Analysis of the Hydro Thermal Behaviour of Waxy Crude during Pipeline Restart

By

Nurzarith Izzat Bt Othman

Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

JUNE 2010

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Analysis of the Hydro Thermal Behaviour of Waxy Crude during Pipeline Restart

by

Nurzarith Izzat Bt Othman

A project dissertation submitted to the

Mechanical Engineering Programme

Universiti Teknologi PETRONAS

in partial fulfilment of the requirement for the

BACHELOR OF ENGINEERING (Hons)

(MECHANICAL ENGINEERING)

Approved by,

____

(A.P. Dr. Hussain Al-Kayiem)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

JUNE 2010

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 of persons

NURZARITH IZZAT BT OTHMAN

ABSTRACT

Crude oil contains many kinds of hydrocarbons including paraffin wax. Paraffin wax deposition is found practically whenever hydrocarbon is produced and transported. It obstructs the flow of oil, lowering oil production, well shut-in and interferes with transportation.

The aim of this project is to investigate the hydro thermal behavior of waxy crude during pipe line restart. To obtain this, the understanding of waxy crude phenomena in the oil and gas industry and the restart methodology are crucial.

This project focuses on the hot oiling method where preheated oil is injected into the pipeline to melt any wax build up in order to initiate the flow. There are two parts covered in this project. The first part is to cover the rheology of waxy crude oils. Here, crude is modelled to be a Bingham Plastic fluid with a yield stress. The second part involves the prediction of pressure distribution, temperature and velocity profile to evaluate the possibility of the pipeline restart where finite time differencing is used.

The flow simulations of the flow of the Bingham Plastic in a pipeline are done. This enables the velocity, temperature and pressure at any pipeline length of interest be predicted. A good study that led to a close prediction of temperature and pressure distribution along a pipeline is beneficial for a better management and further design management.

ACKNOWLEDGEMENT

Given the opportunity to write this acknowledgement brings warm feelings to my heart. Syukur, my Final Year Project (FYP) has become one of my proud achievements. Many thanks and praise to our Mighty Lord, Allah S.W.T., for the blessings and the kindness that He has given me to complete this project.

My humble gratitude goes to my beloved parents, for having so much faith and courage in me and never failed to support me in many ways. Not forgetting my respected supervisor, A.P. Dr. Hussain Al-Kayiem, for the wonderful support and wisdom. The great knowledge and encouragement that you have given me, right from the beginning made it possible for me to complete the given project with great success. Without you, I would not be able to come this far.

My special thanks continues to the panel examiners, Prof. Vijay Raghavan, Dr. Razali Hamzah and Dr. Ahmed Maher for the constructive comments and critical thoughts that helped me a lot in order to improve my project in one way or another. To the lab technicians of Mechanical Engineering Department, especially Mr. Amirul Qhalis and Mr. Ahmad Shahrul, thank you so much for your help and time.

Thank you to Mr. Saiful Azri, Mr. Teh Eng Soon and Mr. Abdul Fattah from PETRONAS Carigali Sarawak Operations (SKO) for your help in providing me with the waxy crude sample and the information that I need.

Last but not least, special appreciation to my friends and colleagues for lending a hand when I needed the most and I must say, the teamwork that we put into while completing our tasks makes the journey a lot easier and possible. I hope all the findings of my project will bring meaningful contributions and benefits to Universiti Teknologi PETRONAS and others.

TABLE OF CONTENTS

LIST OF FIGURES **PAGE**

LIST OF TABLES

ABBREVIATIONS

WAT	Wax Appearance Temperature
PP	Pour Point Temperature
ICF	Incoming Fluid
OGF	Outgoing Fluid
RPM	Revolution Per Minute
API	American Petroleum Institute

NOMENCLATURES

^{o}C	Degree Celcius
L	Total Length
Z	Discretized Length
kPa	Kilopascal
km	Kilometer
D_i	Inside Diameter
D_o	Outside Diameter
P	Pressure
τ	Shear Stress
τ_B	Yield Stress
μ	Viscosity
h	Pipe Elevation
g	Gravitational Constant
T_a	Ambient Temperature
C_P	Specific Heat Capacity
n	Power Law Exponent or Flow Behaviour Index
k	Consistency Index
t	Time
v	Velocity
f	Friction Factor
U	Overall Heat Transfer Coefficient

T_s	Transition Temperature
R	Resistance
k	Thermal Conductivity
He	Hedstrom Number
Re	Reynolds Number
cP	Centipoise

CHAPTER 1

INTRODUCTION

This chapter explains the background of study, problem statement, objectives, scope of study and the significance of the project.

1.1 Background of study

Nowadays, oil is the most essential and primary energy source that is widely used in the world. In the oil and gas industry, pipeline system is extensively used due to its economics and feasibility to convey large amount of crude oil. Thus, it is important to maintain a steady and continuous flow rate to ensure an efficient operation of a pipeline system without any interruptions.

Transportation of more conventional crude oil that exhibits Newtonian behavior with low viscosity and steady physical properties is relatively an easy task. However, a large amount of crude oil throughout the world contains high molecular paraffinic components which may precipitate as wax in low temperatures, especially when transported through a pipeline system at extreme ambient temperature.

Crude oil is made up of very complex mixture formed by hydrocarbons of paraffinic, napthenic and aromatic type, but there are also other organic compounds containing sulphur, oxygen, nickel, iron and copper [1]. The composition of the oil has a direct influence on the rheological properties of the oil.

The primary interest with the transportation of waxy crude is the issue concerning pipeline restart [2]. Although maintaining a continuous fluid flow is important, pipeline shutdowns are sometimes necessary due to equipment maintenance, new equipment installation and emergency cases. Under the non-flowing conditions, when the pipeline is exposed to extreme ambient temperature, the temperature in the pipeline starts to drop.

When a sufficiently low temperature is reached, the waxes crystallize and form an entangled network of crystal which turns the oil to a highly viscous material, rendering the oil more to a solid rather than fluid. In time, they are also responsible to the forming of thick wax deposits in the inner wall of the pipeline thus increasing the power required to pump the oil. In extreme conditions, they may cause pipeline blockage and obstruction to fluid flow.

Figure 1-1 Wax deposits in pipelines [3]

Four techniques are used to enhance the flow in conduits with wax formation namely mechanical by scrapping the inside deposition (pigging), chemical additives, sand abrasion and by thermal imposition (hot oiling). For this project, preliminary investigation of the thermal imposition method is carried out to study the steady-state hydro thermal behaviour of the waxy crude during pipeline restart. Hot oiling involves the injection of preheated oil into the pipeline to melt the wax build up affecting the well flow.

To avoid wax build up, thermal techniques are applied by keeping the temperature of the flowing fluid higher than the Wax Appearance Temperature (WAT) provided the pipeline is not totally blocked, hot fluids are pumped into the pipeline to melt the wax deposits [4].

1.2 Problem Statement

The issues concerning paraffin wax deposition plagues the oil industry and billions of dollars are spent worldwide to prevent and remediate this problem. It can choke the production lines thus reducing the oil production and this will cause a huge loss to the industry.

Conventional methods of management, prevention and remediation have been established and practised over the years. However, as the search of oil and gas moves towards greater water depths at lower temperature, the deposition of paraffin wax has become a major concern [5]. This phenomenon forces the industry to develop new technologies to combat the problem.

In operating a pipeline transporting waxy crude, wax deposition mechanism depends on pressure and temperature. To overcome the deposition, higher pumping pressure is required together with higher fluid temperature for wax removal.

The measurements of temperature and pressure of process fluid are normally conducted at strategic points. Pre-modelling of the problem will reduce the cost and provide better understanding to the fluid flow phenomena, mainly if the flow is non-Newtonian.

In this project, the flow behaviour of the waxy crude in the pipeline at different conditions in investigated. Also, the flow simulation for pipeline restart is studied to predict the velocity profile, temperature profile and the pressure distribution along the pipeline.

1.3 Objectives

The main objectives of this Final Year Project are:

- To model and simulate mathematically the waxy crude flow behaviour during pipeline restart
- To predict the temperature profile, pressure distribution and velocity variation of the waxy crude during pipeline restart

1.4 Scope of Study

This project is divided into two parts. The first part is to investigate the rheology of the waxy crude and its flow behaviour. Here, the crude is modelled to be a Bingham Plastic fluid that has a yield stress. Experiments were conducted on a waxy crude sample to find its properties. Then, the waxy crude is heated to a certain temperature range to study the effects of temperature and shear rates on its viscosity.

The second part involves the prediction of pressure distribution, temperature and velocity profile to evaluate the possibility of the pipeline restart. Finite time difference method is used where the flow regime is discretized into nodes and the average velocity is assumed to be constant along the entire pipeline and thus the temperature and pressure distribution are constant within this finite time difference.

1.5 Significance of the work

Wax formation and deposition are responsible for the high costs involved in the prevention, maintenance and remediation for the crude oil transportation and production. They cause reduction in production, pipeline plugging, and well shut-in, blockage due to the wax deposits on the inner walls, shutdowns and transportation-related problems.

One technique employed to solve this problem is by using thermal imposition. The heat transfer process during the injection of the hot oil is studied and analyzed mathematically and solved numerically. By doing this, the velocity profile, temperature profile and the pressure drop along the pipeline can be predicted to evaluate the possibility to restart the pipeline. A good study that led to a close prediction of temperature and pressure distribution along a pipeline is beneficial for a better management and further design management.

CHAPTER 2

LITERATURE REVIEW

2.1 Part 1: Rheology of Waxy Crude Oils

2.1.1 Non-Newtonian Fluid Behaviour

Based on Wardhaugh et. al.[6], crude oil that behaves like a Newtonian fluid is often regarded as simple fluid with the pressure drop (shear stress) directly proportional to the flow rate (shear rate).

As the crude flows in a subsea pipelines, where it is exposed to very cold environments, it starts to cool and once the temperature drops below its wax appearance temperature (WAT), wax crystals began to precipitate out of the solution and a very rapid increase in viscosity indicates the onset of non-Newtonian flow behavior [6]. At this stage, the proportionality between shear stress and shear rate is no longer direct and the flow behaviour can be classified into three broad types which are time independent, time dependent and viscoelastic fluids.

2.1.1.1 Time Independent Non-Newtonian Behaviour

The viscosity of time independent non-Newtonian fluids is dependent on the shear rate, unlike Newtonian fluids. At any point in the fluid, the shear rate is a function of only shear stress. Such fluids can be divided into pseudoplastics, dilatant and Bingham plastic fluids.

- Psedoplastics

  It is also known as shear-thinning in which its apparent viscosity decreases with increasing shear rate. It can be characterized by the Power Law model with the flow-behaviour index is less than 1 ($n<1$).

