Sudan University of Science and Technology
College of Petroleum Engineering and Technology
Department of Transportation and Refining Engineering

Study of the Effect of Flow Improvers on the operation of Heglig-Port Sudan Pipeline

دراسة تأثيرمحسنات الجريان على الظروف التشغيلية على خط انابيب هجليج-بورتسودان

Project submitted in partial fulfillment of the requirement for the Bachelor of Engineering (Hons.) Degree in Transportation and Refining Engineering

Prepared by

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الإستهلال

قال تعالى:

(وَقُلِ اعْمَلُوا فَسَيَرَى اللَّهُ عَمَلَكُمْ وَرَسُولُهُ
وَالْمُؤْمِنُونَ وَسَتُرَدُّونَ إِلَى عَالِمِ الْغَيْبِ وَالشَّهَادَةِ
فَيُنَبِّئُكُمْ بِمَا كُنْتُمْ تَعْمَلُونَ)

سورة التوبة (105)

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Dedication

This research paper is lovingly dedicated to our beloved and respective parents who have been our constant source of inspiration. They have given us the drive and discipline to tackle any task and overcome obstacles with enthusiasm and determination. Without their love and support this project would not have seen the light.

Abstract

In this research the effect of a flow improver (i.e. Pour Point Depressant) on the operation of Heglig-Port Sudan Pipeline has been studied. Two types of PPD, namely PPD 25J1 and PPD 25J2, have been used with different operation scenarios, by adding either of them to the flowing fluid at different doses (concentrations). The energy (i.e. pressure) required to transport the flowing fluid through the pipeline, has been calculated in every case (scenario). This study utilized PIPESIM software to calculate the pressure losses encountered during the transportation. The optimum scenario has been selected, among all other scenarios, based on the lowest combined cost of the operation of pump stations and the cost of adding PPD. It has been found that the optimum operation scenario is obtained by adding the PPD type 25J1 to the flowing fluid at 500 PPM.

Key words: Neem field oil, PPD, Dose, PIPESIM, Rheology, Cost, Scenario

التجريد

في هذا البحث تم دراسة تأثير محسنات الجريان (مخفضات درجة الإنسكاب) على تشغيل خط أنابيب هجليج-بورتسودان. تم إستخدام نوعين من مخفضات درجة الإنسكاب مع خيارات تشغيلة مختلفة للخط، بحيث يضاف أحدهما للمائع المنساب خلال خط الأنابيب بجرعات (تراكيز) مختلفة. تم حساب الطاقة (الضغط) المطلوبة لنقل المائع المنساب في خط الأنابيب لكل خيار تشغيلي. في هذه الدراسة تم إستخدام التطبيق الحاسوبي PIPESIM في عملية حساب فواقد الضغط خلال عملية النقل. الخيار التشغيلي الأمثل تم إختياره وفقا للتكلفة الأقل الناتجة عن تشغيل محطات الضخ و إضافة مخفض درجة الإنسكاب. وجد أن الخيار التشغيلي الأمثل يمكن تحقيقه عن طريق إضافة مخفض درجة الإنسكاب 25J1 للمائع المنساب بتركيز قدره 500 PPM.

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Nomenclature

n	The power factor or flow behavior index
τ	Shear stress
γ	Shear rate
τ_y	Yield stress
K	Apparent viscosity
η, μ	Viscosity
P	Pressure
T	Temperature
D	Inner diameter
ε	Roughness
δ	Thickness
ρ	Density
g	Gravity
Ө	Angle of pipe
f	Friction factor
v	Velocity
l	Length of pipe
Re	Reynolds number
U	Pipe heat transfer coefficient
API	American Petroleum Institute
CPL	Central Petroleum Laboratories
GNPOC	Greater Nile Operating Company
GOR	Gas Oil Ratio
PPD	Pour Point Depressant
PPM	Part per million
WAT	Wax Appearance Temperature

Chapter 1

Introduction

1.1 Background

Petroleum well flow stream is produced in a form of a complex mixture of various fluids (crude oil, water, basic sediments, etc.) that, collectively, cause various problems during the production, separation, transport and refining of oil. A detailed analysis of the composition of the oil is of a high priority before establishing any process in oil industry **(Chen, 2006).**

Waxes are long-chain saturated alkanes found in many crude oils throughout the world. Crude oil requires special type of handling when waxes are anticipated to be formed. Wax occurrence leads to severe problems in petroleum transport pipelines and processing equipment. These problems include the restriction of flow in pipelines due to paraffin deposition in their walls, and this deposition may reach a level in which the entire pipeline is plugged. On the other hand, wax presence complicates the flow of the oil which results in an oil flowing system that is much more difficult to be predicted and evaluated **(Chen et al., 2006).**

Crude oil is a Newtonian fluid at high temperatures because the waxes are in the molten state. When the temperature drop below the wax appearance temperature, the crude oil is no longer Newtonian, because wax crystals precipitate out of the oil **(Chen et al., 2006)**.

The study of the rheological properties of the oil arises when it is required to define a proper method to prevent any problem caused by wax deposition. This study tends to examine the oil, to come out with certain properties that are related to the flow of oil such as the viscosity.

Several methods can be used to control the problems caused by waxes presence, these include thermal and chemical methods. Solvents and additives are two examples of the methods used for this purpose. Chemicals are added to enhance the rheological properties by reducing the rate of growth of wax crystals, and hence, reducing the wax appearance temperature **(Matho, 2010).**

1.2 Problem Statement

The transportation of waxy crude oils through pipelines encounters several methods are used to ensure safe and appropriate transport of the oil through pipelines. These methods differ in their economics, efficiency and compatibility. Since the Sudanese Heglig-Port Sudan pipeline is an example of pipelines transporting waxy crude oil, thorough investigation and study of its ability to provide safe and economical transportation is required. In order to achieve that successfully, different flow and environmental parameters should be taken into account. These parameters include, but are not limited to, heating treatment, flow improvers or pour point depressant (PPD) injection dosage, number and arrangement of operated pump station, and the type of injected PPD.

1.3 Study Area

Pipeline route:

GNPOC crude oil pipeline (Heglig -Port Sudan pipeline) extends from Heglig, in Southern Kurdufan province, crosses Sudan from the south-west to the north-east where it ends near Port Sudan on the Red Sea. The 1504 kilometer goes alternately through sandy plains and Mountain ranges crossing two peaks, the first close to the Nuba Mountains and the second up the Red Sea Mountains.

Two refineries are fed from this line (At El Obied and Khartoum) to meet the needs of domestic market for petroleum products. Below is the main data of Heglig-Port Sudan pipeline. The profile of the pipeline is shown in appendix (A).

Pipeline information:

- 1504 km of externally coated pipeline with 28 inch inner diameter.
- 6 pump stations, c/w, power generating facility, potable water and camp.
- 14 main block valve stations.
- 2 offtake block valve stations.
- 2 telemeter block valve at river crossing.
- 3 metering stations.

1.4 Objectives

The main objective of this study is to optimize the injection dosage of pour point depressant of Heglig-Port Sudan pipeline, with regards to operation scenarios of the pipeline. The specific objectives of the study are to:

1- Determine the effect of PPD on Neem field oil transportation through Heglig-Port Sudan pipeline,
2- Compare different operation scenarios of the pipeline,
3- Compare different PPD injection doses (concentrations) for specific scenarios,
4- And to come out with the optimum operation scenario from an economical point of view.

1.5 Methodology

The main data required to achieve this project was supplied by GNPOC (which is the owner of the pipeline) and CPL. The final results are obtained as follows:

- A reliable version of PIPESIM software was used to simulate the oil flow after building the pipeline model and defining the flowing oil.
- Two types of pour point depressant were used in the simulation.
- An optimum dose of pour point depressant was chosen after comparing and analyzing the two types with different doses for each.

1.6 Overview of Chapters

- Chapter one gives an introduction to the project.
- Chapter two discusses pervious works carried on the same topic of this project and gives a brief overview of topics related to this project.
- Chapter three discusses the methodology and outline the basis of cost analysis.
- Chapter four supplies a summary of the results and their discussion.
- Chapter five is the conclusion and recommendations of the study.

Chapter 2

Literature Review

2.1 Literature Review

(El-Gamal, 1997) has demonstrated the effect of shear on the viscosity of Umbarka waxy crude during cooling. He has also investigated the influence of a commercial flow improver on the rheological parameters of the tested crude oil during static and dynamic cooling.

The viscosity measurements were performed by a coaxial rotational viscometer equipped with a cooling thermostat bath and the flow improver was added in at different amounts.

El-Gamal has concluded that" shear effect act in the same way sense as flow improvers for improving the cold flow properties of waxy crudes, particularly below the pour point but in different manner. It supplements the role of flow improvers by exerting a minor decrease in dynamic yield strength accompanied with a substantial regular reduction of viscosity. It also delays the non-Newtonian flow behavior of the waxy crude to lower temperatures."

El-Gamal has found that combining both shear and flow improver leads to a significant reduction of both gel strength and apparent viscosity at a temperature range of 32~17°C.

(Al-Zahrani and Al-Fariss, 1998) have developed a generalized viscosity model suitable for describing the non-Newtonian behavior of waxy crudes (i.e. Saudi base oil). Al-Zahrani and Al-Fariss have stated that their model can be also used to predict the rheological properties of the oil within the Newtonian range. The developed model serves as a good technique to predict the viscosity of the oil as a function of shear rate, temperature, and wax concentration. Their test samples were prepared by adding different amounts of paraffin wax to a definite amount of Saudi base oil. The samples were then heated to assure a homogeneous mixture and the viscosity was then measured by a rotational-type viscometer.

(Fouad et al., 2004) have studied the effect of active heating and insulation options for transportation of waxy crude oil in an 8-inch flow line from a platform 10 miles offshore.

They concluded that the active heating option using pipe in pipe configuration is more effective than the insulation alternative.

(Shadi, 2007) has investigated the rheological properties of heavy crude oil (i.e. Canadian crude), using RheoStress RS 100 from Haake Including the effect of shear rate, temperature and oil concentration on the viscosity. Shadi has showed that the viscosity of the heavy crude can be effectively reduced by blending it with a limited amount of lighter crude oil or using an aqueous solution of surfactants.

(Fadul et al., 2012) have conducted experiments on samples of Sudanese crude (i.e. Nile blend) to describe its rheological behavior at different flow and thermal conditions, and hence, identifying the temperature dependency of these properties. They have stated that the abnormal temperature of the crude is in the range 40~42°C. These values were obtained after using a test jar to measure the pour points of the samples. The viscosities were measured by the viscometer VT500 with HAAKE phoenix P2 circulator. They also have accomplished tests on the effect of PPD addition on the rheological properties of the oil samples, and they have found that PPD's effect is higher when the sample is at a high temperature rather than at a low temperature.

