WAX DEPOSITION – TREND OF FORMATION IN CRUDE PIPELINE

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Wax Deposition – Trend Of Formation In Crude Pipeline

By

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Dissertation submitted in partial fulfillment of
the requirements for the
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS
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July 2009

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.

MUHAMMAD SUFFIAN BIN MOHD YUSOFF

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CHAPTER 1: ABSTRACT

Normally most of crude oils contain wax either in small or large percentage. Wax content in crude oils significantly gives some more cost to the production line, transportation and also process plant. So that it play an important role to the operating cost to any sections of oil industry. Wax deposition usually starts when the crude oils are flowing through pipeline or riser. At sea bed and undersea there are low temperature over there which cause wax component in crude oil start to crystallize and precipitate. It also has high viscosity which can cause pumping problems to pipelines. Over certain period of time wax can cause blockage to the pipeline. This kind of problem potentially increase cost of operation and become severe when the operation is being shut down because of pipeline failure. There is a method to overcome this problem by using circulation of hot oil from platform to well. It purposes is to maintain high temperature of flowing crude oil to storage tank, so there are less percentage of wax deposited on the wall surface of tubing. In UTP, most studies on waxes were conducted using batch system. This study will concentrate on continuous system where coolant is circulated in a cold finger flowing through fix amount of hydrocarbon solution. So there is an interest on how is it the deposition process works. Because the way of deposition occurs is different compared to batch system, the pattern and trend of wax deposition is still a question. This research will start by having literature review and number of sets of experiment to collect data and make analysis of wax deposition in a loop. This preliminary report includes project background, problem statement, objective, project scope and limitation, literature review, methodology and references.

CHAPTER 2: INTRODUCTION

2.1 Project Background

In oil production, the crude oil usually composes of unwanted material such as water, wax, asphaltene and emulsions. A waxy crude contain variety of light and intermediate hydrocarbons (paraffin, aromatics, naphtenic) and variety of other heavy organic (non-hydrocarbon) compounds at very low concentrations including resins, asphaltenes, diamondoids, mercaptdans and organometallics. Hydrocarbon of wax can exist in various form such as gas, liquid and solid. Wax generally behaves like plastics at ambient temperature. When it is heated, it becomes a liquid. It also deforms under pressure without heat (Becker, 1997). The non polar group of cycloalkanes is identified to be the most significant element to form wax (Cordoba and Schall, 2000). However, it can aid emulsification off the crude in the production and refining of crudes, as well as in oil spills (Fingas and Tennyson, 1992; Bridie,1980).

A study of wax is conducted to trace the behavior of wax that always deposited on the tube wall during transportation of crude from reservoir to field storage facilities. As the temperature is decreasing while the crude is lifted, the fluidity of crude is decreased. It make more sense when the crude oil compose of more than 80 % of it component are build up from carbon element (Sequiera, 1994)

It has relation with the viscosity of alkanes composition in crude. It might leading to increased pressure drop and blockage of the inside tube and will cause a failure to the transportation of crude to platform. Wax deposit potentially reduces the flow of crude oil and cause greater amount of energy required to maintain the flow. Most of wax deposit problems are due to the lack of proper insulation and heating systems.

Wax component can be originated from alkanes group of C_{20} and above. This show that wax is a heavy hydrocarbon component which has high molecular weight and high melting and boiling point compared to the rest of alkanes which has number of carbon lower than 20 carbons. So it can easily undergo transition of phase from liquid to solid.

2.2 Problem Statement

2.2.1 Problem Identification

The phenomena of wax deposition in storage tank, pipeline and process plant are major issues in oil and gas industry. The environment and condition where the crude oil is stored and transported has played a big role in wax appearance. Pipeline on sea bed passing condition of low temperature there, kinetic motion that involves during transportation and the composition of aromatics and paraffin crude oil represent significant contributor of wax deposition. All these elements are being studied by conducting cold finger experiment where the manipulated variables are involved in real field.

2.2.2 Significant of the Project

The cold finger experiment is a real time basis experiment that supplies the information about rate of wax deposition by measuring the weight of deposited wax versus time. Having manipulated variables such as coolant temperature and composition of wax in hydrocarbon solution will help to trace the information of wax formation trend and it's nature properties.

2.3 Objectives

The objectives of the study:

- To setup cold finger experiment
- To study the effect of wax percentage on wax deposition
- To study the effect of coolant temperature on wax deposition
- To study the crystallization theory and Avrami theory and their effect on wax deposition

2.3.1 Project Scope and Limitation

This project is purposely conducted to study wax problem in a closed loop system. The manipulated variables are taken into consideration to deeply trace and identify the trend of wax precipitation on the wall surface of cold finger. The theory of nucleation and Avrami theory become important in this experiment to explain this phenomenon. The wax deposited is measured using gravimetric method. The asymptotic value of graph of wax deposited versus time is used as reference in this experiment.

2.3.2 Feasibility of the Project within the Scope and Time Frame

This project is very feasible in term of time frame since it can be finish up by the end of month of October by following it module and following the progress planning. All of the methods conducted will give valuable information on wax deposition studies.

CHAPTER 3: LITERATURE REVIEW

Crude oils naturally contains small amounts of n-paraffins (10– 20 wt%) dissolved in a complex 'solvent' which is the oil itself. The paraffins have a broad molecular weight distribution ranging approximately from 10 to 70 carbons. When oil is transported, the temperature of the bulk fluid drops and the solution becomes supersaturated with respect to a certain fraction of paraffins, usually the longest ones. The temperature of onset of crystallisation Tc, well determined by differential scanning calorimetry (DSC), is in the range of 25–50 ˚C. Paraffins start to crystallize and by lowering the temperature larger amounts of crystals are formed. The length of the crystallized paraffins evolves progressively with the temperature, not all of them being crystallized in the thermal range encountered in oil extraction (usually above 0 ˚C) (Kane´a, 2002) .

3.1 Nature of Paraffin

Paraffins are a continuum of high molecular weight alkane [$C_{(n)}H_{(2n+2)}$] saturated hydrocarbons that exist in crude oil. Size can exceed C_{100} with either a normal or branched structure. Normal paraffins exhibit higher melting points than equivalent-sized branched structures. Longer paraffin leads to the higher melting point. This means the larger molecules come out of solution first, so the deepest downhole deposits would be the higher molecular weight paraffins. This means one should analyze the deposit that one is trying to treat by get a downhole sample from the depth where the problem is occurring, not from the surface. Initially paraffins are in equilibrium in the reservoir under certain temperature-pressure conditions. Once this equilibrium is disturbed by production and temperature-pressure conditions change, deposition may occur.

The temperature at which paraffin begins to come out of solution is defined as the cloud point. Cloud points of crude from different wells within a field can vary as much as -1˚C. Pour point is defined as that temperature where the crude sample becomes solid. Paraffin deposits contain 60% or more oil. Paraffin floats on water and is soluble in xylene, n-heptane and crude (generally linear hydrocarbons). A simple field test to determine if a deposit is paraffin is to place a sample of the deposit on aluminum foil on a vehicle radiator cap. If paraffin, the deposit will melt.

TYPE	PARAFFIN WAXES	MICROCRYSTAL WAXES
Normal Paraffins (%)	80-95	0-15
Branched Paraffin (%)	2-15	15-30
Cycloparaffins (%)	2-8	65-70
Melting Point Ranges (°C)	50-65	60-90
Average Molecular Weight	350-430	500-800
Typical Carbon Number	18-36	30-60
Crsytallinity Range (%)	80-90	50-65

Table 3.1.; Typical Composition and Properties of Paraffins. (Furqan, 1999)

Much knowledge has been extracted from the paraffin molecule structure analysis. The branched chain paraffin constitutes micro-crystalline waxes. To a lesser extent straight and aromatic also contribute to micro-crystalline waxes. These microcrystalline waxes aid the growth of macro-crystalline waxes, which are composed largely of n-paraffins, which show up as needle shaped crystals. These macro-crystalline waxes are responsible for paraffin problems in production and transportation. Micro-crystalline waxes contribute most of the tank bottom sludge.

Research by Holder and Winkler (Holder, G.A., 1965) showed that wax from heavy oil on cooling from 16°F to 10°F had a composition of C_{20} and ranged from C_{16} to C_{27}. As temperature increases, the average number of carbon atoms of crystallized wax also increases. Laboratory experiments have demonstrated that the average carbon numbers of waxes precipitated at 14°, 32°, 68° and 86°F were 22, 23, 26 and 29 carbons respectively (Holder & Winkler, 1965). In determining the wax problem indigenous to particular crude, the following should be considered based on this discussion so far on the paraffin structure:

1) Carbon number distribution
2) Concentration of branched paraffin
3) Concentration of n-paraffin
4) The climate/ temperature regimes of the area

Second factor indicates the extent of the problem. First, third and fourth tell about paraffin wax deposition potential. Considerable work efforts by Reistle has shown that different gravity petroleum fraction at various temperature have different paraffin buildup rate. He established that the light ends contribute appreciably to the 6 solubility of waxes, which decrease with decreasing temperature (Reistle, 1932). Schanen research has confirmed the solubility of paraffin in liquid propane is equal to that of decane (Schanen, 1945). Methane solubility at atmospheric pressure is negligible, although its value increases slightly with pressure increases. This information can be discerned that loss of lower molecular weight hydrocarbon affects solubility of waxes to a great extent.

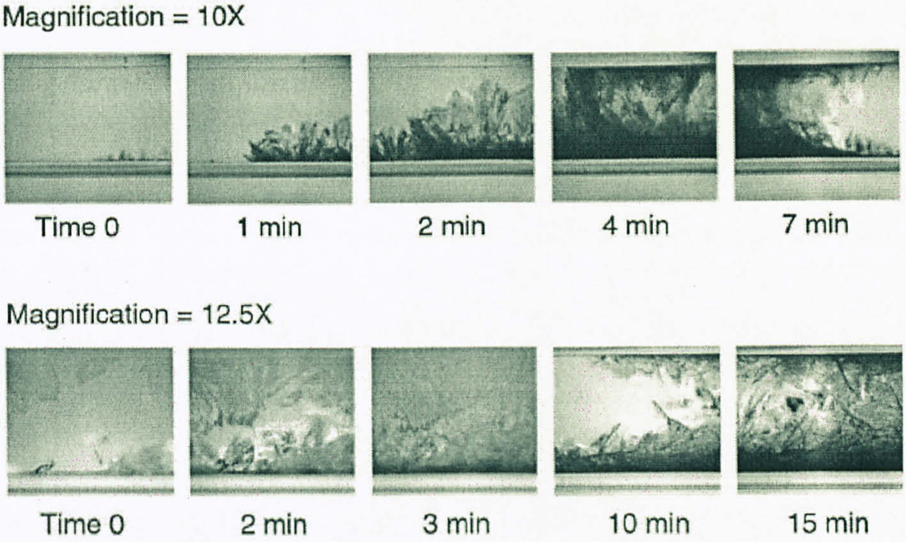

Figure 3.1: Images of wax deposition in a flow condition (Cordoba and Schall, 2001b)

Water plays no role in solubility of paraffin. The length of the alkane units present largely determines the viscosity and the melting point of these complex waxes. An example of this would be the comparison of octa-decylacrylate to methyl-acrylate. Even though polymer exhibit increased viscosity as the polymerization increases (i.e the length of the polymer chain increases), only octadecylacrylate shows signs of clouding and solidifies below 28°C this clouding and solidification was brought on by the interaction of $C_{18}H_{38}$ group, which has a melting point of 28.8°C. We can comprehend from this the alkane nature of waxes present in crude oil (Becker, J.R., 1997).

The type of paraffin that cause paraffin deposition are not just limited to the n-paraffin type as mentioned before, even though they are the crux of most deposits encountered. Mostly straight chain in structure, paraffin can also be branched. Paraffin in organic terms is classified as an oil and asphaltenes. Inorganically-sand, rust, Iron sulfide and scale also contribute to paraffin formation. The site of deposit is dependent on the precipitation point of paraffin, also known as cloud point, availability of surface for adhesion, evaporation of gas or light ends by pressure drop. The light ends here are usually gases like methane, ethane and propane, their lightweight is the result of their simple carbon structure, making them susceptible to easy evaporation. As long as paraffin 7 is suspended in solution, the oil is Newtonian fluid type, but when paraffin particles begin to precipitate, the oil may become thixotropic (Straub *et al*, 1989). The makeup of paraffin deposit varies from different depths in same well having different peak carbon chain numbers. This hints at a stepwise precipitation model.

The deposition mechanism takes place by mechanism which channel both dissolved and precipitated wax crystals laterally. A concentration gradient buildup by the cooling oil leads to the transport and deposition on surface by molecular diffusion. Brownian (molecular diffusion) and shear dispersion are the mechanisms by which previously precipitated wax crystals carried by the oil are channeled laterally (Newberry & Barker, 1982). Formation damage brought on by deposits is predominantly due to molecular diffusion of oil, as a result of cooling by treating fluids. Another reason is the shear dispersion deposition of wax deposits present in the casing and tubing which are changed and forced back into the formation with a pushing action of the pumped fluids (Brown *et al*, 1995).

The deposition of colloidal particles onto the collector's surface in two dimensional flows is best understood by observing the Brownian dynamics simulation method. The Kuwabara model to characterize the flow field, the effects of the total 8 interaction energy curves of various shapes on the collection efficiencies of Brownian particles is examined. These results of simulation obtained are compared and contrasted against standard published experimental data of the deposition rates of Brownian particles for the cases of the repulsive double layer interactions (Elimelech, 1990) and also for the attractive double layer interaction (Elimelech, 1991). These results from the Brownian motion diffusion take into account the size of the particles deposition mechanisms give a better fit with these experimental data than that can be obtained without considering Brownian diffusion (Chang, Y, I et al., 1999).

The need to explore the paraffin deposition at the microscopic level of Brownian motion arises from the fact that we have to understand the precipitation of paraffin particles initially when there are still in the colloidal solution. It is with aid of initial precipitation behavior that starts with in order to comprehend the nature such a deposit we have to fully understand the logistics of the paraffin formation by particle deposition behavior simulated by the stochastic method. Numerous laboratory paraffin buildup simulation models make use of the cloud point to assess the structure, conditions and rate at which the paraffin actually accumulates. Cloud point, in a way relates the physical conditions at which buildup process is initiated to the physical changes that are concurrent as the paraffin molecule goes from being suspended in the solution to a precipitated form.

