High Viscous Fluid Transport Model

by

Tan Ming Chai

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

JUN 2004

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

High Viscous Fluid Transport Model

by

Tan Ming Chai

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,

(Norrulhuda Haji Mohd Taib)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

Jun 2004

CERTIFICATION OF ORIGINALITY

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

TAN MING CHAI

ABSTRACT

The purpose of this study is to develop a fluid flow model, which will describe the transport of high viscous fluid. For high viscous fluid, failure to account for radial variations in liquid viscosity may cause the pipeline pressure drop to be grossly under predicted. The procedures and techniques in modeling of the viscous fluid have been developed, and applied to real life practices.

In this study, a set of mathematical equations was derived from the concepts of basic transport equations, namely the continuity, momentum and energy equations. This set of transport equations relates steady state flow and accounts for heat transfer. PIPEPHASE, a pipeline simulation tool, was used to model the flow of high viscous fluid. The results obtained was analyzed and compared with the high viscous fluid flow model developed from the mathematical equations. A solution algorithm was built to solve for the mathematical model.

The *Dulang D 8-L* crude oil was selected as the high viscous fluid due to its viscous characteristic. The pipeline system used in the analysis was a typical pipeline system available in Sudan operating under Greater Nile Petroleum Operating Co. (GNPOC). All the data pertaining to the pipeline profile and fluid properties are obtained courtesy of PETRONAS Research and Scientific Services (PRSS).

The results obtained show that ordinary pipeline simulation tool under predicts the pressure drop by a factor of 1.5 to 2 depending on the flow rate. The model also shows how the dependency on liquid viscosity results in a bell shaped velocity profile rather than the parabolic Hagen-Poiseulle profile.

ACKNOWLEDGEMENT

I wish to express my sincere appreciation to Norrulhuda Hj. Mohd Taib for allowing me to pursue this study in the "High Viscous Transport Model" as my Final Year Project. I am extremely thankful for her personal guidance, assistance and supervision over the course of this study. The participation of Faiza Mohd Nasir as co-supervisor and Dr. D. M. Annuarraja is appreciated. Appreciation is also extended to Dr. Othman Mamat and Dr. Abdul Huq Abdul Wahhab for several informative discussions.

Dr. Ahmad Bazlee Mat Zain, former Staff Engineer (Flow Assurance) of PETRONAS Research and Scientific Services is also acknowledged for his enlightening discussions and meaningful suggestions. Appreciation is extended to staffs of Petroleum Engineering And Facilities Engineering Group of PETRONAS Research and Scientific Services. I thank them for their kind assistance during the modeling phase and experimental work undertaken at their workstation.

My fellow classmate Nazrulhisham Osman deserves special thanks for his help and constructive thought during crucial phases of this work. I also recognize Roslan Idris, technician in the IT and Media Department for his assistance in providing useful information and suggestions. My message of thanks also goes to the Final Year Project Coordinators, with special mention of Saravanan Karuppanan, Azuraien Japper @ Jaafar and Dr. Fakhruldin Mohd Hashim.

Finally, my warmest thanks go to all my friends, who constantly supported me during the course of this study. I am also thankful for the love from my parents, Acik and Lian. I would like to dedicate this work to my parents, my brothers, Ming Hock, Ming Leng and Ming Kong and to my sister Ming Hong, for their love and encouragement.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

A widely used method of transporting oil is through pipeline. Long distance pipelines, often called transmission lines are used extensively to transport oil from offshore facilities to refinery, market areas and other onshore terminals. The pipeline pressure drop is expected to be large due to the long distance transport to shore.

The prediction of the pipeline pressure loss of the high viscous fluid with strong temperature dependent viscosity is rather difficult, although the fluid is Newtonian in behavior. Ordinary standard, steady state, single phase, one-dimensional pipeline simulation tool is available to model the pipeline pressure gradient. However, the utilization of bulk properties of the fluid by most conventional simulation tools is insufficient to predict the pressure drop.

The study generally focuses on the development of a fluid flow model to estimate the pressure and temperature drop in pipeline transporting high viscous crude oil with temperature dependent viscosity.

1.2 PROBLEM STATEMENT

The variation in oil viscosity across the radius of the pipe is expected to be large due to its temperature dependent nature. Failure to account for radial variation in fluid properties, in particular liquid viscosity may cause the pressure drop prediction of the pipeline to be inaccurate. Therefore, a procedure in developing a more accurate fluid flow model for pipeline pressure gradient, temperature and velocity profile for oil with strong temperature dependent is desirable.

1.3 OBJECTIVES

1.3.1 To explore and develop proper theoretical procedures to model the transportation of high viscous fluid with temperature dependent viscosity.

1.3.2 To model the pipeline pressure gradient for oil with strong temperature dependent viscosity using ordinary steady state, single phase, one dimensional pipeline simulation tool.

1.3.3 To develop a fluid flow model for pipeline pressure gradient specifically for viscous fluid with strong temperature dependent viscosity using the theoretical procedures.

1.4 SCOPE OF STUDY

The study is devoted only on high viscous fluid. Crude oil is chosen as the fluid of study due to its viscous characteristics and the necessity of transporting it in long distance pipelines. The theoretical model of flow for high viscous fluid will be performed. The transport equation namely the continuity, momentum and energy equation will be used to represent the flow characteristics of the viscous fluid. A solution algorithm to the theoretical model will be built using necessary tools. The algorithm will solve equations in an iterative manner to calculate the desired results. The model will be tested on a typical pipeline system. The results of the model will be compared to the results obtained from ordinary pipeline simulation tool.

CHAPTER 2

LITERATURE REVIEW

2.1 FLOW IN A CIRCULAR PIPE

The characteristics of flow and flow behavior are governed by flow regimes. The flow regimes, generally describe the relationships between pressure and velocity. There are two such flow regimes namely laminar flow and turbulent flow. The pressure increases more rapidly when the flow is turbulent than when it is laminar when the velocity is increased, based on the steepness of the slope on the turbulent flow curve as shown in Figure 2.1.

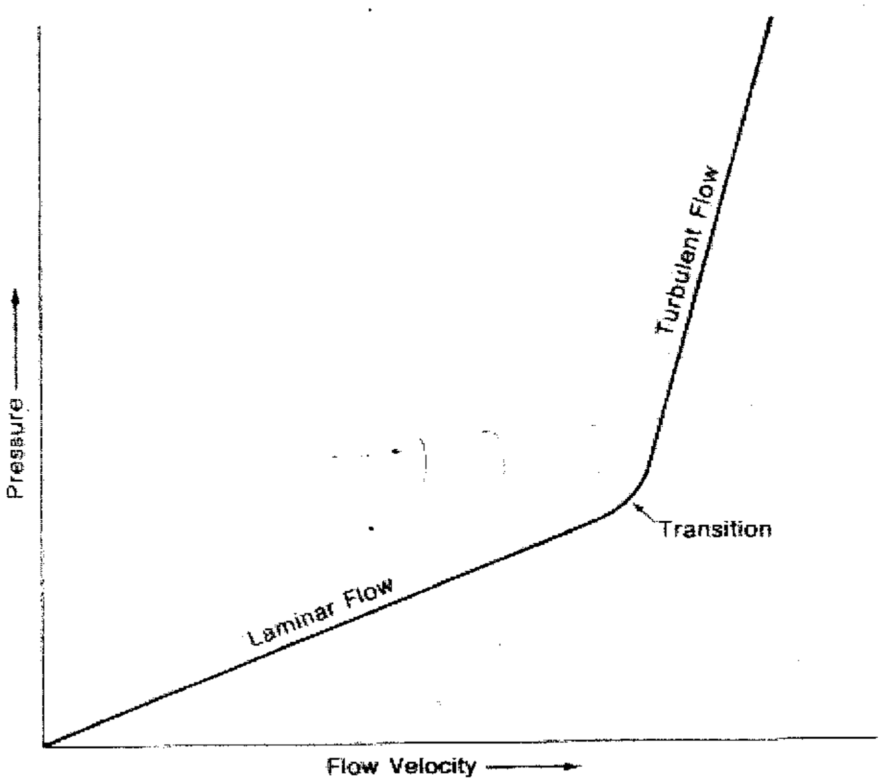

Figure 2.1 : Schematic diagram of laminar and turbulent flow regimes (*Source : Gray and Darley, 1980*)

The laminar flow regime prevails at low velocities. The flow is orderly and the pressure-velocity relationship is a fluctuation of viscous properties. At high velocities, the turbulent flow regime prevails. Flow is disorderly and is governed by the inertial properties of the fluid in motion. Flow equations are empirical.

A dimensionless combination of variables that is important in the study of viscous flow in pipes is known as Reynolds number, N_{Re}. The Reynolds number for flow in circular tube is defined as

$$N_{RE} = \frac{\rho V D}{\mu} \qquad [2.1]$$

where ρ is the fluid density, V is the fluid velocity, D is the pipe diameter and μ is the fluid viscosity. The flow in a round pipe is laminar if the Reynolds number is less than approximately 2100. If the Reynolds number is greater than approximately 4000, the flow is turbulent. The flow may, however switch in between laminar and turbulent conditions in an apparently random fashion if the Reynolds number falls between these two limits. This is termed as the transitional flow.

However, in a fully developed laminar region, the critical Reynolds number corresponding to the onset of turbulence is 2300, although a much larger Reynolds number (Re = 10000) are needed to achieve fully turbulent conditions (Incropera and DeWitt, 1996, p.389).

The velocity of flow in a round pipe increases from zero at the pipe wall to the maximum at the axis of the pipe. The velocity gradient at any two points divided by the distance between these points in the round pipe is defined as the shear rate. The axial force divided by the surface area of the surface area of the cylinder defines the rate of shear strain. The shearing stress and the rate of shearing strain can be related with the relationship as

$$\tau = \mu \frac{dv}{dr} \qquad [2.2]$$

where τ is the shear stress and $\frac{dv}{dr}$ is the shear rate or velocity gradient. The μ is defined as the frictional resistance of the flow of the fluid and is termed as the viscosity of the fluid.

The plot of shearing stress versus the rate of shearing strain is known as the consistency curve (Gray and Darley, 1980, p. 13) as shown in Figure 2.2. Fluids which the shearing is linearly related to the rate of shearing strain are called Newtonian fluids, as laid down in Newton's first law. The consistency curves for Newtonian fluids are straight lines and the viscosity is defined as the slope of the consistency curves. Fluids that do not conform with the Newton's first law, in which the shearing stress in not linearly related to the rate of shearing strain are classified under the general term of non-Newtonian fluids.

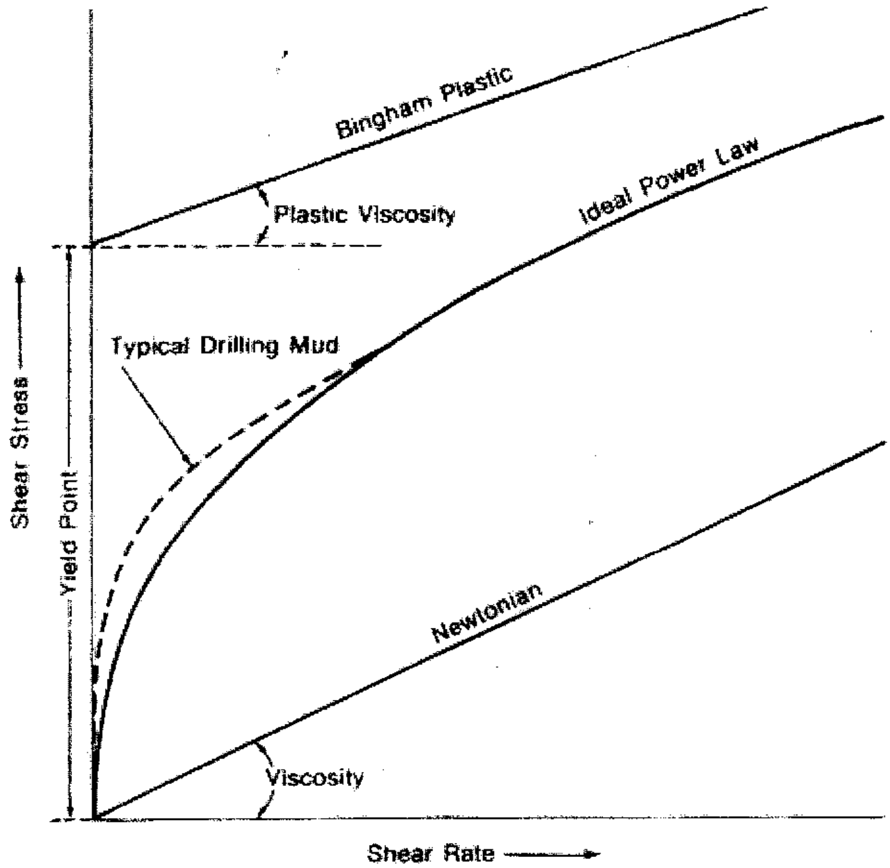

Figure 2.2 : Ideal consistency curve for common flow models *(Source : Gary and Darley, 1980)*

2.2 VELOCITY PROFILE

The flow in the cylindrical pipe is constrained by bounding wall and the viscous effects will grow and meet and permeate the entire flow. At the fully developed region, the velocity profile is constant and the wall shear is constant (White, 1999, p. 331). For either laminar or turbulent flow, the pressure drops linearly with length as shown in Figure 2.3.

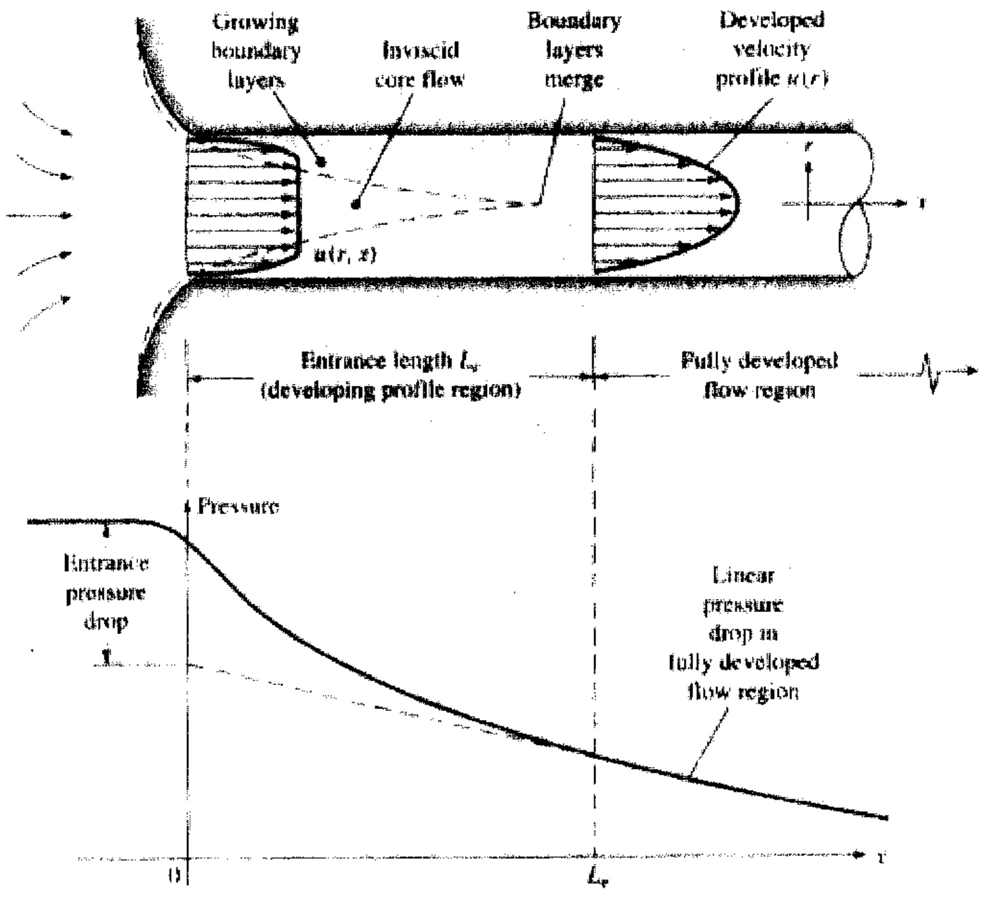

Figure 2.3 : Developing velocity profile and pressure changes in entrance of a flow (*Source : White*)

The velocity of the cylindrical pipe increases from zero at the pipe wall due to the no-slip condition to a maximum at the axis of the pipe resulting in a parabolic velocity profile. This is true for flow in a fully developed laminar region. For turbulent flow, the profile is flatter due to turbulent mixing in radial direction.

2.3 THE TRANSPORT EQUATIONS

The basic transport equations of fluid flow represent the mathematical statements of three laws of conservation for physical systems (Versteeg and Malalasekera, 1995, p. 10), namely

(1) Conservation of mass (Continuity equation)
(2) Conservation of momentum (Newton's second law)
(3) Conservation of energy (First law of thermodynamics)

The cylindrical coordinate system is used to represent the direction of analysis in the pipeline, as shown in Figure 2.4. The radial, axial and azimuthal directions are represented by r, z and θ respectively.

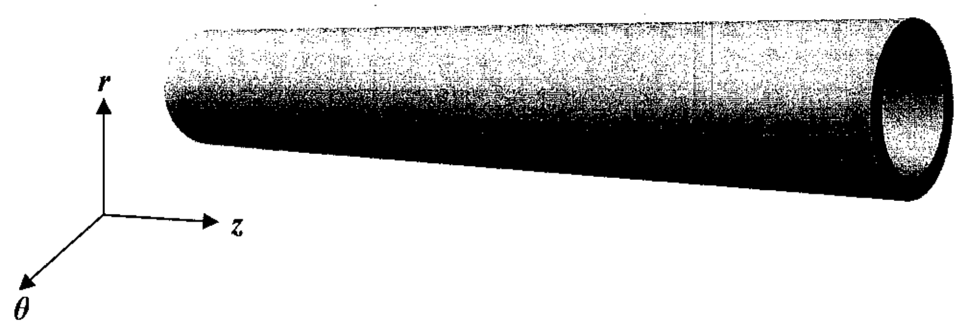

Figure 2.4 : Cylindrical coordinate system used to represent the direction of analysis in the pipeline

For either laminar or turbulent flow, the continuity, momentum and energy equation in the cylindrical coordinates are given by Eqs. 2.3, 2.4 and 2.5 respectively (Bird, Steward and Lightfoot, 2002, p. 846 – 850)

$$\frac{1}{r}\frac{\partial}{\partial r}(\rho r v_z)+\frac{1}{r}\frac{\partial}{\partial \theta}(\rho v_\theta)+\frac{\partial}{\partial z}(\rho v_z)=0 \quad [2.3]$$

$$\rho\left(v_r\frac{\partial v_z}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_z}{\partial \theta}+v_z\frac{\partial v_z}{\partial z}\right)=-\frac{\partial p}{\partial z}-\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\tau_{rz}\right)+\frac{1}{r}\frac{\partial}{\partial \theta}\tau_{\theta z}+\frac{\partial}{\partial z}\tau_{zz}\right]+\rho g_z \quad [2.4]$$

$$\rho \hat{C}_p \left(v_r \frac{\partial T}{\partial r} + \frac{v_\theta}{r} \frac{\partial T}{\partial \theta} + v_z \frac{\partial T}{\partial z} \right) = k \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial \theta^2} \right] + \mu \Phi_v \qquad [2.5]$$

The shear stresses for incompressible Newtonian fluids in Eq. 2.4 are related to the Newton's law of viscosity. The shear stresses are expressed as (Bird, Steward and Lightfoot, 2002, p. 844):-

$$\tau_{rz} = \tau_{zr} = -\mu \left[\frac{\partial v_r}{\partial z} + \frac{\partial v_z}{\partial r} \right] \qquad [2.6]$$

$$\tau_{\theta z} = \tau_{z\theta} = -\mu \left[\frac{1}{r} \frac{\partial v_z}{\partial \theta} + \frac{\partial v_\theta}{\partial z} \right] \qquad [2.7]$$

$$\tau_{zz} = -\mu \left[2 \frac{\partial v_z}{\partial z} \right] + \left(\frac{2}{3}\mu - \kappa \right) (\nabla \cdot \mathbf{v}) \qquad [2.8]$$

in which

$$(\nabla \cdot \mathbf{v}) = \frac{1}{r} \frac{\partial}{\partial r}(r v_r) + \frac{1}{r} \frac{\partial v_\theta}{\partial \theta} + \frac{\partial v_z}{\partial z}$$

2.4 RELATIONSHIP BETWEEN VOLUMETRIC FLOW RATE AND PRESSURE GRADIENT

The volume flow in a circular pipe is given by

$$Q = \int_0^R v_z \, dA = \int_0^R v_z \, 2\pi r \, dr \qquad [2.9]$$

Eq. 2.9 is obtained from the exact solution for laminar fully developed pipe flow. The laminar distribution is called the Hagen-Poisuille flow to commemomerate the experimental work by G. Hagen in 1839 and J. L. Poiseuille in 1940 (White, 1999, p. 341).

For the laminar flow of an incompressible, constant fluid property fluid in a fully developed region of a circular pipe, the velocity profile can be readily determined through (Incropera and DeWitt, 1996, p.391):-

$$V(r) = -\frac{1}{4\mu}\left(\frac{dP}{dz}\right)R^2\left[1-\left(\frac{r}{R}\right)^2\right] \qquad [2.10]$$

From Eq. 2.10, the pressure gradient must always be negative. Hence, the fully developed velocity profile is parabolic. This statement is also justified by Schmidt and Zeldin (1969). Schmidt and Zeldin cited that the cross section of the tube and duct was considered to be composed of two regions; a boundary layer developing near the wall and an inviscid fluid core. A parabolic velocity distribution was assumed in the boundary layer. The velocity profile would be slightly different form the profile obtained by Eq. 2.10 if the fluid properties are not constant. Deissler *et al.* (1951) cited that the variation of oil density, thermal conductivity and viscosity with temperature will have effect on the velocity profile.