(Mahto and Singh, 2013) have aimed to reduce the operating cost and problems encountered during production and transportation of waxy crude oil (i.e. Ankleshwar oil field crude). As for the experiment, Matho and Singh used the Brooke field viscometer for the determination of the viscosity at different temperatures. Later on, they added multiple different amounts of PPD to the crude samples in order to investigate the effect on the rheological properties. They have found that the pour point decreases sharply with the addition of 250 ppm pour point depressant, and the viscosity can be reduced with the addition of less amount of pour point depressant.

2.2 Rheology

Rheology is the study of the flow of materials that behave in an interesting or unusual manner. The relationship between shear stress and shear rate must be established in order to describe the rheological behavior of a fluid.

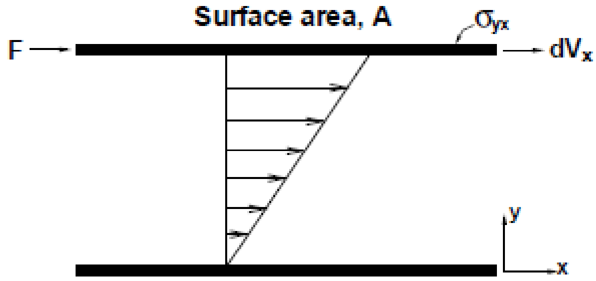


Figure 2-1: An object exhibiting strain under the effect of shear stress **(Chhabra, 2010)**

According to the effects produced under the action of a shear stress, fluids can be classified into:

1- Newtonian fluid.
2- Non-newtonian fluids.

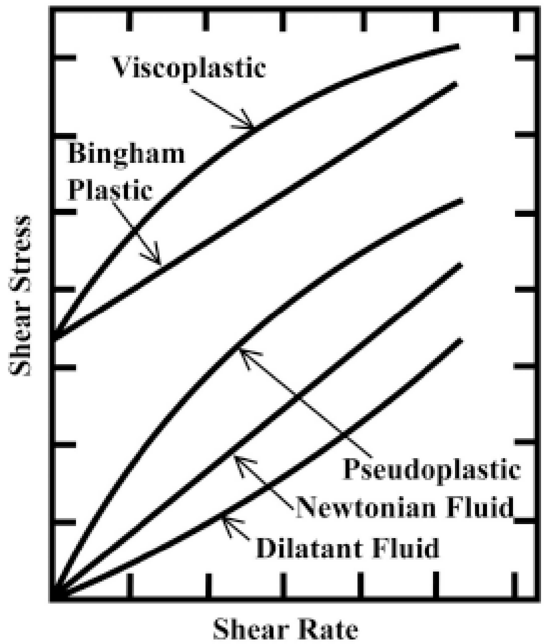


Figure 2-2: The relation between shear stress and shear rate for different fluid types **(Chhabra, 2010)**

2.2.1 Newtonian Fluid

For a Newtonian fluid, the relationship between shear stress and shear rate is linear, with a slope equals to a constant termed the viscosity.

$$\tau = \eta \gamma \qquad (2.1)$$

2.2.2 Non-Newtonian Fluid

A non-Newtonian fluid is that one whose shear rate is not directly proportional to the applied shear stress. It should also be pointed that a non-Newtonian fluid does not possess a constant value of viscosity. This type of fluids is described by the power law as follows:

$$\tau = \mathrm{K}\,\gamma^{n} \tag{2.2}$$

A non-Newtonian fluid can fall within one of the following categories:

1- Time independent fluid.
2- Time dependent fluid.

2.2.2.1 Time Independent Fluid

As stated earlier, this is a non-Newtonian fluid and it can be further classified into:

- Bingham plastic fluid

$$\tau = \tau_y + \mathrm{K}\,\gamma^{n} \tag{2.3}$$

- Pesudo-plastic fluid (shear thinning)

$$\tau = \mathrm{K}\,\gamma^{n}(n < 1) \tag{2.4}$$

- Dilatant fluid (shear thickening)

$$\tau = \mathrm{K}\,\gamma^{n}(n > 1) \tag{2.5}$$

A pseudo-plastic fluid is that one which thins out under shear effect, whilst, a dilatants fluid is vice versa.

2.2.2.2 Time Dependent Fluid

This is also a non-Newtonian fluid that may fall under one of the following categories:

- Thixotropic:

A thixotropic fluid is a fluid whose apparent viscosity decreses with time at constant shear rate.

- Rheopectic:

A rheopectic fluid is a fluid whose apparent viscosity increases with time at constant shear rate.

It must be pointed out that almost all waxy crude oils fall within the pseudo-plastic category.

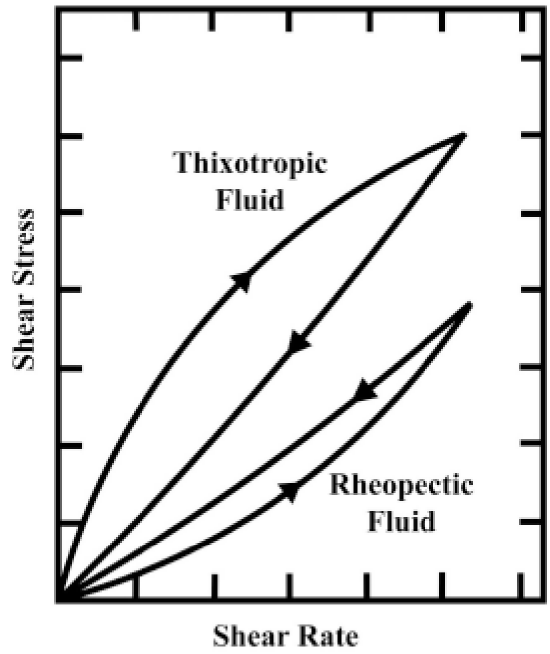


Figure 2-3: The relation between shear stress and shear rate for thixotropic and rheopectic fluids **(Chhabra,2010)**

2.3 Wax formation and WAT

Wax is mainly composed of paraffin hydrocarbons (C18-C36) and naphthenic hydrocarbons (C30-C60). Hydrocarbon constitutes of wax can exist in various state of matter depending on the prevailing temperature and pressure. Right when the wax freezes it forms wax crystals. Crystals formed from paraffins are known as macrocrystalline wax, while those formed form naphthenes are known as microcrystalline wax **(Hartono and Mansoori, 1999)**

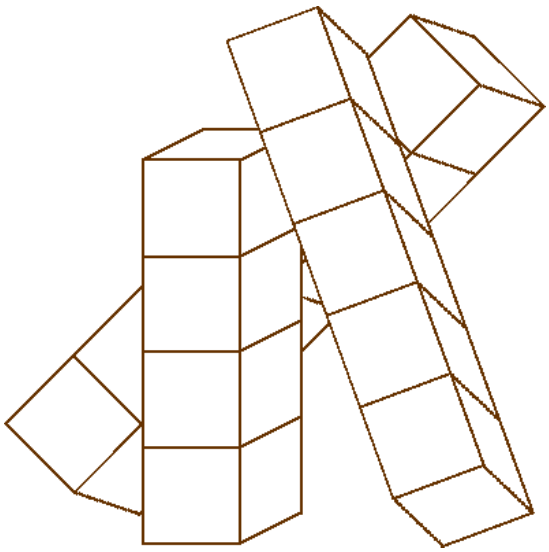


Figure 2-4: Macrocrystalline wax crystals **(Mansoori, n.d.)**

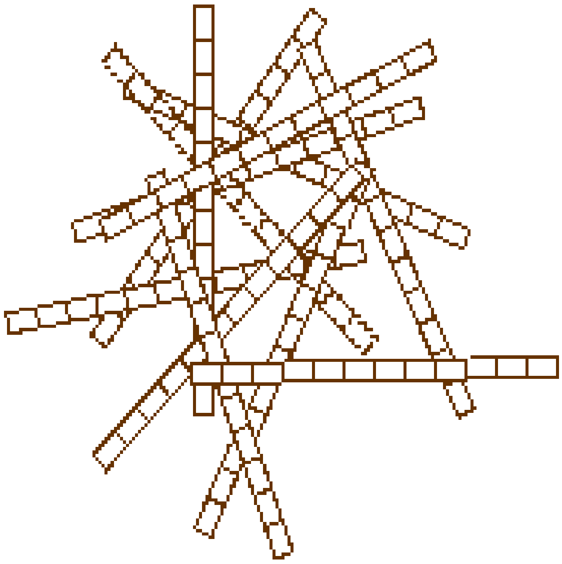


Figure 2-5: Microcrystalline wax crystals **(Mansoori, n.d.)**

As mentioned earlier, wax crystals are formed below some temperature, this temperature is known as wax appearance temperature (WAT). Generally WAT of the flowing fluid is always lower than that detected in the laboratory. This is due to the effect of shear force and turbulence **(Abdulaziz Abdul Kadir et al., 1998)**.

2.4 Wax Caused Problems

Engineers are always faced with problems caused by wax formation in different phases of the oil and gas industry. Basically wax problems evolve when the flow properties of the oil are changed from Newtonian to non-Newtonian behavior **(Shadi, 2007)**.

At the transportation phase, when wax crystals continue to appear, they start to form agglomerates due to the attraction forces between them. This agglomerates build up sharply increases the viscosity and immobilize a significant portion of the continuous phase. Consequently, the flow of the oil is delayed.

One common approach to overcome wax formation problems is to increase the shear rate. Increasing the shear rate will guarantee that the wax agglomerates are broken down into basic particles. However, higher capital cost and operation cost are required to establish this approach in terms of pumps and energy.

Wax deposition in most cases is inevitable. This is mostly the case when the flow of the oil is stopped for maintenance or overhauling. Although low temperature is required for wax crystals to form, some waxy crude oils have high WAT. In such scenarios, the deposition can be as worst as to plug the entire pipeline.

Generally, wax formation and deposition problems lead to the following:

1- A decrease in pipeline cross-sectional area due to the presence of deposits, which then limits throughout and operating capacity.
2- An increase in capital investment due to higher maintenance cost, the cost for remedial action, and prevention.
3- Placing additional strain on pumps, consuming more energy, and requiring additional investment for replacing pumps.
4- A loss of production due to complete blockage of pipes, which lead to costly periodic production shutdowns for maintenance and replacement.

