Simulation of Wax Deposition Model for Various Field

by

Nor Azlina Binti Mohd Nasir

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Chemical Engineering)

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CERTIFICATION OF APPROVAL

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Approved by,

……
(Assoc. Prof. Dr. Nurul Hasan)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
September 2012

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 reference and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(NOR AZLINA BINTI MOHD NASIR)

ABSTRACT

This study is about a wax deposition simulation model is used to represent the behavior of the wax deposition phenomena in the subsea pipelines. As the fluid flow across the subsea pipelines, a cooling process occurs as heat is loss to the surrounding of the seawater. When the bulb temperature (T_b) drops below the Wax Appearance Temperature (WAT), formation of wax deposition onto the pipeline wall occurs. To prevent wax deposition from reducing the flow area, changing the flow and even blockage of the pipelines, pigging operation must be carried out to remove the wax on the pipeline. The aim of this study is to investigate another tool that can be used to estimate pigging operation frequency to remove wax from the pipeline wall and to validate the wax simulation predicted by model with the Mother Paper. In order to achieve the objective, some job will be done by developing suitable model equation to be used as representation for wax deposition thickness, temperature and pressure, performing simulation on wax deposition using real field data to determine the thickness of wax deposition (x) along the pipeline, analyze the temperature (T) and pressure (P) profiles along the pipeline and lastly, comparing wax deposition predicted by a simulation model with Mother Paper.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND NOMENCLATURES

English

A [m^2]	- Inner area of flow pipe
C_p [J/kg.K]	- Specific heat capacity
d [m]	- Inner diameter of flow pipe
f [-]	- Friction factor
L [m]	- Pipe length
m [kg/s]	- Mass flow rate
q [m^3/h]	- Flow rate
r [m]	- Pipe radius
r_0 [m]	- Clean pipe radius
Re [-]	- Reynolds number
t [h]	- Time
T_{out} [^{0}C]	- Outlet temperature
T_{in} [^{0}C]	- Inlet temperature
T_{sea} [^{0}C]	- Sea temperature (surrounding temperature)
T_c [^{0}C]	- Cloud point temperature, also known as WAT
T_p [^{0}C]	- Pour point temperature
ΔT_{LMTD} [^{0}C]	- Log Mean Temperature Different
WAT [^{0}C]	- Wax Appearance Temperature
WDT [^{0}C]	- Wax Dissolution Temperature
P [bar]	- Pressure
Δp [bar]	- Pressure drop
u [m/s]	- Flow velocity
u_0 [m/s]	- Velocity of a clean pipe

x [m]	- Wax thickness
k [W/m.K]	- Conductivity
U [W/m^2.K]	- Overall heat transfer coefficient
F [N]	- Tension
MW [kg/mol]	- Molecular weight

Greek

κ [-]	- Parameter defined in Equation (4)
κ_0 [-]	- Parameter defined in Equation (4) for a clean pipe
ρ [kg/m^3]	- Density
μ [Pa.s]	- Viscosity of oil
ϕ [%]	- Porosity
τ [Pa]	- Shear stress

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND OF STUDY

Flow assurance is a critical concern within petroleum industry, particularly as off-shore fields involved with deep and ultra-deep water conditions which involves high pressure and low temperature (~4 ^{0}C). Flow assurance is normally performed to make sure the gas/oil/liquid from wells is delivered to the point of sale successfully. Flow assurance term was originates in Portuguese as *Garantia do Escoamento*, meaning literally "*Guarantee of Flow*", or Flow Assurance by Petrobras in the early 1990s (Trick, 2012). Flow assurance involves effectively handling many solid deposits, such as, hydrates, asphaltenes, emulsions and waxes (Khalil de Oliveira, et al., 2011).

One of the main unsolved challenges in Flow Assurance is wax deposition in the pipeline. Many researchers in last decades reported and studied that waxes build-up are a complex and very costly problem for the petroleum industry. For subsea pipelines, it has become especially important to resolve the issue of wax build-up, as large scale of oil production in colder regions will be faced with more severe wax deposition (Aiyejina, Chakrabarti, & Sastry, 2011).

Wax is an undesired high molecular alkane (between C_{20} and C_{40}) dissolved in the oil at reservoir conditions. Wax molecules are mostly long chain n-alkanes, and weight% of 1-15 is considered typical in both crude oil and condensates but the composition of wax is different from crude to crude, which is mainly depends on the oil (Aske, 2011). The melting temperature is around 40-50 ^{0}C and the properties of the waxes are ductile in nature, which means instead of cracking, they somewhat deform under tensile stress. The waxes are not amorphous, but have stable crystal structure at lower temperature and its crystal structure is not rigid (Siljuberg, 2012). Wax structure can be divided into two; microcrystalline and macrocrystalline (Morgan, 2007).

At reservoir temperatures of 70-150 ^{0}C and pressures of 50-100 MPa, wax molecules will be dissolved. Due to heat loss to the surrounding, the temperature begins to drop once the crude oil leaves the reservoir (Lee, 2008). When oil is cooled below a certain temperature, wax will start to precipitate. The temperature where wax starts to drop out in the liquid bulk fluid in an observable amount and may deposit on the surface of the pipe wall is called Wax Appearance Temperature (WAT). The other synonymic terms used are cloud point (T_c), Wax Precipitation Temperature (WPT), Wax Formation Temperature (WFT) and Wax Appearance Point (WAP). Throughout the project, term WAT will be consistently be used (Rosvold, 2008). The paraffin wax will become a soft solid (a gel) when the pour point is reached (Botne, 2012). Pour point (T_p) is the lowest temperature at which a liquid remains pourable and the temperature is lower than WAT. When wax content is high, the pour point will be increased. As the temperature decreases until lower than WAT, wax will start to precipitate, and at some point, the precipitate will accumulate to the point where the fluid no longer can flow (Varhaug, 2012).

Wax content is an important characteristic affecting the physical properties of the petroleum crude oils such as the viscosity. Thus, measuring wax content should be a routine job to ensure product quality. The commonly used method to measure the wax content is UOP (Universal Oil Products LLC) solvent extraction method (UOP46) which is by weight. Other methods are the pour point method (ASTM D97-66), wax appearance method which is via polarization microscopy, differential scanning calorimetry (DSC) data, and nuclear magnetic resonance (NMR) (Woods, 2009). All the Mother Paper used are using cross polar microscopy method to measure WAT.

Lots of major consequences will be faced by petroleum industry if the wax deposition remains untreated. According to Bern et al. (1980), over a period of time, due to the wax deposition, the surface roughness of the pipe wall will be increased and the effective diameter of the pipeline will be loss, which will leads to increasing in pressure drop. This will result the reduction in the throughput for the system, and thus production lost occur. The worst case of the wax deposition is that it can caused blockage in the

pipeline. If there is blockage, production need to be stopped and pigging operation must be done to remove the plugged portion. This will end up in wasting time, energy and money (Rosvold, 2008).

There are several method can be used to control the wax deposition, but most the methods have limitation for longer pipelines. The common methods used are pigging, chemical injection, pipeline insulation and active heating (Labes-Carrier, Rønningsen, Kolnes, & Leporcher, 2002). For a short pipeline, approximately 30 km long, pipeline insulation can be used to control wax deposition. Insulation is enough to limit the temperature loss to the surrounding, which eliminates the need to perform regular pigging (Rosvold, 2008). Pipeline insulation can include the external insulation coating on single pipes or pipe-in-pipe systems (Rønningsen, 2006).

Meanwhile, pigging and chemical injection are needed for long distance transport pipeline. Pigging operation is conducted by using a pig which is a solid object with the diameter smaller than the inner diameter of pipeline to scrape off the wax deposit on the inner surface of pipeline (Rosvold, 2008). According to Aske (2011), there are various types of pigs and the selection of pig type is depend on wax properties and operating parameters. Labes-Carrier, Rønningsen, Kolnes, & Leporcher (2002) stated that in early design phase, a maximum wax layer of 2-3 mm is used as criterion for when a pipeline should be pigged in order to avoid a stuck pig incident.

Chemical injection methods may consist of inhibitors, dispersants and dissolvers (Rønningsen, 2006). It is important that the inhibitor has the right concentration at the right place in order to successfully remove a plug. Certain chemicals might be used for plug melting since heat is generated when mixed. Combining chemicals with depressurizing or use of coil tubing may increase the probability for the inhibitor to reach the plug (Rosvold, 2008).

Apart from that, active heating is necessary in order to increase the temperatures, which moves the system out of the wax stable region. This way plugs may be melted

(Rosvold, 2008). This operation can be successfully performed if bundles or electrical heated flow lines are installed (Rønningsen, 2006).

1.2 PROBLEM STATEMENT

The economy for a field is significantly influenced by the wax precipitation and deposition because of the operational and remedial costs are increased in addition to decreasing production. Therefore, prevention and controlling wax deposition is a crucial task for the oil and gas industry. Currently, the most popular method used to overcome wax deposition issue is through pigging operation. However, without a proper wax deposition prediction, the pigging operation cannot be efficiently utilized (Lee, 2008).

The existing methods used by oil and gas industry to predict the pigging operation frequency is by using the wax volume removed from previous pigging operation and pressure variation on the sensors. Yet, there are some problems occur in defining the correct pigging frequency, especially on the wells with no pressure sensors because of the uncertainty on the wax deposition phenomena and its accumulation rate (Noville & Naviera, 2012). Hence, an alternative way is needed to help to find the best pigging frequency and it can be done by using the results from wax deposition modeling to predict wax deposition behavior.

1.3 OBJECTIVES AND SCOPE OF STUDY

The objectives of conducting this project are:

1. To investigate another tool that can be used to estimate pigging operation frequency to remove wax from the pipeline wall.
2. To validate the wax deposition predicted by a simulation model and numerical approach with the Mother Paper.

The scopes of study of this project are:

1) Developing suitable model equations to be used as representation for wax deposition thickness, temperature and pressure.
2) Performing simulation on wax deposition using real field data obtained in the Mother Paper using OLGA software or Microsoft Office Excel.
3) Determining the thickness of wax deposition (x) along the pipeline.
4) Analyzing the temperature (T) profile along the pipeline.
5) Investigating the pressure (P) profile along the pipeline.
6) Comparing wax deposition predicted by a simulation model with Mother Paper.