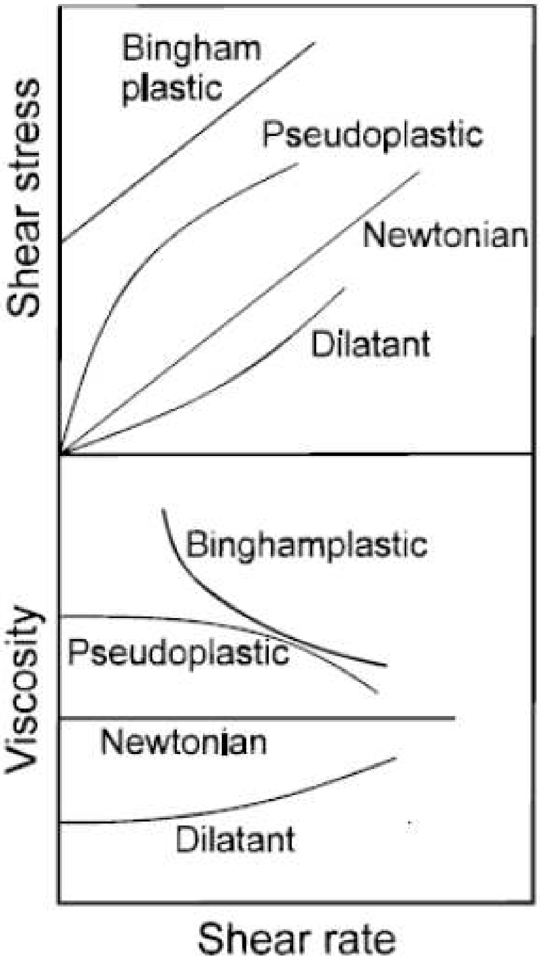


Figure 2-1 Newtonian and Non-Newtonian Behaviours [7]

- Dilatant fluids

  Also known as shear-thickening fluids, exhibits increasing apparent viscosity with increasing shear rate. The power law equation is applicable but with the flow behavior index is greater than unity (n>1).

- Bingham Plastic fluids

  Fluid will not flow until the applied shear stress exceeds the yield point of the fluid. After the yield point has been exceeded, changes in shear stress are proportional to changes in shear rate and the constant proportionality is called plastic viscosity. Like pseudoplastic fluids, Bingham fluids exhibit decreasing viscosity with increasing shear rate.

2.1.1.2 Time Independent Non-Newtonian Behaviour

The non-reproducibility and poor repetition of laboratory experiments with waxy crude were reported [8]. This is due to the fact that the rheology of these gels depends not only on the rate of shear but also on the time the constant shearing is applied. These fluids seem to exhibit a “memory” which fades with time. Fluids with this kind of behavior can be classified as thixotropic or rheopectic fluids.

- Thixotropic fluids

  The structure of the thixotropic fluids will be progressively broken down and the viscosity will decrease with time if it is sheared at a constant rate after a period of rest. Once the shear stress is removed, the apparent viscosity gradually increases and returns to its original value.

- Rheopectic fluids

  Apparent viscosity increases with time after the shear rate is increased to a new constant value.

2.1.1.3 Viscoelastic fluids

Crude exhibits viscoelastic behavior when the gel structure tries to regain its former condition as soon as an applied stress is removed.

2.1.2 Key Rheological Parameters of Waxy Crude

The various rheological parameters which help describe the complex behaviour of waxy crudes are discussed. There properties include the wax appearance temperature (WAT) or cloud point, pour point temperature, viscosity and gel strength.

2.1.2.1 Wax Appearance Temperature (WAT)

This is the most important rheological parameter because it indicates the onset of potential problems while handling waxy crudes. WAT is the temperature at which the first wax crystal precipitates from the solution.

2.1.2.2 Pour Point Temperature

Pour point temperature (PP) is the temperature at which the flow of crude oil stops. It is the lowest temperature at which crude will flow under prescribed conditions and pumpable. Any decrease in temperature below the pour point will cause the crude to stop flowing.

2.1.2.3 Viscosity

Viscosity is the measure of the internal resistance of fluid to flow. In fluids, it is caused by cohesive forces between the molecules. As the temperature of the crude drops, its viscosity increases. Viscosity can be Newtonian, apparent or plastic depending on the flow behaviour of the waxy crude at the given temperature.

Newtonian viscosity, also called dynamic viscosity, characterizes a Newtonian fluid and is independent of shear rate. Apparent viscosity describes a non-Newtonian fluid where no yield stress is necessary to initiate flow and is expressed as the ratio of shear stress to shear rate. Plastic viscosity describes a Bingham Plastic fluid where a yield stress must be overcome to initiate flow.

2.1.3 Phases of Waxy Crude Transformation

In a sub-sea pipeline where the ambient temperature below the pour point of the crude which it is transporting, all three phases of waxy crude transformation processes from Newtonian fluid to a viscous non-Newtonian gel occur [9]. These phases are namely wax precipitation, deposition and gelation.

2.1.3.1 Wax Precipitation

At the reservoir conditions with high pressure and temperature, waxy crude behaves as Newtonian fluid with a low viscosity. This is due to the high solubility of heavy paraffins to keep them fully dissolved in the solution. However, as the crude flows from tubing and subsea pipelines at low ambient temperature below the WAT, wax crystals began to precipitate out of the solution.

2.1.3.2 Wax Deposition

There will be no wax deposition if wax precipitation does not occur. Diffusion of wax particles from the liquid-solid interface to the pipe wall results in the formation of solid deposit on the pipe wall. As the deposit thickness grows, production is affected as effective area of fluid flow gradually decreases, resulting in significant pressure drop across the flow lines.

2.1.3.3 Wax Gelation

Gelation occurs when precipitated and deposited paraffin crystals interact to form entangled networks resulting gelling of the crude and in higher resistance to flow.

2.1.3.4 Yield Phenomenon

Yield stress is a threshold stress which has to be applied for the fluid to start flowing. Wardaugh and Boger [6] defined yield stress as the shear stress at which the gelled oil ceases to behave as a Hookean Solid. Meanwhile, a three-yield concept namely elastic limit, static and dynamic stresses was adopted in past works [10]. The static yield stress as this stress value determines the pump capacity required to initiate flow and ensure pipeline restart.

2.2 Part 2: Pipeline Restart of Waxy Crude

Total pipeline shutdown translates into zero production and loss in revenue. However, sometimes it is necessary to be carried out for equipment maintenance, new equipment installation or emergency equipment breakdown. Thus, it is important to simulate the pipeline restart behaviour to ensure proper and smooth start-up process. This is especially true when the fluid transported is a gelled fluid with a yield stress. In this case, the initial pressure required to initiate the flow has to be higher to overcome the yield stress.

2.2.1 Physical Model

Simulation of pipeline restart of a Bingham Plastic fluid under isothermal condition has been discussed [10]. A physical model of the start-up process was also developed.

The following analysis is based on the journal by Chang et al. [10]. A physical model for start-up flow is developed which is based on a common practice of the usage of another fluid under pressure to displace the cold gelled waxy oil.

For the restart of a pipe of length, L and inside diameter, D that contains gelled crude oil, an incoming fluid (ICF) is pumped to displace the outgoing fluid (OGF).

The ICF must have a different thermal or shear history than that of the gelled waxy oil. It can be water or warm oil from the same source as the gelled oil.

Flow occurs in the pipe when the gelled oil, OGF is gradually displaced by the ICF under a constant applied pressure higher than that of the yield stress of the OGF. The pressure differences across their occupied pipe are expected to change during the flow as the proportions of the two fluids vary with time.

These changes in pressure difference results in time-dependent variations in the wall shear stress distribution in each fluid although the overall pressure drop remains constant.

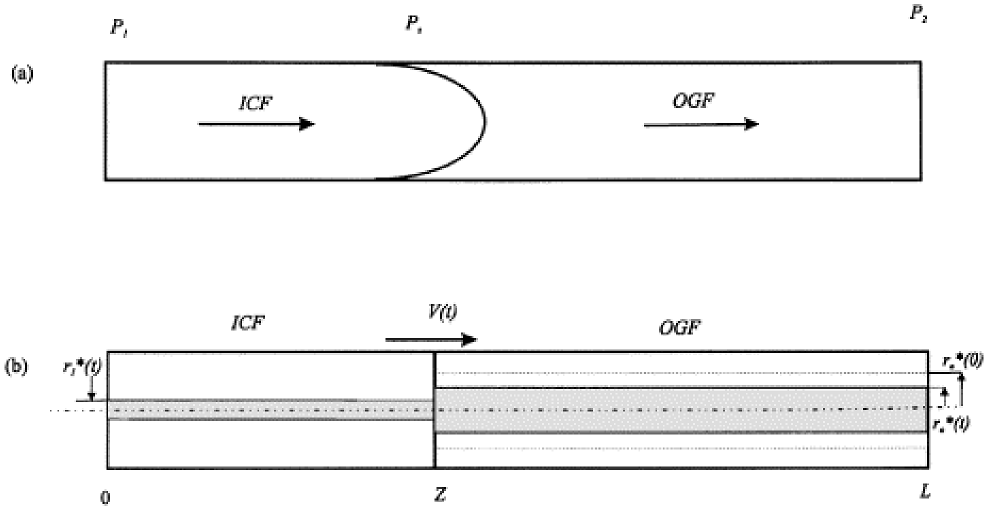


Figure 2-2 Schematic diagram of two-fluid displacement model ((a) True interface; (b) Simplified interface).

Figure 2-2 presents the schematic diagram of the model. During the restart of flow, ICF occupies a section of the length Z(t) in the pipe while OGF occupies the remaining section, (L-Z(t)). A velocity gradient exists across the pipe during the restart process, leading to a semi-ellipsoidal interface formed between ICF and OGF, as shown in Figure 2-2(a).

In Figure 2-2(b), the interface at Z is assumed to be flat as a first approximation. The velocity, V=dZ/dt, is equal to average velocity of the fluid. This assumption is reasonable considering the high consistency of the gelled oil and the long distance of the pipeline.

In the event of start-up, the unsheared plug which is represented by the shaded area exists as Bingham plastic at any instant of time in both ICF and OGF.

To start the flow, a pressure drop is applied to the pipe such that the shear stress at the pipe wall is greater than the initial static yield stress at time, $t=0$.

Several important changes take place as the OGF is displaced by ICF. First, the pressure difference across the ICF will increase while the pressure difference across the OGF decreases. Second, the length of pipe occupied by ICF increases with time while that of the OGF decreases. These two changes result in the variations in the wall shear stress and shear stress distribution for both fluids.

The wall shear stress of OGF will increase with time in most cases as ICF with higher pressure difference displaces it. As time evolves, the shear-induced breakdown will cause a decrease in the oil yield stress as the oil flows in the pipe.

2.2.2 Pressure Drop Simulation

Measurements of pressure and temperature of the process fluid are normally conducted at designated locations. A good prediction of pressure distribution and temperature along a pipeline is beneficial for better management and further design improvement.

In the pressure drop prediction, to achieve a desired flow rate, it is assumed that the upstream pump pressure is equal to the inlet pressure [11]. The downstream pump suction pressure is then calculated iteratively until steady state has been reached. The pressure drop simulation is obtained using Newtonian and non-Newtonian derived friction factors.