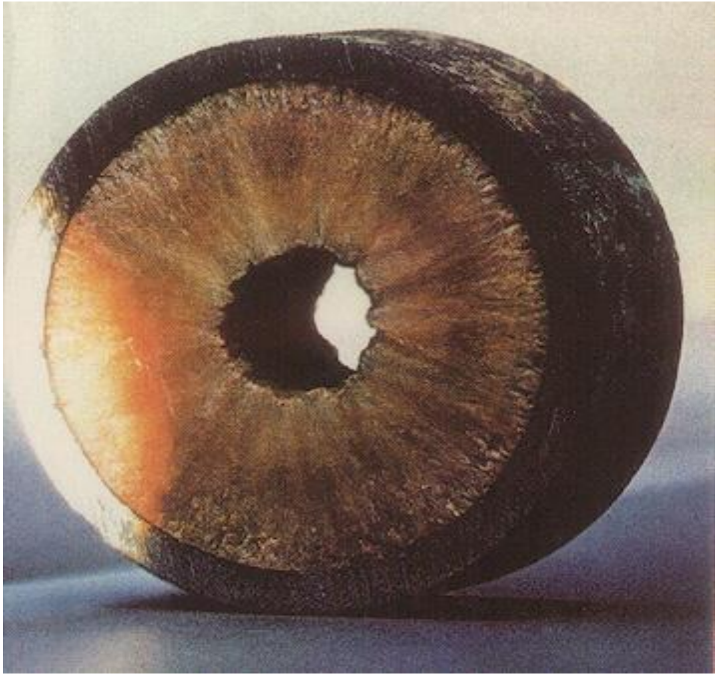


Figure 2-6: Pipeline cross-section pluged due to wax depositon **(Lee, 2008)**

2.5 Control, Prevention and Remediation of Wax Problems

Several methods can be used to control, prevent and remediate the problems caused by wax. The most common methods are the chemical method, thermal method, mechanical method, and biochemical method.

2.5.1 Thermal Method

This method involves heating the crude oil inside the pipe, in such a manner that its temperature is always greater than the wax appearance temperature. The heating is widely achieved in heating stations that are distributed along the pipe root **(Yan, 1987).**

Thermal method is relatively expensive. Normally, it's used in short distance pipes, such as those from individual wells to central processing plant in oil field **(Liu, 2002).**

2.5.2 Biochemical Method

In this method, microbes are used to produce a special type of surfactants to help in reducing the amount of waxes crystals that precipitate out of the continuous phase. This method is suitable for use in well bore **(Ansari et al., 1999; Banat et al., 2000; Matho et al., 2010).**

2.5.3 Chemical Method

Chemical method is the most effective method compared to other methods. The idea here is to add a material in some definite quantity to help in reducing the wax appearance temperature. The materials used for this purpose may include solvents, dispersants, surfactants, and wax crystals modifiers **(Deshmukh and Barambhe, 2008; Matho, 2010)**.

All these materials accomplish the same duty, but differ in their mechanisms. Solvents are added to increase the waxes solubility in the oil, which results in decreasing their precipitation out of the continuous phase.

Dispersants, surfactants, and wax crystal modifiers are considered as pour point depressants **(Dai, 2011)**. Pour point depressant (PPD) is a substance of a long side chains and nitrogen polar groups that helps in adjusting the waxes crystals to a new condition. PPD's attract the waxes to accumulate on their main chains and polar groups, which then prevent the crystals from connecting with each other, hence, resist waxes precipitation.

The effect of a PPD depends on the degree of compatibility between the crude oil and crystals of the modifier, therefore, there is no such a thing like a PPD to treat all waxy crude oils. Moreover, the more the amount of PPD added, the more clearly the effect on the rheological properties of the crude. Generally, the effect of PPD is to decrease the viscosity, but at some point, furthermore addition of PPD will have no effect.

2.5.4 Mechanical Method

Also widely known as pigging method. It's one of the most common methods used in field. In pigging, a solid object (pig) with a diameter smaller than the internal diameter of the pipe, is passed through the pipeline to scrape off the deposited wax as shown in figure 2-7.

The efficiency of this method depends on wax deposition prediction, therefor it is characterized by a high efficiency when there is a proper wax deposition prediction technology **(Lee, 2008).**

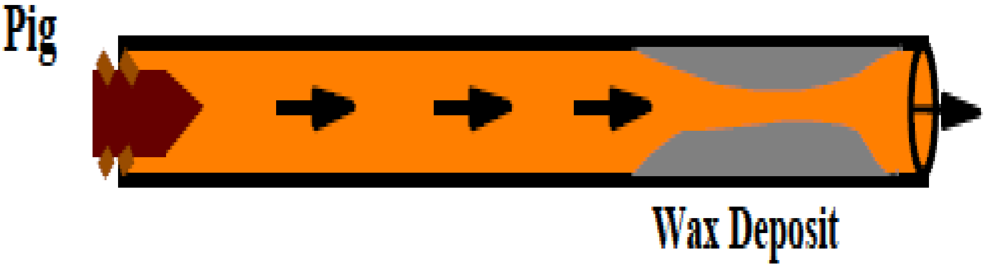
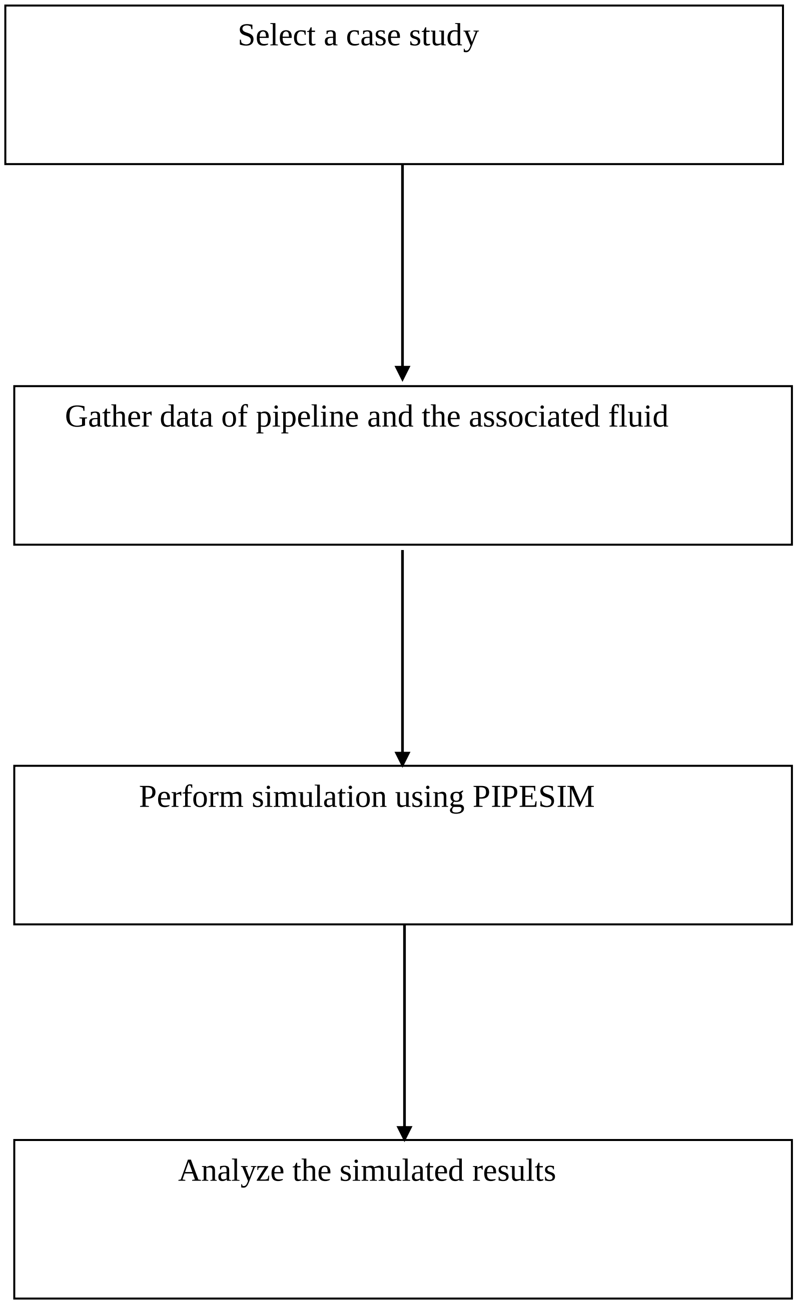


Figure 2-7: Scrape off the wax deposition by a pig **(Lee, 2008)**

Chapter 3

Methodology

3.1 Project Work



3.2 Selection of Case Study

The crude oil that is used in this study is the Neem field oil. PIPESIM software is used to simulate the operation of pipeline with two type of PPD’s, namely PPD25J1 and PPD25J2. Different doses of PPD are considered to come out with the optimum PPD dose and type. Pipeline data (distance, elevation at one kilometer intervals, inner diameter, roughness, and wall thickness), pump stations data, fluid data and thermal data were used in the simulation. This chapter partially discusses the data and methodology of the simulation.

3.3 Overview of PIPESIM

PIPESIM was originally developed by a company called Baker Jardine. Baker Jardine was formed in 1985 to provide software and consultancy services to the oil and gas industry. In April 2001, Baker Jardine was acquired by Schlumberger.

Schlumberger has invested in the redevelopment of the world's leading Production Engineering Software to ensure that it can cope with the fast moving computer industry. PIPESIM incorporates leading-edge Graphical User Interface technology coupled with a field-proven computation engine.

PIPESIM is a steady-state multiphase flow simulator used for the design and diagnostic analysis of oil and gas production systems. PIPESIM software tools model multiphase flow from the reservoir to the wellhead. PIPESIM also analyzes flow line and surface facility performance to generate comprehensive production system analysis.

The concept of flow line in PIPESIM has been used to simulate Heglig–Port Sudan Pipeline.

3.4 Modeling the Pipeline

The pipeline operation can be modeled and simulated using PIPESIM by the following steps:

1- Definition of the physical model

2- Definition of fluid data

3- Running of the model

3.4.1 Definition of the Physical Model

The model (Heglig-Port Sudan pipeline) consists of six pump stations. The first pump station is considered as a source in the pipeline model. The other five pump stations are ordinary pump stations. The model also includes six flow lines and a boundary node, which stands for the terminal station.

The final physical model of the pipeline in PIPESIM is shown in figure 3-1.

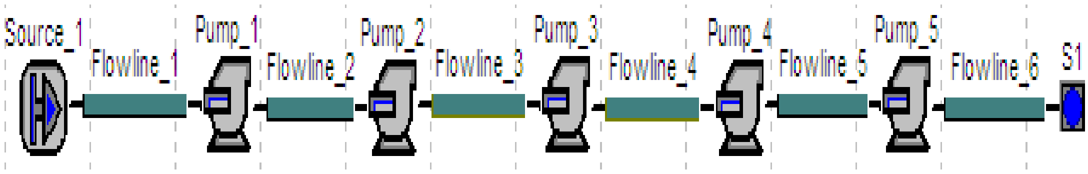
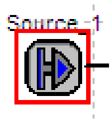
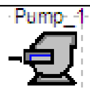
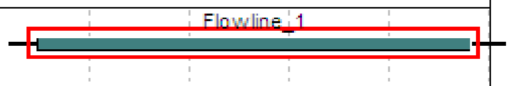


Figure 3-1: The pipeline physical model in PIPESIM

The elements of the pipeline model are shown in table 3-1.

Table 3-1: Symbols of the model elements

Component	Symbol
Source	
Pump	
Flow line	
Boundary node	

The source pressure and temperature are set at 68974.572 kpag and 67.65 C respectively. Pump stations and flow lines data are presented in tables 3-2 and 3-3 respectively. Flow lines distances and elevations data are given in appendix (C).