CHAPTER 2: LITERATURE REVIEW

According to Singh, Lee, Singh, & Sarica (2011), many researchers have made a great progress on understanding the thermodynamic equilibrium and wax deposition mechanism. Molecular diffusion in laminar boundary sub-layer is an important mechanism for the wax deposition in the pipeline. The molecular diffusion is driven by the radial Fickian diffusion of waxes (Brown et al. and Singh et al.). Venkatesan (2003) also mentioned that the effect of shear stress acting on wax can have a great effect on the reduction of wax deposition thickness. But this mechanism is only applicable for cases with high turbulent flow.

Currently, there are lots of commercial wax deposition packages such as TUWAX, OLGA's wax deposition module, PVTsim's Depowax and others have been introduced to enhance the understanding of the thermodynamic equilibrium and deposition wax mechanisms of wax. Unfortunately, since the models used in the software has their own assumptions and limitations, these software packages cannot be fully relied on. For example, laminar flow works well with Singh et al. (2000) model but not the turbulent flow (Venkatesan, 2003).

Validation of wax deposition models have been the focus of several research projects published in the literature but very few attempts have been made to validate the wax deposition models using field data (Singh, Lee, Sarica, & Singh, 2011). Several researchers such as Singh et al. (2000), Venkatesan (2003) and Lee (2008) have performed a deposition experiment by using a flow loop system. Although these researchers are able to fit the modeling parameters to match the experimental data, but few attempts have been made to validate the wax deposition models for real crudes.

Labes-Carrier, Rønningsen, Kolnes, & Leporcher (2002), studied the wax deposition model by using OLGA 2000 for two different North Sea fields. Based on the study, it was found that, wax deposition under field conditions seems to be less severe than

predicted by the model for the multiphase gas condensate line, while it seems to be reasonable agreement between modeling and field experience for the single phase oil case.

Another study has been performed by Noville & Naviera (2012) to predict the suitable pigging frequency for the wells which flow with temperature below the WAT. It was found that the diffusion mechanism, responsible for wax deposition predicted by OLGA code, did not fit the measured field flowing pressure behavior. The main cause for this is because at the pipe location where a restriction occurs, the temperatures reach low values, even negative values. Although the simulations could not characterize the pressure behavior, OLGA could represent the period where the diffusion mechanism was dominant, showing good results when compared with real data.

By using TOWEX simulator, Singh, Lee, Sarica, & Singh (2011) studied that Film Mass Transfer (FMT) model gives higher wax deposition rate compared to Equilibrium model (EM) although the predicted deposition rates from both models have been much lower than the field data. Using default viscosity, both EM and FMT models gave reasonable predictions of the wax deposition rate as compared to deposition rate obtained from the field data.

CHAPTER 3: METHODOLOGY

This section discuss about the research methodology, project activities, key milestone, Gantt chart and the tools required in order to complete this project. Research methodology shows the step by step to carry out the project. Meanwhile, project activities explain about the activities in details so that all work is done systematically and with no work redundant. Key milestone and Gantt chart is required in order to make sure the project is within time frame.

3.1 RESEARCH METHODOLOGY

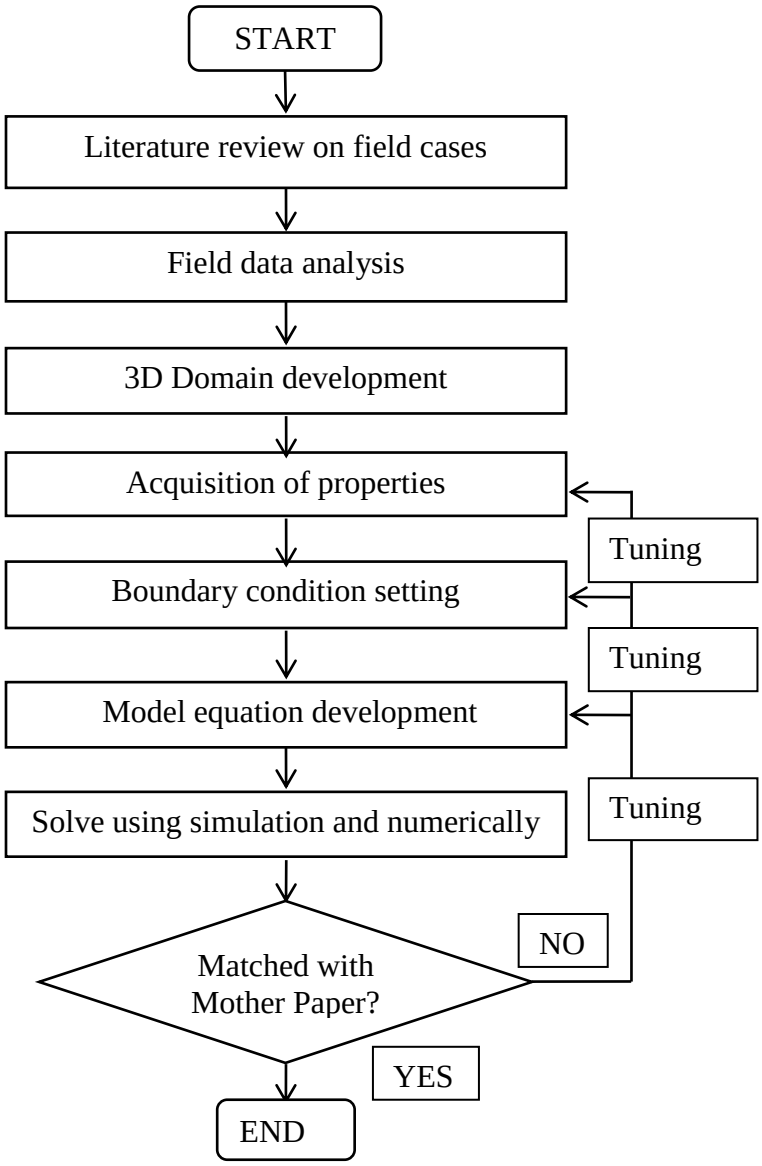

Figure 1: Flow chart for research methodology

3.2 PROJECT ACTIVITIES

Table 1: Activities that have been carried out during FYP I

Week No	Activities	Description
1-2	Introduction to project	- Meeting with Coordinator and Supervisor. - Assigned project title by Supervisor. - Identifying the problem statement. - Identifying objectives and scope of study.
3-4	Software familiarization	- Learning how to use the simulator. - Doing some exercise to get familiarize with the function of the software.
5-8	Literature review on project title	- Performing some research on related journals and articles. - Executing analysis on the real field data in the field cases.
9	Proposal defense	- Oral presentation evaluated by Supervisor and Internal Examiner. - Weaknesses and suggestion for improvement of the project will be highlight.
10-12	Simulating the project	- 3D Domain development - Defining the properties
13-14	Submission of Interim Draft Report and Interim Report	- Submitting draft report to Supervisor for room of improvement and weakness identifying.

Table 2: Activities that will be perform during FYP II

Week No	Activities	Description
1-7	Project work continues	- Continuing the progress of the project work from FYP I
8	Submission of progress report	- Submitting progress report to Supervisor
9-10	Solving the simulation	- Solving the cases for the three journals - Performing comparison on the result obtained by simulation with the result in Mother Paper
11-14	Submission of technical report, dissertation, and oral presentation	- Submitting all the softcopy and hardcopy report to Supervisor - Oral presentation on the project

3.3 KEY MILESTONE

Table 3: Key Milestone

Week	Objectives
FYP I	
6	Submission of extended proposal
9	Proposal defence
13	Submission of Interim draft report
14	Submission of Interim report
FYP II	
8	Submission of progress report
11	Pre-SEDEX and submission of draft report
12	Submission of technical paper and dissertation (soft copy)
13	Oral presentation
14	Submission of project dissertation (hard copy)

3.4 GANTT CHART

Refer to **Appendix IV**.

3.5 TOOL/SOFTWARE REQUIRED

The software required to conduct this project are;

1) OLGA 7 (For wax deposition simulation)

   This project is carried out by using wax deposition module in OLGA 2007 by SPT Group. This wax deposition module is basically a steady state compositional pipeline simulator, in which wax deposit on the pipe wall is overlaid on the steady state results. Since wax deposition is a very slow process relative to the typical residence time, hence steady state approach is chosen. OLGA simulator is based on simple molecular diffusion transport of wax molecules through the laminar sub-layer to the deposition surface. It is assumed that all molecules reaching the surface will stick to it unless the temperature is below than precipitation temperature. This phenomenon is also called no deposition mechanism. Meanwhile, correlation of Hayduk and Minhas is used to calculate the diffusion coefficients (Hayduk & Minhas, 1982). In this version, shear stripping effect is also considered.

   In this module, the important parameters are wax porosity, wax deposition rate, diffusion constant, viscosity and roughness factor. Wax deposition rate is the rate at which solid wax drops out of solution as the temperature falls. The space between the wax crystals occupied by captured liquid oil is called wax porosity. Usually, two values of wax porosity is used, which are 60% and 90% which represent the upper and lower porosity limits. The roughness factor is very important as it will greatly affect the pressure drop in the pipeline.

2) Microsoft Office 2010 Excel (For solving wax deposition model numerically)

3) PVTsim software by Calsep (For fluid properties table)

4) Techplot (For graphic purpose)

5) Digitize It (For graphic purpose)

6) Endnote (For referencing purpose)

7) Microsoft Office 2007 Word (For documentation purpose)

CHAPTER 4: RESULT AND DISCUSSION

4.1 MODEL EQUATION

4.1.1 Pressure profile along the pipeline

To pressure drop profile in pipes can be estimate analytically from Darcy - Weisbach equation (Gudmndsson, 2009) as represented in Equation (1) below (Botne, 2012).

$$\Delta p = \frac{f}{2}\frac{L}{d}\rho u^2 \tag{1}$$

Substitute $u = \frac{4q}{\pi d^2}$ into Equation (1) (Botne, 2012),

$$\Delta p = \frac{f}{2}\frac{L}{d}\rho\left(\frac{4q}{\pi d^2}\right)^2 = \frac{8f}{\pi^2}\frac{L}{d^5}\rho q^2 \tag{2}$$

Where Δp is the pressure drop, f is the friction factor, L is the pipe length, d is the pipe diameter, ρ is the fluid density, u is the fluid velocity and q is the volume flow. Equation (2) shows that pressure drop is inversely proportional to pipe diameter to the power of five. A change in pipe diameter will have a great effect on the frictional pressure drop. When pipe diameter decreases the pressure drop will increase. Pressure drop profile along the pipe can be estimate by varying the value of L. Derivation of Darcy - Weisbach equation is shown in **Appendix I**.