2.2.3 Temperature profile

At the finite time interval, temperature at each point is calculated based on the heat transfer of the fluid contained in the discretized pipe section ΔZ. Conduction heat transfer from one section to another section of the fluid and the heat transfer to the surrounding have been taken into account. The axial conduction from the current fluid element to the next one was assumed to be negligible.

2.2.4 Velocity Profile

From the overall energy balance, the velocity from upstream pump discharge to downstream pump suction at time $t+\Delta t$ can be derived. In the simulation, it is assumed that the average fluid velocity is constant within a finite time difference.

CHAPTER 3

METHODOLOGY

In order to achieve the objectives of this project, research and investigations were done to analyze the steady-state hydro thermal behavior of the waxy crude during restarting. Experiments were conducted in the laboratories to get the physical properties of the waxy crude which are the viscosity dependence on temperature and shear rates. From here, the mathematical formulation of the pressure drop, temperature profile and the velocity profile were done.

3.1 Laboratory Experiments

3.1.1 Objective

- To study the properties of waxy crude and its behavior

3.1.2 Equipment and tools

- Waxy Crude sample, Pressurized Viscometer Model 1100, Computer, Anton Paar Density Meter

3.2 Technique of Analysis

The necessary data will be acquired from the experiments conducted. Based on the data, a set of mathematical formulations is done by acquiring the energy equation and the evaluation of overall heat transfer coefficient, U to evaluate the temperature change. On the other hand, pressure drop evaluation will be obtained from derived friction factors.

3.2.1 Mathematical Formulation of the problem

a) Temperature Profile

Temperature can be derived from basic energy equation. The Overall Heat Transfer Coefficient, U is evaluated in order to solve for the temperature profile.

b) Pressure-drop Simulation

First, the Fanning friction factor, *f* is calculated. To obtain *f*, the fluid must be distinguished to be either Newtonian or Bingham plastic fluid by using Hedstrom number. Then, Reynolds number is calculated to determine the type of flow - laminar or turbulent flow.

3.2.2 Numerical Formulation

The region of flow in the pipeline is discretized into elements. The governing equations obtained were solved by implementing Finite Difference method. From this, the numerical model of the phenomena is constructed.

3.2.3 Solution of the model

The numerical model will be converted to computer programs and is solved by using Microsoft Excel Solver.

3.2.4 Results and Analysis

The results obtained will be compiled. A detailed analysis will be done on the corresponding solution as well as graphs.

3.3 Required Equipment and Software

Viscometer, Anton Paar Density Meter, Microsoft Excel Solver, Experimental Data, Waxy crude sample, ORCADA ™ software

3.4 Gantt Chart

A timeline is prepared for completion of this FYP by the author based on the academic schedule, FYP guideline for students and supervisor requirements.

- FYP 1 (Semester July 2009)

No	Details/Week	1	2	3	4	5	6	7	8	9		10	11	12	13	14
1	Selection of Project Topic	🟦	🟦													
2	Literature survey and information gathering		🟦	🟦	🟦											
3	Submission of Preliminary Report				🟥											
4	Data collection					🟦	🟦	🟦								
5	Mathematical formulation of waxy crude							🟦	🟦	🟦		🟦	🟦			
6	Submission of progress report								🟥							
7	Seminar (compulsory)								🟥							
8	Numerical formulation												🟦	🟦	🟦	🟦
9	Submission of Interim Report Final Draft										Mid Semester break				🟥	
10	Oral Presentation															🟥

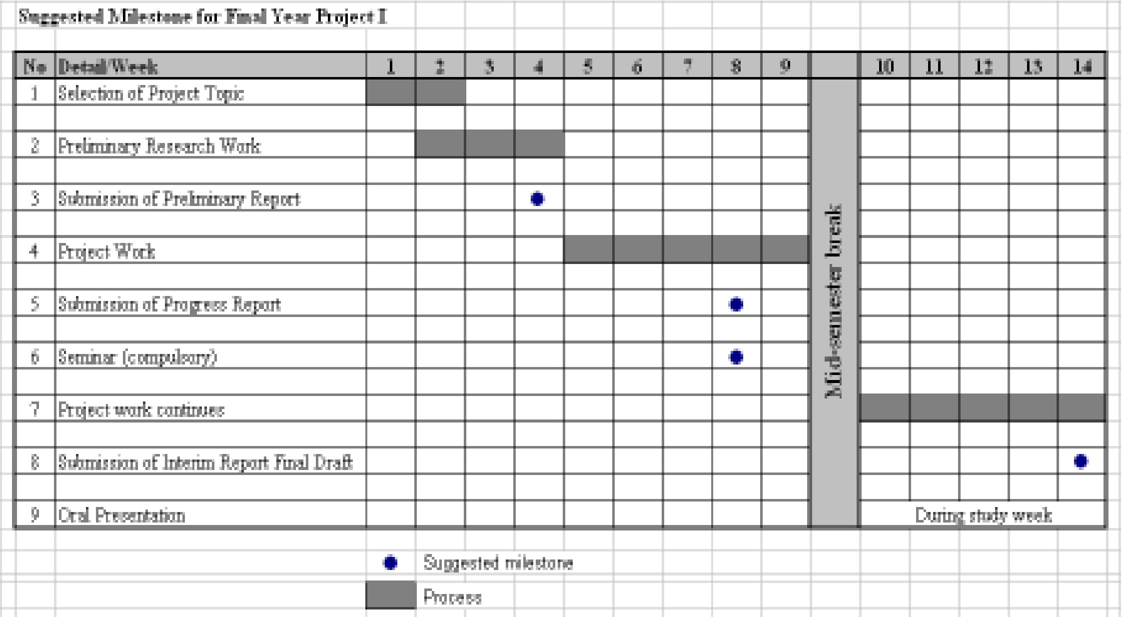
Table 3-1 FYP 1 Gantt Chart

- FYP 2 (Semester Jan 2010)

No	Details/Week	1	2	3	4	5	6	7	8	9		10	11	12	13	14
1	Numerical Formulation/Modelling	🟦	🟦	🟦							Mid Semester break					
2	Submission of Progress Report 1				🟥											
3	Solution of the Model					🟦	🟦	🟦	🟦	🟦		🟦	🟦			
4	Submission of Progress Report 2								🟥							
5	Seminar (compulsory)								🟥							
6	Results Analysis											🟦	🟦	🟦		
7	Poster Exhibition											🟥				
8	Submission of Dissertation Final Draft														🟥	
9	Oral Presentation															🟥
10	Submission of Dissertation (Hardbound)											7 days after oral presentation				

Table 3-2 FYP 2 Gantt Chart

3.5 Milestone



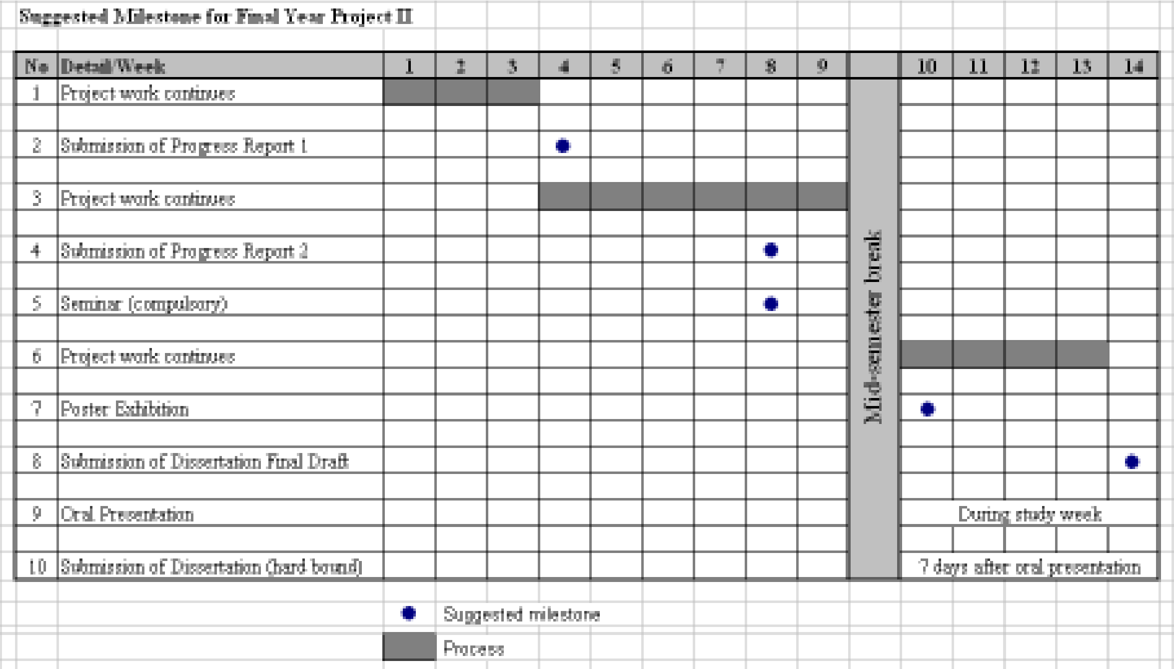
Suggested Milestone for Final Year Project I

No	Detail/Week	1	2	3	4	5	6	7	8	9		10	11	12	13	14
1	Selection of Project Topic	▨	▨								Mid-semester break					
2	Preliminary Research Work		▨	▨	▨											
3	Submission of Preliminary Report				●											
4	Project Work					▨	▨	▨	▨	▨						
5	Submission of Progress Report								●							
6	Seminar (compulsory)								●							
7	Project work continues											▨	▨	▨	▨	▨
8	Submission of Interim Report Final Draft															●
9	Oral Presentation											During study week				

● Suggested milestone

▨ Process

Table 3-3 FYP 1 Milestone



Suggested Milestone for Final Year Project II

No	Detail/Week	1	2	3	4	5	6	7	8	9		10	11	12	13	14
1	Project work continues	▨	▨	▨							Mid-semester break					
2	Submission of Progress Report 1				●											
3	Project work continues				▨	▨	▨	▨	▨	▨						
4	Submission of Progress Report 2								●							
5	Seminar (compulsory)								●							
6	Project work continues											▨	▨	▨	▨	
7	Poster Exhibition											●				
8	Submission of Dissertation Final Draft															●
9	Oral Presentation											During study week				
10	Submission of Dissertation (hard bound)											7 days after oral presentation				