Table 3-2: Discharge pressure of pump stations at 70% efficiency

Pump station	Discharge pressure, kpag
1	58275.378
2	76617.45
3	58198.574
4	56000.776
5	41117.096

Table 3-3: Flow lines data

Inner diameter, D	711.2 mm
Roughness, ε	16.7 mm
Wall thickness, δ	0.381 mm
U	2.5 W/m^2*K

3.4.2 Definition of Fluid Data

The fluid API is 30° with both water cut and GOR equal to zero. Viscosity data is given in appendix (B).

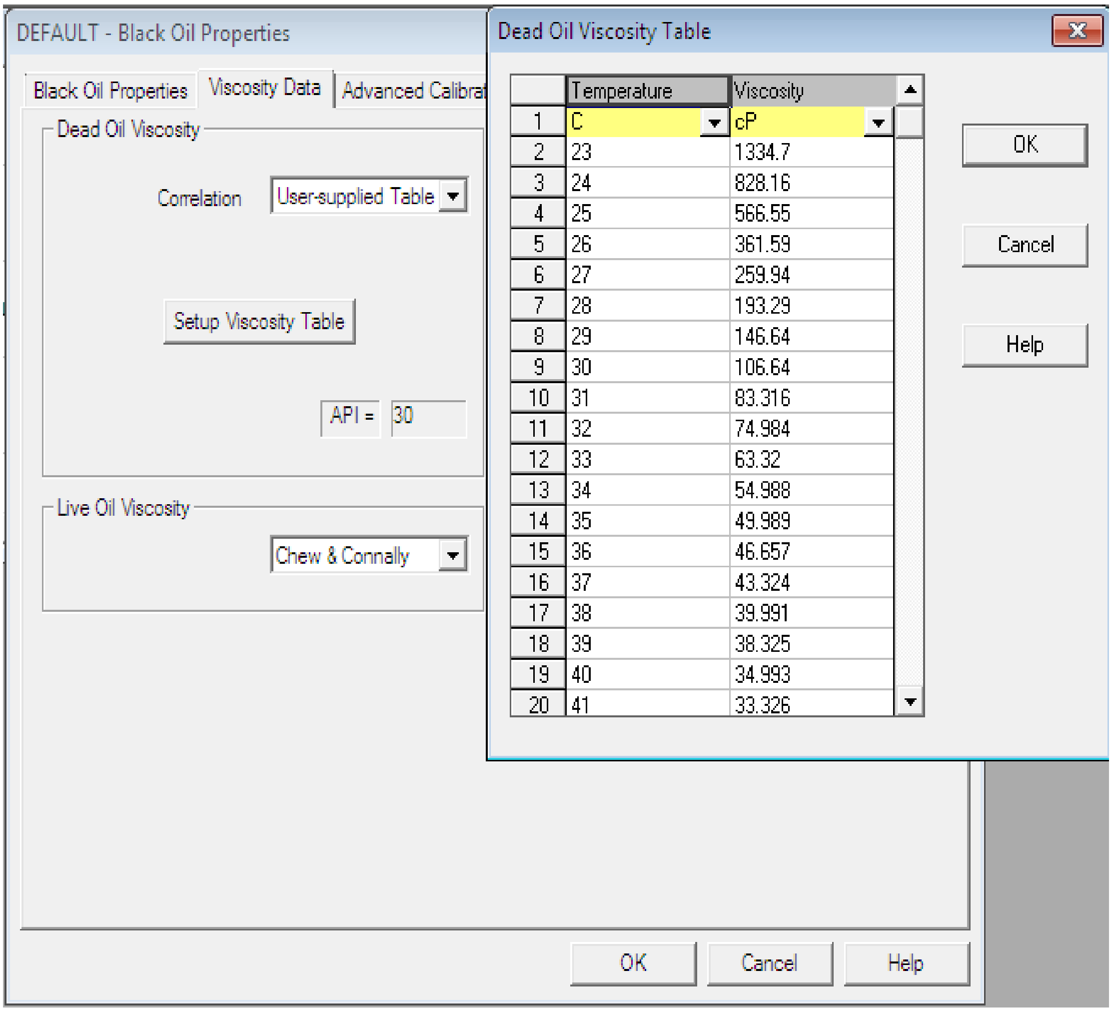


Figure 3-2: Fluid data window in PIPESIM

3.4.3 Running the Model

The physical model has been built and the fluid has been defined. The following steps have been followed to run the model:

1- From the toolbar, select Operations > Pressure/Temperature Profile.

2- Select the property to be calculated (inlet pressure, oulet pressurte, flow rate, or user variable). In our case, oulet pressure option has been selected.

3- Select sensitivity variable (optional) and supply some values for it. This option is not needed in this study.

4- Select the desired initial default profile plot. In this case study, (Pressure vs Total Distance) has been selected.

5- Run the model at 60000 STB/d.

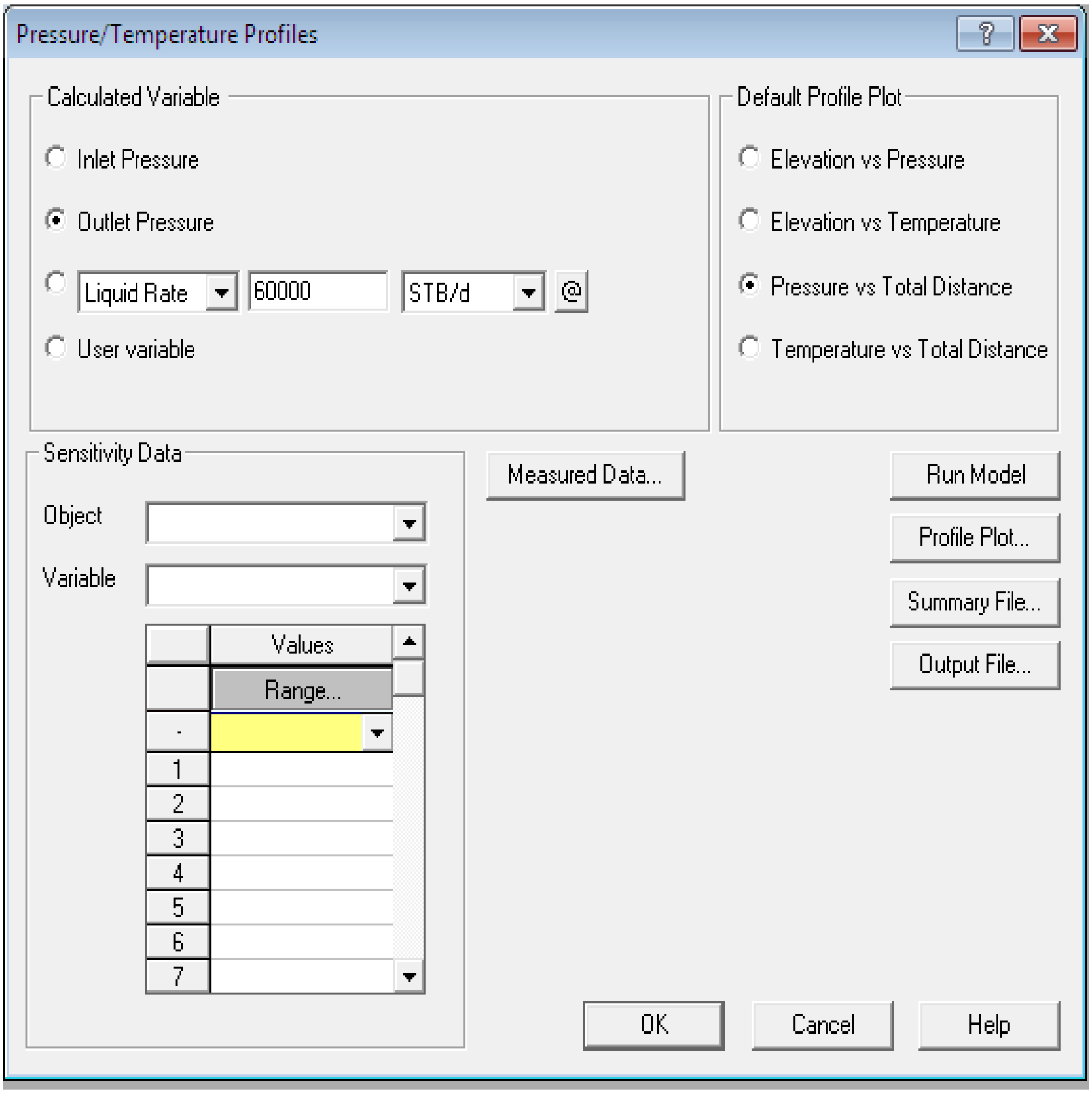


Figure 3-3: Run the model window in PIPESIM

According to the output graph of the model for each PPD type and dose, there are two cases:

- Case (1): the fluid doesn't reach the terminal.
- Case (2): the fluid reaches the terminal. If the remaining pressure is greater than atmospheric pressure, then one pump station has been eliminated (except the pump stations that come before any peak point) at a time and, until case (1) is achieved.

The results (output graphs) of case (1) and case (2) have been discussed in chapter 4.

3.5 Basis of Pressure Drop Calculations in PIPESIM

PIPESIM automatically calculates pressure losses using the following procedure:

$$\frac{dp}{dl} = \left(\frac{dp}{dl}\right)_{elev} + \left(\frac{dp}{dl}\right)_{fric} + \left(\frac{dp}{dl}\right)_{ace} \tag{3.1}$$

Where elevation, friction and acceleration component of pressure drop are:

$$\left(\frac{dp}{dl}\right)_{elev} = -\rho g \sin\theta \tag{3.2}$$

$$\left(\frac{dp}{dl}\right)_{fric} = -\frac{f\rho v^2}{2D} \tag{3.3}$$

$$\left(\frac{dp}{dl}\right)_{ace} = -\rho v \frac{dv}{dl} \tag{3.3}$$

ρ ≡ is fluid density in Ib/ft^3

f ≡ is the friction factor

v ≡ is fluid velocity in ft/s

g ≡ is gravitational acceleration in ft/s^2

θ ≡ is the angle of pipe to horizontal

D ≡ is the pipe diameter

l ≡ is length of the pipe

There are many way to calculate friction factor which depends on Reynolds number

$$Re = \frac{\rho v D}{\mu} \tag{3.4}$$

μ ≡ is fluid viscosity $Ib/ft.s$

The friction factor formula according to flow regime:

1- Laminar flow (Re < 2000)

$$f_{lam} = \frac{64}{Re} \quad (3.5)$$

2- Turbulent flow (Re > 4000)

$$\frac{1}{\sqrt{f_{Turb}}} = 1.74 - 2\log_{10}\left(\frac{2\epsilon}{D} + \frac{18.7}{Re*\sqrt{f_{Turb}}}\right) \quad (3.6)$$

3- Transition flow (2000≤ Re ≤4000)

$$f = \frac{(Re-Re_{\min})(f_{Turb}-f_{lam})}{(Re_{max}-Re_{min})} + f_{lam} \quad (3.7)$$

ϵ ≡is pipe roughness ft

3.6 Cost Estimation

Table 3-4: Annual crude and diesel consumption in pump stations

Pump no.	Crude consumption bbl/year	Diesel consumption m3/year
1	3678.3	106.8
2	953.2	72.9
3	1412.9	168.1
4	0	21.5
5	3226	148.5
6	1017.1	65.4

Annual diesel consumption of vehicles = 204.983 m^3 per year per station.