4.1.2 Estimation of wax deposition thickness by using pressure drop method

Singh et al (2011) used the change in diameter due to wax deposition to estimate the increased in pressure drop. Blasius correlation with Reynolds number is used to estimate friction factor, $f = 0.316/Re^{0.25}$. The Blasius correlation is used for hydraulically smooth pipes and turbulent flow. The increase in pressure drop caused by

reduction of diameter is given by Singh et al. (2011) as Equation (3) below (Botne, 2012):

$$\Delta p = \frac{0.158 L \mu^{0.25}}{(2r)^{1.25}} \rho^{0.75} \left[u_o \left(\frac{2r_o}{2r} \right)^2 \right]^{1.75} \tag{3}$$

where μ is the viscosity, u_0 is the velocity in a clean pipe, r_0 is the radius of a clean pipe and r is the effective radius of the pipe. Then a parameter κ is defined as Equation (4) below:

$$\kappa = \frac{\Delta p}{u_o^{1.75}} = \frac{0.158 L \mu^{0.25}}{(2r)^{4.75}} \rho^{0.75} (2r_o)^{3.5} \tag{4}$$

By measuring the pressure drop, calculating κ and comparing κ with κ_o for a clean pipe as Equation (5) below, wax deposition thickness is calculated:

$$\frac{\kappa}{\kappa_o} = \frac{(2r_o)^{4.75}}{(2r)^{4.75}} \tag{5}$$

The $r = r_o - x$, where x is the deposit thickness. Equation (6) (Botne, 2012b) shows the equation for deposit thickness.

$$x = r_o \left[1 - \left(\frac{\kappa_o}{\kappa} \right)^{1/4.75} \right] \tag{6}$$

The entire derivation is attached in **Appendix II**.

4.1.3 Temperature profile along the pipeline

Since the temperature of the fluid as it enters into the pipeline is generally higher than that of the surroundings, the bulk fluid temperature will generally exhibit an exponential decline as the fluid passes through the pipeline. Assuming single phase flow and steady state in the simulation, a temperature profile may be estimated analytically from Equation (7) (Gudmundsson, 2009) below.

$$T_{out} = T_{sea} + \left(T_{in} - T_{sea}\right)\exp\left[-\frac{U\pi d}{mC_p}L\right] \tag{7}$$

The equation states that under the above assumptions, the temperature T_{out} at a given distance L can be calculated on the basis of the mass flowrate m, the heat capacities C_p, the pipe diameter d, and the overall heat transfer coefficient U. T_{sea} is the sea temperature while T_{in} is the fluid temperature at the inlet to the pipe. This expression may be exploited to optimize the discretization of the problem by assigning cell lengths in such a way that the temperature declines only a predefined amount in each cell. This results in short cell lengths near the inlet, while cells are longer further down the pipeline where the temperature changes less (Lindeloff & Krejbjerg, 2002). The detailed derivation is attached in **Appendix III**.

4.2 WAX DEPOSITION SIMULATION RESULTS AND DISCUSSION

4.2.1 North Sea Oil Systems (Labes-Carrier, Rønningsen, Kolnes, & Leporcher, 2002)

The first case is about a single phase, stabilized oil being transported through a diameter (d) of 0.38 m, approximately length (L) of 43000 m production pipelines from a processing platform to storage and offloading field in North Sea field. This pipeline has been in operation for 11 years since June 2001. Although the production rate is keep on increasing, but it is still below the design rate which is 333.33m^3/h. The composition

and main physical properties of the crude oil is summarized in Table 4 and 5 respectively. By using crossed polar microscopy method, the WAT measured is around 34.2^0C.

Table 4: Composition of crude oil (Labes-Carrier, Rønningsen et al. 2002)

Component group	Mol %	Molecular weight, MW (kg/mol)	Liquid density, ρ (kg/m^3)
C_1	0.064	-	-
C_2	1.257	-	-
C_3	0.599	-	-
i-C_4	3.085	-	-
n-C_4	0.005	-	-
2,2 –DM-C_3	1.787	-	-
i-C_5	3.101	-	-
n-C_5	5.302	-	-
Hexanes	10.137	0.0847	668
Heptanes	11.255	0.0932	730
Octanes	8.677	0.1063	754
Nonanes	54.731	0.1188	775
Decanes plus	0.064	0.2738	865

Table 5: Phyical properties of stable oil (Labes-Carrier et al., 2002)

		Stable oil
Molecular weight (MW) crude oil (kg/mole)		0.193
Density, ρ @ 15 ^{0}C, crude oil (kg/m^3)		827.1
Water content (wt%)		0.36
Wax content (wt%)	Not purified	4.4
	Purified on silica	3.2
Pentane insoluble (wt%)		0.85
Sulphur content (wt%)		0.17
Wax appearance temperature (WAT) (^{0}C)		34.2
Wax dissolution temperature (WDT) (^{0}C)		47
Viscosity, μ (Pa.s)	30 ^{0}C	0.00281
	50 ^{0}C	0.00209
Pour point, T_p (^{0}C)	Minimum (^{0}C)	-24
	Maximum (^{0}C)	-8

Two methods have been used to determine the wax deposition thickness, pressure and temperature along the pipeline; OLGA software and Microsoft Excel. Microsoft Excel will be used to solve the wax deposition model numerically. The main input to the OLGA simulation and the properties of the pipeline are shown in Table 6 and Table 7 below.

Table 6: Input data for simulation (Labes-Carrier et al., 2002)

Parameter	**Value**
Pipe length (L)	43000 m
Pipe ID (d)	0.38 m
Fluid	Stable oil
Inlet temperature (T)	59^0C
Arrival pressure (P)	9.4 bar
Flow rate (q)	333.33 m^3/h
Wax porosity, ϕ	60% 90%

Table 7: Pipeline material data (Labes-Carrier et al., 2002)

Material	Thickness (m)	Conductivity, k (W/m.K)	Density, ρ (kg/m^3)	Heat capacity, C_p (J/kg.K)
Steel	0.0118	43.25	7850	500
Concrete	0.045	1.50	3040	2500
Enamel	0.006	0.60	1465	2115
Trenching	0.60	1.35	3000	2500

The wax deposition profiles predicted by OLGA, Microsoft Excel and from Mother Paper are shown in Figure 2 below. The results obtained are for wax porosity of 60% and a production rate of 333.33m^3/d. From the result, it is clearly shown that the wax deposition predicted by simulation and numerical approach are different from the Mother Paper. The wax deposition thickness obtained from Mother Paper 1 shows that the wax start to precipitate at the middle of the pipeline and the wax thickness can be up to 0.002m (2mm). Compared to the results achieved by student, the thickness of wax deposition at the inner surface of the pipeline is around 0.001m (1mm) and the

deposition starts after the two-third of the pipeline. Although the deposition take place at different length, but the result is reasonably match to each other since the thickness of wax deposition is quite the same.

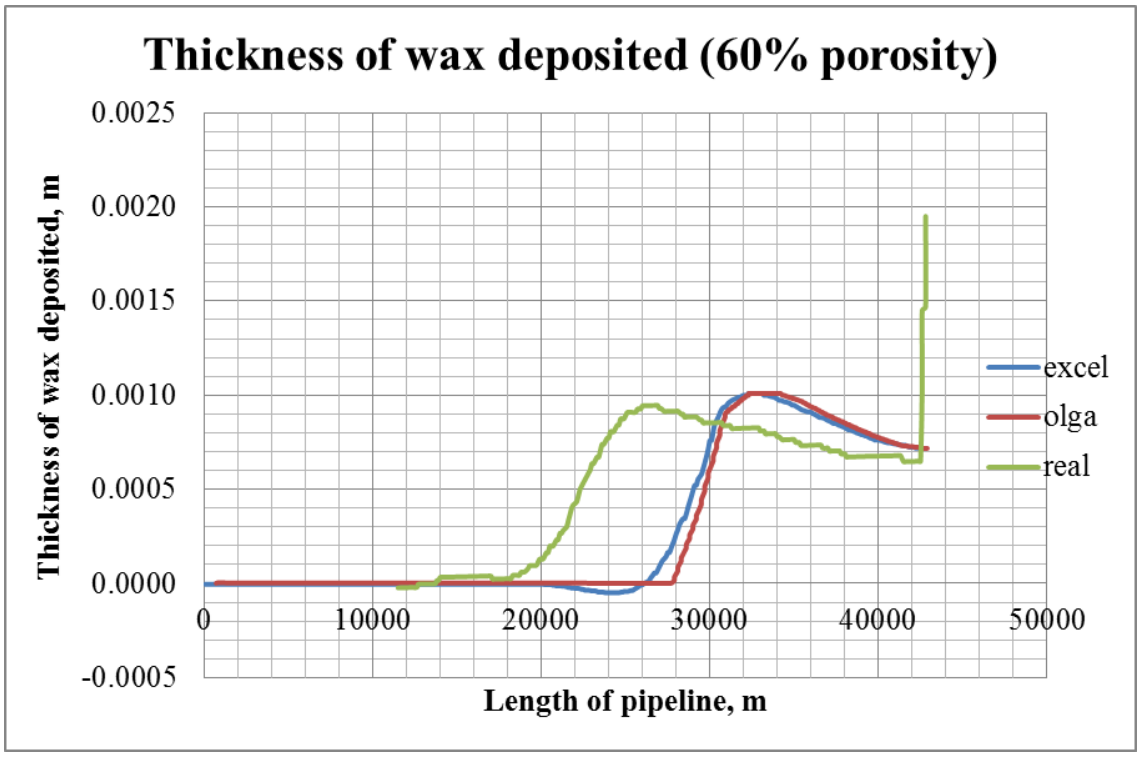

Figure 2: Wax deposition predicted by OLGA and Microsoft Excel after 42 days production (60% porosity) for Mother Paper 1

From OLGA simulation, the total wax deposit mass and volume in the pipeline can be estimated. This is quite useful since the mass collected can be used to determine the frequency of the pigging operation apart from using the thickness of the wax deposited. The total wax deposit mass and volume in the pipeline is 4709.33 kg and 4.9 m^3 respectively. These results demonstrate that the wax deposition in the pipeline is very high. Therefore, by using maximum of 2-3mm wax thickness as pigging criterion, the recommended pigging operation frequency is once a month. The frequency might be a less than usual, but other method can still be used to control the wax deposition.