The average temperature of oil coming out of a well is somewhat higher than the ground temperature. The oil continues to cool on its trip through surface flow lines and can lead to wax deposition. Most of the cooling takes place in the first 500 feet from the wellhead. Also, the radial temperature gradient, near the wall falls rapidly with distance 9 and becomes quite small after a couple hundred feet. From this information we can expect to have lesser deposits, as distance from wellhead becomes negligible after a few hundred feet, as per the dependence on concentration gradient. It is necessary to have a good understanding of paraffin's chemistry. This will be useful in comprehending the rationale behind cloud point. It is essential that we discern the process of paraffin deposition in relation to cloud point. This section offers several references to experimental work performed to determine cloud point. It also looks at the various methods employed for paraffin removal (Furqan, 1999).

3.2 Causes of Paraffin Problems

Paraffin deposition is a thermally driven process. Cooling during production, such as occurs from the loss of gas during production, causes wax to precipitate as temperature drops below the cloud point. The % paraffin in a crude oil is not an indicator of potential paraffin problem, rather it is the cloud point and % paraffin that indicates the magnitude of potential problems. Viscosity and flow rate affect paraffin deposition. High viscosity reduces transport to cold surfaces, reducing deposition. High velocity results in harder deposits. Paraffins cause problems through deposition (formation, tubing, flowline, pipeline), settling (tank bottoms, interfaces), and solidification (high viscosity can cause problems restarting or require very high pressures to pump).

Paraffin problems result from:

1. Natural causes (temperature loss, high volumes of production even if paraffin content is relatively low, gas expansion, pipe cooling due to groundwater aquifers, low surface temperatures),
2. 2 solvent loss (dropping below bubble point, gas production, gas separation, hot oil treatments, heater treaters),
3. Well maintenance operations (temperature drop, water injection, cooling equipment, gas lift, acid/frac jobs with cold fluids).

Field problems include formation plugging, oil wetting of formations that leads to high water production, filter plugging, high viscosity fluid that causes high pumping pressure, coated solids, difficult to treat emulsions, tank bottoms and interfaces in vessels. Sludging with acid treatment is common. To minimize sludging, a two-step treatment process is recommended. First treat with crude containing chemical, followed by acid. Paraffin and/or asphaltene problems can cause formation damage. Reviewing production decline and well history can identify damaged wells. Focus particularly on treatment history (acid, frac) and subsequent response. Wells that have been hot oiled multiple times down the tubing will often be damaged (Ken Barker, 2003).

In cold regions, the *n*-paraffin content greatly affects flow properties of crude oil in production tubing or in transportation pipelines when temperature falls below the wax appearance temperature. Some heavy oils are so waxy that *n*-paraffins solid deposits clog up filters and obstruct pipelines. In order to prevent the plugging of tubing and to improve the flow property of such oils, two distinct methods are widely employed: a chemical technique, which rests on addition of wax inhibitors or flow improvers, and a thermodynamic technique. Wax appearance which is linked to changing temperature and fluid composition caused by bringing the well into production, can be altered by heating or by diluting with light crude oils (Dauphin, 1999).

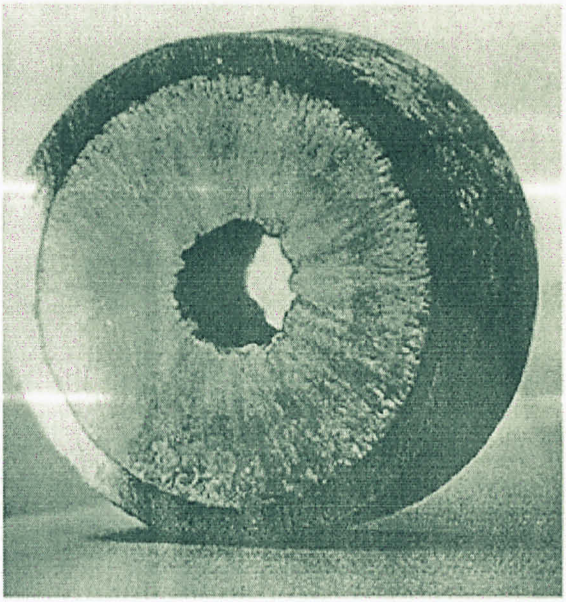

Figure 3.2: Photo of cross section of a pipeline blocked with wax deposit (Singh *et al.*, 2001)

3.3 Avrami Theory

This theory is based on the Avrami equation which describes the growth of crystallinity during crystallization under isothermal conditions. It can also be used to describe the kinetics of crystallization. The Avrami equation is as below:

$$1 - X = \exp [- Kt\ n] \qquad (1)$$

Where:

X is the volume fraction of crystalline material or degree of crystallinity
t is time taken to form crystalline material
K is the growth rate
n is the Avrami exponent

To analyze the Avrami equation further, the following form is generally used:

$$\log [-\ln(1-X)] = \log K + \mathrm{n} \log (t) \qquad (2)$$

For this experiment, volume fraction of crystalline material, X for the Avrami equation would be substituted with relative wax deposition, δr instead

$$\delta\mathrm{r} = \frac{mass\ of\ solid\ wax}{total\ mass\ of\ hydrocarbon\ solution}$$

The deposits on the surface wall would be measured on the basis of mass fractions. Now equation 2 will become:

$$\log [-\ln(1-\delta\mathrm{r})] = \log \mathrm{K} + \mathrm{n} \log (\mathrm{t}) \qquad (3)$$

By plotting a graph of log [-ln (1-δr)] versus log (t), the growth rate, K can be obtained from the intersection of the graph. The Avrami exponent, n can be calculated from the slope of the graph. The negative value for n, is expected due to the nature of the decrystallization slope. However the negative is neglected as the Avrami exponent value deciphers whether the crystallization process is heterogeneous or homogeneous, and also the type of crystallite morphology formed (e.g. rod, disc, sphere and sheaf) can be 8 comprehended. Integer values are usually observed but fractional values of *n* can be observed and this is due to secondary crystallization. The following table gives a list of Avrami exponents and their morphologies:

Morphology	**Instantaneous (Heterogeneous)**	**Sporadic (Homogeneous)**
Rod	1	2
Disc	2	3
Sphere	3	4

Table 3.2: Avrami exponent value and the corresponding nucleation process and growth

3.4 Wax Testing Experiments

Testing procedures for the determination of wax problems in crude oils have evolved over the years from simple visual tests to complex and elaborate methods. Some of the testing methodologies for wax are:

- Cold finger testing
- Pour-point testing
- Cold-filter plugging test
- Dynamic test loops rolled-ball deposit test
- Dynamic rheology
- Sonic testing

3.4.1 Cold Finger Testing

This project use cold finger method to study the effect of composition and temperature. Cold-finger testing used to answer some of the questions about the conditions of temperature at which deposits form. The concept of this test is that a surface (cold finger) is placed in a sample of heated crude oil, and cooling fluid is circulated through the interior of the cold finger. The oil is gently agitated about the cold finger with a magnetic stirrer while the oil is maintained at a temperature above its cloud point, and deposits form on the cold finger's surface. The amount of deposit collected after the test has been run is a measure of the problems the field will experience with the oil. The duration of the test can range from 3– 40 hours and is highly dependent upon the individuals conducting the test.

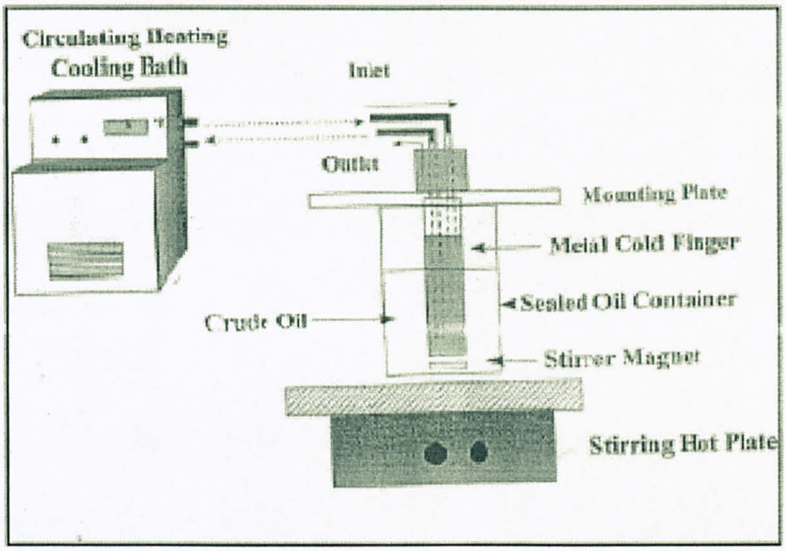

Figure 3.3: Cold Finger Equipment

The experiment will be conducted using continuous/closed system. The flow loop is objectively design to measure the amount of wax deposited on surface cold finger. The solution uses diesel as solvent and high molecular weight of paraffin wax as solute. A flask contains the recirculation hydrocarbon solution. The volume of solution will maintain composition constant within 5% of initial concentration. This reservoir is immersed in water bath during experiment (Cordoba and Schall, 2000).

This project will rely on cold finger surface of the flow loop system. As the flowing coolant circulating through cold finger, wax component will precipitate on the outer surface of cold finger.

3.5 Manipulated Variables in Experiment

The experiment is conducted by manipulating certain parameters. The effect will be seen on the wax deposition rate on the cold finger surface. The manipulated variables are:

1) Coolant Temperature
2) Wax Component Percentage

3.5.1 Coolant Temperature

The temperature of coolant is manipulated by changing the set temperature of chiller. The rate of wax deposition is simply changed with different temperature.

3.5.2 Wax Component Percentage

Wax component in hydrocarbon solution might increase the rate of wax deposition. The higher the composition, the more wax precipitated.

3.6 Schematic Cold Finger Experiment

This experiment is conducted using chiller, cold finger, beaker, stirrer, hot plate, thermometers. The specifications are as follows:

3.6.1 Chiller

To manipulate the temperature of coolant.

3.6.2 Cold Finger

To be test section of experiment.

3.6.3 Beaker

To contain hydrocarbon solution.

3.6.4 Stirrer

To provide agitation mode.

3.6.5 Hot Bath

To heat up and maintain high temperature of hydrocarbon solution.

3.5.6 Chemicals

A paraffin wax (Sigma Aldrich) is used to be solute and the solvent is diesel fuel. The paraffin wax melting point is 53°C. The diesel fuel that is used is high quality diesel which available from pumps station.

CHAPTER 4: METHODOLOGY / PROJECT WORK

4.1 Cold Finger Experiment

The experiment is conducted by having 2 types of manipulated variables which are temperature of coolant and percentage of paraffin wax. These 2 variables are being studied and analyzed as well as there have impact on the thickness of deposited wax. The thickness of wax deposited is converted to mass by gravimetric method. The graph of mass of deposited wax versus time will be plotted according to the series of the experiment.

4.1.1 Effect of Coolant Temperature

The wax solution is prepared by mixing 180ml diesel as solvent and 20gram paraffin wax as solute to get 10wt% of hydrocarbon solution. The solution need to be heated to 50°C by using hot bath. The temperature of coolant is set at 10°C during experiment. The cold finger is immersed in a solution of wax and being observed for 10 minutes time. After 10 minutes time, the mass of wax deposited on the surface of cold finger is measured by gravimetric method. All those steps are repeated for coolant temperature at 12.5°C and 15°C.

4.1.2 Effect of Wax Composition

The wax solution is prepared by mixing 180ml diesel as solvent and 20gram paraffin wax as solute to get 10wt% of hydrocarbon solution. The solution need to be heated to 50°C by using hot bath. The temperature of coolant is set at 10°C during experiment. The cold finger is immersed in a solution of wax and being observed for 10 minutes time. After 10 minutes time, the mass of wax deposited on the surface of cold finger is measured by gravimetric method. All those steps are repeated for coolant temperature at 12.5°C and 15°C. The composition of wax is changed to 15wt% and 20wt% for other set of experiments.

4.2 Cold Finger Equipments

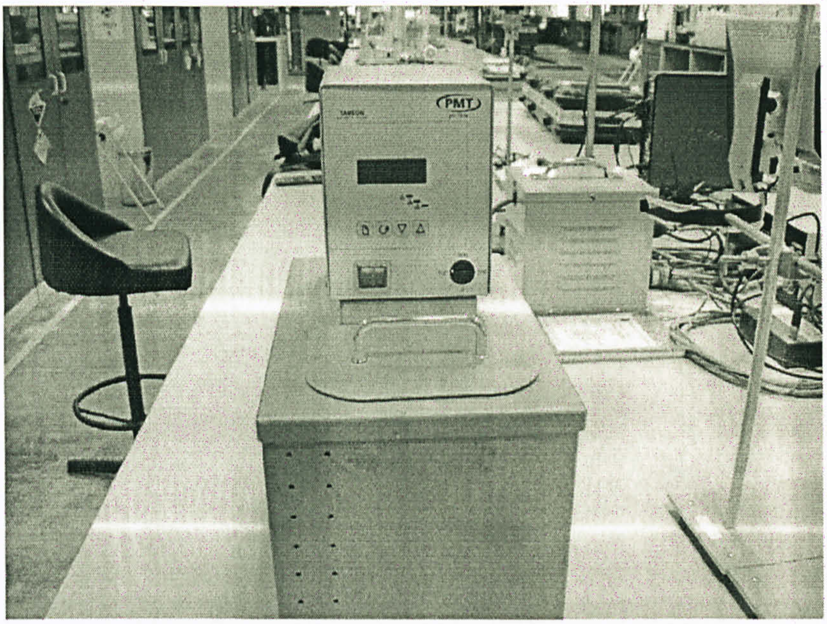

Figure 4.1: Hot Bath

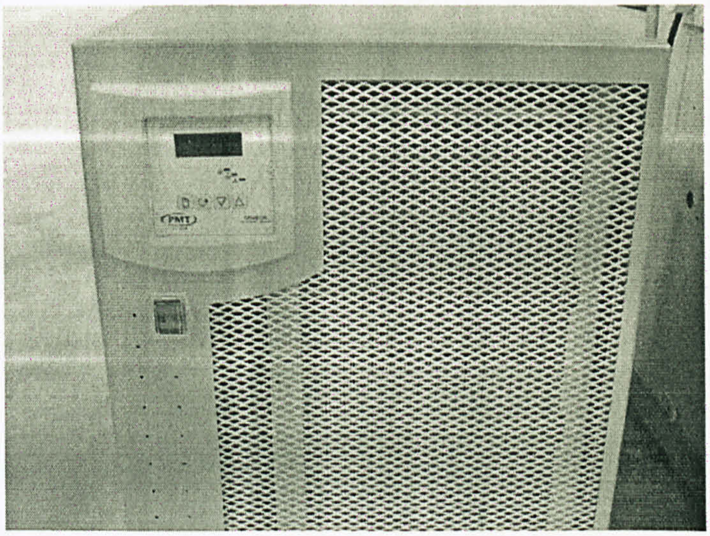

Figure 4.2: Chiller

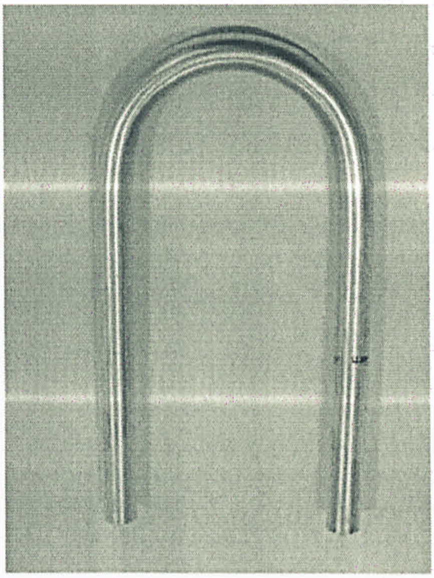

Figure 4.3: Cold Finger (U-shape)

