after 24 hours of drying out.

The upper depicted core was exposed to acid jetting immediately after filter-cake deposition (q=140 cc/min, duration 20 second), right one was acid treated (q=140 cc/min, time=20 sec) after 24 hours of drying out. As it can be seen, the dried up filter-cake was harder to remove. It adhered to the core rock harder. As a result, it allowed less portion of filter-cake was to be removed and dissolved.

- Reverse circulation (back flowing) after jetting. As it can be seen from Figures 4.20-4.21, back flowing cores after the jetting removes more filter-cake then direct flowing. It was valid even when lower flow rate and less jetting duration was employed prior reverse circulation. One more thing to mention: due to the recipe of the drill-in fluid and the relatively low permeability of the rock used, no severe internal damage was caused. It can explain why reverse circulation removed almost all filter-cake that was applied. However, this fact is not directly related to the jetting process itself; it can be characterized as after treatment procedure. Figures 4.22-4.23 show again that even for less jetting duration and flow rate by reverse flowing after treatments there can be better filter-cake removal result achieved.

Figure 4.20: Core with mud cake after acid jetting (q=140 cc/min, duration 60 sec)

Figure 4.21: Core with mud cake after acid jetting (q=100 cc/min, duration 90 sec, reverse circulation after jetting)

Figure 4.22: Core with mud cake after acid jetting (q=140 cc/min, duration 90 sec)

Figure 4.23: Core with mud cake after acid jetting (q=100 cc/min, duration 45 sec, reverse circulation after jetting)

- Wormholing. As it can be seen from CT-Scan pictures of acid jetted core on Figures 4.24 and 4.25, acid not only did remove and dissolve filter-cake, but also initiated wormholes. The wormholes in turn have direct influence on permeability enhancement. As before, the more acid rate or more acid duration is given, the more filter-cake is dissolved. As one may see, wormholes initiate at the center of the core cross section: one at the jet, another next to it. It is however, not a usual situation, for most of the cases a single wormhole initiation was obtained. This dual wormholing can be explained by rock heterogeneity, the fact the preferential porosity-permeability distribution encouraged both of wormholes to initiate simultaneously. Also, initial high jetting flow rate, relatively low duration time of jetting as compared to overall experiment and switching to lower water flowrate may have combined influence on multiple wormholing.

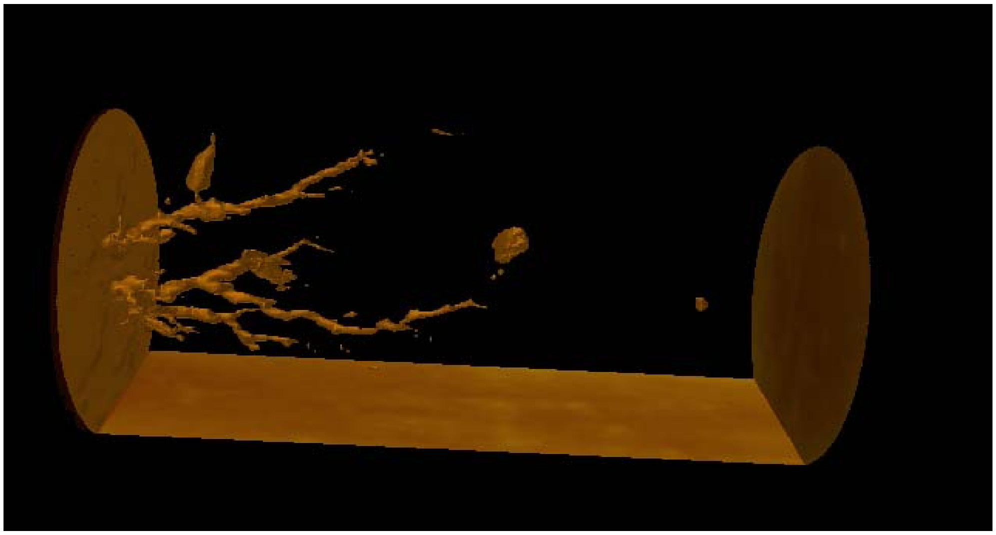


Figure 4.24: 3-D view of a core jetted with acid (q=100 cc/min for 90 second)