● Suggested milestone

▨ Process

Table 3-4 FYP 2 Milestone

3.6 Execution Flow Chart

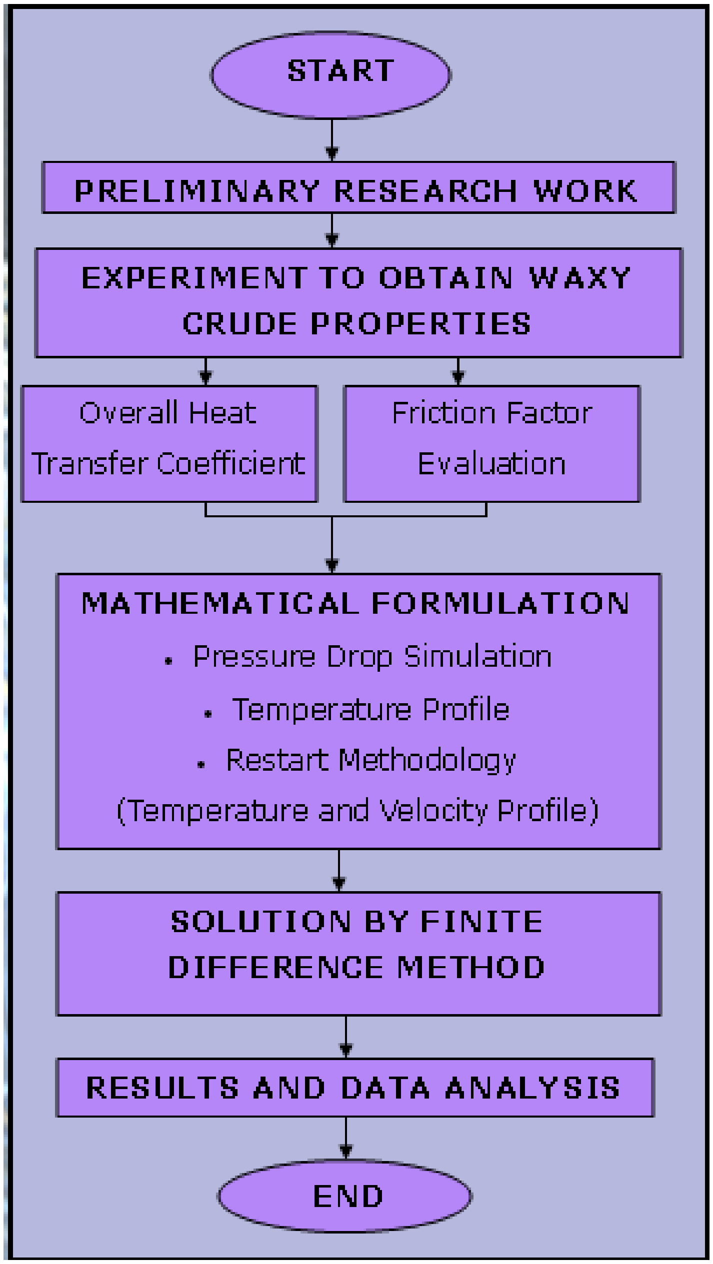


Figure 3-1 Execution Flow Chart

CHAPTER 4

THEORY

4.1 Bingham Plastic Fluids

Waxy crude is a Bingham Plastic fluid that has a yield stress. A higher force is required to push this fluid to restart the flow in pipeline. The shear stress of a Bingham Plastic is given by the following equation [11]:

$$\tau = \tau_B + \mu\left(\frac{-\partial v}{\partial r}\right) \tag{1}$$

Where τ_B (Pa) is the yield stress required to initiate flow, μ (Pa.s) is the viscosity and $\left(\frac{-\partial v}{\partial r}\right)$ is the shear rate (s^{-1}). As τ_B approaches zero, a Newtonian relationship is obtained and μ becomes the Newtonian viscosity.

μ is strongly dependent on temperature, normally via Arrhenius-type relationship. According to Yong and Sharma [11], two empirical equations are used to reflect the experimental data that gives the relationship between viscosity and temperature:

$$\mu = C_1 T^{C_2} \text{ , } T < T_S \tag{2}$$

$$\mu = C_3 e^{C_4 T} \text{ , } T > T_S \tag{3}$$

C_1 to C_4 are empirical constants that fit the rheological property of the waxy crude. The above two equations could be used together by linking them with a transition temperature, T_S, where the change of model takes place.

An Arrhenius-type relationship can be adopted for the temperature dependence of τ_B:

$$\tau_B = C_5 e^{C_6 T} \tag{4}$$

where C_5 and C_6 are empirical contants.

4.2 Temperature profile

By assuming that the fluid is incompressible and that the heat capacities C_P and C_V are almost the same for liquids, fluid temperature at a distance Z can be predicted from simple energy balance [11]:

$$\frac{\partial T}{\partial Z} = -\frac{4U}{\rho D_i v\ C_P}(T - T_a) - \frac{1}{\rho C_P}\frac{\partial P}{\partial Z} - \frac{g}{C_P}\frac{\partial h}{\partial Z} \tag{5}$$

Here, U is the overall heat transfer coefficient, ρ is the density of the process fluid, and v is the average process fluid velocity. D_i, h, g and T_a are inner pipe diameter, pipe elevation, gravitational constant and ambient temperature at a distance Z.

$\frac{\partial P}{\partial Z}$ is the pressure drop over a finite pipeline distance Z.

Overall Heat Transfer Coefficient

The overall heat transfer coefficient, U is predicted to estimate the temperature profile along the pipeline. It is calculated based on various resistances, which are the convective film of process fluid R_{conv}, pipe scaling R_{foul} (if any), pipe wall R_{pipe}, pipe insulation R_{insul}, surrounding soil R_{soil} and convective film of the surrounding fluid R_{surr}.

$$U = \frac{1}{R_{conv} + R_{foul} + R_{pipe} + R_{insul} + R_{soil} + R_{surr}} \tag{6}$$

Where $R_{conv} = \frac{1}{h_i}$;

$$R_{pipe} = \frac{D_1}{2k_{pipe}} \ln(\frac{D_o}{D_i});$$

$$R_{insul} = \frac{D_1}{2k_{insul}} \ln(\frac{2t_{insul} + D_o}{D_o})\ ;$$

$$R_{pipe} = \frac{D_1}{2k_{soil}} \ln(\frac{D_o}{D_i});$$

$$R_{surr} = \frac{1}{h_{surr}}$$

$$R_{foul} = \frac{1}{h_f}$$

In the above equations, D_o and D_i are outer and inner pipe diameters respectively. t_{insul} is the thickness of the insulation and H is the distance between the centerline of the pipe to the ground. k_{pipe}, k_{insul} and k_{soil} are the conductivity of pipe wall material, insulation material and soil respectively. h_f is the heat transfer coefficient due to fouling, while h_i and h_{surr} are the convective film heat transfer coefficients of the process and surrounding fluids that can be predicted by the following equations:

$$h_i = 0.023\ Re^{0.8}\ Pr^{0.3}\ \frac{k_f}{D_i} \quad (7)$$

$$h_{surr} = 0.193\ Re^{0.618} Pr^{0.3}\ \frac{k_{surr}}{2H} \quad (8)$$

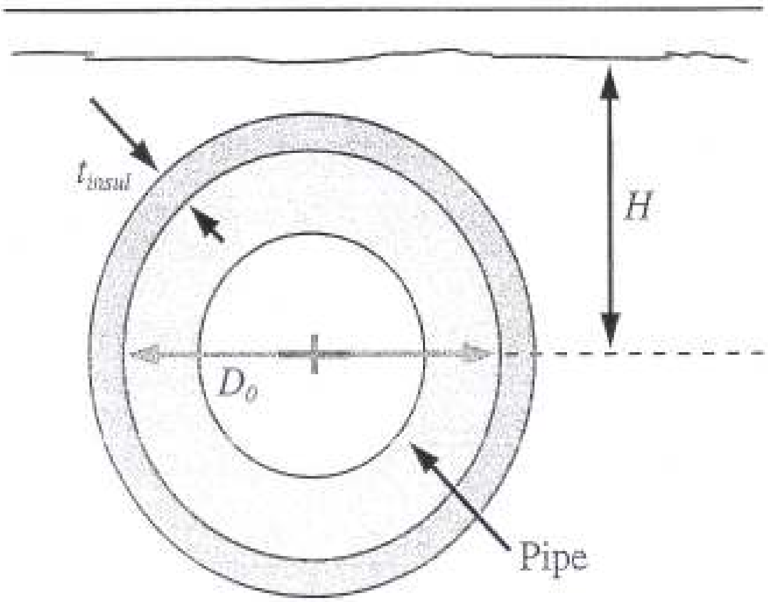


Figure 4-1 Cross-sectional view of the pipe

Prandtl Number, Pr is defined as $\frac{C_P \mu}{k_f}$ where C_p, μ and k_f are the heat capacities, viscosity and conductivity of the fluid. Note that an effective diameter 2H is used for the calculation of Re of the surrounding fluid.

One or more resistance(s) can be set to zero when they are negligible. For example, if there is no surrounding fluid, the velocity of the surrounding fluid can be set to 1 x 10^5 m/s to obtain high h_{surr}, resulting in $R_{surr} = 0$.

4.3 Pressure Drop Simulation

Friction Loss in Pipe

In the pipeline, pressure drop calculation of steady-state flow, the effects of reduction/expansion, bends and valves have been ignored, but effects of temperature and elevation on pressure drop have been considered [11]. A dimensionless number, Hedstrom Number ($He = \frac{D_i^2 p \tau_B}{\mu^2}$), is used to identify whether a fluid is Newtonian or Bingham plastic in nature. If He < 1000, the fluid is said to be Newtonian. Otherwise, the fluid is Bingham plastic that is likely to gel when flow ceases and the fluid temperature drops.

a) Newtonian Fluid

In the case of Newtonian Fluid, if Reynolds number ($Re = \frac{\rho V D}{\mu}$), is greater than 2100, the flow is turbulent; otherwise the flow is laminar. Fanning friction factor,f,can then be calculated using the following equations:

Laminar Flow:

$$f = \frac{16}{Re} \tag{9}$$

Turbulent Flow:

$$\frac{1}{\sqrt{f}} = -4\log_{10}\left(\frac{2RF}{D^1} + \frac{9.38}{Re\sqrt{f}}\right) + 3.48 \tag{10}$$

where RF is the surface roughness factor of the pipe.

b) Bingham Plastic Fluid

In the case of Bingham plastic fluid, the critical Reynolds number, Re_c, is calculated to determine the transition from laminar to turbulent flow of Bingham plastic fluid [12]:

$$\mathrm{Re}_C = \frac{1-\frac{4}{3}\phi_C+\frac{\phi_C^{4}}{3}}{8\phi_C}He \tag{11}$$

Here, ϕ_c is a dimensionless ratio of yield stress to the critical wall shear stress, and can be calculated from the equation below:

$$\frac{\phi_c}{(1-\phi_c)^3} = \frac{He}{16800} \tag{12}$$

If Re < Re_c, then the fluid is laminar region and friction factor can be predicted by the following equation [5]:

$$f = \frac{16}{\mathrm{Re}}\left[1+\frac{1}{6}\frac{He}{\mathrm{Re}}-\frac{He^4}{3f^3\,\mathrm{Re}^7}\right] \tag{13}$$

Otherwise, the fluid is in the turbulent region and a Blasius-type equation can be used to predict f (Chang et al.,1999):

$$f = 10^{c}\,\mathrm{Re}^{-0.193} \tag{14}$$

where $c = -1.378[1+0.146 \exp(-2.9 \times 10^{-5}\,He)]$

The pressure drop across a finite pipe distance ($-\Delta P$) can be obtained by incorporating both pipe friction loss and static loss.