Wax porosity has a great effect on the wax deposition thickness. The greater the wax porosity, the thicker the wax deposition in the pipeline. The effect of the wax porosity

can be clearly shown as in Figure 3 below. From the result shown in Figure 3 ,the thickness is increasing up to 0.004m (4mm) when the wax porosity is increased to 90% and it is quite higher compared to Mother Paper. The recommended pigging frequency when the wax porosity equal to 90% is twice a month. However, the real wax porosity obtained from the wax sampling in the pig receiver is 55%. The real thickness might be less than predicted by simulation, but there is also a possibility that during the pigging operation is done, some liquid might have been squeezed out.

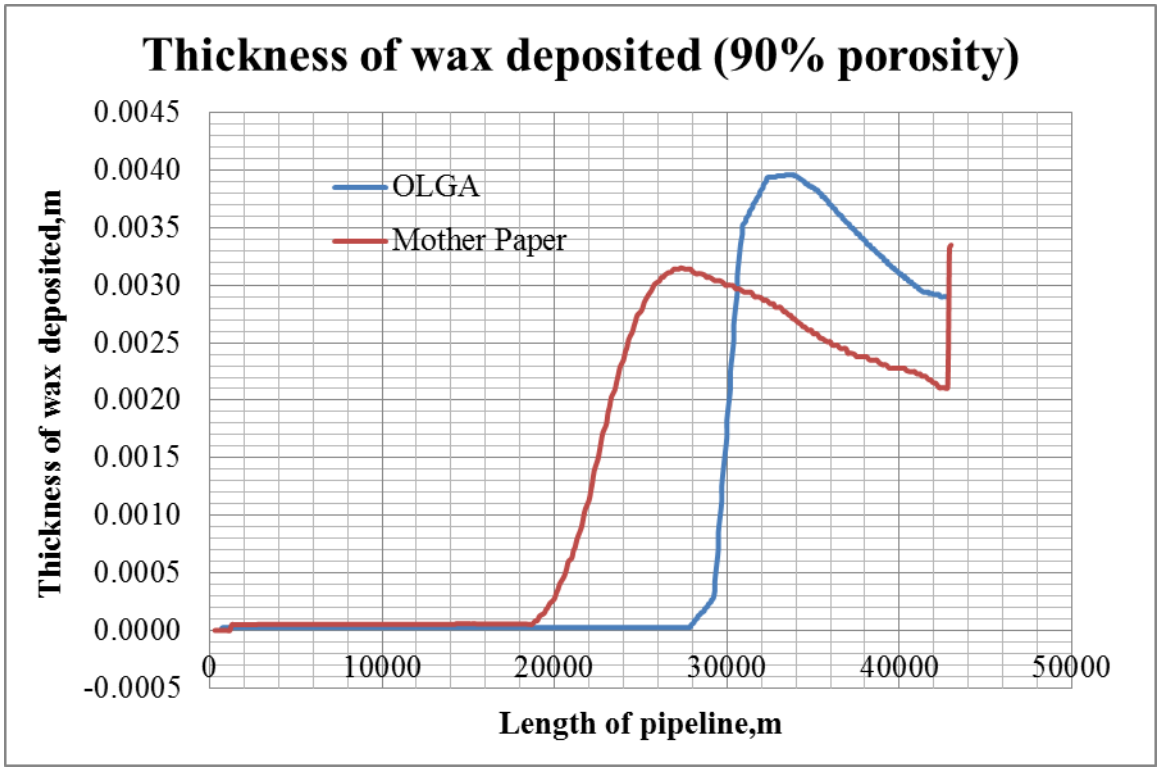

Figure 3: Wax deposition thickness at 90% porosity for Mother Paper 1

The fluid temperature profile along the pipeline is shown as in Figure 4 below. The temperature profiles obtained are match to each other and from the result, it can be proves that the fluid temperature is decreasing as it goes through the pipeline because there is temperature loss to the surrounding when the fluid is transferred from one platform to other platform. For the inlet temperature of 59.0^{0}C, without any tuning, the arrival temperature predicted by OLGA and Microsoft Excel is 16.2^{0}C while the actual field arrival temperature is 16.4^{0}C.

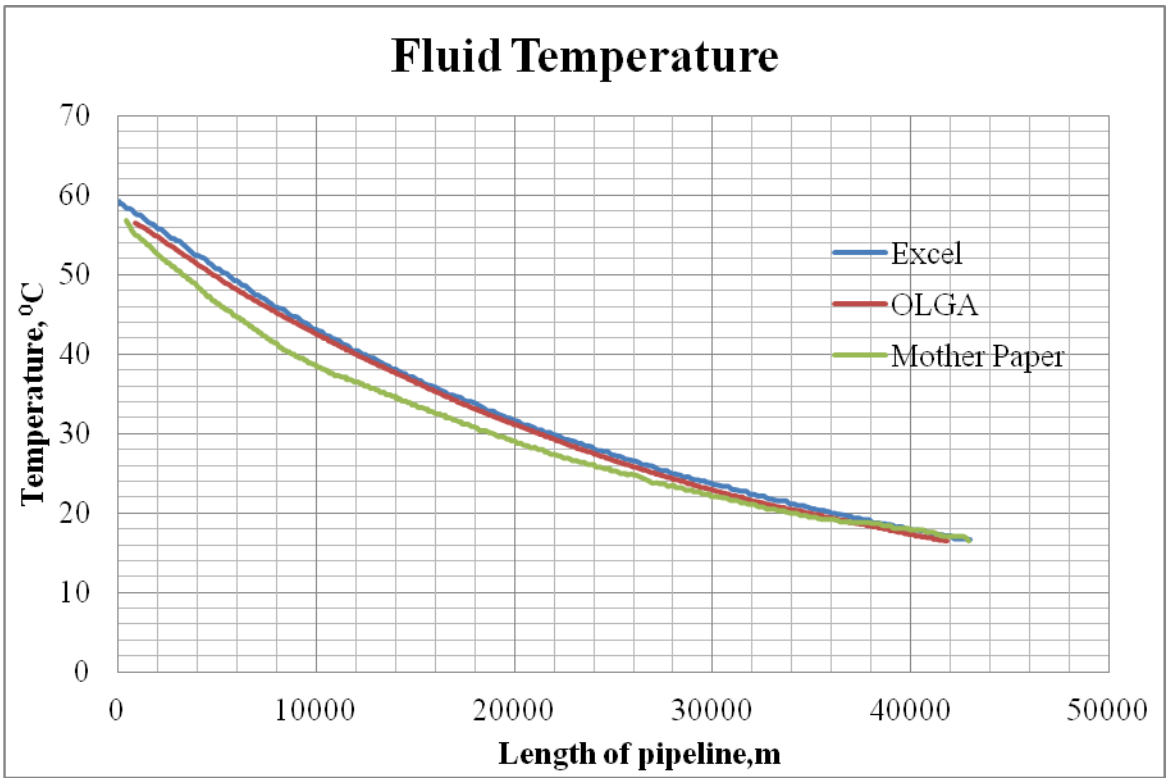

Figure 4: Temperature profile along the pipeline for Mother Paper 1

From OLGA simulation, without any tuning, it is found that WAT is around 22-24^{0}C. Meanwhile, WAT measured by crossed polar microscopy is 34.2^{0}C and the value is quite different by the one predicted by OLGA. It can be proved that WAT predicted by OLGA is relevant when the waxes start to deposit in the pipeline after the temperature of the fluid is 23^{0}C and below. Waxes will only start to deposit once the temperature of the fluid is below than WAT. Therefore, in this case the value predicted by OLGA is relevant to the result obtained.

Another important parameter in wax deposition is pressure along the pipeline. The predicted pressure profile along the pipeline during the steady state operation is shown as in Figure 5 below. The pressure profile obtained by OLGA simulation, numerically approach and Mother Paper is quite different from each other. The only similarity between the three results is the inlet pressure is around 16.9 bara and the outlet pressure is around 10.1 bara. Without any tuning, the pressure drop is 6.8 bara. The outlet

pressure is decreasing due to the waxes deposited in the pipeline and thus increased the pressure drop. This is because, once the waxes are deposited, the effective diameter of the pipeline becomes smaller and hence, the pressure drop increases. This phenomenon also can be described clearly through Equation (2) in which pressure drop is inversely proportional to diameter of the pipeline. The pressure drop can also increases due to the length of the pipeline. This is because as the length increases, the outlet pressure tends to decreases along the pipeline and thus increased the pressure drop.

