

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Scale deposits by natural reservoir fluids and sea water in surface facilities often lead to numerous technical and economical problems due to blocking of fluid flow. Among the problems are reduction in pipe carrying capacity, impedance of heat transfer, increase of operational safety hazards, localization of corrosion attack and increase in operating costs due to inefficiencies, downtime and maintenance. Scale deposits also make the surface inside the pipe rougher. There is a 30% difference in pipeline capacity between the roughest and smoothest surfaces (Jack & Donald, 1976). The difference is much higher when scale deposits are involved. The effects are increased horsepower and cleaning requirements. Common scale deposits include Calcium Sulfate, Calcium Carbonate, Barium Sulfate, Silica and Iron. Among these deposits, Calcium Carbonate is the most common type of scale encountered in the oil industry (Vetter, 1987, Smith et al., 2000).

Scale deposition or scaling is the process of crystallization of soluble minerals to form hard scale. Various chemical or physical treatments have been proposed to decrease scaling. These treatments control the formation of scale by means of either prevention or removal. Methods like chemical injection, acidizing and pH control are applied to prevent and remove scale formation. Most of the treatments can be categorized as chemical treatment.

As chemical treatments can be costly, physical or mechanical treatments can be used because of their flexibility and cost saving. Scale and deposit control by mechanical gadgets and devices generally involve the use of electrical circuits, galvanic cells, magnetism or variations and combination of these. In particular, magnetic treatments in scale control have attracted much attention for over 100 years (Gabrielli et al., 2001).

The magnetic treatment method has very powerful advantages when applied in scale control due to its unique attributes. It is relatively cheap, low maintenance requirement, environmental friendly and saving energy. It does not need to be operated by any personnel and requires no operation shut down. Therefore, magnetic treatment has become possible alternative to the conventional chemical treatment.

However, its efficiency is still a controversial question (Gabrielli et al., 2001). Many reports have appeared dealing with the use of magnetic devices for scale control and they are found to be as effective as they are proven ineffective. Since it was introduced, extensive studies have been done to investigate its effectiveness until today. Generally it is agreed that magnetic treatments' effectiveness in scale control is still in doubt and this is supported by lack of published factual evidence on its performance and explanation of the mechanism of the process. The effectiveness of such application is still in investigation.

This project is to see how scale removal is carried out on pipelines by using Magnetic Descaler (MD). An experimental study was conducted to investigate the effectiveness of the magnetic treatment. The configuration of the magnetic device was manipulated to investigate the effect of different magnetic field densities on scale removal. A set of experiment setup were constructed closely imitating surface pipelines with calcium carbonate deposition on the inner wall surface. The efficiency of the magnetic treatment was investigated by measuring the weight of deposits removed over time.

1.2 PROBLEM STATEMENT

The application of MD in scale control to remove scale formation inside pipes with respect to surface facilities in Malaysia's oil & gas operation is very limited. The application too has never established any proven research data to show that it worked but several successful field case histories. The use of MD in scale control came about as alternative to the use of conventional high cost chemical treatments. The chemical treatments however are proven to be highly efficient in removing and inhibiting the scale formation. The decision to adopt magnetic treatment as opposed to the chemical treatment has raised doubt as to how effective MD could be because knowledge or understanding on the working principle of such application is very limited. Even if there are numerous researches that studied magnetic treatment's effectiveness, the results are mixed between those that proved it is effective and those that proved otherwise. It is therefore the interest of this study to investigate and understand how the scale behaves under the influence of magnetic field and determine the efficiency of the MD in scaling control.

1.3 OBJECTIVES AND SCOPE OF WORK

The aim of this experimental study is to investigate the application of the magnetic descaler (MD) in scale removal. Focus will be put on removal aspect of the application instead of the prevention aspect. The overall objectives of this experimental study are:

- 1. To produce a set of information on scale behaviour under the influence of various magnetic field configuration.**
 - a. To establish relationship between the amount of scale removed and different magnetic field configuration over time.

- 2. To investigate the threshold value of the amount of scale removed by the magnetic descaler.**
 - a. To identify the maximum amount of scale removed under fixed value of magnetic field strength.
 - b. To establish threshold value of scale removal rate in g/min/Tesla

- 3. To identify other governing criteria of the magnetic descaler operation.**
 - a. To investigate the effect of the flow velocity to scale removal rate.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION TO SCALE IN OIL AND GAS INDUSTRY

2.1.1 Definition of Scale

Scale is defined as the solid deposits of hard water. Hard water is defined as water with high mineral contents. Hard water primarily consists of calcium (Ca^{2+}) and magnesium (Mg^{2+}) metal cations, and sometimes other dissolved compounds such as bicarbonates and sulphates. In oil industry, hard water can be referred to as sea water or formation water that has high content of natural minerals. Scale in the oil and gas industry is therefore the solids deposits that are formed from the sea water involved in oil & gas operation. Generally, scale refers to any deposit on equipment surfaces (Jack and Donald, 1976).



Figure 1 : Scale deposit inside surface pipeline.

2.1.2 Types of Scale

There are few types of scale identified in the oil industry. These types of scale exist naturally in the seawater as minerals. There are 5 major types of scale commonly found in oil and gas industry. The following are the descriptions of each type and their respective treatment strategies:

(a) *Calcium Carbonate*

This type of scale originates from the nature of the reservoir itself. It exists in extensive geological deposits including in marine environment. Carbon dioxide and water are the main factors in its dissolution, transport and redeposition process. The scale is formed when there is a decrease in pressure, carbon dioxide release and pH change. This type of scale is the most common and widely spread of all scale deposits (Vetter, 1987; Smith et al., 2000). Although it is the most common, it can be prevented or removed by pH adjustment or acidizing, and is generally the easiest type of scale deposit to control (Jack and Donald, 1976).

(b) *Barium Sulphate*

This type of scale results from water incompatibility either from seawater injection or seawater breakthrough. This type of scale is highly insoluble. The scale is formed when there is a temperature drop across the production processing plant. Unlike other scales, chemical removal of this type of scale is almost impossible (J.M. Paul et al., 1992). Consequently, barium sulphate deposits must be removed mechanically or the equipment must be discarded. Prevention however is possible by the means of removing sulphate ions from seawater or application of barium sulphate scale inhibitors (Jack and Donald, 1976).

(c) Iron Sulphide

Iron Sulphide scale is deposited where microbial enhanced corrosion has become a serious problem. The scale is formed from the reaction of iron oxide from corrosion and hydrogen sulphide. Treatment for iron sulphide is application of a specialist chelating and dissolution agent followed by microbial control with biocide application (Roemex, 2005).

(d) Calcium Sulphate

This type of scale is relatively soluble and only poses a real problem when conditions are close to the solubility limit and super-saturation occurs.

(e) Sodium Chloride

This type of scale is caused by a saturation and evaporation process and is readily removed by warm water in most cases.

2.2 FORMATION AND DEPOSITION OF SCALE

2.2.1 Formation of Scale

There are three simultaneous factors for crystallization to happen
:

1. Supersaturation.
2. Nucleation centers.
3. Adequate contact time. (Jack and Donald, 1976)

(a) Supersaturation

Scale is formed when precipitate from a supersaturated solution is deposited. Reservoir fluids become supersaturated solution because of the high concentration of the fluids, incompatibility mixing of the fluids, changes in temperature and pressure as well as changes in the pH of the fluids that can occur in an oil producing formation, at the bottom of the borehole, in processing equipment, cooling towers, heat exchangers, evaporators, and almost everywhere water is used or handled (Donaldson and Grimes, 1987). All these changes i.e. pressure change, temperature change, pH change etc; result in changes in solubility of the solution thus inducing crystallization.

(b) Nucleation centers

Nucleation centers or crystallization centers exist in the form of foreign particles, ions or microcrystals. These crystallization centers are the initial points where soluble forms of minerals become crystals. These centers help to relieve the supersaturated solution by allowing soluble

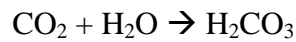
minerals to precipitate by forming crystals. These crystallization centers however are entrapped by the water molecule complexes in the crude oil mixture. Therefore, in order to relieve the supersaturated solution, the soluble minerals will form crystals at other crystallization centers that are not entrapped by the water molecules complexes. These alternative nucleation sites could be welds, scratches, fingerprints, or microscopic cracks of the internal surface of the pipes. Corroding surfaces also offer numerous sites for nucleation activity.

(c) Adequate contact time

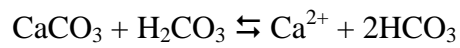
After a solution has become saturated and crystallization has occurred, sufficient contact time between the solution and the crystallization sites on the surface is required in order for crystallization to fully happen. The longer the contact time of a surface with the supersaturated solution, the more likely the formation becomes. The time required varies from seconds to years depending on the degree of supersaturation., the minerals, the nucleation sites, temperature, pressure and pH factors.

2.2.2 Formation of Calcium Carbonate Scale

Calcium Carbonate scale is the most common and widely spread of all scale deposits (Jack and Donald, 1976). Almost all naturally occurring waters contain some soluble calcium. Simple contact with air or decaying organic matter in the soil will expose this calcium to varying concentrations of carbon dioxide. Water in contact with air or decaying organic matter, readily absorbs CO₂ gas converting it to weak acid.



This weak acid can dissolve certain minerals such as calcium carbonate to form the soluble calcium bicarbonate.



This reaction allows calcium carbonate to be dissolved, transported and redeposited at some point as calcium carbonate again.

Microscopically, the reason for scale formation is easy to understand with a few basic laws of crystallography. Reservoir fluids carry significant amount of minerals mainly calcium carbonate. These minerals that are naturally dissolved in the reservoir fluids, often deposited inside the surface pipelines as a result of crystallization due to change in pressure, temperature or pH (Jack and Donald, 1976). This is because these minerals are said to have undergone phase change.

The change from the dissolved calcium bicarbonate to hard scale (calcium carbonate deposits) is a phase change from liquid to crystalline. Any phase

change needs a nucleation center. Nucleation center acts as a crystallization center for the minerals.