Figure 4.4: Weight Scale

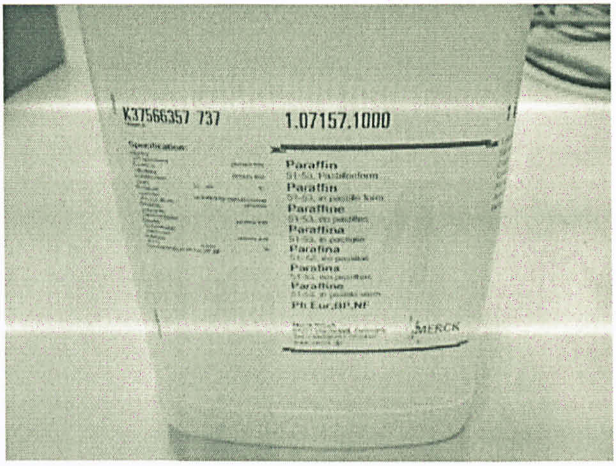

Figure 4.5: Paraffin Wax

Figure 4.6: Hydrocarbon Solution With Varies Concentration of Wax

CHAPTER 5: RESULT AND DISCUSSION

5.1 Experiment Conducted Using 20 wt%

The experiment has been conducted to study the deposition rate of 20 wt % of paraffin wax. The temperature of coolant was set at -5°C while the hydrocarbon solution is at 60°C. The experiment was run at 15 minutes time with the rate of deposition per minute was measured every minute manually. The rate was calculated by removing the deposited wax on cold finger surface using hair dryer to impose heat and force to remove it. After that, the wax was measured using weight scale. The mass deposited was then calculated with the time to get the rate of wax deposition.

The result is a shown in the table below:

Time (min)	Initial weight (g)	Final weight (g)	Weight of wax deposited (g)
0	15.44	15.44	0.00
1	16.84	16.84	1.40
2	18.20	18.20	2.76
3	19.34	19.34	3.90
4	20.64	20.64	5.20
5	21.92	21.92	6.48
6	23.32	23.32	7.87
7	24.77	24.77	9.33
8	26.16	26.16	10.72
9	27.48	27.48	12.04
10	28.88	28.88	13.44
11	30.33	30.33	14.89
12	31.60	31.60	16.16
13	33.01	33.01	17.57
14	34.40	34.40	18.96
15	35.78	35.78	20.34

Table 5.1: Rate of deposition at 20wt% of paraffin wax

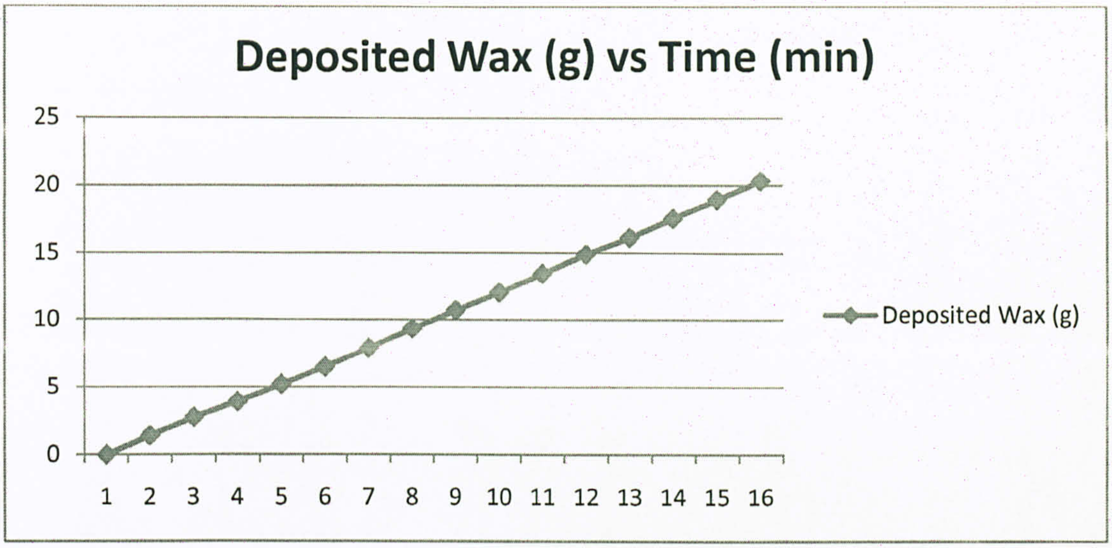

Figure 5.1: Graph of rate of wax deposition

The rate of deposition is about 1.2-1.4 g/minute. Until t=15min, the percentage wax deposited was about 50.85%. Based on slope of the graph, probably the deposition of wax could stop around t=30min. by knowing this trend, the wax composition will be reduced to shorten the period of experiment. The next experiment will be conducted using small composition of wax and the measurement of deposition is shifted to 3-5 minutes compared to 1 minute in this experiment.

Problems

The rate of deposition is same until the 16th minute of experiment. The increment range for every minute is from 1.2g/minute-1.4g/.minute. It shows that the deposition that takes place is already constant because it achieves the asymptotic value. This happens at temperature of -5°C which is very cold. So the temperature of coolant should be increased to avoid the asymptotic value in a very short time. The temperature of coolant will be at range of minimum 10°C to maximum 15°C. In that ranges of temperature, the deposition process will take place at lower rate and it is easier to study the asymptotic value of the deposition.

It is also important to decrease the temperature of hot bath to ensure deposition occurs and lowering the dissolving rate of deposited wax. When hot bath is very hot the deposited wax will dissolve back. This is because wax appearance temperature plays a big role for the deposition to occur. Using high temperature will not encourage the solution temperature to achieve WAT solely. There might be fluctuation and the dissolving process keep comes at temperature of 60°C.

When the wax composition is high the amount of wax deposited per minute is high until no more deposition can takes places around the limited surface area of cold finger. So the asymptotic value is very fast within a minute. The coated wax on surface of cold finger becomes insulation layer, so the rate of deposition will no more increases as desired. It creates difficulties to trace the behavior of wax deposition.

Overall observation from this experiment shows that the set point of temperature for both coolant and hot bath and the composition of wax in solution should be changed to suit the behavior of wax deposition.

5.2 Experiment Conducted Using 10 Wt% at 3 Different Points of Temperature

The experiment has been conducted to study the deposition rate of 10 wt % of paraffin wax. The temperature of coolant was manipulated between 10°C to 15°C while the hydrocarbon solution is at 50°C. The experiment was run at 12 minutes time with the rate of deposition per minute was measured every minute manually. The rate was calculated by removing the deposited wax on cold finger surface using hair dryer to impose heat and force to remove it. After that, the wax was measured using weight scale. The mass deposited was then calculated with the time to get the rate of wax deposition. The experiment was repeated for two times to get the average value.

The result is a shown in the table below:

a) **10.0°C**

T (min)	Mass(g)	Deposited (g)
0	103.8831	0.0000
1	104.3062	0.4232
2	104.3035	0.4205
3	104.3073	0.4243
4	104.3186	0.4355
5	104.3176	0.4346
6	104.3205	0.4375
7	104.3507	0.4676
8	104.3385	0.4555
9	104.4066	0.5235
10	104.3685	0.4854

Table 5.2: Table of wax deposited for 10 minutes at T =10°C and 10wt% of wax composition

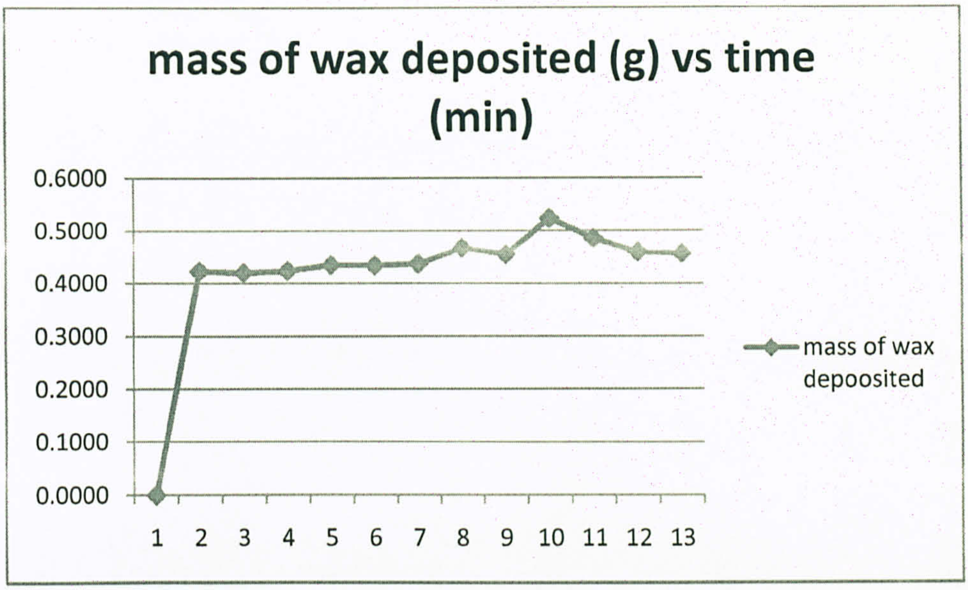

Figure 5.2: Graph of mass of wax deposited for 10 minutes time at T =10°C and 10wt% of wax composition

b) 12.5°C

T (min)	Mass(g)	Deposited (g)
0	103.3911	0.0000
1	103.6861	0.2950
2	103.6885	0.2974
3	103.7191	0.3280
4	103.7198	0.3287
5	103.723	0.3319
6	103.7208	0.3297
7	103.7294	0.3383
8	103.7371	0.3460
9	103.7263	0.3352
10	103.7389	0.3478

Table 5.3: Table of wax deposited for 10 minutes at T =12.5°C and 10wt% of wax composition

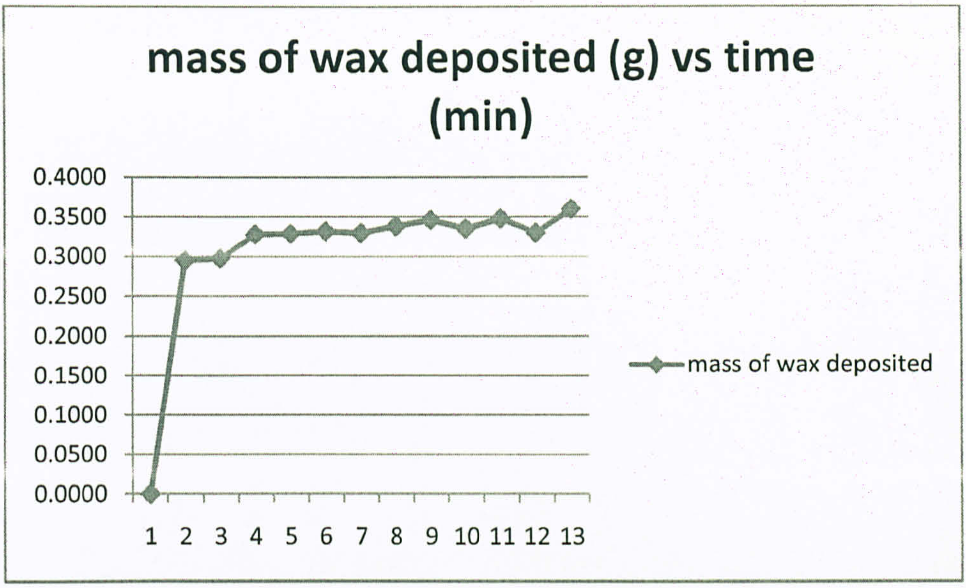

Figure 5.3: Graph of mass of wax deposited for 10 minutes time at T =12.5˚C and 10wt% of wax composition

c) 15˚C

T (min)	Mass(g)	Deposited (g)
0	104.3807	0.0000
1	104.569	0.1883
2	104.6021	0.2214
3	104.614	0.2333
4	104.673	0.2923
5	104.6714	0.2907
6	104.6563	0.2756
7	104.667	0.2863
8	104.6778	0.2971
9	104.7459	0.3652
10	104.6882	0.3075

Table 5.4: Table of wax deposited for 10 minutes at T =15˚C and 10wt% of wax composition

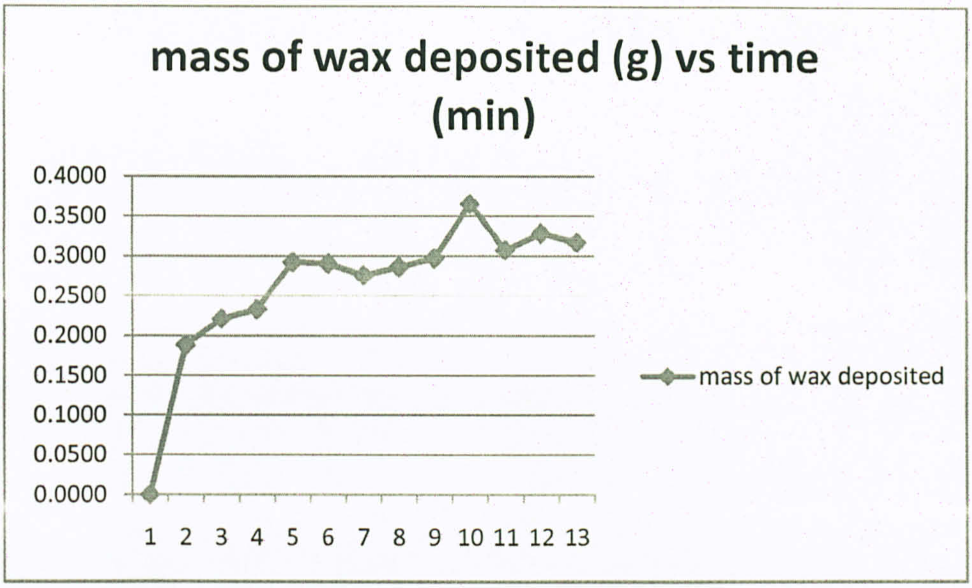

Figure 5.4: Graph of mass of wax deposited for 10 minutes time at T =15°C and 10wt% of wax composition

Problems

The results shows positive trend for wax formation study. It comes after changes have been practiced to the range of coolant temperature, hot bath temperature and composition of wax. The asymptotic point has been delayed in order to observe the trend of increments per minute of the wax formation. There is clear sign from the graph plotted where mass of wax deposited at 10°C is higher than the mass of wax deposited at 15°C.