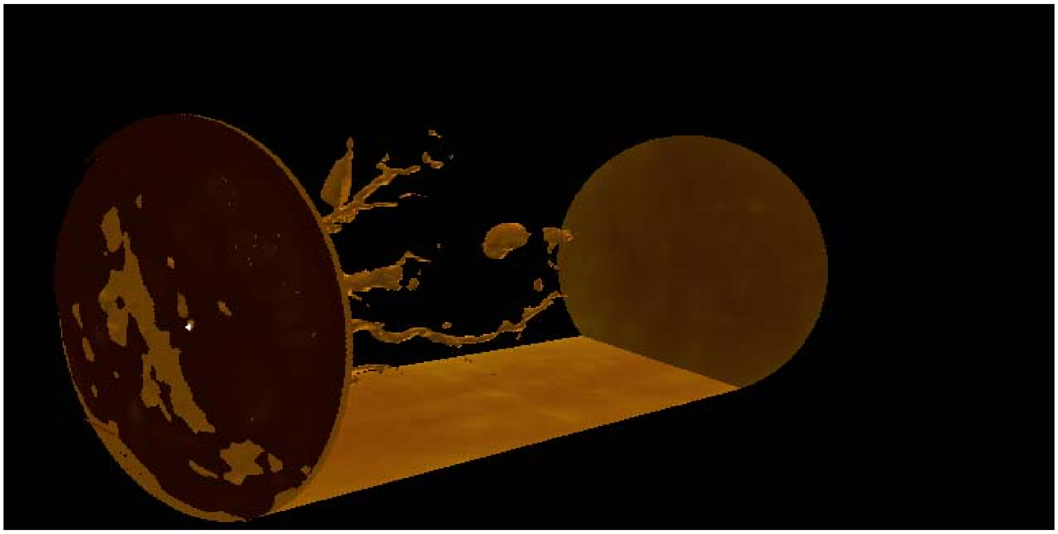


Figure 4.25: Angled 3-D view of the same core

On Figure 4.25 the remains of filter-cake can be recognized (left side of the core). Vugs that aid in wormhole initiation can be seen, too. It is clear that wormholes greatly enhance permeability and are the main contributors in the permeability enhancement for the experiment. But, excessive wormhole formation during the very beginning of jetting may interfere with efficient filter-cake removal, because most of acid will be spent on further development of the wormholes and no acid will be available for the cake removal and dissolution process. The optimum set of parameters (i.e. pressure, flowrate, duration and jetting orifice size) to minimize multiple excessive wormholing formation should be investigated additionally.

4.5 Well Performance Comparison after Jetting (Acid vs. Water)

The calculation of productivity index ratios helps to compare benefits of different kinds of jetting from a well performance stand point. Taking the particular core on figure 4.24, acid jetted for 90 seconds with 100 cc/minute of acid we calculate the skin factor for this core. The wormhole length according to CT-Scan is approximately 6 inches (0.5 ft); assume an imaginary well with a wellbore radius 0.328 ft. Applying formula for skin evaluation in acid treated cores by Buijse and Glasbergen[23], obtain:

$$s_{wh} = -\ln \frac{r_{wh}}{r_w} \tag{4.6}$$

$$s_{wh} = -\ln \frac{0.5 + 0.328}{0.328} \tag{4.7}$$

The skin after acid jetting is s_{wh}= -0.92; the skin for a water jetted core is s=0, since ratio of prior-to-damage to restored permeability is 1, like was previously mentioned.

The productivity index is:

$$J = \frac{q}{p_e - p_{wf}} = \frac{kh}{141.2 B\mu [\ln \frac{r_e}{r_w} + s]} \tag{4.8}$$

For the same well chosen the properties like B, μ, h, k are the same, so the productivity indexes ratio for acid and water treated well after simplification is:

$$\frac{J_{acid}}{J_{water}} = \frac{\ln \frac{r_e}{r_w}}{\ln(\frac{r_e}{r_w} + s_{wh})} \tag{4.9}$$

Accepting drainage radius r_e=2980 ft, we get:

$$\frac{J_{acid}}{J_{water}} = \frac{\ln \frac{2980}{0.328}}{(\ln \frac{2980}{0.328} - 0.92)} \tag{4.10}$$

$$\frac{J_{acid}}{J_{water}} = \frac{9.11}{8.19} = 1.11 \tag{4.11}$$

This example calculation illustrates that acid jetting improves the productivity index compared with water jetting by a small amount (about 11%). Since water restores permeability to the original level, there should be a lot of consideration given prior to commencement of an acid jetting.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Two apparatus (one for filter-cake deposition, another for jetting) were designed, built up, and modernized. A series of experiments were conducted to determine the most relevant variables. The resulting conclusions are:

- Acid jetting is more efficient than water jetting due to combination of mechanical scouring action and chemical dissolution of both filter-cake and core itself. It implies that not only does acid cleaning job but also provides stimulation, enhancing original permeability.