The pressure drop across a distance ΔZ is calculated according to that discussed above for a steady-state operation:

$$(-\Delta P) = \frac{2f\rho v^2 \Delta Z}{D_i} + \rho g \Delta h \tag{15}$$

In the above equation, f is the fanning friction factor, v is the average fluid velocity, ρ is the fluid density, D_i is the inner diameter of the pipe, g is the gravitational constant and Δh is the elevation corresponding to ΔZ.

In the pressure drop prediction, it has been assumed that the upstream pump pressure is equal to the inlet pressure set to achieve a desired flow rate. The downstream pump suction pressure is then calculated iteratively until it has reached steady-state, or equal to the set outlet pressure.

4.4 Restart Methodology

Based on a journal by Yong and Sharma [10], the initial conditions of a pipeline restart simulation are the final conditions of total pipeline shutdown, i.e. the final conditions of the cooled shut-in fluid. When the shut-in fluid starts to flow, the average velocity in the pipe will increase from zero to a steady-state value that corresponds to this flow rate. The incoming fluid fills one section of the pipe, ΔZ this results in the same amount of shut-in fluid being pushed out at the other end of the pipe. Steady state is reached when the flow is fully developed and uniform, i.e. the temperature profile, pressure distribution and velocity profile along the total length of pipeline remain constant.

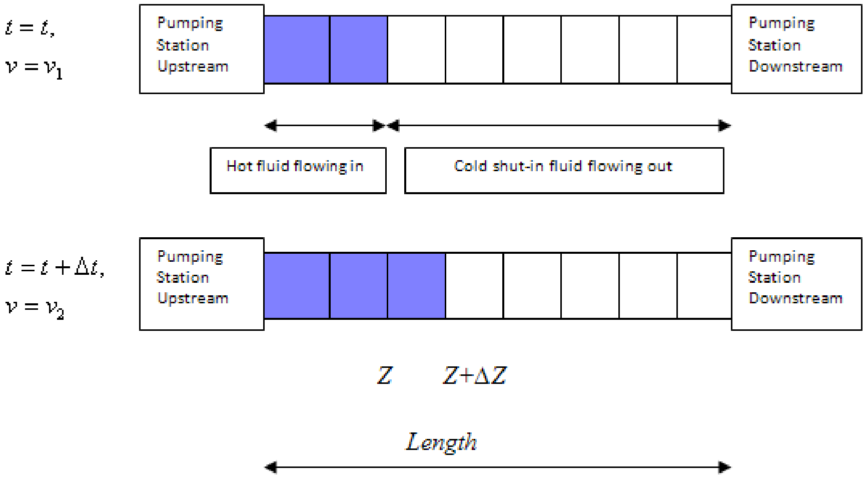


Figure 4-2 Flow of Fluid within finite time difference

If the initial pressure drop is high enough to break down the gelled fluid and initiate flow, only then the pipeline restart is possible. The initial pressure drop, $(-\Delta P)$ has to be greater than the yield stress, τ_B of the shut-in fluid which is strongly dependent on temperature. In pipeline restart simulation, it is assumed that within a finite time difference, Δt, the average velocity is constant along the entire pipeline and thus the temperature and pressure distribution are constant within this finite time difference.

Temperature Profile for Restart

In a finite time interval analysis, the temperature at each point is calculated based on the heat transfer of the fluid contained in a pipe distance ΔZ. Conduction of heat from one section to another section of the fluid, Q_a, has been considered as well as the heat transfer to the surrounding, Q_r. The axial conduction from current fluid element to the next one was assumed to be negligible.

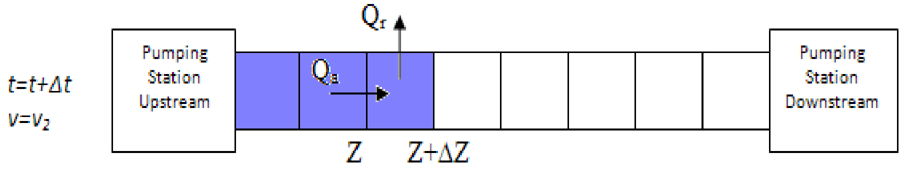


Figure 4-3 Heat Transfer of a fluid element

Therefore, the temperature at a distance $Z + \Delta Z$ at time $t + \Delta t$ is given by:

$$T_{Z+\Delta Z,t+\Delta t} = T_{Z,t} + c_{T1} - c_{T2}(T_{Z,t} - T_a) + c_{T3}(T_{Z.t+\Delta t} - T_{Z.t}) - c_{T4} \tag{16}$$

Where $c_{T1} = \dfrac{-\Delta P}{\rho C_P}$ $\qquad$ $c_{T3} = \dfrac{4U\Delta Z}{\rho v C_P D_i}$

$c_{T3} = \dfrac{kf}{\rho v C_P \Delta Z}$ $\qquad$ $c_{T4} = \dfrac{g\Delta h}{C_P}$

C_P, U, k_f are the specific heat capacity of the fluid, overall heat transfer coefficient and conductivity of the fluid respectively. T_a is the ambient temperature outside the pipeline.

Velocity Profile for Restart

The velocity at time $t + \Delta t$ can be derived from overall energy balance, from discharge of upstream pump (point 1) to suction of downstream pump (point 2):

$$\frac{P_1}{\rho g} + \frac{V_1^{\;2}}{2g} + h_1 - 4f\frac{L}{Di}\frac{v^2}{2g} = \frac{P_2}{\rho g} + \frac{V_2^{\;2}}{2g} + h_2 + \frac{L}{g}\frac{dv}{dt} \tag{17}$$

The average fluid velocity is assumed to be independent of pipe radius and distance, $v_1 = v_2 = v$, an expression for calculating the velocity at time $t + \Delta t$ is as below:

$$v_{t+\Delta t} = A\frac{C-1}{C+1} \tag{18}$$

Where $A = \sqrt{\frac{a}{b}}$;

$$C = \frac{A + v_t}{A - v_t}e^{2Ab\Delta t}$$

$$a = \frac{1}{\rho}(-\frac{\partial P}{\partial z}) - g(\frac{\partial h}{\partial z});$$

$$b = \frac{2f}{D_i}$$

CHAPTER 5

EXPERIMENTAL SETUP

5.1 Fluid Properties

Apparatus: Anton Paar Portable Density Meter DMA 35N, beaker

Sample: Waxy Crude from the trunkline of J4, Balingian, Bintulu, Sarawak.

Procedure:

1) Before any measurements are performed, the resistance of all materials in contact with the sample is checked.
    - Materials in contact with the samples are
      -PTFE(pump piston, filling tube)
      -Borosilicate glass (measuring cell, pump cylinder)

2) The sample is filled into the measuring cell completely. It is ensured that the cell is free of bubbles. Bubbles seriously interfere with the measurement.
3) The sample temperature is ensured to be higher than ambient temperature.
4) The lever of the pump is pushed down.
5) The filling tube is submerged in the sample.
6) The pump lever is slowly released.
7) The measuring results are displayed on the screen.
8) The measuring cell is carefully cleaned after each series of measurements to avoid deposit of coatings.

5.2 Laboratory experiment:

Viscosity versus Temperature at different shear rates

- To measure the effect of temperature on the viscosity of the waxy crude at different shear rates

5.2.1 Equipment and tools

- Waxy Crude sample
- Pressurized Viscometer Model 1100
- Computer

5.2.2 Procedures

Sample Preparation prior to testing: Standardizations

1. The sample is heated to 80°C for 2 hours to eliminate previous thermal and shear histories
2. Next, it is cooled quiescently to room temperature and kept at this temperature for at least 48 hours before usage.

Testing the sample:

3. The bob with size R1B5 is installed by sliding it onto the bob shaft with the tapered end down and is screwed securely into place.
4. The viscometer is connected to a computer to do the data recording. ORCADA ™ software will be utilized.
5. The corresponding sample amount is 52 ml is filled into the sample cup. The sample cup is held by hand and the bob is positioned in the center. The sample cup is pushed up past the o-ring.
6. The sample cup is held in place and the “Jog” switch on the front panel is pressed. The “Jog” switch is rotated at 60 RPM.

   Note: The ORCADA ™ software must be open in order to use the “Jog switch”.

7. The bath is pre-heat to the desired temperature without applying any initial heat to the sample. The bath will be raised once it has reached the temperature set point to begin heating the sample.
8. The sample is heated to 80 °C as indicated in the table below. After 10 minutes, the sample is cooled to 30 °C. At the same time, the rotor is rotated at shear rate 10 $^{s-1}$. Steps 5-8 are repeated with different values of shear rates which are 50 $^{s-1}$, ,200 $^{s-1}$ and 300 $^{s-1}$.
9. The viscosity and temperature data is recorded simultaneously by the ORCADA ™ software during cooling.

Figure 5-1 Pressurized Viscometer

Figure 5-2 Anton Paar Density Meter

CHAPTER 6

RESULTS AND DISCUSSIONS

In this chapter, Part 1 discusses the results obtained from various laboratory experiments are presented and analyzed in detail. Firstly, the properties of the waxy crude such as the density, specific gravity and API number is presented. Next, the relationship between viscosity and temperature at different shear rate will be discussed. The shear rate and corresponding shear stress are studied and from here, the Bingham yield stress is calculated. Then, the effect of shear rate on viscosity readings are presented and discussed.

Meanwhile, Part 2 explains the pipeline restart cases which involve the simulation of velocity profile, pressure distribution and temperature profile along a pipeline.

6.1 Part 1: Rheology of Waxy Crude Oils

6.1.1 Fluid Properties

- Density: 0.850 g/cm^3 or 850 kg/m^3
- Specific Gravity: (850 kg/m^3) / (1000 kg/m^3) = 0.85
- API Gravity: (141.5/0.85)-131.5=34.97°API

6.1.2 Laboratory Experiments

6.1.2.1 Viscosity dependence on temperature at different shear rates

At all shear rates, it is shown that viscosity decreases as temperature increases. Paraffin wax solubility is very sensitive to temperature variation. At elevated temperature, they usually remain dissolved within the oil. On the other hand, when temperature is lowered, it solidifies, making the oil more viscous, thus increasing the viscosity of the oil.