As discussed before, the free convection effect still takes place where the dissolving occurs due to buoyancy effect of fluid. It happens when the density of solution fluctuates according to the difference in temperature between the top level of fluid and the bottom level of fluid.

Other problems that might rise is the accuracy of weight measurement for the deposited mass. The possible errors that might comes are splash effect when the wax deposited is blown by hair dryer and the volatile effect where evaporation may takes place when the wax deposited is blown by hair dryer. But the trend of weight measurement still consistent and the deviation is lowered.

5.3 Experiment of Wax Deposition at 3 Different Temperatures and 3 Different Wax Compositions

The temperature of coolant is varied from 10°C to 15°C flowing through cold finger which is immersed in hot bath at 50°C. The deposition takes place in 10 minutes time. The wax deposited is blown by hair dryer to dissolve the wax in a beaker and then the weight is measured. The composition of wax and diesel are on mass basis.

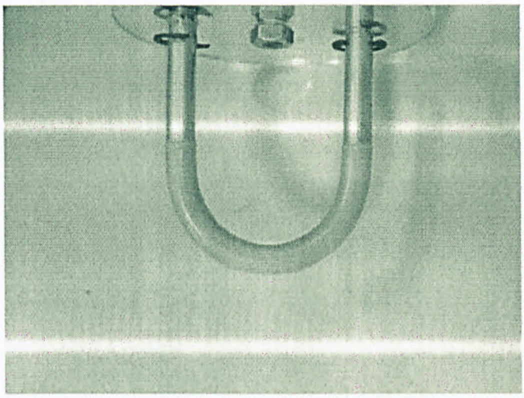

Figure 5.5: Wax deposited on outer surface of cold finger

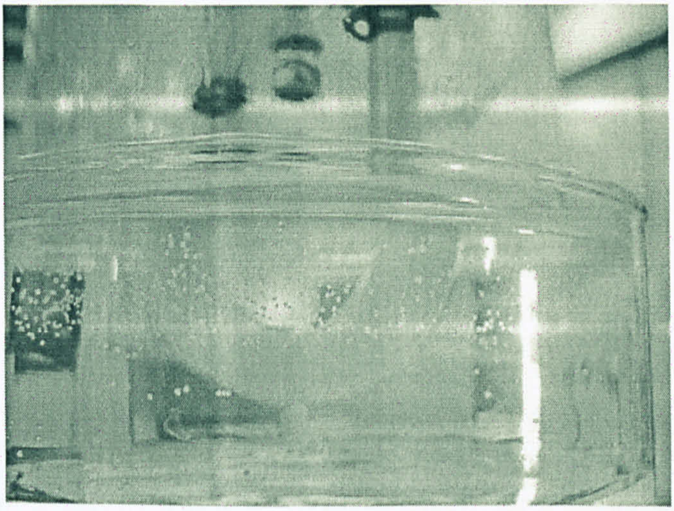

Figure 5.6: Wax depositing on surface of cold finger

1) For Wax composition = 10%, (20 gram paraffin wax + 180 gram diesel)

a) **Temperature, T = 10°C**

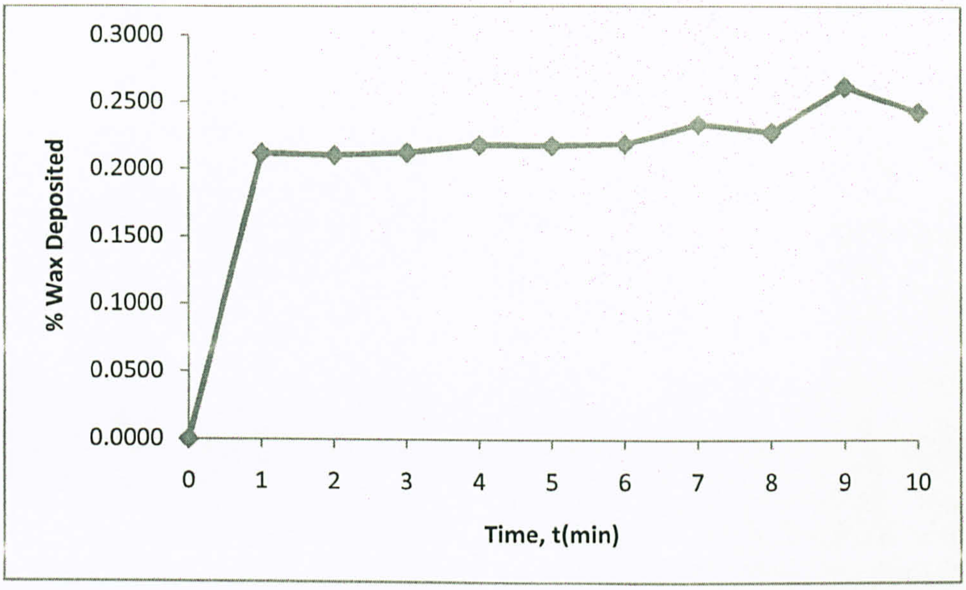

Figure 5.7: Graph of Percentage Wax Deposited (%) vs Time, t (min) at Temperature 10°C

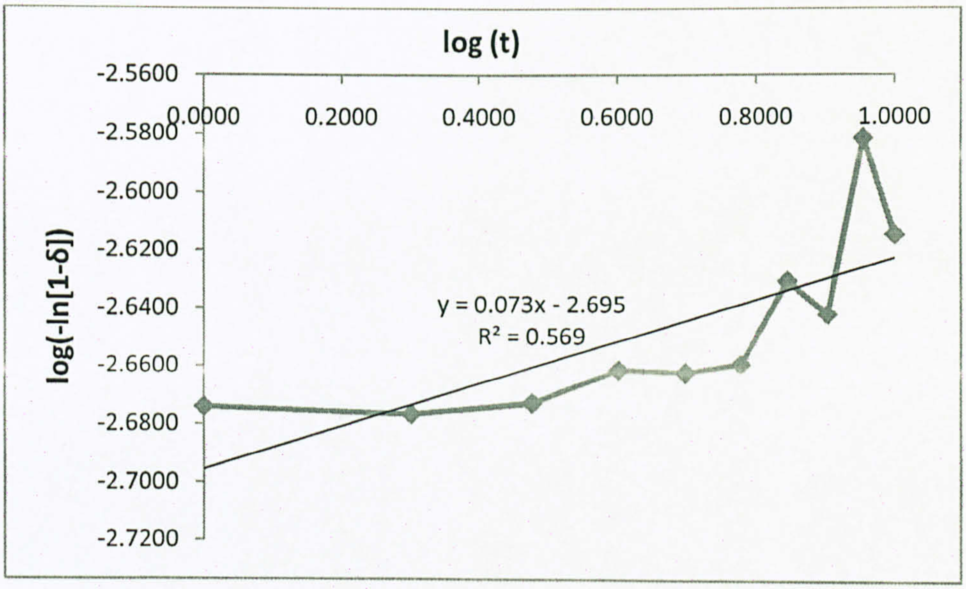

Figure 5.8: Graph of log(-ln[1-δ]) vs log (t) from Avrami's kinetic theory.

Avrami's kinetic equation:

$\log[-\ln(1-\delta r)] = \log K + n \log(t)$

From equation,

$Y = 0.073x - 2.695$

Where $\log K_1 = -2.695$, $n_1 = 0.073$

Thus, parameter for crystallization kinetic, $K_1 = 0.002018 \text{min}^{-1}$

Avrami exponent, $n_1 = 0.073$

b) Temperature, T = 12.5°C

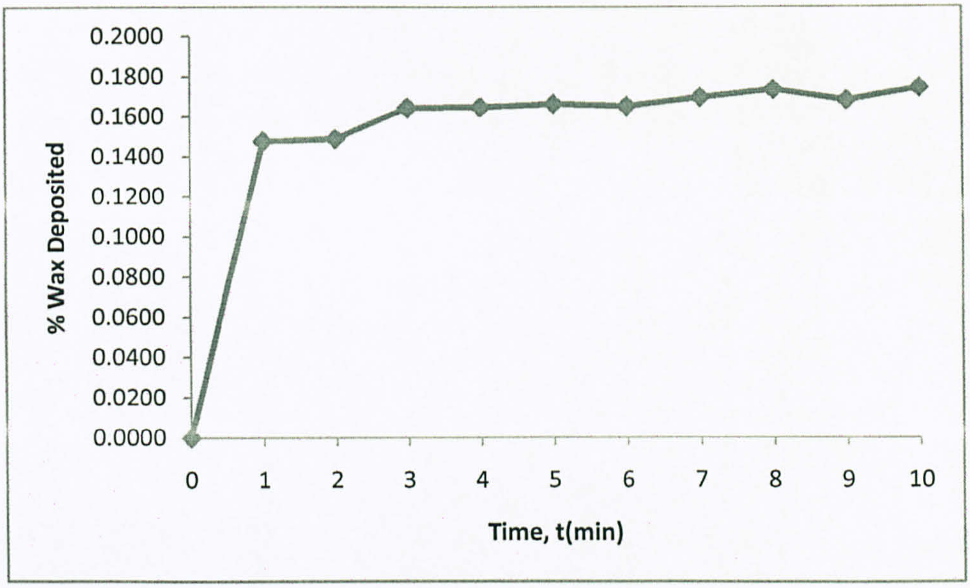

Figure 5.9: Graph of Percentage Wax Deposited (%) vs Time, t (min) at Temperature 12.5°C

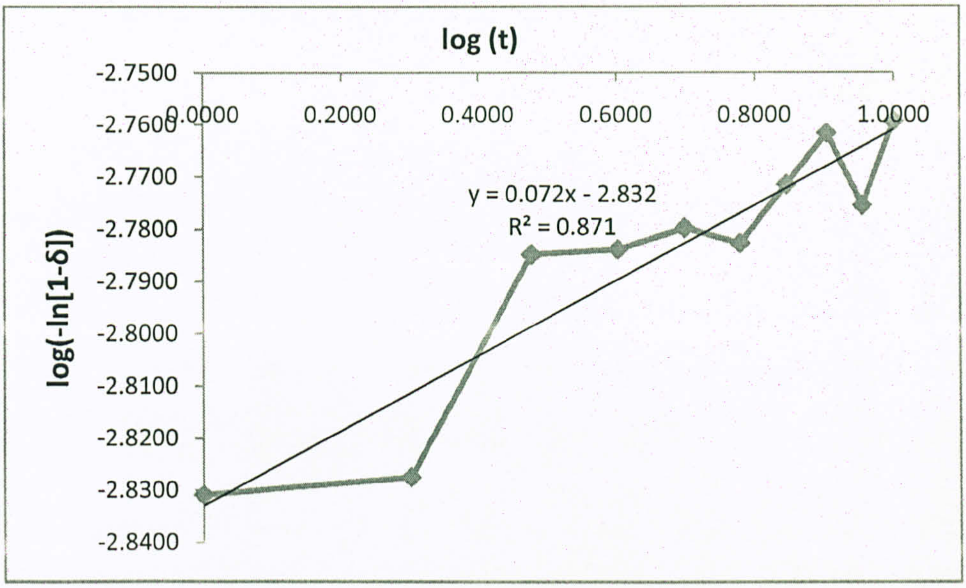

Figure 5.10: Graph of log(-ln[1-δ]) vs log (t) from Avrami's kinetic theory.