2.5 HEAT TRANSFER CORRELATIONS IN A CIRCULAR PIPE

For a cylindrical pipe with length very large compared to the diameter, it may be assumed that the heat flows only in a radial direction. As such the heat transfer in the radial direction is given by Fourier's law of heat conduction.

$$q = -kA\frac{dT}{dr} \qquad [2.11]$$

The amount of heat transfer, q is related to the overall heat transfer coefficient, U and is given by

$$q = UA\Delta T \qquad [2.12]$$

Substituting Eq. 2.12 into Eq. 2.11 yields

$$U\,A\,\Delta T \;=\; -k\,A\frac{dT}{dr} \qquad [2.13]$$

$$U\left(T_w - T_a\right) = -\,k\frac{dT}{dr} \qquad [2.14]$$

In the analysis, the convection heat transfer is also considered. The equation related to heat convection is given by Eq. 2.15.

$$q = \dot{m}\,C_p\,\frac{dT}{dz} \qquad [2.15]$$

where $\dot{m} = \rho Q$. Substituting this expression into Eq. 2.15 yields

$$q = \rho Q C_p \frac{dT}{dz} \qquad [2.16]$$

$$U\left(T_w - T_a\right)2\pi R = QC_p\rho\frac{dT}{dz} \qquad [2.17]$$

The value of U can also be obtained using the following equation :-

$$\frac{1}{U} = \frac{1}{h_{Oil}} + \frac{r_1}{k_{Pipe}}\ln\frac{r_1 + r_2}{r_1} + \frac{r_1}{k_{Soil}}\ln\frac{r_1 + r_2 + r_3}{r_1 + r_2} + \frac{r_1}{r_1 + r_2 + r_3}\frac{1}{h_\infty} \qquad [2.18]$$

where r_1 = Pipe radius

r_2 = Pipe thickness

r_3 = Buried depth

This expression is a function of inside crude oil heat transfer coefficient (h_{oil}), outside heat transfer coefficient (h_∞), thermal conductivity of the pipe (k_{Pipe}), thermal conductivity of the soil (k_{Soil}), the pipe radius (r_1), the pipe thickness (r_2) and the buried depth (r_3). This expression is derived base on one-dimensional, steadsy state conduction for a cylindrical wall (Incropera and DeWitt, 1996, p.92). The outside heat transfer coefficient (h_∞) values will differ for different surroundings such as for seawater, soil and air.

2.6 THE MEAN TEMPERATURE

The mean or bulk temperature of the fluid is defined in terms of the thermal energy transported by the fluid as it moves past the cross section. In this analysis, the velocity, temperature and pressure gradient will be evaluated at the mean or bulk temperature.

The mean temperature is defined as

$$T_m = \frac{\int_{A_c} \rho V C_v T \, dA_c}{\dot{m} C_v} \qquad [2.19]$$

For incompressible flow in a circular pipe, the value of C_v is constant (Incropera and DeWitt, 1996, p.394). By taking this assumption into account, Eq. 2.18 can be simplified into

$$T_m = \frac{1}{Q}\int_0^R T(r) v_r(r) 2\pi r \, dr \qquad [2.20]$$

CHAPTER 3

METHODOLOGY

3.1 MODELING OF HIGH VISCOUS FLUID

Purpose	: To derive a set of equations for the analysis of high viscous fluid flow transport model
Tools / Equipments	: *Mathematica v5.0* (Theoretical equations)

The basic transport equations will be used to model the transportation of high viscous fluid. A set of governing equation for steady state high viscous fluid flow with heat transfer will be established using the continuity, momentum and energy equation given in Eqs. 2.3, 2.4 and 2.5 respectively.

Basically, the transport equations which consist of non linear partial differential equations will be reduced to non linear, ordinary partial differential equations by making necessary assumptions. A set of theoretical procedures consists of governing equations describing a high viscous model will be established.

3.2 MATHEMATICAL MODELING

Purpose	: To model the pipeline pressure gradient for high viscous fluid using conventional steady state, one-dimensional pipeline simulation tool
Tools / Equipments	: *PIPEPHASE v7.41*

The PIPEPHASE simulation tool will be used to model and simulate the pipeline pressure gradient for the high viscous fluid. All the required input parameters to the model must be gathered prior to the simulation. The results from the simulation using PIPEPHASE will be compared to the results obtained from the flow model, developed from the mathematical model. Some comparisons between these two models will be highlighted.

PIPEPHASE has been identified as the simulation tool because of its capability to model steady state multiphase flow in oil pipeline systems. It also covers the complete range of fluids in the petroleum industry, including single phase or black oil. Since oil has been identified as the high viscous fluid of interest, PIPEPHASE would be an essential tool. The software was also chosen because it's easily accessible in PETRONAS Research and Scientific Services (PRSS).

The pipeline system that will be used in the simulation is a typical pipeline system in Sudan. A section of the 1505 km pipeline will be considered in the simulation work. The pipeline operator is Greater Nile Petroleum Operating Co. (GNPOC). The section of the pipeline considered is a buried pipeline with ambient temperature of $32°C$.

3.3 DEVELOPMENT OF VISCOSITY CORRELATION

Purpose : To develop a set of viscosity as a function of temperature correlation using experimental data

Tools / Equipments : Haake Rotational Viscometer and Microsoft Excel

The viscosity of the *Dulang D 8-L* crude oil sample was determined using the Haake Rotational Viscometer as shown in Figure 3.1. The test was conducted in PETRONAS Research and Scientific Services and the experimental data was used in developing the correlation.

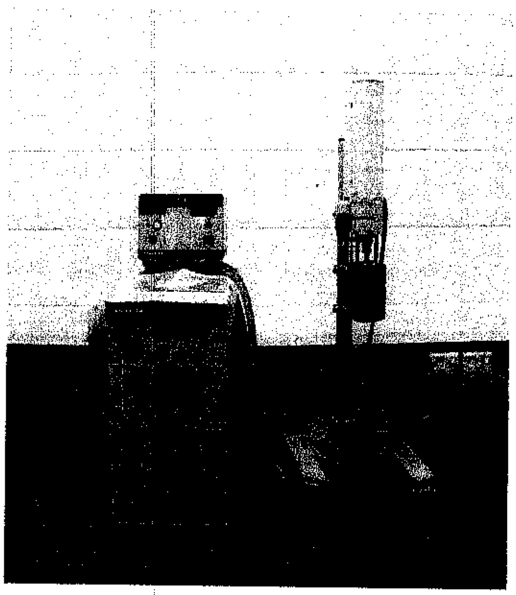

Figure 3.1 : Haake Rotational Viscometer

The viscosity as a function of temperature correlation will be used to assist the modeling of the high viscous fluid. Since viscosity is one of the main parameter of studies in the project, the experimental data will yield a more accurate prediction. The viscosity as a function of temperature correlations were developed using Microsoft Excel based on the experimental data. The temperature range was discretized into four different segments to minimize the error in predicting the viscosity. The correlation developed is further described in Section 4.3.

3.4 COMPOSITIONAL ANALYSIS OF FLUID

Purpose	: To obtain the compositional of the Dulang D 8-L crude oil sample
Tools / Equipments	: High Temeprature Gas Chromatograph

The hydrocarbon distribution of crude oil can be determined by conduction a compositional analysis using chromatography. Chromatography is a physical separation method in which components to be separated are distributed between two phases; one constituting a stationary bed, the other being a fluid that percolates through or along the stationary bed. The separation process occurs as a result of repeated sorption-desorption acts during the movement of the sample components along the stationary bed, the separation is due to differences in the distribution coefficients of the individual sample components.

Gas chromatography is a type of chromatography that employs gas as a mobile phase. The mobile phase or carrier gas, which in under pressure, moves a vaporized sample from the injection port through a stationary phase to a detector where the ionized sample produces electrical signals, normally measured by an integrator and recorded as a strip chart or chromatogram. The analysis is usually conducted at high temperature and it is termed high temperature gas chromatography (HTGC).

The analysis was conducted in PETRONAS Research. The high temperature high gas chromatography (HTGC) analysis was performed using Hewlett Packard 5890

Series II Plus gas chromatograph. The instrument is equipped with 25m aluminium clad capillary column coated with HT-5 liquid film (SGE column). Figure 3.2 shows the Hewlett Packard 5890 Series II Plus gas chromatograph.

Test Conditions

The HTGC equipment must be set into certain conditions before execution. Table 3.1 summarizes the test conditions for the HTGC analysis for high viscous crude.

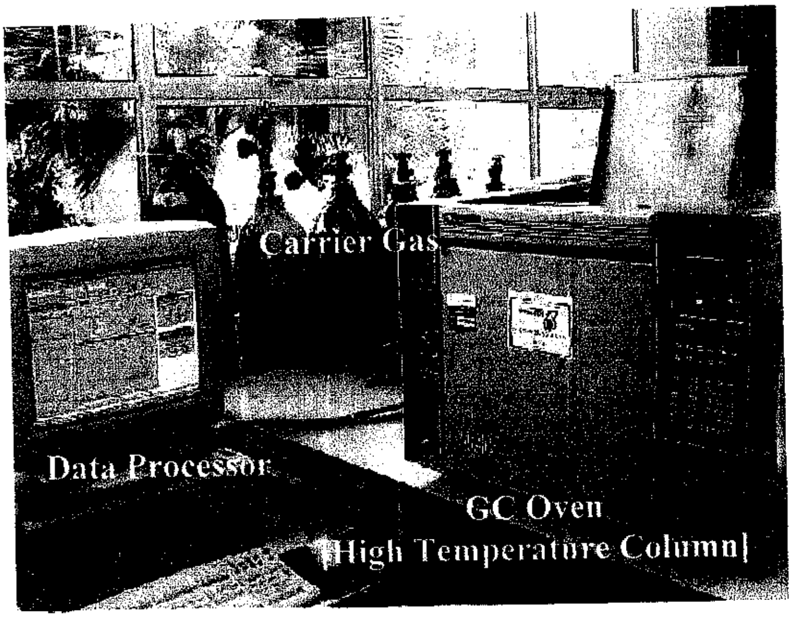

Figure 3.2 : Hewlett Packard 5890 Series II Plus gas chromatograph equipment

Table 2.1 **:** HTGC analysis test conditions

Injection Port Temperature	400 °C
Detector Temperature	400 °C
Initial Oven Temperature	70 °C
Initial Hold Time	2 min
Final Oven Temperature	400 °C
Final Hold Time	50 min
Programmed Rate	8 $^{\circ}C/_{min}$
Carrier Gas	Helium
Flow Rate	2 $^{mL}/_{min}$
Split Ratio	20 : 1

The results obtained will be used as an input parameter to generate compositional properties that will be used at the later phase of the modeling of the high viscous model.

3.5 GENERATION OF *LOOK-UP* TABLES

Purpose	: To generate a compositional properties "look-up" table from the standard compositional analysis
Tools / Equipments	: *WAX v1.0.0*

The WAX v1.0.0 is a computer program developed by PRSS together with University of Tulsa (TU) for the prediction of paraffin deposition during single-phase and two-phase gas-oil flow in horizontal and near horizontal flowlines and vertical wellbores.

The program is modular in structure and assumes a steady state, one-dimensional flow, and conservation of energy principal. The program performs paraffin deposition prediction during multiphase flow in pipelines and wellbores This is accomplished by coupling or integrating two-phase flow hydrodynamics, solid-liquid-vapor thermodynamics and two-phase flow heat transfer and flow pattern dependent paraffin deposition into one modular program.

Using the results from the standard compositional analysis as an input, the program will generate look-up tables. These look-up tables consist of compositional properties for the fluid at different temperature and pressure range. These look-up tables will be used in the fluid properties generator to determine the fluid properties of the fluid at the desired temperature and pressure. Figure 3.3 shows the Paraffin Deposition Model user interface.

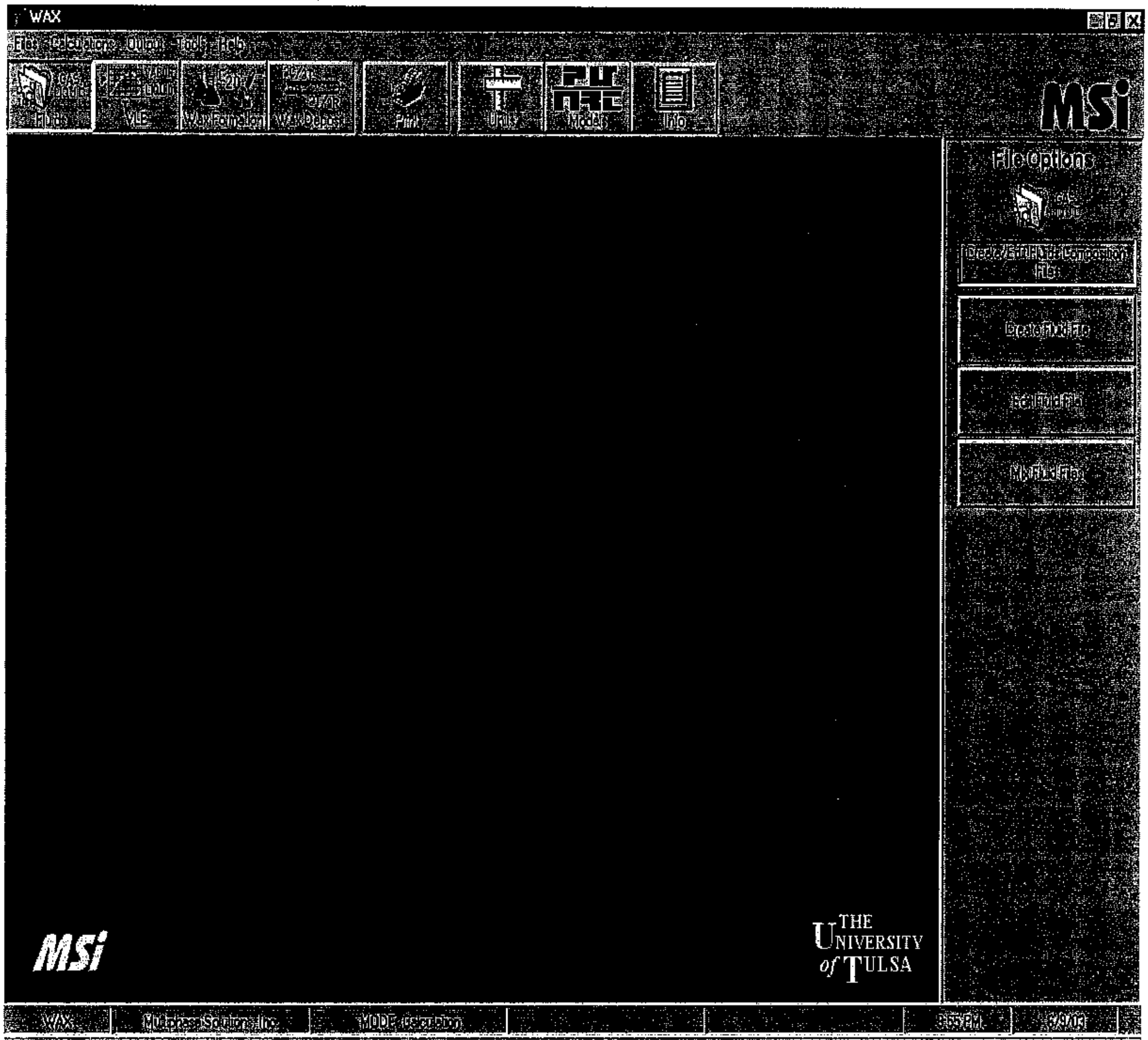

Figure 3.3 : The paraffin deposition model user interface

3.6 SOLUTION ALGORTIHM FOR THE MATHEMATICAL MODEL

Purpose	: To build a solution algorithm to solve the mathematical model
Tools / Equipments	: FORTRAN 90 Programming Language

A solution algorithm will be build to solve the non linear, partial differential equations established in the mathematical modeling phase. The algorithm will solve equations in an iterative manner to calculate the desired results.

FORTRAN 90/95 has been chosen as it has been identified as a powerful programming language in the field of engineering and applied science. FORTRAN programs usually execute faster because of its built-in array features and its powerful intrinsic functions, and because C/C++ pointers inhibit optimization within loops. FORTRAN 90/95 also has better support for parallel or multi-processor architectures, a feature of increasing practical importance in reducing progmming time.

3.7 VALIDATION OF FLUID FLOW MODEL

Purpose : To validate the modeling results with theory

Tools / Equipments : *Not applicable* (Theoretical formulas)

The flow model will be tested on typical pipeline systems transporting high viscous fluids. The results from the fluid model will be compared with the results obtained from PIPEPHASE. The results from both the models will then be compared and validated via theoretical calculations. This will assist in guiding towards correct modeling steps and yield more accurate results.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 MODELING OF HIGH VISCOUS FLUID

4.1.1 Model Requirement

The modeling of the high viscous fluid was performed using PIPEPHASE. All the input pressure and temperature parameters as well as fluid properties required are shown in Table 4.1. Table 4.2 and Table 4.3 show the pipeline profile and the heat transfer properties used to perform the simulation.

Table 4.1 : Input parameters required to perform the steady state simulation with PIPEPHASE.

PVT	
Fluid Properties	
Liquid Gravity	36.600 *API*
Heat Capacity	0.449 $BTU/lb \cdot F$
Gas-oil-ratio (GOR)	677.59 ft^3/bbl
Watercut	0 %
Viscosity (Point 1)	
Temperature	28.0 °*C*
Viscosity	7.0 *cP*
Viscosity (Point 2)	
Temperature	80.0 °*C*
Viscosity	383.3 *cP*

Table 4.2 : Pipeline properties used in the simulation.

PIPELINE DATA	
Length	250.0 *km*
Elevation Change	0 *km*
Inside Diameter	689.76 *mm*
Pipe Inside Roughness	0.0257 *mm*

Table 4.3 : Heat transfer properties used in the simulation.

Heat Transfer Data	
Ambient Temperature	32 $°C$
Soil Thermal Conductivity	1.5 $W/m \cdot °C$
Pipe Thermal conductivity	50 $W/m \cdot °C$
Pipe Thickness	10.72 mm
Buried Depth	1000 m

4.1.2 Modeling Parameters

The pipeline used in the modeling of the high viscous fluid is a typical pipeline system in Khartoum North, Sudan. The total pipeline length is $1505\,km$. The pipeline considered in the simulation and modeling work consists of only a section of the entire pipeline with a length of $250\,km$. The section of the pipeline is a buried pipeline with a depth of $1000\,m$. The critical Reynolds number is set to be at 2100.

The PIPEPHASE simulation was performed by varying the flow rate of the crude oil. The flow rates used in the simulation were :-

- ☑ $5000\, m^3/day$
- ☑ $10000\, m^3/day$
- ☑ $15000\, m^3/day$
- ☑ $20000\, m^3/day$
- ☑ $25000\, m^3/day$

The export temperature for the oil is set to be at $80\,°C$ and the outlet pressure is set to be at $100\,psia$. The ambient temperature of the soil is $32\,°C$ for all simulations.

4.1.3 Results Analysis

Table 4.4 shows the pressures required to flow the crude oil at different flow rates. As the flow rate increases, the required export pressure also shows a significant increase. Similarly, the arrival temperature of the crude oil at the sink increases with increase in the flow rate. As the crude oil flows at a high velocity, the cooling effect occurs at a relatively low rate. As a result, the temperature recorded at the sink is higher.

Table 4.4 : Required export pressures and arrival temperature at different flow rates

Flow Rate, $Q\left(m^3/day\right)$	Required Export Pressure		Arrival Temperature, $T\ (°C)$
	$P(psig)$	$P(kPa)$	
5000	170.604	1176.27	32.0
10000	228.804	1577.54	32.2
15000	289.904	1998.81	33.4
20000	415.704	2866.17	36.3
25000	572.504	3947.26	37.3

Besides the effect export pressure and arrival temperature, the transition between laminar and turbulent flow is also affected at different flow rate. As shown in Table 4.5, the transition point occurs at 26.396 m measured from the entrance of the pipeline at a flow rate of $5000\,m^3/day$. As the velocity of the crude oil increases, the length required for the flow to change from turbulent to laminar is longer. However, at a flow rate of $25000\,m^3/day$ the flow remains turbulent throughout the pipeline.