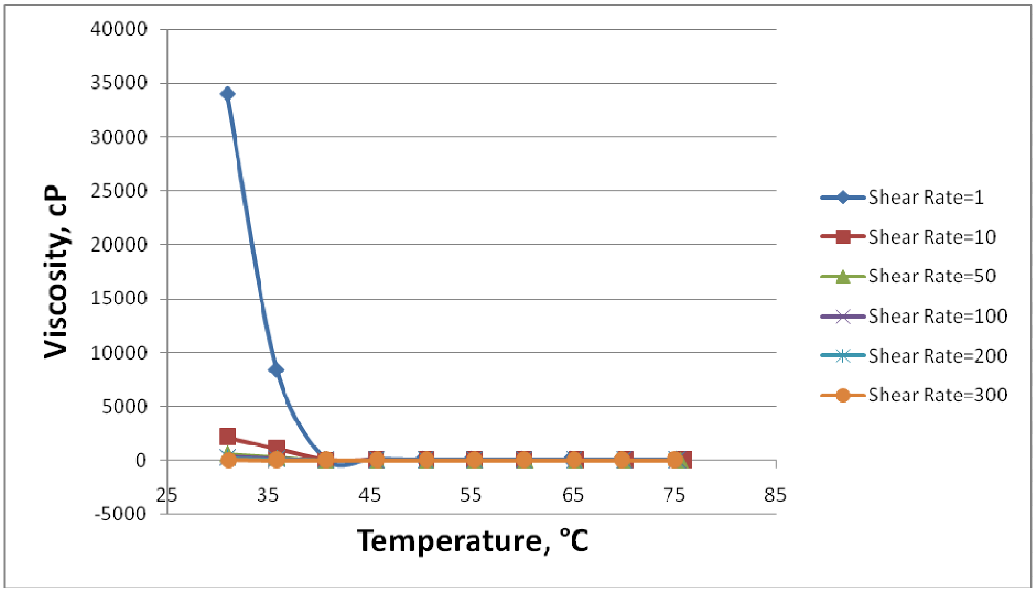


Figure 6-1 The effect of temperature on the viscosity at different shear rates

From the Figure 6-1, it is also shown that at high temperatures, the rheological properties of waxy crude stimulate a linear relationship (Newtonian fluids). This indicates that at high temperatures, the shear rate has less effect on viscosity and viscosity depends heavily on temperature. On the other hand, at lower temperatures, the shear rate has a larger effect on the waxy crude and this portrays the non-Newtonian behavior. This result is with good agreement with the ones obtained by Ooi and Sharma [11] from PRSB in their research.

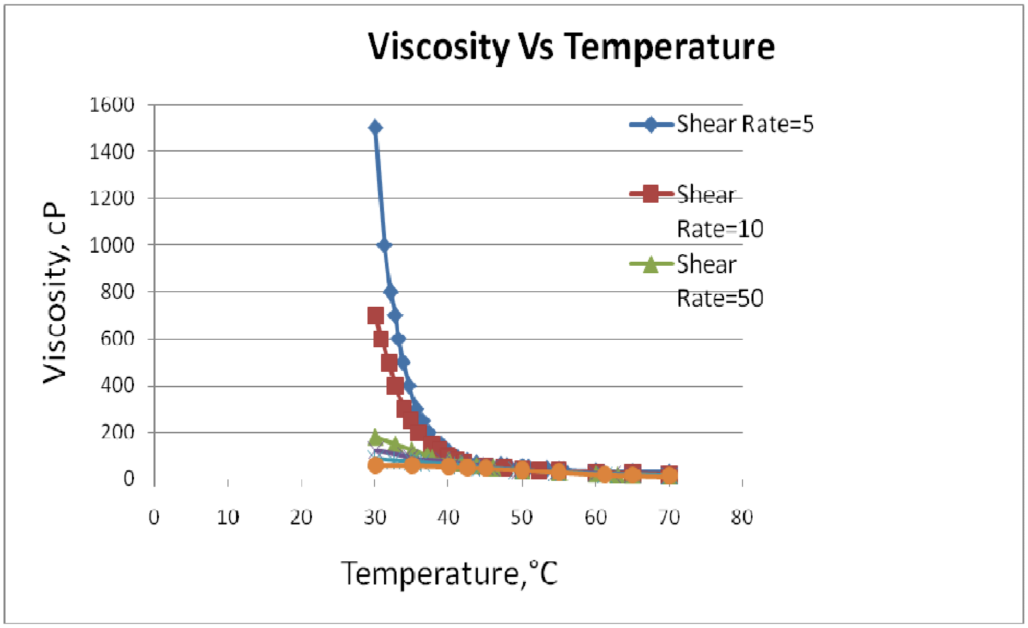


Figure 6-2 Viscosity at different temperature (Results from PRSB)

6.1.2.2 Yield stress dependence on temperature

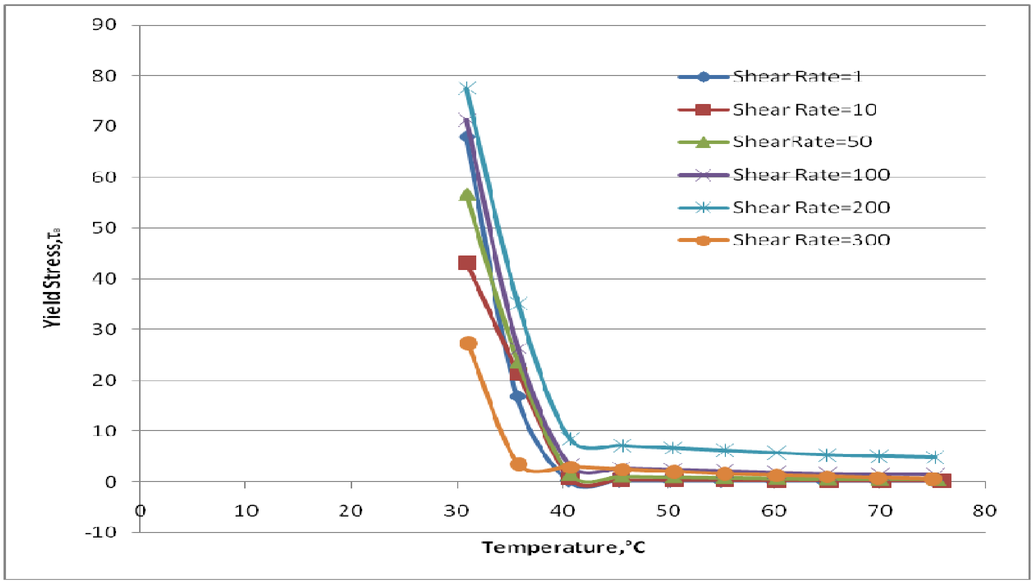


Figure 6-3 Yield Stress at various temperatures

Regardless of the shear rate values, it is shown that yield stress increases as the temperature is lowered.

At low temperatures, yield stress values are considerably high. This indicates that higher pumping pressure is required to initiate the flow in pipelines.

6.1.2.3 Relationship between Shear Stress and Shear Rate

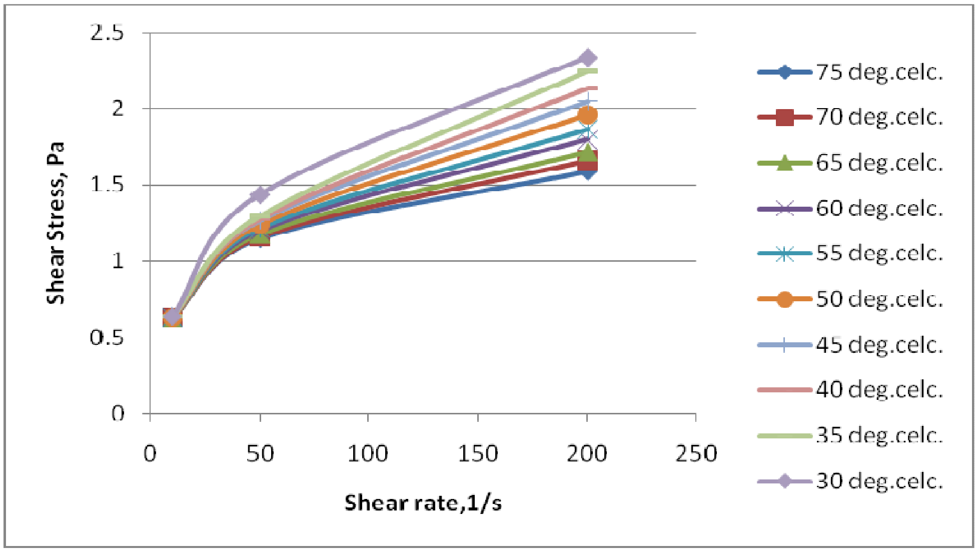


Figure 6-4 Imposed shear rates and the corresponding shear stress value

It is shown that there are two distinct flow regions. The first region denotes the low shear rates up to 50 s^{-1} and the second region is denoted by shear rates up to 200s-1. In both regions, it is observed the increment of shear stress value with increasing shear rate.

In the first region, exponential increase of shear stress is observed with increasing shear rate. This can be modeled by Power Law equation: $\tau = k\dot{\gamma}^n$ .In the second region, a gradual increase of shear stress is observed with the increase of shear rate and indicates a non-Newtonian pseudoplastic character with yield value. By increasing the shear rate, the dissipated energy is high enough to overcome the yield stress and resume the fluid flow. At lower temperatures, the dissipated energy is mostly directed to decrease the progressive yield stress and thus less amount of energy to decrease the viscosity.

6.1.2.4 Viscosity dependence shear rates

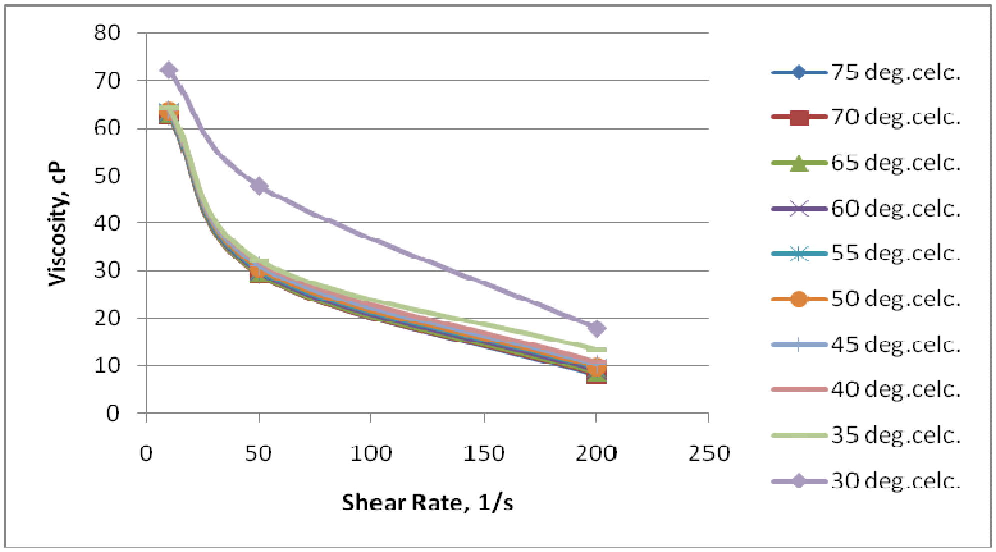
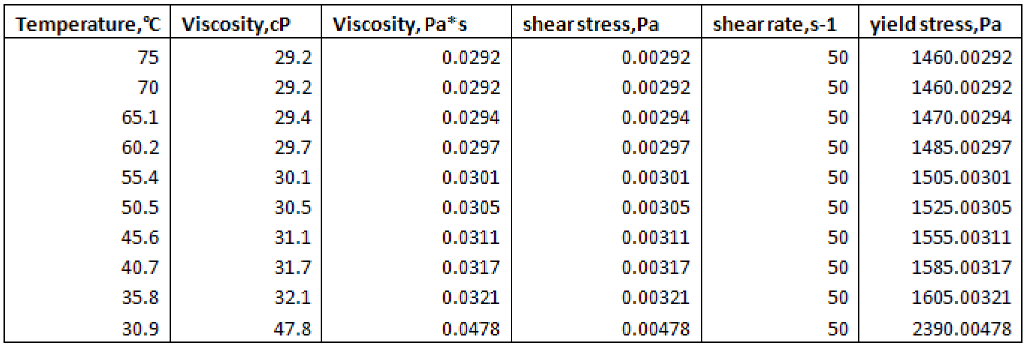


Figure 6-5 Viscosity values at different shear rates

It is shown that viscosity decreases approximately linearly with increasing shear rate at all temperatures. It is also noted that the rate at which the viscosity is decreasing is lowered at higher shear rates.

