Use of Magnetic Field in Paraffin Wax Deposition Control for Surface Facilities

by

Chai Set Lee

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

DECEMBER 2008

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Use Of Magnetic Field In Paraffin Wax Deposition Control For Surface Facilities

by

Chai Set Lee

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

(Putri Nurizatulshira bt. Buang)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

December 2008

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

CHAI SET LEE

ABSTRACT

Paraffin deposition is one of the major catastrophes that plague the oil industry around the world, causing problems such as clogging, equipment malfunction, etc. Millions of dollars are spent annually to carry out remedial activities. Magnetic field technology which has long history in treating hard water, is one of the new techniques to control paraffin deposition. Magnetic field is utilized through the application of Magnetic Fluid Controller (MFC), where magneto hydrodynamics and Lorentz force governs the magnetic effect on deposits. One of the direct effects of magnetic field on crude is temporary reduction in viscosity. Inadequacy of research and evidence has discouraged local oil companies to integrate this technology into their systems even though there are several success records. This research intends to produce a set of information on the behavior of paraffin wax under the influence of magnetic field and to investigate the effect of magnetic field in wax deposition control and temporary viscosity reduction. The scope of work includes review on the behavior of paraffin wax under magnetic field, understanding on the basic concept of magnetic fields and other related theories, and design as well as execution of experiments to investigate the magnetic field effects. An experimental setup consists of a closed flow loop, MFC and a pump, is used to study the effect of three variables; magnets orientation, magnetic field density and flow rate on the removal rate. Experiments were carried out under four conditions as a result of different combination of these variables where difference in initial and final values of deposited wax mass and viscosity are the parameters that define the effectiveness. These parameters were plotted over time and pattern analyzed. Condition 1 with magnets configuration 1 and flow rate of 373.32 L/hr generates 15.00 mT of flux density, provides the highest removal rate of 12.53 mg/L/Tesla. Fluid viscosity reduction of 1.56 cP was observed after 30 minutes exposure, and the value returns to initial viscosity after 114 minutes. Based on results, magnetic field technology is an effective technique to solve paraffin deposition and viscosity problems. However, several adjustments are needed to cater for actual industry application where crude is the flowing liquid, with bigger and longer pipeline, as well as different pumping capacity.

ACKNOWLEDGEMENT

First of all, I thank God for allowing me to complete this project successfully within time. He has opened doors for me and provided me with strength and determination when challenges come in the way. I am thankful for He has given me hope and kept my faith high in Him as well as the opportunity to learn new things and to get to know amazing individuals who has helped me along the course of this project completion.

My deepest appreciation to my supervisor, Mdm Putri Nurizatulshira, for her wonderful guidance and advises which has helped and encouraged me a lot ever since the beginning of the project. She has always been very attentive towards the quality of my work and always makes herself available for consultation to help me even in the time of busyness. She also has taught me on non-technical subjects such as time management and work ethics. I am grateful to have such an amazing supervisor, who is inspirational and heartwarming.

My earnest gratitude also goes to my co-supervisor, AP Dr Razali Hamzah for his supervision and inspiring critiques which has helped me to improve the quality of my work. He has given me amazing ideas and recommendations to conduct the research with absolute objectives in mind. I also thanked him for his inputs and advise during seminars and presentations that has aspired me to carry out the experiments with more attention and responsibility.

Last but not least, I thank all who has involved directly or indirectly in contribution to this project completion. Among all, the technicians from Block 17, 18 and 21, who has assisted me to build the prototype and provided me with spaces in the lab to conduct the experiments as well as usage of lab equipments. I also thank my friends and families who have always been there for me when I need them. Without all of you, I would never have the courage and strength to move on and complete this project successfully.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background

Paraffin deposition in wells and surface facilities, is one of the many problems in crude oil production around the world. Over the time, the deposition can choke the production lines thereby reducing the oil production to uneconomical levels, and normally, shutdowns are necessary to apply various remedial solutions. In addition, the cost of its removal greatly adds to the overall cost of production, sometimes lowering net profit margin of a company.

Conventional deposit removal methods include mechanically scraping the equipment surfaces, contacting with organic solvents and the application of hot oils or external heat. The degree of success varies for each method, but all of them need frequent execution, aside from expensive cost and professional operators. Furthermore, with the oil and gas industry now moving towards deep sea exploration, there will be difficulties to implement these conventional methods in deep marine environment.

Transportation of offshore oil via deepwater pipelines poses another threat in terms of reduction in viscosity. Temperature in the deepwater pipe is stable but low, making the crude very viscous. Since viscosity is the degree of resistance to flow, having low viscous crude will enhance transportation. At present, the oil is heated undersea via electrically heating element. Implementation will be difficult in deeper location.

Most company is searching for cheaper yet effective technique to solve the problems. Magnetic field technology which is applied in the Magnetic Flow Conditioner (MFC) is claimed to be effective at inhibiting and removing deposits with direct viscosity reduction effect. In addition, cost to employ this technology is more economical when compared to other method. This study is developed based on that claim to investigate the technology and working principle as well as its effectiveness.

1.2 Problem Statement

MFC was included into PETRONAS's long term scale management plan for the Tinggi oilfield at offshore Terengganu which face severe scaling deposition with 26% reduction per year in production from 1995 to 1997. Kabir and Haron (2000) stated that due to insufficient evidences of MFC's success application in the upstream oil industry, PETRONAS decided to initiate pilot study on some of the commercially available MFC tools to verify those verbally claimed success before implementation. At that time, only one commercial magnetic tool has been tried with no benefits observed. However, in 2001, the collaboration with Magnetic Technology Australia (MTA) which ended up with installation of specially designed Scale-X™ MFC has been a total success. PETRONAS engineers realized that MFC can only be effective if it was designed according to plant design and fluid process conditions. After 8 months of close observation, the MFC has completely stopped scale build up in standpipes and control valves.

There are claims that magnetic field is effective at controlling paraffin deposition and at the same time temporarily reducing the crude viscosity. However, the claim was not solidly proven since even the magnetic tool manufacturers do not have concrete evidences or research results to explain the working principle. Despite the fact that magnetic field technology is not recent, little understanding on the subject has been developed since its introduction. As a result, only a small number of companies agreed to integrate the MFC to their production system for trial. Concurrently, the application of it in the local oil and gas industry is very limited especially in controlling paraffin deposition, even though there are several success stories overseas.

1.3 Significance of study

Numerous hypotheses on how MFC controls paraffin deposition has arises without appropriate research. This study will go to the basic of magnetic fields and investigate the application of it in MFC. Experiment which emulates the actual situation will be designed with several modifications and assumptions. Experimental evidences obtained and conclusions drawn from this study are very important to establish a new technique in wax deposition control. Through this study, industry application of magnetic field especially for surface facilities improvement can be widened and viscosity problem in crude transportation can be solved, both which leads to optimum production and transportation.

1.4 Objectives

Objectives are goals to be achieved through this study. Having established objectives will keep the project moving in the right direction. Several objectives have been identified:

- To produce a set of information on paraffin wax behavior under magnetic field
- To study the effect of magnetic field in paraffin wax deposition control
- To investigate the effect of magnets orientation, magnetic field density and flow rate on paraffin removal rate
- To investigate the direct effect of magnetic field on crude viscosity

1.5 Scope of Study

The chemical and physical properties of paraffin will be studied. Subjects on paraffin wax deposition process, and effect of magnetic field in deposition control and crude viscosity, will also be included. To appreciate the working principle of Magnetic Fluid Conditioner (MFC), it is best to understand the basic concept of magnetic field. This study extends investigation into exploring the idea of magnet bar orientation, magnetic field lines and densities, as well as magneto-hydrodynamics. Experiments shall be developed to resemble crude flows in the pipelines mounting a magnetic fluid conditioner to generate magnetic field and a pump to mobilize the fluid. This is so that the results obtained later will be applicable to the industry with addition of correction factors. Results gathered will be analyzed and relevant recommendations will be generated for further improvement.

CHAPTER 2

LITERATURE REVIEW

2.1 Paraffin Characterization

Hydrocarbons are divided into two main classes, aliphatic and aromatic. Alkanes family with the general formula of C_nH_{2n+2}, is the extension of the aliphatic class, along with alkenes, alkynes, and cycloalkanes. Alkanes are also called paraffin hydrocarbon, or more commonly known only as paraffins. Paraffin molecules are saturated hydrocarbons containing carbon and hydrogen atoms in straight (normal) or branched chains (isomer), where all of the carbon-hydrogen and carbon-carbon bonds are single bonds. Paraffin can appear as solids, liquids or gases depending on temperature and pressure. The first four alkanes are gases at standard condition. With increasing number of carbon atoms, the volatility, which is the tendency of substance to vaporize, will decrease. As a result, the next 13 alkanes, pentane through heptadecane, are liquid, while those containing 18 or more carbon atoms are solid at same condition.

2.1.1 Chemical Properties of Paraffin Wax

Waxy crude usually made up of a variety of light and intermediate hydrocarbons, wax and other non-hydrocarbon compounds. The wax present in petroleum crudes primarily consist of paraffin hydrocarbons (C18 - C36) known as paraffin wax and naphthenic hydrocarbons (C30 - C60). Depending on their temperature and pressure, these components can exist in various states. According to the European Wax Federation (EWF), paraffin waxes have a carbon number distribution of n-alkanes from 18 to 45 and a total 0 - 40% content of iso- and cycloalkanes. Intermediate waxes are n-alkanes with carbon number of 22 to 60 and a total content of iso- and cycloalkanes of 30 – 60 %. Hydrocarbon components of wax can exist in various states of matter depending on their temperature and pressure. These are straight chained and branch chained compounds, and are generally inert and resistant to attack by acids, bases, and oxidizing agents. The strong single bonds between carbon and hydrogen and between carbon and carbon are attacked only by very strong reactants at ordinary temperature.

2.1.2 Physical Properties of Paraffin Wax

Paraffin wax appears physically as white, odorless, and tasteless waxy solid. It is insoluble in water, but soluble in ether, benzene, and certain esters especially at elevated temperature. The solubility decreases with increasing molar mass which means higher melting point of the waxes where typical melting point is between about 47 °C to 64 °C.

According to the US National Physical Laboratory, the density of paraffin wax is around 0.9 g/cm3. The same organization also listed pure paraffin wax as an excellent electrical insulator, with an electrical resistivity of between 1013 and 1017 ohm meter which is higher than nearly all other materials. The resistivity usually decreases rapidly as the temperature is increased and may be reduced temporarily or permanently by irradiation.

Specific heat capacity is the measure of heat energy required to increase the temperature of a unit quantity of a substance by a certain degrees. Heat of fusion is the amount of thermal energy required to change 1 mole of substance from a solid to a liquid or vice versa. Paraffin wax ($C_{25}H_{52}$) has excellent ability to store heat, with a specific heat capacity of 2.14–2.9 J/g.K, and heat of fusion of 200 – 220 J/g.

2.2 Paraffin Precipitation

At reservoir temperature and pressure, the different molecules that made up crude oil are in thermodynamic equilibrium. Thermodynamic equilibrium is a condition where change in a system's thermal and chemical activities are constant over time, and the sum of all forces and torques acting on the body is zero. Production activities which requires migration of reservoir fluid to the surface, alters this equilibrium. Paraffin molecules are typically fully dissolved in the reservoir fluid. Solid phase appears when solubility reduces as temperature drops in the wellbore and production lines. The formation of solid crystals from a homogeneous (uniform) solution is known as crystallization. Crystallization of solid paraffin is actually an example of liquid-solid phase equilibrium, the solution of heavier hydrocarbon in which lighter hydrocarbons is a solvent. Generally, heavier solids will precipitate whenever the carrying capacity of the fluid solvent decreases.

Cloud point temperature is defined as the temperature at which dissolved solids in oil begin to form and separate from the oil. It is the main factor that controls the saturation of paraffin wax in oil. Since the ground temperature is less than the reservoir temperature, the oil cools as it moves upward. As oil flows up, the solution gas is liberated because of the drop in pressure. The loss of gas and lowering of temperature at shallower depths causes the oil to precipitate waxes. They also cause oil viscosity to increase, further choking off flowlines. When closer to the surface, the lower temperature below cloud point, or Wax Appearance Temperature (WAT), paraffinic hydrocarbon liquids form paraffin or wax solid phase. According to S.Todi and M.Deo (2006), the combined effect of flow rate, heat flux and deposition surface topology were seen to play a role in the structure and strength of the final deposit.

2.3 Mechanism of Lateral Transport of Waxy Residue

Kadir et al. (2000) suggested the wax solids formed will migrate to the pipe wall by three lateral means: molecular diffusion, Brownian diffusion, and shear dispersion with addition of gravity settling. However, when one or more of these transport mechanisms are very weak or absent, the wax will remain in the flow streamline and no deposition will occur on the pipe wall.

2.3.1 Molecular Diffusion

Diffusion is the movement of particles from an area of high concentration to an area of low concentration in a given volume of fluid. When oil is being cooled, there will be a temperature gradient across the laminar sub layer of oil closest to the pipe wall. If temperatures are below the cloud point temperature, precipitated solid particles will appear in the flowing oil where the liquid phase will be in equilibrium with the solid phase. The temperature profile near the wall, therefore, will lead to a concentration gradient of dissolved wax where the concentration of wax is highest at the pipe wall which is transported toward the wall by molecular diffusion.

2.3.2 Brownian Diffusion

Collision between the thermally agitated oil molecules with the solid waxy crystals will lead to small random Brownian movements of the suspended particles. Brownian motion is the random movement of particles suspended in a liquid or gas. If there is a concentration gradient of these particles, Brownian motion will lead to a net transport, which in nature and mathematical description is similar to diffusion.

2.3.3 Shear Dispersion

Shear dispersion describes the relationship between deposition rate and shear rate. Deposition rates decreases with higher shear rates. Shear rate is the measure of shear deformation. In a shear flow when small particles are suspended in laminar motion fluid, they will transverse to the direction of flow and reduce their speed and angular velocities due to induced velocity fields. Shear flow is the fluid motion having a velocity field characterized by the presence of local variation of a velocity vector in a given direction.

Adjacent fluid to the particle will have circulatory motion and exerts drag force on neighboring particles. In a shear field, each particle passes and interacts with nearby particles in slower or faster moving streamlines. If the particle concentration is high, then a significant number of multi-particle interactions will occur and result in net lateral transport and particles dispersion.

2.3.4 Gravity Settling

Precipitated waxy crystals are denser than the surrounding liquid oil phase. If there is no interaction between the particles, they would settle in a gravity field and could be deposited at the bottom of pipes or tanks. However, mathematical studies by Burger et al. (1981) suggested that shear dispersion might re-disperse the settled solids in pipeline flow; therefore, any effect of gravity settling on wax deposition essentially would be eliminated.

2.4 Deposition Problems

In the evaluation of the performance of wax inhibitors on paraffin deposition of Nigerian crude oils, Bello et al. (2006) found that millions of dollars were spent every year by the Nigerian operators to control the deposition and other related problems. In addition to that, money is lost every time the plant shutdown or temporary production discontinuation for remedial activities. Economically, this amount of annual expenditure could affect the financial state of an organization. Paraffin deposition can take place in the production tubing (well), surface equipment and the surface flow line where it poses different threats at each of these locations.

In the production of oil from subterranean formations, deposited paraffin from the oil tends to clog the pores of the reservoir rock, well casing, and tubing through which the oil flows to the surface. The deposits also cause subsurface and surface equipment plugging and malfunction. If sufficient wax is deposited over time, the production system can become partially or totally blocked, thus having a significant fall in the oil production efficiency. Wax deposition in well tubing and process equipment may lead to more frequent shutdowns and operational problems.

Deposition in pipeline will lead to higher viscosity with increased energy consumption for pumping. The wax crystals reduce the effective cross sectional area of the pipe and increase the pipeline roughness, which results in an increase in pressure drop. Wax deposition in pipe leads to more frequent and risky pigging requirements in pipelines. If the wax deposits get too thick, they often reduce the capacity of the pipeline and cause the pigs to get stuck.

Surface equipment including the pumps will cause equipment malfunction. Clogged pipeline requires higher pressure to move the liquid, exceeding pump capacity, components of pump broken leading to repair cost and downtime cost. Surface valve and surface storage equipment such as tanks, will also be affected, where paraffin wax removal work is needed.

2.5 Conventional Paraffin Wax Control Methods

There are a number of methods which has been used in the industry as deposition remedial solution which can be further categorized as either removal or inhibition techniques. The difference between these two is that removal techniques have to be repeated as soon as the organic deposits reform while inhibition offers a longer-lasting protection. Both techniques can involve mechanical method, chemical method, thermal method or combination between. With certain exceptions, most of these approaches have the disadvantage of requiring an interruption in production and thereby result in a loss of revenue.

2.5.1 Mechanical Means

The success of mechanical pigging is highly dependent upon the properties of the debris in the pipeline, the pig design, and the transport capacity of the fluid in the line. Problematic high specific-gravity materials or deposits with high adhesive properties, or complex mixtures of emulsified solids and water cannot be solved by this technique. Following are several mechanical methods which are commonly used in the industry as according to Bosch, Schmitt and Eastlund (1992).

- *Mechanical scrapers and cutters* are used in cases where paraffin buildup is extreme. For surface pipeline, pump scrappers are used to remove the accumulated paraffin periodically. In tubing strings, scrapers are installed on the sucker rod where the up and down motion of sucker rod keeps the scrapers moving keeping the tubing free of paraffin accumulation. However, this method results in tubing and pipe wear, and it is normally used only when other methods are not effective. The main problem with mechanical scrapers is that they are not only expensive, but to use them, the well has to be shut down during treatments.

- *Mechanical pigging.* Pigs can be fitted with brushes or scraper elements to agitate the deposits adhering to pipeline walls. The pig is repeatedly passed through the pipeline to swab deposits from it until virtually no deposit is to be found in the pig receiving station. However, it is hard to determine whether at the end of this procedure the pipeline is actually clean. In addition, it is possible to get the pig stuck in the pipe with thick deposit.
- *Intelligent pigging*, such as magnetic flux leakage (MFL) and the new optical inspection (Opto-Pig), yield superior readings. Some allow for three-dimensional, almost visual inspection of the whole interior of the pipeline. Consequently the results are easier to interpret and reruns are unnecessary provided the pipeline is clean.

2.5.2 Thermal Means

- *Hot oiling and hot watering*, one of the most common methods used, involves injecting heated oil or water into the tubing string until the paraffin is dissolved. According to Mansure and Barker (1994), the dissolved paraffin and accompanying solids may plug the formation around the well bore and cause a decrease in the productivity of the well. Hot oiling also may vaporize oil in the tubing faster than the pump lifts oil.

2.5.3 Chemical Means

Chemical cleaning technology is proven and can be used to remove hydrocarbons, grease, corrosion products, and scales from pipeline systems. In subsea pipeline systems, particularly for those in deepwater where the ambient temperature is low, the effectiveness of most chemical treatments is often compromised.

Deposited paraffin can also contain gums, resins, asphaltic material, crude oil, sand, silt, corrosion products, scale, and in many instances, water. Due to the wide range of paraffin wax carbon chain lengths and the almost infinite number of impurities, the effectiveness of any chemical treatment can vary significantly from one wax to another.

- *Injection of chemical inhibitors* is an approach where chemicals are injected into a production stream before paraffin deposition begins to prevent any precipitation. With time, the chemical will also dissolve already deposited paraffin crystals.
- *Injection of chemical solvents where* various types of solvents which have been used to dissolve the paraffins include benzene, xylene, toluene, gasoline and heavier distillates, carbon tetrachloride and carbon disulfide. Nevertheless, the cost of such chemicals may make this option unattractive.

2.5.4 Combination Means

- *Advanced chemical cleaning* are chemical cleaning in conjunction with the use of mechanical pigs removes a greater volume of debris with fewer runs. Chemical cleaning, by definition, means the use of liquid cleaners mixed in diluents to form a cleaning solution that can be pushed through a pipeline by pigs.

2.6 New Technology for Paraffin Control

Researchers have come up with several new techniques to control the paraffin wax deposition either in the reservoir well or surface system. These new technologies are much more effective, cheaper and require less execution besides less hazardous to both operators and environment.

2.6.1 Microbial Technology

The microbial treatment is based on the activity naturally occurring bacteria which have the ability to produce biosurfactant in the form of biological molecules. Microbial treatment control paraffin deposition by reducing the length of paraffin molecule or cracking of long chain paraffin. Biosurfactant enables fluid to dissolve paraffins and remove paraffin-based skin damage from the well bore (Ayoub et al, 2003 and Banat et al, 1999).

The microorganisms are generally live, naturally occurring, specifically isolated bacteria and must have the following characteristics (Lazar et al, 1999).

- Facultative anaerobic, working in the presence or absence of oxygen
- Non-pathogenic, not causing disease
- Contain no sulphate-reducing bacteria or mucous-forming bacteria
- Not genetically altered
- Water based and environmentally safe.

Microbial treatment has several advantageous; eliminate any deposition problems along the production flow line and reduce the viscosity of crude oil along with increase in API and decrease in pour and cloud points of crude oil at the same time.