- Acid jetting is a chemically dominated process, since most portions of filter-cake were actually dissolved, not scoured like it would be for mechanically dominated process.

- Two terms representing ratios of permeability after jetting to damaged (R_D) and original (R_S) core permeability aid to estimate acid vs. water jetting. Depending on acid volume, flowrate and jetting duration R_S for acid was 2 to 7 times bigger than for water, which was about 1 for every treatment.

- Despite water jetting has less pronounced effect on permeability enhancement and overall leaves more filter-cake on core face as compared to acid, for the low to moderate permeability reservoirs having shallow invaded zone and no severe damage observed, it can be safer and cheaper alternative to acid jetting. It restores permeability to a prior-to-damage level and the difference in resulting productivity index between the two types of jetting is not great (5-10%). The other considerations are treatment costs, some possibility to lose the well and dangers related to acid when performing the job. This should be taken into account during job design.

- Jetting duration has direct impact on filter-cake removal efficiency. It also enhances permeability, introducing additional stimulation.

- Jetting flow rate shows direct influence on removal efficiency. Higher acid flow rate removes more mud from the core face. Also, like previously mentioned more acid volume dissolves more carbonate rock and enhances permeability.

- Acid jetting causes wormholing. Wormholes themselves form following pattern of the rock. Vugs, different densities and porosity/permeability heterogeneities have significant impact on its formation. But excessive wormholing may offset filter-cake removal efficiency, therefore it is should be avoided.

- Reverse flow after treatment helps to remove more remaining mud from the core face; it proves to be more efficient technology.

- As seen in curves in Figures A.1-A.4, water jetting treatment pressure has higher rate than acid jetting. It can be attributed to the fact that acid reaction process dissolves rock and creates wormholes, which in turn enhances injectivity and permeability in particular. It gives lower pressure readings during the process. This process should be further investigated.

- As seen on Figures A.1-A.4 long transient was observed during every acid jet treatment. This can be explained that the acid container outlet diameter was confined to 1/8’’ as well as lines diameter for the syringe feed pump engaged in the jetting was ¼”. This guided to pressure build up and such a transient behavior.

- Lower rock permeability results in shallower invaded zone, therefore thinner internal filter-cake. No severe damage was observed, which can also be attributed to less damaging drill-in fluid with sized calcium carbonate content.

5.2 Recommendations for Acid Jetting Treatment Design

While designing treatment, the following should be taken care of:

- More acid means more removal efficiency. However, if dissolution and matrix stimulation is not required, calculation of volume of acid to dissolve only mud cake is required. The filter-cake obtained in the experiment had thickness 3-4 mm, assumptions of the cake thickness in the field conditions should be defined based on either experience or logs/cores.

- For low permeability reservoirs with low damage zone and shallow internal filter-cake, water jetting is cheaper safer alternative since it restores permeability to its original level and avoids difficulties and dangers typical for acid jetting. The productivity index increase after acid jetting only 5 to 10 % more as compared to water treatment.

- Jetting process efficiency depends on flowrate and duration of the treatment. Higher flowrate gives higher removal efficiency; longer acid jetting duration yields the same result. The more acid is spent the more dissolution is achieved. As said above, for only jetting without stimulation, one should more carefully consider/calculate acid volume to remove mud-cake.

- Treating pressure is important, since it controls amount of acid penetrating rock. However, the pressure should be lower than the rock fracture gradient.

- Rock geology and lithology should be considered for it may give hints on most preferential ways wormhole will develop.

- Filter-cake thickness depends on rock properties and permeability in particular. It also depends on mud type and composition. During design, these parameters also should be considered.

5.3 Future Work

Other variables influencing filter-cake removal efficiency are to be found out. This work does not consider those variables' impact on removal efficiency and therefore on success of jetting job. The variables are:

- Standoff which is a distance between core face and jetting nozzle. As previously mentioned, the standoff should be equal to magnitude of eight orifice diameter, according to the industry reports.

- Jets rotation. Industry experiments and field tests report that rotating jets with 360 degree coverage provides best removal efficiency.