Diesel and crude consumption is obtain from appendix (D).

Table 3-5: Prices of PPD, crude, and diesel

Item	Unit price
PPD 25J1 200	1.7 $/Liter
PPD 25J2 200	1.7 $/Liter
Crude	103 $/bbl
Diesel	0.77 $/Litre

*Note: Crude oil price is based on Nile blend price.

3.6.1 Cost Formulas

The operation cost and the cost of PPD are calculated using the following equations:

$$\text{Cost of PPD} = \text{Cost of PPD unit price} * \text{Quantity} \tag{3.10}$$

$$\text{Operation Expenses (OPEX)}^{**} = \text{Crude cost} + \text{Diesel Cost} + \text{Labor wage} \tag{3.11}$$

$$\text{Crude Cost} = \text{Cost of crude unit price} * \text{Quantity consumed} \tag{3.12}$$

$$\text{Diesel Cost} = \text{Cost of diesel unit price} * \text{Quantity consumed} \tag{3.13}$$

$$\text{Labor Wage} = \text{Supervisors wage} + \text{Operators wage} \tag{3.14}$$

$$\text{Total Cost} = \text{Operation Expenses} + \text{Cost of PPD} \tag{3.15}$$

**Note: OPEX are calculated for each pump station individually.

Chapter 4

Results and Discussion

In this chapter results obtained using PIPESIM Simulator are presented for different operation scenarios of Heglig-Port Sudan pipeline. For every scenario, the flow improver is evaluated in terms of type and injection dosage in order to come out with satisfactory recommendations.

4.1 Summary of Different Operation Scenarios

Table 4-1: The results of PIPESIM

Scenario Number	PPD Type	Operated pump stations	Distance reached, km	Remaining pressure, bar
1	NA	6	431878.6090	2.1577
2	25J1 500	1,2,4,5,6	1502453.57	253.3228
3	25J1 750	1,2,4,5,6	1502453.57	260.9134
4	25J1 1000	1,2,4,5,6	1502453.57	284.1585
5	25J1 1250	1,2,4,5,6	1502453.57	302.8905
6	25J2 500	1,2,4,5,6	602012.138	2.5571
7	25J2 750	1,2,4,5,6	1502453.57	208.5
8	25J2 1000	1,2,4,5,6	1502453.57	231.2447
9	25J2 1250	1,2,4,5,6	1502453.57	329.1671
10	25J1 500	1,3,4,5,6	1502528.57	253.287
11	25J1 750	1,3,4,5,6	1502528.57	260.8935
12	25J1 1000	1,3,4,5,6	1502528.57	315.7554
13	25J1 1250	1,3,4,5,6	1502528.57	302.8825
14	25J2 500	1,3,4,5,6	501874.074	2.3276
15	25J2 750	1,3,4,5,6	1502528.57	331.7423
16	25J2 1000	1,3,4,5,6	1502528.57	474.6198
17	25J2 1250	1,3,4,5,6	1502528.57	329.1532
18	25J1 500	1,2,3,4,6	1500496.39	261.4471

Table 4-1: The results of PIPESIM

Scenario Number	PPD Type	Operated pump stations	Distance reached, km	Remaining pressure, bar
19	25J1 750	1,2,3,4,6	1500496.39	288.3792
20	25J1 1000	1,2,3,4,6	1500496.39	291.3091
21	25J1 1250	1,2,3,4,6	1500496.39	351.3665
22	25J2 500	1,2,3,4,6	1500496.39	627.8178
23	25J2 750	1,2,3,4,6	1500496.39	216.0557
24	25J2 1000	1,2,3,4,6	1500496.39	457.1504
25	25J2 1250	1,2,3,4,6	1500496.39	466.5838
26	25J1 500	1,2,4,6	1502491.57	261.0699
27	25J2 500	1,2,4,6	1502491.57	339.7782
28	25J1 750	1,2,4,6	1502491.57	452.9372
29	25J2 750	1,2,4,6	1502491.57	215.8491
30	**25J1 500**	**1,4,6**	**1504500.58**	**261.0244**
31	25J2 500	1,4,6	452862.055	0.8414
32	25J1 750	1,4,6	1504500.58	268.28
33	25J2 750	1,4,6	764265.587	0.117
34	25J1 1000	1,4,6	1504500.58	291.1498
35	25J2 1000	1,4,6	764265.587	0.6172
36	25J2 1250	1,4,6	1504500.58	335.3187
37	25J1 500	1,6	901509.539	0.618
38	25J2 500	1,6	452867.057	0.8377
39	25J1 750	1,6	1021390.75	0.1919
40	25J2 750	1,6	764268.584	0.1161
41	25J1 1000	1,6	1239391.15	0.1317
42	25J2 1000	1,6	764268.584	0.61610
43	**25J1 1250**	**1,6**	**1503717.76**	**313.7107**
44	25J2 1250	1,6	1503717.76	340.247

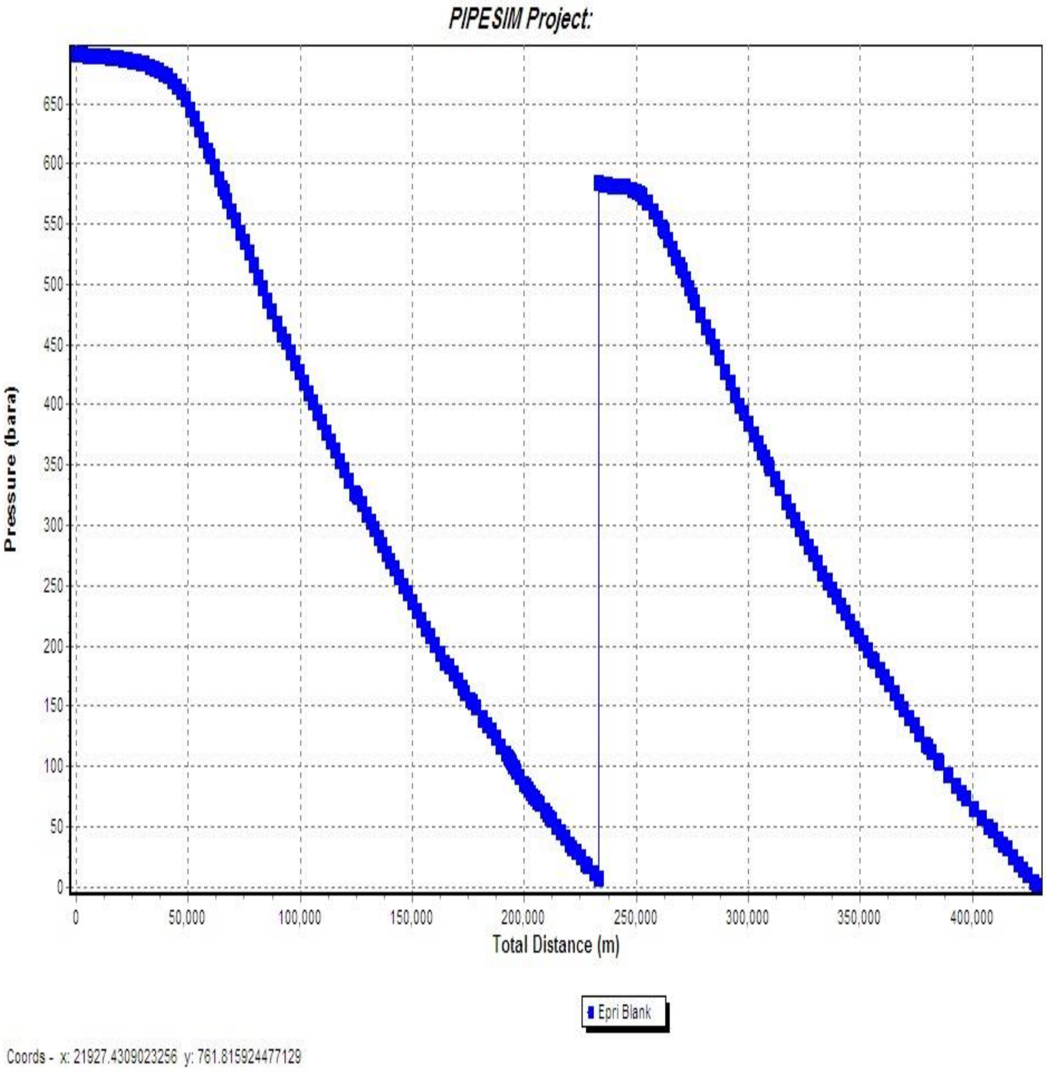


Figure 4-1: Pressure-Distance profile (6 pump stations without PPD injection)

Obviously, when all pump stations are operated and no PPD is injected, the pumped fluid losses the ability to reach the terminal station. Operation with 5 or 4 pump stations is enhanced by the addition of either PPD 25J1 or PPD 25J2, and regardless of the injected dose, the pumped fluid will regain its ability to reach the terminal station in almost all scenarios with remaining pressure far more than atmospheric pressure.