2.6.2 Electromagnetic Field Technology

In electromagnetic treatment, a device generates a magnetic field such that an electric field is induced in association with the magnetic field. Electric fields are created by differences in voltage where higher voltage, stronger resultant field. Magnetic fields are created when electric current flows, where greater the current, the stronger the magnetic field. One of the many theories on the technology is that the electromagnetic field will polarize the molecules within dielectric medium. Paraffin and asphaltene molecules have the ability to polarize, therefore are sensitive to the electromagnetic field. The molecules will align themselves along the field and reduces the effect of physiosorption, which is the process of attachment of nonionic substances to solid.

However, the effect of polarization is not permanent, thus, another hypothesis of aggregate/disaggregate was developed. Based on this hypothesis, when suspended paraffin/asphaltene is exposed to a combined effect of electromagnetic fields with certain intensity and vibration, the aggregate size is reduced. Principally, the field affects the nucleation phenomena by disturbing the crystal centers formation, preventing crystallization process.

2.6.3 Ultrasonic Technology

Researchers at the University of Wyoming's Chemical and Petroleum Engineering Department have developed and filed an international patent application on a System and Method for the Mitigation of Paraffin Wax Deposition from Crude Oil Using Ultrasonic Waves. At least one ultrasonic frequency generating device is positioned adjacent to the production tubing walls which will produce a total of three ultrasonic frequencies, one of which is designed to disintegrate any of the wax that forms. The second frequency will break down the wax forming molecules into smaller molecules while the third will inhibit the wax from attaching to the production tubing walls. The value of frequency emitter can be preset so that the most suitable wave frequency will be used to prevent wax buildup. The present invention not only prevents precipitates from forming on the pipes, it also breaks wax bonds thereby increasing flow rates and production efficiency.

2.6.4 Magnetic Field Technology

Since the turn of the 19th century, literature has mentioned the effects of lodestones (magnetite) and naturally occurring magnetic mineral formations. Although magnetic water treatment (MWT) products have been promoted since the 1930's, they are not widely accepted due to inadequate research support. In Europe for past 40 years, magnets have been an economical and ecological approach to deal with the scaling and mineral formation problems associated with hard water. Nowadays, most magnetic treatment applications in the domestic sector involve conditioning water for drinking, cooking, laundry, washing, swimming pool and spa center.

When "magnetically" treated water is used, the formation of hardness and scale is noticeably reduced. Magnetic field is generated through magnetic fluid conditioner, which operates automatically and permanently using no external power source, and has no moving parts exposed to wear. As water, an electrically conductive fluid, passes through the magnetic field, clusters of water molecules are broken down and aligned along the magnetic flux vector. Magnetically charged water molecules have greater ionic charge than the minerals, increasing the attraction between mineral ions and water molecules which results in the formation of smaller more disperse mineral compounds that remain in suspension and do not adhere to pipes.

2.7 Magnetic Field Technology in Paraffin Deposition Control

Thousands of magnetic field application in oil and gas industry through magnetic fluid conditioner has been implemented worldwide. Onshore deposition problems are normally solved with physical and chemical methods, but as the oil industry is moving towards deep water well, deposition in hard-to-reach subsea flow lines may present difficulties. Magnetic field technology is one of the best options to solve these problems due to its characteristics. However, the mechanism of its effect on wax deposition is still dimly understood.

According to Wang Biao et al. (1995), magnetic paraffin inhibitor is extensively adopted in most oilfields in China. The inhibitors are usually installed in the depth of 600-1000 m in the oil well. It is a major paraffin-inhibiting method in China, been applied in 14400 wells and encouraging results have been continually produced. Besides China, there are also many success application of this magnetic devise in the United States.

A number of experiments have been carried out by researchers around the world to find out the operating principle behind this technology. Vieira (1996) conducted a trial in 1995 where the reduction of viscosity was visible in the tested samples but no influence on the Wax Appearance Temperature (WAT) and pour point were observed. According to Marques and Rocha (1997), there are claims that the interaction between crude and a magnetic field is actually dependent on other polar compounds present in crude and not the paraffin crystals. Von Flatern (1997) has different thought, stated that the tool creates nucleation sites in the fluid where paraffin crystals will deposit in the flow rather than on pipe walls. However, Marques and Rocha (1997) stated they have proven that pure paraffin in hydrocarbon solutions does show susceptibility to magnetic treatments. Their experiments shown a time-dependent viscosity reduction in samples that undergone the magnetic treatment. They also observed changes in paraffin crystallization habit using Scanning Electron Microscope (SEM).

2.7.1 Magnetic Field

A magnet is a material that produces magnetic field. The magnitude of magnetic field is measured in Tesla (T). A magnet always has two poles, the North and the South Pole. When like poles are brought together, the force they experience is a repulsive force. On the other hand, when two magnets are brought together so that opposite poles approach each other, the force is attractive, thus, proving the theory that opposites attract, and likes repel. The effects of a magnet on its surroundings are represented by the magnetic field lines where the magnetic field is most intense at the poles of the magnet. It may seems like the magnetic field lines exit from the North Pole of a magnet and enter at the South Pole, but in reality the lines are progressing in loops as shown in figure below.

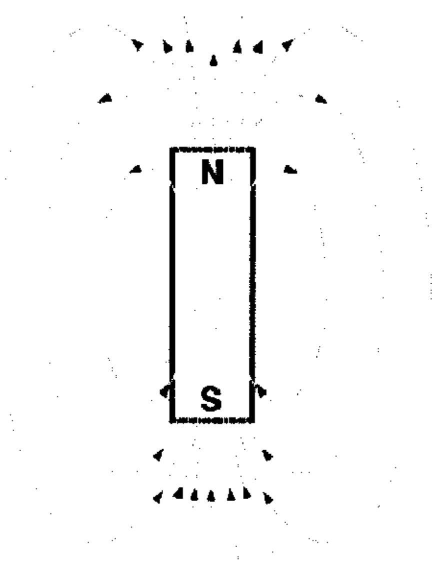


Figure 2.1: Magnetic Field Lines

Magnetic lines have a number of important properties, which include:

- All lines seek the path of least resistance between opposite magnetic poles.
- All lines never cross one another.
- All lines have the same strength.
- Density decreases moving from area of higher permeability to lower permeability area.
- Density decreases with increasing distance from the poles.

The magnetic field exerts force on a moving charge when the charge moves in a magnetic field. The direction of the magnetic force can be determined using the right-hand rule. The magnetic force depends on several factors: the charge of the particle, q; the speed of the particle, v; the magnitude of the magnetic field, B; and the magnitude of the angle between the velocity vector and the magnetic field vector, θ. Experiment shows that the magnitude of the force experienced by this particle is given by the following:

$$F = q\, v\, B \sin\theta \quad \text{(Newton, N)} \qquad [1]$$

The force vanishes if the particle moves parallel or in the direction of the field ($\theta = 0$), the maximum force is experienced when the particle moves perpendicular or at right angles to the field, so that $\theta = 90°$, $\sin \theta = 1$. Therefore, the goal is to achieve maximum magnetic force by creating magnetic field lines at right angle when two similar magnets brought near to each other.

Different orientation of magnetic poles will produce different pattern of magnetic field lines. In order to make the field visible, a magnetograph will be produced using iron powder where the particles will align themselves with the lines of magnetic force produced by the magnet. The pattern will be visibly clear when placed on a piece of paper on top of the magnet.

2.7.2 Magneto-hydrodynamics

MagnetoHydroDynamics (MHD) is the science that deals with the interaction of a (perpendicular) magnetic field with an electrically conducting fluid. MHD depends completely upon magnetic fields as its only source of energy. The term magneto-hydrodynamic comes from the combination of three words; *magneto* means magnetic field, *hydro* means liquid and *dynamics* means movement. It concerns the dynamic of magnetic fields in electrically conducting fluids. The principle of magneto hydrodynamic is that magnetic fields can induce currents in a moving conductive fluid, which create forces on the fluid and also change the magnetic field itself.

The Baylor University Magnetic Group (1984) stated, "A fundamental law of physics states that the motion of a conductor through a magnetic field will cause a voltage to be produced. This principle of electromagnetic induction was first demonstrated by Faraday, and applies not only to conducting solids such as wires, but also to conducting fluids such as aqueous solutions containing dissolved electrolytes." Therefore, voltage will be produced when fluid containing dissolved ions flow through a magnetic field.

The Baylor researchers measured the magnetohydrodynamic effect from a series of electrical measurements made within the areas of condensed magnetic flux, while various flow rates of a sodium chloride solution were circulated through it. Both voltage and current were measured. They found that the denser the magnetic flux, the more current flowed and the measured voltage was a linear function of solution flow rate. The performances of MFC in oil wells have proven Baylor's findings.

The relationship established from Baylor's research is similar to Lorentz principle where the magnetic flux and flow rate affects the magnitude of voltages produced from a flowing fluid with charged particles, which correspond to electric field. Lorentz force is the force experiences by a charged particle at right angle to its direction of travel as it passes through a magnetic field.

The Lorentz force is given by the equation below:

$$F = q\,(E + v \times B) \qquad [2]$$

where F = Force (N), q = Electric charge (Coulomb)

B = Magnetic field density (Tesla), v = Velocity (m/s)

E = Electric field (volts/m)

For inorganic scales which contains polar molecules, Marques and Rocha (1997) states that the action of Lorentz forces in the particle electrical double layer causes a change in its charge. Electrical double layer exists around a particle, describing the potential variation at particle's surface where ions of opposite charge concentrate at the surface. The change in charge affects both particle-particle and particle-to-liquid interactions thus altering the growth of paraffin crystal and affect its deposition

However, for organic scales like paraffin wax, the authors concluded that so far the Lorentz forces are concerned; it is difficult to explain the interaction between a magnetic field and hypothetical crude which only contains non – polar molecules. Unless the magnetic forces exerted is actually acting on the polar molecules commingled with crude, it is impossible to explain in the language of physics and chemistry the phenomenon provided by magnetic fields on paraffin deposition.

2.7.3 Magnetic Fluid Conditioner (MFC) in Paraffin Control

Professor John Donaldson and Dr. Sue Grimes from Chemistry Department of City University, London, states that; "A magnetic field will interact with any substance that carries a charge, however small in any fluid. The nuclei on which the crystals start growing and the growing crystallites are very small and will have charged surface. As they pass through the magnetic field, these charged particles encounter considerable forces as the magnetic field interacts with them. The magnet field acts at the surface of the crystallites modifying the nature of the charges at the surface. This alters the growth of the crystal in general and on specific planes."

Mag-Well Company, a US-based company and one of the few manufacturers of MFC defined Magnetic Fluid Conditioner (MFC) as a simple hydrodynamic generator which alters the growth pattern of paraffin and scale crystals, and inhibits their clinging to pipeline walls. The MFC does not require any external power to function, and apply permanent magnet which does not lose its strength. MFC installations are environmentally safe and cost effective without the potential damage to the formation and production equipment associated with chemical, thermal or mechanical methods.

The magnetic fields interact with the charged crystal nuclei in the fluids, affecting precipitation. The electrical charges on the crystal nuclei and the growing crystallites are affected at the surface, altering the growth of the crystals in general and on specific planes. Paraffin build-up can be avoided because the crystals grow differently in size, shape, rate, number, and alteration in their solubility. One of the powerful advantageous of MFC is that it lowers the cloud point of the fluids by as much as 60°F allowing the paraffin to remain in solution.

S.Rocha (1997) concluded that when crude is flowing through an adequate magnetic field, the paraffin molecules will tend to align their poles with the poles of magnetic field. Changes in both electrons rotation and translation patterns leads to changes in their orbital angular momentum and disturbs the crystal agglomeration process. When placed under magnetic field, weak dipoles are developed in the paraffin molecules. There will be repulsion force between these molecules and at the same time, changes their structure and in the way they move. Therefore, they are prevented from precipitating out of solution to form wax on the walls.

2.7.4 Theoretical discussion on Magnetic Fluid Conditioners

The following mathematical relation is based on the work of Marques et al. (1997). Every work done on or by a system can be related to a change in its boundary (PdV), where the internal energy of the system (U) can be expressed in terms of the system entropy, volume and amount of moles of each of its components, as

$$U = TdS - PdV \qquad [3]$$

where	S = Entropy (J/K)	T = Temperature (K)
	V = Volume (m^3)	P = Pressure (bar)

The work to magnetize a specific component is one of the types of work that may affect the system. Model and Reid (1974) derived an expression for the work done by magnetic field on a given component of a thermodynamic system as follows:

$$W = V_s \mu_o \int_o^M H dM \qquad [4]$$

$$M = \left(\frac{\mu}{\mu_o} - 1\right) H \qquad [5]$$

where	W	=	Work (J)
	V	=	Volume of system (m^3)
	H	=	Magnetic field strength (A/m)
	M	=	Magnetization (A/m)
	μ_o	=	Free space magnetic permeability (H/m)
	μ	=	Actual substance magnetic permeability (H/m)

The actual material magnetic permeability (μ) is a function of material, pressure, temperature, and magnetic field strength. Adding equation [4] to fundamental equation of internal energy of a system [3], the following equation can be derived:

$$U = TdS - PdV + V_s\mu_o HdM + \sum_j \mu_j \, dN_j \qquad [6]$$

Equation [6] shows that the application of magnetic field on a given thermodynamic system can affect the crystallization temperature which will later affect the wax deposition process. Experiments carried out by Rocha (1997) with paraffins in organic solvents confirm the claim.

Corney (1993) states that the success of MFC application lies on the accurate determination of the environment of a system where MFC will be properly engineered for that particular system. Field tests proved that the amount and density of magnetic flux in the treatment area is one of the primary considerations in designing an MFC.

2.8 Magnetic Field Technology in Crude Viscosity Reduction

Viscosity is a measure of the resistance of a fluid to flow and measure of fluid friction. Viscous crude will impair transportation where high viscosity leads to huge pressure drop that makes it impossible to simply pump the fluid in single-phase flow, even of large diameter. Different solutions have been developed to transport heavy oil in pipeline like heat or chemical dilution.

When crude flows in pipeline, there will be a zone near the fluid-pipe wall boundary where the fluid has zero velocity relative to the boundary. This is the no-slip condition where the fluid is pictured as stick to the surface. At some distance away from the boundary, the flow speed is equal to that of the fluid. Boundary layer is the region between these two fluid conditions. As a result of velocity loss, shear stress is imparted onto the boundary. Crude oil is a non-Newtonian fluid, where viscosity changes with applied shear stress.

Rao and Xu (2006) stated that viscosity can be related to the magnetic permeability, μ which is equal to the magnetic flux density B established within the material by a magnetizing field divided by the magnetic field strength H of the magnetizing field. It is assumed that the magnetic permeability of particles, μ_p is different from the magnetic permeability of the base liquid, μ_f.

Following work is based published paper by Rao and Xu (2006). Particles are polarized along the magnetic field direction in a magnetic field. There will be interaction between that dipole and the magnetic field. The strength of that interaction is defined by magnetic dipole moment. If the particles uniform spheres of radius a, the dipole moment can be expressed as:

$$\vec{m} = \vec{H}a^3(\mu_p - \mu_f)/(\mu_p + 2\mu_f) \quad [7]$$

where	$\vec{m}$	=	Dipole moment ($A.m^2$)
	$\vec{H}$	=	Magnetic field acting on spheres (T)
	a	=	Radius of particle (μm)
	μ_f	=	Magnetic permeability of fluid
	μ_p	=	Magnetic permeability of particle

The interaction between two induced magnetic dipoles can be expressed as

$$U = \mu_f m^2(1 - 3cos^2\theta)/r^3 \quad [8]$$

where	U	=	Interaction of two magnetic dipoles (J)
	μ_f	=	Magnetic permeability of fluid
	m	=	Dipole moment ($A.m^2$)
	θ	=	Angle between field and line joining the dipoles
	r	=	Distance between dipoles (m)

If this interaction is strong enough to overcome the Brownian motion, the particles aggregate and align in the field direction. This aggregation will change the rheological property of the crude oil and leads to viscosity reduction. This viscosity reduction is temporary, where after several hours, the aggregated particles will disaggregate, return to initial rheological state and viscosity. However, the process is repeatable and the period of low viscosity is long enough for many important applications.

2.8.1 Magnetic Fluid Conditioner (MFC) in Viscosity Reduction

MFC can be applied to reduce crude viscosity where temporary viscosity reduction is the direct effect of passing fluid through magnetic field. Studies by Tao and Xu (2006) concluded that magnetic field can significantly reduce the viscosity of crude oil for several hours where it temporary aggregates paraffin particles inside crude oil into large ones. According to them, the effect of magnetic field on crude viscosity is very controversial where Chow (1999) found that magnetic field increased the viscosity and Rocha (2000) found opposite result while Flatern (1997) reported no effect.

Through their series of experiment, Tao and Xu (2006) postulated that the particle aggregation changes the rheological properties of the crude oil and leads to viscosity reduction. Rheology is a branch of physics dealing with the way matter flows and changes shape. Their experiments show a reduction of 19 % in viscosity when 40.97 cP crude is subjected to the influence of 1.33 T magnetic field for 50 s under the crude Wax Appearance Temperature (WAT). After 50s, they observed gradual increment in viscosity but still under the initial value. The original rheological state was recovered after about 8 hours.

CHAPTER 3

METHODOLOGY

This section of the report will discuss on the methods and procedures applied throughout the conduct of the experiment which comprises of many related individual task. Every task was executed based on scientific approach, regardless of whether it is a standard experiment practice or a designed experimental procedure. The whole experiment was carried out in the laboratory at constant room temperature of 23°C and atmospheric pressure of 1 atm.

3.1 Magnetic Field Lines

A series of experiment was conducted to observe the pattern of magnetic field lines produced when magnets were arranged in different configurations. The purpose of this observation is to narrow down the number of possible magnets configurations to be further investigated. The magnetic field lines generated can be visualized via the alignment of iron fillings with the magnetic field.

3.1.1 Materials and Equipment

The table that follows summarized the types and quantity of materials and equipment used in this experiment. The magnet functions to provide magnetic field lines while the black magnetic ink which is available in spray can, functions to give visual image of the fields. The ink is sprayed on the plastic piece which is supported at four points using paper boxes of same height as the magnets, to provide even surface for better representation. Cleaner and cloth are used to clean the plastic piece each time an experiment is completed. Images produced were documented using digital camera enable further analysis to be done later.

Table 3.1: Materials and Equipment

No.	Item	Quantity
1.	MEGAFERRITE permanent magnet	4 unit
2.	Clear plastic piece (14" x 9")	1 unit
3.	Black magnetic ink (500 mL)	2 unit
4.	Cleaner (500 mL)	1 unit
5.	Clean cloth	1 unit
6.	Paper box	4 unit
7.	Digital camera	1 unit

3.1.2 Experiment Procedure

The procedure is developed based on the standard scientific experiment to investigate magnetic field. However, instead of using dry iron fillings, it is replaced with black magnetic ink which is iron fillings soaked in oil. The liquid provides more mobility to the iron to displace from one point to another, in-line with the magnetic field lines.

1) Magnets were placed in desired configuration.
2) Surface of the plastic piece was made sure to be clean and dry.
3) Four small paper boxes were placed at four corners surrounding the magnets.
4) Plastic piece was placed over the magnets, supported by the boxes.
5) Can of black magnetic ink was shake before used.
6) Even layers of ink were sprayed over the plastic surface.
7) Ink was allowed to form pattern for 2 minutes.
8) Observation was made on the formed pattern.
9) Digital image was captured using digital camera.
10) Cleaner was shake and sprayed over the plastic piece.
11) Dry cloth was used to wipe clean the surface.
12) Repeat step 1 to 11 for different configurations.

3.2 Flow Rate

Flow rate of the liquid plays a critical role in generating magnetic force which will act on the paraffin and remove the deposition. This means that flow rate is one of variables that determine the removal rate of the paraffin wax in the pipe. Thus, it is very important to quantify the flow rate so that the rate at which the removal rate is optimum can be determined.

3.2.1 Material and Equipment

Tools and equipment involves are the experiment setup for wax removal, a 100 ml measuring cylinder and a stopwatch.

3.2.2 Experiment Procedure

Following steps describe the procedures followed in measuring the flow rate:

1. Experiment was setup according to procedure in 3.2.
2. Experiment was run and allowed a few minutes to stabilize.
3. Measuring cylinder was placed at the end of the flow loop.
4. Stopwatch was started simultaneously.
5. Measuring cylinder was pulled away from the pipe outflow before fully filled.
6. Stopwatch was stopped simultaneously.
7. Volume of water in cylinder and time taken were recorded.
8. Flow rate was obtained by dividing volume with time.
9. Repeat step 1 to step 8 for 5 times to get better accuracy.
10. Final value was determined from the average of all 6 readings.

3.3 Wax Deposition Removal

Wax deposition removal is the major part of the whole experiment since this research is focusing on the ability of magnetic field to remove wax deposits. This experiment setup was designed based on the work of Marques et.al (1997) in the study of paraffin crystallization process under the influence of magnetic fields and chemicals.

The parameter defining the workability of the technology is the mass of deposits removed over a period of time under certain magnetic strength. Several variables will be integrated to investigate their effects on the deposits removal rate. These variables include magnets configuration and flow rate. Previous sections have discussed in detail the procedure used to identify best magnet configuration and to determine flow rate. For each run of experiment, the total time is set at 4 hours where reading will be taken every 30 minutes interval.

3.3.1 Materials and Equipment

Most of the materials and equipment required are not available in the labs. Procurement from external vendors was made after evaluating quotations from each vendor to get the best price. The table below shows the type of items, their functions as well as required quantities.