Most of the time foreign particles or ions in the reservoir fluids may serve as such centers. However, almost all of these potential centers are entrapped by the water-molecule complexes of sea water which have cage-like structure (Kronenberg, 1985). Therefore these foreign particles and ions cannot act as crystallization centers. When this happens, the crystallization can start only at the materials that make up the container walls. This explains why dissolved calcium bicarbonate deposited on the surface material of the inner wall of the pipes. From here, the deposition grows in layers until it becomes thick and form a very narrow flow path causing the reservoir fluid flow interfered.

2.3 SCALE CONTROL METHOD

The problem of scale deposition in surface facilities can be solved either by prevention of the scale from being formed and deposited, or removal of the scale in the cases where the scale has been deposited and is clogging the surface facilities flowlines and equipments.

2.3.2 Prevention and Inhibition of Scale

Methods used to prevent scale formation include chemical inhibitors, removal of dissolved and suspended solids or mechanical gadgets and devices.

(a) Prevention by Dissolved and Suspended Solids Removal

This method removes potential scale and deposit-forming constituents from water. Waters used for cooling, heating and process is pretreated before it is used in the system. Settling or subsidence is a simple process for allowing suspended solids to settle out of water without any chemical or mechanical treatment (Jack and Donald, 1976). Other than settling and subsidence, process like clarification or coagulation is used to remove dissolved and suspended solids. This process utilizes both chemical and mechanical treatment of finely divided solids that are usually too small to settle. Chemicals are added that combine or react with these small solids so that large masses form. These large masses tend to settle rapidly.

(b) Prevention by Chemical Inhibitors

This method works by injecting some chemicals (scale inhibitors) into wells, surface flowlines and even into reservoir formation. This scale

inhibitors works by some type of surface mechanism. This process will inhibit scale formation and this method of injecting and retaining scale inhibitor chemical into formation is called squeeze treatment (Meyers et al., 1985).

(c) Prevention by Mechanical Gadgets and Devices

Adoption of mechanical gadgets and devices in scale prevention has been inconsistent, not widely spread and short term in usage (Jack and Donald, 1976). This is because of the inconsistent results that these gadgets produced. This method generally involves the use of electrical circuits, galvanic cells, magnetism or variations and combinations of these. Magnetic treatments in scale control have attracted much attention due to its flexibility and low cost. The mechanism of prevention of these gadgets and devices varies from each other. In particular, magnetic descaler (MD) works by creating disturbance in the water that produces crystallization centers for the minerals. Instead of forming scale deposits on the wall, these minerals will crystallize at the crystallization centers produced from the magnetic disturbances by the MD.

2.3.3 Removal of Scale

It is difficult to remove scale as opposed to prevent scale. However, there are numerous treatments and techniques that can be used to remove or assist in the removal of deposits. There are three general options for scale removal:

1. Mechanical methods
2. Chemical methods
3. Combination chemical/mechanical (Jack and Donald, 1976)

(a) Mechanical Scale Removal

Common methods using mechanical devices are preferred in scale removal inside flowlines or tubes. These mechanical devices include rattlers or vibrators which are powered by air, water or electricity that pound or vibrate the tubes. Other devices such as scrappers, brushes, cutting heads of various types among others are used to physically remove the scale inside the flowlines. There are also techniques such as, ultrasonic cleaning, thermal shock and high pressure jetting are used to remove the scale. One important method to be noticed is magnetic descaler (MD). Scale removal by MD works by the same principle as in scale prevention. The magnetic disturbance created by the magnetic field will produce crystallization centers. Nearby mineral molecules rush from all sides including those from the wall to their crystallization center, where they form micro-crystals (Kronenberg, 1985). These micro-crystals will flow with the fluid and finally come out of the system.

(b) Chemical Scale Removal

There are many available chemical agents for removing scale. The nature of these agents can be classified as below:

1. Acids
2. Alkalies
3. Organic acids, salts and sequestrants
4. Surfactants, degreasers and organic solvents.

Because of the extensive occurrences of calcium carbonate scale in oil industry, much of the chemical scale removal methods are catered to this type of scale. Since calcium carbonate scale is acid-soluble and dissolves readily in many types of acids, acid treatment is adopted in removing calcium carbonate scale in surface pipelines. The most common acid is hydrochloric acid (HCL). For instance, during shutdown, surface flowlines are soaked with certain concentration and mix of HCL acid and other chemicals. After soaked, the acids are circulated and replaced within the flowlines for few days until scale dissolved. Other than acids, chelating agents such as amino polycarboxylic acids are adopted to remove scale. These agents are used to dissolve scale deposits especially barium sulphate which is difficult to remove except by mechanical means (Paul et. al., 1992)

2.4 REMOVAL OF SCALE USING MAGNETIC TREATMENT

2.4.1 Review on Magnetic Field Concept

The strength of a magnet is given by its magnetic flux density, which is measured in units of Gauss. A magnetic field is a vector and denoted by \mathbf{B} . A magnetic field can be represented graphically by magnetic field lines.

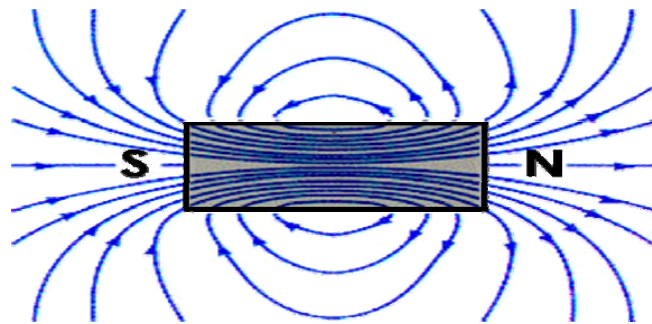


Figure 2: Magnetic Field Lines in a typical magnet bar.

The distance between them is an indication of the strength of the field. The closer they are, the stronger the field. For example, the number of lines per square centimeter is a measure of the strength of the magnetic field. The unit of \mathbf{B} is Gauss (10^{-4} N/A•m). Specifically, 1 Gauss is equivalent to 1 magnetic field line within 1 square centimeter. Another SI unit for \mathbf{B} is Tesla (T) where $1 \text{ T} = 1 \text{ N/A}\cdot\text{m}$. Mathematically the magnitude of \mathbf{B} is equal to *flux per unit area* across an area at right angles to the magnetic field.

$$|\mathbf{B}| = \frac{d\Phi_B}{dA} \quad (\text{N/A}\cdot\text{m}) \quad (1.1)$$

Where Φ_B = Total magnetic flux

A = Area of surface where magnetic flux passes through.

2.4.2 Principle of Magnetohydrodynamics

The magnetic descaler (MD) operates by the magnetohydrodynamics theory. The word magnetohydrodynamics (MHD) is derived from *magneto-* meaning magnetic field, and *hydro-* meaning liquid, and *-dynamics* meaning movement. The idea of MHD is that magnetic fields can induce currents in a moving conductive fluid (examples of such fluids include plasmas, liquid metals, and salt water), which create forces on the fluid, and also change the magnetic field itself.

The magnetic field on water based perpendicular to the strong magnetic field will produce an electromotive potential called the Lorentz force (Ghulam et al., 2001). This electromotive potential creates an induced electric current in the conductive fluid (in this case the reservoir fluid), resulting in the orientation of dipolarity of water in the direction of electron field. These changes in polarity orientation will cause water- molecule complexes to break and release the captive particles inside the complexes. These particles will help to reduce formation of scale on the pipe surface.

Therefore, to have best removal rate, the magnitude of the Lorentz force must be big. Magnitude of Lorentz force is the biggest when the velocity vector of the flow is perpendicular with the magnetic field lines (Gabrielli et al., 2001). Thus, it is important to ensure that the configuration of the magnetic descaler (MD) unit is arranged in such a way that it will produce magnetic field lines perpendicular with the velocity of the flow. According to MHD principles, the velocity of the fluid flow is directly proportional to the force created. The higher the velocity, the more effective is the removal rate.

2.4.3 Removal of Calcium Carbonate Scale by Magnetic Descaler (MD)

Removal of calcium carbonate scale by MD is done by creating a disturbance in the water that produces crystallization centers for the minerals. It has been demonstrated that these crystallization centers such as foreign particles and ions are trapped by water-molecule complexes that have cage-like structure (Kronenberg, 1985).

Therefore, it is important to break a few of these water-molecule complexes so that their internal captive particles become free. Once free, they act as centers for mineral molecules and form micro-crystals. Nearby mineral molecules rush from all sides including those from the wall to their crystallization center, where they form micro-crystals. These micro-crystals will flow with the fluid and finally come out of the system. This would leave less calcium carbonate to form hard scale on the walls.

The disturbance can be produced when the fluid flowing inside the pipe passes through the magnetic field of the MD units. This will induce the Lorentz force effect to occur.

2.4.4 Magnetic Descaler

In order to break the water-molecule complexes, it is required to create a disturbance in the fluid. The disturbance can be mechanical whirling, sonic disturbance, electrical frequencies and magnetic disturbances. They all reduce the formation of hard scale to some extent. Magnetic Descaler (MD) has become increasingly more popular for a number of reasons. Permanent magnet materials have been developed in recent decades to be 100 times as strong and much more durable than the old-fashioned magnets made out of steel (Kronenberg, 1985). In contrast to steel magnets, which weaken with age, modern ceramic magnets do not show any changes with age.

The effects of magnetic fields on running conductive fluids have been observed long before these better magnets were developed. Patents on treatment of conductive fluids with magnets appeared as early as the 1950s (Kronenberg, 1985). Though these magnets were not very strong, their effects were described as making the fluid appear to behave as if it was soft, as if its mineral content was lowered. Noticeably less scale was produced after prolonged use.

The MD unit is a series of very powerful permanent magnets mounted in a case equipped with standard pipe threads or flanges at each end. For the purpose of the experiment however, the MD used will be the ones used for domestic application usually used at homes (Refer Figure 3). The MD are sized by flow rate not line size.

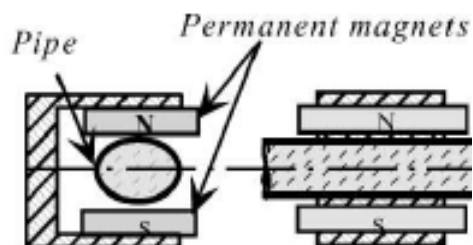


Figure 3: Domestic magnetic descaler.