Table 4.5 : The occurrence transition at $N_{RE} = 2100$

Flow Rate, $Q\left(m^3/day\right)$	Transition Point (km) (Reynolds Number, $N_{RE} = 2100$)
5000	26.396
10000	67.055
15000	129.094
20000	221.218
25000	No transition

TEMPERATURE PROFILE

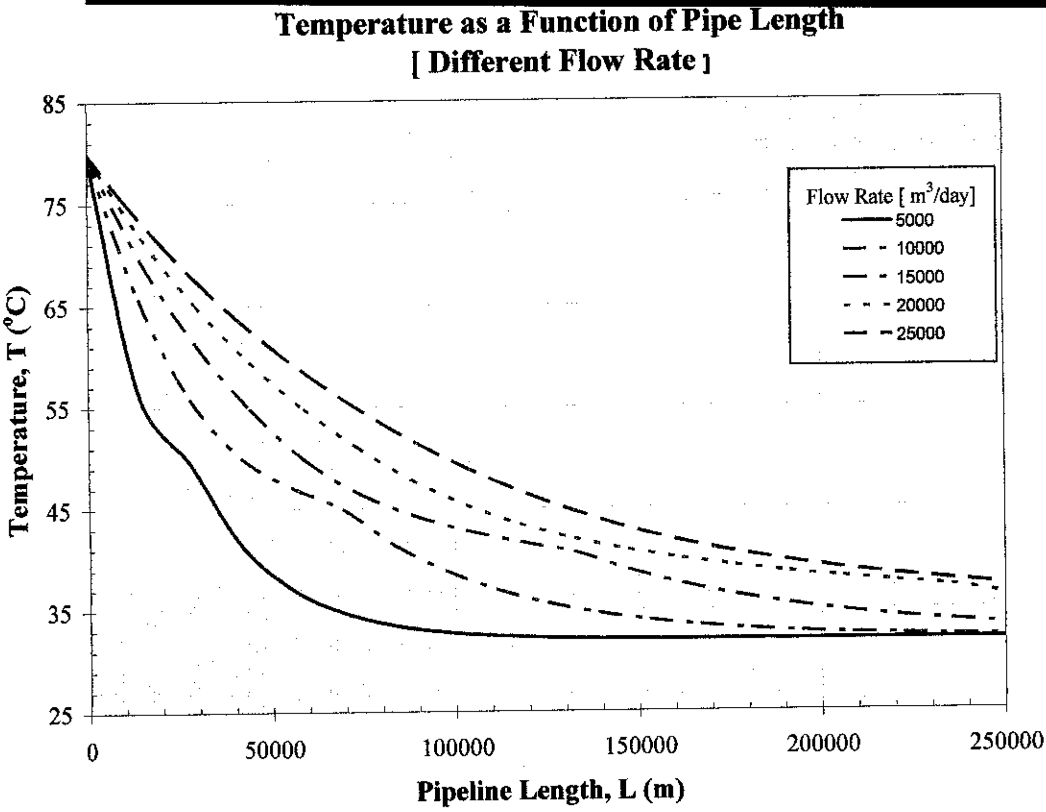

Figure 4.1 : Temperature profile of the entire system.

PRESSURE PROFILE

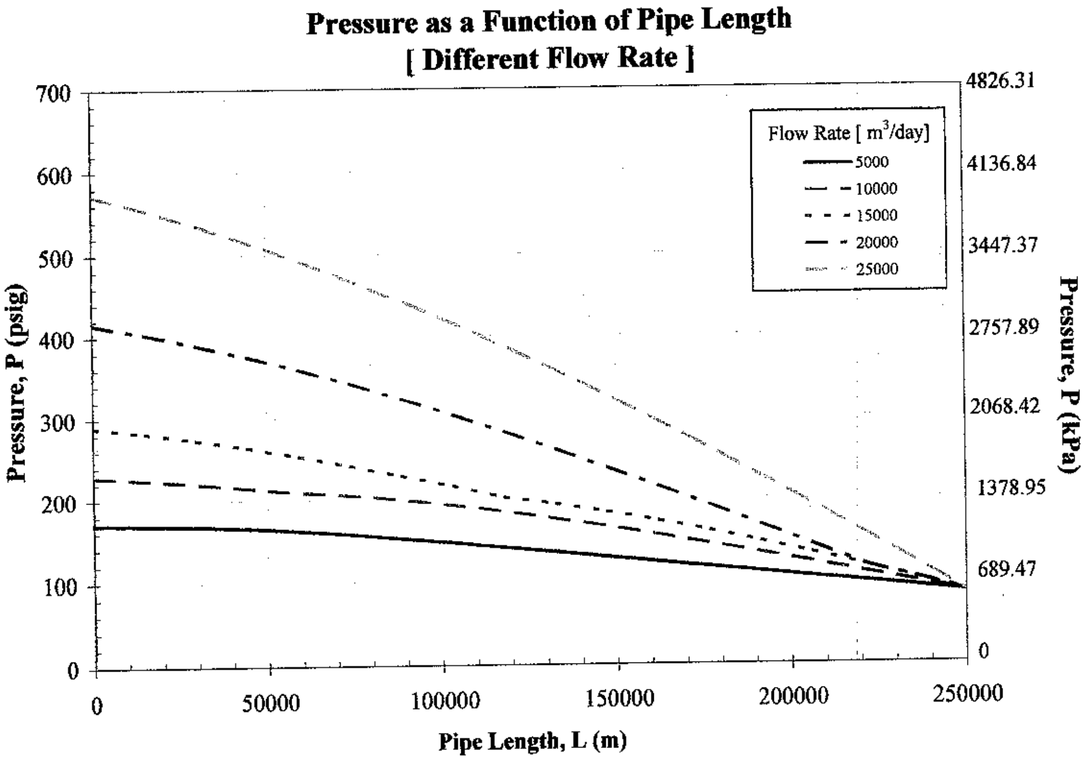

Figure 4.2 : Pressure profile of the entire system.

The temperature profile for entire system at different flow rates is shown in Figure 4.1. The temperature drops significantly with an increase in the pipeline length. At low flow rate, the temperature curve is rather flat as compared to those at higher flow rate. This might be due to the occurrence of the transitional flow between the turbulent and laminar region. The temperature remains constant at the laminar region. A similar trend is observed in the pressure profile of the system as shown in Figure 4.2. The pressure curve is rather flat at flow rate of $5000\, {m^3}/{day}$. However, as the flow rate increases, the steepness of these curves increases.

TEMPERATURE PROFILE

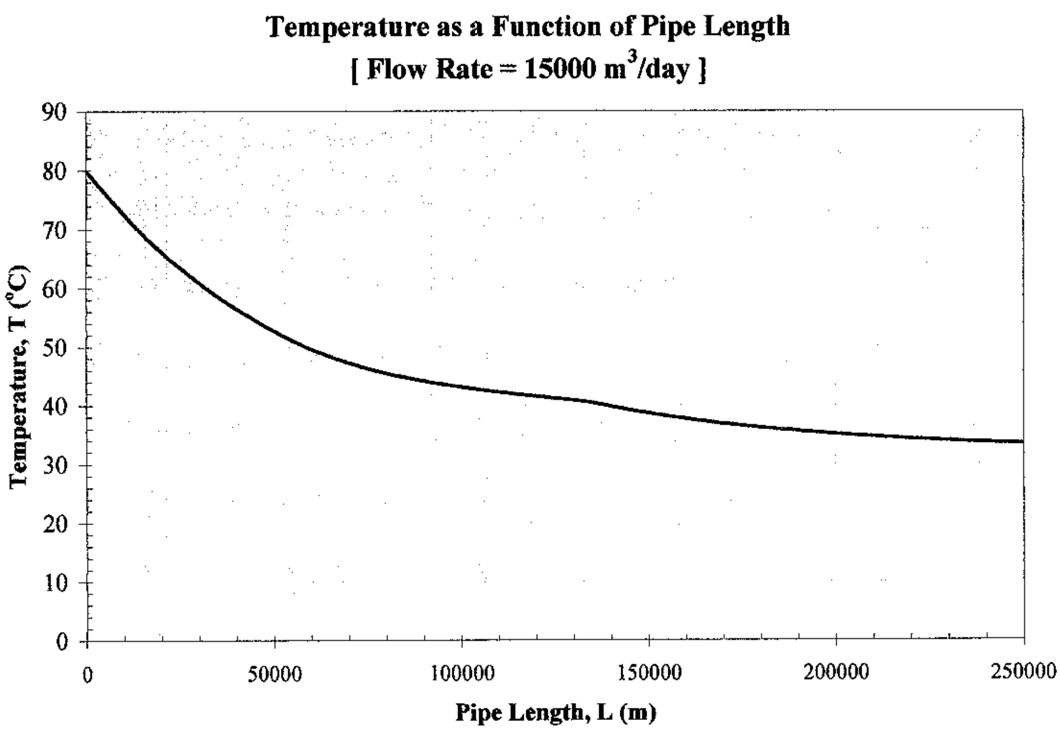

Figure 4.3 : Temperature profile at flow rate of $15000\, {m^3}/{day}$

Figure 4.3 and Figure 4.4 are the temperature and pressure profiles for the pipeline system at a flow rate of $15000\, {m^3}/{day}$. These profiles are extracted from Figure 4.1 and Figure 4.2 respectively for analysis. Both the temperature and pressure decreases as the length of the pipeline increases. In Figure 4.3 and Figure 4.4, the effect of transition between turbulent and laminar flow causes a slight kink in both these curves.

PRESSURE PROFILE

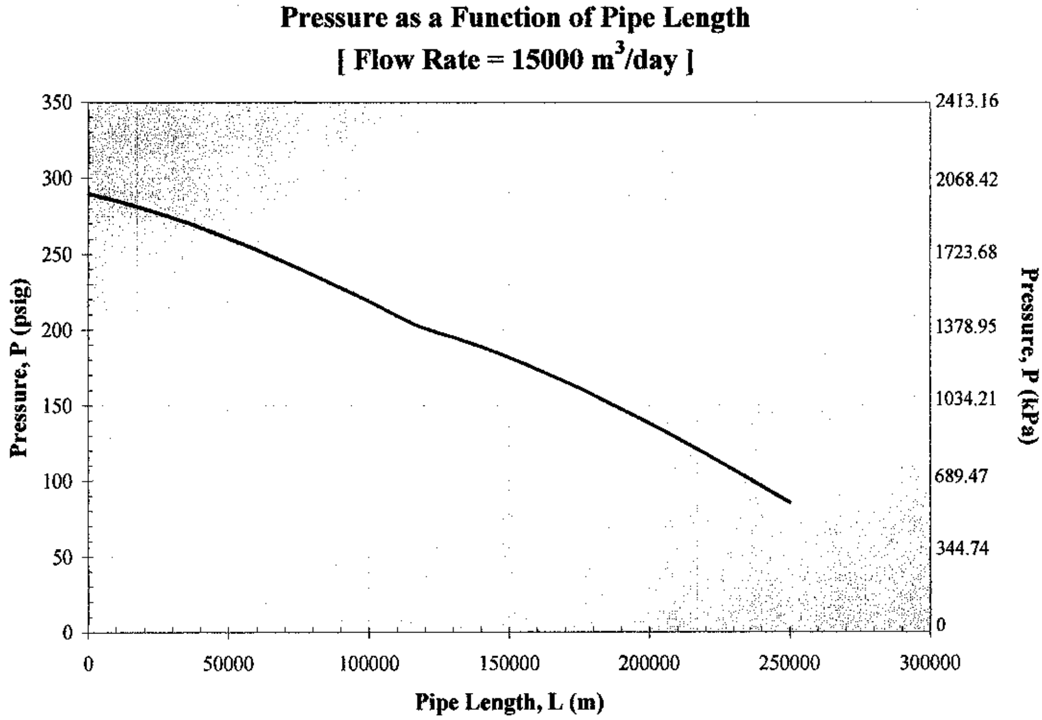

Figure 4.4 : Pressure profile at flow rate of 15000 m^3/day

REYNOLDS NUMBER, N_{RE} PLOT

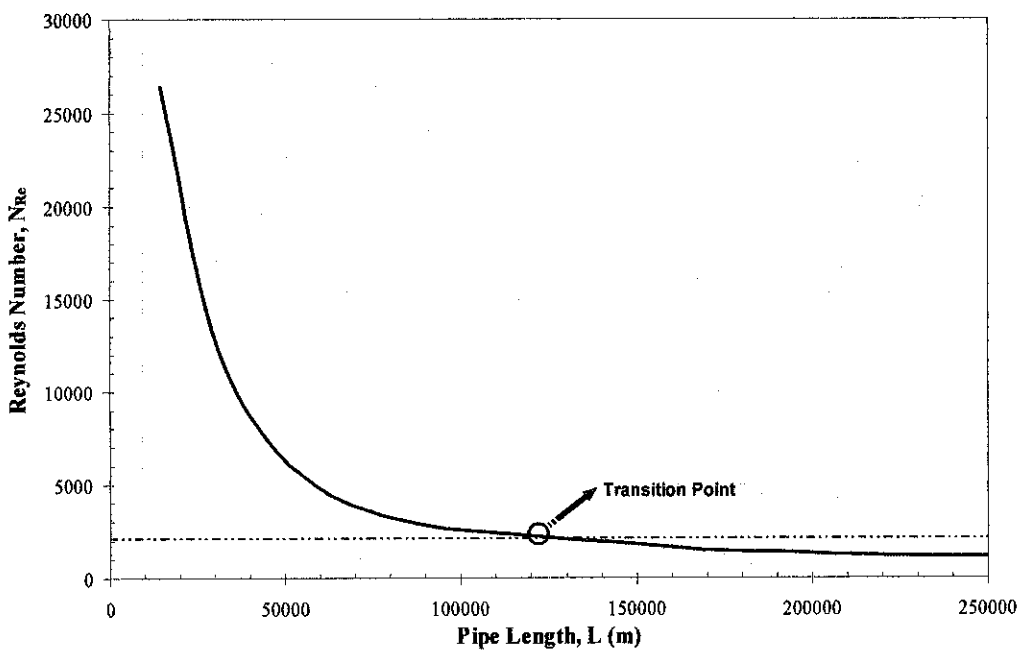

Figure 4.5 : Reynolds number plot at flow rate of 15000 m^3/day

The transition point occurs at 129.094 km measured from the entrance of the pipeline. The Reynolds number plot at the flow rate of $15000 \, {m^3}/{day}$ is shown in Figure 4.5. Figure 4.6 shows the viscosity profile of the crude oil as a function of temperature. The viscosity of the crude oil is strongly dependent on the temperature parameter. At relatively high temperature, the viscosity is relatively low. However, if the temperature drops drastically, the viscosity increases significantly.

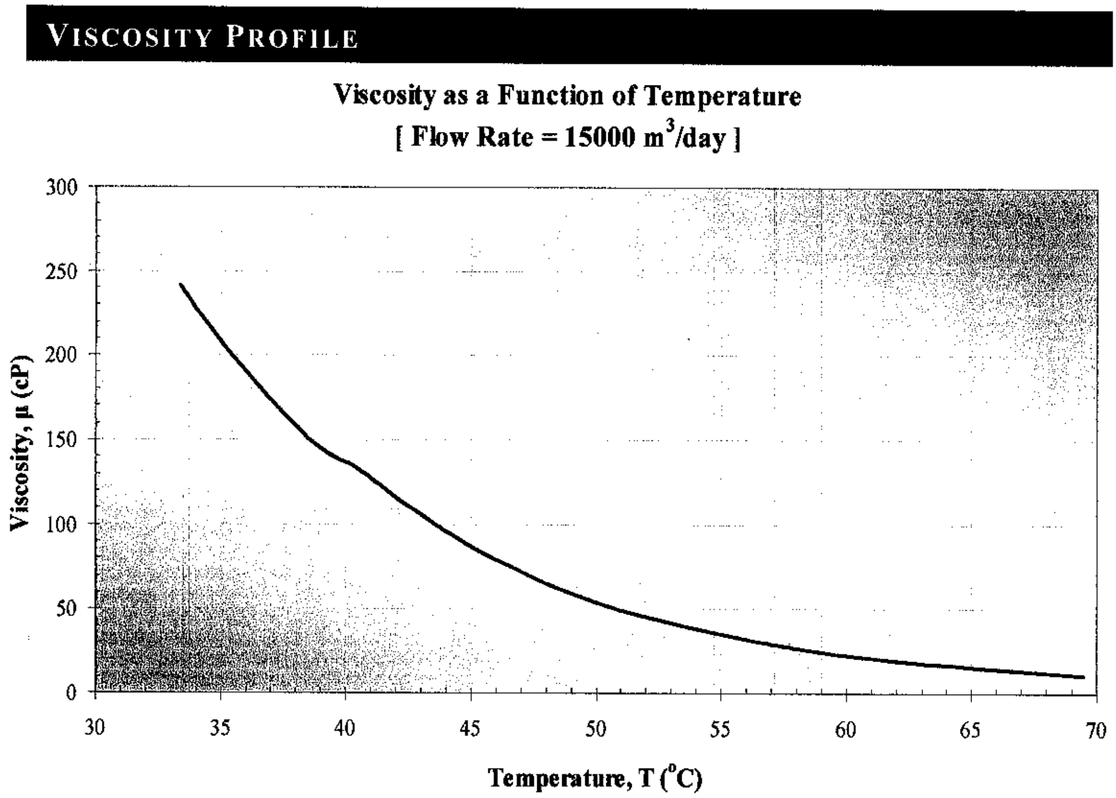

Figure 4.6 : Viscosity profile at flow rate of $15000 \, {m^3}/{day}$

Besides the viscosity profile, the form of the velocity profile for the laminar flow of an incompressible, constant property fluid in the fully developed region of a circular tube can also be determined. The velocity profile can be developed using Eq. 2.10. The velocity as a function of pipe radius is shown in Figure 4.7. In Figure 4.7, the fully developed velocity profile is parabolic. At the surface of the tube or at the pipe wall, the velocity is zero due to no-slip condition.

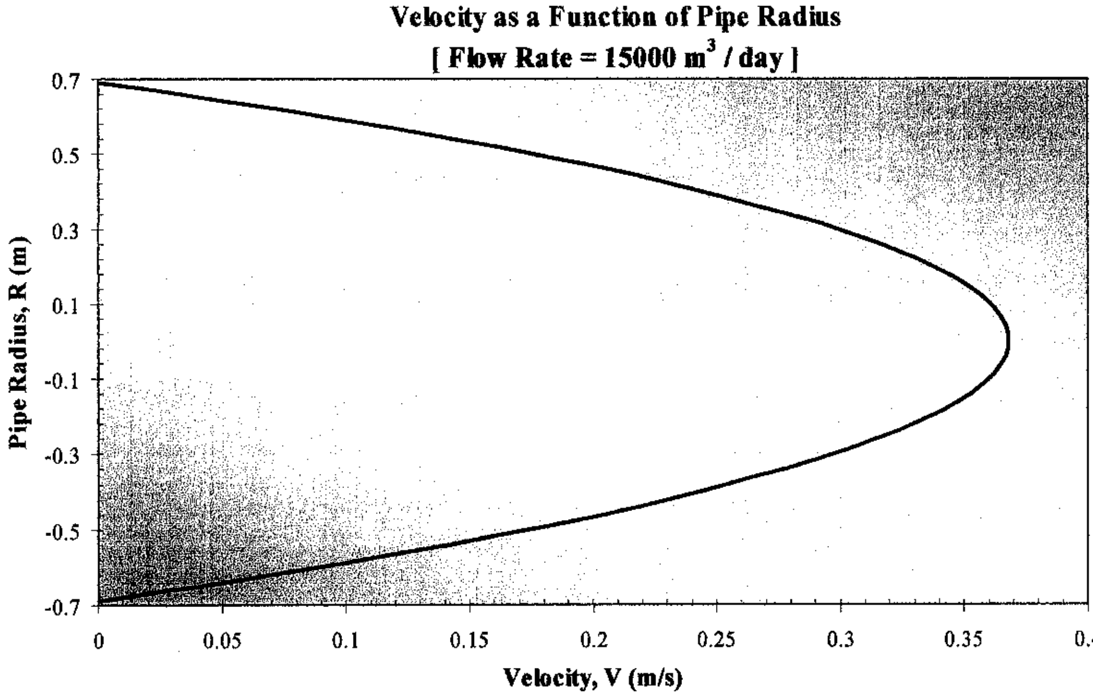

Figure 4.7 : Velocity profile at flow rate of $15000\, {m^3}/{day}$

APPENDIX B shows the numerical results obtained from the modeling of high viscous fluid with *PIPEPHASE v7.41*.

4.2 MATHEMATICAL MODELING

4.2.1 Continuity Equation

The continuity equation for cylindrical coordinates is given in Eq. 2.3. Assuming the azimuthal and radial velocity to be zero, Eq. 2.3 can be simplified into

$$\frac{\partial}{\partial z}(\rho v_z)=0 \qquad [4.1]$$

For a fluid with constant density, the density gradient is assumed to be negligible at any given point in the pipeline. With this assumption, Eq. 4.1 can be further reduced into

$$\frac{\partial v_z}{\partial z}=0 \qquad [4.2]$$

In most engineering applications, the assumptions of constant density results in considerable simplification and very little error.

4.2.2 Momentum Equation

The same assumptions for continuity equation also apply for the momentum equation. For horizontal pipeline, $g_z = 0$. Substituting Eq. 4.2 into Eq. 2.4 would yield

$$\frac{\partial P}{dz} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\left[\mu(r)\frac{\partial v_z}{\partial r} \right] \right) \quad [4.3]$$

The viscosity, μ term in Eq. 4.3 is defined as a function of radial coordinate, r.

4.2.3 Energy Equation

For the energy equation, heat conduction in the z-direction is much smaller than heat convection. Therefore, the term $\frac{\partial^2 T}{\partial z^2}$ can be considered negligible (Bird, Steward and Lightfoot, 2002, p. 342). By applying the same assumptions as those for the continuity and momentum equation, Eq. 2.5 can be simplified to

$$\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r} \right) = \frac{r\rho C_p}{k}\frac{\partial T}{\partial z} v_z(r) \quad [4.4a]$$

The velocity, v_z in Eq. 4.4 is defined as a function of radial coordinate, r. Eq. 4.4 can be further simplified into

$$\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r} \right) = \frac{r}{\alpha}\frac{\partial T}{\partial z} v_z(r) \quad [4.4b]$$

The term α in Eq. 9 is the liquid diffusivity and is defined as

$$\alpha = \frac{k}{\rho C_p} \quad [4.4c]$$

In Eq. 4.4c, k is the thermal conductivity of oil and C_p is the isobaric heat capacity of oil.