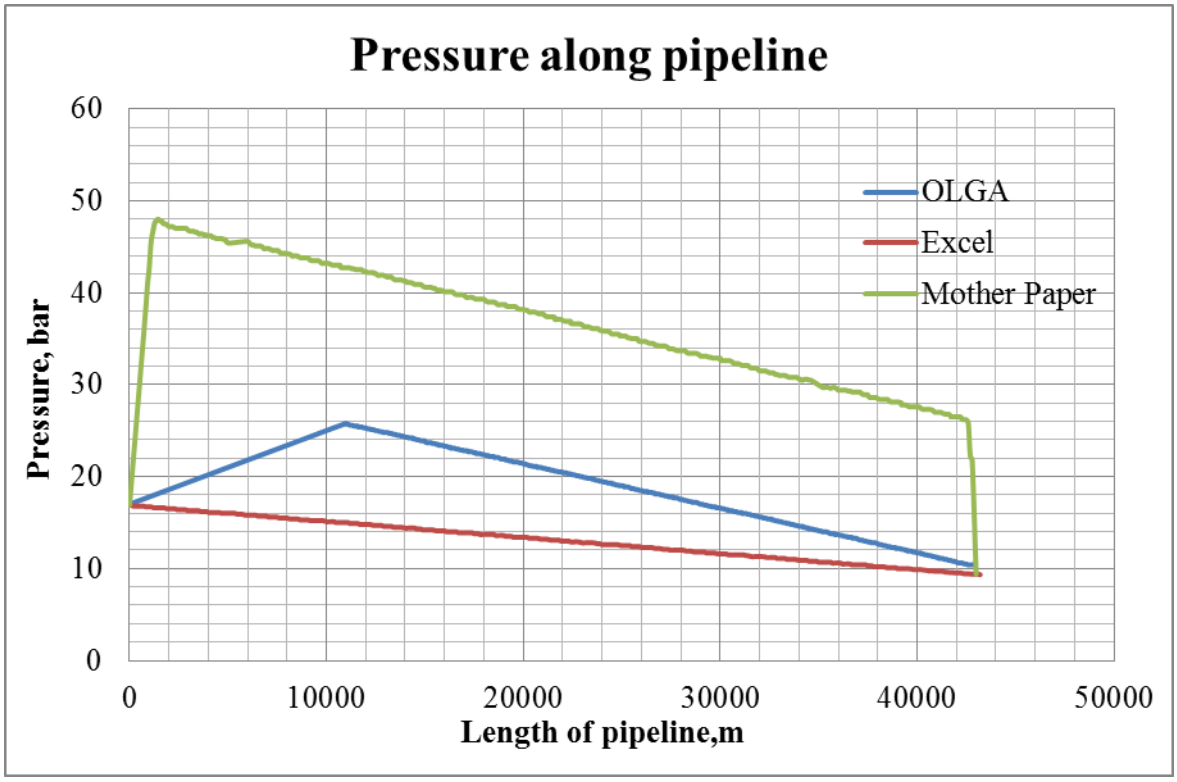

Figure 5: The pressure profile along the pipeline for Mother Paper 1

The pressure profile predicted different from each other due to the surface roughness of the inner pipeline. The surface roughness is depends on the wax deposition in the pipeline. The higher the surface roughness factor, the higher the pressure drops. Since the Mother Paper did not include the roughness factor, hence the student need to guess the value and this caused the pressure profile to be different. The pressure profile achieved when using numerical approach also different because the method did not

include the surface roughness factor in the calculation and it is mainly on the diameter of the pipeline. This is the reason why the pressure profile for the numerical method is quite different from the OLGA simulation.

4.2.2 Petrobras field in Campos Basin

The second Mother Paper is about a Petrobras field in Campos Basin. Noville & Naviera (2012) reported that the field data is obtained from the Permanent Downhole Gauge (PDG) and Temperature and Pressure Transmitter (TPT) sensors installed. Supposedly, the student needs to use two methods to validate the result and estimate the best pigging operation frequency. Due to lack of information and unknown problem occurs, the result from the OLGA simulation cannot be generated. Hence, the result from numerical approach will be used to be compared with the Mother Paper. Table 8 below shows the general properties of the field.

Table 8: Operating data (Noville and Naviera, 2012)

Parameter	Value
Export temperature (T)	78 ^{0}C
Arrival pressure (P)	11.67 bar
Arrival temperature (T)	5 ^{0}C
Temperature of crude oil entering pipeline (T)	78 ^{0}C
Wax appearance temperature (WAT)	17.1 ^{0}C
Flow rate of oil (q)	17.33 m^3/h
Internal diameter of pipeline (d)	0.1524 m
Pipe length (L)	6000 m

By using the information from Table 8 above, the student solve the equations developed to find the wax deposition thickness, fluid temperature and pressure along the pipeline. The wax deposition thickness is calculated by using pressure drop method as represented in Equation (6). Figure 6 below shows the comparison of wax deposition thickness between numerical approach and Mother Paper. The wax thickness predicted by Excel is around 0.07m while the maximum thickness by Mother Paper is 0.04m. The

result obtained is much deviated from the Mother Paper. This is because, when using numerical approach, many parameters are not been considered. The numerical approach only consider information such as diameter of pipeline, viscosity, pressure drop, mass flow, length of pipeline and velocity of the fluid but not parameters that are very crucial such as are porosity, diffusion coefficient, wax roughness, shear stress, aging and others. So, this is the reason of the deviation in the wax deposition thickness predicted by the numerical approach.

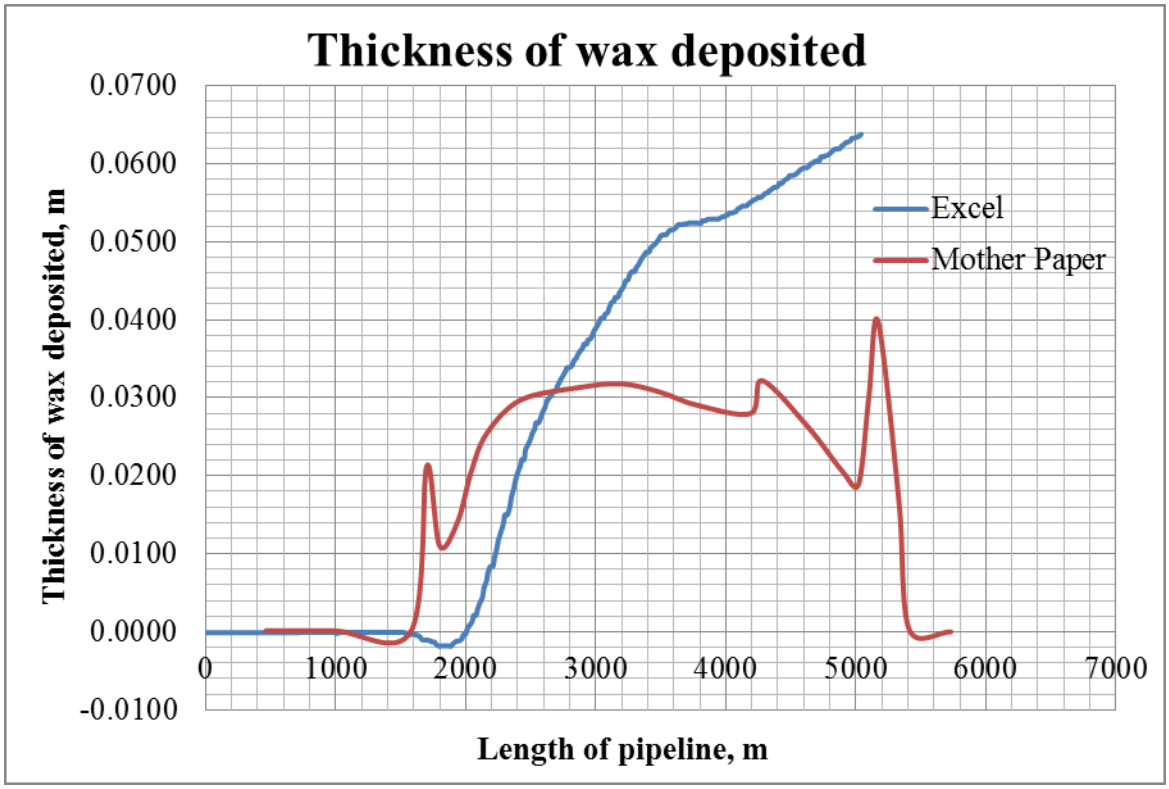

Figure 6: Thickness of wax deposited for Mother Paper 2

In term of predicting where the wax deposition started, the result obtained by numerical approach is quite reliable since both wax deposition start at one-third of the pipeline length. From the thickness of the wax deposited in the pipeline estimated by the numerical method, the frequency of the pigging operation can be estimated. Based on thickness of 0.026m, the current frequency of pigging operation is once every 14 days. Since the thickness of wax deposition predicted by Excel for 30 days production is 0.063m, hence the best recommendation for the pigging frequency is once for every 10

days of production. Although 10 days production is considered short period, but it is important to prevent the blockage of the pipeline and to avoid incident of pig stuck during pigging operation.

Although the validation of wax deposition thickness using numerical approach is not quite successful, but the temperature and pressure profile calculated by using Equation (7) and Equation (2) respectively is reasonably matched with the Mother Paper. Figure 7 below shows the comparison between fluid temperatures calculated by Excel with Mother Paper. The outlet temperature for both results is the same which is 5^0C. The temperature of the fluid keeps on decreasing due to the heat loss to the surrounding. Even though there is slightly different temperature especially at length of 3000m to 6000m, but it still proves that the temperature decreasing along the pipeline. The trend shows that the temperature decrease faster at early of the pipeline and this is where the waxes start to deposit along the pipeline.