2.4.5 Benefits of Magnetic Descaler

The increase application of magnetic descaler (MD) in scale control is because of its flexibility and cost. Perhaps, the most notably factor why MD is adopted is the cost involved. As opposed to expensive conventional chemical treatments, MD application involves less operational cost in the long run. Once installed, MD units do not need any personnel to operate it. This can reduce the possibility of occupational hazards from occurring. Since MD units consist of permanent magnets, no electrical power is needed to generate the magnetic field as opposed the electromagnetic devices. Furthermore, due to its operating mechanism that is environmental friendly, it is viewed as better alternatives to some conventional chemical treatments that are very polluting to some extent.

MD application is also preferred because of the fact that it does not need any plant shutdown to operate. Once installed, it can operate for a longer time. This is due to the fact that MD consists of modern ceramic magnets that do not show any changes in strength with respect to age (Kronenberg, 1985).

2.5 EFFECT OF MAGNETIC FIELD ON SCALE DEPOSITION

2.5.1 Changes in Scale Characterization

Donaldson and Grimes (1987) conducted few experiments to investigate the effect of magnetic field on scale deposition. The experiment uses calcium carbonate scale and the magnets with 1.75 kiloGauss to 2.5 kiloGauss. From the results, it was shown that the magnetic treatment of the supersaturated fluids can change the particle size, the crystallinity, the crystal morphology, the crystal phase, the solubility of the precipitates in the fluid and the rate of precipitation of the minerals (Donaldson et al., 1987)

(a) Changes in Particle Size

Magnetic field causes the precipitates to form large crystal size as compared to small crystal size under no magnetic field. Large crystal size is good because it does not form scale the way small crystal do. In other words, the tendency of large crystal to form scale is less that of small crystal thus reducing the formation of scale. Although it may seem as if the theory is more to scale inhibition, but a descaling action can also arise as a consequence of the effect because of resulting changes is scale-fluid equilibria. The experiment also suggested that there is a relationship between calcium carbonate precipitates particle size with the strength of magnetic field.

(b) Changes in Crystallinity

Small crystallites combined together much more easily under the influence of magnetic field. This results in larger combined crystals.

(c) Changes in Morphology

The effect of magnetic field on the growing crystals in magnetically treated fluids can also lead to changes in the relative rates of growth of the possible external faces of the growing crystals.

(d) Changes in Crystal Phase

It is evident from the experiment that the chemical phase of the precipitates obtained can be changed if the fluids containing them are subjected to magnetic field. The data samples of calcium carbonate showed that the calcite to aragonite ratio changed from about 80:20 for water passed through a zero-field MD unit to 20:80 for water passed through a 2500G unit.

(e) Changes in Solubility

The experiment suggests that the magnetic treatment of fluids leads to an increase in the solubility of the minerals in the fluids.

2.5.2 Reduction in the Amount of Scale Formed

Farshad et al. (2002) conducted a comprehensive experiment to investigate the effect of magnetic field on calcium sulphate formation. Two types of Neodymium-Iron-Boron magnets were used with configuration of magnetic field strength of 1.1 kG and 5.5 kG respectively. Four solutions with different concentrations of CaSO_4 were used with different temperature. The weight of the scale coupon was measured to investigate the physical reduction of the scale. From the result, it can be seen that there is a reduction of the CaSO_4 amount after measuring the weight of the scale coupon after the magnetic treatment.

2.6 FACTORS AFFECTING THE MAGNETIC TREATMENT OF SCALE

Farshad et al. (2002) explained in their experiment the factors that affect the magnetic treatment of the solutions. The following are the factors:

2.6.1 Saturation of the Fluids

The amount of scale formed depends on the amount of calcium sulfate in each solution. It was seen that the upper saturated solution had the highest amount of scale formed with and without magnetic treatment, whereas the under saturated solution was circulated through the magnetic systems. It is found that the amount of scale removed under magnetic treatment will be highest when the solution is under saturated.

2.6.2 Temperature

Increase in temperature will reduce the surface tension of the fluid. Low surface tension result in less scale formation. The combination of increase in temperature and magnetic treatment will reduce surface tension significantly.

2.6.3 Strength of the Magnetic Field

The magnetic system with magnetic field of 5.5 kG formed less scale deposits as opposed to the system with magnetic field of 1.1 kG. This is simply because the former has stronger magnetic field.

Farshad et al. (2002) also highlighted that the affects of the magnetic treatment is dependent on the geometry of the magnets, the type of magnetic settings used, and the space between the magnets and the solutions. Apart from that, the velocity of the fluid

also has an effect in scale deposition. The higher the velocity, thinner scale was formed and vice versa.

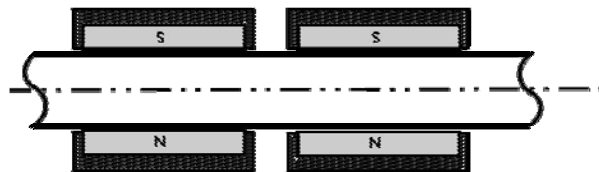
2.7 PAST WORKS

C. Gabrielli et al (2000) carried out an experiment to see the effect of calcium carbonate scale prevention using magnetic water treatment. A home made magnetic device was built with permanent magnets for treating scaling waters. Its efficiency was evaluated by measuring the remaining ionic calcium at the output of the device by means of an ion selective electrode. The experiment studied the effect of length of treatment, effect of flow velocity, effect of material of the pipe, and effect of the configuration of the magnetic device in scale prevention. It is important to notice, however, that Gabrielli's experiment focused on the prevention aspect of the scale instead of removal. The effect of configuration of the magnetic device and flow velocity are discussed below:

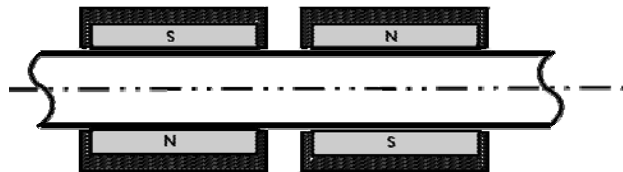
2.7.1 Influence of Different Magnetic Device Configuration

The experiment was conducted on 2 different configurations as shown below:

(a) Non-Inverted permanent magnets



(b) Inverted permanent magnets



The experiment concluded that the magnetic device with inverted configuration produced better efficiency of the magnetic device as opposed to non-inverted. It has been proven also that with inverted configuration, scaling times and nucleation times for calcium carbonate scale is the longest. It means that it is difficult for calcium carbonate to deposit as scale under inverted configuration thus prevent from scale formation.

2.7.2 Influence of Different Flow Velocity

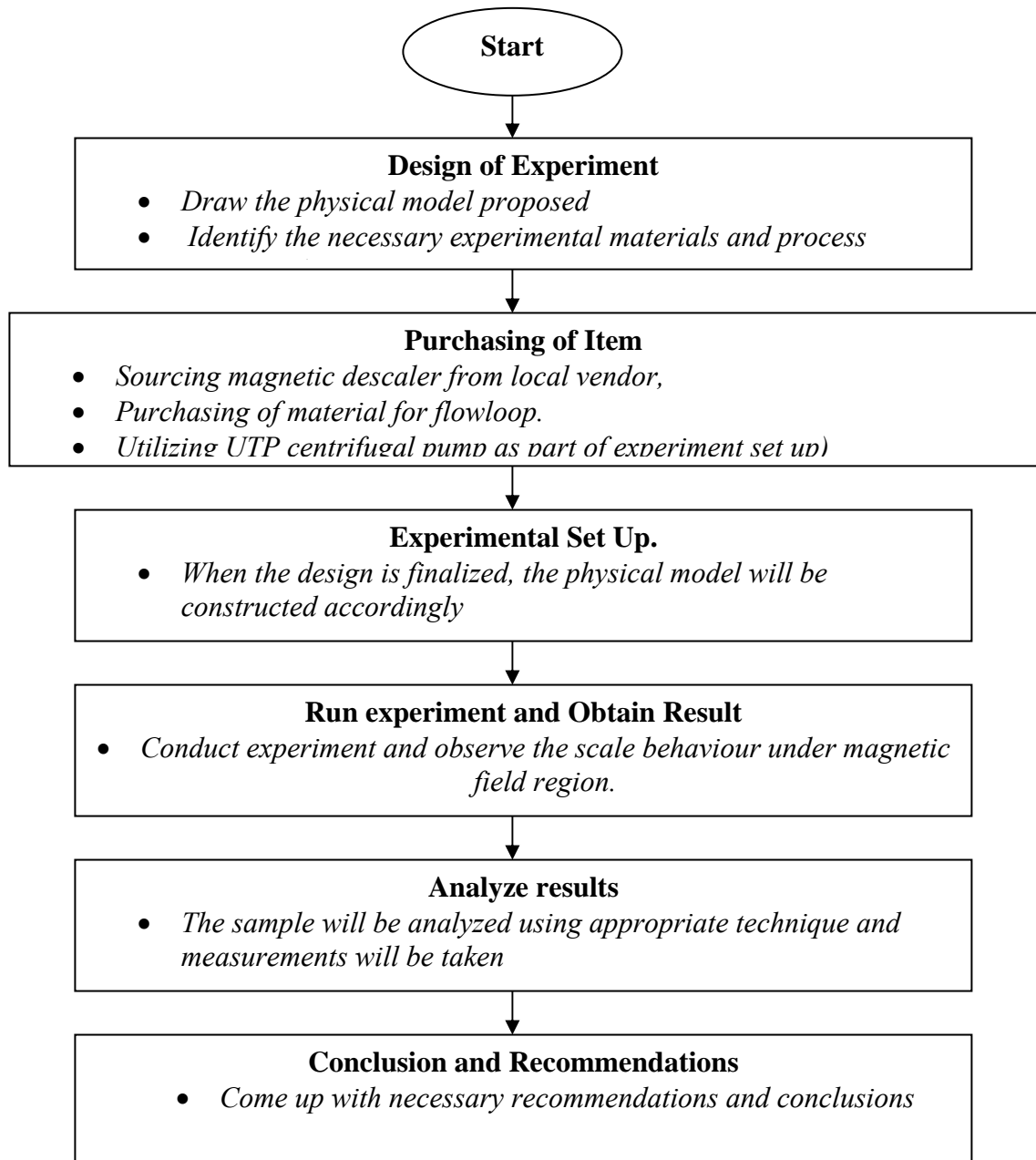
C. Gabrielli et al (2000) also concludes that the scaling times and the nucleation times increased with increased velocity.