4.2.4 Flow in the Fully Developed Laminar Region

By assuming that the axial pressure gradient $\frac{dP}{dz}$ to be independent of radial position, Eq. 4.3 can be integrated in to

$$\frac{dv_z}{dr} = \frac{1}{2}\frac{dP}{dz}\frac{r}{\mu(r)} \qquad [4.5]$$

Although the viscosity is a function of pressure and temperature, Strand and Djuve (2000) have suggested that it is conveniently and sufficiently accurate to express this as a function of radial coordinate, r as

$$\mu(r) = \frac{\mu_o - \mu_m}{R^2} C_1 (r)^3 + \mu_m \qquad [4.6]$$

where

μ_o = Viscosity at the at the wall of the pipe

μ_m = Viscosity in the center of the pipe

C_1 = Constant

R = Radius of the pipe

Substitution of Eq. 4.6 into Eq. 4.5 can be integrated to

$$v_z = \frac{1}{2}\frac{dP}{dz}\left(\arctan \frac{\left[-A^{1/3} + 2B^{1/3} r\right]}{\sqrt{3} A^{2/3} B^{1/3}} - \frac{\ln\left[B^{1/3} + A^{1/3} r\right]}{3A^{2/3} B^{1/3}} + \frac{\ln\left[B^{2/3} - A^{1/3} + A^{2/3} r\right]}{6A^{2/3} B^{1/3}} \right) \qquad [4.7]$$

Defining V as axial velocity divided by pressure gradient

$$v_z = V \frac{dP}{dz} \qquad [4.8]$$

Substituting Eq. 4.8 into Eq. 4.7 would yield

$$V(r)=\frac{1}{2}\left[\arctan\frac{\left[-A^{1/3}+2B^{1/3}r\right]}{\sqrt{3}A^{2/3}B^{1/3}}-\frac{\ln\left[B^{1/3}+A^{1/3}r\right]}{3A^{2/3}B^{1/3}}+\frac{\ln\left[B^{2/3}-A^{1/3}+A^{2/3}r\right]}{6A^{2/3}B^{1/3}}\right] \qquad [4.9]$$

where $A=\frac{\mu_o-\mu_m}{R^2}C_1$ and $B=\mu_m$.

A typical viscosity profile based on Eq. 4.6 has been plotted, assuming the values of the pipeline wall viscosity, μ_o, center viscosity, μ_m and constant, C_1. The typical viscosity profile is shown in Figure 4.8.

VISCOSITY PROFILE [STRAND & DJUVE]

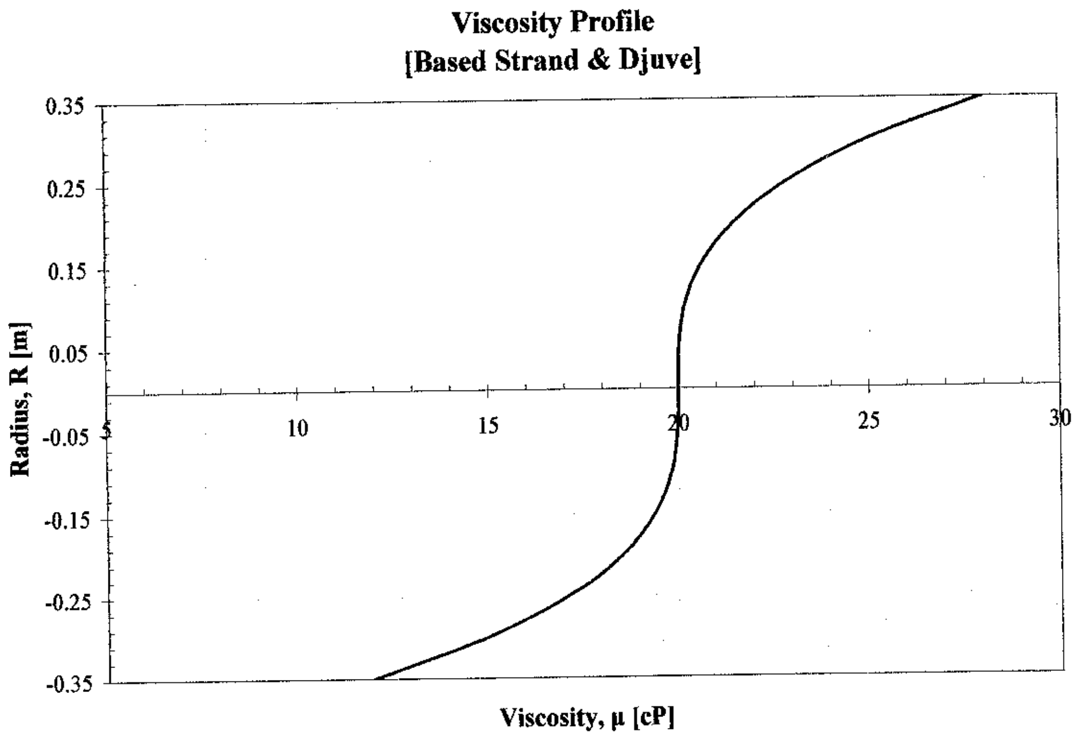

Figure 4.8 : Viscosity profile represented by Strand and Djuve equation.

The profile was generated using Microsoft Excel and the trial-and-error method was used by altering the values of the pipeline wall viscosity, μ_o, center viscosity, μ_m and constant, C_1 respectively.

This profile, however does not truly reflect the viscosity in the radial direction of the system. This is because the wall viscosity is not the same at the wall on both extreme. A smooth parabolic profile, similar to the velocity profile but in reflected direction is anticipated. As such, the equation suggested by Strand and Djuve (2000) does not really represent the viscosity profile in the radial direction. A slight modification was done on the equation. Based on trial-and-error, it was found that the incremental radius, r raised to the power of three (3) constitutes to the discrepancy in the profile. Through trial-and -error, it was found that the power is supposed to be two (2) rather than three (3). As such, the modified Strand and Djuve (2000) is as follow :-

$$\mu(r) = \frac{\mu_o - \mu_m}{R^2} C_1 (r)^2 + \mu_m \qquad [4.10]$$

The viscosity profile represented by the modified Strand and Djuve is shown in Figure 4.9.

VISCOSITY PROFILE [MODIFIED STRAND & DJUVE]

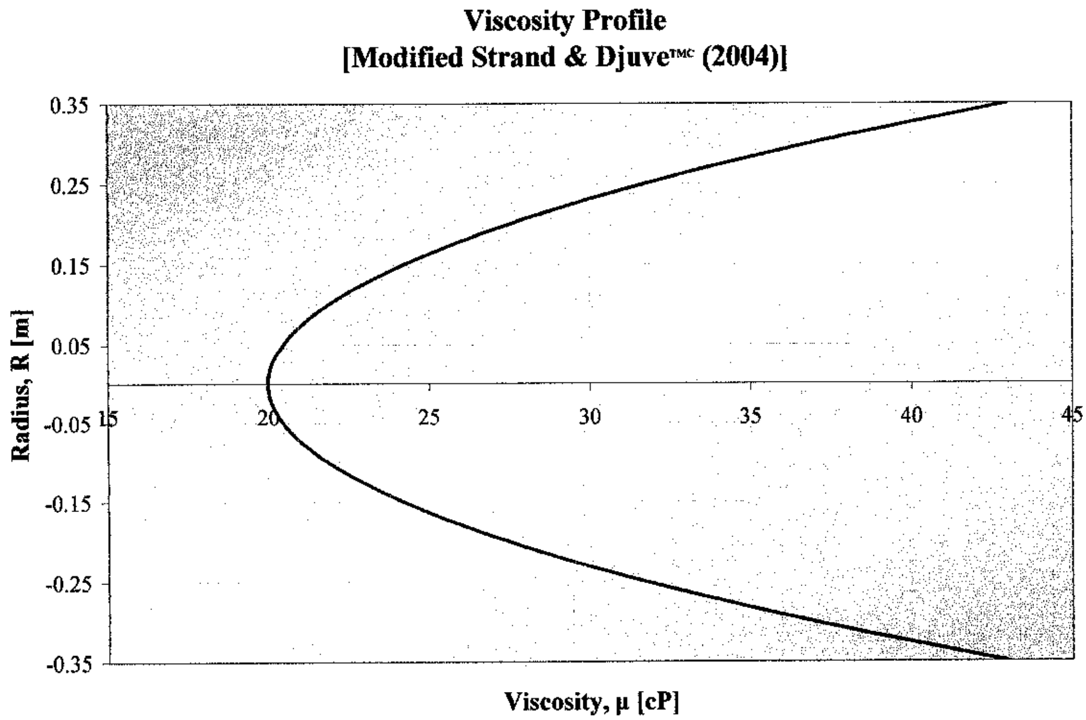

Figure 4.9 : Viscosity profile represented by modified Strand and Djuve equation.

4.2.5 Correction on the Mathematical Model

A correction on the mathematical model was done due to the discrepancy in the Strand & Djuve (2000) correlation. The modified Strand & Djuve (2004) correlation is represented in Eq. 4.10.

Eq 4.7 and Eq. 4.9 are no longer valid due to discrepancy. Substituting Eq. 4.10 into Eq. 4.6 yields

$$V(r) = \frac{1}{2}\frac{dP}{dz}\frac{\ln\left[B + Ar^2\right]}{2A} \qquad [4.11]$$

where $A = \frac{\mu_o - \mu_m}{R^2}C_1$ and $B = \mu_m$.

The velocity profile divided by pressure gradient according to Strand and Djuve (2000) may be parameterized as

$$V(r) = C_2\left(\cos\left[\frac{r}{C_3}\right] + C_4\right) \qquad [4.12]$$

Substitution of Eq. 4.12 in to Eq. 4.4b can be integrated to

$$\frac{dT}{dr} = \frac{1}{r}\left[\frac{1}{\alpha}\frac{dT}{dz}\frac{dP}{dz}C_2\left(C_3 r\sin\left[\frac{r}{C_3}\right] + C_3^{\,2}\cos\left[\frac{r}{C_3}\right] + \frac{1}{2}r^2C_4\right)\right] \qquad [4.13]$$

Eq. 4.13 can be further integrated to yield

$$T(r) = \frac{1}{\alpha}\frac{dT}{dz}\frac{dP}{dz}C_2\left(-C_3^{\,2}\cos\left[\frac{r}{C_3}\right] + C_3^{\,2}\int_0^{r/C_3}\frac{\cos(t)}{t}dt + \frac{1}{2}r^2C_4\right) \qquad [4.14]$$

Up to this point, the governing equations for the pressure-temperature gradient as well as the viscosity correlation for the viscosity profile have been developed. These equations will be solved simultaneously with the partial differential equations for flow in a fully developed laminar region. **APPENDIX A** provides the complete derivation of the mathematical model.

4.3 VISCOSITY AS A FUNCTION OF TEMERATURE CORRELATION

The viscosity of the *Dulang D 8-L* crude was obtained by conducting an experiment using the *Haake Viscometer.* The test was conducted at a shear rate of $100s^{-1}$ to simulate a laminar flow condition. The experiment was conducted at a temperature range of 10°C to 85°C. The low temperature, generally assembles the seabed condition while the reservoir pressure is represented by the high temperature.

The viscosity profile of the *Dulang D 8-L* crude is shown in Figure 4.10. As shown, the viscosity of the crude decreases as the temperature increases. The viscosity profile will be used to assist in the modeling of the high viscous fluid.

VISCOSITY PROFILE [EXPERIMENTAL DATA]

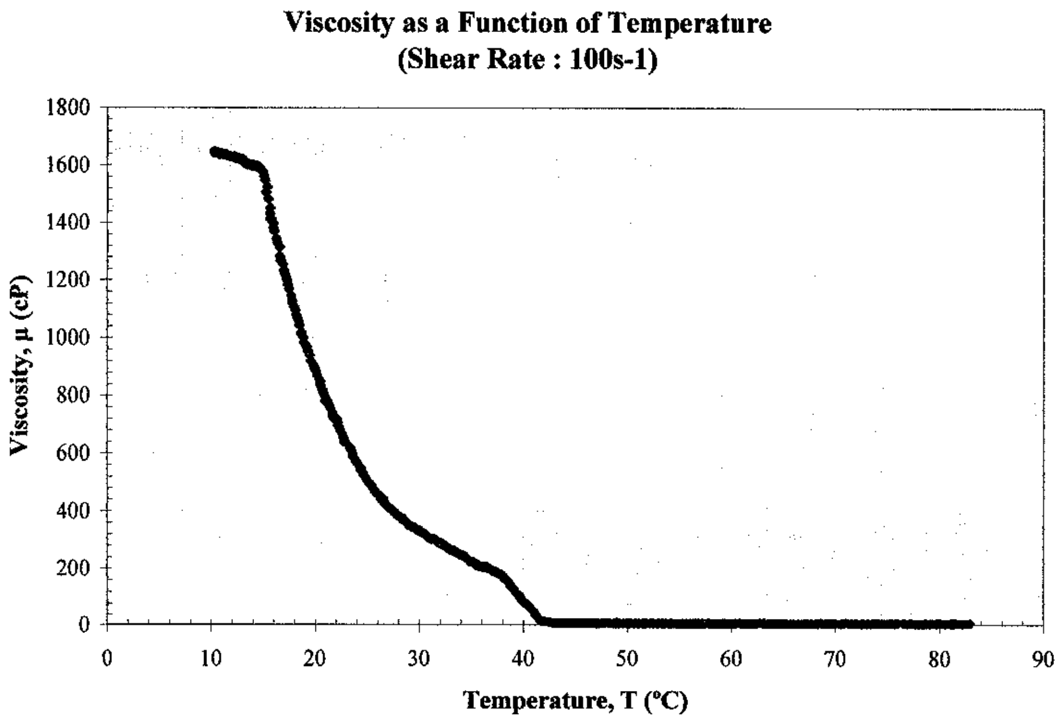

Figure 4.10 : Viscosity profile of the *Dulang D 8-L* crude oil (Experimental data)

From the experimental data of the viscosity of the *Dulang D 8-L* crude, a set of equation relating viscosity and temperature was developed. The equations will be used to assist the modeling of the high viscous fluid. The development of the viscosity correlations was accomplished using Microsoft Excel.

The experimental data were discretized into few sections to minimize the error. From the data, four (4) correlations relating these two parameters were obtained. These equations are :-

$\mu = -0.0335T + 8.1064$ for $44°C \leq T \leq 100°C$ [4.16a]

$\mu = 7.0508T^2 - 612.22T + 13295$ for $39°C \leq T < 44°C$ [4.16b]

$\mu = -1317T^3 + 13.566T^2 - 484.05T + 6196$ for $19°C \leq T < 39°C$ [4.16c]

$\mu = 0.3379T^4 - 19.688T^3 + 411.1T^2 + 13835$ for $4°C \leq T < 19°C$ [4.16d]

where the units for μ and T are in centipoises (*cP*) and Celcius (*°C*) respectively. Each equation is only valid for the temperature range as stated in the parenthesis. The viscosity correlation is only valid for temperature range of 4°C to 100°C. These equations are subjected to an average of 5 – 10% error based on deviation from the experimental data and prediction from the correlations. Figure 4.11 shows the experimental data and the line representing the prediction from the correlation.

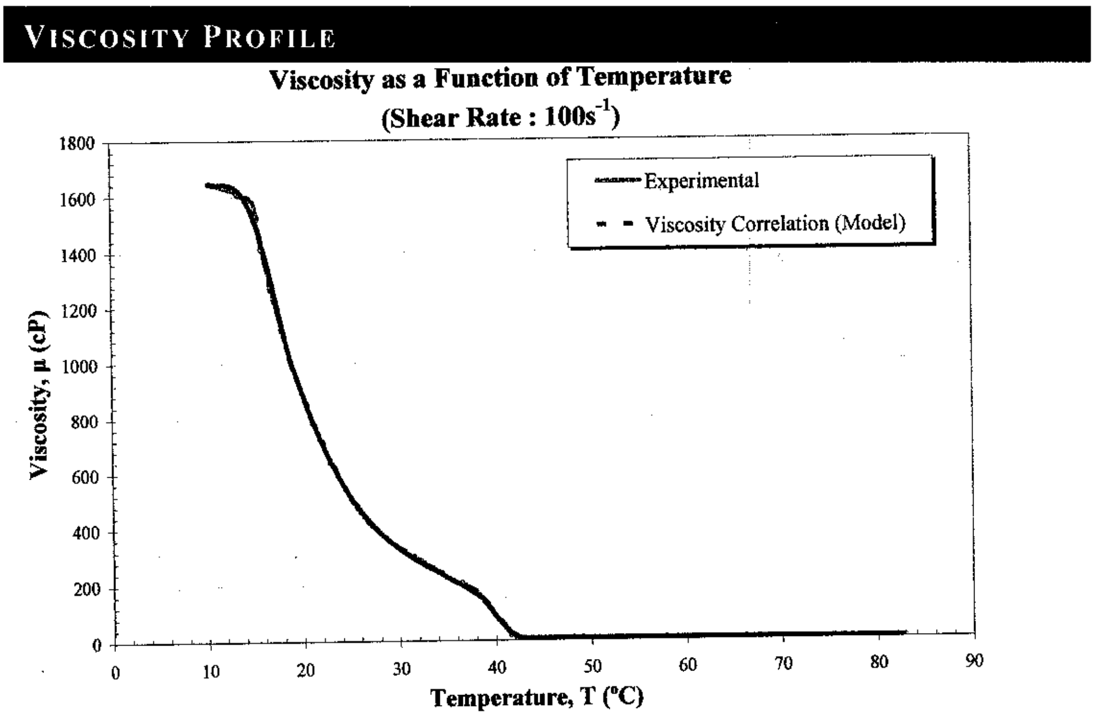

Figure 4.11 : The experimental data and the predicted viscosity of the *Dulang D 8-L* crude

4.4 COMPOSITIONAL ANALYSIS OF DULANG D 8-L CRUDE OIL

Figure 4.12 shows the chromatogram for the *Dulang D 8-L* stock tank oil. The area under each peak represents the weight percent (wt %) of the carbon component under appropriate retention time. By performing integration on the area under the curve, the weight fraction of the carbon components and plus fraction are known. The carbon distribution of the *Dulang D 8-L* stock tank oil is shown in Table 4.6 and Table 4.7 provide the properties of the plus fraction.

Table 4.6 : Properties of the C_{40+} fraction

Properties of C40+ Fraction		
Weight Faction	***Molecular Weight***	***Specific Gravity***
0.5707	567.77	0.93

These values will be used in the Wax 1.0.0 software developed by TU-MSi to generate the desired fluid properties.

4.5 ALGORITHM FOR MODELING OF HIGH VISCOUS FLUID

The viscosity correlation and the equations from the mathematical model will be used to model the mathematical model. A solution algorithm will be developed to solve the viscosity correlation together with the mathematical model. Prior to the modeling, an algorithm for the modeling of high viscous fluid was developed. The algorithm for the model is as shown in Figure 4.13.