Table 3.2: Materials & Equipment

No	Item	Function	Quantity
1.	MEGAFERRITE magnet (MFC)	Provide magnet effect	4 unit
2.	Aquarium pump (25 W)	Mobilize liquid to flow	1 unit
3.	Plastic container	Contain liquid to be circulated	1 unit
4.	Zinc container	Contain melted paraffin	1 unit
5.	¾" Galvanized Iron (GI) pipe	Mount MFC and as 'control' pipe	2'
6.	¾" PVC pipe	Construct flow loop	8'
7.	¾" Globe valve	Control flow rate	1 unit
8.	Solid Paraffin	Raw material	1 kg
9.	Weighting scale	Weigh sample	1 unit

3.3.2 Experiment Setup

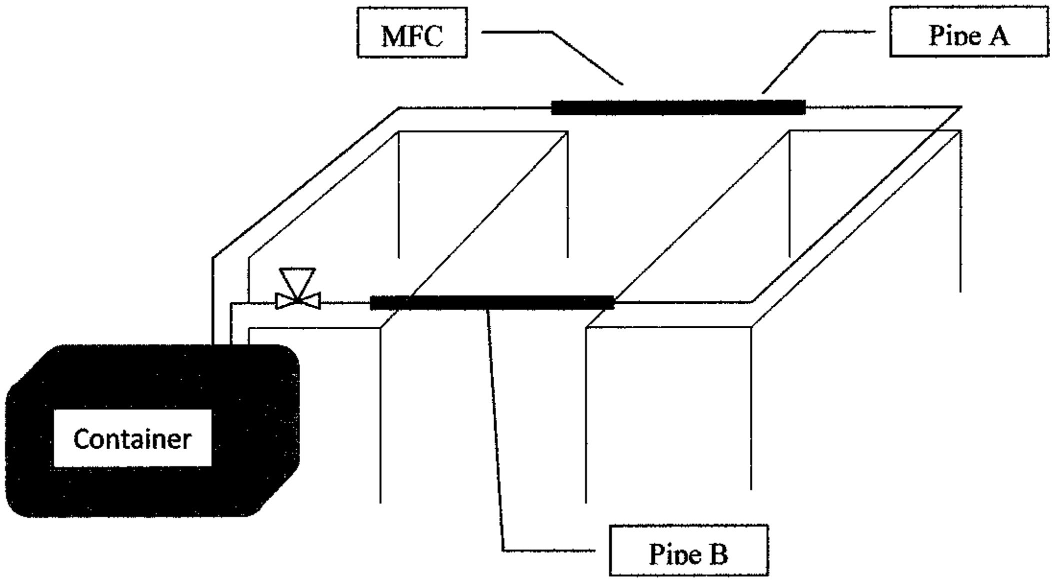


Figure 3.1: Experiment setup

Figure 3.1 roughly depicted the arrangement of all the equipment. The whole flow loop is constructed from PVC pipes represented by normal black lines, except for Pipe A and B which are made from GI pipes; both are coated with paraffin but the MFC is mounted on Pipe A only while the later is a control sample without MFC. The aquarium pump is placed inside the container, with cotton filter at the suction part of pump. The whole structure is supported by mild steel put together using bolts and nuts, indicated by the red lines.

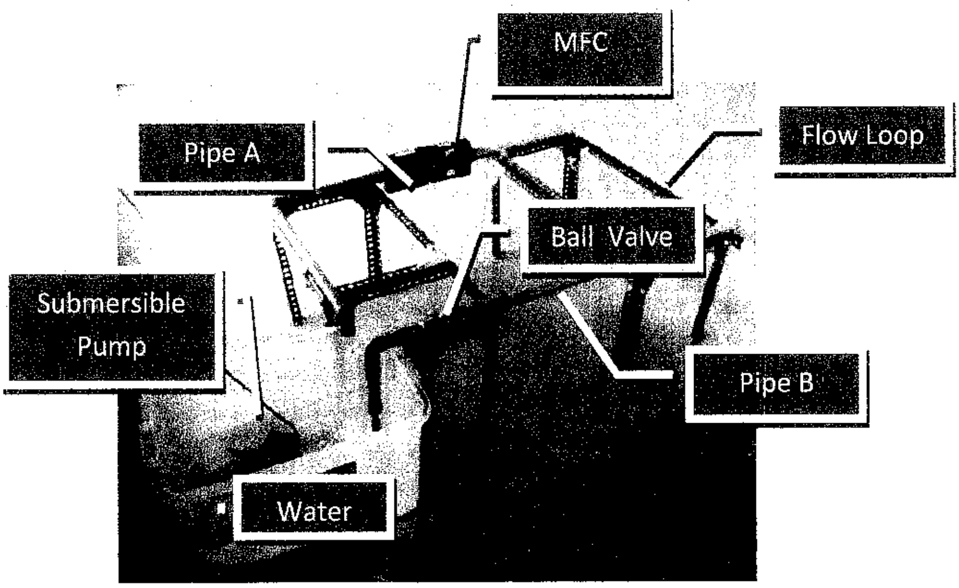


Figure 3.2: Actual Experiment Setup

Figure above shows the actual setup for the experiment. The entire setup is placed on level ground to eliminate elevation change. A closed flow loop is chosen because flow rate of fluid flowing inside a closed loop is constant at any point along the loop with minor disturbances from bends and joints. The magnets (MFC) are placed on the opposite side of the pump in order to let fluid to stabilize and achieve constant rate in order to eliminate any possible effect of turbulence and high flow rate on wax removal.

Following procedures are made on the assumption the experiment is carried out at room condition. Water is used as medium in this experiment to avoid contamination and because of limited quantity of crude available. All weighing activities are based on ASTM E617 - 97(2003) Standard Specification for Laboratory Weights and Precision Mass Standards.

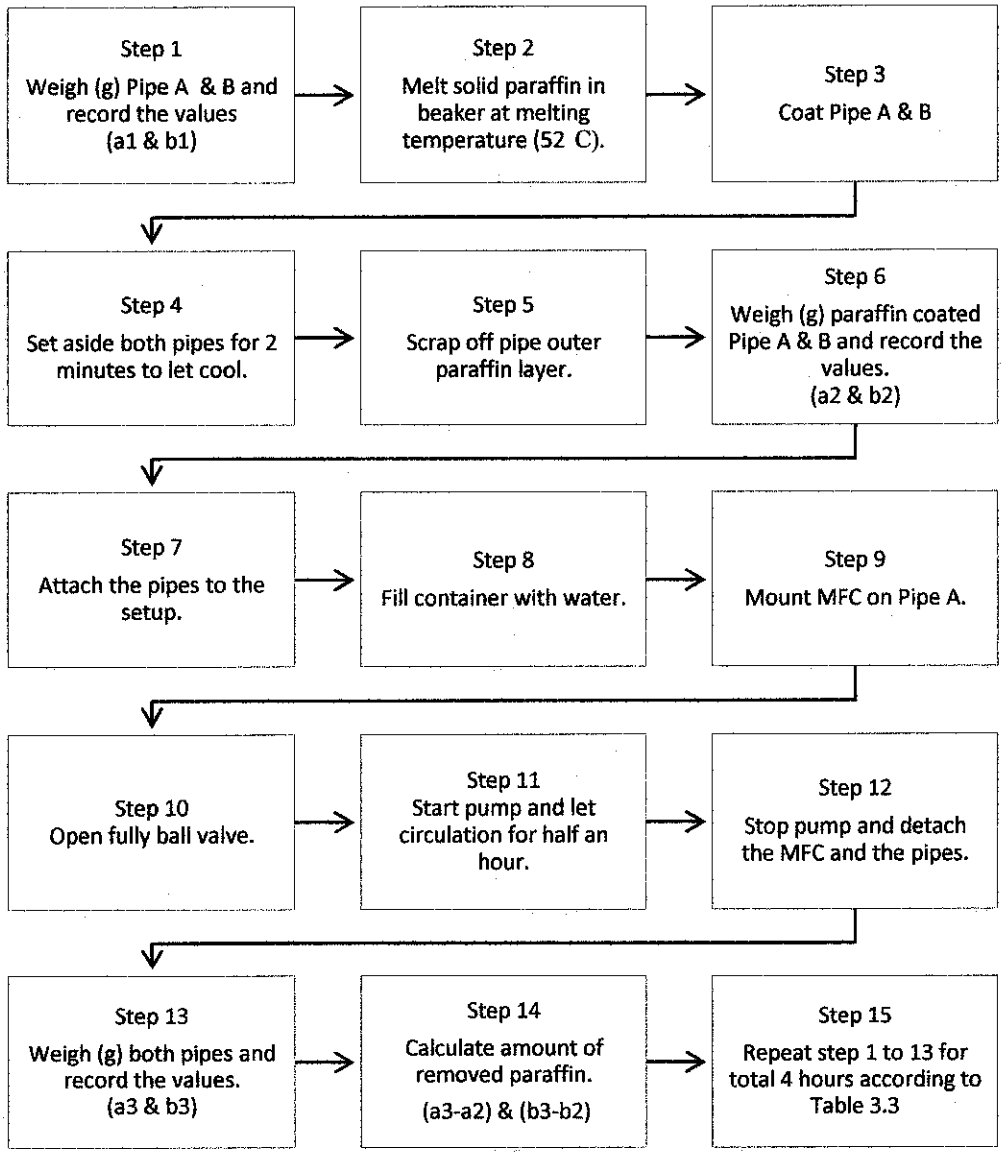


Figure 3.3: Experiment procedure

Table 3.3: Variable parameters

Condition	Magnets Configuration	Valve opening
1	Configuration 1	Full
2	Configuration 1	Half
3	Configuration 2	Full
4	Configuration 2	Half

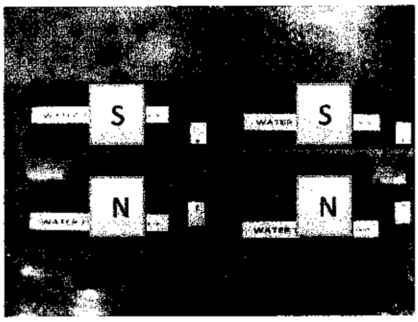


Figure 3.4: Configuration 1

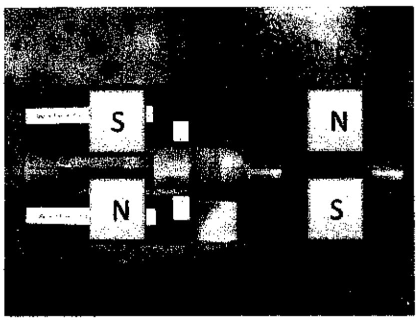
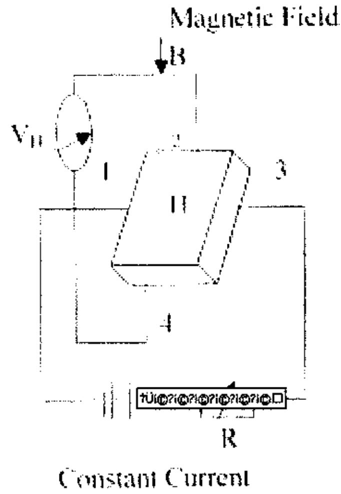


Figure 3.5: Configuration 2

3.4 Magnetic Flux Density

Magnets configuration which presents the best magnetic field lines in the previous part was further investigated where the magnetic flux density, for each magnet was measured along the magnet surface in mm Tesla. The tool used for this investigation is called Magnetometer. It operates according to the principle of Hall Effect.



Source: www.e-magnet.cn

Figure 3.6: Magnetometer operating principle

When Hall element H is placed in the magnetic induction field with intensity B and connect a constant current I through end 1 and 3, then a voltage VH would occur between end 2 and 4, after amplified by the arithmetic amplifier, it outputs to the display and the relevant readings of magnetic flux density will be displayed on the LED.

Hall voltage, VH	=	SH x I x B x Sin 90

SH	=	Sensitivity of Hall element (mV/mA x T)
I	=	Current at control end (mA)
B	=	Magnet Field (T)
Sin 90	=	Angle between element and magnetic field

3.4.1 Experiment Procedure

The procedure used in this experiment is actually the operating procedure of this equipment. Readings were taken at 12 points on the pipe in between the two magnets, as depicted in the figure below. These readings were taken when the wax removal experiment is on-going according to arrangement in Table 3.3.

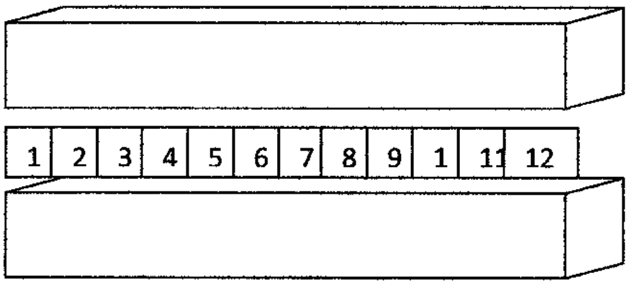


Figure 3.7: Measurement points

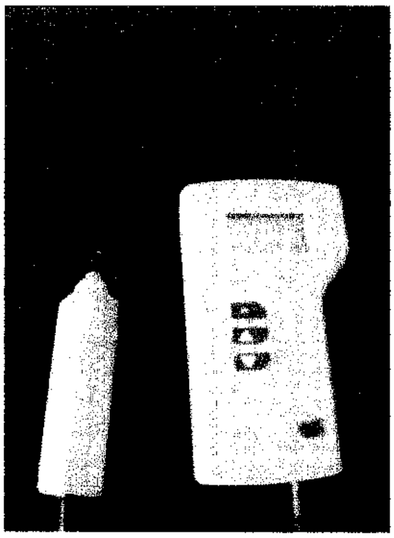


Figure 3.8: Magnetometer

1) 'ON' button was pushed to turn on the meter.
2) Meter probe was placed at right angle to magnet at point 1.
3) Range of reading was adjusted as required.
4) Measurement was taken when reading stabilized. (Repeat 3 times)
5) Step 2 to 4 were repeated for the next point of interest.

3.5 Viscosity Reduction

Reduction in viscosity of flowing liquid is a direct effect of magnetic field acting on wax deposits. Practically, in order to ensure the results obtained is close to the actual situation, waste diesel was used to represent crude oil. Even though the properties are slightly differing from one another, several adjustments can be made later to achieve compatibility.

There are two parts of this experiment, first is to observe the changes in fluid viscosity over time and the later is to determine the time taken for the viscosity to return to initial value.

3.5.1 Materials and Equipment

The materials and equipment required in this experiment are the whole experiment setup for wax removal as defined in section 3.4.2 with and addition of a digital viscometer. The subject of interest is the changes in viscosity of the flowing liquid. The viscosity is measured in unit cP.

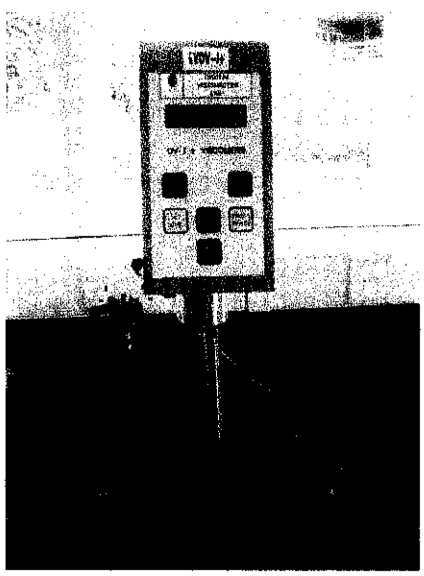


Figure 3.9: Digital Viscometer

3.5.2 Experiment Procedure

This experiment for investigating viscosity was conducted using the best combination of magnets configuration and valve opening determined from wax removal experiment where the highest removal rate was achieved.

a) Changes in Viscosity over Exposure Time

1. Initial viscosity of waste diesel was measured and value recorded.
2. Pump was started and experiment was run with waste diesel as flowing fluid.
3. Sample of fluid as taken after 15 minutes.
4. Sample viscosity was measured and value recorded.
5. Step 3-4 were repeated for a total time of 2 hours.
6. Graph of viscosity versus time was plotted.

   *All samples are to be returned to container except the sample after 30 minutes.

b) Time taken to return to Initial Value

1. Viscosity of sample from 30 minutes run was measured and value recorded.
2. Sample was left for 15 minutes.
3. Viscosity of sample was measured and value recorded.
4. Step 2-3 were repeated for a total time of 2 hours.
5. Graph of viscosity versus time was plotted.

CHAPTER 4

RESULTS AND DISCUSSION

All results obtained from the experiments were compiled and graphically displayed. Detailed analyses were performed and related discussions were generated. Precise recording of results is very important in order to draw credible conclusions and provide relevant recommendations.

4.1 Magnetic Field Lines

A set of experiment has been carried out to investigate the magnetic field lines pattern when magnets were placed in different configurations. The lines are normally viewed as coming out from North pole, entering at South pole. Actual fact is that the lines are going in closed loops from pole to pole.

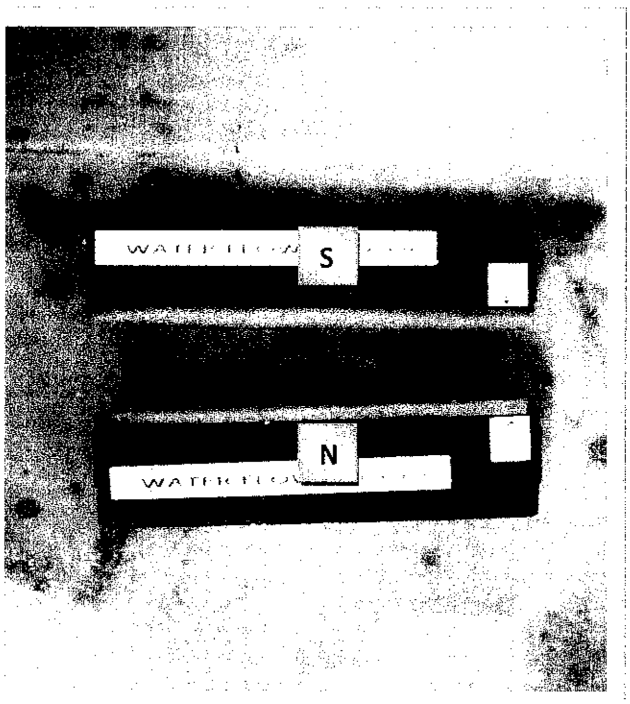


Figure 4.1: North and South Poles on magnets

There are a total of 8 different configurations of two or more magnets combination assessed in this experiment. All the magnets arrangement and actual results can be found in Appendix 1. Out of this number, there are two distinct configurations which displayed the best magnetic field lines where all the lines were at right angle to the direction of fluid flow. This is the requirement to achieve maximum Lorentz force for wax deposits removal.