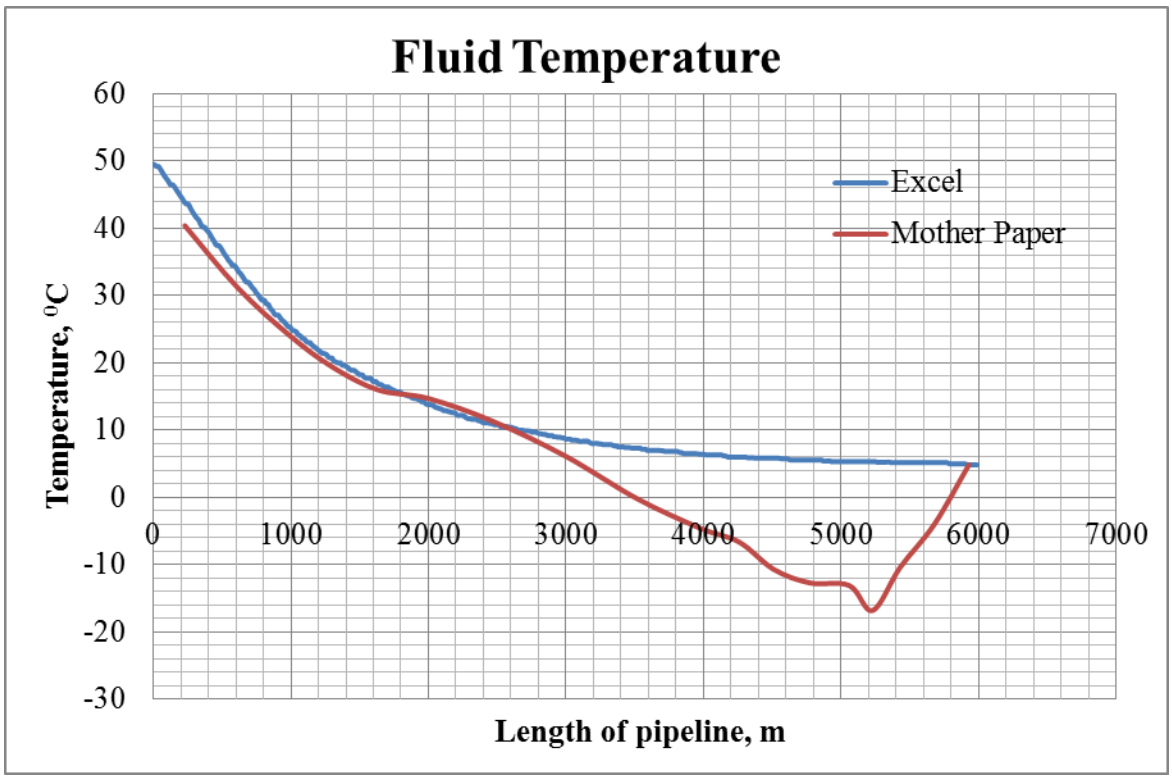

Figure 7: Fluid temperature profile for Mother Paper 2

The pressure profile along the pipeline is shown as in Figure 8 below. The inlet pressure and outlet pressure of both results are quite match. The pressure drop calculated by numerical method is 14.24 bara while Mother Paper give pressure drop of 13.7 bara. The pressure shows an increasing trend due to the wax deposited in the pipeline wall. Wax deposited cause the diameter of the pipeline to be smaller and surface roughness increases, and thus caused the pressure drop to be increasing. It is important to observe the pressure drop from time to time since it is the indicator for the diameter to be smaller which the reduction is mainly due to the waxes deposited at the inner surface of the pipeline.

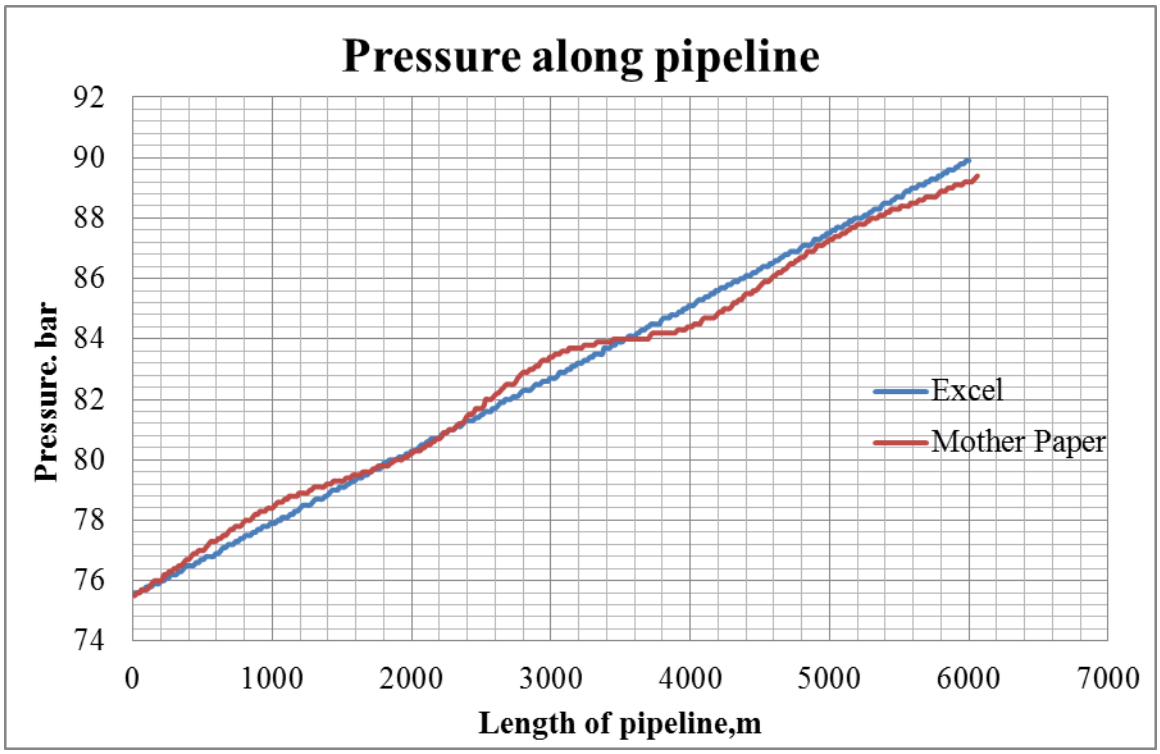

Figure 8: Pressure profile along pipeline for Mother Paper 2

4.2.3 Field data from an Indonesian offshore production and crude oil pipeline systems

Third Mother Paper is about an Indonesian Offshore production system with a subsea pipeline transporting crude oil from a central processing platform (CPP) to a Floating Production Storage Offloading (FPSO). The single phase crude oil pipeline has a 0.305 m diameter and is 23000 m long. The properties of the production system are summarized as in Table 9 and 10 below.

Table 9: Operating data (Singh et al., 2011)

Parameter	Value
Export temperature (T)	73.89 ^{0}C
Arrival pressure (P)	24.13 bar
Arrival temperature (T)	26.67-29.44 ^{0}C
Average seabed temperature (T)	25 ^{0}C
Temperature of crude oil entering pipeline (T)	73.89 ^{0}C
Wax appearance temperature (WAT)	57.78 ^{0}C
Thermal conductivity of steel pipeline (k)	44 W/m.K
Flow rate of oil (q)	349.78 m^3/h
Roughness	50 x 10^{-9} m

Table 10: External Heat Transfer Coefficient (EHTC) used in simulations for non-insulated half buried pipeline (Singh et al., 2011)

Pipeline segment (CPP Seafloor to base of flexible riser)	Segment Length, L (m)	Segment ID, d (m)	Segment OD (m)	EHTC (W/m^2/K)
	23000	0.305	0.324	22 (0.050 m concrete over steel)

Similar to Mother Paper 2, the student used numerical method to determine the wax deposition thickness for Mother Paper 3. This is because even the student has used the correct value of properties needed, but the simulation still cannot generate the wax deposition thickness. Somehow, the OLGA simulation can produce result for the temperature and pressure profile along the pipeline. Therefore, numerical method will be used to determine the wax deposition thickness for this Mother Paper.

Figure 9 below shows the comparison between wax thicknesses calculated by Excel and Mother Paper. Although the wax thickness calculated by Excel is lower than Mother Paper, but it is quite practical. Both results show that the wax has highest thickness at the middle of the pipeline. The waxes thickness by Mother Paper is higher than 0.01m while the thickness calculated by using Equation (6) is lower than 0.008m. The differences might be because of the diffusion coefficient, shear stress, wax porosity and others that are not considered in the Equation (6). Based on the result, the estimated pigging frequency is twice a month.

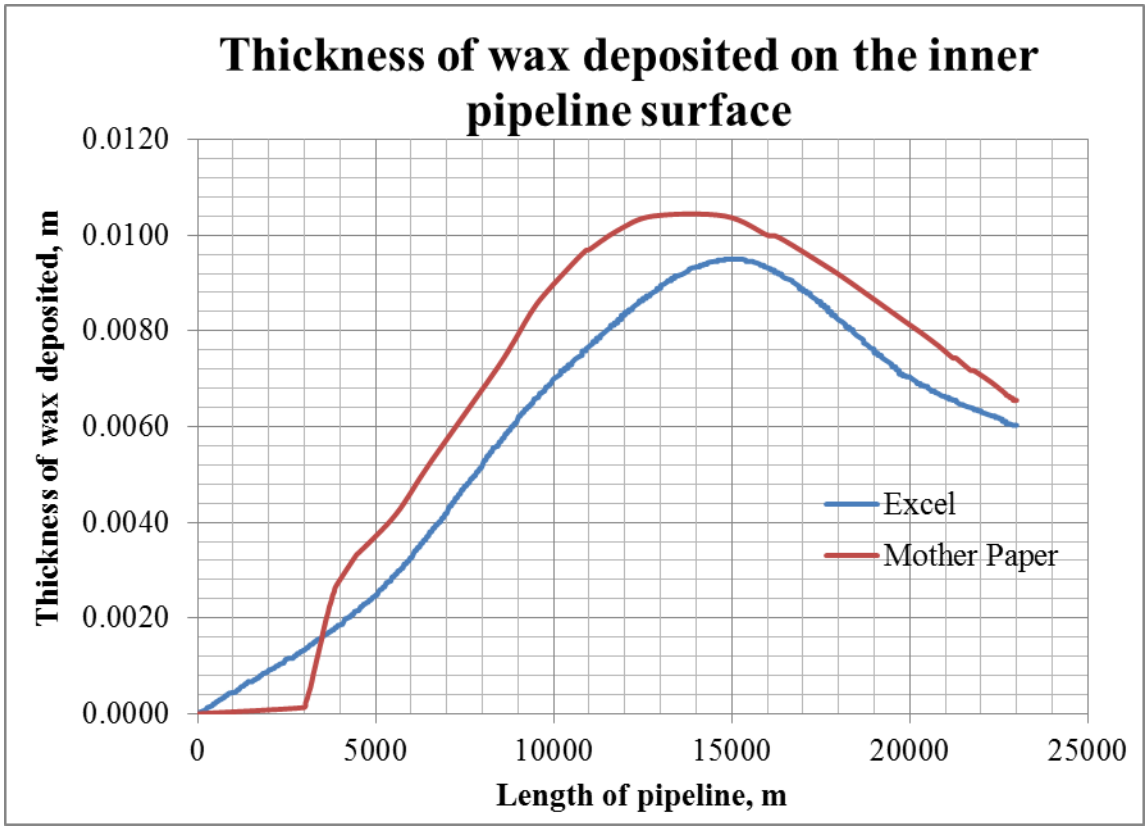

Figure 9: Thickness of wax deposition for Mother Paper 3

The temperature profile predicted by OLGA, Excel and Mother Paper are shown in Figure 10 below. From the graph, the temperature profiles are rationally matched to each other. The inlet temperature is around 73^0C and the arrival temperature is around

30^0C. Since the pipeline is long enough, the fluid temperature tend to decrease due to heat loss to the surrounding. The WAT measured by cross polar microscopy is around 58.3^0C. The value is rational enough since the waxes start to deposit after the fluid temperature is less than 60.0^0C.