- Number of jets. Bigger jet number gives better coverage and therefore efficiency.

- Treating fluid. Different acid concentrations and abrasive content need to be investigated.

- An optimal set of parameters helping to avoid multiple wormholing during jetting should be experimentally established.

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APPENDIX A

JETTING TREATMENT PRESSURE CURVES

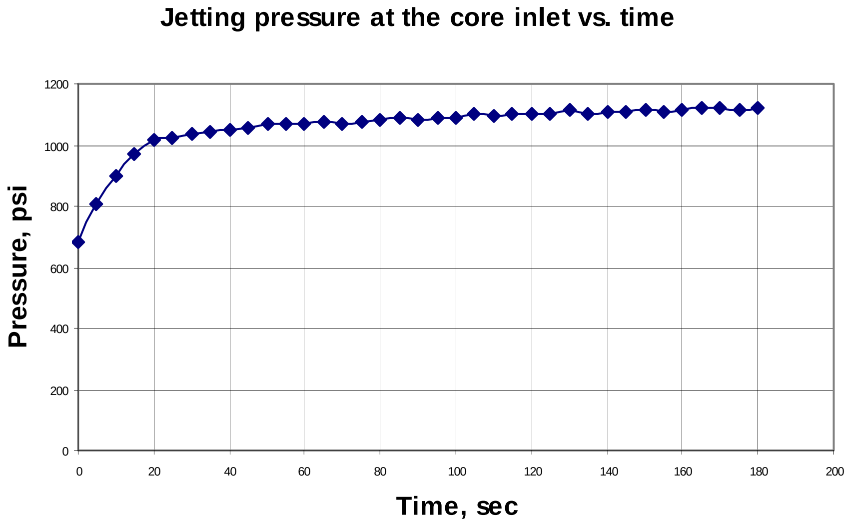

Figure A.1: Pressure during acid jetting for 180 sec at q=140 cc/min