CHAPTER 3

METHODOLOGY

3.1 PROCESS FLOWCHART

The strategy of completing this experimental study is based on the workflow illustrated below.



3.2 EXPERIMENTAL SETUP / DETAILS

3.2.1 Experimental Materials

For this experiment, calcium carbonate was used as the scale deposit. This is because calcium carbonate scale is the most widespread and most common scale deposits found in oil and gas industry (Vetter, 1987; Smith et al., 2000). The calcium carbonate was deposited inside a 3/4 inch galvanized iron pipe by inserting calcium carbonate precipitates that were prepared by mixing calcium carbonate powder with water. PVC pipes were used to build the flowloop for the experiment (See figure 4). All the related materials illustrated in figure 4 are described in table 1.

Table 1: Raw materials for the experiment.

No.	Description	Pack Size/Length	Qty	Total Price (RM)	Total Amount
010	Calcium Carbonate Precipitated GR for analysis reagent (1.02066.1000) from MERCK Sdn. Bhd)	1 kg	1	326.00	1 kg
020	3/4" Galvanized Iron Pipes	2 ft	2	20.00	4 ft
030	PVC Pipes and Connectors	Misc	Misc	30.00	8 ft
040	Pipe Support Steel	Misc	Misc	51.00	12 ft
TOTAL :				427.00	

3.2.2 Process Equipments

An aquarium pump of 25 W with maximum delivery volume of 1500 litres/hour was used in this experiment. This pump was installed at the location shown in Figure 4. Due to financial constraint, magnetic descaler (MD) unit that was being used in industry was replaced by two MD units used for domestic application. This magnetic descaler (MD) units both measure 5.125 inches long, 1.625 inches deep, and 1.5 inches wide and can be installed and is effective on pipes measuring 0.25 inches to 4 inches in diameter. The MD units consist of two ultra strong ferrite magnets each. Force of the magnets adds up to 300 pound power that collectively would lift 300 pounds of load.

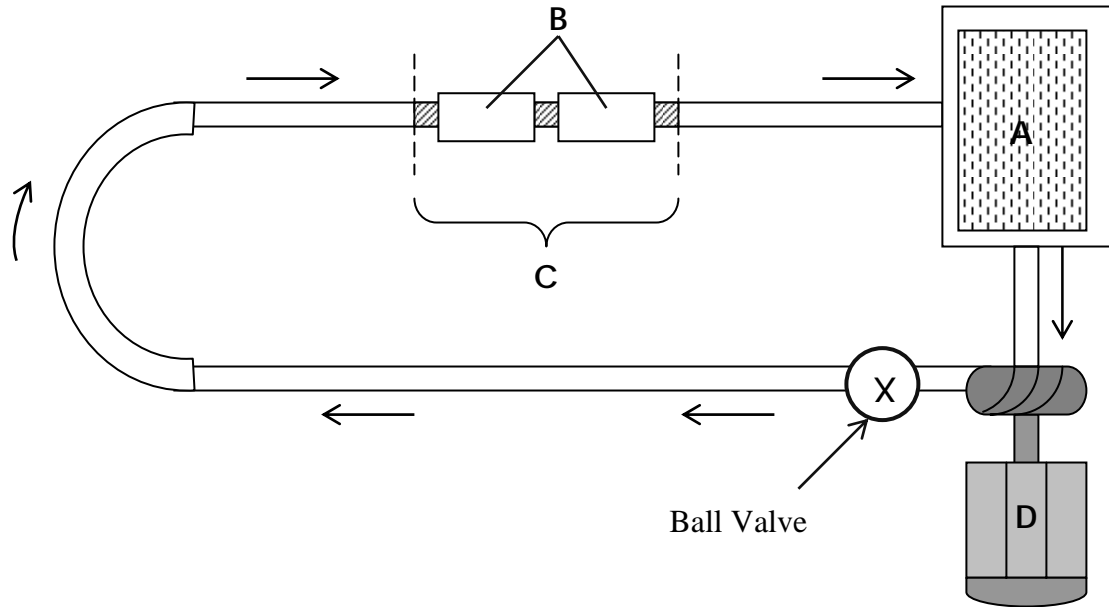
Table 2: Equipment and instruments for the experiment

No.	Description	Qty	Specification
010	25 W aquarium pump	1	1500 litres/hour Maximum Delivery Head
020	Magnetic Descaler Unit	2	Mega ferrite Magnet up to 300 pound of power.

3.3 EXPERIMENTAL PROCEDURE

3.3.1 Experimental Arrangement

The experiment has the following arrangement.



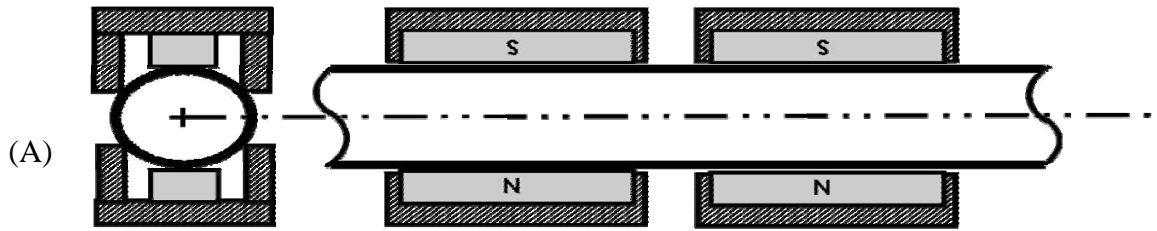
A	Water Basin to hold water
B	Magnetic Descaler Units.
C	3/4" Galvanized Iron spool that can be tied in and off.
D	Aquarium Pump (25 W)

Figure 4: General arrangement of the experiment.

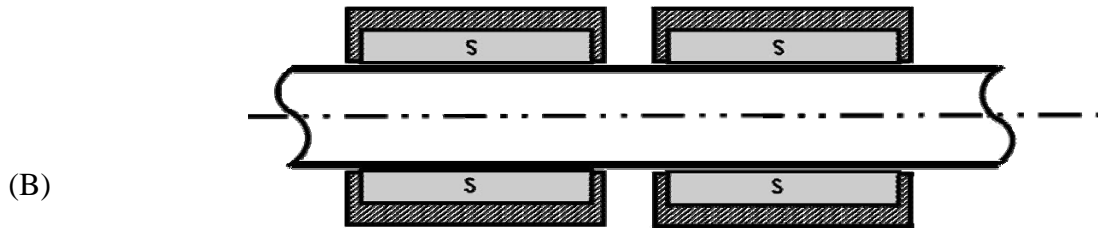
Figure 4 shows the experiment setup and equipment used in the study. Water basin was used to hold water. The 3/4 inches galvanized iron pipe denoted as C, can be tied in and tied off to allow measurements and observation of the scale deposits inside the pipe. The MD units were installed on the galvanized iron steel pipe with different configurations for every trial.

For the purpose of comparison, a control sample was introduced to see the effect of scale removal without any magnetic treatment. This control sample is a mere galvanized iron spool without magnetic descaler (MD) installed on it. For the 3/4" galvanized iron spool (test sample), it was prepared with readily deposited calcium carbonate scale inside it.

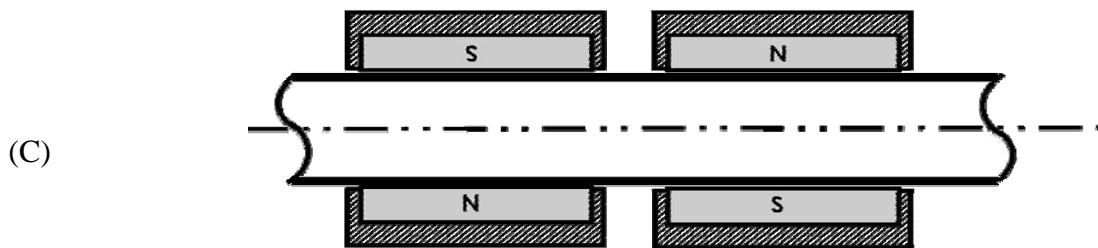
Tap water was used as the flowing fluid. The reason water was used as opposed to crude oil was because water is the main factor in calcium carbonate's dissolution, transport and redeposition process (Jack and Donald, 1976). Four different arrangements of MD units are shown in Figure 5.



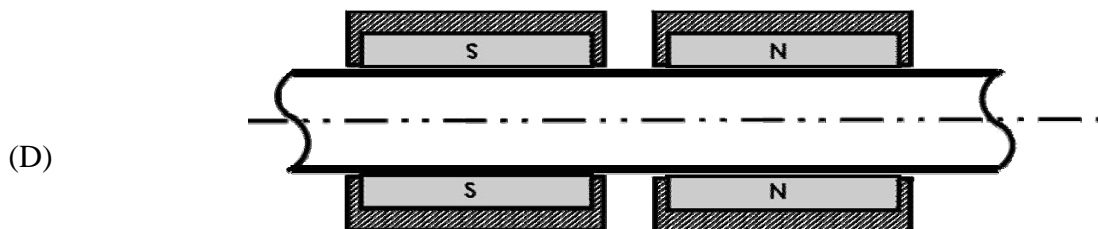
Configuration 1



Configuration 2



Configuration 3



Configuration 4

Figure 5: Four different configurations of the magnetic descender units for the experiment to study the effect of various magnetic field lines configuration on scale behaviour.

3.3.2 Procedures

(a) Procedure A: Measurement of Magnetic Flux Density of MD units

A Magnetic Flux Density Sensor is used to determine the value of magnetic flux density of MD units. For Configuration 1, the sensor is drawn at points of interest of MD units. The values of magnetic flux density at those points are taken in miliTesla. All these values are summed up and divided to take the average reading of Configuration 1. The steps are repeated for Configuration 2,3 and 4.