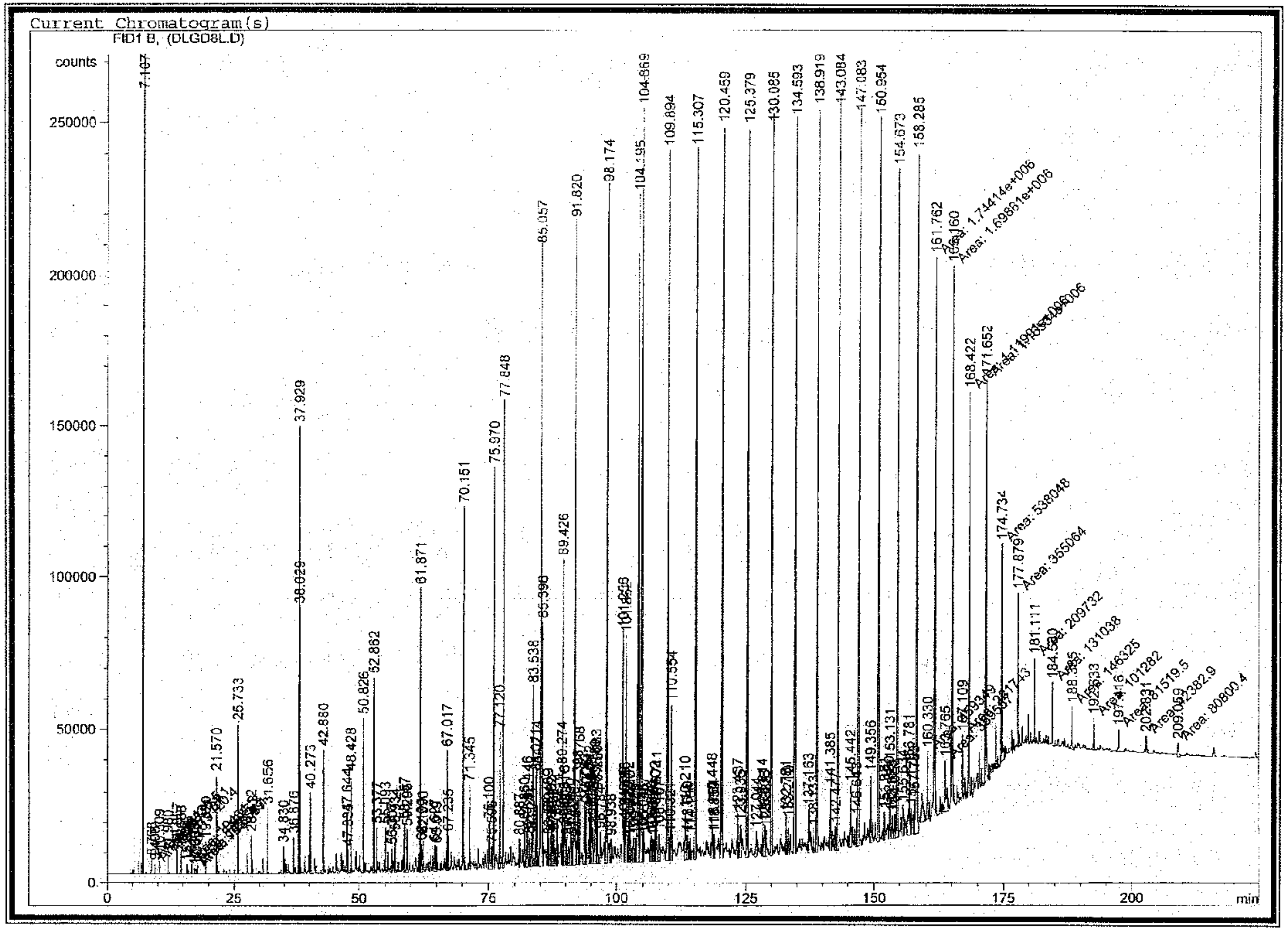

Figure 4.12: Chromatogram for the Dulang D -L stock tank oil from the HTGC analysis

Table 4.7 **:** Standard compositional analysis of the Dulang D 8-L crude oil by high temperature gas chromatography (HTGC)

Component	Area			Percent Area	n-paraffin Fraction
	n-component	iso-component	Total		
C6	16992.080	0.000	16992.080	0.02018	1.00000
C7	51385.380	151510.518	202895.898	0.24093	0.25326
C8	132093.400	484258.480	616351.880	0.73188	0.21431
C9	209628.200	1579525.850	1789154.050	2.12450	0.11717
C10	343866.400	549109.010	892975.410	1.06035	0.38508
C11	516663.100	497952.810	1014615.910	1.20479	0.50922
C12	760859.600	629279.040	1390138.640	1.65070	0.54733
C13	1048603.000	1391240.900	2439843.900	2.89716	0.42978
C14	1754716.000	1481828.010	3236544.010	3.84318	0.54216
C15	1878371.000	2837258.530	4715629.530	5.59950	0.39833
C16	2004293.000	2371588.310	4375881.310	5.19607	0.45803
C17	2196180.000	2107557.170	4303737.170	5.11041	0.51030
C18	2300781.000	3858916.390	6159697.390	7.31424	0.37352
C19	2489416.000	972538.400	3461954.400	4.11084	0.71908
C20	2346897.000	270482.500	2617379.500	3.10797	0.89666
C21	2371699.000	261727.500	2633426.500	3.12702	0.90061
C22	2452625.000	522423.490	2975048.490	3.53268	0.82440
C23	2533477.000	283766.600	2817243.600	3.34529	0.89928
C24	2582441.000	194403.490	2776844.490	3.29732	0.92999
C25	2701149.000	326143.850	3027292.850	3.59471	0.89227
C26	2609772.000	262830.700	2872602.700	3.41103	0.90850
C27	2642961.000	237169.900	2880130.900	3.41997	0.91765
C28	2346351.000	335690.900	2682041.900	3.18475	0.87484
C29	2267625.000	422683.310	2690308.310	3.19457	0.84289
C30	1807392.000	405989.500	2213381.500	2.62825	0.81658
C31	1840544.000	402770.220	2243314.220	2.66379	0.82046
C32	1311351.000	594311.700	1905662.700	2.26285	0.68813
C33	1438481.000	883074.510	2321555.510	2.75670	0.61962
C34	1090108.000	1355437.100	2445545.100	2.90393	0.44575
C35	597634.100	1893461.800	2491095.900	2.95801	0.23991
C36	669438.800	2275398.000	2944836.800	3.49680	0.22733
C37	646774.600	1948256.500	2595031.100	3.08143	0.24924
C38	438739.500	1520212.800	1958952.300	2.32613	0.22397
C39	262346.800	0.000	262346.800	0.31152	1.00000
C40	81519.500	0.000	81519.500	0.09680	1.00000
C41	82382.900	0.000	82382.900	0.09782	1.00000
C42	80800.400	0.000	80800.400	0.09595	1.00000
Total	50906357.760	33308797.788	84215155.548	100.0000	

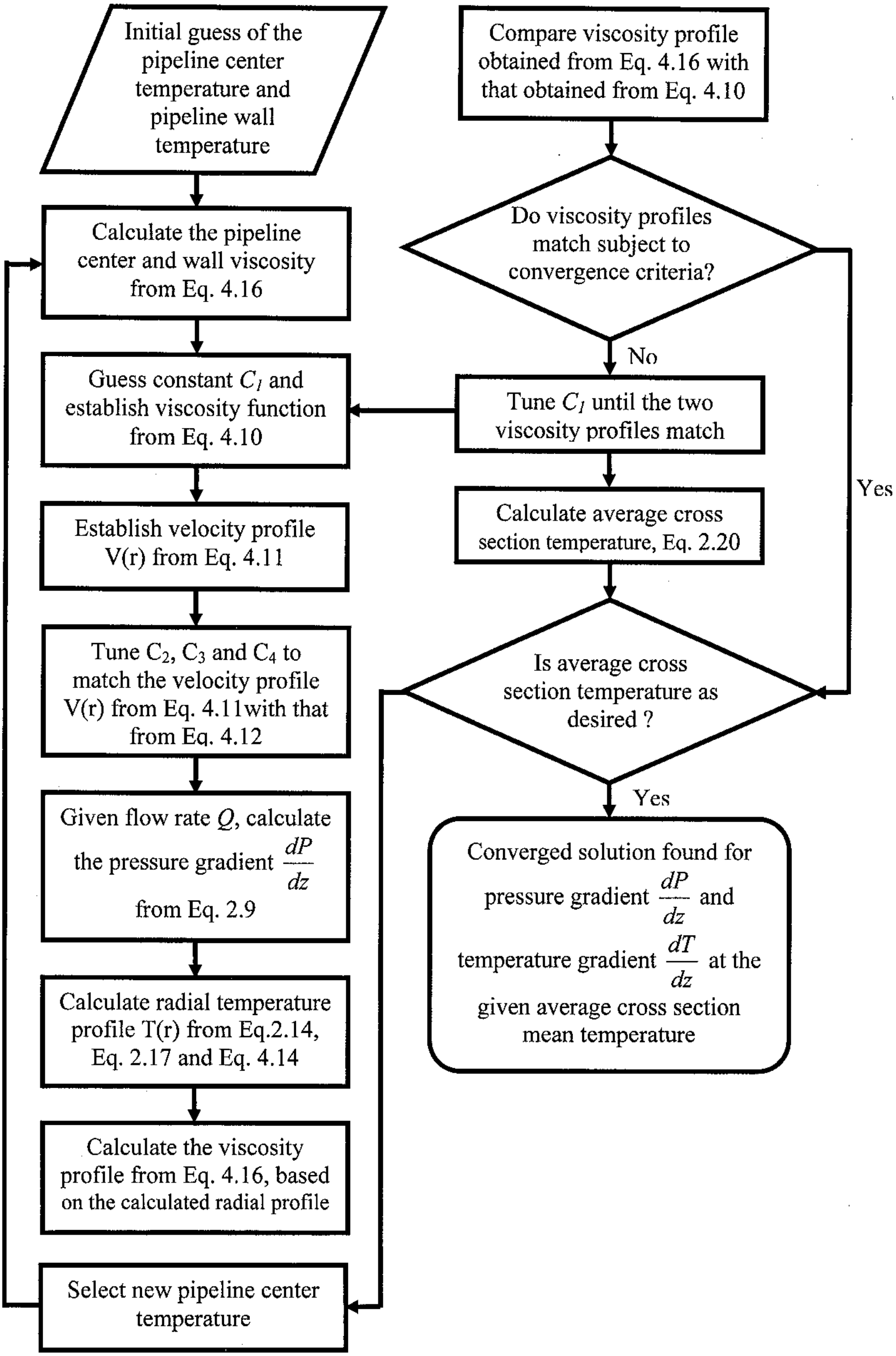

Figure 4.13 : The algorithm for the ***High Viscous Fluid Transport Model***

4.6 HIGH VISCOUS TRANSPORT MODEL CALCULATIONS

The high viscous transport model simulations have been performed with similar flow rates as the PIPEPHASE simulations. The export temperature of the crude oil is set to $80°C$, the required arrival pressure is set to *100 psia* and the ambient soil temperature of $32°C$.

The high viscous transport model has also been used to calculate the required export pressure. The same cases apply for the PIPEPHASE simulations presented in Section 4.1. It is seen in Table 4.7 that for all flow rates, the PIPEPHASE predicts a lower export pressure than the transport model. The prediction on the expected arrival temperature was also tabulated and it is shown in Table 4.8.

Table 4.8: Calculated export pressure

Flow Rate, $Q\left(m^3/day\right)$	Required Export Pressure			
	PIPEPHASE		High Viscous Transport Model (HVTM)	
	P (psig)	P (kPa)	P (psig)	P (kPa)
5000	170.604	1176.27	327.966	2261.237
10000	228.804	1577.54	473.141	3262.180
15000	289.904	1998.81	513.145	3537.995
2000	415.704	2866.17	663.882	4577.286
25000	572.504	3947.26	789.446	5443.022

Table 4.9 : Calculated arrival temperature

Flow Rate, $Q\left(m^3/day\right)$	Arrival Temperature, T $(°C)$	
	PIPEPHASE	HVTM
5000	32.0	30.726
10000	32.2	33.324
15000	33.4	35.248
20000	36.3	40.805
25000	37.3	48.624

Axial Pressure Profile

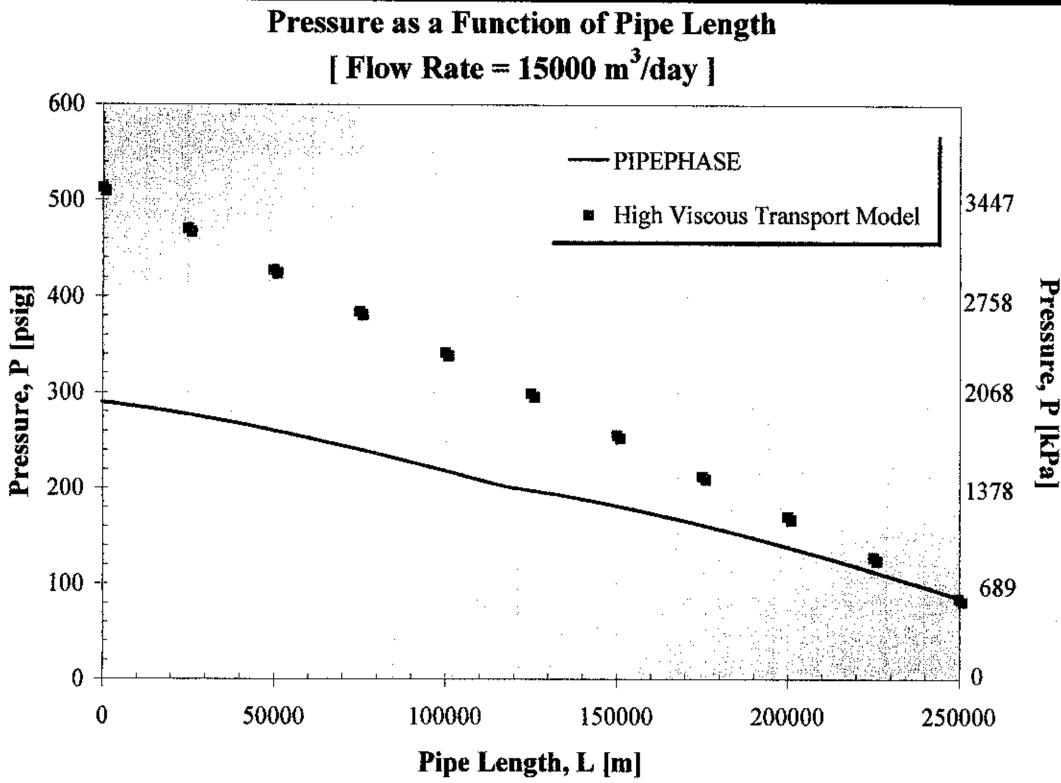

Figure 4.14 : Pressure profile at flow rate of $15000\,{m^3}/{day}$

Axial Temperature Profile

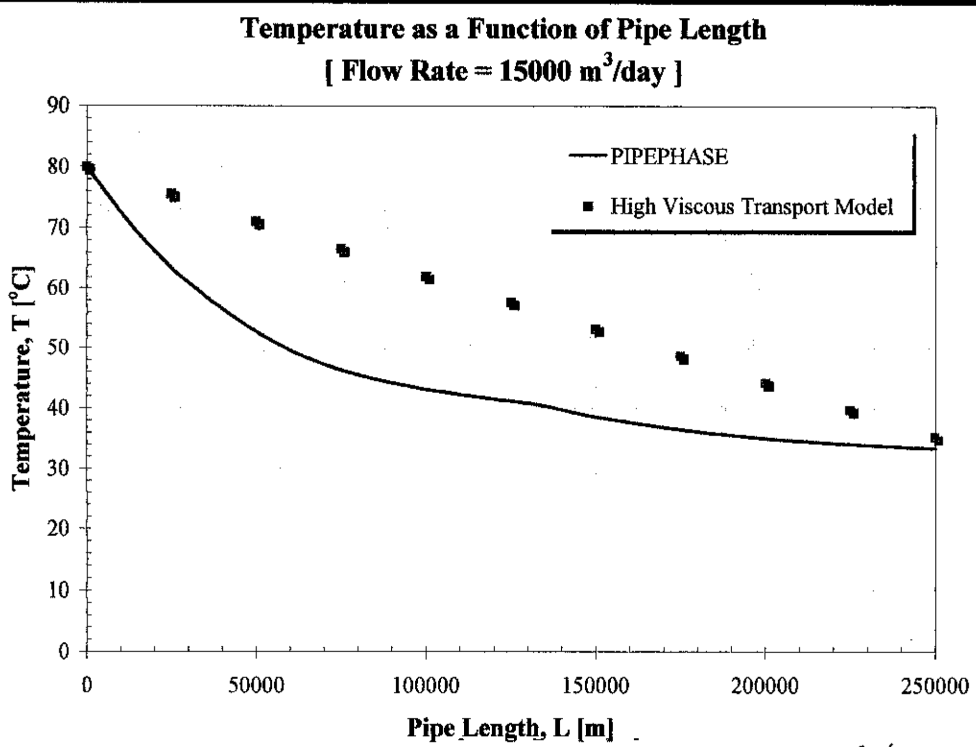

Figure 4.15 : Temperature profile at flow rate of $15000\,{m^3}/{day}$

Axial pipeline pressure and temperature profiles as obtained by PIPEPHASE and calculated by the transport model are shown in Figure 4.14 and Figure 4.15 respectively. From Figure 4.14, the high viscous transport predicts a higher export pressure than PIPEPHASE. It is also evident that the pipeline pressure drop is under predicted by a certain factor. The axial temperature profile also displays a similar trend.

Figure 4.16, 4.17 and 4.18 show examples of the velocity, viscosity and temperature profiles calculated from the high viscous transport model for $15000 \, {m^3}/{day}$ export flow rate. Figure 4.16 includes both the velocity profile from the transport model as well as the parabolic Hagen-Poiseulli's velocity profile both for $15000 \, {m^3}/{day}$ flow rate.

RADIAL VELOCITY PROFILE

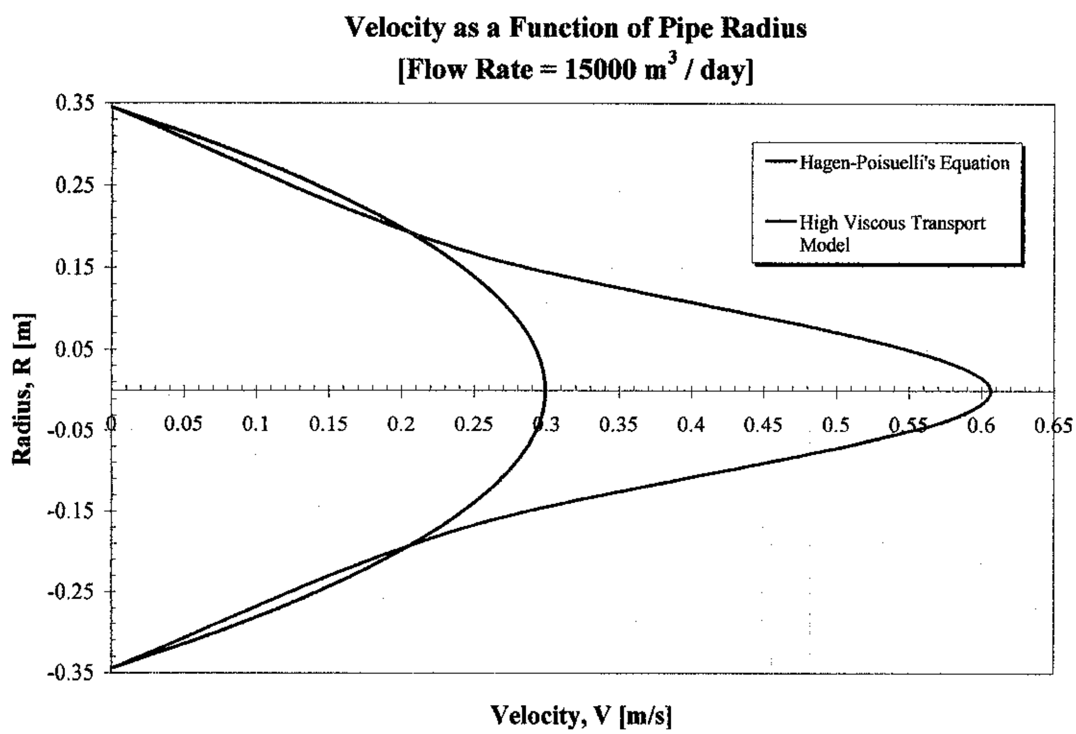

Figure 4.16 : Radial velocity profile at flow rate of $15000 \, {m^3}/{day}$

Radial Temperature Profile

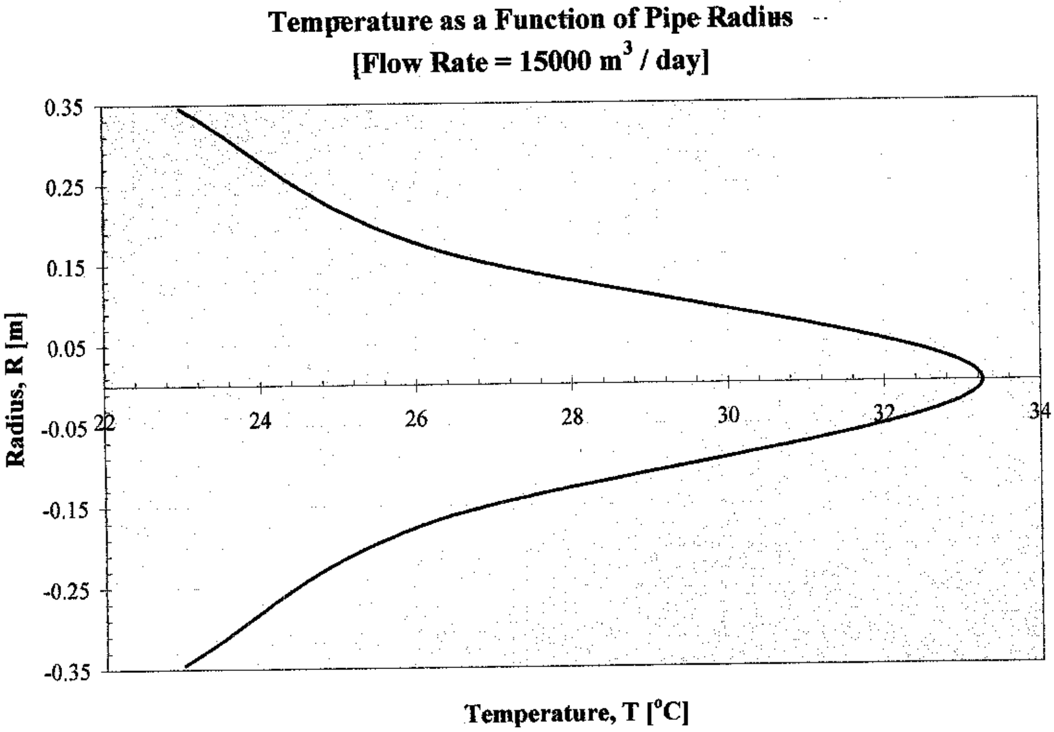

Figure 4.17 : Radial temperature profile at flow rate of $15000\,{}^{m^3}\!/_{day}$

Radial Viscosity Profile

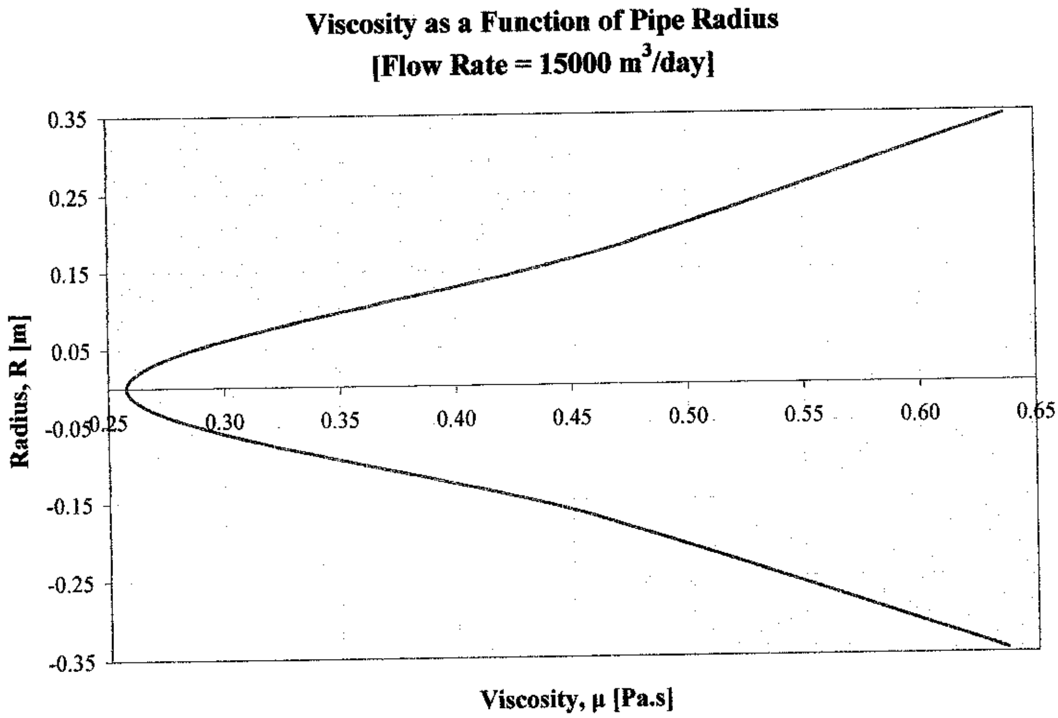

Figure 4.18 : Radial viscosity profile at flow rate of $15000\,{}^{m^3}\!/_{day}$

The viscosity at the maximum temperature (33.26 °C) is 0.25788 Pa.s while the viscosity at the wall (23°C) is 0.63687 Pa.s, as shown in Figure 4.17 and Figure 4.18 respectively.