Avrami's kinetic equation:

log [-ln(1-δr)] = log K + n log (t)

From equation,

$Y = 0.072x - 2.832$

Where $\log K_1 = -2.832$, $n_1 = 0.072$

Thus, parameter for crystallization kinetic, $K_1 = 0.001472\text{min}^{-1}$

Avrami exponent, $n_1 = 0.072$

c) Temperature, T = 15°C

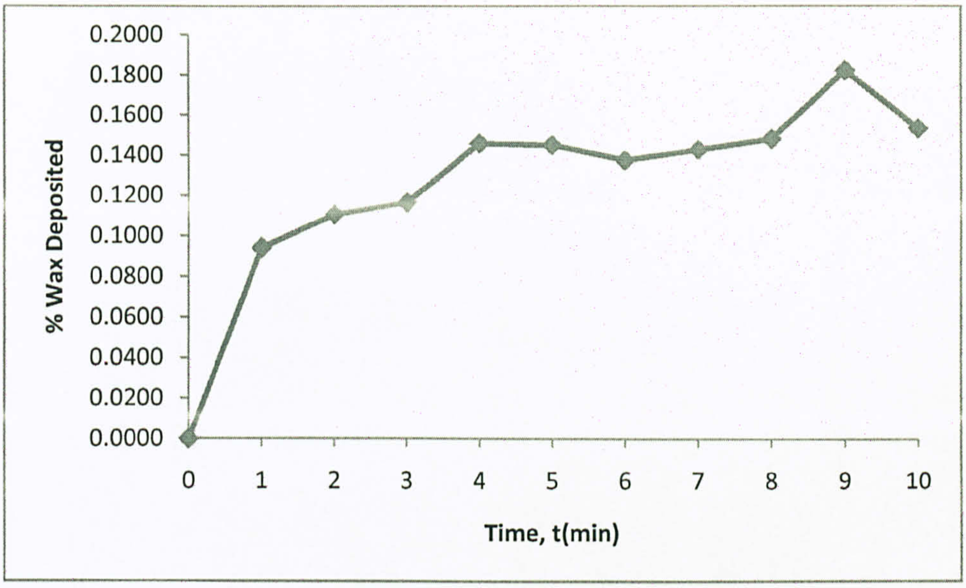

Figure5.11: Graph of Percentage Wax Deposited (%) vs Time, t (min) at Temperature 15°C

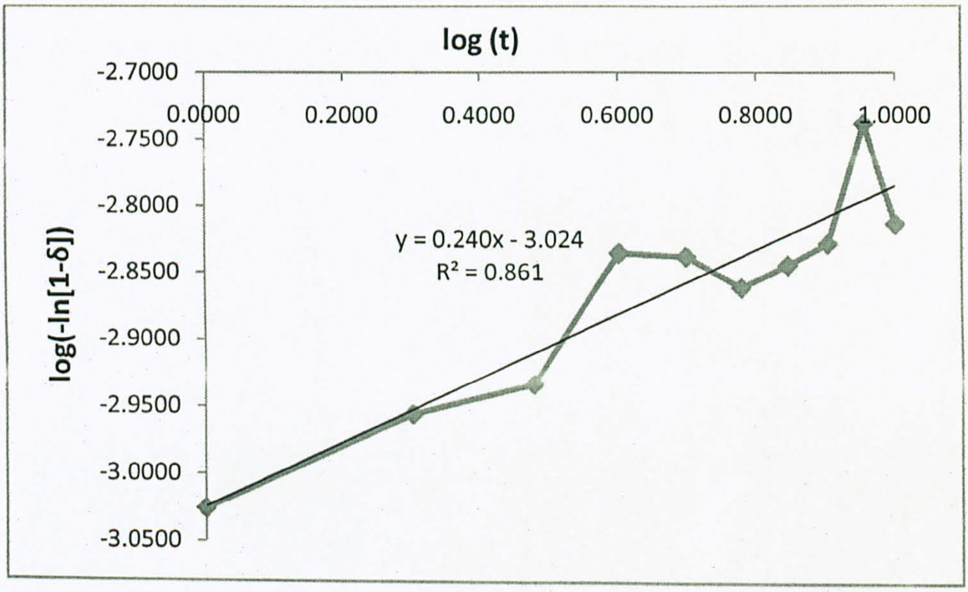

Figure 5.12: Graph of log(-ln[1-δ]) vs log (t) from Avrami's kinetic theory.

Avrami's kinetic equation:

$\log[-\ln(1-\delta r)] = \log K + n \log(t)$

From equation,

$Y = 0.240x - 3.024$

Where $\log K_1 = -3.024$, $n_1 = 0.240$

Thus, parameter for crystallization kinetic, $K_1 = 0.000946\text{min}^{-1}$

Avrami exponent, $n_1 = 0.240$

2) For Wax composition = 15%, (30 gram paraffin wax + 170 gram diesel)

a) Temperature = 10°C

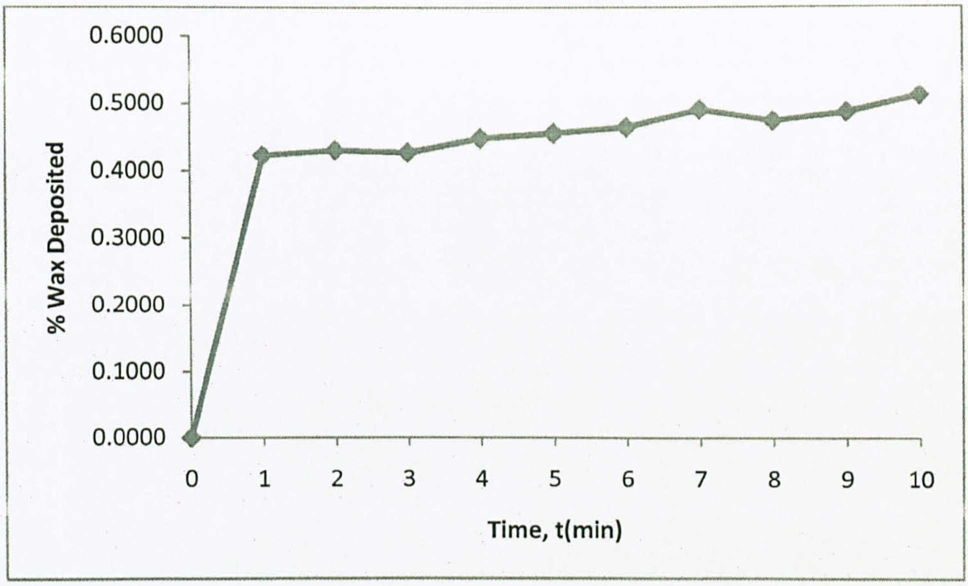

Figure 5.13: Graph of Percentage Wax Deposited (%) vs Time, t (min) at Temperature 10°C

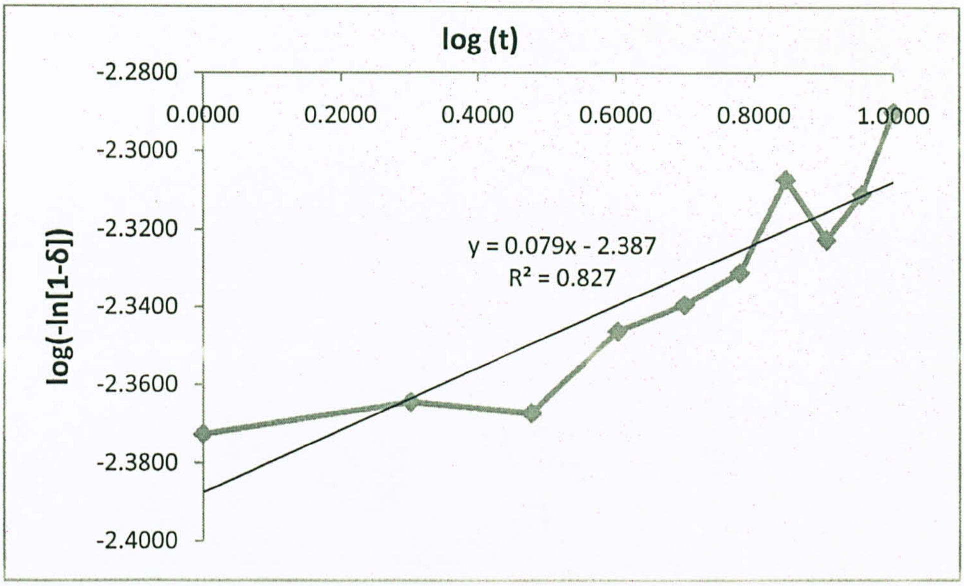

Figure 5.14: Graph of log(-ln[1-δ]) vs log (t) from Avrami's kinetic theory.

Avrami's kinetic equation:

log [-ln(1-δr)] = log K + n log (t)

From equation,

$Y = 0.079x - 2.387$

Where $\log K_1 = -2.387$, $n_1 = 0.079$

Thus, parameter for crystallization kinetic, $K_1 = 0.004102 \text{min}^{-1}$

Avrami exponent, $n_1 = 0.079$

b) Temperature = 12.5°C

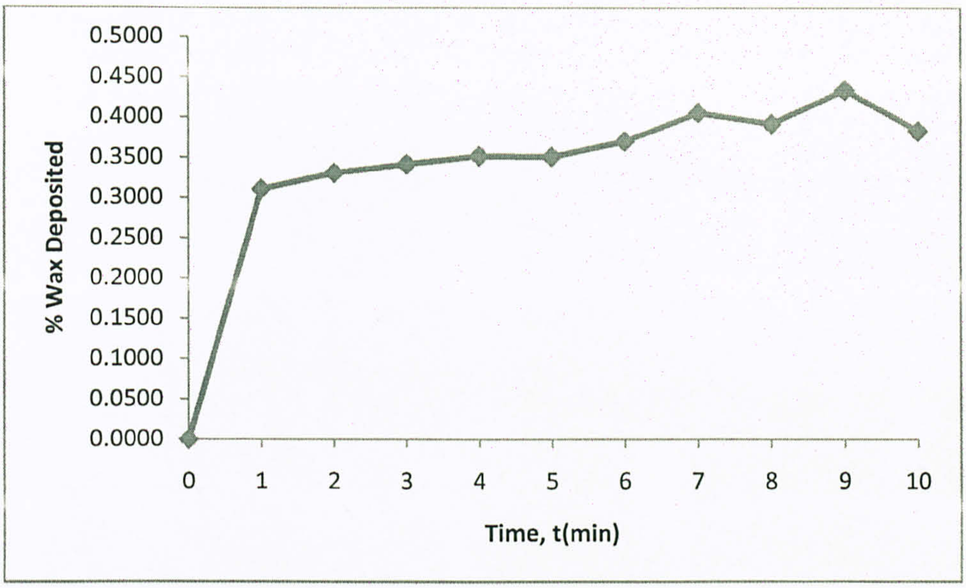

Figure 5.15: Graph of Percentage Wax Deposited (%) vs Time, t (min) at Temperature 12.5°C

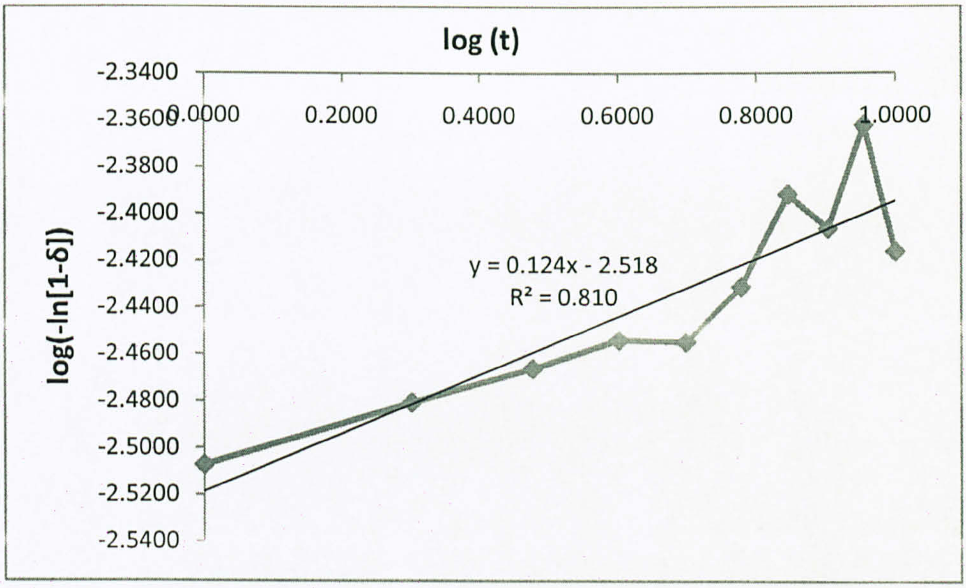

Figure 5.16: Graph of log(-ln[1-δ]) vs log (t) from Avrami's kinetic theory.

Avrami's kinetic equation:

$\log[-\ln(1-\delta r)] = \log K + n \log(t)$

From equation,

$Y = 0.124x - 2.518$

Where $\log K_1 = -2.518$, $n_1 = 0.124$

Thus, parameter for crystallization kinetic, $K_1 = 0.003034\text{min}^{-1}$

Avrami exponent, $n_1 = 0.124$

c) Temperature, T = 15.0°C

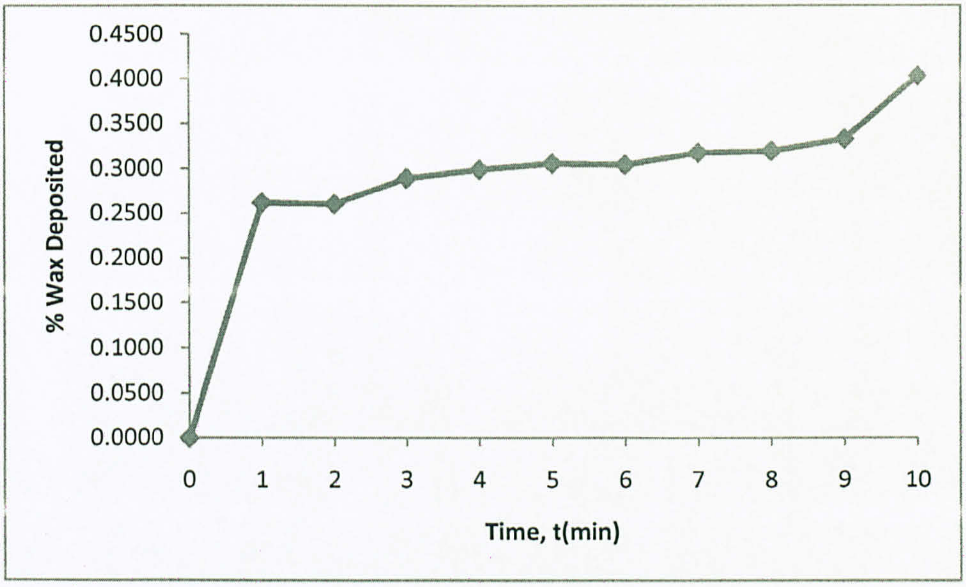

Figure 5.17: Graph of Percentage Wax Deposited (%) vs Time, t (min) at Temperature 15°C

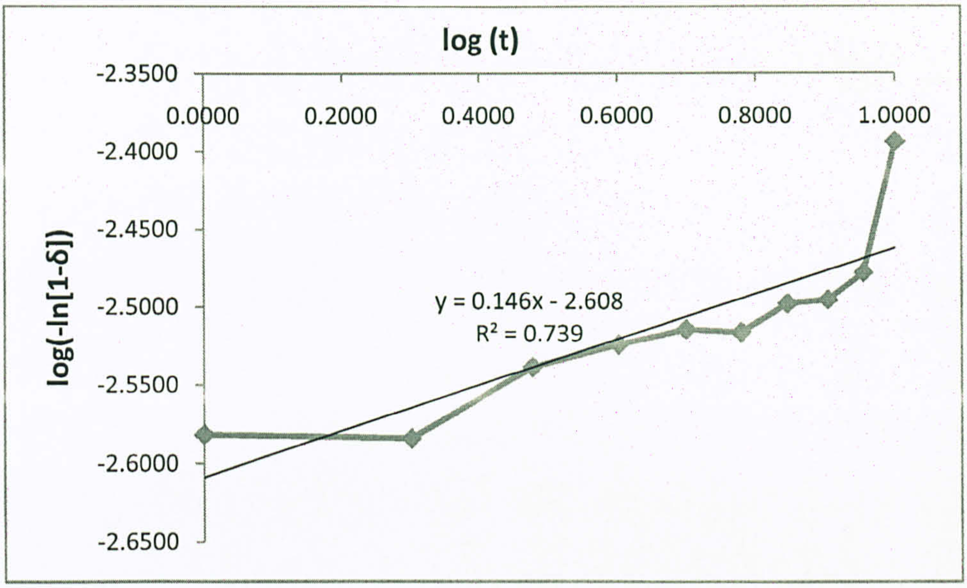

Figure 5.18: Graph of log(-ln[1-δ]) vs log (t) from Avrami's kinetic theory.