(b) Procedure B: Displaying pattern of MD unit's magnetic field lines

Magnetic Particle Inspection (MPI) spray is used to display the pattern of MD unit's magnetic field lines. MD unit is arranged as in Configuration 1 (Figure 5) and a white plastic board is laid upon the MD unit. MPI is sprayed over the surface of the plastic board at about 20cm away from the surface. The pattern of the magnetic field lines is observed and digital images of the pattern are captured. The steps are repeated for Configuration 2, 3 and 4.

(c) Procedure C: Investigating Scale Removal Rate of MD units

This experiment is based on setup shown in Figure 4. The weight in kilogram of a 3/4" galvanized iron pipe is measured (m_1). Calcium carbonate powder is dissolved into water inside an aluminum container. The 3/4" galvanized iron pipe is dipped into the aluminum container for 2 minutes. The pipe is pulled out and let dry. This causes layers of calcium carbonate to develop inside and outside the wall surface of the pipe. The

layer on the outside of the pipe's wall is removed by brush. The weight of the pipe is then measured (m_2). The pipe is attached to the experiment setup and MD units are mounted onto the pipe. MD units are arranged as in Configuration 1. The pump is run and the fluid is circulated for 15 minutes. The pump is switched off. MD units and the galvanized iron pipes are detached from the setup. The weight of the pipes is measured (m_3). Amount of calcium carbonate removed is calculated ($m_2 - m_3$). The steps are repeated for every 15 minutes of 3 hours run or more depending on the results. The whole experiment is repeated using Configuration 2, 3 and 4. After all configurations are done, the experiment is repeated using Configuration 1 with the ball valve half-opened. This is to investigate the effect of flow velocity on scale removal by MD units.

3.4 EXPERIMENT LIMITATIONS

The limitations and constraints of the experiment are summarized as below:

1. The MD's magnetic strength used in this study is fairly low. Magnetic Descaler (MD) units used in this experiment are domestic magnetic descaler normally installed at homes with scale problem found inside various pipes such as heater pipes, and shower pipes. The industrial scale MD unit is too expensive to be purchased.
2. Water is used as the fluid instead of crude oil thus reducing the possibility of getting the results as accurate as the real application. Crude oil is difficult to be sourced. The only hydrocarbon fluid available was diesel that has been used in various tests. The concern is that the diesel might contain iron or steel elements that might stick to the MD field area and eventually affect the weight measurement of the pipe.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 MAGNETIC DESCALER PROPERTIES

4.1.1 Measurement of Magnetic Flux Density of MD units

This experiment was conducted based on procedure A to determine the magnetic flux density (magnetic strength) at points of interest of MD unit for all 4 configurations. Figure 6 shows the points of interest where readings are taken for each configuration. Readings from these points are summed up and divided to determine the average value of magnetic field densities for each configuration.

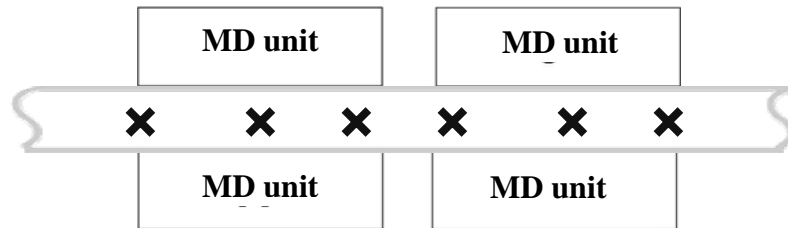


Figure 6: Points of interest (X) where readings of magnetic field densities are taken.

Table 3: Average magnetic flux densities of MD unit of Configuration 1,2,3 and 4.

Configuration	Average Magnetic Flux Densities (miliTesla)
1	16.70
2	2.83
3	16.50
4	5.83

Table 3 shows that Configuration 1 has the highest magnetic flux densities value with 16.7 mT followed by Configuration 3 with 16.5 mT. This indicates that the magnetic flux or magnetic field lines of both configurations are very dense and concentrated at the points where readings are taken. This can be attributed to the magnetic field lines of both configurations that are perpendicular to the pipe.

4.1.3 MPI test to display Magnetic Field Lines of MD unit.

The test is conducted based on procedure B. The MPI test is conducted on all configurations to display the pattern of magnetic field lines of each configuration shown in Figure 5.

Table 4: Pattern of magnetic field lines for Configuration 1.

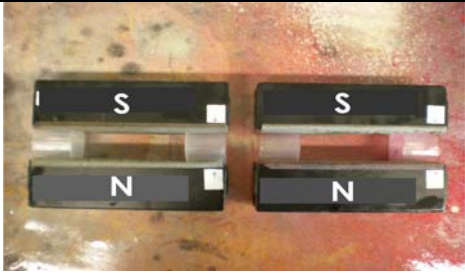
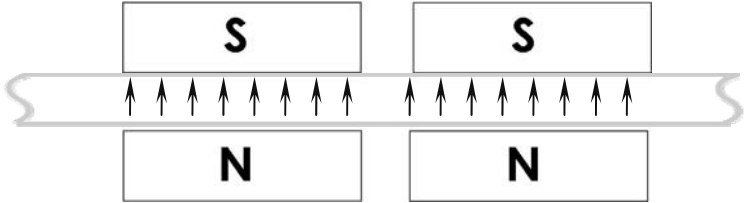
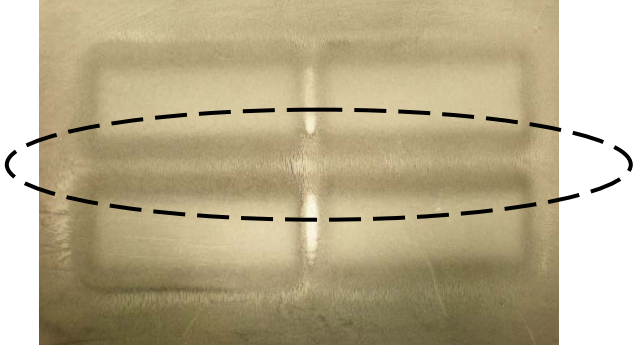
Configuration 1

Theoretical

Actual


Table 4 shows that magnetic field lines of Configuration 1 are perpendicular to the pipe. In this configuration, the actual pattern shows that the magnetic field lines between the MD units are significantly dense and concentrated. This is backed by the high value of magnetic flux densities as measured in section 4.1.1 (Table 3).

When a conducting fluid is flowing through the pipe, it will flow across these dense magnetic field lines. It follows that the velocity vector of the flowing fluid will be perpendicular to these magnetic field lines and thus will create the desired Lorentz force effect.

Table 5: Pattern of magnetic field lines for Configuration 2

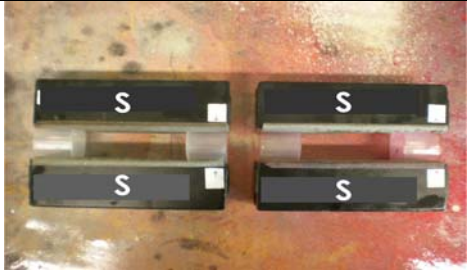
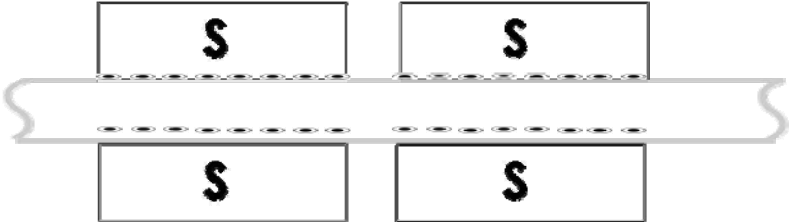
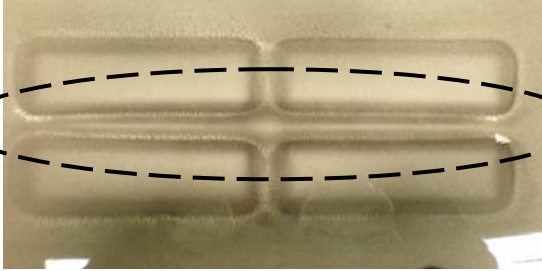
Configuration 2	
	
Theoretical	
	
<p>◉ = Magnetic Field Line going into the page</p>	
Actual	
	<p>Zero Field Area</p>

Table 5 shows that Configuration 2 has magnetic field lines that appear to be going into the page. The opposing field due to the same pole has caused the magnetic field lines to repel of each other instead of attracting. As a result, it leaves the gap between MD units with less or no magnetic field lines. It is convenient to refer this gap with less or no magnetic field lines as zero field area. When a conducting fluid is flowing across this area, there is less or zero Lorentz force effect observed.

Table 6: Pattern of magnetic field lines for Configuration 3

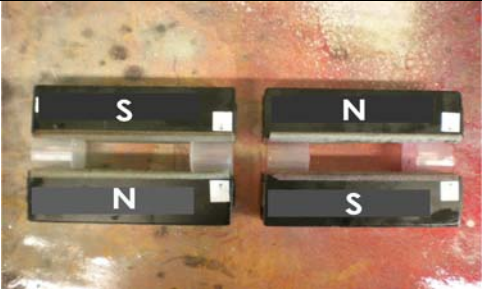
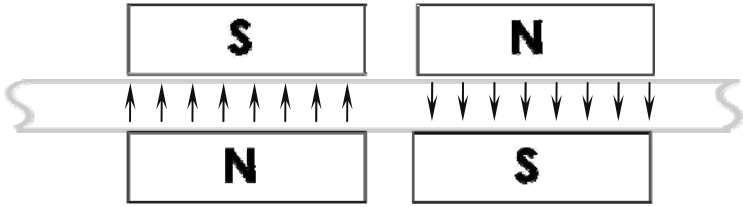
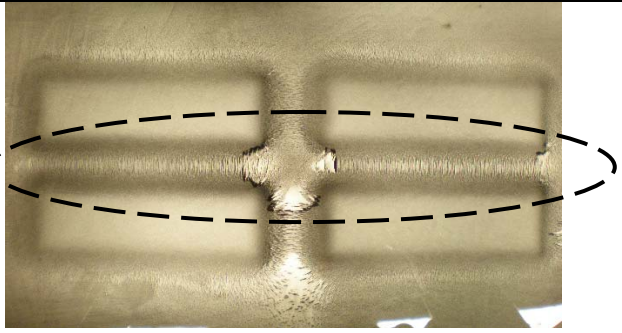
Configuration 3	
	
Theoretical	
	
Actual	
	

Table 6 shows the magnetic field lines pattern of Configuration 3 is more or less the same with Configuration 1. The magnetic field lines are more concentrated and dense at the gap between MD units. These magnetic field lines are perpendicular to the pipe and when a conducting fluid is flowing across the field, the same Lorentz force effect in Configuration 1 is observed.