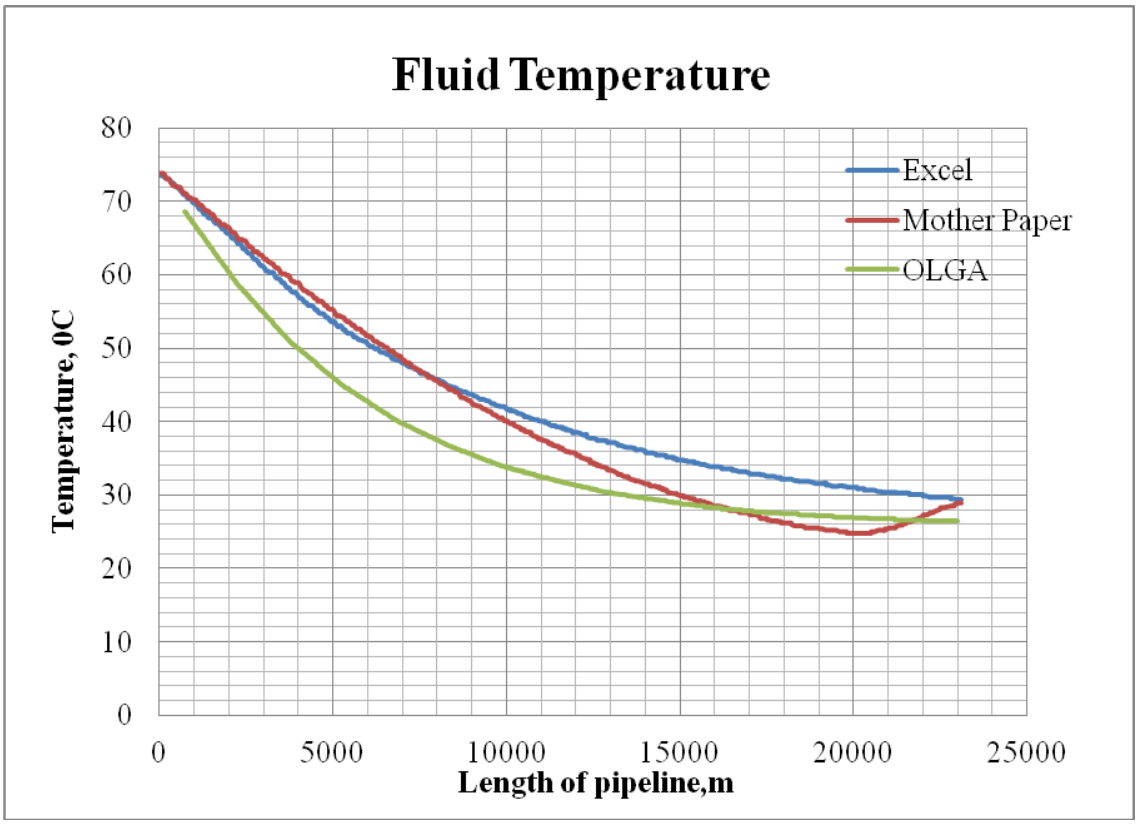

Figure 10: Fluid temperature profile for Mother Paper 3

Figure 11 below shows the comparison between pressure profiles predicted by OLGA simulation and calculated by Excel. According to Mother Paper, the pressure drop keep on increasing from 13.79 bar to 20.68 bar due to the wax deposition. Based on the graph, the pressure drop estimate by OLGA is quite high compared to pressure drop calculated by Excel. The pressure drop calculated by Excel is around 18 bar and it is quite same to Mother Paper. The pressure drop predicted by OLGA is too large which is mainly depending on the surface roughness set in the simulation. If the surface roughness is too large, the pressure drop will also increase. Since the Mother Paper did not mention about the surface roughness factor, it is difficult to estimate the pressure

drop by using simulation method. The best method is to use numerical method as it can give the paramount value.

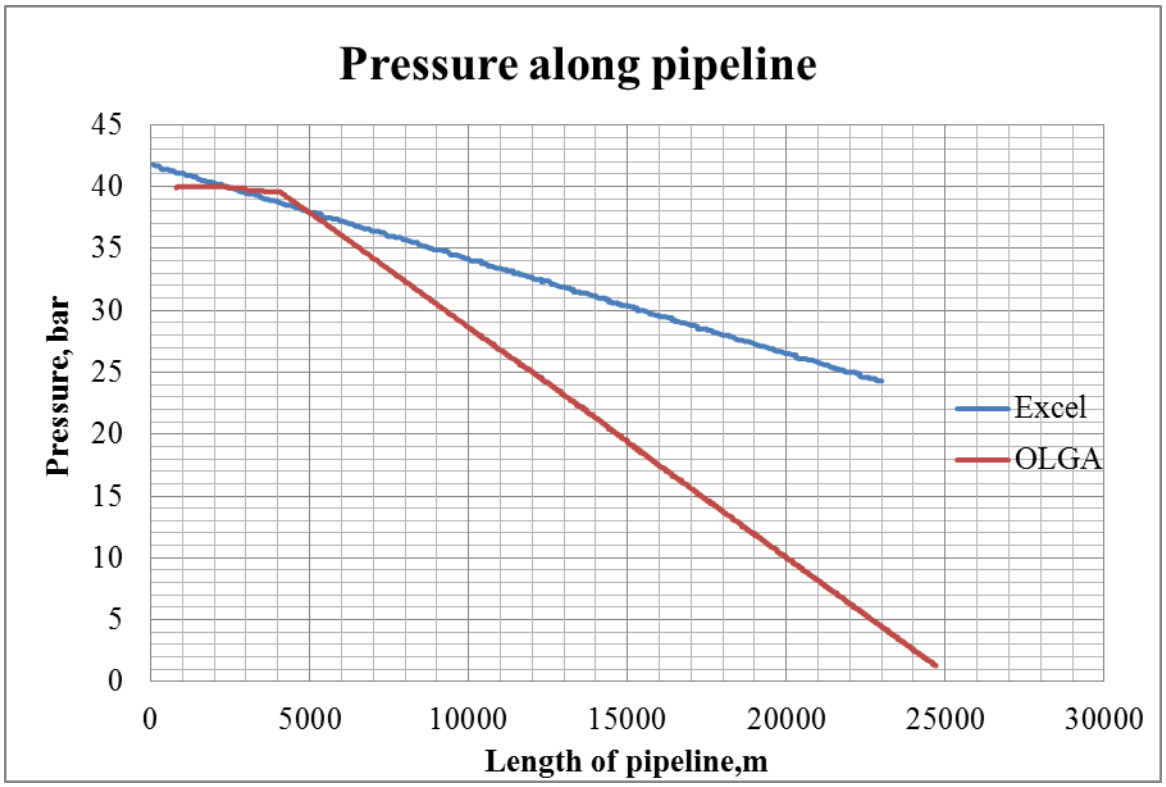

Figure 11: Pressure profile along pipeline for Mother Paper 3

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

Once the crude oil is transferred from reservoir to the platform, the temperature of the fluid will decrease due to the heat loss to surrounding. Wax deposition will be formed once the fluid temperature is below than WAT. Wax deposition will cause a lot of problem to production and transporting crude oil as it will cause the diameter of the pipeline to decrease which will lead to increase in pressure drop and reduction in flow area. Several methods can be done to control the wax deposition such as pigging, chemical injection, active heating and insulation. The most popular method used is pigging operation.

In this study, wax deposition simulation using OLGA simulator and numerical approach using Microsoft Excel will be used to predict the behavior of the wax deposition. The aims of this project is to investigate another tool that can be used to predict the pigging frequency to remove the wax deposited on the pipeline wall and to validate the wax deposition predicted by simulation and numerically with the Mother Paper. From the simulation result attained, the pigging operation frequency can be estimated and hence the objective is achieved. The simulation can predict the thickness of the wax deposition in the pipeline as well as the wax mass and volume deposited.

Based on the wax thickness, it can be concluded that the recommended pigging frequency is once a month for Mother Paper 1, once every 10 days for Mother Paper 2 and lastly twice a month for Mother Paper 3. In some way, the pigging frequency still depends on the efficiency of the previous pigging operation. Besides that, the outlet pressure and temperature predicted by OLGA is also a good match to the actual value obtained in the Mother Paper. Although WAT obtained by OLGA simulation is different from WAT measured by polar cross microscopy, but the value is relevant with the wax deposition formed. Therefore, this project is a triumph as the objectives is successfully achieved.

5.2 RECOMMENDATION

This project can be said a successful project since the objectives is achieved. Throughout completing this project, several uncertainties occur which caused the simulation process to be disrupted. Some information that might not be important is not included in the research paper but this information is needed when defining the properties of the simulation. Thus, the student needs to use trial and error method to guess the value of the properties needed. Therefore, it is recommended that good field data is used to perform the simulation. To achieve this, the student can used the data from the nearest field which is available in Malaysia instead of using the field data from the literature review.

Besides that, to gain a very accurate result, an understanding about the wax deposition phenomena is required. To predict the pigging frequency, it is not enough by only using the data needed and performing the simulation, and then gets the result, but a profound understanding on the wax deposition phenomena in flowing systems is really important. Thus, the effort to understand the wax deposition behavior must be increased.