4.1.1 Configuration 1

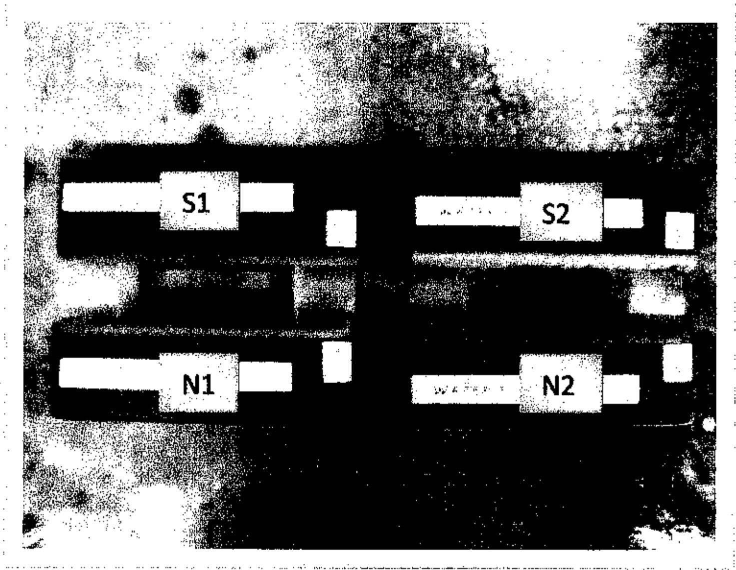


Figure 4.2: Magnets arrangement (Con. 1)

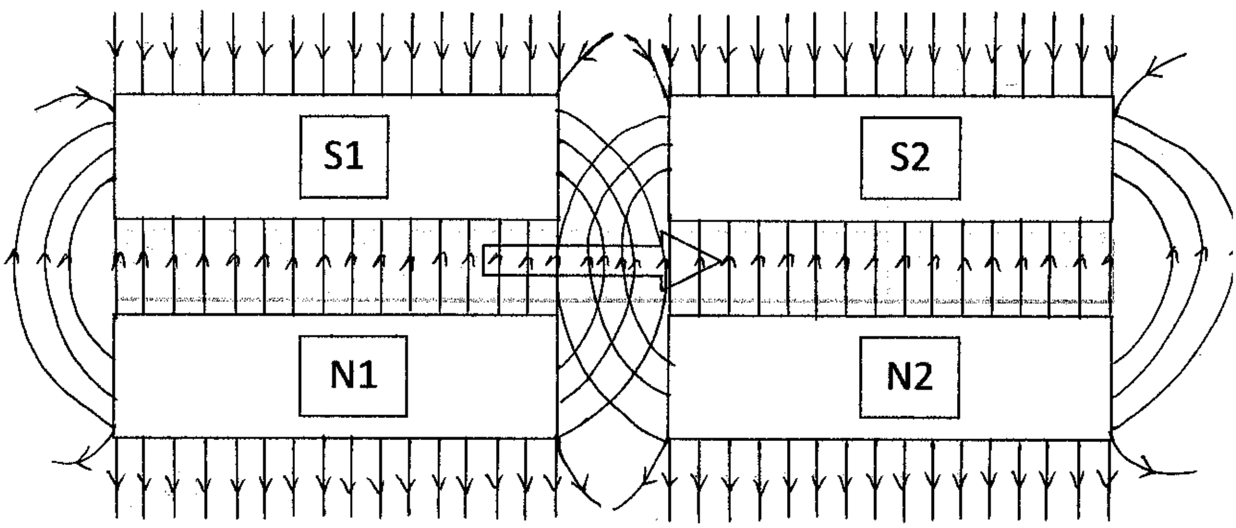


Figure 4.3: Theoretical field pattern (Con. 1)

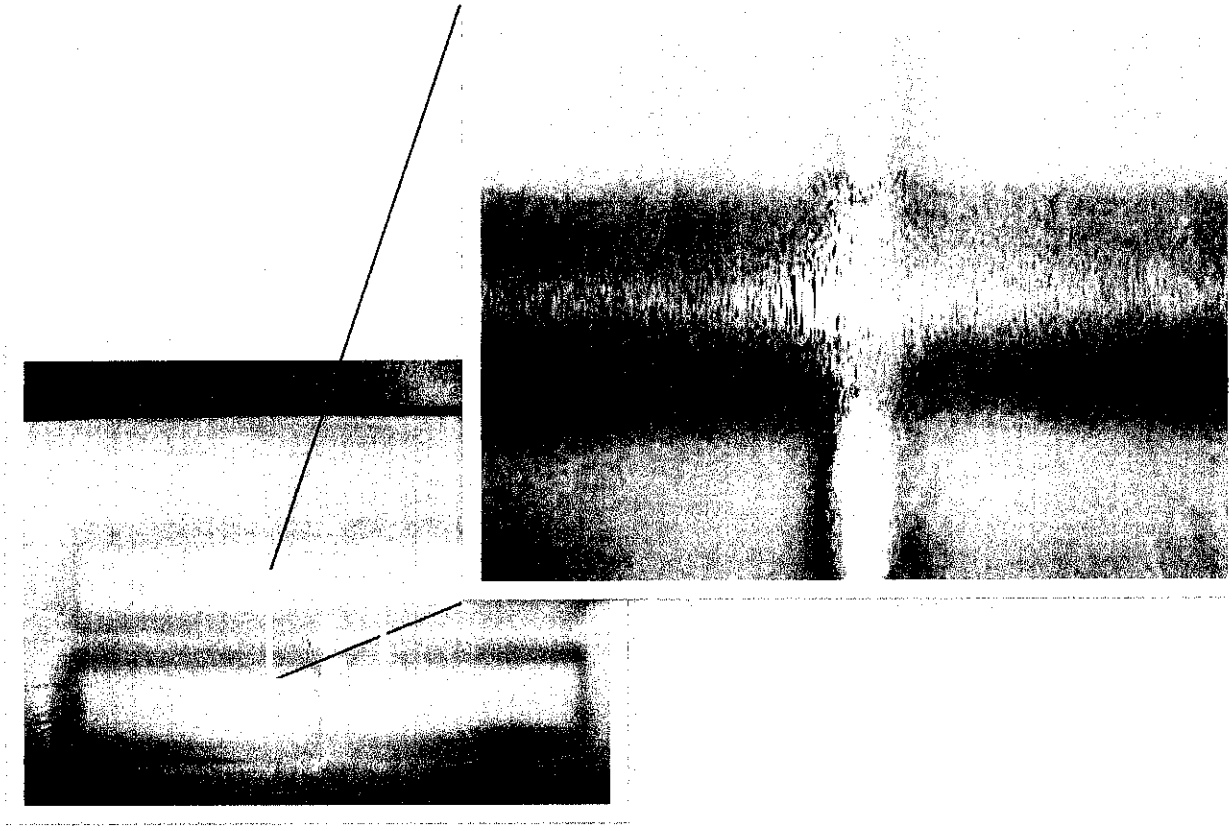


Figure 4.4: Actual field pattern (Con. 1)

Figure 4.2 shows the arrangement for Configuration 1 where the pipe will be placed along the length of each magnet. On top of the pipe are both South poles while at the bottom are the North poles. Hence, theoretically no line is expected at the area between both magnets at the top portion or bottom. Lines will only be crossing along the length of magnets between the top magnet and the bottom magnet which are of different poles. The actual result is indeed in accord with the theoretical image where all the lines were at right angle to direction of flow along the length of pipe as in Figure 4.4.

4.1.2 Configuration 2

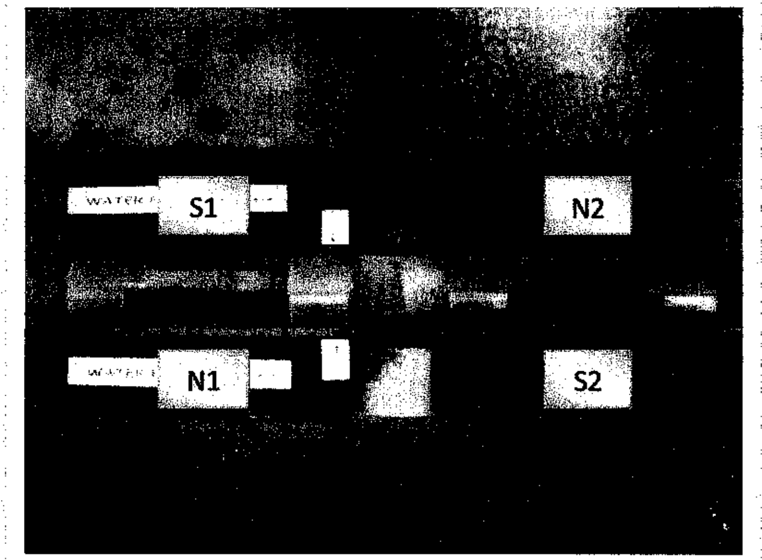


Figure 4.5: Magnets arrangement (Con. 2)

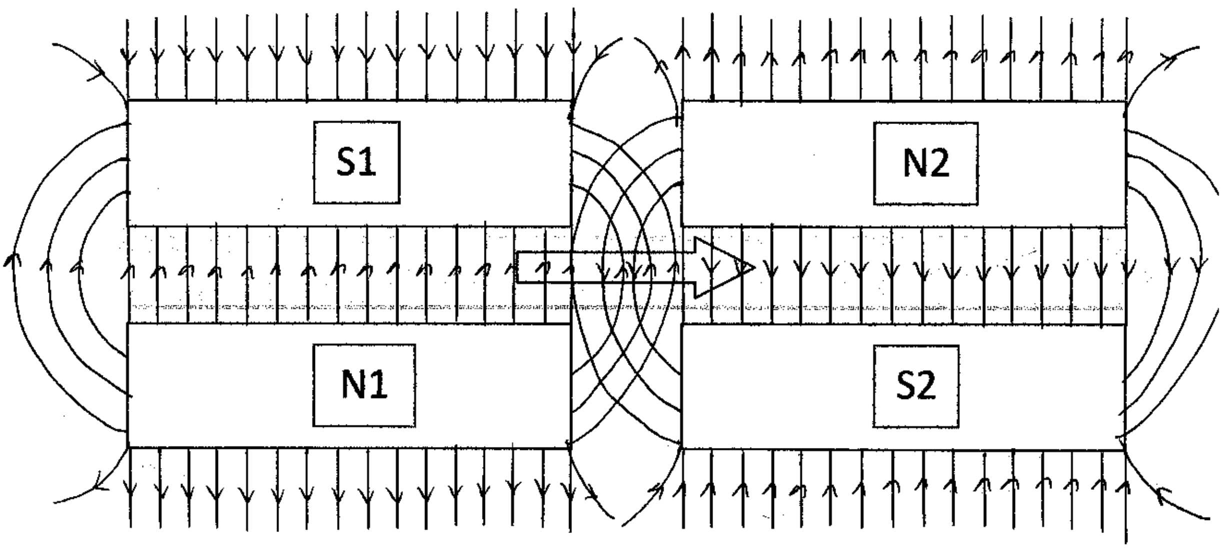


Figure 4.6: Theoretical field pattern (Con. 2)

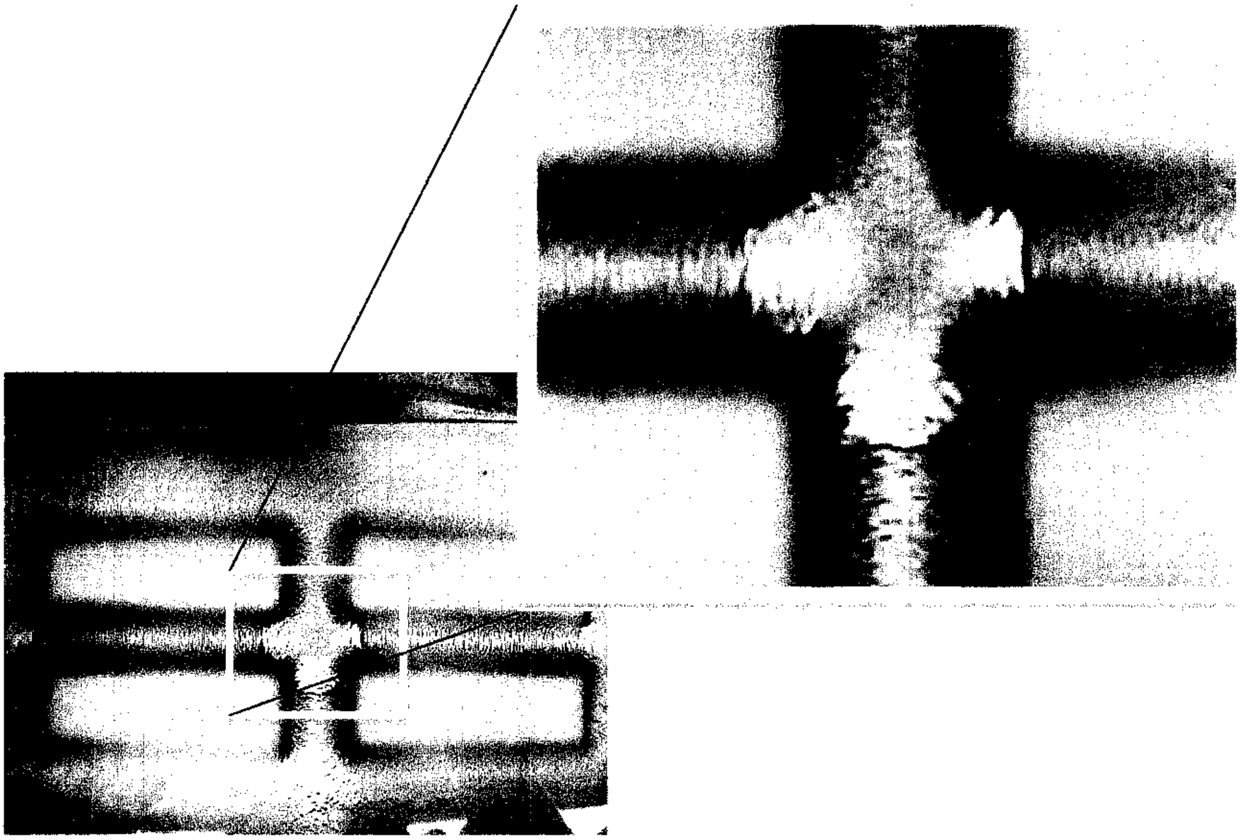


Figure 4.7: Actual field pattern (Con. 2)

Arrangement of magnets for Configuration 2 can be seen from Figure 4.5. Magnets are positioned in a way that opposite poles are facing each other, increasing the number of field lines. Field lines are expected to present across all intersection of magnets, maximizing the possibility that wax removal rate will be higher compared to other configurations. The pattern from experiment as in Figure 4.7 is consistent with the predicted pattern in Figure 4.6.

Both Configuration 1 and 2 will be used in the wax removal experiment where highest removal rate indicates the better choice for further investigation.

4.2 Magnetic Flux Density

The magnetic field can be visualized as magnetic field lines. Magnetic flux density can be quantified in unit of mili Tesla, using a tool called magnetometer which operates on Halls Effect principle. North pole will give a positive values while a negative value indicates South pole. Four different conditions were assessed for magnetic flux density.

Readings were taken at 12 points on the pipe sandwiched by the magnets after fluid starts circulating in the flow loop. Each reading was taken three times for every point to obtain precise value. The average of the twelve values is the magnetic flux density for one magnet. Therefore, the average of the averages of all magnets will be taken as the final value for a magnets configuration. The standard deviation or tolerance also has been calculated to provide an acceptable range for the value.

4.2.1 Sample Results for Configuration 1 with Valve Fully Opened

Table 4.1: Pair S1 and N1

Point	Reading 1	Reading 2	Reading 3	Average Value	Standard Deviation
1	-15	-15	-15	15.00	0.0000
2	-14	-15	-16	15.00	1.0000
3	-14	-15	-19	16.00	2.6458
4	-17	-16	-20	17.67	2.0817
5	-18	-15	-19	17.33	2.0817
6	-17	-16	-21	18.00	2.6458
7	-18	-17	-22	19.00	2.6458
8	-15	-18	-20	17.67	2.5166
9	-16	-20	-21	19.00	2.6458
10	-12	-18	-20	16.67	4.1633
11	-14	-18	-19	17.00	2.6458
12	-15	-19	-18	17.33	2.0817
				Σ = -205.67	Σ = 27.1537

Mean of Average Value = 205.67 / 12

= 17.13

Mean of Standard Deviation = 27.1537/12

= 2.2628

Magnetic Flux Density for Pair S1 and N1 = 17.13 ± 2.26 mT

Table 4.2: Pair S2 and N2

Point	Reading 1	Reading 2	Reading 3	Average Value	Standard Deviation
1	-15	-15	-15	15.00	0.0000
2	-14	-15	-14	14.33	0.7071
3	-14	-14	-14	14.00	0.0000
4	-14	-13	-13	13.33	0.7071
5	-13	-13	-14	13.33	0.7071
6	-11	-12	-14	12.33	1.5811
7	-11	-10	-14	11.67	2.1213
8	-10	-12	-12	11.33	1.2247
9	-11	-12	-12	11.67	0.7071
10	-12	-12	-11	11.67	0.7071
11	-13	-11	-13	12.33	1.2247
12	-14	-13	-13	13.33	0.7071
				Σ = -154.33	Σ = 9.3827

Mean of Average Value = 154.33 / 12

= 12.86

Mean of Standard Deviation = 9.3827/12

= 0.7819

Magnetic Flux Density for Pair S2 and N2 = 12.86 ± 0.78 mT

Therefore, the Magnetic Flux Density for Configuration 1 when the valve is fully opened is the average value of flux density for both pair S1 & N1 and S2 & N2 which is **15.00 ± 1.52mT**. For further reference, all other results are available in Appendix 2.

4.2.2 Magnetic Flux Density for All Conditions

Table 4.3: Summary of Magnetic Flux Density

No.	Configuration	Valve Opening	Flux Density (m Tesla)
1	1	Full	15.00 ± 1.52
2	1	Half	14.87 ± 0.71
3	2	Full	12.05 ± 1.05
4	2	Half	12.01 ± 1.00

The table above summarizes the values of magnetic flux density for all four conditions. It is obvious that when magnets were arranged in Configuration 1 with the ball valve fully opened will give the highest flux density at 15.00 m Tesla. This value is closely followed behind by Configuration 1 with the half opened valve at 14.87 m Tesla. The percentage difference between these two values is 0.99%. This small difference is due to the fact that the fluid flow rate does not affect the flux density which depends totally on magnets position and combined magnetic strength.

This is proven right when magnets which are arranged in Configuration 2 give smaller value of magnetic flux density. For Configuration 2 with valve fully opened, a flux density of 12.05 m Tesla is attained. Similar to the previous case, even though the valve opening was half, the value of magnetic flux density does not differ much. In this case, the percentage of difference is 0.33%.

However, it is obvious that both Configurations 2 give smaller value of magnetic flux density compared to Configurations 1. The reason lies behind the position of North and South poles which directly affect the magnetic force direction. Theoretically, from the front view, the magnetic field lines will begin at North pole to South pole. All direction is by reference to axis direction in Figure 4.8.

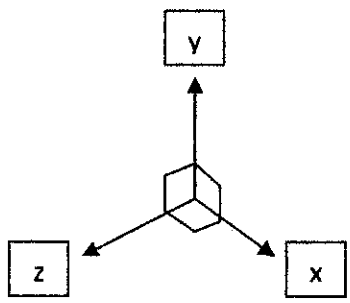


Figure 4.8: Axis direction

As can be seen in Figure 4.3, for Configuration 1, South poles S1 and S2 are both at the same side of the pipe as well as the North poles N1 and N2 at the opposite side. Magnetic field lines will travel from bottom to top or positive y-direction. The arrow indicates the direction of flow which is from left to right or positive x-direction. By right hand rule, the direction of force generated is outward or positive z-direction. Since both magnets pairs of S1&N1 and S2&N2 have the same direction of force, thus, the cumulative force is bigger and acting at the same direction.

However, for Configuration 2, South poles S1 and S2 are at opposite side of the pipe. The same case goes to North poles N1 and N2 which results in different direction of magnetic field lines for both pair S1&N1 and S2&N2. Figure 4.6 depicts the arrangement of magnets of Configuration 2 and the direction of flow in positive x-direction. For pair S1&N1, the South pole is on top of North pole, theoretically the magnetic field lines will travel from bottom to top or positive y-direction. On the other hand, for pair S2&N2, the South pole is at the bottom of North pole where magnetic field lines will travel from top to bottom or negative y-direction. By right hand rule, force generated by pair S1&N1 will be in positive z-direction while pair S2&N2 will generate force in negative z-direction. Therefore, because of having opposing direction force components, the cumulative force generated is lesser than the force generated by configuration 1.

4.3 Flow Rate

Flow rate is referring to volumetric flow rate or how much volume of fluid passes a point in a specific period of time. The flow rate corresponds to the opening of the valve has been investigated using a stop watch and a 100 ml cylinder. A total of 6 readings were taken and the average will be the final value. All results on flow rate is available in Appendix 3.

Table 4.4: Flow Rate for Valve Fully and Half Opened

No.	Valve Opening	Flow Rate (mL/s)	Flow Rate (L/hr)	Standard Deviation
1	Full	103.70	373.32	10.94
2	Half	53.48	192.56	10.27

Full results and sample calculations are available in Appendix section. From data in the Table 4.4, when the valve is fully opened, more volume of liquid is flowing passes a point within a second. Half opened valve resulted in volumetric flow rate value half than the value for fully opened valve. The pump characteristics described in the operating manual indicated that the full capacity of the pump is 1500 l/hr. It seems like the pump is not performing at its optimum capacity during the experiment. However, the reliability of the results can be ambiguous since it was done by one person only in which there might be a lot of human error where response time between taking the water volume and stopping the stopwatch will in some way affect the accuracy of readings.

4.4 Wax Deposition Removal

Through previous experiments on magnetic field lines and flow rate, four conditions have been identified and tested in the wax deposition removal experiment. For each condition, a total time of 4 hours was allocated with readings taken between 30 minutes interval. In order to get more precise results, each reading was taken 3 times and the average is the final value.

A weighing scale with sensitivity up to 3 or more decimal points was used to get accurate reading. It was assumed there is 0.1% of water in the pipe which was removed from all pipe mass readings. All values recorded are presented in table form available in Appendix section. Using these values, graphical representations are generated to highlight visible pattern changes through the graphs.

4.4.1 Sample Results for Configuration 1 with Valve Fully Opened

Table 4.5: Summary of mass for pipes

	Pipe A (g)	Pipe B (g)
Initial mass of pipe without wax	456.645	457.970
Initial mass of pipe with wax	468.787	468.800
Final mass of pipe with wax	468.506	468.799

Table 4.6: Mass of pipes over time

Time (Hour)	Pipe A	Pipe B
0.0	468.787	468.800
0.5	468.750	468.799
1.0	468.716	468.799
1.5	468.679	468.800
2.0	468.644	468.799
2.5	468.610	468.801
3.0	468.575	468.799
3.5	468.540	468.799
4.0	468.506	468.799

From data in Table 4.5 and 4.6, values for wax alone can be obtained. The mass for wax at any time is the difference between the values of mass of pipe at that particular time and the initial mass of pipe without wax.