4.7 DISCUSSIONS ON FINDINGS

The results obtained from the simulation of the Dulang D 8-L crude oil for the flow rate of $15000 \,{}^{m^3}\!/_{day}$ shows that the pressure drop in the pipeline is predicted to be 9.0 kPa with the transport model. The analysis from PIPEPHASE predicts a pressure drop of 5.0 kPa. From both the results, the pipeline pressure drop will be under predicted by a certain factor using PIPEPHASE. For the case of $15000 \,{}^{m^3}\!/_{day}$ flow rate, the pressure drop is under predicted by a factor of approximately 2. The results illustrate how the failure to account the radial viscosity will affect the analysis of flow assurance for viscous fluid.

Due to the cooling effect the wall of the pipe, the fluid near the wall will have substantially higher viscosity than the center of the pipe as shown in Figure 4.18. The center and wall temperature in this case is at 33.26 °C and 23°C respectively. The higher the viscosity of the fluid, the slower the fluid will flow and it creates a resistant to flow. This radial viscosity gradient thus causes an effective decrease of cross sectional area available for flow.

The velocity profile obtained from the transport model also deviates from the Hagen-Poiseulle's profile. The Hagen-Poiseuille profile is parabolic. However, the transport model predicts a bell shaped velocity. The velocity profile has an inflection point close to the wall. Such feature is normally linked with flows with adverse pressure gradient (White, 1999, p 405). The higher viscosity at the wall also constitutes towards the bell shaped velocity profile rather than a parabolic one.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

A proper theoretical procedure to model the transportation of high viscous fluid has been developed with the completion of the mathematical model. The mathematical model was developed using the basic transport equations namely the continuity, momentum and energy equation. The transport equations which consist of non linear partial differential equations will be reduced to non linear, ordinary partial differential equations by making necessary assumptions. A set of theoretical procedures consists of governing equations describing a high viscous model will be established.

A solution algorithm was built to solve the non linear, partial differential equations established in the mathematical modeling phase. The algorithm will solve equations in an iterative manner to calculate the desired results. FORTRAN 90/95 has been chosen as it has been identified as the most powerful programming language in the field of engineering and applied science. The results from the solution algorithm were compared with the simulation results from PIPEPHASE. PIPEPHASE has been identified as an ordinary steady state one dimensional pipeline simulation tool to model the high viscous fluid as a comparison with the fluid flow model.

The *Dulang D 8-L* crude oil has been identified as the high viscous fluid and analysis using this fluid was carried out using the fluid flow model. The pipeline system that was used in the simulation is a typical pipeline system in Sudan. A section of the 1505 *km* pipeline will be considered in the simulation work. The analysis focuses mainly on the failure to account for radial variation in fluid properties in particular liquid viscosity may cause the pressure drop prediction of the pipeline to be inaccurate.

From the results obtained from the high viscous transport model, the pressure required to flow the crude oil through the transportation line is relatively larger. Furthermore, for the case of export of oil in a 28" buried pipeline, it is demonstrated that PIPEPHASE under predicts the pressure drop by a factor of 1.5 to 2.0. Such discrepancy occurs in prediction of pressure drop occurs is due to the failure of ordinary pipeline simulation tool to account for the strong radial variations in liquid viscosity. The temperature at the wall is relatively lower as compared to the pipeline center temperature due to cooling effect. As such, the viscosity of the crude oil is much higher as compared to the viscosity at the center of the pipe. The viscosity gradient creates a resistant to flow and thus reduces the effective flowing area.

Similarly, the velocity profile obtained through the fluid flow model differs from the profile proposed by Hagen-Poisueille. The velocity profile by Poiseuille's is a parabolic profile. However, the velocity profile obtained through the fluid flow model reassembles a bell shaped profile. The velocity profile has an inflection point near the wall. The occurrence of the inflection point is associated to the adverse pressure gradient. This again is linked to the radial viscous effect. The viscosity gradient as a result of difference in temperature at the wall and the center of the pipe generally decreases the effective cross sectional area for flow.

The high viscous transport model generally proves that failure to account for radial variation in liquid viscosity will cause the pressure drop to be under predicted by a factor of 1.5 to 2 depending on the flow rate. With the available of such model, the required pumping capacity can be determined. These will made analysis of flow assurance more accurate to certain extends. The analysis described was carried on a buried pipeline system. If the analysis were to be carried out on a sub-sea pipeline, the results of variation in oil viscosity would be more significant due to low ambient temperature.

The high viscous transport model would be an essential tool in analysis of flow assurance. It will be an useful tool in prediction the pressure drop especially when it deep water environment. Since the most oil and gas operators are considering deep water exploration, this tool would be beneficial in measuring the pressure drop.

5.2 RECOMMENDATION & FUTURE WORK FOR EXPANSION

Thus far the high viscous transport model has been developed. However, there are still more space for further improvement. One of the improvements that need to be undertaken is to ensure that the model is dynamically independent. Due to some undetectable error in the present model, it is not dynamically independent. User has to input new pipeline center and wall temperature until the results converged. Improvement can be made to ensure that the model will dynamically iterates the calculation until the desired results is obtained. If this feature were to be included, the hassle for the user to input new temperature would be reduced.

The model was developed using FORTRAN 90/95. To improve usability, the present model could be into a graphical user interface (GUI). With such interface, the modeling task would be made easy. Any changes in one of the modeling parameter can be made easily, while holding other parameters constant. Besides GUI, web-base model could also be build to ensure accessibility of the model by just a click of the mouse. However, these features could be made possible if the model has been tested extensively.

To ensure the model delivers accurate and precise results, experimental analysis could be conducted. Experimental work using small scale pipeline system or loop can be use to test the reliability of the model. With such facilities, concurrent simulation can be done simultaneously. This is accomplished by linking the model with the flow loop to ensure accurate yet precise results. By doing so, any necessary correction factor can be introduce to improve the results both experimental and prediction.

The present model is only valid for pipeline system without elevation. Further work could be done to include analysis for pipeline with slight elevation. Extensive analysis could also be done to include other pipe components. Among the pipe components that can be consider in analysis are elbows, bends, tees and valves. If these components were to be accounted for in analysis, major head losses as well as minor losses must be considered thoroughly in evaluating the pressure drop. A new sets of governing equation must be derived from the basic transport equations.

The scope of the project can be extended to investigate the flow characteristics of high viscous fluid in complex pipeline system (i.e. pipeline with elevation and joints). The integration of the model can also be done with computational fluid dynamic (CFD) software to further the analysis of the behavior of the high viscous fluid.

REFERENCES

Incropera, Frank P. and DeWitt, David P., 1996, *Introduction to Heat Transfer*, Third Edition, New York, USA, John Wiley & Sons, Inc.

Gray, George R. and Darley, H.C.H., 1980, *Composition and Properties of Oil Well Drilling Fluids*, Fourth Edition, Texas, USA, Gulf publishing Company

White, Frank M., 1999, *Fluid Mechanics*, Fourth Edition, New York, USA, McGraw-Hill International Ltd.

Bird, R. Byron, Steward, Warren E. and Lightfoot, Edwin N., 2002, *Transport Phenomena*, Second Edition, New York, USA, John Wiley & Sons, Inc.

Versteeg H. K. and Malalasekera, 1995, *An Introduction to Computational Fluid Dynamics : The Finite Volume Method*, New York, USA, Longman Group Ltd.

Strand, B and Djuve, S M, 2000, *Pipeline Transport of Oil with Strongly Temperature Dependent Viscosity*, Paper presented at the 2nd BHRG Conference in Multiphase Technology, North American.

White, Frank M., 1991, *Viscous Fluid Flow,* Second Edition, New York, USA, McGraw-Hill International Ltd.

Holman, J. P., 2001, *Heat Transfer*, Eight Edition, New York, USA, McGraw Hill International Ltd.

Deissler, Robert G., *Analytical Investigations of Fully Developed Laminar Flow in Tubes with Heat Transfer with Fluid Properties Variable along the Radius*, National Advisory Committee for Aeronautics (NACA), Technical Note 2410, Washington, 1951.

Schmidt, F. W. and Zeldin, B., *Laminar Flows in Inlet Section of Tubes and Ducts*, AIChE Journal, July 1969.

APPENDIX A

MATHEMATICAL MODELING

A1 MATHEMATICAL MODELING ~ PRELIMINARY PHASE

The first phase of the mathematical modeling is developed a set of governing equations for steady state flow with heat transfer in the fully developed laminar region. The continuity, momentum and energy equations will be utilized in this phase of the mathematical modeling.

[1] Continuity Equation

The continuity equation in cylindrical coordinates is given by Eq. 1.

$$\frac{1}{r}\frac{\partial}{\partial r}(\rho r v_r)+\frac{1}{r}\frac{\partial}{\partial \theta}(\rho v_\theta)+\frac{\partial}{\partial z}(\rho v_z)=0 \qquad [1]$$

Assuming the azimuthal and radial velocity to be zero, Eq. 1 can be simplified in to

$$\frac{\partial}{\partial z}(\rho v_z)=0 \qquad [2]$$

For a fluid with constant density, the axial density is assumed to be negligible at any given point in the pipeline. With this assumption, Eq. 2 can be further simplified in to

$$\frac{\partial v_z}{\partial z}=0 \qquad [3]$$

In most engineering applications, the assumptions of constant density results in considerable simplification and very little error.

[2] Momentum Equation

The momentum equation for cylindrical coordinates in the axial direction is given by Eq. 4.

$$\rho\left(v_r\frac{\partial v_z}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_z}{\partial \theta}+v_z\frac{\partial v_z}{\partial z}\right)=-\frac{\partial P}{dz}-\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\tau_{rz}\right)+\frac{1}{r}\frac{\partial}{\partial \theta}\tau_{\theta z}+\frac{\partial}{\partial z}\tau_{zz}\right]+\rho gz \qquad [4]$$

The same assumptions for continuity equation apply for the momentum equation. For horizontal pipeline, $g_z = 0$ Substituting Eq. 3 into Eq. 4 would yield

$$-\frac{\partial P}{dz}-\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\left[-\mu\frac{\partial v_z}{\partial r}\right]\right)\right]=0 \qquad [5]$$

The viscosity, μ is defined as a function of radial coordinate, r. As such,

$$\frac{\partial P}{dz}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\left[\mu(r)\frac{\partial v_z}{\partial r}\right]\right) \qquad [6]$$

[3] Energy Equation

The energy equation for cylindrical coordinates is given by Eq. 7.

$$\rho C_p\left(v_r\frac{\partial T}{\partial r}+\frac{v_\theta}{r}\frac{\partial T}{\partial \theta}+v_z\frac{\partial T}{\partial z}\right)=k\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2}+\frac{\partial^2 T}{\partial z^2}\right]+\mu\Phi_v \qquad [7]$$

In the z-direction, heat conduction is much smaller than heat convection, so the term $\frac{\partial^2 T}{\partial z^2}$ can be neglected. By using the same assumptions as applied on the continuity and momentum equation, the energy equation of the system can be reduced to

$$\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)=\frac{r\rho C_p}{k}\frac{\partial T}{\partial z}v_z(r) \qquad [8]$$

The velocity, v_z in Eq. 8 is defined as a function of radial coordinate, r. Eq. 8 can be further simplified in to

$$\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)=\frac{r}{\alpha}\frac{\partial T}{\partial z}v_z(r) \qquad [9]$$

The term α in Eq. 9 is the liquid diffusivity and is defined as

$$\alpha=\frac{k}{\rho C_p} \qquad [10]$$

In Eq. 10, k is the thermal conductivity of oil and C_p is the isobaric heat capacity of oil.

A2 MATHEMATICAL MODELING ~ SECOND PHASE

The second phase of the mathematical modeling is the continuation from the earlier phase. In the first phase, the continuity, momentum and energy equation has been simplified for analysis purposes. In the second phase of the mathematical modeling, the governing equation for the pipeline pressure gradient would be defined. The equation to develop the velocity profile of the system would also be defined.

(Note :The mathematical integration in section is performed using Mathematica v5.0)

Eq. 6 can be rearranged in to the following expression

$$\frac{d}{dr}\left(r\left[\mu(r)\frac{dv_z}{dr}\right]\right)=r\frac{dP}{dz} \qquad [6b]$$

By assuming that the axial pressure gradient $\frac{dP}{dz}$ to be independent of radial position, Eq. 6 can be integrated to Eq. 11.

$$\frac{dv_z}{dr}=\frac{1}{2}\frac{dP}{dz}\frac{r}{\mu(r)} \qquad [11]$$

Steps in arriving to Eq. 11.

Integrating both sides of the Eq. 7

$$\int d\left(r\left[\mu(r)\frac{dv_z}{dr}\right]\right) = \int r\frac{dP}{dz}dr$$

$$= \frac{dP}{dz}\int r\,dr$$

$$r\,\mu(r)\frac{dv_z}{dr} = \frac{dP}{dz}\frac{r^2}{2}$$

$$\frac{dv_z}{dr} = \frac{dP}{dz}\frac{r^2}{2}\frac{1}{r}\frac{1}{\mu(r)}$$

$$\frac{dv_z}{dr} = \frac{1}{2}\frac{dP}{dz}\frac{r}{\mu(r)} \qquad [11]$$

$$\boxed{\frac{dv_z}{dr} = \frac{1}{2}\frac{dP}{dz}\frac{r}{\mu(r)}}$$

Although the viscosity is a function of pressure and temperature, Strand and Djuve have suggested that it has been conveniently and sufficiently accurate to express this as a function of radial coordinate, r as

$$\mu(r) = \frac{\mu_o - \mu_m}{R^2}C_1(r)^3 + \mu_m \qquad [12]$$

where

μ_o = Viscosity at the at the wall of the pipe

μ_m = Viscosity in the center of the pipe

C_1 = Constant

R = Radius of the pipe

The constant, C_1 is a function of $\frac{1}{r}$ $[0 < C_1 < R]$.

Substitution of Eq. 12 into Eq. 11 can be integrated to

$$v_z = \frac{1}{2}\frac{dP}{dz}\left(\arctan\frac{\left[-A^{1/3} + 2B^{1/3} r\right]}{\sqrt{3}A^{2/3}B^{1/3}} - \frac{\ln\left[B^{1/3} + A^{1/3} r\right]}{3A^{2/3}B^{1/3}} + \frac{\ln\left[B^{2/3} - A^{1/3} + A^{2/3} r\right]}{6A^{2/3}B^{1/3}} \right) \qquad [13]$$

Steps in arriving to Eq. 13.

$$\frac{dv_z}{dr} = \frac{1}{2}\frac{dP}{dz}\frac{r}{\frac{\mu_o - \mu_m}{R^2}C_1(r)^3 + \mu_m}$$

Integrating both sides of the equation

$$\int dv_z = \int \frac{1}{2}\frac{dP}{dz}\frac{r}{\frac{\mu_o - \mu_m}{R^2}C_1(r)^3 + \mu_m}\partial r$$

$$\int \partial v_z = \frac{1}{2}\frac{dP}{dz}\int \frac{r}{\frac{\mu_o - \mu_m}{R^2}C_1(r)^3 + \mu_m}\partial r$$

Let $A = \frac{\mu_o - \mu_m}{R^2}C_1$ and $B = \mu_m$

$$\int \frac{r}{\frac{\mu_o - \mu_m}{R^2}C_1(r)^3 + \mu_m}\partial r = \int \frac{r}{Ar^3 + B}$$

$$= \arctan\frac{\left[-A^{1/3} + 2B^{1/3} r\right]}{\sqrt{3}A^{2/3}B^{1/3}} - \frac{\ln\left[B^{1/3} + A^{1/3} r\right]}{3A^{2/3}B^{1/3}} + \cdots$$

$$+ \frac{\ln\left[B^{2/3} - A^{1/3} + A^{2/3} r\right]}{6A^{2/3}B^{1/3}}$$

$$v_z = \frac{1}{2}\frac{dP}{dz}\left(\arctan\frac{\left[-A^{1/3} + 2B^{1/3} r\right]}{\sqrt{3}A^{2/3}B^{1/3}} - \frac{\ln\left[B^{1/3} + A^{1/3} r\right]}{3A^{2/3}B^{1/3}} + \frac{\ln\left[B^{2/3} - A^{1/3} + A^{2/3} r\right]}{6A^{2/3}B^{1/3}} \right) \qquad [13]$$

$$v_z = \frac{1}{2}\frac{dP}{dz}\left(\arctan\frac{\left[-A^{1/3} + 2B^{1/3} r\right]}{\sqrt{3}A^{2/3}B^{1/3}} - \frac{\ln\left[B^{1/3} + A^{1/3} r\right]}{3A^{2/3}B^{1/3}} + \frac{\ln\left[B^{2/3} - A^{1/3} + A^{2/3} r\right]}{6A^{2/3}B^{1/3}} \right)$$

Defining V as axial velocity divided by pressure gradient

$$v_z = V\frac{dP}{dz} \qquad [14]$$

Substituting Eq. 14 into Eq. 13 would yield

$$V(r) = \frac{1}{2}\left[\arctan\frac{\left[-A^{1/3} + 2B^{1/3} r\right]}{\sqrt{3}A^{2/3}B^{1/3}} - \frac{\ln\left[B^{1/3} + A^{1/3} r\right]}{3A^{2/3}B^{1/3}} + \frac{\ln\left[B^{2/3} - A^{1/3} + A^{2/3} r\right]}{6A^{2/3}B^{1/3}} \right] \qquad [15]$$

The velocity profile divided by pressure gradient according to Strand and Djuve may be parameterized as

$$V(r) = C_2\left(\cos\left[\frac{r}{C_3}\right] + C_4\right) \qquad [16]$$

Substitution of Eq. 16 in to Eq. 9 can be integrated to

$$\frac{dT}{dr} = \frac{1}{r}\left[\frac{1}{\alpha}\frac{dT}{dz}\frac{dP}{dz}C_2\left(C_3 r\sin\left[\frac{r}{C_3}\right] + C_3^{\,2}\cos\left[\frac{r}{C_3}\right] + \frac{1}{2}r^2 C_4\right)\right] \qquad [17]$$

Steps in arriving to Eq. 17

$$\frac{d}{dr}\left(r\frac{dT}{dr}\right) = \frac{r}{\alpha}\frac{dT}{dz}\frac{dP}{dz}V(r)$$

Integrating both sides of the equation

$$\int d\left(r\frac{dT}{dr}\right) = \int \frac{r}{\alpha}\frac{dT}{dz}\frac{dP}{dz}\left[C_2\left(\cos\left[\frac{r}{C_3}\right] + C_4\right)\right] dr$$

$$r\frac{dT}{dr}=\frac{1}{\alpha}\frac{dT}{dz}\frac{dP}{dz}C_2\int r\left[C_2\left(\cos\left[\frac{r}{C_3}\right]+C_4\right)\right]dr$$

$$\frac{dT}{dr}=\frac{1}{r}\left[\frac{1}{\alpha}\frac{dT}{dz}\frac{dP}{dz}C_2\left(C_3 r\sin\left[\frac{r}{C_3}\right]+C_3^2\cos\left[\frac{r}{C_3}\right]+\frac{1}{2}r^2C_4\right)\right] \qquad [17]$$

$$\boxed{\frac{dT}{dr}=\frac{1}{r}\left[\frac{1}{\alpha}\frac{dT}{dz}\frac{dP}{dz}C_2\left(C_3 r\sin\left[\frac{r}{C_3}\right]+C_3^2\cos\left[\frac{r}{C_3}\right]+\frac{1}{2}r^2C_4\right)\right]}$$

Eq. 17 can be further integrated to yield

$$T(r)=\frac{1}{\alpha}\frac{dT}{dz}\frac{dP}{dz}C_2\left(-C_3^2\cos\left[\frac{r}{C_3}\right]+C_3^2\int_0^{r/C_3}\frac{\cos(t)}{t}dt+\frac{1}{2}r^2C_4\right) \qquad [18]$$

$$\boxed{T(r)=\frac{1}{\alpha}\frac{dT}{dz}\frac{dP}{dz}C_2\left(-C_3^2\cos\left[\frac{r}{C_3}\right]+C_3^2\int_0^{r/C_3}\frac{\cos(t)}{t}dt+\frac{1}{2}r^2C_4\right)}$$

A3 CORRECTION ON THE MATHEMATICAL MODEL

As described earlier, there is an discrepancy in the Strand and Djuve equation, the modeified equation is given in Eq. 19.

$$\mu(r)=\frac{\mu_o-\mu_m}{R^2}C_1(r)^2+\mu_m \qquad [19]$$

Substitution of Eq. 1 into Eq. 11 can be integrated to

$$V(r)=\frac{1}{2}\frac{dP}{dz}\frac{\ln\left[B+Ar^2\right]}{2A} \qquad [20]$$

where $A=\frac{\mu_o-\mu_m}{R^2}C_1$ and $B=\mu_m$.