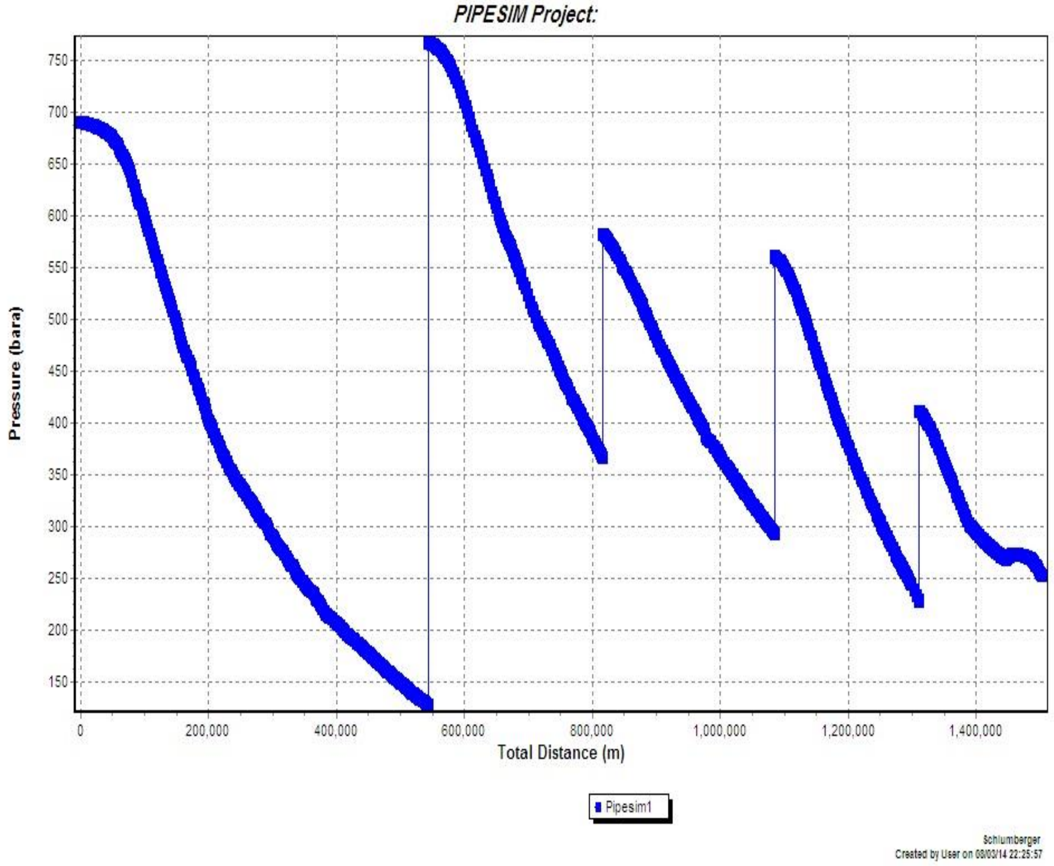


Figure 4-2: Pressure-Distance profile (5 pump stations with PPD injection)

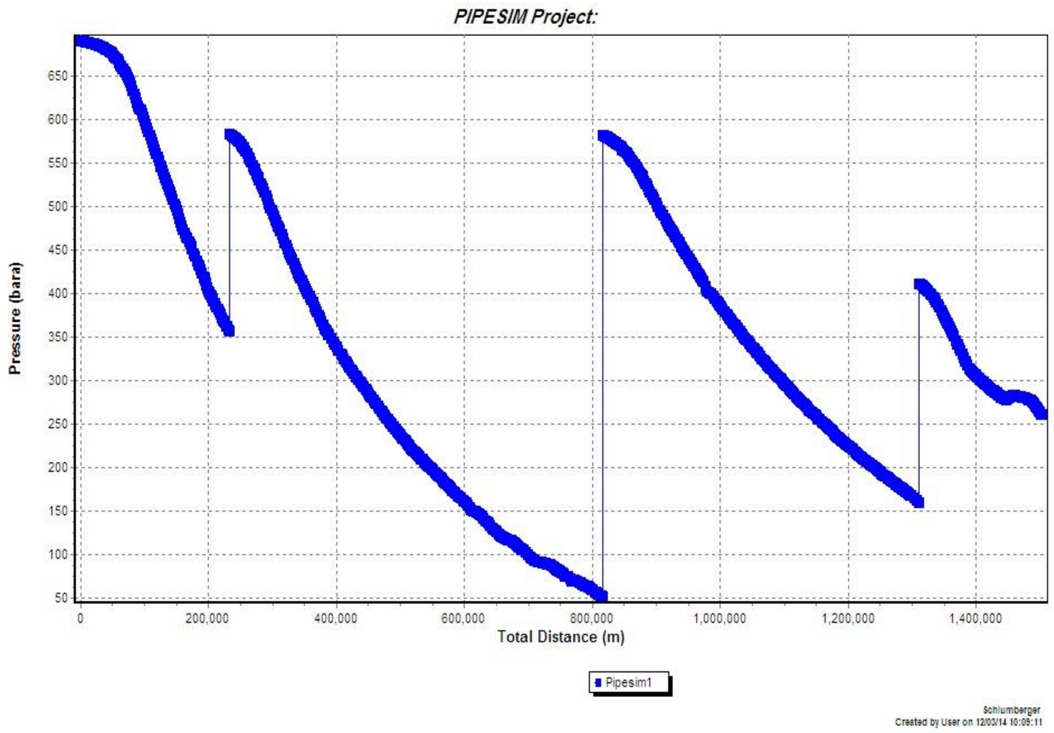


Figure 4-3: Pressure-Distance profile (4 pump stations with PPD injection)

Superiority of PPD 25J1 over PPD 25J2 can be observed when 3 pump stations are operated. All injection doses of PPD 25J1 have the ability to deliver the pumped fluid to the terminal station with a sufficient amount of remaining pressure, while this is not the case when PPD 25J2 is added. Therefore, only the scenarios that involves the injection of PPD 25J1 will be considered in cost analysis. Finally, operation with 2 pump stations is applicable in both cases.

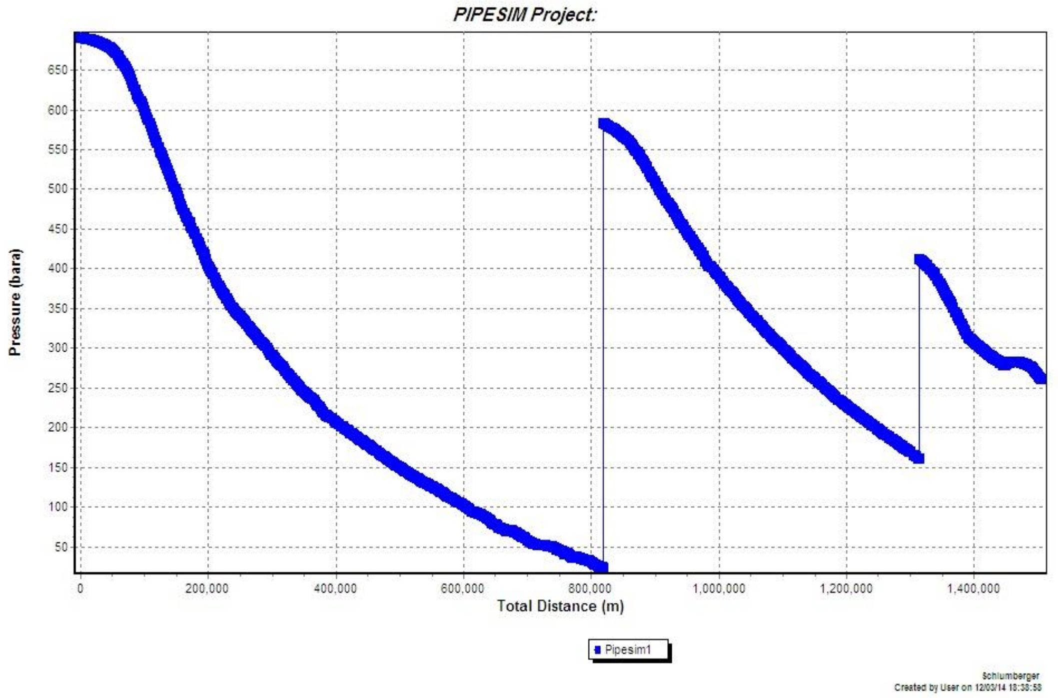


Figure 4-4: Pressure-Distance profile (3 pump stations with PPD 25J1 injected)

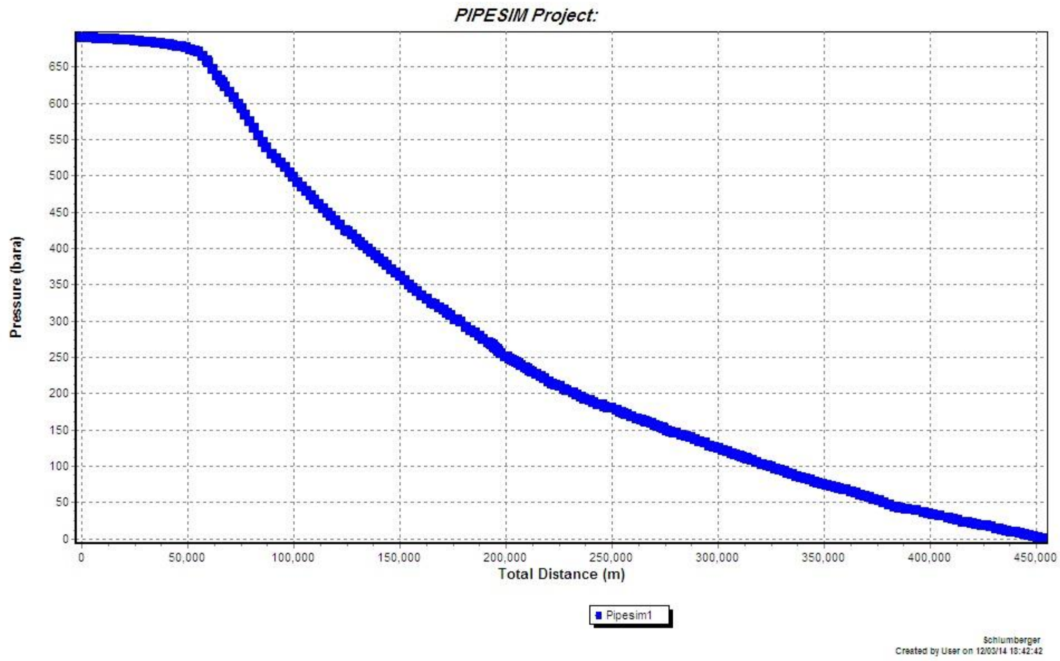


Figure 4-5: Pressure-Distance profile (3 pump stations with PPD 25J2 injected)

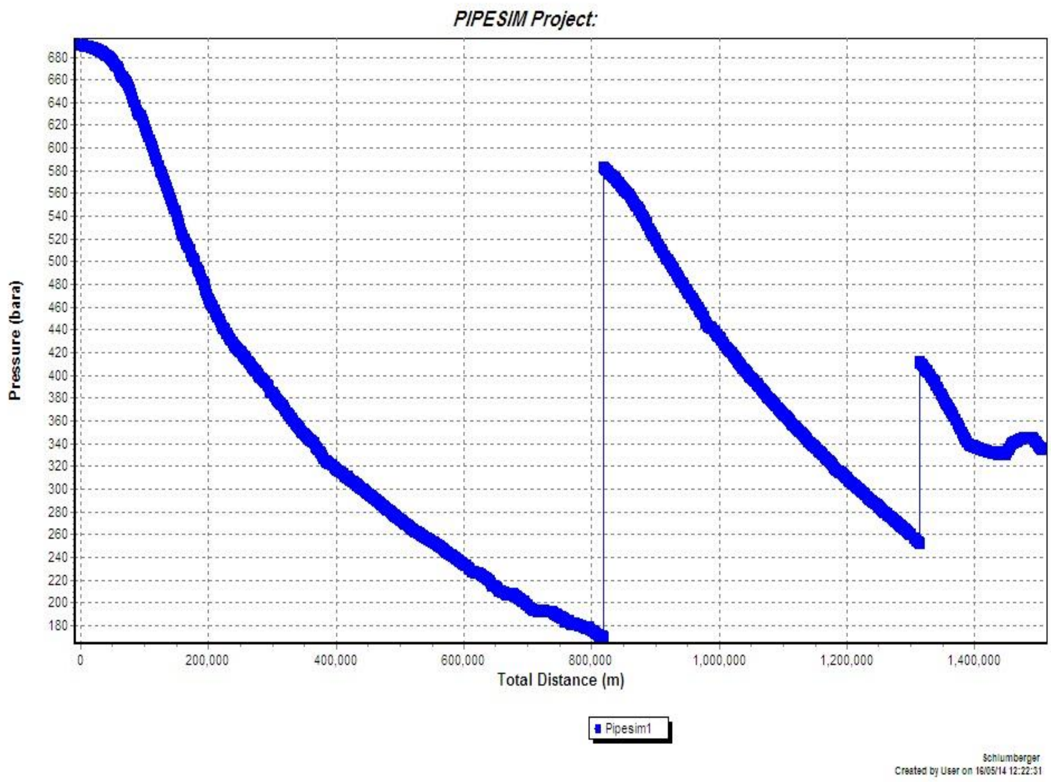


Figure 4-6: Pressure-Distance profile (2 pump stations with PPD 25J2 at 1250 PPM)

4.2 Selection of the Optimum Scenario

Based on the results shown in table 4-1, it can be stated that PPD 25J1 is more effective than PPD 25J2. This is because a wide range of PPD 25J1 doses can be used for the purpose of delivering the flowing fluid to the terminal station. Scenarios that involve the injection of PPD 25J1 are, therefore, only considered in the cost analysis.