Table 4.7: Mass of wax over time

Time (Hour)	Pipe A (g)	Pipe B (g)
0.0	12.142	10.830
0.5	12.105	10.830
1.0	12.071	10.830
1.5	12.034	10.830
2.0	11.999	10.830
2.5	11.965	10.830
3.0	11.930	10.830
3.5	11.895	10.830
4.0	11.861	10.829

Table 4.8: Summary of mass for wax

Initial mass of wax deposited	12.142	10.830
Final mass of wax deposited	11.861	10.829
Mass of wax removed	0.281	0.001

Removal rate is calculated by taking the total mass of wax removed per time in hours per magnetic flux density in Tesla. Sample calculation for removal rate in Pipe A is shown below:

Magnets arrangement = Configuration 1

Valve opening = Fully opened (373.32 L/hr)

Magnetic flux density = 0.01502 Tesla

Mass of wax removed = 0.281 g

$$\text{Removal rate} = \frac{0.281\ \text{g}}{(0.01502\ \text{Tesla})(373.32\ \text{L/hr})(4\ \text{hr})}$$

$$= 0.01253\ \text{g/L/Tesla}$$

$$= \underline{12.53\ \text{mg/L/Tesla}}$$

4.4.2 Results for All Conditions

Following are the graphical representation of results for all four conditions:

*R.R is the acronym for Removal Rate

Condition 1

Magnets arrangement = Configuration 1

Valve opening = Fully opened (373.32 L/hr)

Magnetic flux density = 0.01502 Tesla

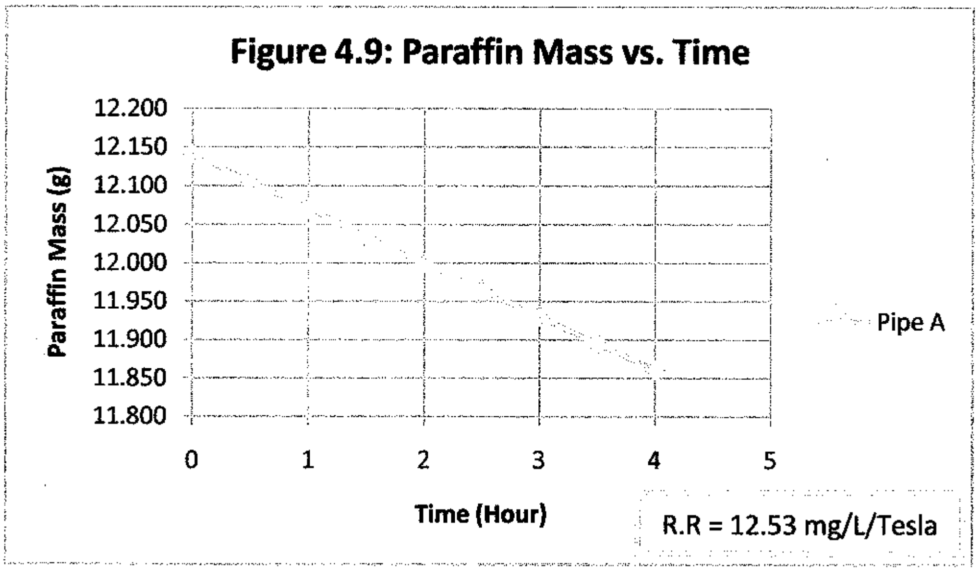


Figure 4.9: Graph of Paraffin Mass vs. Time 1

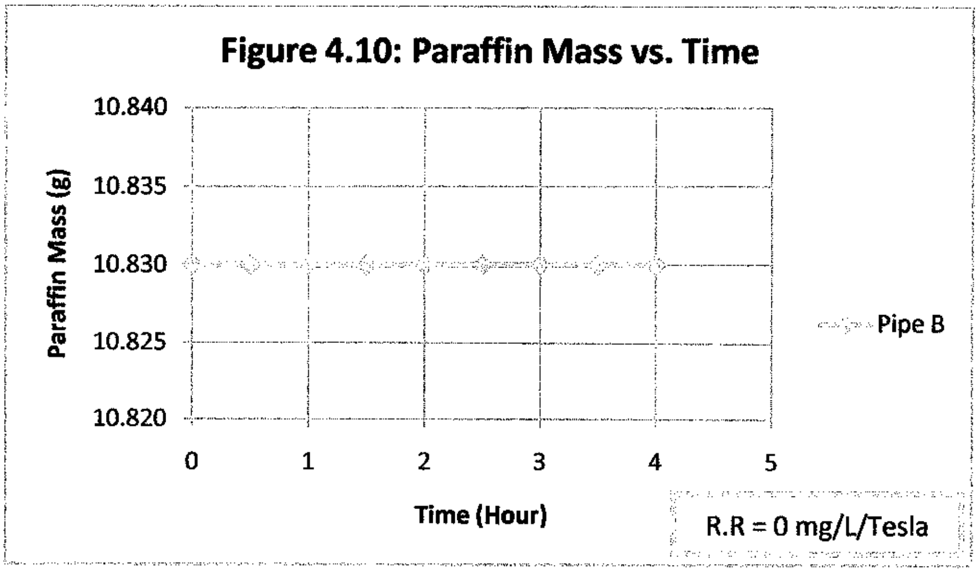


Figure 4.10: Graph of Paraffin Mass vs. Time 2

Graph in Figure 4.9 show the decreasing pattern of paraffin mass at a rate of 12.53 mg/L/Tesla as Pipe A is exposed to magnets with flux density of 0.01502 Tesla for a total time of 4 hours. Graph in Figure 4.10 is showing the changes of paraffin mass in Pipe B which is without any exposure to magnetic effect. As noticed, there are no changes in the paraffin mass at all or constant over time. Therefore, it is confirmed that the wax removed in Pipe A is purely because of magnetic effect that cause Lorentz force and not caused by fluid flowing through the pipe with certain flow rate.

Condition 2

Magnets arrangement	=	Configuration 1
Valve opening	=	Half opened (192.35 L/hr)
Magnetic flux density	=	0.01487 Tesla

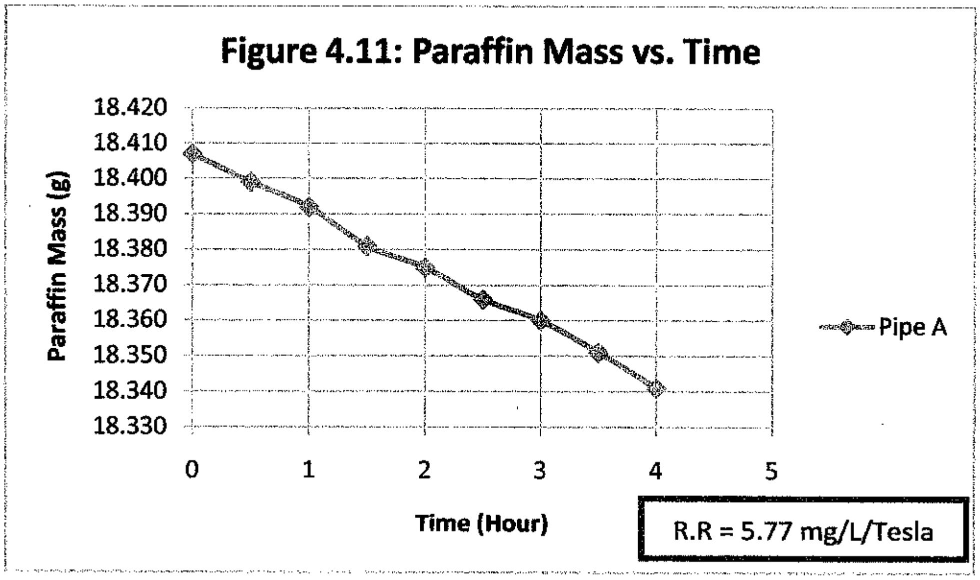


Figure 4.11: Graph of Paraffin Mass vs. Time 3

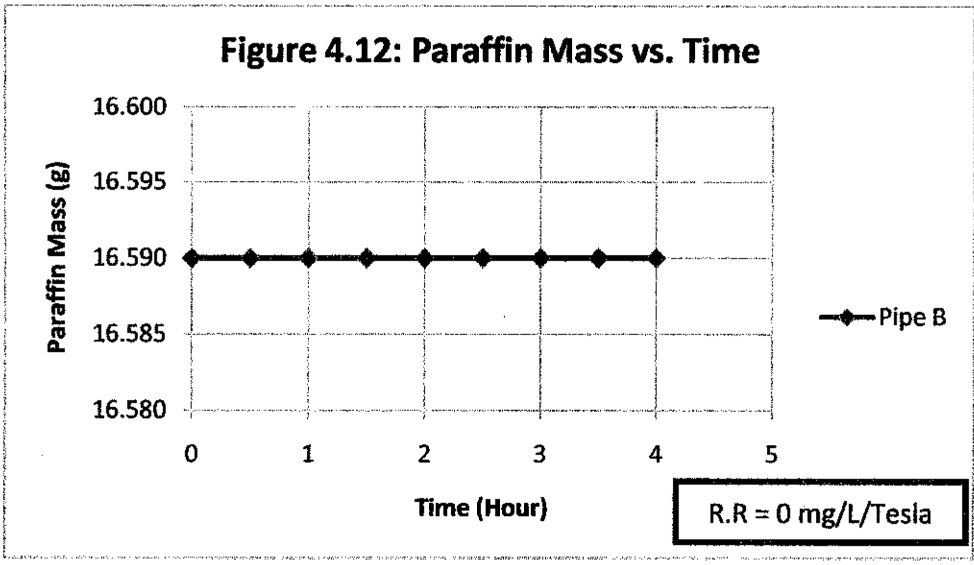


Figure 4.12: Graph of Paraffin Mass vs. Time 4

Graphs in Figure 4.11 and Figure 4.12 are the results obtained when the valve is half opened. When valve opening is halved, the volume of fluid that can pass through is also halved. One of the components of Lorentz force is fluid velocity which can be related to flow rate by the pipe cross sectional area. Thus, decrease in flow rate also decreases the magnitude of Lorentz force. As a result, removal rate in Pipe A which mounted the MFC is almost 54% less than the removal rate in the same pipe for condition 1. As for Pipe B which does not exposed to any magnetic effect, there is no reduction in the mass of deposited paraffin over the entire 4 hours period, similar to Pipe B for condition 1. The value of magnetic flux density for condition 2 is very close to the value for condition 1 as both conditions are using the same magnets configuration. Therefore, it can be concluded that flow rate plays important role in generating Lorentz force for wax removal rate but does not remove the wax single-handedly.

Condition 3

Magnets arrangement = Configuration 2

Valve opening = Fully opened (373.32 L/hr)

Magnetic flux density = 0.01205 Tesla

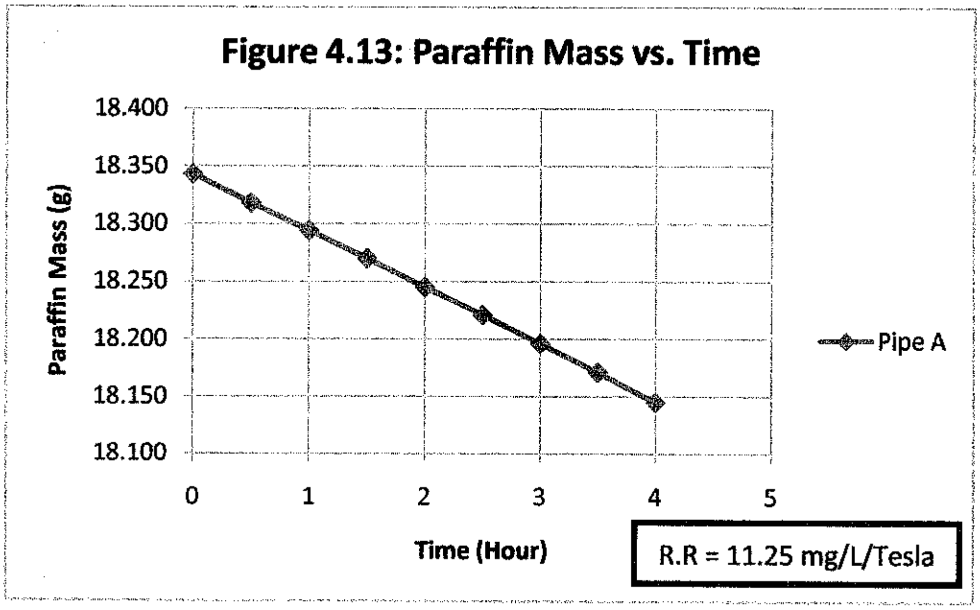


Figure 4.13: Graph of Paraffin Mass vs. Time 5

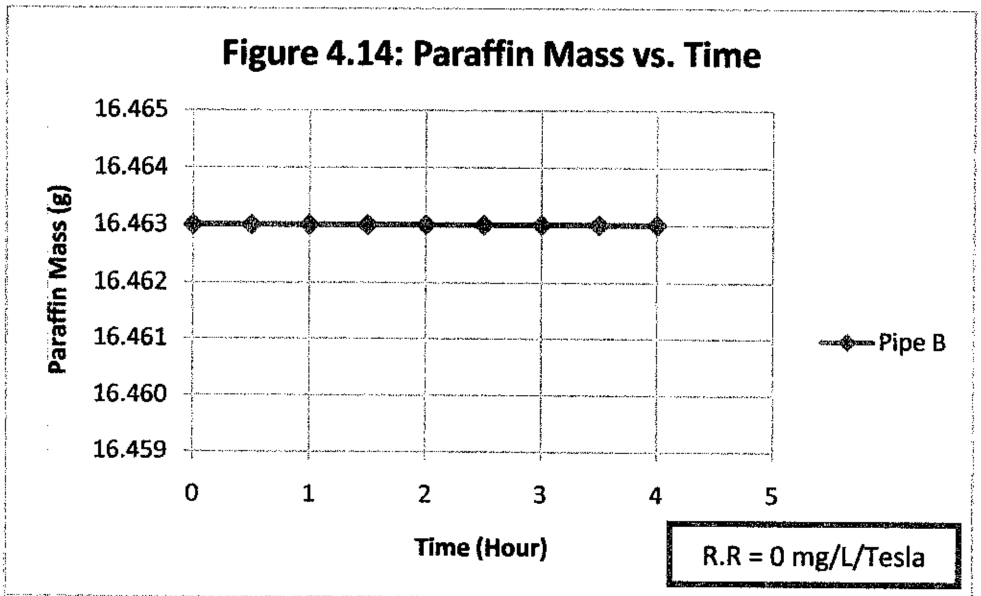


Figure 4.14: Graph of Paraffin Mass vs. Time 6

Magnets in condition 3 are arranged according to Configuration 2, where the magnetic flux density at the pipe is 0.01205 Tesla. This value is 20% less than the magnetic flux density when the magnets are arranged in Configuration 1. The reason behind this has been discussed in section 4.2.2. The valve is fully opened for condition 3 with flow rate of 373.32 L/hr. As can be seen from Figure 4.11, the mass of paraffin deposited in Pipe A decreased at a constant rate of 11.25 mg/L/Tesla, 10% less than the removal rate in Pipe A for condition 1 which is 12.53 mg/L/Tesla. Even though both conditions have the same volumetric flow rate, variation in magnetic flux density has made all the differences. For Pipe B, there is no reduction in the mass of deposited paraffin as in other previous cases of Pipe B because of the absence of magnetic effect.

Condition 4

Magnets arrangement = Configuration 2

Valve opening = Half opened (192.35 L/hr)

Magnetic flux density = 0.01201 Tesla

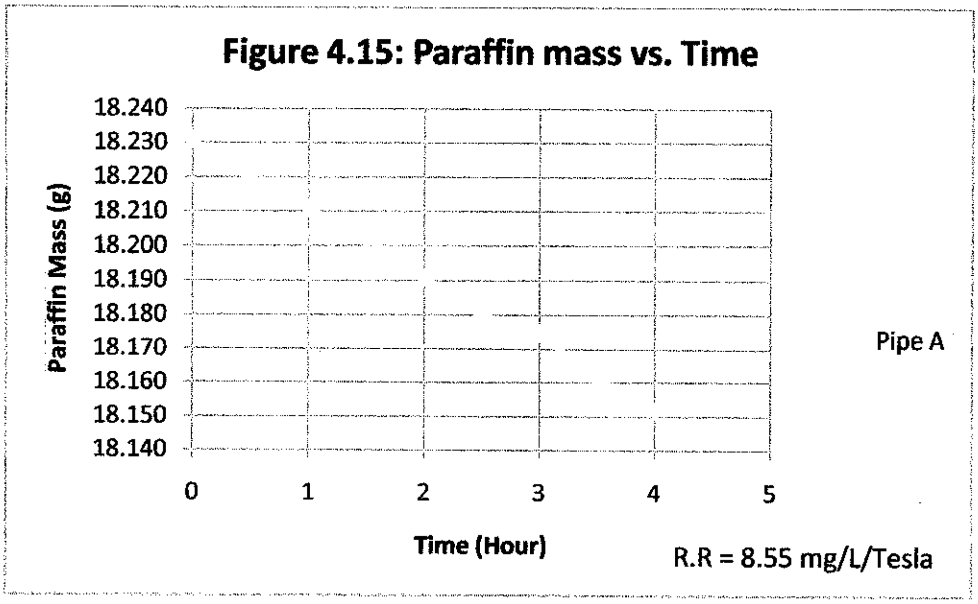


Figure 4.15: Graph of Paraffin Mass vs. Time 7

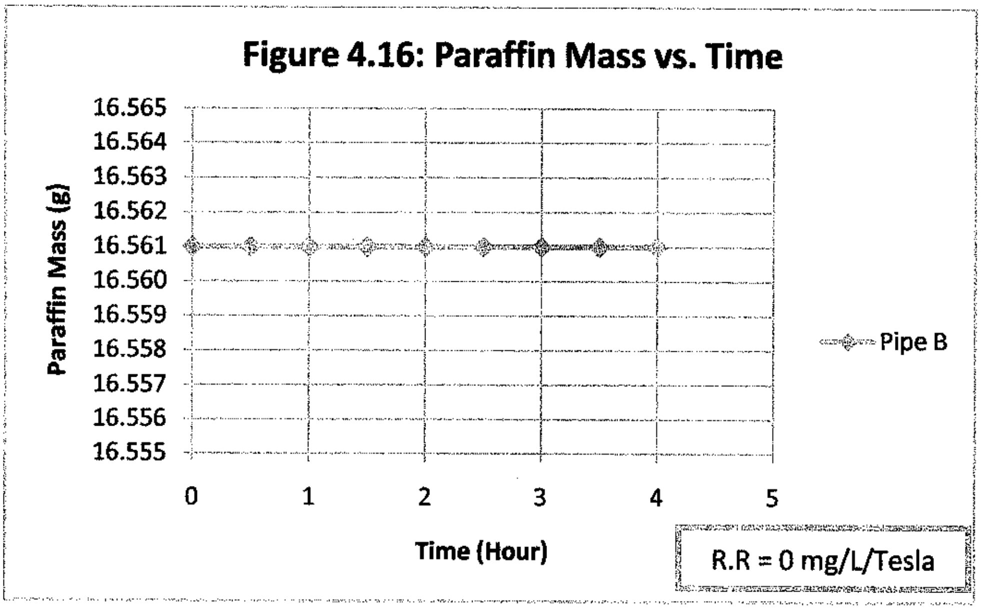


Figure 4.16: Graph of Paraffin Mass vs. Time 8

Magnets for condition 4 are arranged in according to Configuration 2 with the ball valve half opened allowing 192.35 L of fluid to flow per hour. From the graph in Figure 4.15, it can be observed that the mass reduction is at a constant rate of 8.55 mg/L/Tesla, although the pattern is not very smooth. This removal rate value is 24% less than the value for Pipe A in condition 3 due to smaller value of flow rate which directly affect the magnitude of Lorentz force. However, this removal rate is 33% more when compared to result for condition 2 which uses Configuration 1 with the valve half opened. Theoretically, this situation supposes to be in the other way since the magnetic flux density for condition 4 is lesser than condition 2.

This error might occur due to human error as well as system error when taking readings using the weigh scale. The scale is very sensitive even to the presence of surrounding air and the result displayed fluctuates randomly. Thus, this property might contribute to the described error because some readings might be taken even before the number stabilized. Apart from that, poorly calibrated equipment might also contribute to the situation. Due to fact that the experiment for each condition is carried at different time, the equipment may have been calibrated without the knowledge of user and thus a reading with different value of tolerance is taken every time.

4.4.3 Best Condition for Wax Removal

Table 4.9: Summary results of Pipe A for all conditions

Condition	Configuration	Valve Opening	Flow Rate (L/hr)	Magnetic Flux Density (Tesla)	Removal Rate (mg/L/Tesla)
1	1	Full	373.32	0.01502	12.53
2	1	Half	192.35	0.01487	5.77
3	2	Full	373.32	0.01205	11.25
4	2	Half	192.35	0.01201	8.55

Table 4.9 is a summary of results for Pipe A with magnet effect, for all four conditions. Pipe B is not included since there is absolute no significance reduction in the mass of deposited wax. From the table, it is obvious that the highest removal rate occurred in condition 1 when pipe with deposited wax was exposed for 4 hours to magnets arranged in Configuration 1 with flux density of 0.01502 Tesla and flow rate of fluid at 373.32 L/hr. Therefore, condition 1 was used in the following viscosity reduction experiment to investigate the effect of magnetic force on viscosity.

4.5 Viscosity Reduction

Temporary viscosity reduction is a direct effect of the interaction between MFC with fluid. As discussed in methodology section 3.5, there are two parts to this experiment. First is to observe the pattern of viscosity reduction over a total time of 2 hours and second is to determine the time taken for the fluid viscosity to return to initial viscosity after been exposed to MFC for a certain period of time. Readings for both cases are taken at 15 minutes interval and all unit of viscosity are in centi-Poise (cP).

A pure diesel sample was tested as well and the viscosity is found to be 3.13 cP. The difference in viscosity between waste and pure diesel is at 25%. However, the amount of available pure diesel is not adequate for this experiment due to diesel selling policy.