Avrami's kinetic equation:

log [-ln(1-δr)] = log K + n log (t)

From equation,

$Y = 0.146x - 2.608$

Where $\log K_1 = -2.608$, $n_1 = 0.146$

Thus, parameter for crystallization kinetic, $K_1 = 0.002466\text{min}^{-1}$

Avrami exponent, $n_1 = 0.146$

3) For Wax composition = 20%, (40 gram paraffin wax + 160 gram diesel)

a) Temperature = 10°C

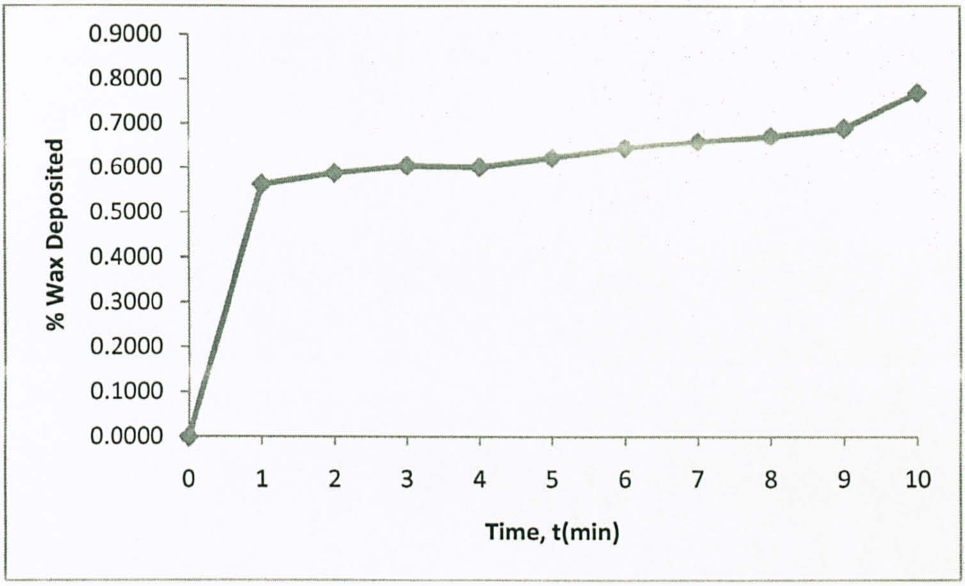

Figure 5.19: Graph of Percentage Wax Deposited (%) vs Time, t (min) at Temperature 10°C

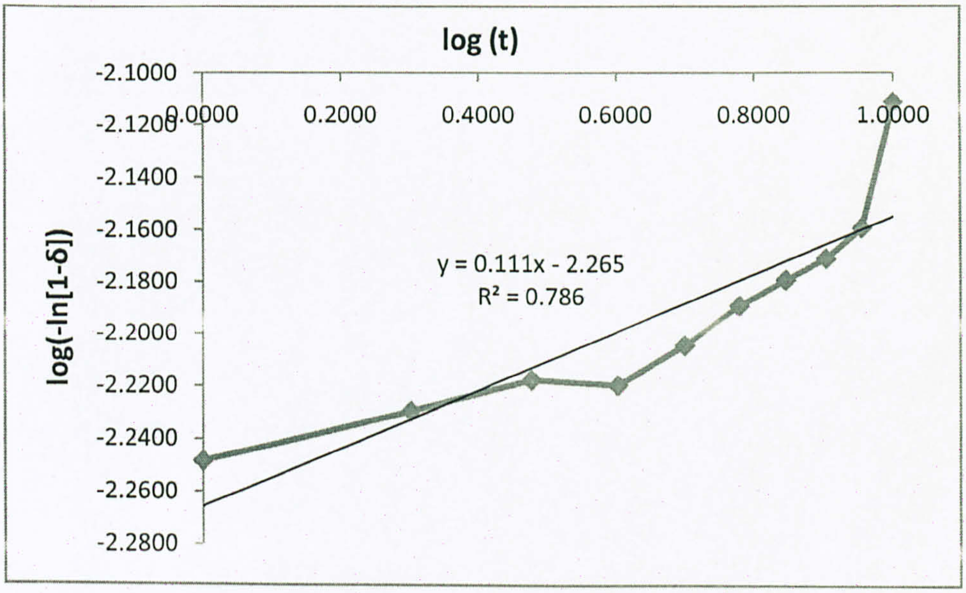

Figure 5.20: Graph of log(-ln[1-δ]) vs log (t) from Avrami's kinetic theory.

Avrami's kinetic equation:

$$\log[-\ln(1-\delta r)] = \log K + n \log(t)$$

From equation,

$Y = 0.111x - 2.265$

Where $\log K_1 = -2.265$, $n_1 = 0.111$

Thus, parameter for crystallization kinetic, $K_1 = 0.005433\text{min}^{-1}$

Avrami exponent, $n_1 = 0.111$

b) Temperature = 12.5°C

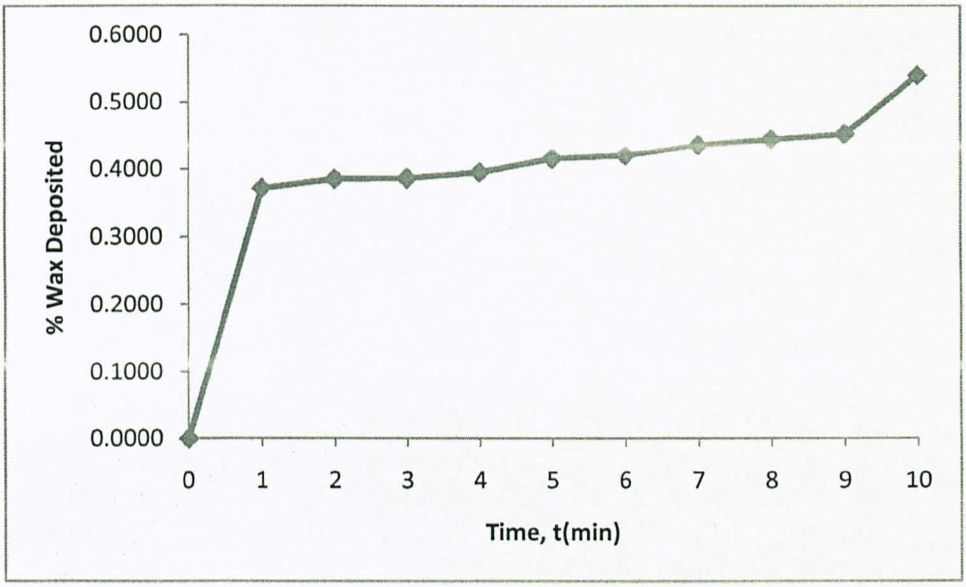

Figure 5.21: Graph of Percentage Wax Deposited (%) vs Time, t (min) at Temperature 12.5°C

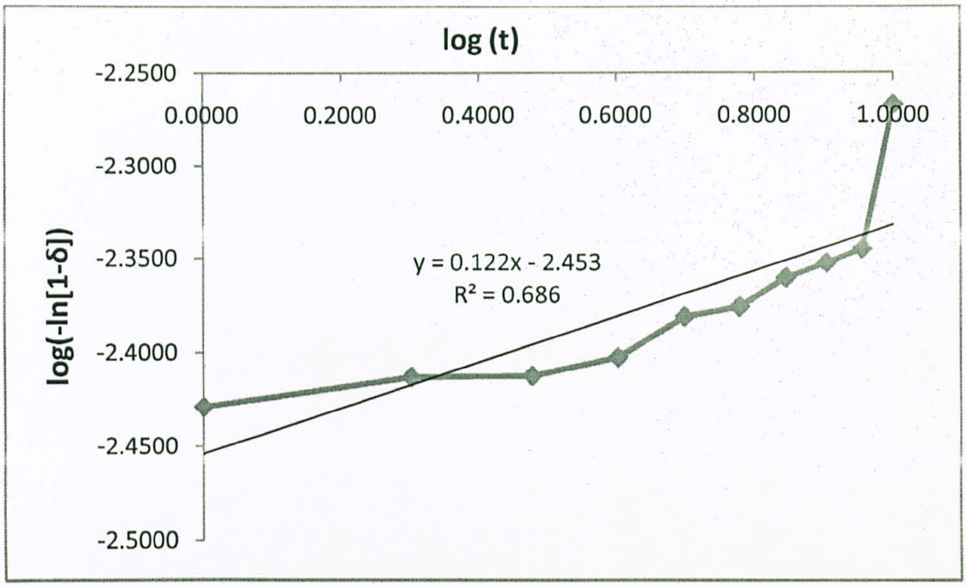

Figure 5.22: Graph of log(-ln[1-δ]) vs log (t) from Avrami's kinetic theory.

Avrami's kinetic equation:

log [-ln(1-δr)] = log K + n log (t)

From equation,

$Y = 0.122x - 2.453$

Where $\log K_1 = -2.453$, $n_1 = 0.122$

Thus, parameter for crystallization kinetic, $K_1 = 0.003524\text{min}^{-1}$

Avrami exponent, $n_1 = 0.122$

c) Temperature = 15°C

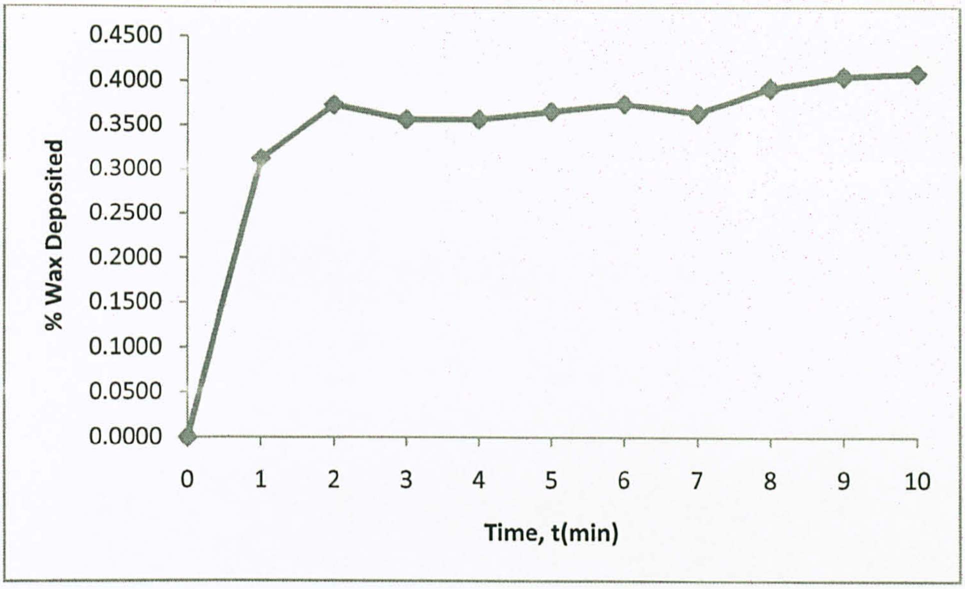

Figure 5.23: Graph of Percentage Wax Deposited (%) vs Time, t (min) at Temperature 15°C

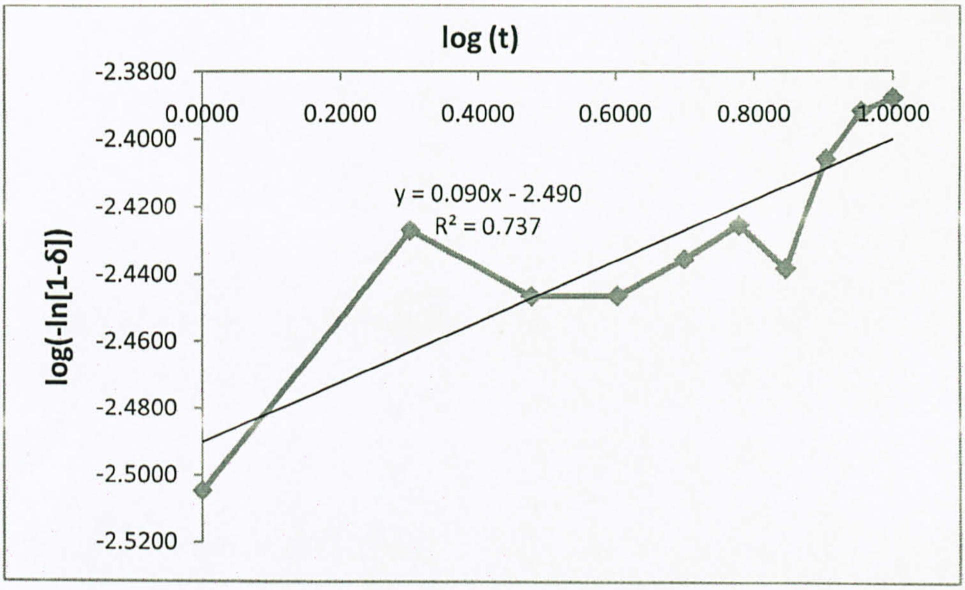

Figure 5.24: Graph of log(-ln[1-δ]) vs log (t) from Avrami's kinetic theory.