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APPENDICES

APPENDIX I: Derivation of pressure drop in the pipeline

Pressure drop applies to flow area, $A = \pi r^2$ happened when the tension acting on the wall area $2\pi r \Delta L$. Given $F_p = F_\tau$ (Gudmundsson, 2009),

$$\Delta p \pi r^2 = 2\pi r \Delta L \tau \tag{8}$$

So, the tension can be expressed as Equation (9) (Gudmundsson, 2009),

$$\tau = \frac{\Delta p \pi r^2}{2\pi r \Delta L} = \frac{r}{2}\frac{\Delta p}{\Delta L} \tag{9}$$

Tension in pipeline can also be related with kinetic energy per volume of the empirical equation (Gudmundsson, 2009).

$$\tau = \frac{1}{8} f \rho u^2 \tag{10}$$

Where f = friction factor. Therefore,

$$\frac{r}{2}\frac{\Delta p}{\Delta L} = \frac{1}{8} f \rho u^2 \tag{11}$$

Result in Dorcy-Weisbach equation for pressure loss in the pipeline (Gudmundsson, 2009).

$$\Delta p = \frac{f}{2}\frac{\Delta L}{d} \rho u^2 \tag{12}$$

This equation is for both laminar and turbulent flow. Given $u = q / A$,

$$u = \frac{4q}{\pi d^2} \tag{13}$$

Substitute Equation (13) into (12) (Gudmundsson, 2009) ,

$$\Delta p = \frac{f}{2}\frac{\Delta L}{d}\rho\left(\frac{4q}{\pi d^2}\right)^2 = \frac{8f}{\pi^2}\frac{\Delta L}{d^5}\rho q^2 \tag{14}$$

APPENDIX II: Derivation of wax thickness using pressure drop method

Singh, Lee et al. (2011) used the change in diameter of the pipeline due to wax deposition to quantify the increased in pressure drop. Blasius correlation, as presented in Equation (15), with Reynolds number is used to estimate the friction factor. Blasius correlation is used for hydraulically smooth pipes and turbulent flow. The basis for this calculation is the Darey-Weisbach Equation (16) (Botne, 2012a).

Assumptions:

- Smooth pipe.
- Wax deposition is evenly distributed in pipeline.

$$f = \frac{0.316}{\mathrm{Re}^{0.25}} \tag{15}$$

$$\Delta p = \frac{f}{2}\frac{L}{d}\rho u^2 \tag{16}$$

Insert Equation (15) into (16).

$$\Delta p = \frac{0.316}{2\,\mathrm{Re}^{0.25}}\frac{L}{d}\rho u^2 \tag{17}$$

Replace diameter with d=2r.

$$\Delta p = \frac{0.316}{2\,\mathrm{Re}^{0.25}} \frac{L}{2r} \rho u^2$$

Rewrite

$$\Delta p = \frac{0.158L}{2r} \frac{\rho u^2}{\mathrm{Re}^{0.25}} \tag{18}$$

Reynolds number is given as,

$$\mathrm{Re} = \frac{\rho u d}{\mu} = \frac{2r\rho u}{\mu} \tag{19}$$

Insert Equation (19) into (18) (Botne, 2012b)

$$\Delta p = \frac{0.158L}{2r} \left(\frac{\mu}{2\rho u r} \right)^{0.25} \rho u^2 \tag{20}$$

Rewrite

$$\Delta p = \frac{0.158L}{2r} \left(\frac{\mu^{0.25}}{(2r)^{0.25} \rho^{0.25} u^{0.25}} \right) \rho u^2$$

Rewrite

$$\Delta p = \frac{0.158L\mu^{0.25}}{(2r)^{1.25}} \rho^{0.75} u^{1.75} \tag{21}$$

When the wax deposition increased, the diameter of the pipe will be decreased and thus the velocity of the fluid will be increased. All the other parameters will remain unchanged except for radius of the pipeline. The production rate also remains constant although there is wax deposition (Botne, 2012b).

$$q_{no\ wax} = q_{with\ wax} \tag{22}$$

$$q = uA \tag{23}$$

Fill Equation (22) with (23) (Botne, 2012b)

$$u_o A_o = uA \tag{24}$$

Replace area with $A = \pi r^2$,

$$u_o \pi r_o^{\ 2} = u\pi r^{\ 2} \tag{25}$$

Solve for u.

$$u = u_o \left(\frac{r_o}{r} \right)^2$$

Rewrite.

$$u = u_o \left(\frac{2r_o}{2r} \right)^2 \tag{26}$$

Insert Equation (26) into Equation (21) (Botne, 2012b)

$$\Delta p = \frac{0.158 L \mu^{0.25}}{(2r)^{1.25}} \rho^{0.75} \left[u_o \left(\frac{2r_o}{2r} \right)^2 \right]^{1.75} \tag{27}$$

Rewrite

$$\Delta p = \frac{0.158 L \mu^{0.25}}{(2r)^{1.25}} \rho^{0.75} u_o^{\ 1.75} \left(\frac{2r_o}{2r} \right)^{3.5}$$

Rewrite the above equation

$$\Delta p = \frac{0.158 L \mu^{0.25}}{(2r)^{4.75}} \rho^{0.75} u_o^{1.75} (2r_o)^{3.5} \tag{28}$$

A parameter called k has been introduced by Singh et al. (2011) to normalized fluctuations in the pressure drop caused by flow rate changes (Botne, 2012b).

$$k = \frac{\Delta p}{u_o^{1.75}} \tag{29}$$

Insert Equation (28) into Equation (29).

$$k = \frac{0.158 L \mu^{0.25}}{(2r)^{4.75}} \rho^{0.75} u_o^{1.75} (2r_o)^{3.5} \left(\frac{1}{u_o^{1.75}} \right) \tag{30}$$

Rewrite the equation above.

$$k = \frac{0.158 L \mu^{0.25}}{(2r)^{4.75}} \rho^{0.75} (2r_o)^{3.5} \tag{31}$$

By comparing k before and after deposition, wax thickness can be calculated (Botne, 2012b).

$$\frac{k}{k_o} = \frac{(2r_o)^{4.75}}{(2r)^{4.75}} \tag{32}$$

Radius can be specified as $r = r_o - x$. Replace r in the Equation (32) (Botne, 2012b).

$$\frac{k}{k_o} = \frac{(2r_o)^{4.75}}{(2r_o - 2x)^{4.75}} \tag{33}$$

Turn the equation,

$$\frac{k_o}{k} = \frac{\left(2r_o - 2x\right)^{4.75}}{\left(2r_o\right)^{4.75}}$$

Rewrite,

$$\frac{2r_o - 2x}{2r_o} = \left(\frac{k_o}{k}\right)^{1/4.75}$$

Rearrange.

$$2r_o - 2x = 2r_o\left(\frac{k_o}{k}\right)^{1/4.75}$$

$$2x = 2r_o - 2r_o\left(\frac{k_o}{k}\right)^{1/4.75}$$

Solve for x.

$$x = r_o - r_o\left(\frac{k_o}{k}\right)^{1/4.75} \tag{34}$$

Simplify the Equation (34),

$$x = r_o\left[1 - \left(\frac{k_o}{k}\right)^{1/4.75}\right] \tag{35}$$

APPENDIX III: Derivation for temperature profile in the pipeline

Flow and temperature are assumed to be stable. Fluid flowing inside the pipeline is cooled from the outside temperature which is at constant temperature. The pipeline is considered a long heat exchanger with cooling from the outside (Gudmundsson, 2009).

$$\mathrm{q} = \mathrm{UA}\Delta\mathrm{T}_{\mathrm{LMTD}} \tag{36}$$

The efficiency of the fluid in the pipeline is expressed as

$$q = mC_p\left(T_{in} - T_{out}\right) \tag{37}$$

Log mean temperature difference is given as

$$\Delta T_{LMTD} = \frac{\left(T_{in} - T_{sea}\right) - \left(T_{out} - T_{sea}\right)}{\ln\dfrac{\left(T_{in} - T_{sea}\right)}{\left(T_{out} - T_{sea}\right)}} \tag{38}$$

Constant T_{sea} will give

$$\Delta T_{LMTD} = \frac{T_{in} - T_{out}}{\ln\dfrac{\left(T_{in} - T_{sea}\right)}{\left(T_{out} - T_{sea}\right)}} \tag{39}$$

Heat the transition from the outside providing cooling fluid in the pipeline.

$$mC_p\left(T_{in} - T_{out}\right) = U\pi dL\frac{T_{in} - T_{out}}{\ln\dfrac{\left(T_{in} - T_{sea}\right)}{\left(T_{out} - T_{sea}\right)}} \tag{40}$$

Rewrite,

$$\ln\frac{\left(T_{in} - T_{sea}\right)}{\left(T_{out} - T_{sea}\right)} = \frac{U\pi dL}{mC_p} \tag{41}$$

$$\ln\frac{\left(T_{out} - T_{sea}\right)}{\left(T_{in} - T_{sea}\right)} = -\frac{U\pi dL}{mC_p} \tag{42}$$

Result in,

$$T_{out} = T_{sea} + (T_{in} - T_{sea}) \exp\left(-\frac{U\pi d}{mC_p} L \right) \tag{43}$$

APPENDIX IV: Gantt Chart

No	Detail / Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Final Year Project I															
1	Literature review on journals containing field data		■	■	■	■	■	■	■						
2	Field data analysis				■	■	■	■	■						
3	Submission of Extended Proposal Defense						■								
4	Proposal Defense									■					
5	Domain creation										■	■	■		
6	Define properties										■	■	■		
7	Submission of Interim Draft Report													■	
8	Submission of Interim Report														■
Final Year Project II															
1	Boundary condition setting	■	■	■	■	■	■	■							
2	Model equation setting	■	■	■	■	■	■	■							
3	Submission of progress report								■						
4	Solving simulation			■	■	■	■	■	■	■					
5	Comparison with field data						■	■	■	■					
6	Pre-SEDEX											■			
7	Submission of draft report											■			
8	Submission of technical paper and dissertation (soft copy)												■		
9	Oral presentation													■	
10	Submission of project dissertation (hard copy)														■

Figure 12: Gantt chart for the project