4.5.1 Changes in Viscosity over Exposure Time

Table 4.10: Viscosity of Waste Diesel over Time

Time (minutes)	Viscosity (cP)
0	2.34
15	1.56
30	0.78
45	0.78
60	0.78
75	0.78
90	0.78
105	0.78
120	0.78

Initial viscosity of the fluid used which is waste diesel is found to be 2.34 cP. After 30 minutes of exposure to magnetic effect from MFC with flux density of 0.01502 Tesla, the value dropped to 0.78 cP and remained at that value for the remaining experiment time. The graph that follows is a graphical representation to show the change pattern of viscosity over the time. As seen from Figure 4.17, the graph is a linear line connecting all the points. The reduction in viscosity with respect to time according to the study conducted by Marques and Rocha (1997) is supposed to be an exponential smooth curve. Readings can be taken between shorter intervals for results improvement.

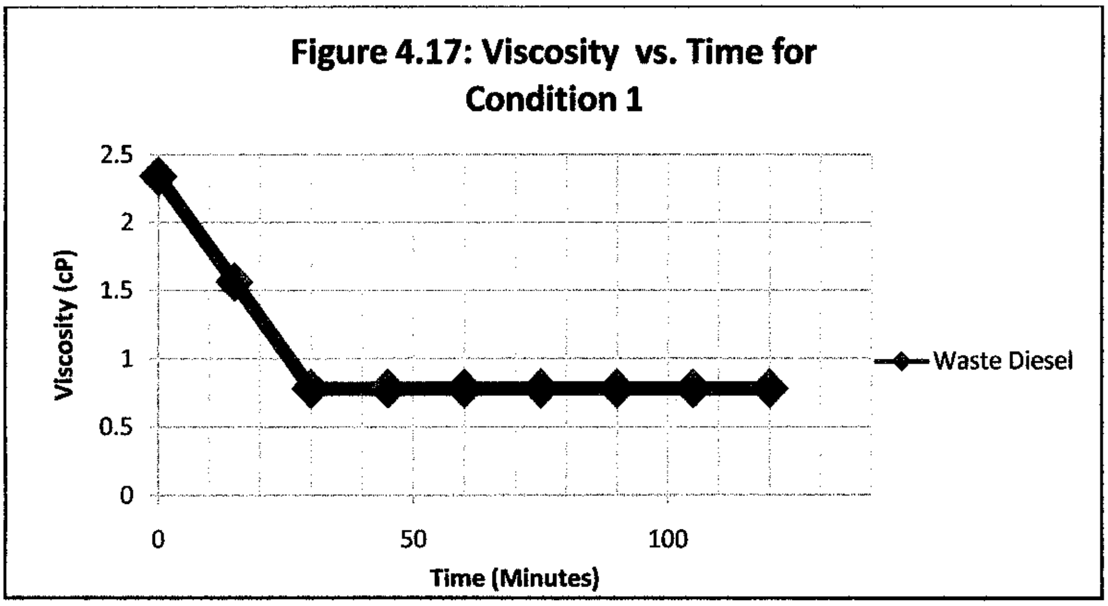


Figure 4.17: Graph of Viscosity versus Time for Waste Diesel

4.5.2 Time taken to return to Initial Value

Table 4.11: Viscosity of idle Waste Diesel over Time

Time (minutes)	Reading 1 (cP)	Reading 2 (cP)	Reading 3 (cP)	Average (cP)	Standard Deviation
0	0.78	0.78	0.78	0.78	0.0000
17	0.78	0.79	0.78	0.78	0.0058
31	0.78	0.78	0.78	0.78	0.0000
65	0.79	0.78	0.78	0.78	0.0058
78	1.54	1.54	1.56	1.55	0.0115
94	1.55	1.56	1.55	1.56	0.0058
114	2.34	2.34	2.33	2.34	0.0058
139	2.33	2.35	2.34	2.34	0.0100

After 30 minutes of experiment run, a sample of waste diesel was taken and measured its viscosity. This sample was then left idle before the next measurement was taken. As can be seen from the table above, the time interval is not consistent because this experiment is run concurrently with the experiment to observe changes in viscosity over time. However, these values are reliable because readings were taken for at least three times each time and the average value is taken as the final value. At 114 minutes, the value of viscosity has returned to its initial value of 2.34 cP. With this result, it is proven that MFC does impose magnetic effect that could momentarily reduce the fluid viscosity. However, it is highly recommended to repeat this experiment with consistent and smaller time interval so that the exact time the viscosity changes can be determined. To use crude oil instead of waste diesel is also highly recommended to observe the situation in actual condition. The graph below is a graphical representation of the data in Table 4.11.

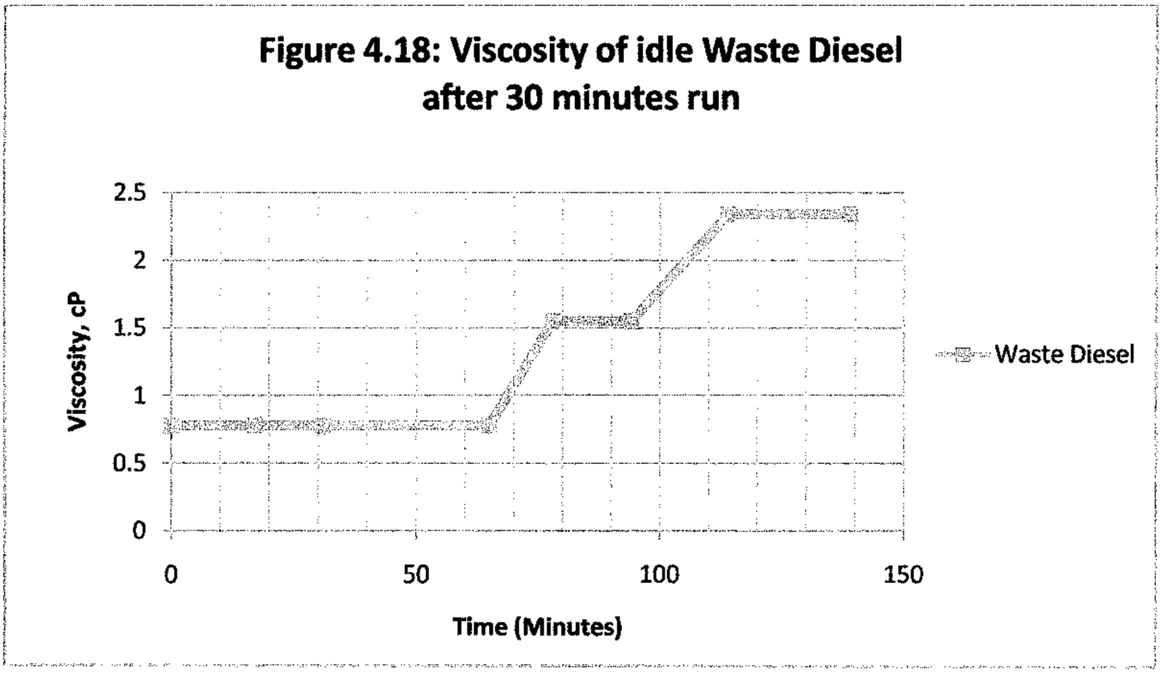


Figure 4.18: Graph of Viscosity versus Time for idle Waste Diesel

CHAPTER 5

CONCLUSION

Waxy crude consists of a variety of light and intermediate hydrocarbons, wax and other non-hydrocarbon compounds. Under different temperature and pressure, these components can exist in different states of matter. When paraffin reaches Wax Appearance Temperature (WAT), paraffin starts to precipitate. Paraffin deposition from waxy crude causes many problems in crude oil production such as clogging of well tubing and surface flowlines, etc.

Viscosity of crude increases with respect to temperature drop during production. Viscous crude impairs transportation where high viscosity leads to huge pressure drop in pumping. There are many methods to control paraffin deposition, for instance, mechanical scrapping and chemical injection. Current method to reduce crude viscosity includes heat dilution.

However, all methods to control paraffin deposition and lower viscosity will be difficult to apply as petroleum industry moves towards deep-sea well. New methods of paraffin control have been developed through microbial technology, electromagnetic field technology, ultrasonic technology and magnetic field technology.

Magnetic field technology is of interest in this project, where the effects of magnetic field of Magnetic Fluid Conditioner (MFC) on paraffin deposition and viscosity reduction are to be investigated. Magnetodydrodynamics and Lorentz are the governing principle behind paraffin deposition control while dipole interaction is the key for viscosity reduction.

There are four main objectives of this project, first is to produce a set of information on paraffin wax behavior under magnetic field. The second objective is to study the effect of magnetic field in paraffin wax deposition control. These two objectives are achieved partially through information gathering on works conducted by other people on this subject and another through analysis of experiment results. The third objective is to investigate the effect of magnets orientation, magnetic field density and flow rate on removal rate. The fourth objective is to investigate the direct effect of magnetic field on crude viscosity. Both the third and fourth objectives were achieved through the conduct of experiments and analysis of results obtained.

Experiment was designed in order to achieve these objectives with mass of paraffin removed as direct indicator of effectiveness in deposition control. On the other hand, viscosity values measured using viscometer indicates the magnetic field effect on viscosity. Out of the eight different combination of magnets position, based on the magnetic field lines pattern produced, two configurations, namely Configuration 1 and Configuration 2, have been further investigated in the following experiment. In addition, the opening of the ball valve either in full or half has produced 4 different conditions to be investigated.

Another component of Lorentz force, magnetic field density for each condition has been measured using a magnetometer. Condition 1 and 2 which applies Configuration 1 have the highest value with 0.01502 Tesla followed by condition 3 and 4 which applies Configuration 2 with 0.01205 Tesla. The results from this measurement reveal that the magnets arrangement does indeed affects the magnetic flux density and that the opening of valve which directly controls the flow rate does not influence the value of magnetic flux density.

Galvanized Iron (G.I) pipes were used in the wax removal experiment. This material is the closest to the real situation where Carbon Steel (C.S) pipes were used. This experiment was run under 4 different conditions where results show that condition 1 is the best with the highest removal rate of 12.52 mg/L/Tesla followed by condition 3 with 11.25 mg/L/Tesla and condition 4 with 8.55 mg/L/Tesla. Lowest removal rate is 5.77 mg/L/Tesla in condition 2. From the results, it is concluded that flow rate of flowing fluid affects the removal rate greatly. Velocity of fluid, which is part of the components of Lorentz force, is related to flow rate by the cross-sectional area of the pipe. Condition 1 was further investigated for potential in viscosity reduction.

First part of viscosity experiment disclosed that reduction in viscosity is indeed a direct effect of magnetic force by MFC on flowing fluid. Waste diesel with initial viscosity of 2.34 cP was used in this experiment. After circulation and exposure to MFC for total time of 2 hours, the final viscosity is 0.78 cP, a reduction of 67%. The second part of viscosity experiment was on the time taken for the viscosity of fluid to return to initial value. A sample of waste diesel which was exposed to MFC for 30 minutes was measured for viscosity and left idles for a period of time before the next measurement. Results obtained shows that the viscosity returned to initial value after 114 minutes. This value will be different when another liquid with different properties is tested. Therefore, taking into account the time for the viscosity to return to initial value, converted proportionally to the distance travelled by fluid in the pipeline. The installation distance of one MFC with another MFC along the pipeline must be carefully planned so that before the viscosity of fluid could increase to initial value, magnetic field from the next MFC will act on the fluid, which will decrease the viscosity or maintain the low value for a very long period until arrival at end of pipeline.

All in all, this study has achieved all the objectives as stated before. Study on paraffin behavior and effects of magnetic field on paraffin have been discussed in the literature review section where all related theories and hypothesis have been reviewed. This experiment also has provided experimental evidences to support the claim of the use of magnetic field in controlling wax deposition problem and reduce crude viscosity. Results from this study will have significant impact in the industry to solve problems in crude production and transportation.

CHAPTER 6

FUTURE WORKS AND RECOMMENDATIONS

Future works and improvements for project's continuation have been identified as follows:

1. To investigate effect of different type of magnets in experiment.
   Magnets can be made from many categories of materials and each material provides different properties to the magnet. Using variation in magnet type will produce more comprehensive data as compared to only one type of magnet.

2. To investigate the combination effect of both conventional method and magnetic field on the removal of deposition.
   Execution of conventional paraffin removal method with magnetic field method should be looked into in terms of effectiveness and economic wise. Decision to apply only one method or more will affect integrity of equipment and pipeline as well as the company.

3. To design experiment for study on magnetic field effects on paraffin inhibition.
   Magnetic field generated by MFC has been proven in terms of paraffin removal. A study on paraffin inhibition should be carried out to assess the ability of magnetic field to prevent wax build-up. If proven, magnetic field technology will be the ultimate method in both inhibit and removal of paraffin deposits.

4. To investigate use electromagnetic field in paraffin deposition control.
   Electromagnetic field is a combination of magnetic field and electric field. The effectiveness of additional effect with electric field on paraffin should be investigated.

REFERENCES

ASTM International, http://www.astm.org/e617-97/htm, Standard Specification for Laboratory Weights and Precision Mass Standards. Visited on 2 November 2008.

Attomi A., Musrati I.EL, Gammoudi B.EL, "Microbial Prevention of Wax Deposition during Transportation and Production of Crude Oil", 2005. Retrieved on 24 May 2008 from
http://www.lpilibya.org/web/index.php?option=com_docman&task=doc_view&gid =42

Furlow. W, September, "Magnetic fluid conditioners' success depends on factors", 1998. Retrieved on 2 February 2008 from http://www.offshore-ag.com/articles/ARTICLE_ID=24268

Garcia M.C., "Paraffin Depostion in Oil Production", 2001.
Society of Petroleum Engineers Inc.

Giangiacomo. L, "Rocky Mountain Oilfied Testing Center Project Test Results", 1997. Retrieved on 2 May 2008 from http://www.rmotc.doe.gov/Pdfs/96pt12.pdf

Kabir A.H, Haron J, "Scaling Challenges in Tinggi Operation – A Case History of Scaling Management", 2000. Society of Petroleum Engineers Inc.

Kadir A.A.A., Ismail I. and Sengodan P., "Managing Paraffin Wax Deposition in Oil Well", Universiti Teknologi Malaysia, Skudai, Johor, Malaysia, 1997. Retrieved on 29 February 2008 from http://eprints.utm.my/4089/

Leiroz A.T. and Azevedo L.F.A, "Studies on the Mechanisms of Wax Deposition in Pipelines", Offshore Technology Conference, 2005. Retrieved on 24 May 2008 from http://202.120.57.205/cdbook/otc-2005/pdfs/otc17081.pdf

Loskutova. Yu.V., Yudina, N.V., Pisareva S.I., "Effect of Magnetic Field on the Paramagnetic, Antioxidant, and Viscosity Characteristics of Some Crude Oils", 2008. Retrieved on 20 April 2008 from http://www.springerlink.com/content/h25190652368041g/fulltext.pdf

Mag-Tek Incorporated, <http://www.magtekinc.com/>. Visited on 26 March 2008.

Marques L.C.C., Rocha N.O., Machado A.L.C., Neves G.B.M, Viera L.C., Dittz C.H., "Study of Paraffin Crystallization Process Under The Influence of Magnetic Fields and Chemicals", Petrobas Research Center, Rio de Janeiro, Brazil, 1997. Retrieved on 26 March 2008 from http://www.magtekinc.com/services1.htm

Odessa, "Magnetics, do they really inhibit Paraffin & Mineral Scale Deposition?", 2002. Retrieved on 25 May 2008 from http://www.magniflo.com/Papers/MAGNETICS,%20DO%20THEY%20REALLY.pdf

Phuong Thung, Van Huong, "Studying the Mechanism of Magnetic Field Influence on Paraffin Crude Oil Viscosity and Wax Deposition Reductions", 2001. Society of Petroleum Engineers Inc.

Tao R. and Xu X.., "Reducing the Viscosity of Crude Oil by Pulsed Electric or Magnetic Field", Temple University, Philadelphia, Pennsylvania, 2006. Retrieved on 5 February 2008 from http://pubs.acs.org/cgibin/abstract.cgi/enfuem/2006/20/i05/abs/ef060072x.html

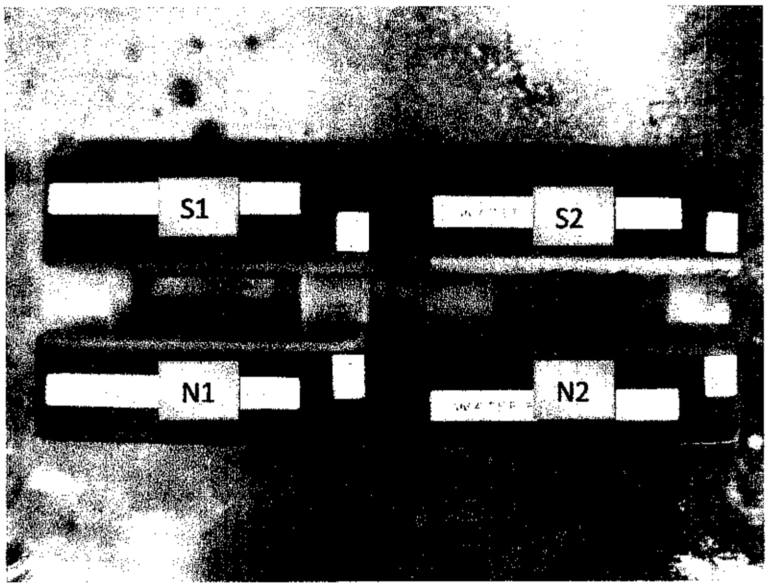
Truman A.H, Walmsley M, Osman A, Rahim Z.A, "Magnetic Fluid Conditioners Eliminate Severe Scale Problem on South China Sea Offshore Oil Platform", 2002. 30th Annual Australasian Chemical Engineering Conference.

Wang B. and Dong L., "Paraffin Characteristics of Waxy Crude Oils in China and the Methods of Paraffin Removal and Inhibition", 1995. Society of Petroleum Engineers Inc.

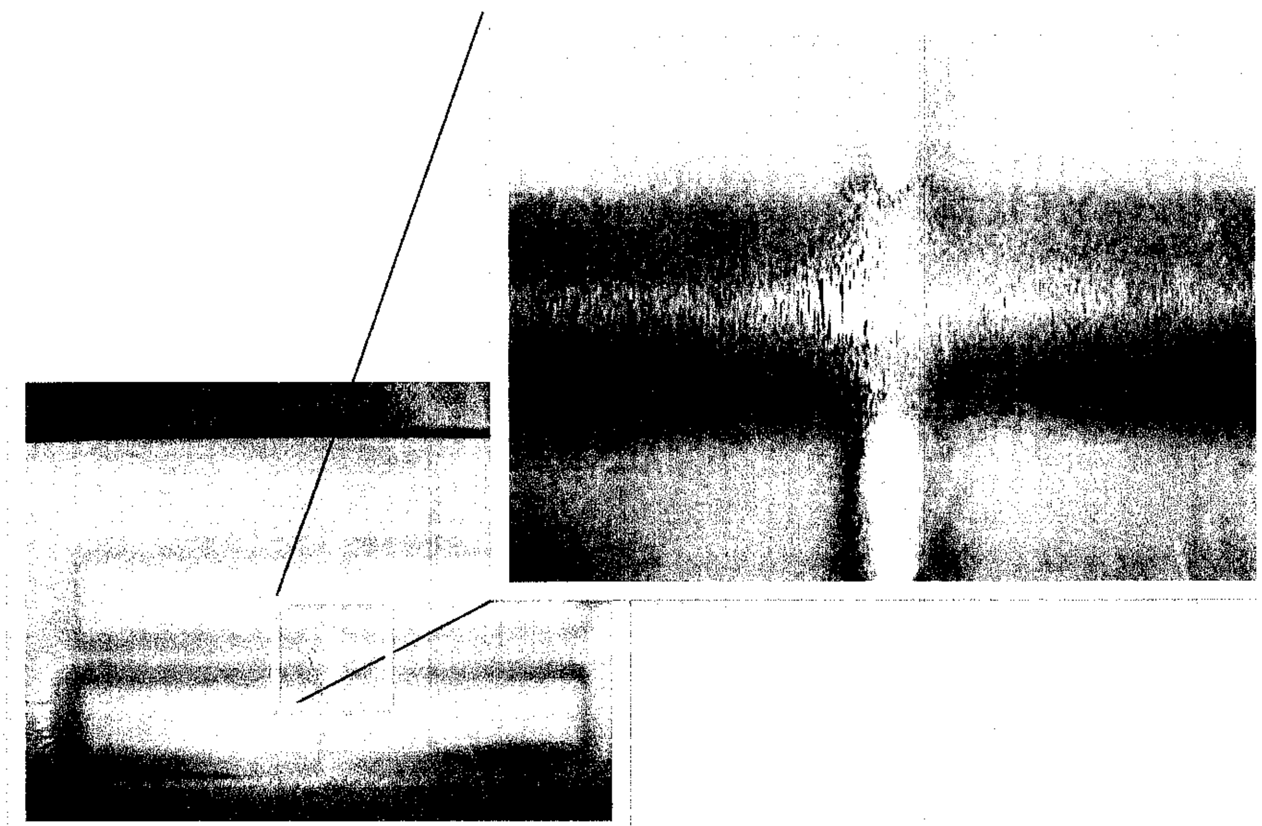
Wiltz, J and Ditzig, A.F., "Magnetic fuel treatment apparatus for attachment to fuel line", 2005. Retrieved on 23 May 2008 from
http://www.patentstorm.us/patents/6890432-escription.html

Zulkifli Abdul Rahim, "Solution to Scale Control in the Tinggi Offshore Oillfield", 2002. Petronas Carigali Sdn Bhd, Malaysia (PCSB).