Avrami's kinetic equation:

$\log [-\ln(1-\delta r)] = \log K + n \log (t)$

From equation,

$Y = 0.090x - 2.490$

Where $\log K_1 = -2.490$, $n_1 = 0.090$

Thus, parameter for crystallization kinetic, $K_1 = 0.003236\ \text{min}^{-1}$

Avrami exponent, $n_1 = 0.090$

5.3.1 Avrami Exponent And Growth Rate Constant For Result Obtained

	10%		
Temperature	**10.0°C**	**12.5°C**	**15.0°C**
n	0.073	0.072	0.24
K (min^{-1})	0.002018	0.001472	0.000946

Table 5.5: Table of Avrami exponent and growth rate constant for 10% wax composition

	15%		
Temperature	**10.0°C**	**12.5°C**	**15.0°C**
n	0.079	0.124	0.146
K (min^{-1})	0.004102	0.003034	0.002466

Table 5.6: Table of Avrami exponent and growth rate constant for 15% wax composition

	20%		
Temperature	**10.0°C**	**12.5°C**	**15.0°C**
n	0.111	0.122	0.09
K (min^{-1})	0.005433	0.003524	0.003236

Table 5.7: Table of Avrami exponent and growth rate constant for 20% wax composition

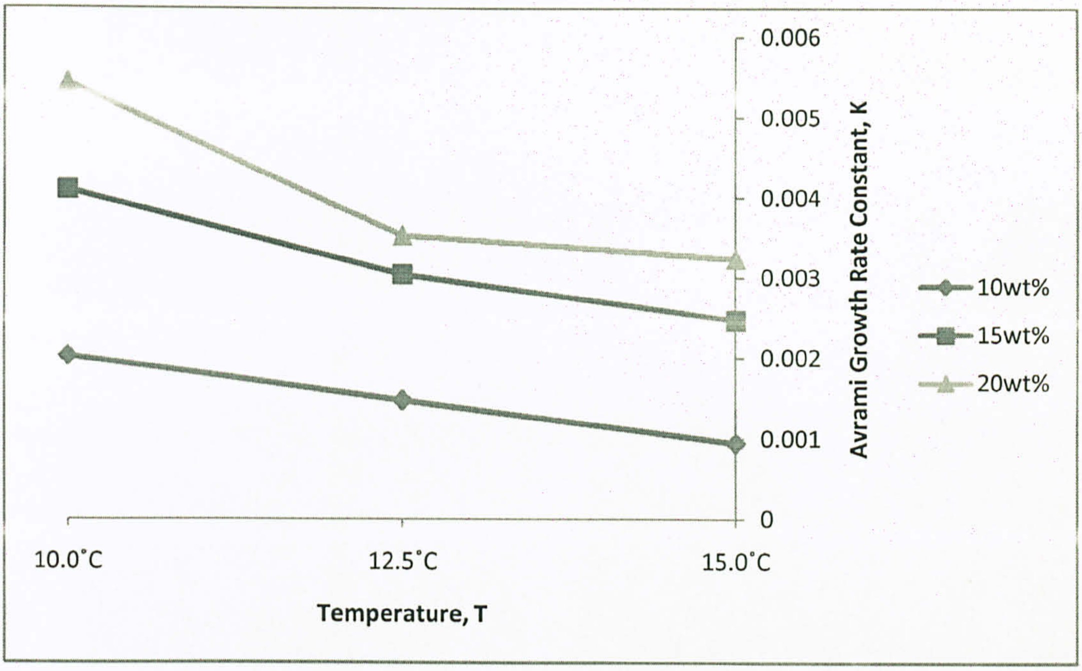

Figure 5.25: Summary graph of Avrami Growth Rate Constant vs Temperature for 10wt%, 15wt% and 20wt% wax composition

Discussion

For the value of K, there are some indications that explain the wax deposition rate phenomenon. It is primarily depends on concentration of wax then followed by temperature of cold finger. The highest wax composition dominantly is at the top of overall K value, and followed by the lowest temperature among them.

5.3.2Summary for Wax Deposition at Different Temperature

The deposition occurred can be understood by having such graph that can summarize the deposition phenomena that can takes place at different temperature and different composition. There is real difference of deposition rate when the different values of temperature are imposed to different percentage of wax deposition.

a) 10% Wax Composition

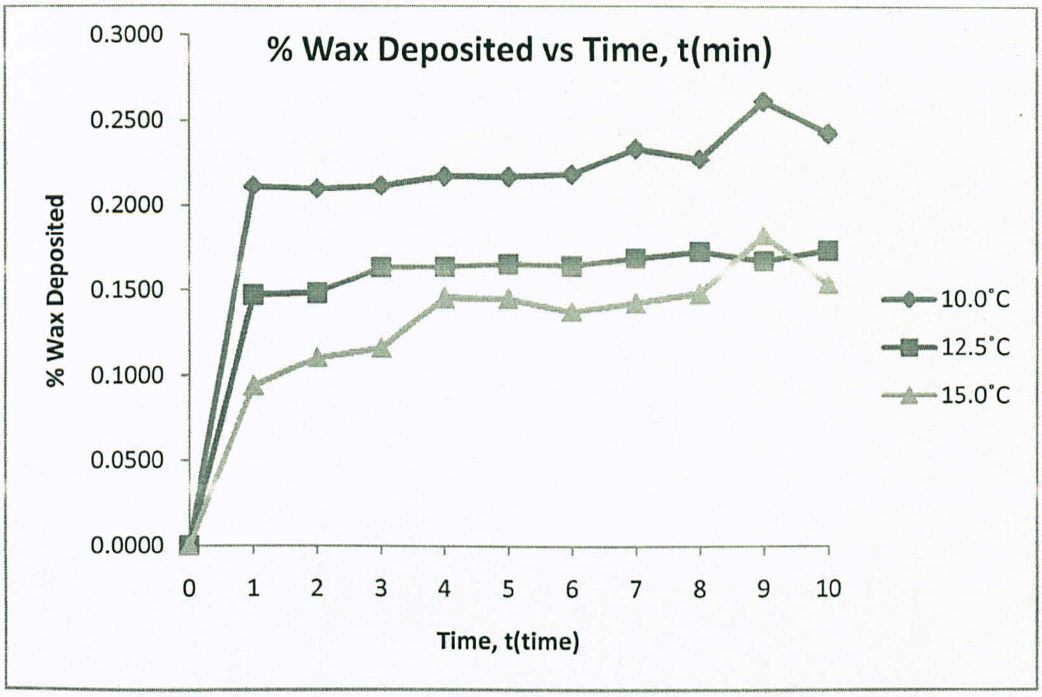

Figure 5.26: Graph of Percentage Wax Deposited (%) vs Time, t (min) at Different Temperature for 10% Wax Composition

b) 15% Wax Composition

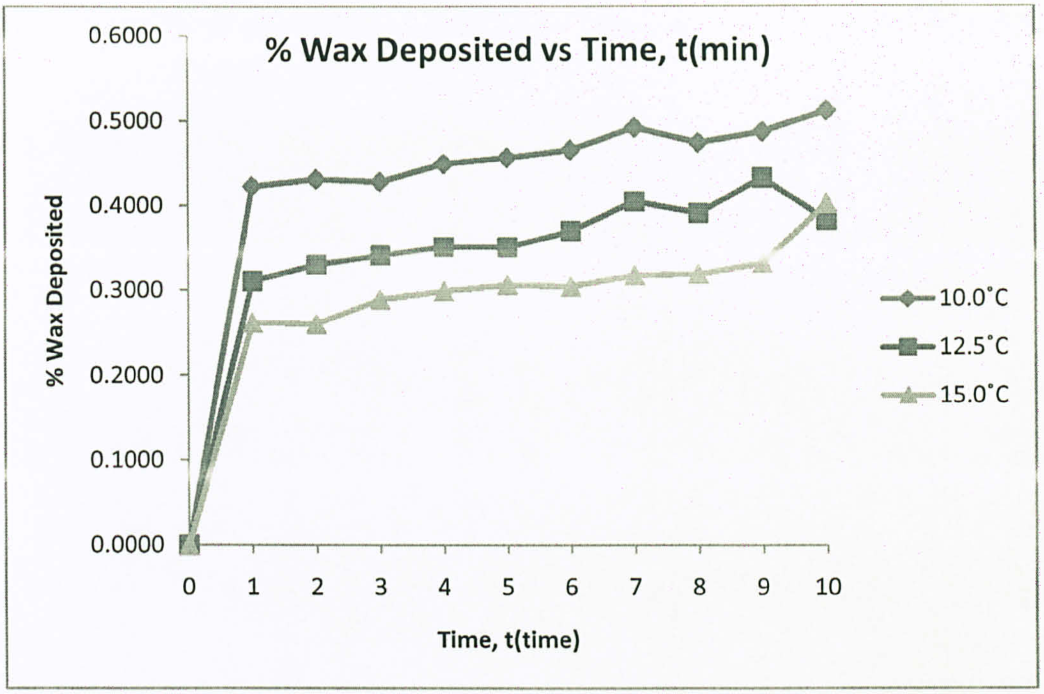

Figure 5.27: Graph of Percentage Wax Deposited (%) vs Time, t (min) at Different Temperature for 15% Wax Composition

c) 20% Wax Composition

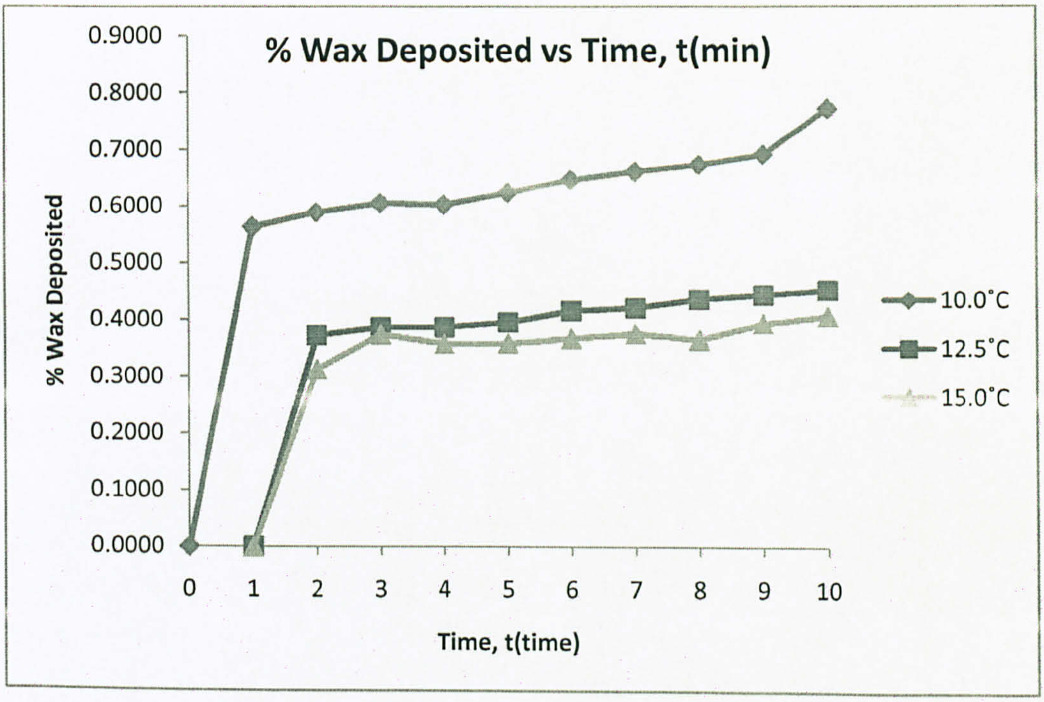

Figure 5.28: Graph of Percentage Wax Deposited (%) vs Time, t (min) at Different Temperature for 20% Wax Composition

5.3.3 Summary for Wax Deposition at Different % Wax Composition

a) 10.0°C

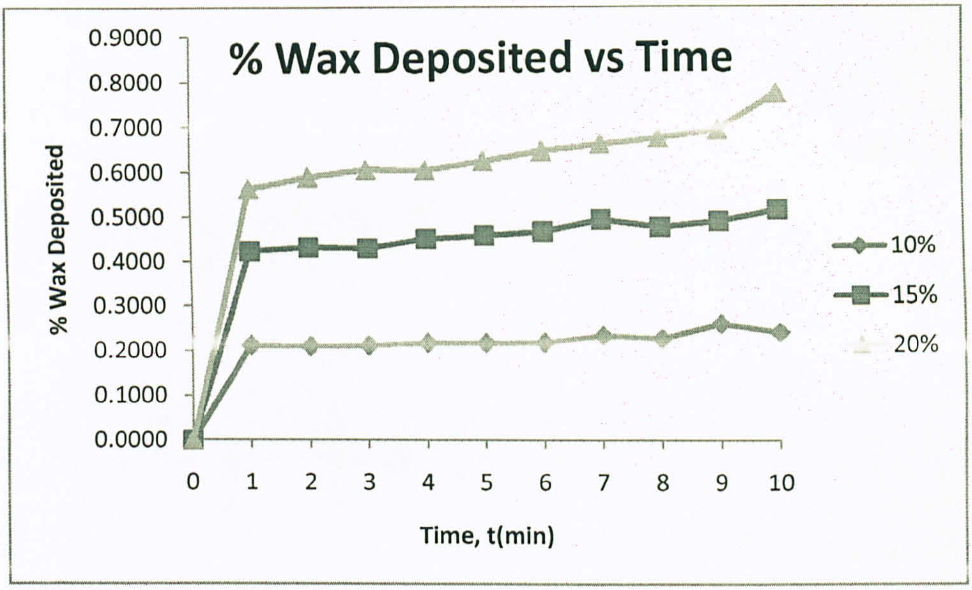

Figure 5.29: Graph of Percentage Wax Deposited (%) vs Time, t (min) at Different Wax Composition at T =10.0°C