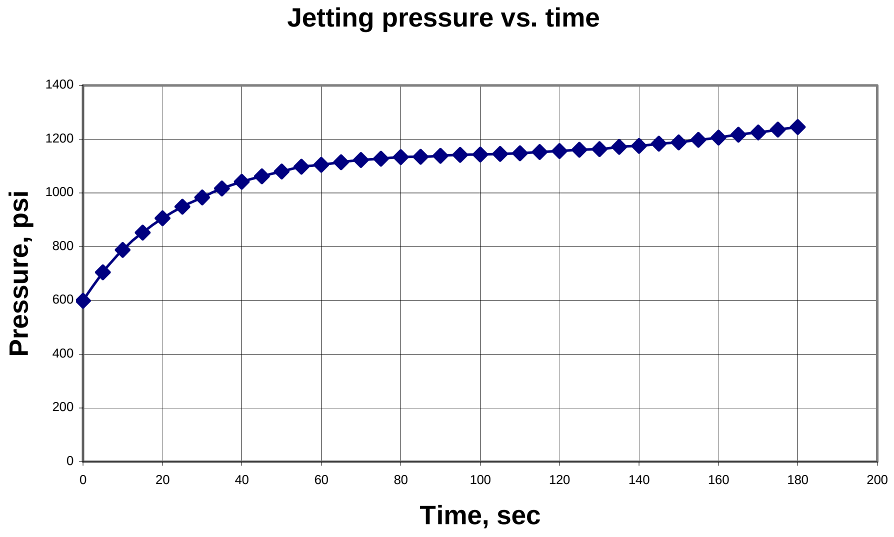

Figure A.2: Pressure during water jetting for180 sec at q=140 cc/min

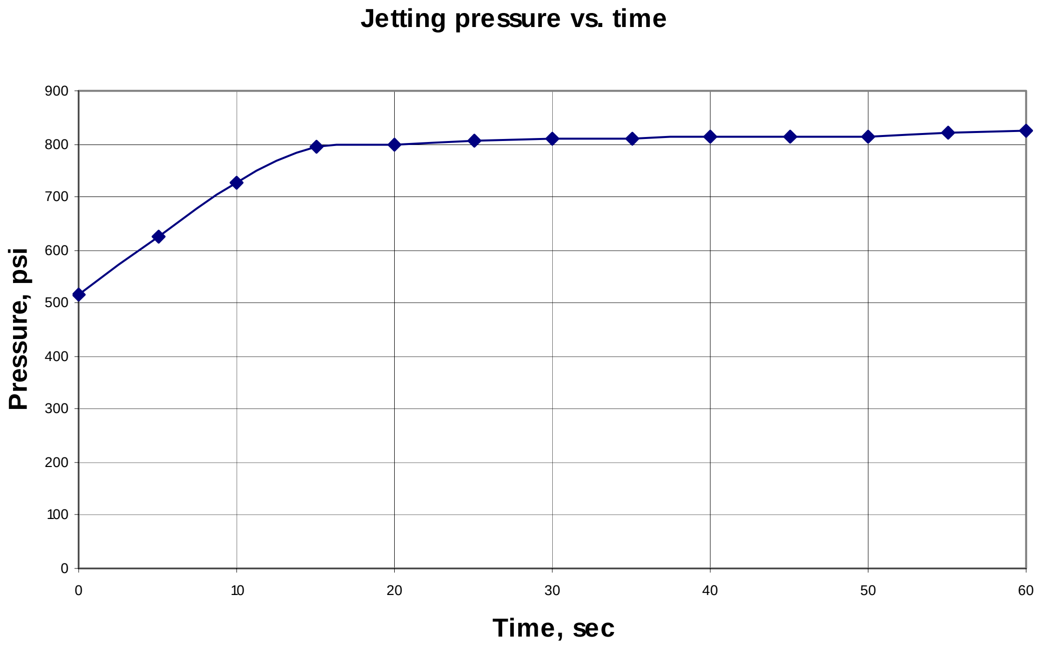

Figure A.3: Pressure during acid jetting for 60 sec at q=100 cc/min

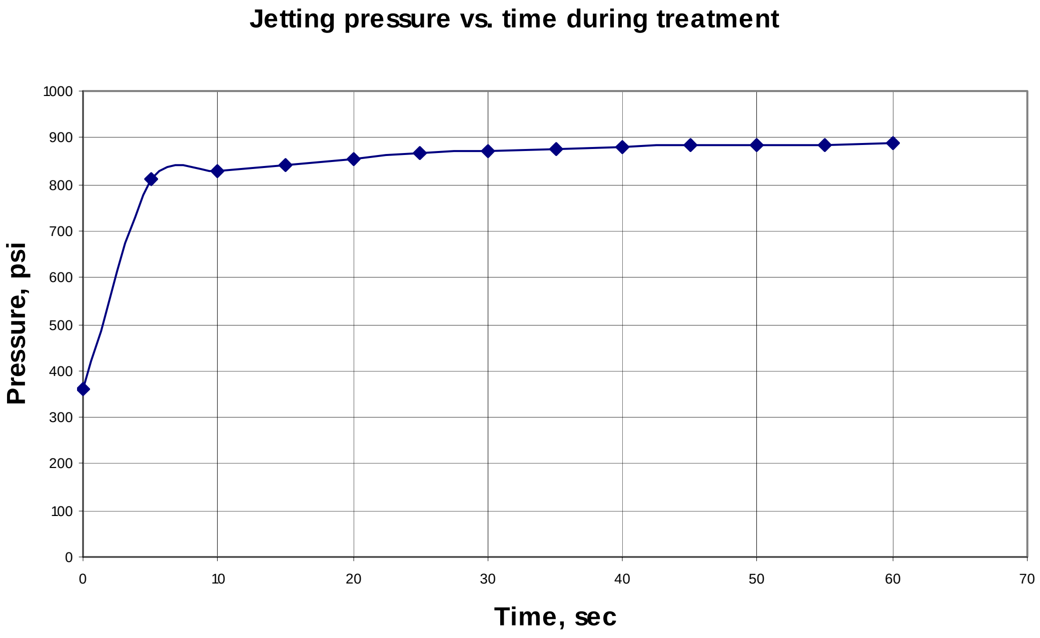

Figure A.4: Pressure during water jetting for 60 sec at q=100 cc/min

APPENDIX B

WORMHOLE INITIATION CT-SCAN PICTURES

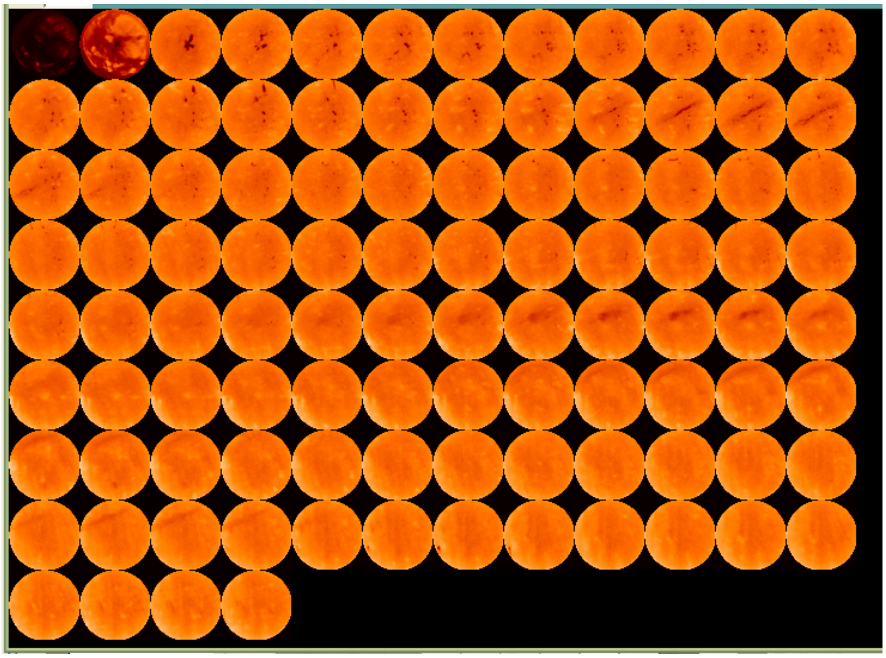

Figure B.1: Slice-by-slice transverse cross section view of the core sections (100 slices)