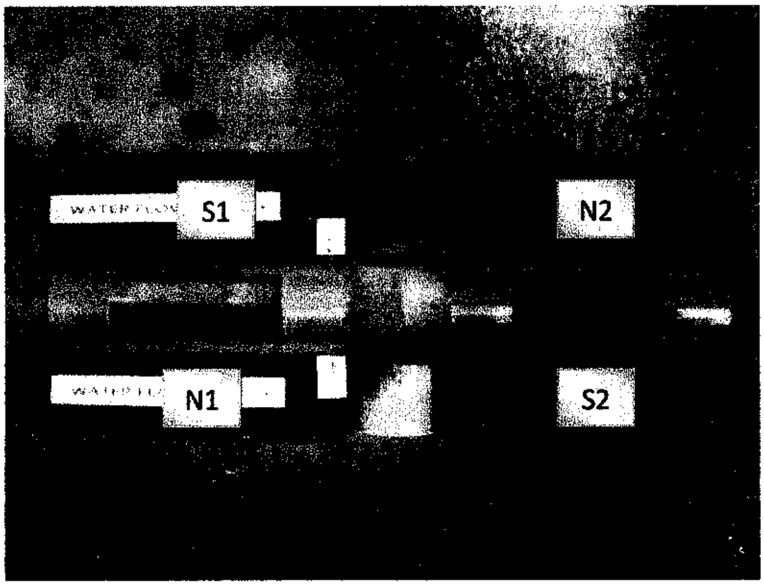
APPENDIX 1



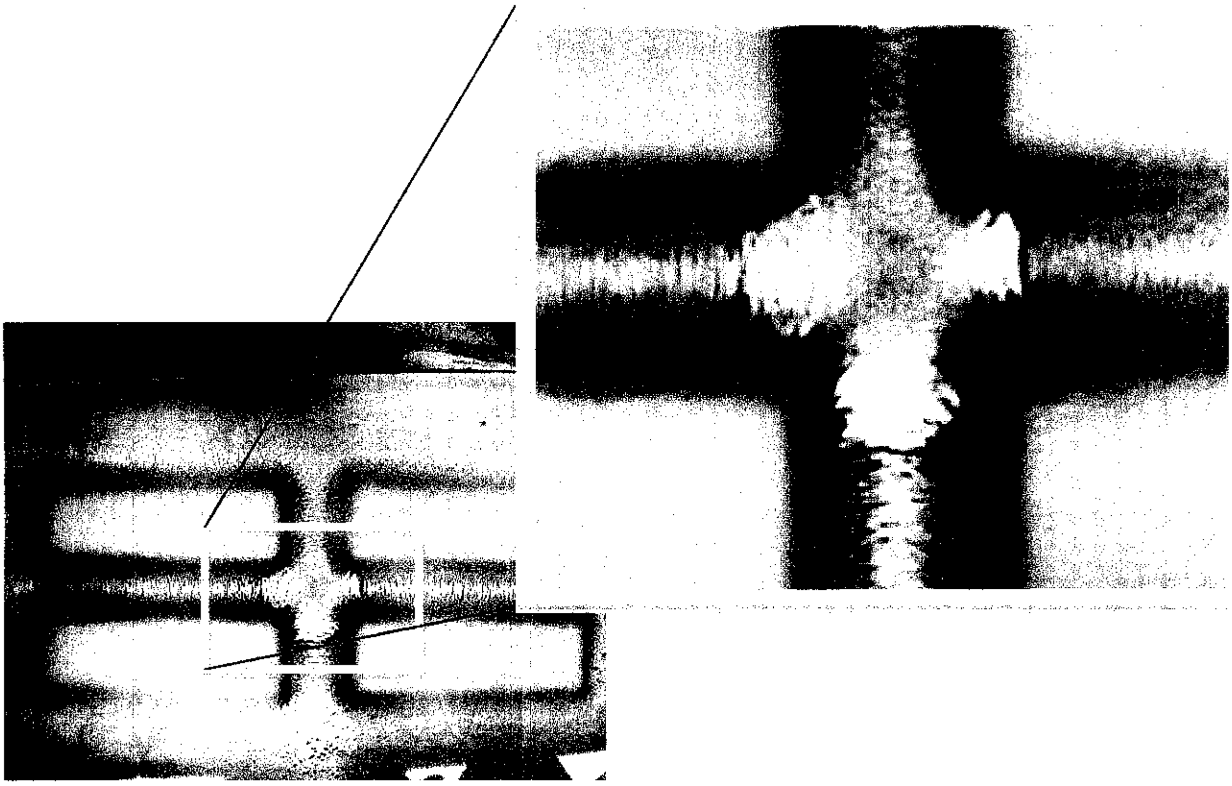
Appendix 1.1: Magnets arrangement (Con. 1)



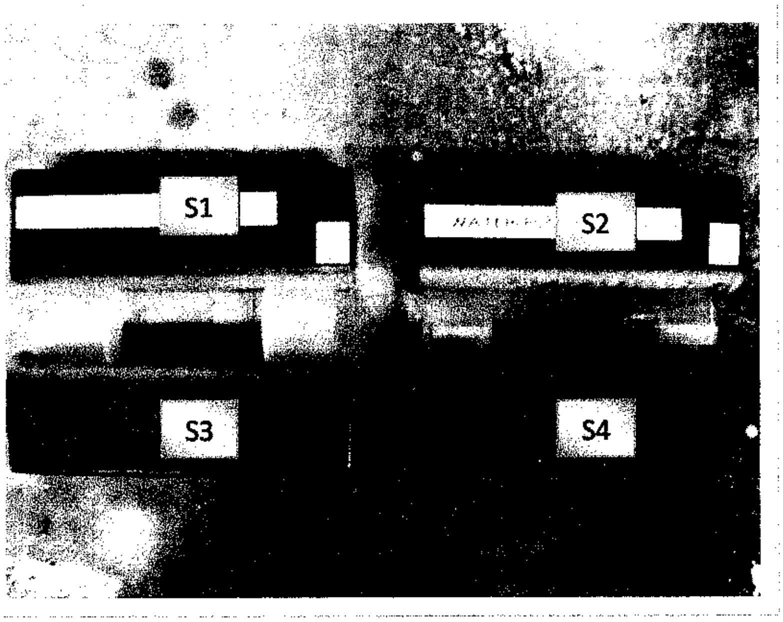
Appendix 1.2: Actual field pattern (Con. 1)



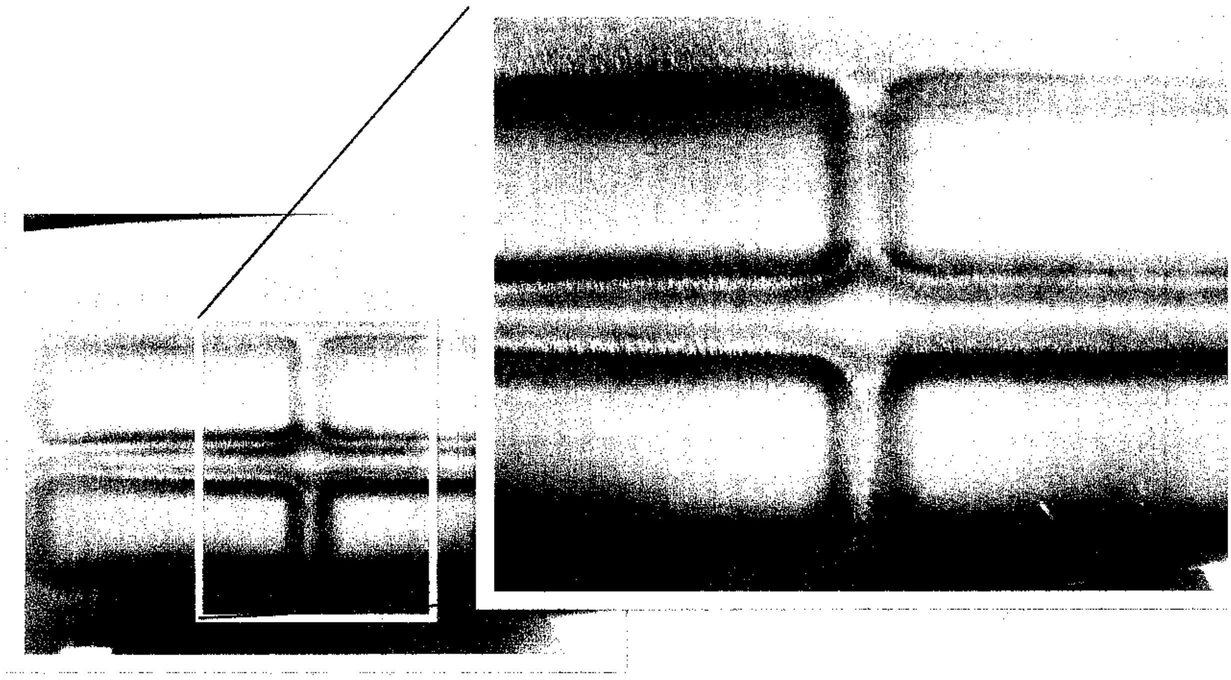
Appendix 1.3: Magnets arrangement (Con. 2)



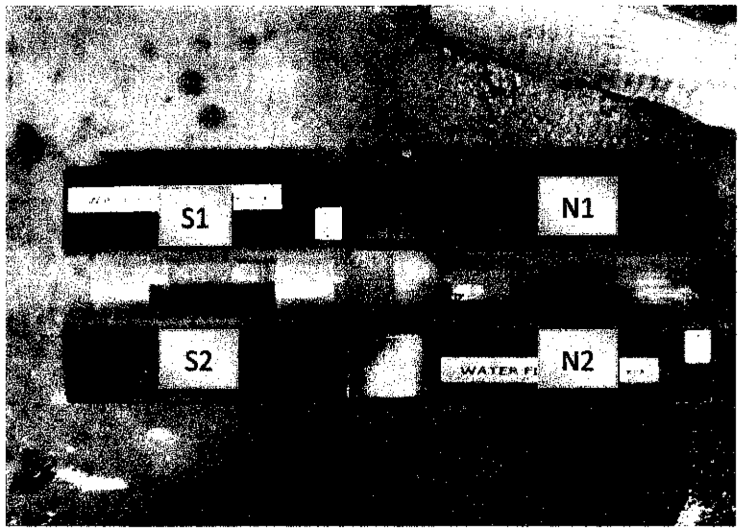
Appendix 1.4: Actual field pattern (Con. 2)



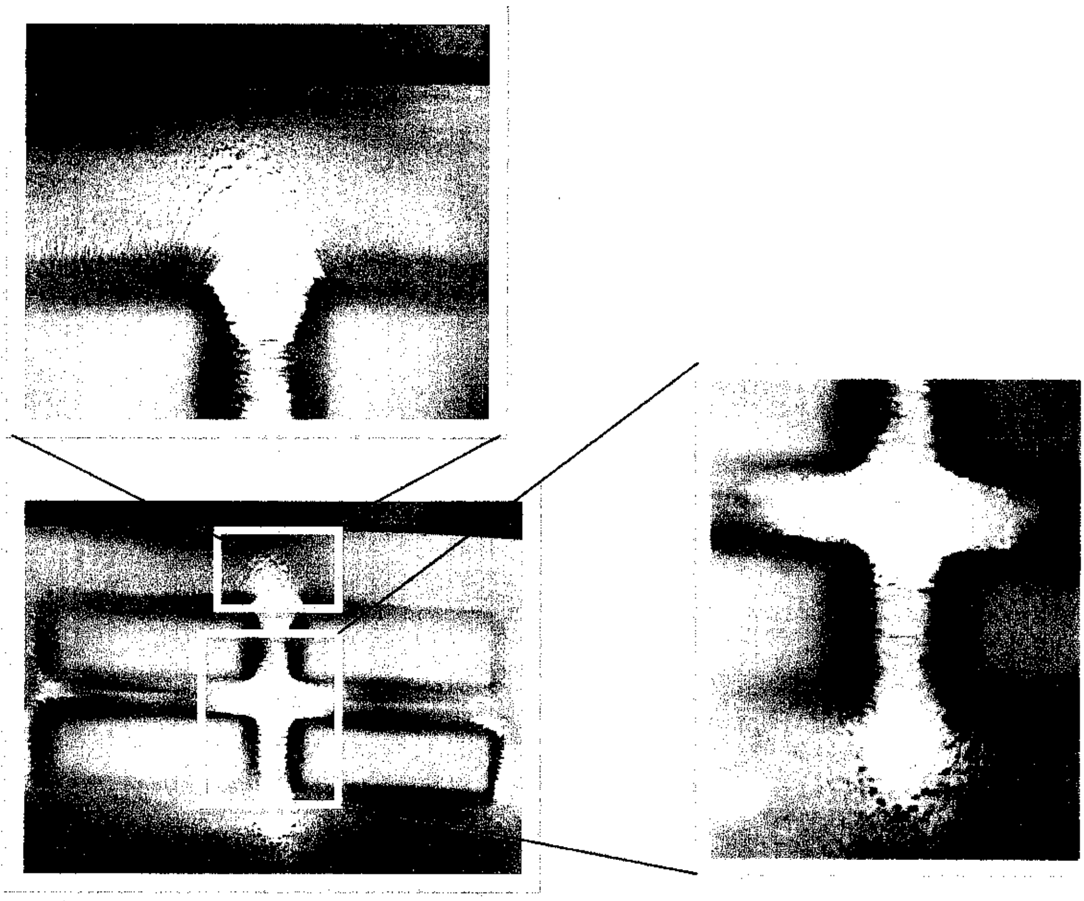
Appendix 1.5: Magnets arrangement (Con. 3)



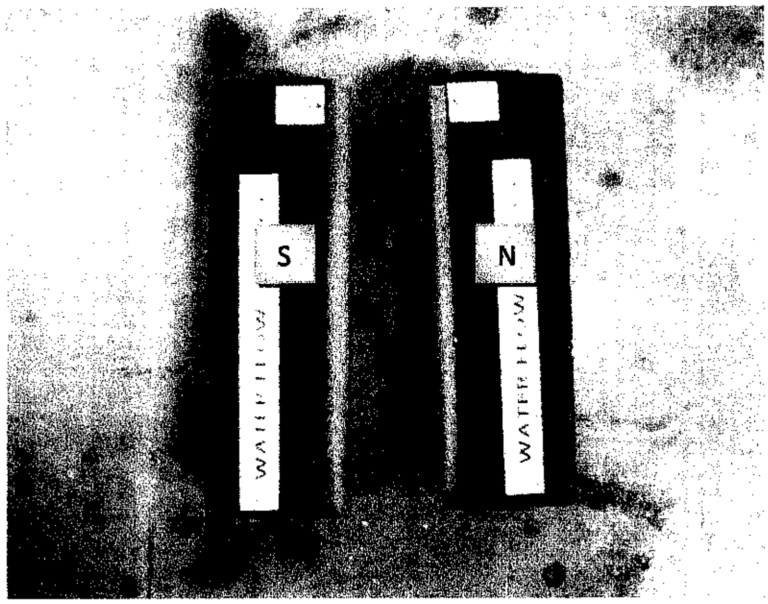
Appendix 1.6: Actual field pattern (Con. 3)



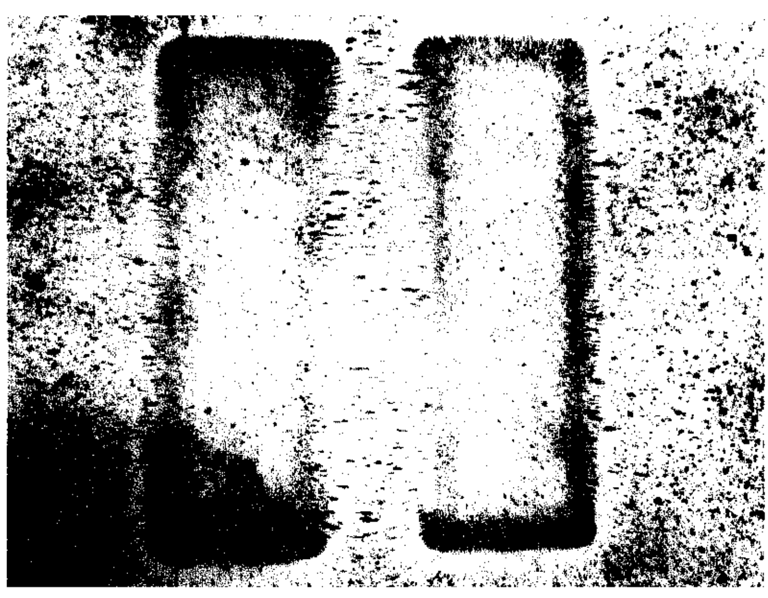
Appendix 1.7: Magnets arrangement (Con. 4)



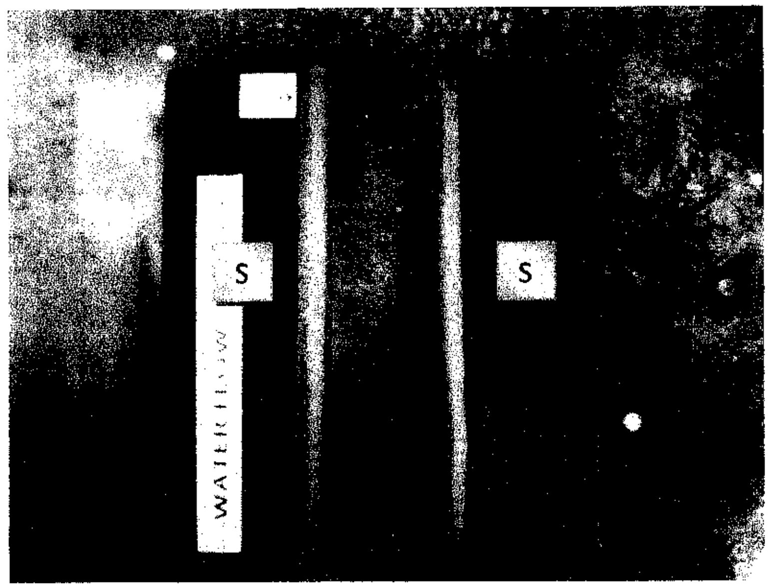
Appendix 1.8: Actual field pattern (Con. 4)



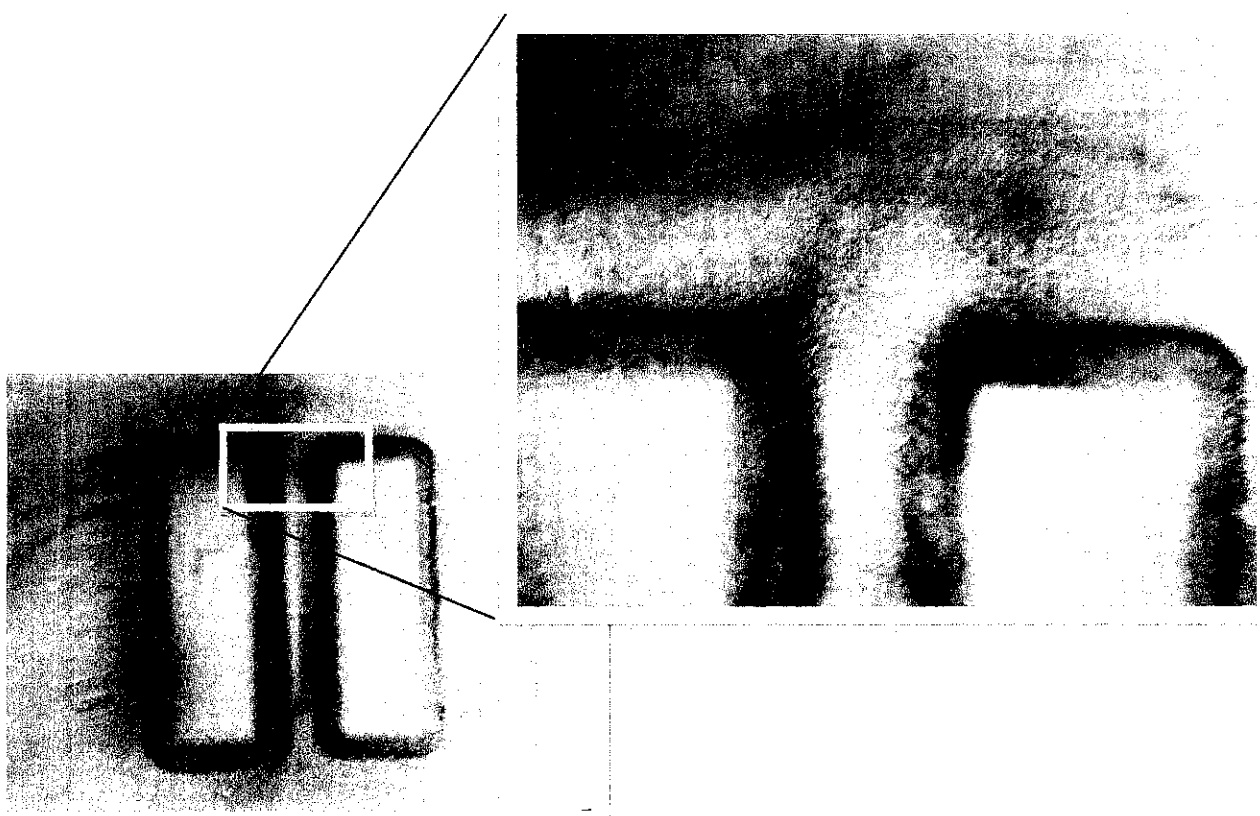
Appendix 1.9: Magnets arrangement (Con. 5)