b) 12.5°C

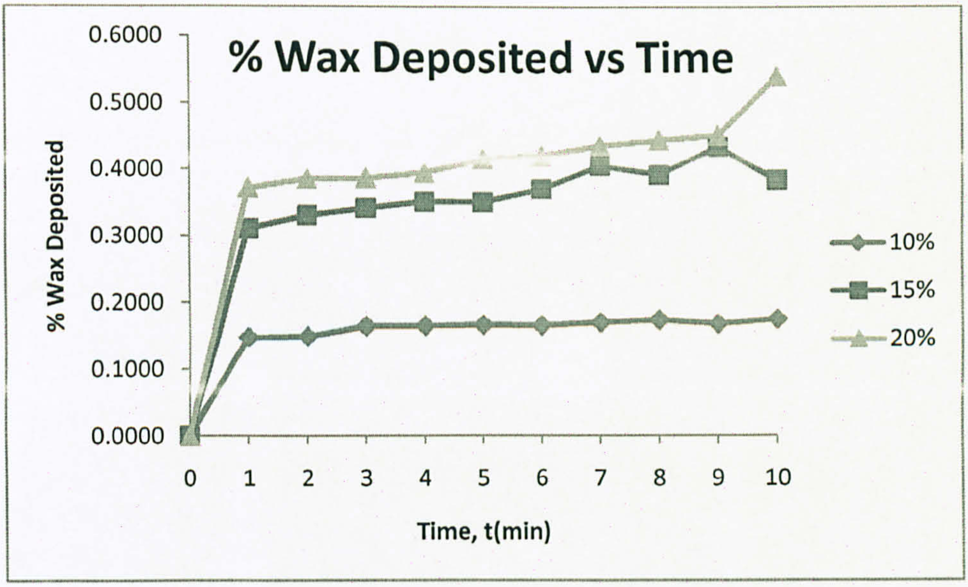

Figure 5.30: Graph of Percentage Wax Deposited (%) vs Time, t (min) at Different Wax Composition at T =12.5°C

c) 15°C

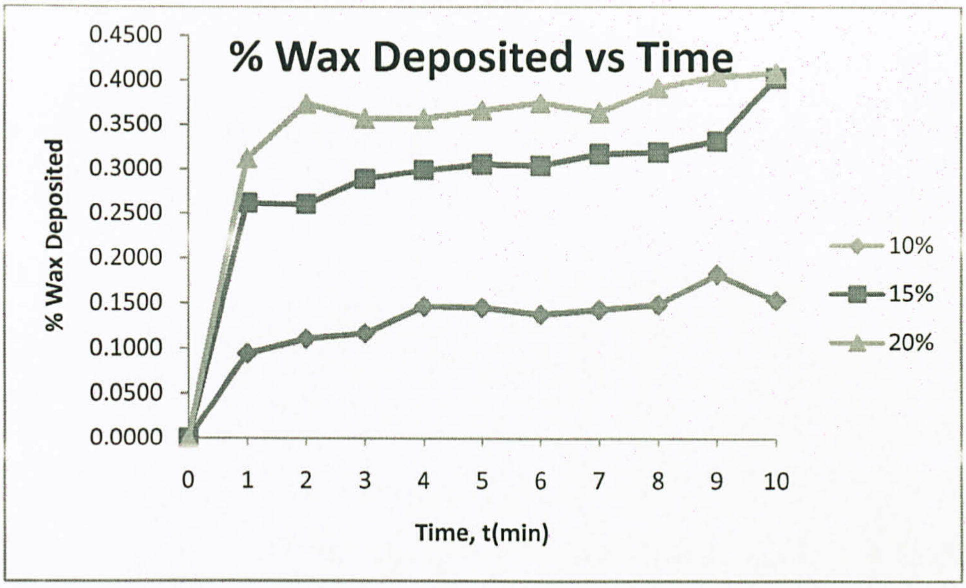

Figure 5.31: Graph of Percentage Wax Deposited (%) vs Time, t (min) at Different Wax Composition at T =15.0°C

5.3.4 Discussion and Problems for Experiment 5.3

There are differences among those concentrations of wax used in term of range of wax deposited. We can see that when the wax composition increases, the range of the Y-axis in the graph increases.

This is because the wax deposition rate is significantly changes with increasing wax composition. The higher wax composition, the larger rate of deposition will takes place.

This analysis show whenever crude oil comes with larger composition of wax there will be higher rate of deposition of wax and the maintenance will be harder. By lowering the composition of wax such as using hot oil circulation, based on trend for this experiment, it might lower the rate of wax deposition significantly compared to increase the temperature of crude oil within pipeline using other method that can overcomes the low temperature there.

It is highly recommended for the further research the concern is given on how the composition can be manipulated to reduce the wax problem. This can save energy because heating consumes lot of energy that significantly increases the utility cost. By pumping more hot oil in the crude oil pipeline, it saves operation cost where it consumes little energy. It will be economically efficient when utility cost can be reduced.

Further more complex mixture of crude oil will have larger rate then model oil which is used in this experiment. The phenomena of heat losses from pipeline to the sea water will just lowering the efficiency of production. So that, when there only heating method to overcome wax problems in crude oil pipeline this might not challenge the using of hot oil circulation which makes lower concentration of wax in crude pipeline.. Based on this experiment the lowest point of K occurs when there is higher temperature and lowest composition of wax. So, hot oil circulation can be used to serve as solvent for the waxy crude oil.

CHAPTER 6: CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The study shows the trend of wax deposition and formation are rely on temperature of cold surface and also composition of wax. This has been shown by the value of avrami growth rate constant, K = 0.005433 min^{-1} which stands for highest value of K occurs at $T_{coolant}$ = 10°C and 20wt%. It means the highest deposition rate occur at lowest temperature and highest wt% of wax composition. The result indicates the lowest K value occurs at the highest temperature and lowest wt% of wax composition where K = 0.000946 min^{-1} which $T_{coolant}$ = 15°C and 10 wt% of wax composition.

This phenomenon clearly shows that wax deposition can takes place easily at lower temperature at seabed and it is enhanced once again with higher wax composition in crude oil. From these 2 variables there are chances to overcome or minimizing the effect of wax deposition such as ultrasound, pigging and hot oil circulation. Thus, the concept of heat impose on waxy solution works as they can overcome the Wax Appearance Temperature (WAT) and minimizing the composition of wax.

6.2 Recommendation

The apparatus used should be up to date in order to have lesser value of error and standard deviation. Measurement of wax deposited weight by gravimetric method might have some errors due to splash or vaporization. But the trend and consistency for this experiment are consistent and can be accepted.

Chapter 7: References

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APPENDICES

Appendix A: 10wt%

Calculation of mass of wax deposited, δr

$$\delta r = \frac{mass\ of\ solid\ wax}{total\ mass\ of\ hydrocarbon\ solution}$$

Calculation of Avrami Growth rate constant and exponent

$$\log[-\ln(1-X)] = \log K + n \log(t)$$

X is the volume fraction of crystalline material or degree of crystallinity

t is time taken to form crystalline material

K is the growth rate

n is the Avrami exponent

Appendix B: 10wt% Wax Composition

For T = 10°C

t (min)	deposited (g)	δr	%	X	Y
0	0.0000	0.0000	0.0000	#NUM!	#NUM!
1	0.4232	0.0021	0.2116	0.0000	-2.6741
2	0.4205	0.0021	0.2102	0.3010	-2.6769
3	0.4243	0.0021	0.2121	0.4771	-2.6729
4	0.4355	0.0022	0.2178	0.6021	-2.6616
5	0.4346	0.0022	0.2173	0.6990	-2.6625
6	0.4374	0.0022	0.2187	0.7782	-2.6596
7	0.4676	0.0023	0.2338	0.8451	-2.6306
8	0.4554	0.0023	0.2277	0.9031	-2.6421
9	0.5235	0.0026	0.2618	0.9542	-2.5815
10	0.4854	0.0024	0.2427	1.0000	-2.6144

Table B1: Data for Average Value of Wax Deposited for T =10.0°C

For T = 12.5°C

t (min)	deposited (g)	δr	%	X	Y
0	0.0000	0.0000	0.0000	#NUM!	#NUM!
1	0.2950	0.0015	0.1475	0.0000	-2.8309
2	0.2974	0.0015	0.1487	0.3010	-2.8274
3	0.3280	0.0016	0.1640	0.4771	-2.7849
4	0.3287	0.0016	0.1644	0.6021	-2.7839
5	0.3319	0.0017	0.1659	0.6990	-2.7797
6	0.3297	0.0016	0.1648	0.7782	-2.7826
7	0.3383	0.0017	0.1691	0.8451	-2.7714
8	0.3460	0.0017	0.1730	0.9031	-2.7616
9	0.3352	0.0017	0.1676	0.9542	-2.7754
10	0.3478	0.0017	0.1739	1.0000	-2.7593

Table B2: Data for Average Value of Wax Deposited for T =12.5°C

For T = 15°C

t (min)	**deposited (g)**	**δr**	**%**	**X**	**Y**
0	0.0000	0.0000	0.0000	#NUM!	#NUM!
1	0.1883	0.0009	0.0941	0.0000	-3.0260
2	0.2214	0.0011	0.1107	0.3010	-2.9556
3	0.2332	0.0012	0.1166	0.4771	-2.9330
4	0.2923	0.0015	0.1461	0.6021	-2.8349
5	0.2906	0.0015	0.1453	0.6990	-2.8373
6	0.2755	0.0014	0.1378	0.7782	-2.8605
7	0.2862	0.0014	0.1431	0.8451	-2.8440
8	0.2971	0.0015	0.1485	0.9031	-2.8278
9	0.3652	0.0018	0.1826	0.9542	-2.7381
10	0.3075	0.0015	0.1537	1.0000	-2.8129

Table B3: Data for Average Value of Wax Deposited for T =15.0°C

Appendix C: 15wt% Wax Composition

For T = 10°C

t (min)	deposited (g)	δr	%	X	Y
0	0.0000	0.0000	0.0000	#NUM!	#NUM!
1	0.8462	0.0042	0.4231	0.0000	-2.3726
2	0.8625	0.0043	0.4312	0.3010	-2.3644
3	0.8568	0.0043	0.4284	0.4771	-2.3672
4	0.8991	0.0045	0.4496	0.6021	-2.3462
5	0.9135	0.0046	0.4567	0.6990	-2.3394
6	0.9309	0.0047	0.4655	0.7782	-2.3311
7	0.9835	0.0049	0.4918	0.8451	-2.3072
8	0.9493	0.0047	0.4747	0.9031	-2.3226
9	0.9750	0.0049	0.4875	0.9542	-2.3110
10	1.0235	0.0051	0.5117	1.0000	-2.2898

Table C1: Data for Average Value of Wax Deposited for T =10.0°C

For T = 12.5˚C

t (min)	deposited (g)	δr	%	X	Y
0	0.0000	0.0000	0.0000	#NUM!	#NUM!
1	0.6210	0.0031	0.3105	0.0000	-2.5072
2	0.6605	0.0033	0.3302	0.3010	-2.4804
3	0.6825	0.0034	0.3412	0.4771	-2.4662
4	0.7020	0.0035	0.3510	0.6021	-2.4539
5	0.7006	0.0035	0.3503	0.6990	-2.4548
6	0.7396	0.0037	0.3698	0.7782	-2.4312
7	0.8102	0.0041	0.4051	0.8451	-2.3915
8	0.7830	0.0039	0.3915	0.9031	-2.4064
9	0.8668	0.0043	0.4334	0.9542	-2.3621
10	0.7658	0.0038	0.3829	1.0000	-2.4161

Table C2: Data for Average Value of Wax Deposited for T =12.5˚C

For T = 15°C

t (min)	**deposited (g)**	**δr**	**%**	**X**	**Y**
0	0.0000	0.0000	0.0000	#NUM!	#NUM!
1	0.5234	0.0026	0.2617	0.0000	-2.5816
2	0.5205	0.0026	0.2602	0.3010	-2.5840
3	0.5780	0.0029	0.2890	0.4771	-2.5385
4	0.5975	0.0030	0.2987	0.6021	-2.5241
5	0.6112	0.0031	0.3056	0.6990	-2.5142
6	0.6085	0.0030	0.3043	0.7782	-2.5161
7	0.6350	0.0032	0.3175	0.8451	-2.4976
8	0.6384	0.0032	0.3192	0.9031	-2.4952
9	0.6648	0.0033	0.3324	0.9542	-2.4776
10	0.8062	0.0040	0.4031	1.0000	-2.3937

Table C3: Data for Average Value of Wax Deposited for T =15°C

Appendix D: 20wt% Wax Composition

For T = 10°C

t (min)	deposited (g)	δr	%	X	Y
0	0.0000	0.0000	0.0000	#NUM!	#NUM!
1	1.1256	0.0056	0.5628	0.0000	-2.2484
2	1.1769	0.0059	0.5884	0.3010	-2.2290
3	1.2092	0.0060	0.6046	0.4771	-2.2172
4	1.2036	0.0060	0.6018	0.6021	-2.2192
5	1.2463	0.0062	0.6232	0.6990	-2.2041
6	1.2908	0.0065	0.6454	0.7782	-2.1888
7	1.3198	0.0066	0.6599	0.8451	-2.1791
8	1.3452	0.0067	0.6726	0.9031	-2.1708
9	1.3821	0.0069	0.6910	0.9542	-2.1590
10	1.5421	0.0077	0.7710	1.0000	-2.1113

Table D1: Data for Average Value of Wax Deposited for T =10.0°C

For T = 12.5°C

t (min)	deposited (g)	δr	%	X	Y
0	0.0000	0.0000	0.0000	#NUM!	#NUM!
1	0.7435	0.0037	0.3717	0.0000	-2.4289
2	0.7711	0.0039	0.3856	0.3010	-2.4131
3	0.7725	0.0039	0.3862	0.4771	-2.4123
4	0.7902	0.0040	0.3951	0.6021	-2.4024
5	0.8306	0.0042	0.4153	0.6990	-2.3807
6	0.8407	0.0042	0.4204	0.7782	-2.3754
7	0.8711	0.0044	0.4356	0.8451	-2.3600
8	0.8872	0.0044	0.4436	0.9031	-2.3520
9	0.9026	0.0045	0.4513	0.9542	-2.3446
10	1.0785	0.0054	0.5392	1.0000	-2.2670

Table D2: Data for Average Value of Wax Deposited for T =12.5°C

For T = 15°C

t (min)	deposited (g)	δr	%	X	Y
0	0.0000	0.0000	0.0000	#NUM!	#NUM!
1	0.6249	0.0031	0.3125	0.0000	-2.5045
2	0.7469	0.0037	0.3734	0.3010	-2.4270
3	0.7141	0.0036	0.3570	0.4771	-2.4465
4	0.7142	0.0036	0.3571	0.6021	-2.4465
5	0.7321	0.0037	0.3661	0.6990	-2.4357
6	0.7493	0.0037	0.3746	0.7782	-2.4256
7	0.7272	0.0036	0.3636	0.8451	-2.4386
8	0.7838	0.0039	0.3919	0.9031	-2.4060
9	0.8100	0.0040	0.4050	0.9542	-2.3917
10	0.8172	0.0041	0.4086	1.0000	-2.3878

Table D3: Data for Average Value of Wax Deposited for T =15°C