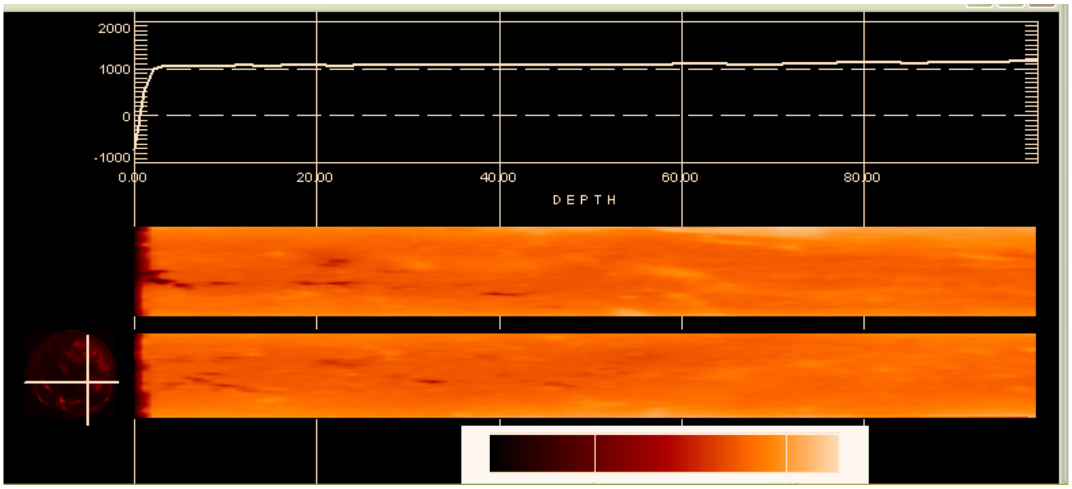

Figure B.2: Side view of the core cross-section along its length

APPENDIX C

CURVES OF MEASURED CORE PERMEABILITY AFTER JETTING

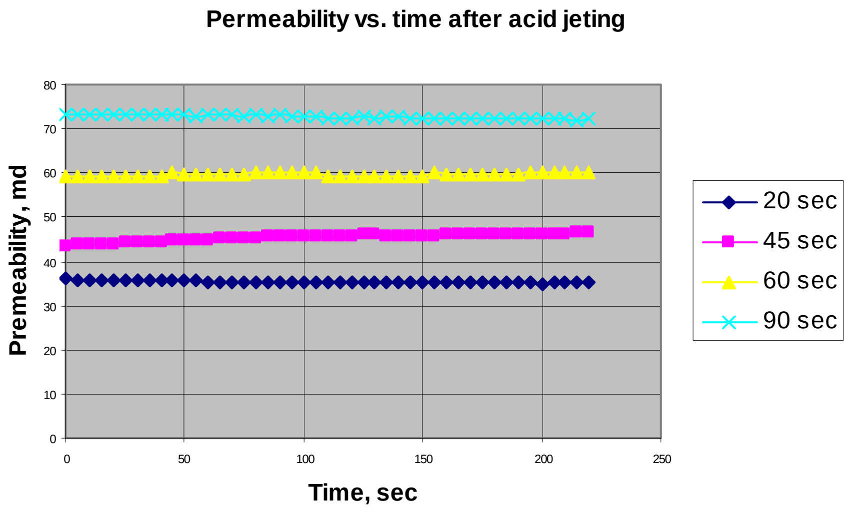

Figure C.1: Permeability after acid jetting with different durations

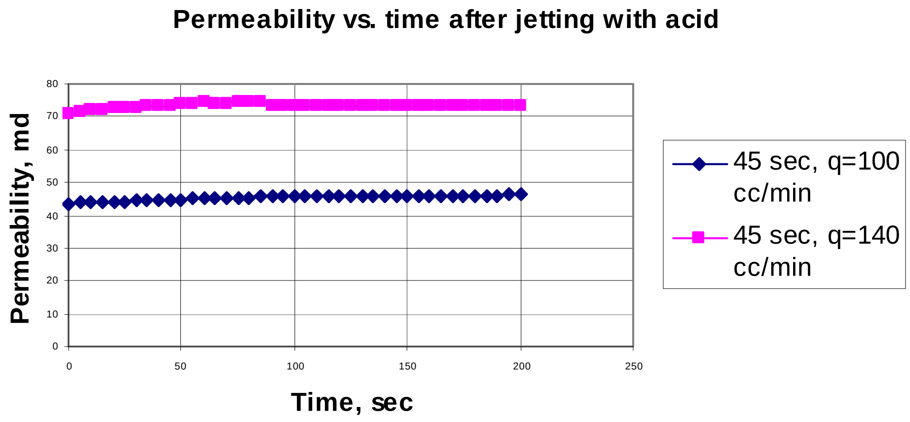

Figure C.2: Permeability after jetting with acid at different flow rates (durations are 45 sec for both experiments)