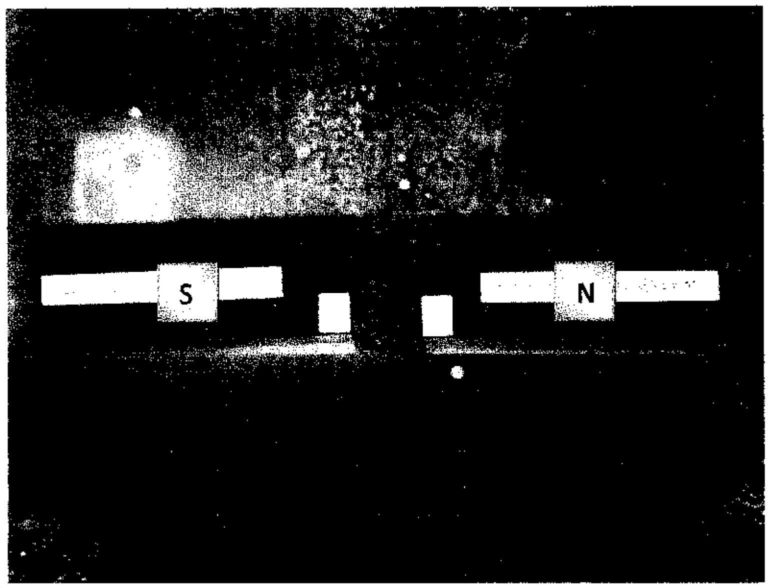
Appendix 1.10: Actual field pattern (Con. 5)



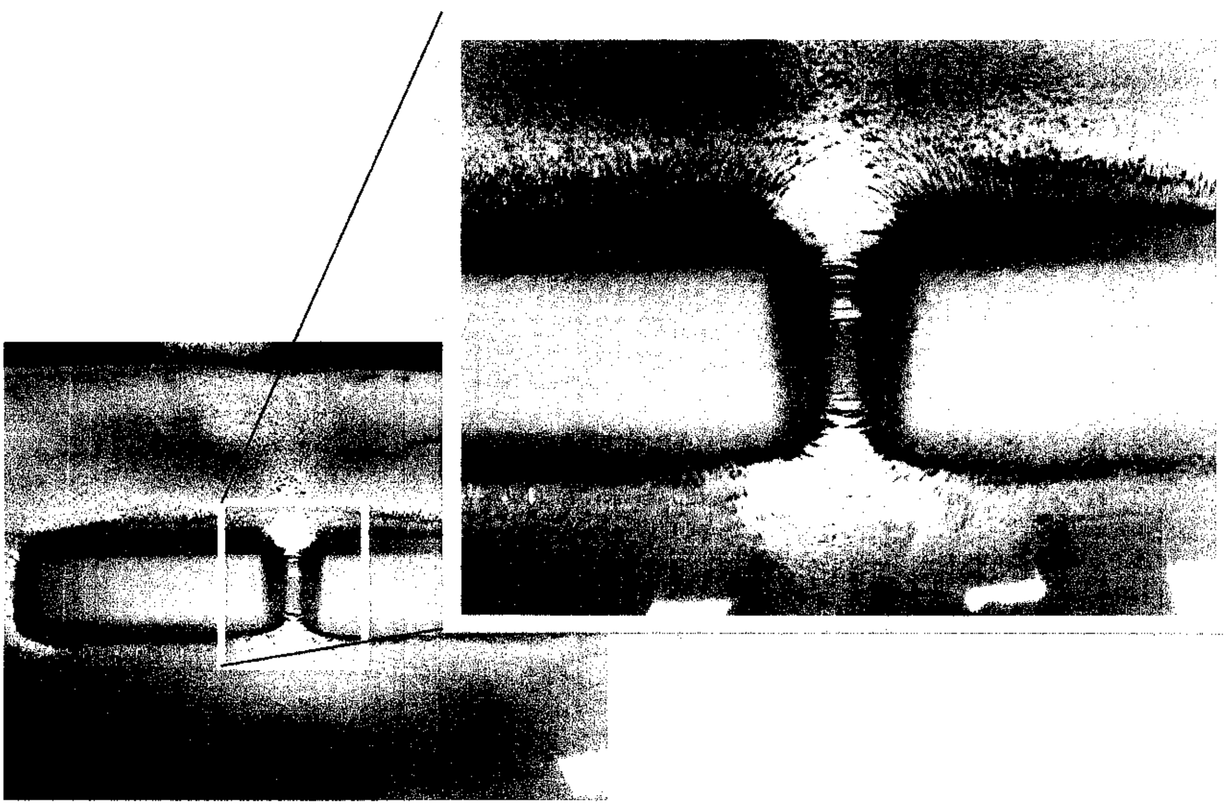
Appendix 1.11: Magnets arrangement (Con. 6)



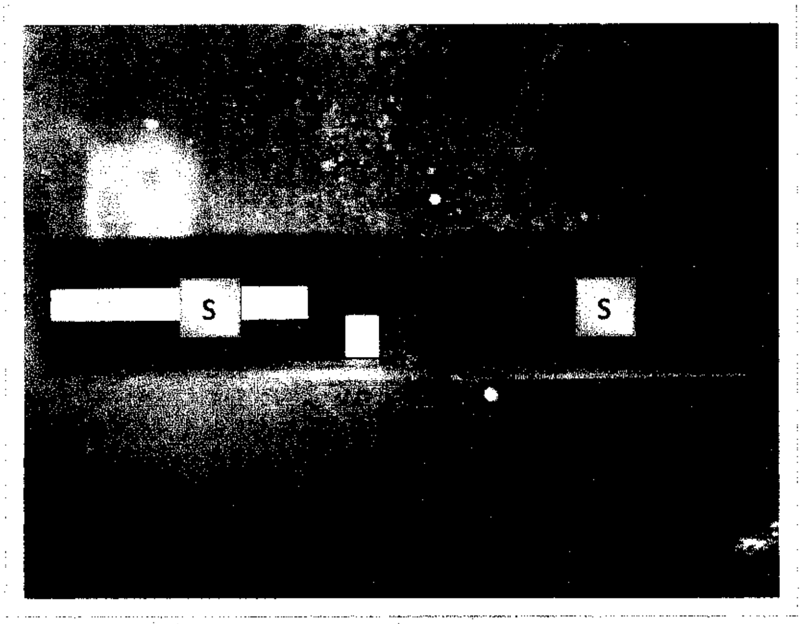
Appendix 1.12: Actual field pattern (Con. 6)



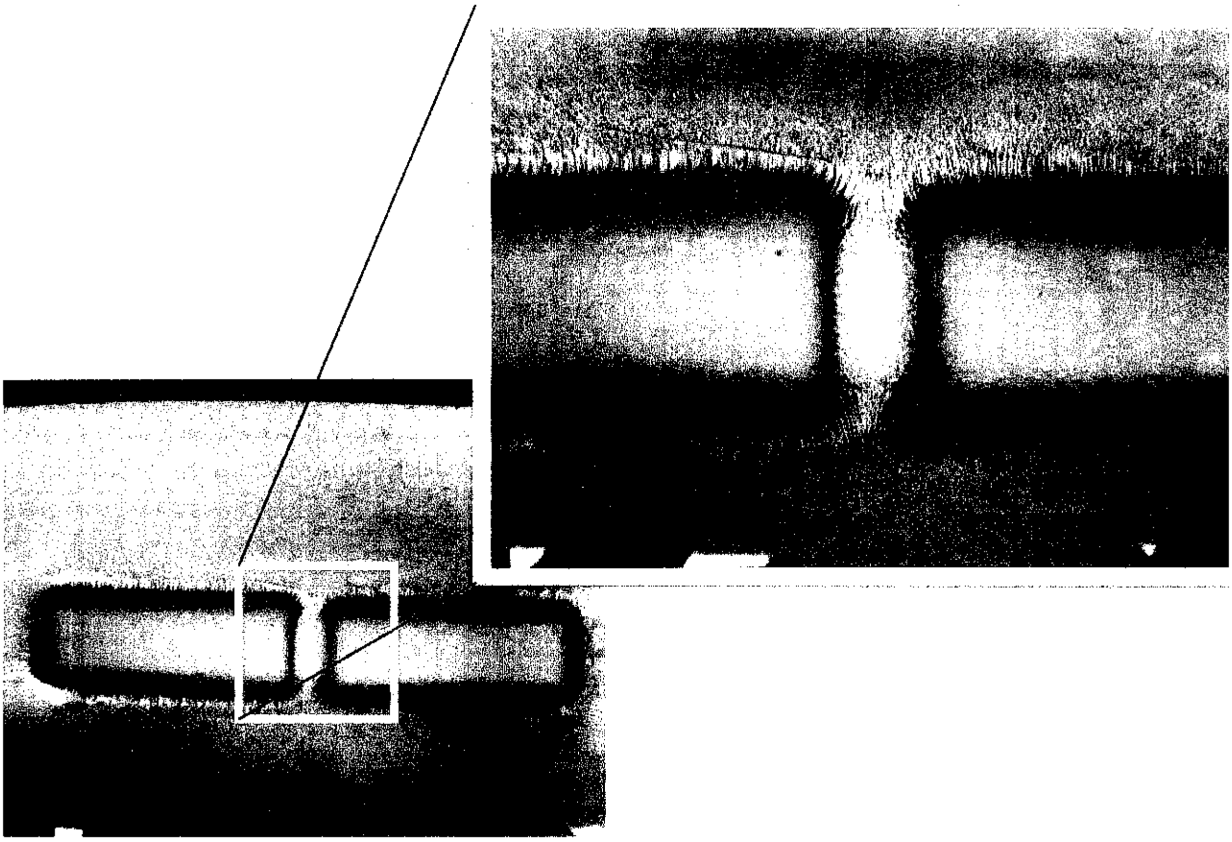
Appendix 1.13: Magnets arrangement (Con. 7)



Appendix 1.14: Actual field pattern (Con. 7)



Appendix 1.15: Magnets arrangement (Con. 8)



Appendix 1.16: Actual field pattern (Con. 8)

APPENDIX 2

Appendix 2.1: Magnetic Flux Density for Pair S1&N1 of Condition 1

(Configuration 1 with Valve Fully Opened)

Point	Reading 1	Reading 2	Reading 3	Average Value	Standard Deviation
1	-15	-15	-15	15.00	0.0000
2	-14	-15	-16	15.00	1.0000
3	-14	-15	-19	16.00	2.6458
4	-17	-16	-20	17.67	2.0817
5	-18	-15	-19	17.33	2.0817
6	-17	-16	-21	18.00	2.6458
7	-18	-17	-22	19.00	2.6458
8	-15	-18	-20	17.67	2.5166
9	-16	-20	-21	19.00	2.6458
10	-12	-18	-20	16.67	4.1633
11	-14	-18	-19	17.00	2.6458
12	-15	-19	-18	17.33	2.0817

Magnetic Flux Density for Pair S1 and N1 = $\underline{17.13 \pm 2.26 \text{ mT}}$

Appendix 2.2: Magnetic Flux Density for Pair S2&N2 of Condition 1

(Configuration 1 with Valve Fully Opened)

Point	Reading 1	Reading 2	Reading 3	Average Value	Standard Deviation
1	-15	-15	-15	15.00	0.0000
2	-14	-15	-14	14.33	0.7071
3	-14	-14	-14	14.00	0.0000
4	-14	-13	-13	13.33	0.7071
5	-13	-13	-14	13.33	0.7071
6	-11	-12	-14	12.33	1.5811
7	-11	-10	-14	11.67	2.1213
8	-10	-12	-12	11.33	1.2247
9	-11	-12	-12	11.67	0.7071
10	-12	-12	-11	11.67	0.7071
11	-13	-11	-13	12.33	1.2247
12	-14	-13	-13	13.33	0.7071

Magnetic Flux Density for Pair S2 and N2 = 12.86 ± 0.78 mT

Appendix 2.3: Magnetic Flux Density for Pair S1&N1 of Condition 2

(Configuration 1 with Valve Half Opened)

Point	Reading 1	Reading 2	Reading 3	Average Value	Standard Deviation
1	-14	-13	-14	13.67	0.5774
2	-14	-14	-14	14.00	0.0000
3	-13	-14	-14	13.67	0.5774
4	-14	-15	-15	14.67	0.5774
5	-15	-16	-14	15.00	1.0000
6	-14	-15	-15	14.67	0.5774
7	-15	-16	-16	15.67	0.5774
8	-14	-17	-16	15.67	1.5275
9	-12	-15	-15	14.00	1.7321
10	-14	-16	-15	15.00	1.0000
11	-14	-16	-16	15.33	1.1547
12	-16	-17	-17	16.67	0.5774

Magnetic Flux Density for Pair S1 and N1 = <u>14.83 ± 0.82 mT</u>

Appendix 2.4: Magnetic Flux Density for Pair S2&N2 of Condition 2

(Configuration 1 with Valve Half Opened)

Point	Reading 1	Reading 2	Reading 3	Average Value	Standard Deviation
1	-14	-14	-15	14.33	0.5774
2	-14	-13	-14	13.67	0.5774
3	-13	-12	-14	13.00	1.0000
4	-14	-13	-15	14.00	1.0000
5	-14	-14	-16	14.67	1.1547
6	-15	-14	-14	14.33	0.5774
7	-15	-15	-15	15.00	0.0000
8	-15	-16	-16	15.67	0.5774
9	-14	-15	-14	14.33	0.5774
10	-15	-16	-16	15.67	0.5774
11	-16	-16	-16	16.00	0.0000
12	-17	-18	-18	17.67	0.5774

Magnetic Flux Density for Pair S2 and N2 = $\underline{14.86 \pm 0.60\ \text{mT}}$

Appendix 2.5: Magnetic Flux Density for Pair S1&N1 of Condition 3

(Configuration 2 with Valve Fully Opened)

Point	Reading 1	Reading 2	Reading 3	Average Value	Standard Deviation
1	16	14	15	15.00	1.0000
2	15	10	14	13.00	2.6458
3	15	14	14	14.33	0.5774
4	14	15	15	14.67	0.5774
5	15	13	15	14.33	1.1547
6	14	11	14	13.00	1.7321
7	14	16	14	14.67	1.1547
8	14	13	14	13.67	0.5774
9	13	14	15	14.00	1.0000
10	13	14	16	14.33	1.5275
11	11	15	16	14.00	2.6458
12	12	15	17	14.67	2.5166

Magnetic Flux Density for Pair S1 and N1 = $\underline{14.14 \pm 1.42 \text{ mT}}$

Appendix 2.5: Magnetic Flux Density for Pair S2&N2 of Condition 3

(Configuration 2 with Valve Fully Opened)

Point	Reading 1	Reading 2	Reading 3	Average Value	Standard Deviation
1	10	12	10	10.67	1.1547
2	10	11	10	10.33	0.5774
3	8	10	9	9.00	1.0000
4	9	9	8	8.67	0.5774
5	9	9	9	9.00	0.0000
6	9	10	9	9.33	0.5774
7	9	10	9	9.33	0.5774
8	10	11	10	10.33	0.5774
9	9	11	10	10.00	1.0000
10	10	11	10	10.33	0.5774
11	10	12	11	11.00	1.0000
12	11	12	12	11.67	0.5774

Magnetic Flux Density for Pair S2 and N2 = <u>9.97 ± 0.68 mT</u>

Appendix 2.6: Magnetic Flux Density for Pair S1&N1 of Condition 4

(Configuration 2 with Valve Half Opened)

Point	Reading 1	Reading 2	Reading 3	Average Value	Standard Deviation
1	15	14	15	14.67	0.5774
2	15	10	14	13.00	2.6458
3	14	14	14	14.00	0.0000
4	14	15	15	14.67	0.5774
5	15	13	15	14.33	1.1547
6	14	11	14	13.00	1.7321
7	14	16	14	14.67	1.1547
8	14	13	14	13.67	0.5774
9	13	14	15	14.00	1.0000
10	13	14	16	14.33	1.5275
11	11	15	16	14.00	2.6458
12	12	15	17	14.67	2.5166

Magnetic Flux Density for Pair S1 and N1 = 14.08 ± 1.32 mT

Appendix 2.7: Magnetic Flux Density for Pair S2&N2 of Condition 4

(Configuration 2 with Valve Half Opened)

Point	Reading 1	Reading 2	Reading 3	Average Value	Standard Deviation
1	10	12	10	10.67	1.1547
2	9	11	10	10.00	1.0000
3	9	10	9	9.33	0.5774
4	9	9	8	8.67	0.5774
5	9	9	9	9.00	0.0000
6	9	10	9	9.33	0.5774
7	9	10	9	9.33	0.5774
8	10	11	10	10.33	0.5774
9	9	11	10	10.00	1.0000
10	10	11	10	10.33	0.5774
11	10	11	11	10.67	0.5774
12	11	12	12	11.67	0.5774

Magnetic Flux Density for Pair S2 and N2 = $\underline{9.94 \pm 0.65 \text{ mT}}$

APPENDIX 3

Appendix 3.1: Flow Rate when Valve Fully Opened

No.	Volume of Water (mL)	Time (s)	Flow Rate (mL/s)	Flow Rate (L/hr)
1	80	0.8	100.00	360.00
2	97	0.9	107.78	388.01
3	93	0.9	103.33	371.99
4	91	0.9	101.11	364.00
5	93	0.9	103.33	371.99
6	96	0.9	106.67	384.01

Flow rate of liquid when valve fully opened = 373.33 ± 10.94 L/hr

Appendix 3.2: Flow Rate when Valve Half Opened

No.	Volume of Water (mL)	Time (s)	Flow Rate (mL/s)	Flow Rate (L/hr)
1	82	1.6	51.25	184.50
2	98	1.7	57.65	207.54
3	95	1.8	52.78	190.01
4	92	1.8	51.11	184.00
5	93	1.8	51.67	186.01
6	96	1.7	56.47	203.29

Flow rate of liquid when valve half opened = 192.56 ± 10.27 L/hr

APPENDIX 4

Appendix 4.1: Mass of pipes for Condition 1

Time (Hour)	Pipe A	Pipe B
0.0	468.787	468.800
0.5	468.750	468.799
1.0	468.716	468.799
1.5	468.679	468.800
2.0	468.644	468.799
2.5	468.610	468.801
3.0	468.575	468.799
3.5	468.540	468.799
4.0	468.506	468.799

Appendix 4.2: Mass of Wax in pipes for Condition 1

Time (hour)	Pipe A (g)	Pipe B (g)
0.0	12.142	10.830
0.5	12.105	10.830
1.0	12.071	10.830
1.5	12.034	10.830
2.0	11.999	10.830
2.5	11.965	10.830
3.0	11.930	10.830
3.5	11.895	10.830
4.0	11.861	10.830

Appendix 4.3: Mass of pipes for Condition 2

Time (Hour)	Pipe A	Pipe B
0.0	475.052	474.560
0.5	475.044	474.560
1.0	475.037	474.560
1.5	475.026	474.560
2.0	475.020	474.560
2.5	475.011	474.560
3.0	475.005	474.560
3.5	474.996	474.560
4.0	474.986	474.560

Appendix 4.4: Mass of Wax in pipes for Condition 2

Time (hour)	Pipe A (g)	Pipe B (g)
0.0	18.407	16.590
0.5	18.399	16.590
1.0	18.392	16.590
1.5	18.381	16.590
2.0	18.375	16.590
2.5	18.366	16.590
3.0	18.360	16.590
3.5	18.351	16.590
4.0	18.341	16.590

Appendix 4.5: Mass of pipes for Condition 3

Time (Hour)	Pipe A	Pipe B
0.0	474.988	474.433
0.5	474.963	474.433
1.0	474.939	474.433
1.5	474.915	474.433
2.0	474.890	474.433
2.5	474.866	474.433
3.0	474.841	474.433
3.5	474.816	474.433
4.0	474.790	474.433

Appendix 4.6: Mass of Wax in pipes for Condition 3

Time (hour)	Pipe A (g)	Pipe B (g)
0.0	18.343	16.463
0.5	18.318	16.463
1.0	18.294	16.463
1.5	18.270	16.463
2.0	18.245	16.463
2.5	18.221	16.463
3.0	18.196	16.463
3.5	18.171	16.463
4.0	18.145	16.463

Appendix 4.7: Mass of pipes for Condition 4

Time (Hour)	Pipe A	Pipe B
0.0	474.876	474.531
0.5	474.864	474.531
1.0	474.856	474.531
1.5	474.847	474.531
2.0	474.836	474.531
2.5	474.825	474.531
3.0	474.820	474.531
3.5	474.806	474.531
4.0	474.797	474.531

Appendix 4.8: Mass of Wax in pipes for Condition 4

Time (hour)	Pipe A (g)	Pipe B (g)
0.0	18.231	16.561
0.5	18.219	16.561
1.0	18.211	16.561
1.5	18.202	16.561
2.0	18.191	16.561
2.5	18.180	16.561
3.0	18.175	16.561
3.5	18.161	16.561
4.0	18.152	16.561