Both scenarios (30) and (43) are selected among all other scenarios. That's because those two scenarios are characterized by the least requirement of pump stations and the injected PPD concentration.

Comparison must be done between scenarios (30) and (43) to select the best scenario of all. The comparison is based on total cost (sum of the operation cost and the cost of PPD) of each scenario.

4.2.1 Scenario 30

This scenario consists of three pump stations (pump station number 1, pump station number 4 and pump station number 6), with PPD 25J1 injected at 500 PPM. The Pressure-Distance profile of this scenario is shown in figure 4-7.

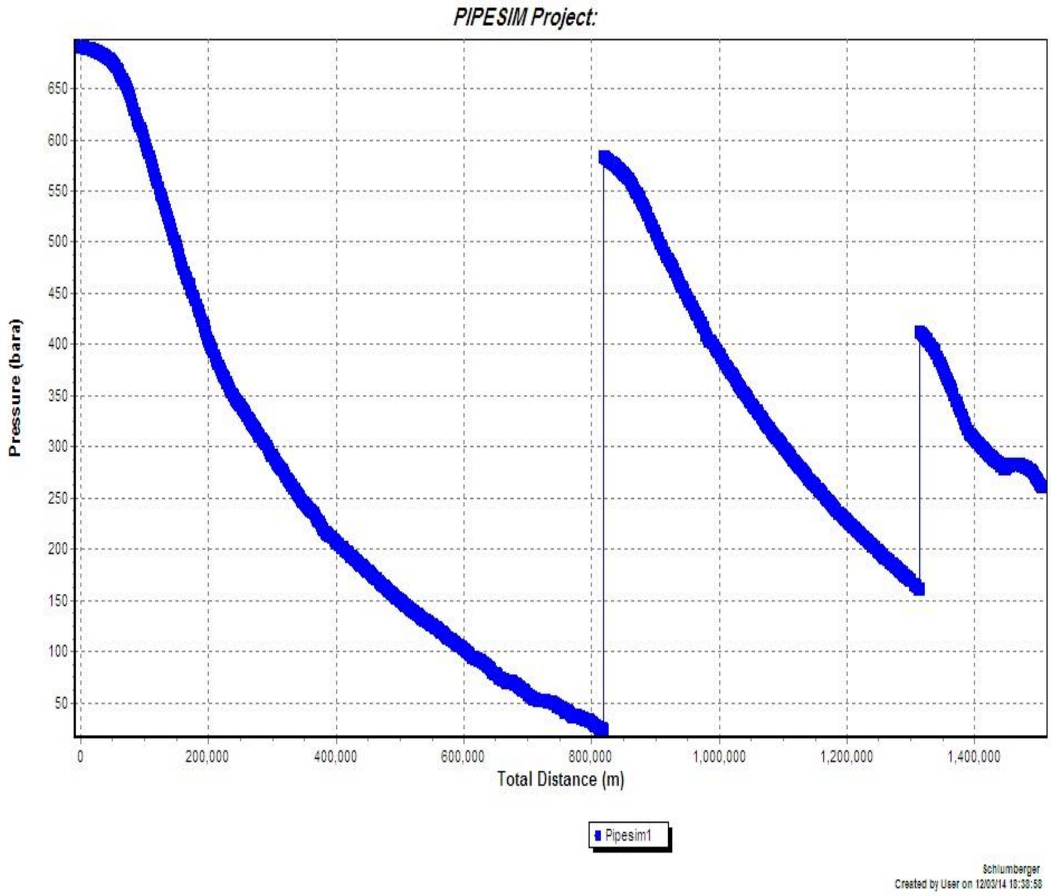


Figure 4-7: Pressure-Distance profile of scenario 30

Table 4-2: Crude and diesel consumption in pump stations operated in scenario 30

Pump station number	Crude consumption, bbl/year	Diesel consumption, m^3/year
1	3678.3	106.8
4	0	21.5
6	1017.1	65.4

Using equations ((3.10) - (3.15)), the following table results:

Table 4-3: Expenses of pump stations operation in scenario 30

Component	Expenses/cost, $/year
Crude consumption	149149
Diesel consumption	3042008.798
Labor	96000
PPD	1323246
Sum	4610403.798

4.2.2 Scenario 43

This scenario consists of two pump stations (pump station number 1 and pump station number 6), with PPD 25J1 injected at 1250 PPM.

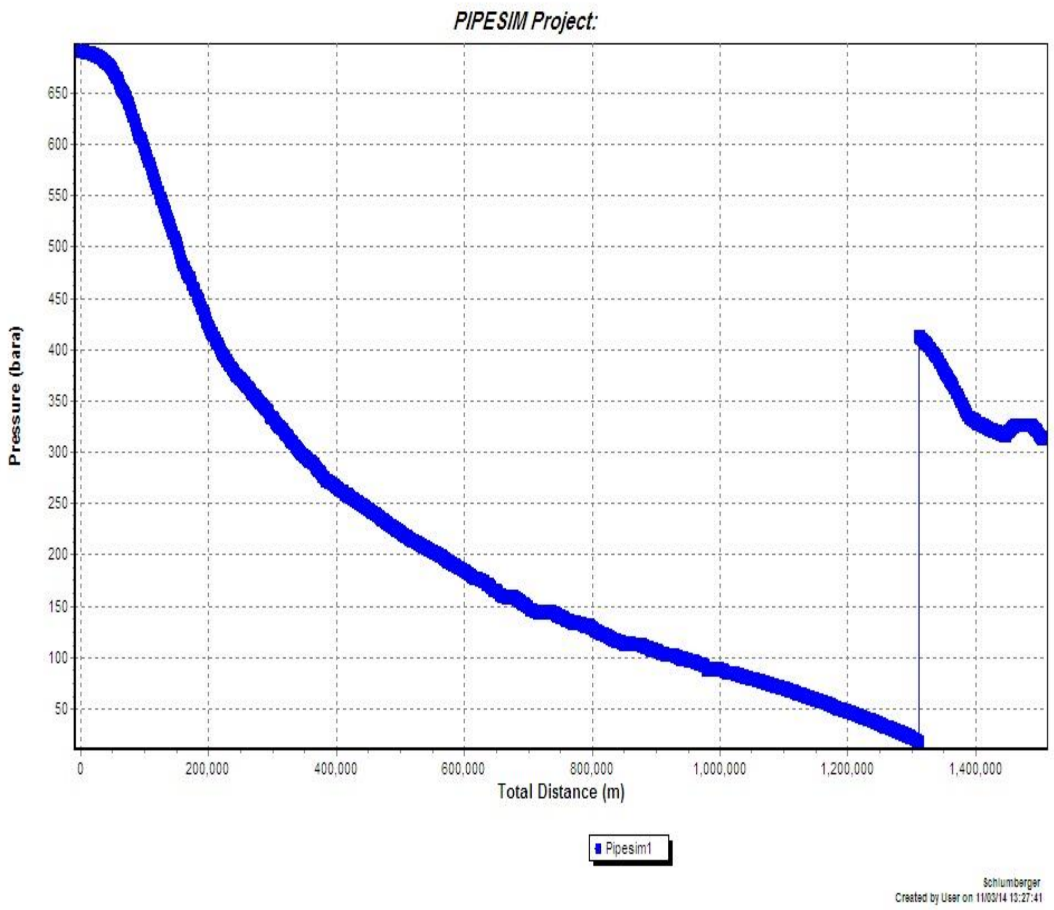


Figure 4-8: Pressure-Distance-Distance profile of scenario 43

Table 4-4: Crude and diesel consumption in pump stations operated in scenario 43

Pump number	Crude consumption, bbl/year	Diesel consumption, m^3/year
1	3678.3	106.8
6	1017.1	65.4

Using equations ((3.10) - (3.15)), the following table results:

Table 4-5: Expenses of pump station operation in scenario 43

Component	Expenses $/year
Crude consumption	132594
Diesel consumption	3042008.798
Labor	96000
Cost of PPD	3308115
Sum	6578717.798

Comparing the results of tables 4.3 and 4.5, it's clear that scenario 30 involves less expense than scenario 43. Therefore, it's safe to state that, among all other options (scenarios), scenario 30 is the most economical one to ensure the deliverability of the pumped fluid to the terminal station.

Chapter 5

Conclusion& Recommendations

5.1 Conclusion

Study of the transportation of Neem field oil through Heglig-Port Sudan pipeline in operation phase has been conducted using the PIPESIM simulator. From the simulation results alongside economical evaluation, the following outcomes can be drawn from the investigation:

Pumping the crude, with the desired flow rate, without PPD treatment, results in failure of the crude to reach the terminal station. Therefore, a certain PPD is selected to enhance the flow of Neem field oil and facilitate its transport to the terminal station.

For the sake of transporting the Neem field oil through Heglig-Port Sudan pipeline with the minimum allowable possible cost, a comparison study has been conducted on the effect of addition of two types of PPD, namely PPD 25J1 and PPD 25J2 at several injection doses. This comparison study utilized PIPESIM software to help in calculating the pressure losses along the pipeline route. The results obtained from PIPESIM simulation, the cost of operation of pump stations, and the cost of PPD together have been used as a basis for the comparison.

Two scenarios were found feasible, namely scenario 30 and scenario 43, and cost analysis has been established for each of them. According to the expenses involved in each of the two scenarios, scenario 30 serves best in delivering the pumped fluid to the terminal station at the minimum cost.