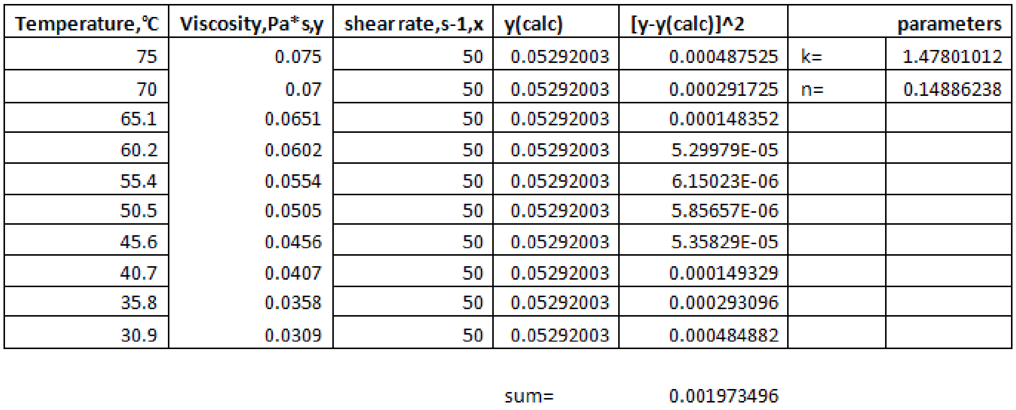
Table 6-1 Bingham Yield stress calculation



Temperature,℃	Viscosity,cP	Viscosity, Pa*s	shear stress,Pa	shear rate,s-1	yield stress,Pa
75	29.2	0.0292	0.00292	50	1460.00292
70	29.2	0.0292	0.00292	50	1460.00292
65.1	29.4	0.0294	0.00294	50	1470.00294
60.2	29.7	0.0297	0.00297	50	1485.00297
55.4	30.1	0.0301	0.00301	50	1505.00301
50.5	30.5	0.0305	0.00305	50	1525.00305
45.6	31.1	0.0311	0.00311	50	1555.00311
40.7	31.7	0.0317	0.00317	50	1585.00317
35.8	32.1	0.0321	0.00321	50	1605.00321
30.9	47.8	0.0478	0.00478	50	2390.00478

The calculated value of the Bingham yield stress from the table agrees with the previous comment stating that the yield stress increases with increasing viscosity. This means that, a higher pumping pressure is required to resume the flow to restart the pipeline when the yield stress is considerably high.

Table 6-2 Power Law constants calculation



Temperature,℃	Viscosity,Pa*s,y	shear rate,s-1,x	y(calc)	[y-y(calc)]^2		parameters
75	0.075	50	0.05292003	0.000487525	k=	1.47801012
70	0.07	50	0.05292003	0.000291725	n=	0.14886238
65.1	0.0651	50	0.05292003	0.000148352		
60.2	0.0602	50	0.05292003	5.29979E-05		
55.4	0.0554	50	0.05292003	6.15023E-06		
50.5	0.0505	50	0.05292003	5.85657E-06		
45.6	0.0456	50	0.05292003	5.35829E-05		
40.7	0.0407	50	0.05292003	0.000149329		
35.8	0.0358	50	0.05292003	0.000293096		
30.9	0.0309	50	0.05292003	0.000484882		

sum= 0.001973496

Apart from that, the constants for the Power Law Model are also calculated by using nonlinear least-square curve fitting method with Microsoft Excel Solver to get the values of ‘k’ and ‘n’. K is a measure of fluid’s thickness and is called ‘consistency index’. Meanwhile, the parameter ‘n’ is called the Power Law exponent or the flow behavior index. This is a measure of the degree of deviation from Newtonian behavior. The calculated value of ‘n’ is 0.14886238 which is lesser than 1. This means that the fluid is pseudoplastic.

6.2 Part 2: Pipeline Restart of Waxy Crude

The following is based on the work by Ooi and Duhita [10]. In the pipeline restart simulation, it was assumed that the pipeline under investigation was totally shut down for 192 hours and the process fluid was cooled at the ambient temperature of 29°C, at varying elevations. The discharge pressure of the upstream pump was set at 10000 kPa, while the suction pressure of the downstream pump was set at 500 kPa. This pressure drop was intended to get a steady state the average fluid velocity of about 1.34 m/s.

For the simulation, a value of an average velocity that is constant at a certain finite time interval was assumed. From this, pressure drop and temperature profile were calculated by using equations (15) and (16). Once the pressure drop and temperature simulation were completed for the whole pipeline length, both calculated values were then used to compute the average fluid velocity via equation (18). Should the calculated value of the average velocity is not the same the first guess, iterations have to be done until the convergence of the fluid average velocity is achieved. The incoming fluid moves to the next ΔZ and the entire calculation was repeated for another time increment.

6.2.1 Velocity Profile

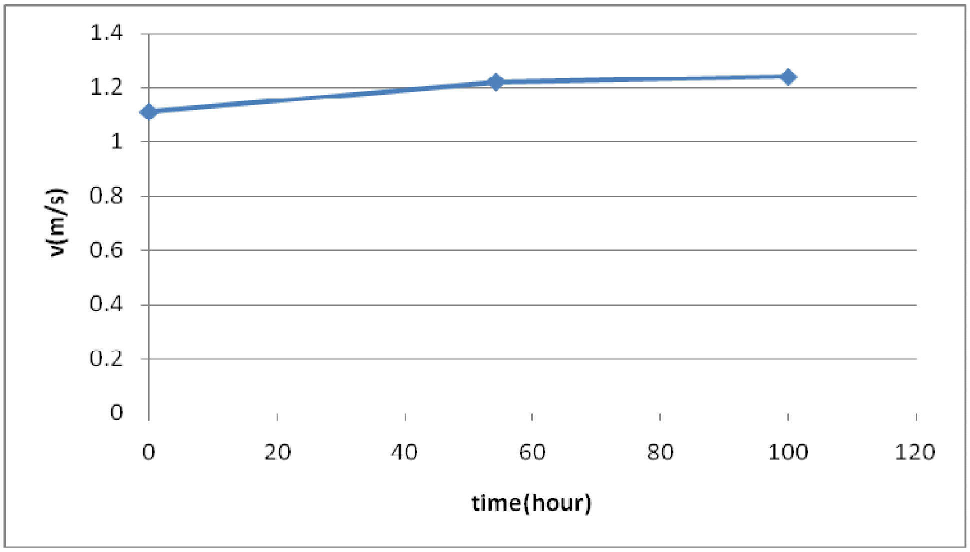


Figure 6-6 Velocity profile for a pipeline restart

Figure 6-6 shows the plot for average fluid velocity against time. The initial fluid velocity was instantaneously increased to about 1.1 m/s and gradually reached the steady state value of 1.34 m/s. The instantaneous increase of the velocity is due to the pressure drop introduced by the set discharge and suction pumps.

6.2.2 Temperature Profile

The temperature profile along the pipeline was plotted against selected times in Figure 6-7. When the hot fluid is injected and fills up the pipeline, the same amount of cooled gelled fluid is pushed out. The sudden drop in temperature at approximately at 80 km indicates the location where transition from hot fluid to cooled gelled fluid takes place. The fluid temperature decreases exponentially with pipeline distance once the temperature has reached steady state.

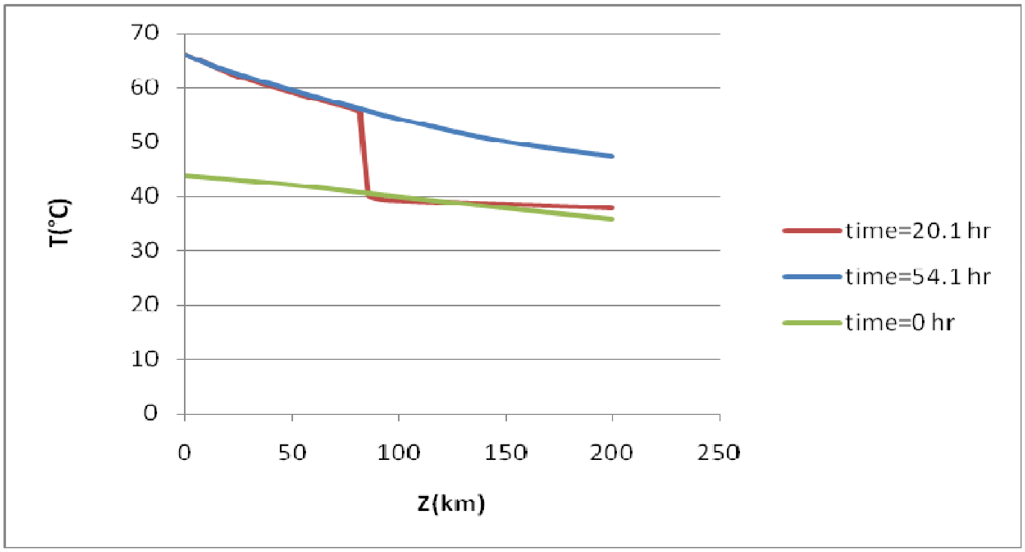


Figure 6-7 Temperature profile of a pipeline restart at various startup times

6.2.3 Pressure distribution along the pipeline

Pressure losses in pipelines are caused by pipe friction loss as well as the static loss due to the elevation. Here, the pressure distribution is obtained via derived friction factors. The fluctuating values of the pressure with pipeline length are due to the varying elevation of the pipeline.