Table 7: Pattern of magnetic field lines for Configuration 4

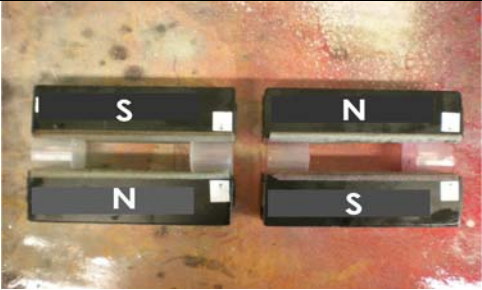
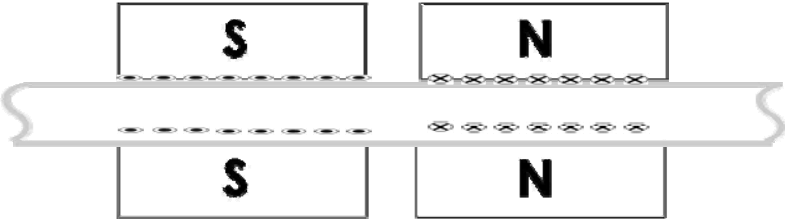
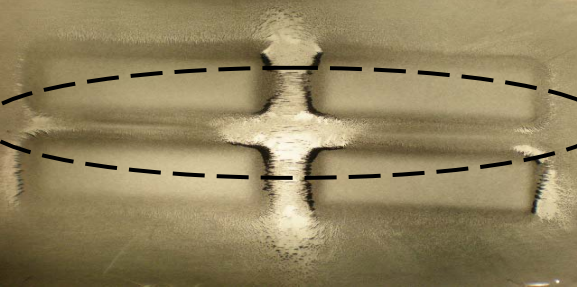
Configuration 4

Theoretical

<p>⊗ = Magnetic Field Line going out of the page</p> <p>⊙ = Magnetic Field Line going into the page</p>
Actual


Table 7 shows that the magnetic field lines pattern of Configuration 4 is similar to that of Configuration 2. From the results, Configurations 1 and 3 have the most magnetic field lines that are perpendicular to the flow of the fluid flow. By Magnetohydrodynamics theory, Configuration 1 and 3 would have the most effective scale removal rate among all configurations. This is backed by the results obtained in section 4.2 (Figure 7 and 9)

4.2 CALCIUM CARBONATE REMOVAL RATE

4.2.1 Influence of 4 Different Configurations of MD units

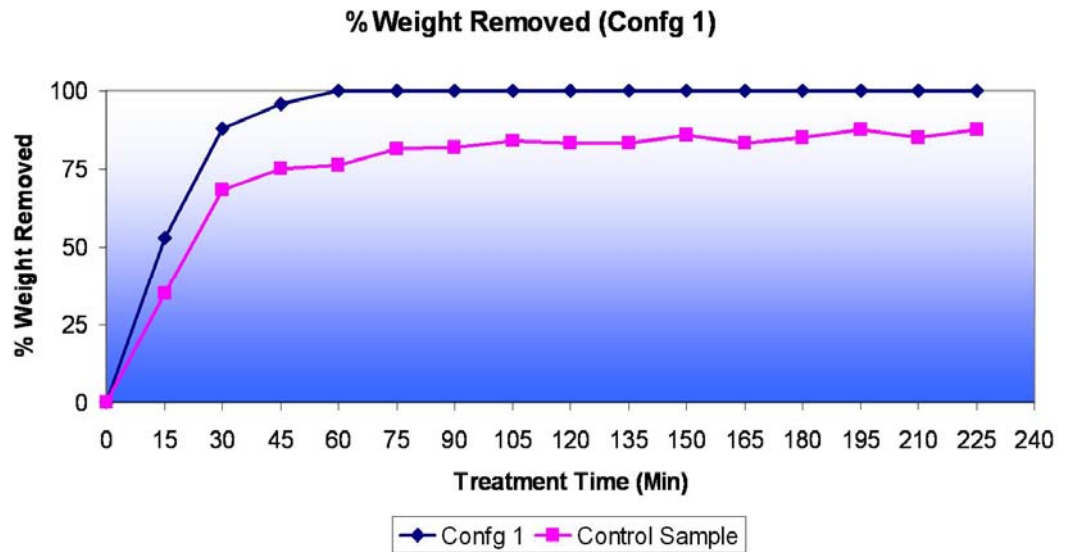


Figure 7: Weight of Scale Removed versus Treatment Time for Configuration 1

This experiment is conducted based on Procedure C. Figure 7 shows the amount of scale removed by MD units using Configuration 1 and the control sample. The amount of scale removed is expressed in terms of weight percentage of original weight of the scale deposits.

Figure 7 shows that the control sample can remove approximately 86% of the scale deposits inside the pipe despite having no MD units installed. This can be explained by the tap water that is being used for the experiment. Tap water can be considered as undersaturated solution and because of this, it leaves more room for the hard scale deposits inside the pipe to easily dissolve back into the water as calcium bicarbonate and be flushed off the system.

However, even after 3 hours of treatment time, the control sample still cannot remove 100% of the scale deposits inside the pipe and the values remain around 86%. This demonstrated that even undersaturated tap water is not able to dissolve 100% of scale inside the pipe.

The experiment is then repeated by installing MD units as Configuration 1. The result shows that by installing MD units as Configuration 1, scale removal have become more effective as opposed to control sample. Figure 7 shows that Configuration 1 can remove 100% of scale deposits inside the pipe after 60 minutes treatment time. This can be attributed to the magnetic field lines of Configuration 1 that are dense and concentrated across the area of interest.

The magnetic field lines that are perpendicular to the velocity vector of the flowing fluid allow Lorentz force effect to take place. This in turn causes the water molecule complexes to break and release the captive crystallization centers. The sudden abundance of crystallization centers in the fluid helps to intensify the effort of dissolving the scale inside the pipe.

When the scale is dissolved into calcium bicarbonate by the undersaturated water, it causes the water to become saturated thus allowing less scale deposits to be dissolved. However, in the presence of crystallization centers, the dissolved calcium bicarbonate will form suspended crystals at these centers. When much of the dissolved calcium bicarbonate forms crystals, the water becomes undersaturated again and therefore allowing more scale to be dissolved. This is why the scale removal of Configuration 1 is much better and faster than the sample control (Figure 7)

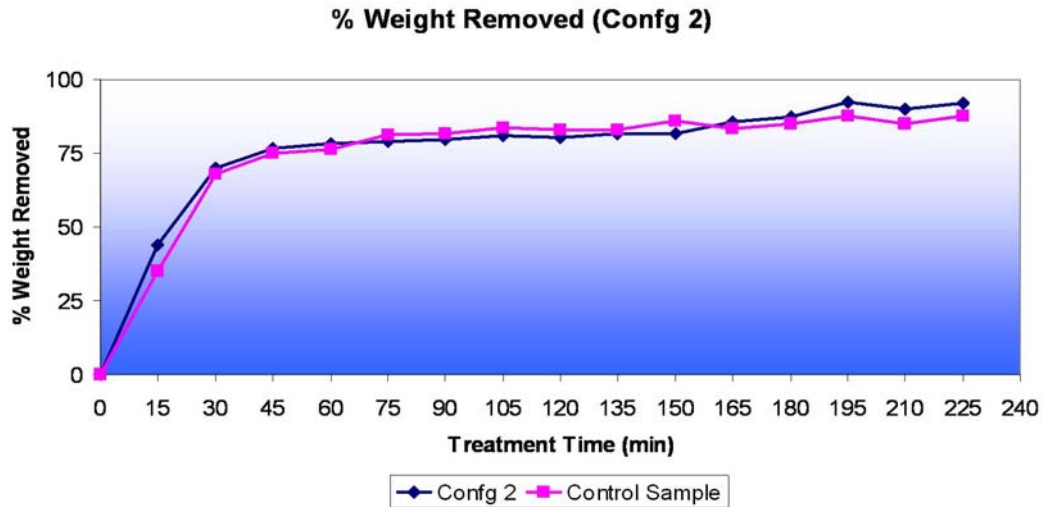


Figure 8: Weight of Scale Removed versus Treatment Time for Configuration 2

Figure 8 shows the amount of scale removed by Configuration 2 versus treatment time. The weight is expressed in terms of weight percentage of the original weight of the scale deposits inside the pipe. The figure shows that even after 3 hours of treatment time, Configuration 2 still cannot remove 100% of the scale deposits inside the pipe. The pattern of the result of Configuration 2 is very similar to that of control sample. This tells that Configuration 2 has less or no effect at all to the scale removal. Despite Configuration 2 seems to have removed approximately 81% of scale deposits inside the pipe after 45 minutes, it is important to note that this can be attributed to the undersaturated water that enables the scale to be dissolved into the water, not because of Configuration 2.

Table 5 shows that Configuration 2 has less or no magnetic fields between the MD units. This area can be regard as Zero Field area. When water flows across this area, the effect of scale removal is more or less the same with control sample which has no MD units installed at all.