Steps in arriving in Eq. 20.

Integrating both sides of the equation

$$\int dv_z = \int \frac{1}{2}\frac{dP}{dz}\frac{r}{\frac{\mu_o - \mu_m}{R^2}C_1(r)^2 + \mu_m}\partial r$$

$$\int \partial v_z = \frac{1}{2}\frac{dP}{dz}\int \frac{r}{\frac{\mu_o - \mu_m}{R^2}C_1(r)^2 + \mu_m}\partial r$$

Let $A = \frac{\mu_o - \mu_m}{R^2}C_1$ and $B = \mu_m$

$$\int \frac{r}{\frac{\mu_o - \mu_m}{R^2}C_1(r)^2 + \mu_m}\partial r = \int \frac{r}{Ar^2 + B}$$

$$= \frac{\ln\left[B + Ar^2\right]}{2A}$$

$$V(r) = \frac{1}{2}\frac{dP}{dz}\frac{\ln\left[B + Ar^2\right]}{2A}$$

$$\boxed{V(r) = \frac{1}{2}\frac{dP}{dz}\frac{\ln\left[B + Ar^2\right]}{2A}}$$

RELATIONSHIP BETWEEN VOLUMETRIC FLOW RATE AND PRESSURE GRADIENT

The volume flow in a circular pipe is given by

$$Q = \int_0^R v_z\, dA = \int_0^R v_z\, 2\pi r\, dr \qquad [19]$$

Combining Eq. 14 and Eq. 16 into Eq. 19 yield

$$
\begin{aligned}
Q &= \int_0^R v_z \, dA \\
&= \int_0^R v_z \, 2\pi r \, dr \\
&= \int_0^R V \frac{dP}{dz} 2\pi r \, dr \\
&= \int_0^R C_2 \left(\cos\left[\frac{r}{C_3}\right] + C_4 \right) \frac{dP}{dz} 2\pi r \, dr
\end{aligned}
$$

$$
Q = \frac{dP}{dz} \int_0^R C_2 \left(\cos\left[\frac{r}{C_3}\right] + C_4 \right) 2\pi r \, dr \qquad [21]
$$

$$
\boxed{Q = \frac{dP}{dz} \int_0^R C_2 \left(\cos\left[\frac{r}{C_3}\right] + C_4 \right) 2\pi r \, dr}
$$

A4 HEAT TRANSFER CORRELATIONS IN A CIRCULAR PIPE

For a cylindrical pipe with length very large compared to the diameter, it may be assumed that the heat flows only in a radial direction. As such the heat transfer in the radial direction is given by Fourier's law of heat conduction.

$$
q = -kA\frac{dT}{dr} \qquad [22]
$$

The amount of heat transfer, q is related to the overall heat transfer coefficient, U and is given by

$$
q = UA\Delta T \qquad [23]
$$

Substituting Eq. 22 into Eq. 21 yields

$$
UA\Delta T = -kA\frac{dT}{dr} \qquad [24]
$$

$$U(T_w - T_a) = -k\frac{dT}{dr} \qquad [25]$$

In the analysis, the convection heat transfer is also considered. The equation related to heat convection is given by Eq. 25.

$$q = \dot{m}C_p \frac{dT}{dz} \qquad [26]$$

where $\dot{m} = \rho Q$. Substituting this expression into Eq. 25 yields

$$q = \rho Q C_p \frac{dT}{dz} \qquad [27]$$

$$U(T_w - T_a)2\pi R = QC_p\rho\frac{dT}{dr} \qquad [28]$$

A5 THE MEAN TEMPERATURE

The mean or bulk temperature of the fluid is defined in terms of the thermal energy transported by the fluid as it moves past the cross section. In this analysis, the velocity, temperature and pressure gradient will be evaluated at the mean or bulk temperature.

The mean temperature is defined as

$$T_m = \frac{\int_{A_c} \rho V C_v T \, dA_c}{\dot{m}C_v} \qquad [29]$$

For incompressible flow in a circular pipe, the value of C_v is constant (Incropera and DeWitt, 1996, p.394). By taking this assumption into account, Eq. 28 can be simplified into

$$T_m = \frac{\int_{A_c} \rho V C_v T \, dA_c}{\dot{m} C_v}$$

$$= \frac{\int_{A_c} \rho V C_v T \, dA_c}{\rho Q C_v}$$

$$= \frac{1}{Q} \int_0^R T(r) v_r(r) 2\pi r \, dr$$

$$T_m = \frac{1}{Q} \int_0^R T(r) v_r(r) 2\pi r \, dr \qquad [30]$$

$$\boxed{T_m = \frac{1}{Q} \int_0^R T(r) v_r(r) 2\pi r \, dr}$$

The equations developed in the mathematical model may be used to solve in an iterative manner to calculate these parameters :-

- Pressure gradient
- Temperature gradient
- Velocity profile
- Viscosity profile

These parameters can be determined if the average cross section temperature or the mean temperature is known.

APPENDIX B

SIMULATION RESULTS FROM PIPEPHASE

This section presents the results from the modelling of high viscous fluid with PIPEPHASE v7.41. The pressure and temperature drop across the pipe at different flow rates are given in the tables below.

Flow Rate = 5000 m^3/day

Distance [m]	Pressure [psig]	Temperature [°C]
0.000	0.0000	170.641
13888.897	45567.2461	169.518
27777.793	91134.4922	168.398
41666.689	136701.7344	166.419
55555.586	182268.9844	163.192
69444.484	227836.2344	158.969
83333.377	273403.4688	154.078
97222.275	318970.7188	148.782
111111.173	364537.9688	143.251
125000.071	410105.2188	137.590
138888.968	455672.4688	131.856
152777.857	501239.6875	126.082
166666.755	546806.9375	120.287
180555.652	592374.1875	114.480
194444.550	637941.4375	108.667
208333.448	683508.6875	102.850
222222.346	729075.9375	97.032
236111.244	774643.1875	91.213
250000.141	820210.4375	85.393

Flow Rate = 10000 m^3/day

Distance [m]	Pressure [psig]	Temperature [°C]
0.000	0.0000	228.781
13888.897	45567.2461	225.361
27777.793	91134.4922	221.083
41666.689	136701.7344	216.034
55555.586	182268.9844	210.449
69444.484	227836.2344	206.641
83333.377	273403.4688	201.889
97222.275	318970.7188	195.849
111111.173	364537.9688	188.646
125000.071	410105.2188	180.450
138888.968	455672.4688	171.440
152777.857	501239.6875	161.785
166666.755	546806.9375	151.629
180555.652	592374.1875	141.091
194444.550	637941.4375	130.265
208333.448	683508.6875	119.225
222222.346	729075.9375	108.024
236111.244	774643.1875	96.706
250000.141	820210.4375	85.302

Flow Rate = 15000 m^3/day

Distance [m]	Pressure [psig]	Temperature [^oC]
0.000	0.0000	289.868
14705.890	48247.6719	282.706
29411.781	96495.3438	274.306
44117.671	144743.0156	264.671
58823.562	192990.6875	253.851
73529.452	241238.3594	242.004
88235.342	289486.0313	229.376
102941.228	337733.6875	216.177
117647.123	385981.3750	202.537
132353.009	434229.0313	193.664
147058.904	482476.7188	183.765
161764.790	530724.3750	172.544
176470.685	578972.0625	160.140
191176.580	627219.7500	146.697
205882.456	675467.3750	132.363
220588.351	723715.0625	117.273
235294.246	771962.7500	101.552
250000.141	820210.4375	85.307

Flow Rate = 20000 m^3/day

Distance [m]	Pressure [psig]	Temperature [°C]
0.000	0.0000	415.706
14705.890	48247.6719	404.011
29411.781	96495.3438	390.834
44117.671	144743.0156	376.158
58823.562	192990.6875	360.024
73529.452	241238.3594	342.473
88235.342	289486.0313	323.588
102941.228	337733.6875	303.498
117647.123	385981.3750	282.395
132353.009	434229.0313	260.460
147058.904	482476.7188	237.854
161764.790	530724.3750	214.700
176470.685	578972.0625	191.088
191176.580	627219.7500	167.086
205882.456	675467.3750	142.737
220588.351	723715.0625	118.074
235294.246	771962.7500	102.102
250000.141	820210.4375	85.308

Flow Rate = 25000 m^3/day

Distance [m]	Pressure [psig]	Temperature [°C]
0.000	0.0000	572.523
10000.006	32808.4180	561.000
20000.012	65616.8359	548.693
30000.016	98425.2500	535.592
40000.023	131233.6719	521.694
50000.025	164042.0781	507.000
60000.032	196850.5000	491.513
70000.039	229658.9219	475.256
80000.046	262467.3438	458.248
90000.049	295275.7500	440.501
100000.051	328084.1563	422.045
110000.063	360892.5938	402.905
120000.065	393701.0000	383.113
130000.067	426509.4063	362.701
140000.079	459317.8438	341.709
150000.081	492126.2500	320.193
160000.093	524934.6875	298.199
170000.085	557743.0625	275.773
180000.097	590551.5000	252.959
190000.109	623359.9375	229.798
200000.102	656168.3125	206.324
210000.113	688976.7500	182.569
220000.125	721785.1875	158.560
230000.118	754593.5625	134.320
240000.130	787402.0000	109.866
250000.141	820210.4375	85.216

The variations of liquid viscosity and Reynolds Number, N_{RE} at different temperature and pressure. The flow rate is constant in this simulation.

Flow Rate, Q [m^3 / day]	Distance [m]	Pressure [psig]	Temperature [°C]	Liquid Viscosity [cP]	Reynolds Number, N_{RE}
15000	0.000	289.868	80.000	0.000	0.000
	14705.890	282.706	69.454	10.216	26390.688
	29411.781	274.306	61.260	20.290	13287.687
	44117.671	264.671	54.888	35.049	7692.442
	58823.562	253.851	49.931	54.066	4986.646
	73529.452	242.004	46.563	74.709	3608.804
	88235.342	229.376	44.358	92.986	2899.453
	102941.228	216.177	42.822	107.814	2500.674
	117647.123	202.537	41.652	120.057	2245.668
	132353.009	193.664	40.642	130.972	2058.522
	147058.904	183.765	38.891	146.294	1842.928
	161764.790	172.544	37.495	166.051	1623.647
	176470.685	160.140	36.382	183.786	1466.970
	191176.580	146.697	35.494	199.334	1352.543
	205882.456	132.363	34.786	212.711	1267.489
	220588.351	117.273	34.222	224.044	1203.371
	235294.246	101.552	33.772	233.531	1154.486
	250000.141	85.307	33.413	241.395	1116.876

APPENDIX C

HIGH VISCOUSS TRANSPORT MODEL

[FORTRAN SOURCE CODE]

This section provides the FORTRAN 90/95 source codes for the high viscous transport model.