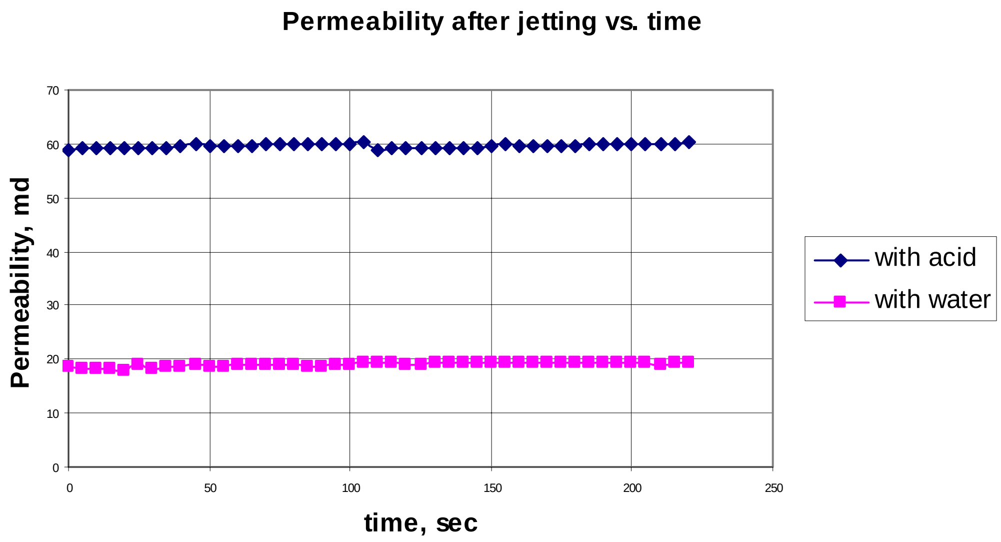

Figure C.3: Comparison of resulting permeability vs. time after jetting with water and acid (q=100 cc/min, duration time 60 sec)

APPENDIX D

PICTURES OF DEPOSITED FILTER-CAKE BEFORE JETTING

Figure D.1: Core with just formed filter-cake-1

Figure D.2: Core with just formed filter-cake-2

VITA

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This thesis was typed by the author.