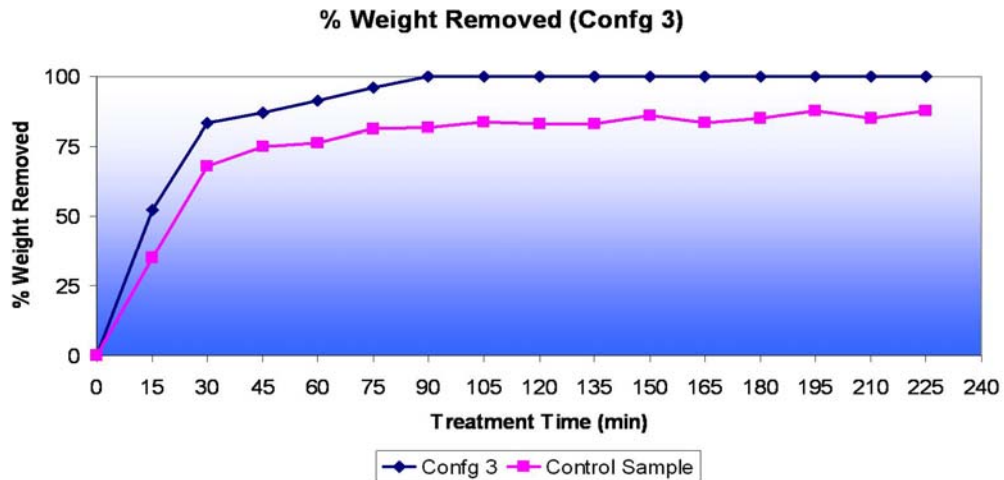


Figure 9: Weight of Scale Removed versus Treatment Time for Configuration 3

Figure 9 shows that Configuration 3 can remove 100% of the scale deposits after 90 minutes of treatment time. Similar to Configuration 1, Configuration 3 is able to remove all the scale deposits inside the pipe except it takes more time as opposed to Configuration 1.

However, Gabrielli C. (2001) explains that, MD units arranged such as Configuration 3 should produce better result than that of Configuration 1. His experiment suggests that MD units that are arranged such as Configuration 3 improve the efficiency of the MD better than Configuration 1 (Refer section 2.7). Therefore the result obtained in this experiment for Configuration 3 appears to be contradicting the results obtained in Gabrielli's work. This contradiction can be explained by the poor preparation of the scale deposition inside the pipe that caused it to become brittle and weak formation. The scale prepared for Configuration 3 might have not been as good and strong as in Configuration 1. This may be caused by the variation in the process of preparing the scale deposits. Thus scale removal was easy for Configuration 3 as opposed to scale removal in Configuration 1. This variation should be minimized and controlled to achieve consistency.

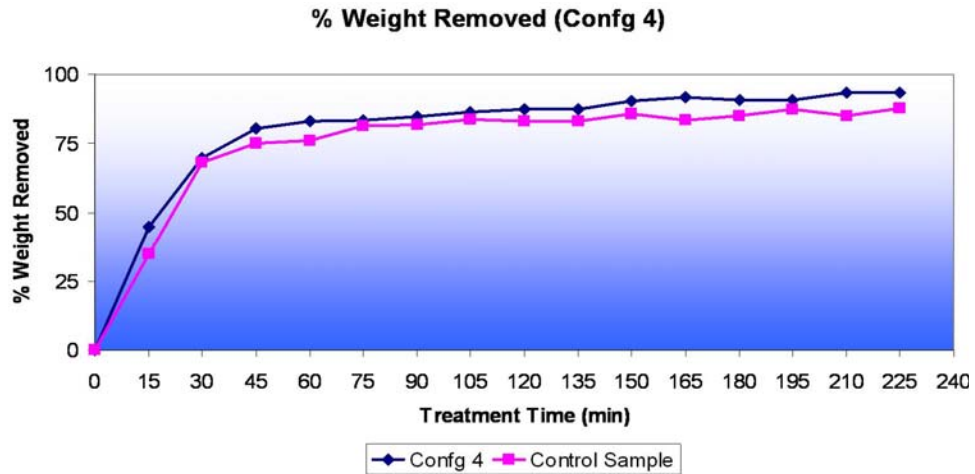


Figure 10: Weight of Scale Removed versus Treatment Time for Configuration 4

Figure 10 shows the amount of scale removed by Configuration 4. Configuration 2 is proven to have no effect on scale removal inside the pipe. Likewise, because of the less or no magnetic field lines between the MD units, Configuration 4 is not able to remove 100% of the scale deposits inside the pipe even after 3 hours of treatment time. The approximate amount of 87% of scale removed using Configuration 4 can be attributed to the understaturated water that is the primary mechanism of the scale dissolution.

It is important to note that for all configurations, the amount of scale removed from $t = 0$ to $t = 15$ is so sudden and abrupt. Figure 7 shows that, for the first 15 minutes, Configuration 1 is able to remove more than 50% of the scale deposits. Likewise, Configuration 2,3,4 and the control sample are able to remove significant amount of scale deposits in the first few minutes of the experiment.

This can be explained by the poor preparation of the scale deposits inside the pipe. During the preparation of the scale deposits inside the pipe, the calcium carbonate scale that is readily deposited is let dry for 1 day at room temperature. Some times, the scale deposits are overly dried that they become brittle. Thus,

during the experiment, when the pump is switched on, the sudden turbulence rush of the water might have removed great amount of these brittle scale before the flow can become stable.

The table below shows MD units with Configuration 1 & 3 with its corresponding calcium carbonate removal rate in g/min/Tesla.

Table 8: Threshold value of the amount of scale removed in g/min/Tesla for Configuration 1 & 3

Configuration (Magnetic Flux Densities in mT)	100% removal time (min)	Removal Rate (g/min/T)
1 (16.7 mT)	60	26.6427
3 (16.5 mT)	90	7.6566

4.2.1 Influence of Different Flow Velocity

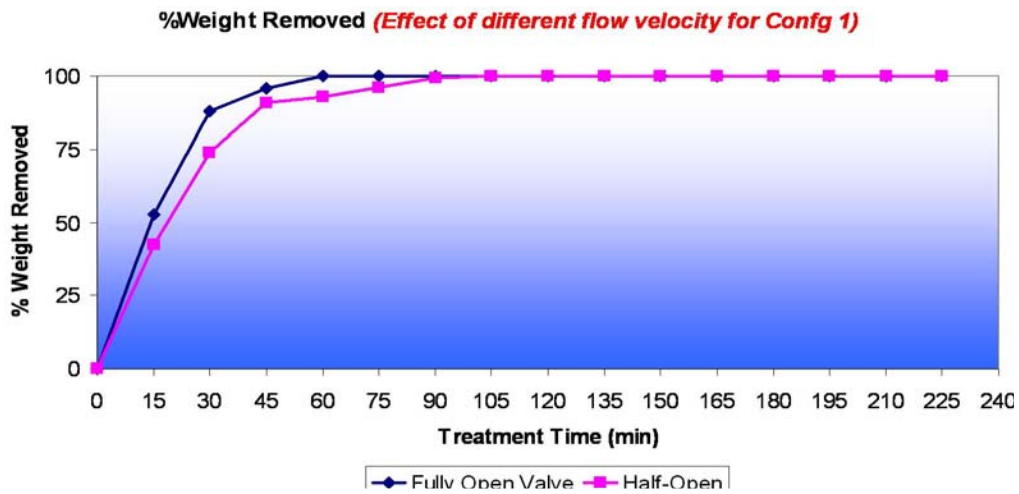


Figure 11: Weight of Scale Removed between Fully Open and Half Open Valve

Figure 11 shows the effect of different flow velocity on scale removal by MD units. The experiment is run based on Procedure C. The figure shows that experiment with fully open valve (103.70 ml/s) can remove 100% of scale deposits in shorter time as opposed to half open valve (approximately 51.9 ml/s).

The reason is easy to understand when the Lorentz force effect is directly proportional to the velocity vector of the flow (Gabrielli C., 2001). The higher the magnitude of the velocity, the higher is the magnitude of the Lorentz force, thus the better the effect. From the results, it is proven that, the higher the velocity, the more effective is MD application.

CHAPTER 5

CONCLUSION & RECOMMENDATION

5.1 Conclusion

This experimental study is conducted to investigate the applications of magnetic descaler (MD) in scale control, which in particular focuses on the removal of scale. The main objective of the study is to investigate the effect of 4 different MD units configuration on scale removal, to come up with the threshold value of the removal rate in g/min/T and to investigate the effect of different flow velocity on scale removal by MD application.

In chapter 1, the background of scale problem is discussed. Scale deposit lead to economical and technical problems by blocking the flow of fluid. Various chemical or physical treatments have been proposed to decrease scaling. Magnetic descaler (MD) effectiveness in scale removal is still in doubt. Many studies proved MD is as ineffective as it is proven effective. It is therefore the interest of this study to investigate and understand how the scale behaves under the influence of magnetic field and determine the efficiency of the MD in scaling control.

Among of all scale deposits, calcium carbonate is the most common and the most widespread scale deposits found in oil and gas industry. It is decided that the experiment will investigate on calcium carbonate scale only.

MD units operate on magnetohydrodynamics principle, the combination of the fluid flow and the magnetic field creates a magnetic disturbance that will remove the scale. The magnetic field lines that are perpendicular to the velocity vector of the flow produce Lorentz force effect which helps to dissolve the scale deposits inside the pipe.

Calcium Carbonate scale removal rate using MD units depends on three factors which are the saturation of the fluid, the temperature of the fluid and the magnetic strength. In this study, the temperature and magnetic strength are kept constant.

The saturation of the fluid, in this case tap water, determines the amount of scale removed under MD application. If the water is saturated, there is less room for hard scale on the pipe to be dissolved into the fluid thus less scale removal. If the water is undersaturated, there is more room for hard scale deposits to be dissolved into the water as calcium bicarbonate.

Thus, it is known that when undersaturated water flows inside the pipe, the hard calcium carbonate scale naturally dissolves into the water as calcium bicarbonate. However, the ability of water to dissolve the scale is limited as demonstrated by the control sample. At one point, the flowing water will not allow any dissolution of hard scale deposits. This is proven in Figure 7 where the control sample can only remove approximately 86% of the scale deposits even after 3 hours treatment time. This value remains so at approximately 86%.

However, when Configuration 1 is applied, it is seen that the scale can be removed completely. Configuration 1 is able to remove 100% of the scale deposit after 60 minutes treatment time. Configuration 1 has the highest magnetic flux densities of 16.7 mT among all 4 configurations (Table 3).

Only Configuration 1 & 3 can remove 100% of the scale deposits inside the pipe. This can be attributed to the magnetic field lines of both configurations that are perpendicular to the velocity vector of the flow (Table 4). Configuration 1 has the highest threshold value of removal rate with 26.6427 g/min/T followed by Configuration 3 with 7.6566 g/min/T.