FORTRAN 90/95 SOURCE CODES for HIGH VISCOUS TRANSPORT MODEL

```
!---------------------------------------------------------------------------------------------!

PROGRAM MAIN

IMPLICIT NONE

!--PARAMATERS FROM TUFFP---------------------------------------------
 CHARACTER :: FTHM*150, TDYN*150, FILETHM*150
 REAL  :: T,P,DENG,DENL,GMF,VISG,VISL,CPG,CPL,THKG
 REAL :: THKL,SURL,ENTH,SF,SMW,FMW,ROS,ROF,DCDT,TCLOUD,VISLW

!--PARAMETERS FROM HVTM----------------------------------------------
REAL :: TEMPWALL, TEMPCENTER, TEMPAVERAGE, MEANTEMP
REAL :: VISCOWALL, VISCOCENTER, VISCOSITY1, VISCOSITY2, VISCOSITYL
REAL :: VELOCITY1, VELOCITY2, FLOWRATE, DPDZ
REAL :: A, B, RADIUS, C1, C2, C3, C4, CONSTANT
REAL :: VELERROR1, VELERROR2, VELERROR3
REAL :: VISCOERROR1
REAL :: DELTAR1, DELTAR3
REAL :: ALPHA, U, H1, H4
REAL :: KSOIL, KPIPE, NU, REYNOLDSNO
REAL :: DTDZ, DTDR
REAL :: AMBIENTTEMP, WALLTEMP, TEMPRADIUS
REAL :: PINLET, POUTLET, PCONSTANT
REAL :: TEMPOUTLET, TEMPINLET, TCONSTANT
REAL :: TERM1, TERM2, TERM3, TERM4
REAL :: PIPE_LENGTH, LENGTH, DEPTH, THICKNESS
REAL :: AREA, VELOCITY
REAL :: PI = 3.14159
INTEGER :: INPUTSTATUS , OPENSTATUS

INTEGER   NOUT
REAL      A1, ABS, B1, ERRABS, ERREST, ERROR, ERRREL, EXACT1, F1, RESULT
INTRINSIC  ABS
EXTERNAL  F1, QDAGS, UMACH

REAL      A2, B2, ERRABS2, ERREST2, ERROR2, ERRREL2, EXACT2, F2, RESULT2
EXTERNAL  F2

REAL      CI, VALUE, X
EXTERNAL  CI
```

```
OPEN(UNIT=50, FILE="ALL_IN_ONE_RESULTS.TXT",STATUS="UNKNOWN")
WRITE(50,*)"=========================================================================="
WRITE(50,*)"                HIGH VISCOUS TRANSPORT MODEL                 "
WRITE(50,*)"                    VERSION 0.0.00               "
WRITE(50,*)"                        BY                "
WRITE(50,*)"                TAN MING CHAI (0000 1498)               "
WRITE(50,*)"              MECHANICAL ENGINEERING PROGRAMME                  "
WRITE(50,*)"=========================================================================="

WRITE(50,*)"                 FINAL YEAR DESIGN PROJECT                 "
WRITE(50,*)"                UNIVERSITI TEKNOLOGI PETRONAS                "
WRITE(50,*)"                  ALL RIGHTS RESERVED               "


!--KEY PARAMETERS IN HVTM----------------------------------------------------------------
        RADIUS     = 0.34488  !UNIT = [m]
        PIPE_LENGTH = 250000   !UNIT = [m]
        TEMPINLET   = 80      !UNIT = [DEGREE CELCIUS]
        POUTLET     = 584.148  !UNIT = [kPA]
        C1          = 0.25          !UNIT = [DIMENSIONLESS] ~ROUGH ESTIMATION~

  KSOIL      = 1.5     !UNIT = [W / m.deg. C]     THERMAL CONDUCTIVITY OF SOIL
        KPIPE       = 50.0    !UNIT = [W / m.deg. C]     THERMAL CONDUCTIVITY OF PIPE
        DEPTH       = 1000    !UNIT = [m]                BURIED DEPTH
        THICKNESS   = 0.01072  !UNIT = [m]               PIPE THICKNESS
        AMBIENTTEMP = 32.0    !UNIT = [DEGREE CELCIUS]   AMBIENT TEMPERATURE

        PRINT*, " ENTER THE FLOW RATE FOR ANALYSIS (IN m3/s) :-"
        PRINT*, " 1. 0.05787 m3/s OR  5000 bbl/day "
        PRINT*, " 2. 0.11570 m3/s OR 10000 bbl/day "
        PRINT*, " 3. 0.17361 m3/s OR 15000 bbl/day "
        PRINT*, " 4. 0.23148 m3/s OR 20000 bbl/day "
        PRINT*, " 5. 0.28935 m3/s OR 25000 bbl/day "

        READ*, FLOWRATE                              !UNIT = [m3/s]

        IF (FLOWRATE == 0.05787) THEN
        PCONSTANT = -0.01
        TCONSTANT = 1.8
        ELSE IF (FLOWRATE == 0.011570) THEN
        PCONSTANT = -0.133
        TCONSTANT = 4.75
        ELSE IF (FLOWRATE == 0.17361) THEN
        PCONSTANT = -0.02
```

```
        TCONSTANT = 4.75
        ELSE IF (FLOWRATE == 0.23148 .OR. FLOWRATE == 0.28935) THEN
        PCONSTANT = -0.025
        TCONSTANT = 8.0
        END IF

WRITE(50,*)
!*****************************************************************************************
!  HIGH VISCOUS TRANSPORT MODEL
!        PART ONE
!*****************************************************************************************
PRINT*, "ENTER WALL TEMPERATURE :- "
READ*, TEMPWALL
PRINT*, "ENTER CENTER TEMPERATURE :- "
READ*, TEMPCENTER

        IF (TEMPWALL >= 44) THEN
        VISCOWALL = -0.0335*TEMPWALL + 8.1064
        ELSE IF (TEMPWALL >= 39 .AND. TEMPWALL < 44) THEN
        VISCOWALL = 7.0508*(TEMPWALL**2) - 612.22*TEMPWALL + 13295
        ELSE IF (TEMPWALL >= 19 .AND. TEMPWALL < 39) THEN
        VISCOWALL = -0.1317*(TEMPWALL**3) + 13.566*(TEMPWALL**2) - 484.05*TEMPWALL + 6196
        ELSE IF (TEMPWALL >= 4 .AND. TEMPWALL < 19) THEN
        VISCOWALL = 0.3379*(TEMPWALL**4) - 19.688*(TEMPWALL**3) + 411.1*(TEMPWALL**2) - 3698*TEMPWALL + 13835
        END IF

        TEMPCENTER = 1.0*TEMPCENTER
        IF (TEMPCENTER >= 44) THEN
        VISCOCENTER = -0.0335*TEMPCENTER + 8.1064
        ELSE IF (TEMPCENTER >= 39 .AND. TEMPCENTER < 44) THEN
        VISCOCENTER = 7.0508*(TEMPCENTER**2) - 612.22*TEMPCENTER + 13295
        ELSE IF (TEMPCENTER >= 19 .AND. TEMPCENTER < 39) THEN
        VISCOCENTER = -0.1317*(TEMPCENTER**3) + 13.566*(TEMPCENTER**2) - 484.05*TEMPCENTER + 6196
        ELSE IF (TEMPCENTER >= 4 .AND. TEMPCENTER < 19) THEN
        VISCOCENTER = 0.3379*(TEMPCENTER**4) - 19.688*(TEMPCENTER**3) + 411.1*(TEMPCENTER**2) - 3698*TEMPCENTER + 13835
        END IF

        TEMPAVERAGE = (TEMPWALL+TEMPCENTER)/2

        PRINT*, TEMPWALL, VISCOWALL, "cP"
        PRINT*, TEMPCENTER, VISCOCENTER, "cP"

        VISCOWALL = VISCOWALL*0.001
        VISCOCENTER = VISCOCENTER*0.001
```

```
      PRINT*, "---CONVERSION----"
      PRINT*, TEMPWALL, VISCOWALL, "Pa.s"
      PRINT*, TEMPCENTER, VISCOCENTER, "Pa.s"

!****************************************************************** END OF HVTM PART ONE ***


!+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
!
!                  FLUID PROPERTIES GENERATOR
!         PROGRAM DEVELOPED BY TULSA UNIVERSITY FLUID FLOW PROJECT TEAM
!          COURTESY OF DR AHMAD BAZLEE MAT ZAIN (PhD, TULSA UNIVERSITY)
!
!+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

!**********************************************************************
!   SPECIFY *.TAB AND *.THM LOOK UP TABLES HERE
!         *.TAB FILE IS GENERATED OUTSIDE
!         *.THM FILE GENERATED OUTSIDE
!**********************************************************************
      FTHM='DULANG.THM'
      FILETHM='DULANG.TAB'
      TDYN='VARIABLES.TXT'
!**********************************************************************
!         READ *.THM LOOK UP TABLE FOR DC/DT
!**********************************************************************
      CALL READDCDT(FTHM,TDYN)
!**********************************************************************
!         READ *.TAB LOOK UP TABLEPROGRAM VISCOSITYTRIAL1 FOR FLUID PROPERTIES
!**********************************************************************
      CALL READPROP(FILETHM)
!**********************************************************************
   P=.109431E+07
      T= TEMPAVERAGE
      CALL GETFLPRP(T,P,DENG,DENL,GMF,VISG,VISL,CPG,CPL,THKG,THKL,SURL,ENTH)
      T=T+273.15
   CALL THERMO(SF,SMW,FMW,ROS,ROF,T,P,DCDT,TCLOUD,VISLW)
      T=T-273.15
      WRITE (*,*)  T,P,DENG,DENL,GMF,VISG,VISL,CPG,CPL,THKG,THKL,SURL,ENTH

!++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++ END OF PROGRAM BY TUFFP +++
```

```
!*************************************************************************************
!   HIGH VISCOUS TRANSPORT MODEL
!          PART TWO
!*************************************************************************************

OPEN(UNIT=15, FILE="SUMMARY.TXT",STATUS="REPLACE")
OPEN(UNIT=16, FILE="CONSTANT.TXT",STATUS="REPLACE")
OPEN(UNIT=17, FILE="CONSTANTINTEGRAL.TXT",STATUS="UNKNOWN")
OPEN(UNIT=18, FILE="VISCOSITY1.TXT",STATUS="UNKNOWN")
OPEN(UNIT=19, FILE="VISCOSITY2_TEMPRADIUS.TXT",STATUS="UNKNOWN")
OPEN(UNIT=20, FILE="CONSTANTPROPINTEGRAL.TXT",STATUS="UNKNOWN")

  AREA = PI*(RADIUS**2)/4
        A = (VISCOWALL - VISCOCENTER)*C1/(RADIUS**2)
        B = VISCOCENTER

                DO DELTAR1 = -RADIUS, RADIUS, 0.17244

                VISCOSITY1 = ((VISCOWALL-VISCOCENTER)*C1*(DELTAR1**2)/(RADIUS**2)) + VISCOCENTER
                DO
                VELOCITY1 = 0.5*((LOG(B + A*(RADIUS**2)))/(2*A) - (LOG(B + A*(DELTAR1**2)))/(2*A))

                CALL RANDOM_NUMBER (C2)
                CALL RANDOM_NUMBER (C3)
                CALL RANDOM_NUMBER (C4)
                VELOCITY2 = C2*((COS(DELTAR1/C3))+C4)

                VELERROR1 = ABS(VELOCITY1 - VELOCITY2)
                IF (VELOCITY1 == 0) THEN
                VELERROR3 = 1
                VELERROR2 = (VELERROR1 / VELERROR3)

                ELSE
                VELERROR3 = VELOCITY1
                VELERROR2 = (VELERROR1 / VELERROR3)

                END IF

                IF ((VELERROR1 / VELERROR3) < 0.000001) EXIT

                END DO

        WRITE(15,11) DELTAR1, VELOCITY1, VELOCITY2
        11 FORMAT(1X, F10.5, 3X, F10.5, 3X, F10.5)
```

```fortran
        WRITE(16,12) DELTAR1, C2, C3, C4
        12 FORMAT(1X, F10.5, 3X, F10.5, 3X, F10.5, 3X, F10.5)

        WRITE(18,13) DELTAR1, VISCOSITY1
        13 FORMAT(1X, F10.5, 3X, F10.5)

        PRINT*, "----VELOCITY----"
        PRINT*, DELTAR1, VELOCITY1, VELOCITY2, VISCOSITY1

        END DO

        WRITE(17,10) C2, C3, C4
        10 FORMAT(1X, F10.5  &
                 /1X, F10.5 &
                 /1X, F10.5)

!***************************************************************** END OF HVTM PART TWO ***

  !~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
  ! MATHEMATICAL INTEGRATION ROUTINE
  !~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

  ! Get output unit number
    CALL UMACH (2, NOUT)
  ! Set limits of integration
    A1 = 0.0
    B1 = RADIUS
  ! Set error tolerances
    ERRABS = 0.0
    ERRREL = 0.001
    CALL QDAGS (F1, A1, B1, ERRABS, ERRREL, RESULT, ERREST)
  ! Print results
    EXACT1 = -4.0
    ERROR = ABS(RESULT-EXACT1)
    WRITE (NOUT,150) RESULT, EXACT1
    150 FORMAT (' Computed =', F8.3, 13X, ' Exact =', F8.3)

  !~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~ END OF ROUTINE ~~~

!******************************************************************************************
!  HIGH VISCOUS TRANSPORT MODEL
!        PART THREE
!******************************************************************************************
```

```
        DPDZ = FLOWRATE / RESULT
        PRINT*, DPDZ

OPEN (UNIT=16, FILE="CONSTANT.TXT", STATUS="OLD", ACTION="READ", POSITION="REWIND")
        ALPHA = THKL / (DENL*CPL)
        H4 = 25.0 !AIR CONVECTION
        NU = 3.66 !NUSSELT NUMBER
        H1 = 2*RADIUS*NU/THKL
        WALLTEMP = TEMPWALL

        !PRINT*, ALPHA
        TERM1 = 1/H1
        TERM2 = (RADIUS/KPIPE)*LOG((RADIUS+THICKNESS)+RADIUS)
TERM3 = (RADIUS/KSOIL)*LOG((RADIUS+THICKNESS+DEPTH)/(RADIUS+THICKNESS))
TERM4 = (1/H4)*(RADIUS/(RADIUS+THICKNESS+DEPTH))
U = 1/(TERM1+TERM2+TERM3+TERM4)
        !PRINT*, U
                DO
                READ (16, FMT=12,IOSTAT=INPUTSTATUS) DELTAR3, C2, C3, C4
                IF (INPUTSTATUS > 0) STOP "***INPUT ERROR***"
                IF (INPUTSTATUS < 0) EXIT ! END OF FILE
                DTDR = (1/RADIUS)*((1/ALPHA)*DTDZ*DPDZ*C2*(C3*DELTAR3*SIN(DELTAR3/C3)+(C3**2)*COS(DELTAR3/C3)+0.5*(DELTAR3**2)*C4))
 DTDZ = (U*(WALLTEMP - AMBIENTTEMP)*2*PI*RADIUS) / (FLOWRATE*CPL*DENL)

                ! Compute
                 X    = ABS(DELTAR3/C3)
                 IF (X==0) THEN
                 VALUE = 0
                 ELSE
                 VALUE = CI(X)
                 END IF
                ! Print the results
                 CALL UMACH (2, NOUT)
                !WRITE (NOUT,1000) X, VALUE
 !1000  FORMAT (' CI(', F6.3, ') = ', F6.3)
       CONSTANT = TEMPWALL - (1/ALPHA)*DTDZ*DPDZ*C2*((-C3**2)*COS(RADIUS/C3) + (C3**2)*VALUE + 0.5*(RADIUS**2)*C4)
                TEMPRADIUS = ((1/ALPHA)*DTDZ*DPDZ*C2*(-(C3**2)*COS(DELTAR3/C3) + (C3**2)*VALUE + 0.5*(DELTAR3**2)*C4)) + CONSTANT

                        IF (TEMPRADIUS >= 44) THEN
                        VISCOSITY2 = -0.0335*TEMPRADIUS + 8.1064
                        ELSE IF (TEMPRADIUS >= 39 .AND. TEMPRADIUS < 44) THEN
                        VISCOSITY2 = 7.0508*(TEMPRADIUS**2) - 612.22*TEMPRADIUS + 13295
                        ELSE IF (TEMPRADIUS >= 19 .AND. TEMPRADIUS < 39) THEN
                        VISCOSITY2 = -0.1317*(TEMPRADIUS**3) + 13.566*(TEMPRADIUS**2) - 484.05*TEMPRADIUS + 6196
```

```
                    ELSE IF (TEMPRADIUS >= 4 .AND. TEMPRADIUS < 19) THEN
                    VISCOSITY2 = 0.3379*(TEMPRADIUS**4) - 19.688*(TEMPRADIUS**3) + 411.1*(TEMPRADIUS**2) - 3698*TEMPRADIUS + 13835
                    END IF
                    VISCOSITY2 = VISCOSITY2*0.001

            WRITE(19,14) VISCOSITY2, TEMPRADIUS
            14 FORMAT(1X, F10.5, 6X, F10.5)
            PRINT*, DTDR, DTDZ, TEMPRADIUS, VISCOSITY2
            END DO

            WRITE(20,20) TEMPWALL, ALPHA, DTDZ, DPDZ, VALUE
     20 FORMAT(1X, F20.10 &
                       /1X, F20.10 &
                       /1X, F20.10 &
                              /1X, F20.10 &
                              /1X, F20.10 )

        OPEN (UNIT=18, FILE="VISCOSITY1.TXT", STATUS="OLD", ACTION="READ", POSITION="REWIND")
        OPEN (UNIT=19, FILE="VISCOSITY2_TEMPRADIUS.TXT", STATUS="OLD", ACTION="READ", POSITION="REWIND")
        IF (OPENSTATUS > 0) STOP "***CANNOT OPEN FILE***"
  PRINT*, "-------------------------------------------------------------------"

        DO
        READ (18, FMT=13,IOSTAT=INPUTSTATUS) DELTAR1, VISCOSITY1
  IF (INPUTSTATUS > 0) STOP "***INPUT ERROR***"
        IF (INPUTSTATUS < 0) EXIT ! END OF FILE

        READ (19, FMT=14,IOSTAT=INPUTSTATUS) VISCOSITY2, TEMPRADIUS
        IF (INPUTSTATUS > 0) STOP "***INPUT ERROR***"
        IF (INPUTSTATUS < 0) EXIT ! END OF FILE
        VISCOERROR1 = ABS(VISCOSITY1-VISCOSITY2)
        PRINT*, "---VISCOSITY----"
        PRINT*, VISCOSITY1, VISCOSITY2, VISCOERROR1
        END DO

!   Get output unit number
    CALL UMACH (2, NOUT)
!   Set limits of integration
    A2 = 0.0
    B2 = RADIUS
!   Set error tolerances
    ERRABS2 = 0.0
    ERRREL2 = 0.001
```

```fortran
   CALL QDAGS (F2, A2, B2, ERRABS2, ERRREL2, RESULT2, ERREST2)
!  Print results
   EXACT2 = -5.0
   ERROR2 = ABS(RESULT2-EXACT2)
   WRITE (NOUT,160) RESULT2, EXACT2
160  FORMAT (' Computed =', F20.10, 13X, ' Exact =', F8.3)
         MEANTEMP = RESULT2/FLOWRATE
         PRINT*, "MEAN TEMPERATURE =", MEANTEMP
         PRINT*, RESULT, FLOWRATE
         PRINT*, FLOWRATE/RESULT
         PRINT*, "CPL = ", CPL
         DTDZ = U*(TEMPWALL-AMBIENTTEMP)*2.0*3.142*RADIUS/(FLOWRATE*CPL*DENL)
         PRINT*, "DPDZ =", DPDZ

!*************************************************************** END OF HVTM PART THREE ***

!*********************************************************************************
!  HIGH VISCOUS TRANSPORT MODEL
!       PART FOUR
!*********************************************************************************
         OPEN(UNIT=30, FILE="PRESSURE_ONLY.TXT",STATUS="UNKNOWN")
         DO LENGTH = -PIPE_LENGTH, 0, 25000
         PINLET = PCONSTANT*(FLOWRATE/RESULT)*(LENGTH) +  POUTLET !kPa
         WRITE(30,40) PINLET
         40 FORMAT(1X, F15.5)
   END DO

         OPEN(UNIT=31, FILE="TEMPERATURE_ONLY.TXT",STATUS="UNKNOWN")
         DO LENGTH = 0, PIPE_LENGTH, 25000
         TEMPOUTLET = TCONSTANT*((U*(TEMPWALL-AMBIENTTEMP)*2*PI*RADIUS)/(FLOWRATE*CPL*DENL))*(LENGTH) + TEMPINLET
         WRITE(31,41) LENGTH, TEMPOUTLET
         41 FORMAT(1X, F15.5, 5X, F15.5)
         END DO

         WRITE(50,*)"AXIAL PRESSURE & TEMPERATURE PROFILE          HIGH VISCOUS TRANSPORT MODEL"
         WRITE(50,*)"------------------------------------------------------------------------------"
         WRITE(50,*)
         WRITE(50,*)"    LENGTH, L      PRESSURE, P        TEMPERATURE,              "
         WRITE(50,*)"     [M]            [kPa]         [DEG. CELCIUS]             "
         WRITE(50,*)"    ==========     ============      ===============             "

         OPEN (UNIT=30, FILE="PRESSURE_ONLY.TXT", STATUS="OLD", ACTION="READ", POSITION="REWIND")
         OPEN (UNIT=31, FILE="TEMPERATURE_ONLY.TXT", STATUS="OLD", ACTION="READ", POSITION="REWIND")
         OPEN (UNIT=32, FILE="FLUID_PROPERTIES.TXT",STATUS="UNKNOWN")
```

```
	DO
	READ (30, FMT=40, IOSTAT=INPUTSTATUS) PINLET
IF (INPUTSTATUS > 0) STOP "***INPUT ERROR***"
	IF (INPUTSTATUS < 0) EXIT ! END OF FILE

	READ (31, FMT=41, IOSTAT=INPUTSTATUS) LENGTH, TEMPOUTLET
IF (INPUTSTATUS > 0) STOP "***INPUT ERROR***"
	IF (INPUTSTATUS < 0) EXIT ! END OF FILE

	!*******************************************************************
	!	READ *.TAB LOOK UP TABLEPROGRAM VISCOSITYTRIAL1 FOR FLUID PROPERTIES
	!*******************************************************************
	 CALL READPROP(FILETHM)
!*******************************************************************
		P= PINLET ! 0.1094310E07
		T= TEMPOUTLET
		CALL GETFLPRP(T,P,DENG,DENL,GMF,VISG,VISL,CPG,CPL,THKG,THKL,SURL,ENTH)
		T=T+273.15
		CALL THERMO(SF,SMW,FMW,ROS,ROF,T,P,DCDT,TCLOUD,VISLW)
		T=T-273.15

			IF (TEMPOUTLET >= 44) THEN
			VISCOSITYL = -0.0335*TEMPOUTLET + 8.1064
			ELSE IF (TEMPOUTLET >= 39 .AND. TEMPOUTLET < 44) THEN
			VISCOSITYL = 7.0508*(TEMPOUTLET**2) - 612.22*TEMPOUTLET + 13295
			ELSE IF (TEMPOUTLET >= 19 .AND. TEMPOUTLET < 39) THEN
			VISCOSITYL = -0.1317*(TEMPOUTLET**3) + 13.566*(TEMPOUTLET**2) - 484.05*TEMPOUTLET + 6196
			ELSE IF (TEMPOUTLET >= 4 .AND. TEMPOUTLET < 19) THEN
			VISCOSITYL = 0.3379*(TEMPOUTLET**4) - 19.688*(TEMPOUTLET**3) + 411.1*(TEMPOUTLET**2) - 3698*TEMPOUTLET + 13835
			END IF
			VISCOSITYL = VISCOSITYL*0.001

		VELOCITY = FLOWRATE/AREA
		REYNOLDSNO = DENL*VELOCITY*(2*RADIUS)/VISCOSITYL
		PRINT*, REYNOLDSNO

		WRITE(32,42) DENL, VISCOSITYL, CPL, REYNOLDSNO
		42 FORMAT(1X, F15.5, 3X, F8.5, 3X, F10.5, 3X, F13.5)
	END DO

	OPEN (UNIT=30, FILE="PRESSURE_ONLY.TXT", STATUS="OLD", ACTION="READ", POSITION="REWIND")
	OPEN (UNIT=31, FILE="TEMPERATURE_ONLY.TXT", STATUS="OLD", ACTION="READ", POSITION="REWIND")
	DO
```

```
READ (30, FMT=40, IOSTAT=INPUTSTATUS) PINLET
IF (INPUTSTATUS > 0) STOP "***INPUT ERROR***"
IF (INPUTSTATUS < 0) EXIT ! END OF FILE

READ (31, FMT=41, IOSTAT=INPUTSTATUS) LENGTH, TEMPOUTLET
 IF (INPUTSTATUS > 0) STOP "***INPUT ERROR***"
IF (INPUTSTATUS < 0) EXIT ! END OF FILE
WRITE(50,*)" ",LENGTH,"     ",PINLET,"    ", TEMPOUTLET
END DO

WRITE(50,*)"
                "

WRITE(50,*)"
                "

WRITE(50,*)"FLUID PROPERTIES ALONG PIPELINE              HIGH VISCOUS TRANSPORT MODEL"
WRITE(50,*)"-----------------------------------------------------------------------------"
WRITE(50,*)"              LIQUID      LIQUID       LIQUID               "
WRITE(50,*)"    LENGTH      DENSITY      VISCOSITY  SPECIFIC HEAT      REYNOLDS   "
WRITE(50,*)"     [m]        [kg/m3]        [Pa.s]   [kJ/kg.deg C]      NUMBER     "

OPEN (UNIT=31, FILE="TEMPERATURE_ONLY.TXT", STATUS="OLD", ACTION="READ", POSITION="REWIND")
OPEN (UNIT=32, FILE="FLUID_PROPERTIES.TXT", STATUS="OLD", ACTION="READ", POSITION="REWIND")

DO
READ (32, FMT=42, IOSTAT=INPUTSTATUS) DENL, VISCOSITYL, CPL, REYNOLDSNO
IF (INPUTSTATUS > 0) STOP "***INPUT ERROR***"
IF (INPUTSTATUS < 0) EXIT ! END OF FILE
WRITE(50,43) PIPE_LENGTH, DENL, VISCOSITYL, CPL, REYNOLDSNO
43 FORMAT(4X, F12.5, 3X, F10.5, 3X, F10.5, 6X, F10.5, 7X, F10.3 )
END DO

WRITE(50,*)"
                "

WRITE(50,*)"
                "

WRITE(50,*)"RADIAL VELOCITY, TEMPERATURE & VISCOSITY        HIGH VISCOUS TRANSPORT MODEL"
WRITE(50,*)"-----------------------------------------------------------------------------"
WRITE(50,*)"WALL TEMPERATURE          = ", TEMPWALL, " DEGREE CELCIUS"
WRITE(50,*)"CENTER TEMPERATURE        = ", TEMPCENTER, " DEGREE CELCIUS"
WRITE(50,*)"AVERAGE TEMPERATURE       = ", TEMPAVERAGE, " DEGREE CELCIUS"
WRITE(50,*)"CALCULATED MEAN TEMPERATURE = ", MEANTEMP, " DEGREE CELCIUS"
WRITE(50,*)"
                "

WRITE(50,*)"DPDZ                  = ", DPDZ, " Pa / m"
```

```
        WRITE(50,*)"FLOWRATE              = ", FLOWRATE, " m3/ s"
        WRITE(50,*)"                                                  "

        WRITE(50,*)"              RADIAL      RADIAL      RADIAL          "
        WRITE(50,*)"   RADIUS     VELOCITY    TEMPERATURE   VISCOSITY         "
        WRITE(50,*)"    [m]        [m/s]       [deg. c]     [Pa.s]       "
        WRITE(50,*)"  ========   ==========   ============  ===========     "
        OPEN (UNIT=15, FILE="SUMMARY.TXT", STATUS="OLD", ACTION="READ", POSITION="REWIND")
        OPEN (UNIT=19, FILE="VISCOSITY2_TEMPRADIUS.TXT", STATUS="OLD", ACTION="READ", POSITION="REWIND")

        DO
        READ (15, FMT=11, IOSTAT=INPUTSTATUS) DELTAR1, VELOCITY1, VELOCITY2
        IF (INPUTSTATUS > 0) STOP "***INPUT ERROR***"
        IF (INPUTSTATUS < 0) EXIT ! END OF FILE

        READ (19, FMT=14, IOSTAT=INPUTSTATUS) VISCOSITY2, TEMPRADIUS
        IF (INPUTSTATUS > 0) STOP "***INPUT ERROR***"
        IF (INPUTSTATUS < 0) EXIT ! END OF FILE
        WRITE(50,*) DELTAR1, VELOCITY1, TEMPRADIUS, VISCOSITY2
        END DO

!****************************************************************** END OF HVTM PART FOUR ***

END PROGRAM MAIN

!*************************************************************************** END OF HVTM ***

   REAL FUNCTION F1 (DELTAR2)
   REAL      DELTAR2, C2, C3, C4
   REAL, PARAMETER :: PI =3.14159
        INTRINSIC COS
        OPEN(UNIT=17,FILE="CONSTANTINTEGRAL.TXT",STATUS="OLD", ACTION="READ", POSITION="REWIND")
        READ(17,*) C2,C3,C4
   F1 = (C2 * (COS(DELTAR2/C3)) + C4) * (2*PI*DELTAR2)
   RETURN
   END

        REAL FUNCTION F2 (DELTAR3)
        REAL      DELTAR3, C2, C3, C4
        REAL      TEMPRADIUS, ALPHA, DTDZ, DPDZ, VALUE, CONSTANT, TEMPWALL
        REAL, PARAMETER :: PI =3.14159
        REAL, PARAMETER :: RADIUS = 0.34488
        INTRINSIC COS
        OPEN(UNIT=17,FILE="CONSTANTINTEGRAL.TXT",STATUS="OLD", ACTION="READ", POSITION="REWIND")
```

```
READ(17,*) C2,C3,C4
OPEN(UNIT=20,FILE="CONSTANTPROPINTEGRAL.TXT",STATUS="OLD", ACTION="READ", POSITION="REWIND")
READ(20,*) TEMPWALL, ALPHA, DTDZ, DPDZ, VALUE
CONSTANT = TEMPWALL - (1/ALPHA)*DTDZ*DPDZ*C2*((-C3**2)*COS(RADIUS/C3) + (C3**2)*VALUE + 0.5*(RADIUS**2)*C4)
TEMPRADIUS = ((1/ALPHA)*DTDZ*DPDZ*C2*(-(C3**2)*COS(DELTAR3/C3) + (C3**2)*VALUE + 0.5*(DELTAR3**2)*C4)) + CONSTANT
F2 = (C2 * (COS(DELTAR3/C3)) + C4) * TEMPRADIUS* (2*PI*DELTAR3)
RETURN
END
```