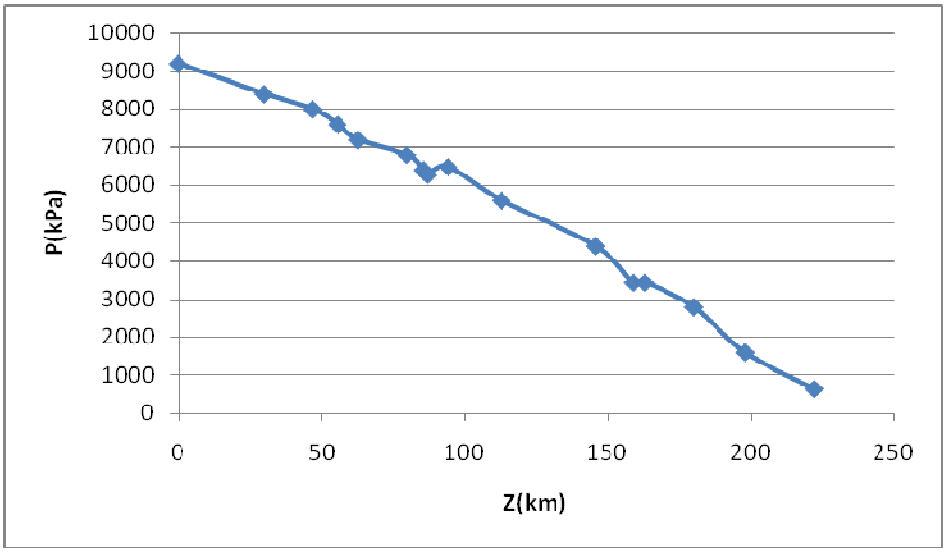


Figure 6-8 Pressure distribution along a pipeline

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

Waxy crude flow behaviour during pipeline restart is investigated. Other than that, the pressure distribution, velocity variation and temperature profile of the waxy crude have been successfully predicted.

Waxy crude behaves like a Newtonian fluid at high temperature but at sufficiently low temperatures, it exhibits a non-Newtonian fluid with a yield stress and is known as Bingham Plastic fluid. Higher pumping pressure is required to initiate the flow of pipelines transporting waxy crude and this pressure must exceed the yield stress of the fluid.

It is shown that pressure drop and temperature profile of the Bingham Plastic fluid can be predicted via derived friction factors and basic energy equation respectively.

The simulation of pipeline restart can be done by assuming that the average fluid velocity is constant within a finite time difference. The velocity profiles, pressure distribution as well as temperature profile were shown in this work.

7.2 Recommendations

A waxy crude sample with lower API gravity (heavy-weight crude) is recommended to be tested to observe a more significant behaviour under varying conditions due to the higher wax content.

Other than that, collaboration with PETRONAS Research Sdn. Bhd. can be helpful. Certain experiment including wax appearance temperature, pour point and wax content measurements can be investigated.

Pipeline restart field data should be acquired in the future to compare the simulated results and the real situation. This can proof whether the analysis done is sufficient or can be further improved.

The steady state flow model can be improved to investigate a more transient behaviour of the flow. This is especially true at the early stage of the pipeline restart where the flow is still developing and has not reach the steady state.

REFERENCES

[1] A. Fasano,L.Fusi & S.Correra (2004), *Mathematical Models for Waxy Crude Oils*,Italy.

[2] Guillaume Vinay, Anthony Wachs & Jean-Francois Agassant (2005), *Numerical Simulation for Non-isothermal Viscosplastic Waxy Crude Oil Flows*, France.

[3] http://tigger.uic.edu/~mansoori/Wax.and.Waxy.Crude_html

[4] Mustafa Versan Kok & Onder Saracoglu (2000), *Mathematical Modelling of Wax Deposition in Crude Oil Pipeline Systems*, Society of Petroleum Engineers, SPE64514, 2000.

[5] Banki, Hoteit and Firoozabadi, *Mathematical Formulation and numerical modeling of wax deposition in pipelined from enthalpy-porosity approach and irreversible thermodynamics,* International Journal of Heat and Mass Transfer 51 (2008) 3387-3398.

[6] Wardaugh, L.T., Boger, D.V., and Toner, S. P. 1988. Rheology of Waxy Crude Oils. Paper SPE 17625 presented at the SPE International Meeting on Petroleum Engineering, Tianjin, China, 1-4 November.

[7] Pederson, K.S., and Ronningsen, H.P. 2000. Effect of Precipitated Wax on Viscosity – A Model for Predicting Non-Newtonian Viscosity of Crude Oils. *Energy&Fuels* **14**:43-51

[8] Davenport, T.C. and Somper, R.S.H. 1971. The Yield Value and Breakdown of Crude Oil Gels. *J. Inst. Pet.* **57** (554), 86-105.

[9] Chiedozie K. Ewkeribe (2008), Quiescent Gelation of Waxy Crudes and Restart of Shut-in Subsea Pipelines, Oklahoma.

[10] Chang, C., Nguyen, Q.D. & RØnningsen, H.P. (1999), *Isothermal Start-Up of Pipeline Transporting Waxy Crude Oil*, JNNFM 87, 127-154.

[11] Yong & Sharma, *Steady State Flow and Restart of Waxy Crude in a Pipeline*, PETRONAS Technology Journal 2 (1) 2009, 44-52.

[12] Chhabra, R.P. & Richardson, J.F. (1999), Non-Newtonian Flow in the Process Industries, Butterworth-Heinemann, Oxford.

Appendices

shear rate=1s-1

Temperature,°C	Viscosity,cP	shear stress,Pa	shear rate,s-1	yield stress,Pa
75.1	109.2	10.92	1	86.02
69.6	110.3	11.03	1	80.63
64.6	110.7	11.07	1	75.67
59.8	112.2	11.22	1	71.02
54.9	120.3	12.03	1	66.93
50.1	122.2	12.22	1	62.32
45.3	128.5	12.85	1	58.15
40.5	149.4	14.94	1	55.44
35.7	8426.9	842.69	1	878.39
30.9	33982.5	3398.25	1	3429.15

shear rate=10s-1

Temperature,°C	Viscosity,cP	shear stress,Pa	shear rate,s-1	yield stress,Pa
75.9	13.5	1.35	10	760.35
70.1	14.2	1.42	10	702.42
65.2	15.5	1.55	10	653.55
60.2	16.2	1.62	10	603.62
55.3	18.5	1.85	10	554.85
50.5	19.7	1.97	10	506.97
45.5	22.8	2.28	10	457.28
40.7	37.2	3.72	10	410.72
35.8	1071.5	107.15	10	465.15
30.9	2164	216.4	10	525.4

shear rate=50s-1

Temperature,°C	Viscosity,cP	shear stress,Pa	shear rate,s-1	yield stress,Pa
75.5	4.7	0.47	50	3775.47
70	5.6	0.56	50	3500.56
65.1	6	0.6	50	3255.6
60.3	7.1	0.71	50	3015.71
55.3	8.3	0.83	50	2765.83
50.5	9.6	0.96	50	2525.96
45.6	11	1.1	50	2281.1
40.7	14.9	1.49	50	2036.49
35.8	236	23.6	50	1813.6
30.9	566.7	56.67	50	1601.67

shear rate=100s-1

Temperature,°C	Viscosity,cP	shear stress,Pa	shear rate,s-1	yield stress,Pa
75.3	7.2	0.72	100	7530.72
70	7.9	0.79	100	7000.79
65	8.4	0.84	100	6500.84
60.2	9.5	0.95	100	6020.95
55.3	10.8	1.08	100	5531.08
50.4	12.1	1.21	100	5041.21
45.5	13.4	1.34	100	4551.34
40.7	16.7	1.67	100	4071.67
35.8	131.6	13.16	100	3593.16
30.9	357.2	35.72	100	3125.72

shear rate=200s-1

Temperature,°C	Viscosity,cP	shear stress,Pa	shear rate,s-1	yield stress,Pa
75.2	12.2	1.22	200	15041.22
69.9	12.8	1.28	200	13981.28
65	13.4	1.34	200	13001.34
60.2	14.5	1.45	200	12041.45
55.3	15.6	1.56	200	11061.56
50.4	16.8	1.68	200	10081.68
45.6	18.1	1.81	200	9121.81
40.7	21.2	2.12	200	8142.12
35.8	87.7	8.77	200	7168.77
30.9	193.7	19.37	200	6199.37

shear rate=300s-1

Temperature,°C	Viscosity,cP	shear stress,Pa	shear rate,s-1	yield stress,Pa
75	1	0.1	300	22500.1
69.8	1.4	0.14	300	20940.14
65	1.8	0.18	300	19500.18
60.2	2.1	0.21	300	18060.21
55.3	2.7	0.27	300	16590.27
50.5	3.4	0.34	300	15150.34
45.6	4.1	0.41	300	13680.41
40.7	4.9	0.49	300	12210.49
35.8	5.9	0.59	300	10740.59
31	45.6	4.56	300	9304.56

Temperture vs. Viscosity

shear rate=1

Temperature,x	Viscosity,y
75.1	109.2
69.6	110.3
64.6	110.7
59.8	112.2
54.9	120.3
50.1	122.2
45.3	128.5
40.5	149.4
35.7	8426.9
30.9	33982.5

shear rate=100

Temperature,x	Viscosity,y
75.3	7.2
70	7.9
65	8.4
60.2	9.5
55.3	10.8
50.4	12.1
45.5	13.4
40.7	16.7
35.8	131.6
30.9	357.2

shear rate=10

Temperature,x	Viscosity,y
75.9	13.5
70.1	14.2
65.2	15.5
60.2	16.2
55.3	18.5
50.5	19.7
45.5	22.8
40.7	37.2
35.8	1071.5
30.9	2164

shear rate=200

Temperature,x	Viscosity,y
75.2	12.2
69.9	12.8
65	13.4
60.2	14.5
55.3	15.6
50.4	16.8
45.6	18.1
40.7	21.2
35.8	87.7
30.9	193.7

shear rate=50

Temperature,x	Viscosity,y
75.5	4.7
70	5.6
65.1	6
60.3	7.1
55.3	8.3
50.5	9.6
45.6	11
40.7	14.9
35.8	236
30.9	566.7

shear rate=300

Temperature,x	Viscosity,y
75	1
69.8	1.4
65	1.8
60.2	2.1
55.3	2.7
50.5	3.4
45.6	4.1
40.7	4.9
35.8	5.9
31	45.6

Shear Rate vs. Viscosity

Temperature=50°C

Shear rate, x	Viscosity,cP
10	63.7
50	30.5
200	9.8

Temperature=70°C

Shear rate, x	Viscosity,cP
10	62.8
50	29.2
200	8.3

Temperature=45°C

Shear rate, x	Viscosity,cP
10	63.9
50	31.1
200	10.3

Temperature=65°C

Shear rate, x	Viscosity,cP
10	63.1
50	29.4
200	8.6

Temperature=40°C

Shear rate, x	Viscosity,cP
10	64.1
50	31.7
200	10.7

Temperature=60°C

Shear rate, x	Viscosity,cP
10	63.2
50	29.7
200	9

Temperature=35°C

Shear rate, x	Viscosity,cP
10	64.3
50	32.1
200	13.3

Temperature=55°C

Shear rate, x	Viscosity,cP
10	63.4
50	30.1
200	9.4

Temperature=30°C

Shear rate, x	Viscosity,cP
10	72.2
50	47.8
200	17.8

Temperature=75°C

Shear rate, x	Viscosity,cP
10	62.7
50	29.2
200	8