This study also shows that, MD application is more effective when the velocity of the fluid is increased. The time it takes for MD units to remove 100% of scale deposits when the valve is fully open is shorter as opposed to the time it takes when the valve is half open. It is concluded that from this study the higher the velocity the more effective is MD application in removing scale.

5.2 Recommendation for Future Works

Future works as extension to this study and recommendations to improve the experiment are suggested as follows:

1. Further study to investigate the effect of different magnetic field strength (in Tesla unit) on scale removal of Configuration 1 & 3 by manipulating the distance between MD units and the pipe.
2. Weight measurements to be taken at a smaller time interval instead of 15 minutes.
3. Improved technique to be used in preparing Calcium Carbonate scale deposit inside the GI pipe such that it will closely imitate the real process of Calcium Carbonate Scale Deposition.
4. Further investigation on scale prevention using the same MD application.

REFERENCES

Amethyst Galleries. 21 March 2008 <<http://www.galleries.com/minerals/carbonat/aragonit/aragonite.htm>>

Fred F. Farshad & Silivia M. Vargas, “*Scale Prevention, a magnetic Treatment Approach*”, SPE 77850, 2002.

Fred F. Farshad, J. Linsley, O.Kuznetsov, S. Vargas, “*The Effect of Magnetic Treatment on Calcium Sulfate Formation*”, SPE 76767, 2002.

G. Von Oppen and Melchert F.(2005) “*Physics for Engineers and Scientists.*” Infinity Science Press, Hingham, Massachusetts.

Gabrielli C. (2001). “*Magnetic Water Treatment for Scale Prevention.*” *Wat. Res.* Vol **35**, (13), 3249-3259

Ghulam M. Mustafa, Osman Ahmed Hamed, (2001). “*Studies on Effectiveness of Magnetic Fluid Conditioner in Control of Scale Formation in MSF Plant*” Saline Water Conversion Corporation, Technical Report.

Hoadley, 18 April 2008 <<http://www.coolmagnetman.com/magfield.htm>>

J.M. Paul and E.R. Fieler, “*A New Solvent for Oilfield Scales*”, SPE 24847, 1992

J. D. Donaldson & S.M. Grimes, “*Control of Scale in Sea Water Applications by Magnetic Treatment of Fluids*”, SPE 16540/1, 1987.

Jack C. Cowan and Donald J. Weintritt. (1976) "*Water-Formed Scale Deposits*" Gulf Publishing Company, Houston, Texas.

Kronenberg K. J. (1985) "*Experimental evidence for effects of magnetic fields on moving water*" IEEE Trans. Mag. **21**, 2059.

Kronenberg, Klaus J. (August 1993) "*Magnetized: What makes treating water with magnets so alluring*" Aqua Magazine, pp. 20-24

Kronenberg, Klaus J. (September 1993) "*Magnetized II: More alluring facts about treating water with magnets*" Aqua Magazine, pp 20-23

Magnatek, 2 May 2008 <<http://www.magna-tek.com/how%20does%20it%20work.htm>>

Meyers, K.O., Skillman, H.L., "*The Chemistry and Design of Scale Inhibitor Squeeze Treatments*", SPE 13550-MS, 1985

Mike R. Powell, 8 May 2008 <<http://www.csicop.org/si/9801/powell.html>>

O.J. Vetter, "*Calcium Carbonate Scale in Oilfield Operations*", SPE 16908, 1987.

Roemex, 10 May 2008 <<http://www.roemex.com/production/scale.htm>>

Young and Freedman (2004) *University Physics with Modern Physics* 11th Edition Addison Wesley, San Francisco.

APPENDIX

Appendix A: Results and Tables

Table 9: Amount of scale removed in gram by Configuration 1,2,3,4 and Control Sample

	Configuration 1	
	(gram)	% removed
Coated Scale, gram	26.696	0
Scale removed at t-15 (min)	14.073	52.71576266
Scale removed at t-30	23.498	88.02067726
Scale removed at t-45	25.556	95.72969733
Scale removed at t-60	26.696	100
Scale removed at t-75	26.696	100
Scale removed at t-90	26.696	100
Scale removed at t-105	26.696	100
Scale removed at t-120	26.696	100
Scale removed at t-135	26.696	100
Scale removed at t-150	26.696	100
Scale removed at t-165	26.696	100
Scale removed at t-180	26.696	100
Scale removed at t-195	26.696	100
Scale removed at t-210	26.696	100
Scale Removed at t-225	26.696	100

	Configuration 2	
	(gram)	% removed
Coated Scale, gram	17.861	0
Scale removed at t-15 (min)	7.841	43.90011757
Scale removed at t-30	12.499	69.97928447
Scale removed at t-45	13.674	76.5578635
Scale removed at t-60	13.994	78.34947651
Scale removed at t-75	14.108	78.98773865
Scale removed at t-90	14.211	79.56441409
Scale removed at t-105	14.461	80.96411175
Scale removed at t-120	14.372	80.46581938
Scale removed at t-135	14.601	81.74234365
Scale removed at t-150	14.561	81.52399082
Scale removed at t-165	15.304	85.68389228
Scale removed at t-180	15.569	87.1675718
Scale removed at t-195	16.466	92.18968703
Scale removed at t-210	16.108	90.14052965
Scale Removed at t-225	16.406	91.85375959

	Configuration 3	
	(gram)	% removed
Coated Scale, <i>gram</i>	11.370	0
Scale removed at t-15 (min)	5.969	52.49780123
Scale removed at t-30	9.466	83.25417766
Scale removed at t-45	9.892	87.00087951
Scale removed at t-60	10.369	91.19613017
Scale removed at t-75	10.916	96.00703606
Scale removed at t-90	11.370	100
Scale removed at t-105	11.370	100
Scale removed at t-120	11.370	100
Scale removed at t-135	11.370	100
Scale removed at t-150	11.370	100
Scale removed at t-165	11.370	100
Scale removed at t-180	11.370	100
Scale removed at t-195	11.370	100
Scale removed at t-210	11.370	100
Scale Removed at t-225	11.370	100

	Configuration 4	
	(gram)	% removed
Coated Scale, <i>gram</i>	11.198	0
Scale removed at t-15 (min)	5.009	44.731202
Scale removed at t-30	7.831	69.93213074
Scale removed at t-45	8.995	80.32684408
Scale removed at t-60	9.306	83.10412574
Scale removed at t-75	9.352	83.51491338
Scale removed at t-90	9.477	84.63118414
Scale removed at t-105	9.664	86.3011252
Scale removed at t-120	9.767	87.22093231
Scale removed at t-135	9.795	87.47097696
Scale removed at t-150	10.131	90.47151277
Scale removed at t-165	10.255	91.57885337
Scale removed at t-180	10.152	90.65904626
Scale removed at t-195	10.16	90.73048759
Scale removed at t-210	10.466	93.46311841
Scale Removed at t-225	10.463	93.43632792

	Control Sample	
	(gram)	% removed
Coated Scale, gram	11.802	0
Scale removed at t-15 (min)	4.126	34.96610169
Scale removed at t-30	8.037	68.11016949
Scale removed at t-45	8.869	75.16101695
Scale removed at t-60	8.997	76.24576271
Scale removed at t-75	9.597	81.33050847
Scale removed at t-90	9.64	81.69491525
Scale removed at t-105	9.889	83.80508475
Scale removed at t-120	9.801	83.05932203
Scale removed at t-135	9.807	83.11016949
Scale removed at t-150	10.129	85.83898305
Scale removed at t-165	9.823	83.24576271
Scale removed at t-180	10.037	85.05932203
Scale removed at t-195	10.325	87.50000000
Scale removed at t-210	10.027	84.97457627
Scale Removed at t-225	10.341	87.63559322

Table 10: Amount of scale removed in gram by Configuration 1 with ball valve is half-closed

	Configuration 1 – Half-Closed valve (appx 51.9 ml/s)	
	(gram)	% removed
Coated Scale, gram	23.462	0
Scale removed at t-15 (min)	9.924	42.2981843
Scale removed at t-30	17.326	73.84707186
Scale removed at t-45	21.31	90.82772142
Scale removed at t-60	21.752	92.71161879
Scale removed at t-75	22.543	96.08302787
Scale removed at t-90	23.312	99.36066831
Scale removed at t-105	23.462	100
Scale removed at t-120	23.462	100
Scale removed at t-135	23.462	100
Scale removed at t-150	23.462	100
Scale removed at t-165	23.462	100
Scale removed at t-180	23.462	100
Scale removed at t-195	23.462	100
Scale removed at t-210	23.462	100
Scale Removed at t-225	23.462	100

Appendix B: Lorentz Force Theory

Lorentz Force

Lorentz force is the force on a point charge due to electromagnetic fields. It is given by the following equation in terms of the electric and magnetic fields.

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}), \quad (\text{E.1})$$

Where,

\mathbf{F} is the force (in newtons)

\mathbf{E} is the electric field (in volts per meter)

\mathbf{B} is the magnetic field (in teslas)

q is the electric charge of the particle (in coulombs)

\mathbf{v} is the instantaneous velocity of the particle (in meters per second)

\times is the vector cross product

∇ and $\nabla \times$ are gradient and curl, respectively. The term $q\mathbf{E}$ is called the **electric force**, while the term $q\mathbf{v} \times \mathbf{B}$ is called the **magnetic force**.

or equivalently the following equation in terms of the vector potential and scalar potential:

$$\mathbf{F} = q\left(-\nabla\phi - \frac{\partial\mathbf{A}}{\partial t} + \mathbf{v} \times (\nabla \times \mathbf{A})\right), \quad (\text{E.2})$$

where:

\mathbf{A} and ϕ are the magnetic vector potential and electrostatic potential, respectively, which are related to \mathbf{E} and \mathbf{B} by

$$\mathbf{E} = -\nabla\phi - \frac{\partial\mathbf{A}}{\partial t}$$

(E.3)

$$\mathbf{B} = \nabla \times \mathbf{A}. \quad (\text{E.4})$$

Note that these are vector equations: All the quantities written in boldface are vectors (in particular, **F**, **E**, **v**, **B**, **A**).