5.2 Recommendations

1- Due to the lack of Nile blend data, Neem field oil data has been used in this study instead. It’s believed that a more accurate study requires data of Nile blend.

2- Experimental tests must be carried out to obtain fresh viscosity-temperature data instead of using old data.

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Appendices

Appendix (A)

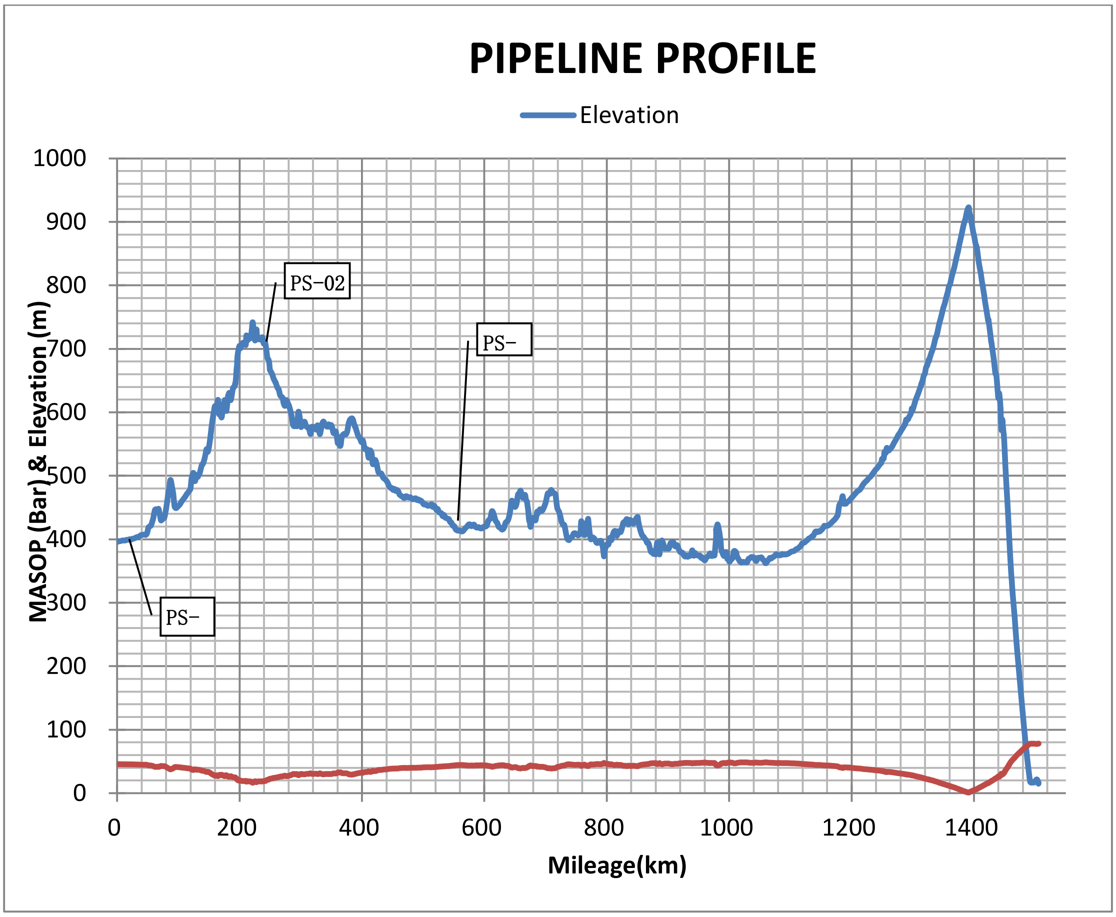

Figure A-1: Heglig-Port Sudan pipeline profile

Appendix (B)

Table B-1: NEEM temperature- viscosity data using PPD 25J1 at 500 PPM

Temperature, ◦C	Viscosity, cp
80	8.331556
75	9.997867
70	9.997867
65	11.66418
60	13.33049
55	14.9968
53	16.66311
51	18.32942
49	19.99573
48	23.32836
47	24.99467
46	26.66098
45	26.66098
44	28.32729
43	29.9936
42	29.9936
41	33.32622
40	34.99253
39	38.32516
38	39.99147
37	43.32409
36	46.65671
35	49.98933
34	54.98827
33	63.31982
32	74.984
31	83.31556
30	106.6439
29	146.6354

Table B-1: NEEM temperature- viscosity data using PPD 25J1 at 500 PPM(continue)

28	193.2921
27	259.9445
26	361.5895
25	566.5458
24	828.1566
23	1334.715

Table B-2: NEEM temperature- viscosity data using PPD 25J1 at 750 PPM

Temperature, ◦C	Viscosity, cp
79	8.331556
77	8.331556
75	8.331556
73	8.331556
71	8.331556
69	8.331556
67	9.997867
65	9.997867
63	9.997867
61	11.66418
59	11.66418
57	11.66418
55	14.9968
53	14.9968
51	18.32942
49	19.99573
47	23.32836
46	26.66098
45	28.32729
44	31.65991
43	33.32622
42	36.65884

Table B-2: NEEM temperature- viscosity data using PPD 25J1 at 750 PPM(continue)

41	39.99147
40	44.9904
39	48.32302
38	53.32196
37	56.65458
36	61.65351
35	66.65244
34	76.65031
33	86.64818
32	96.64604
31	113.3092
30	144.9691
29	178.2953
28	219.9531
27	281.6066
26	388.2505

Table A-3: NEEM temperature- viscosity data using PPD 25J1 at 1000 PPM

Temperature C	Viscosity cp
80	9.997867
78	9.997867
76	9.997867
74	9.997867
72	9.997867
70	9.997867
68	9.997867
66	9.997867
64	9.997867
62	9.997867

Table A-3: NEEM temperature- viscosity data using PPD 25J1 at 1000 PPM(continue)

60	11.66418
58	11.66418
56	13.33049
54	14.9968
52	16.66311
50	19.99573
48	21.66204
46	28.32729
44	33.32622
42	36.65884
40	43.32409
38	51.65564
36	63.31982
34	74.984
32	98.31236
30	133.3049
28	211.6215
26	341.5938

Table B-4: NEEM temperature- viscosity data using PPD 25J1 at 1250 PPM

Temperature, ◦C	Viscosity, cp
80	8.331556
78	8.331556
76	8.331556
74	8.331556
72	9.997867
70	9.997867
68	9.997867
66	9.997867
64	9.997867

Table B-4: NEEM temperature- viscosity data using PPD 25J1 at 1250 PPM(continue)

62	11.66418
60	11.66418
58	13.33049
56	13.33049
54	14.9968
52	16.66311
51	18.32942
50	19.99573
49	21.66204
48	23.32836
47	26.66098
46	28.32729
45	29.9936
44	34.99253
43	36.65884
42	38.32516
41	43.32409
40	46.65671
39	48.32302
38	53.32196
37	59.9872
36	64.98613
35	71.65138
34	79.98293
33	88.31449
32	106.6439
31	123.307
30	144.9691
29	174.9627
28	209.9552

Table B-5: NEEM temperature- viscosity data using PPD 25J2 at 500 PPM

Temperature, ◦C	Viscosity, cp
80	9.997867
78	9.997867
76	9.997867
74	9.997867
72	11.66418
70	11.66418
68	11.66418
66	11.66418
64	11.66418
62	13.33049
60	13.33049
58	13.33049
56	16.66311
53	18.32942
51	18.32942
49	21.66204
47	23.32836
45	23.32836
43	26.66098
42	28.32729
41	29.9936
40	31.65991
39	34.99253
38	34.99253
37	39.99147
36	41.65778
35	46.65671
34	54.98827
33	64.98613
32	81.64924

Table B-5: NEEM temperature- viscosity data using PPD 25J2 at 500 PPM(continue)

31	98.31236
30	733.1769
29	756.5052
28	824.824
27	1096.433
26	1586.328

Table B-6: NEEM temperature- viscosity data using PPD 25J2 at 750 PPM

Temperature, ◦C	Viscosity cp
80	9.997867
78	9.997867
76	9.997867
74	11.66418
72	11.66418
70	11.66418
68	11.66418
66	13.33049
64	13.33049
62	14.9968
60	14.9968
58	14.9968
56	16.66311
54	16.66311
52	18.32942
50	18.32942
48	21.66204
46	23.32836
44	26.66098
43	26.66098
42	29.9936

Table B-6: NEEM temperature- viscosity data using PPD 25J2 at 750 PPM(continue)

41	31.65991
40	33.32622
39	34.99253
38	38.32516
37	38.32516
36	43.32409
35	46.65671
34	51.65564
33	59.9872
32	69.98507
31	89.9808
30	111.6428
29	166.6311
28	236.6162
27	353.258
26	554.8816
25	1288.058
24	1448.024

Table B-7: NEEM temperature- viscosity data using PPD 25J2 at 1000 PPM

Temperature, ◦C	Viscosity, cp
80	9.997867
78	9.997867
76	9.997867
74	9.997867
72	9.997867
70	9.997867
68	9.997867
66	11.66418
64	11.66418

Table B-7: NEEM temperature- viscosity data using PPD 25J2 at 1000 PPM

62	11.66418
60	13.33049
58	14.9968
56	14.9968
54	16.66311
52	18.32942
50	19.99573
48	21.66204
46	23.32836
44	23.32836
43	24.99467
42	26.66098
41	28.32729
40	29.9936
39	33.32622
38	34.99253
37	36.65884
36	39.99147
35	43.32409
34	51.65564
33	56.65458
32	68.31876
31	86.64818
30	101.645
29	148.3017
28	204.9563
27	291.6044
26	431.5746
25	744.8411
24	1166.418

Table B-8: NEEM temperature- viscosity data using PPD 25J2 at 1250 PPM

Temperature, ◦C	Viscosity, cp
80	8.331556
78	8.331556
76	8.331556
74	8.331556
72	8.331556
70	9.997867
68	9.997867
66	9.997867
64	11.66418
62	11.66418
60	11.66418
58	11.66418
56	11.66418
53	14.9968
51	16.66311
49	16.66311
47	21.66204
45	23.32836
44	23.32836
43	24.99467
42	26.66098
41	31.65991
40	34.99253
39	34.99253
38	38.32516
37	41.65778
36	44.9904
35	48.32302
34	53.32196
33	61.65351

Table B-8: NEEM temperature-viscosity data using PPD 25J2 at 1250 PPM (continue)

32	66.65244
31	74.984
30	88.31449
29	103.3113
28	129.9723
27	164.9648
26	201.6236
25	246.614
24	311.6002
23	423.243
22	576.5436
21	798.163
20	1114.762
19	1572.998

Appendix (C)

Table C-1: Pipeline distance-elevation data

Distance, km	Elevation, m
0.017	396.115
0.104	395.950
0.321	396.452
0.622	396.610
1.104	396.562
3.049	396.820
5.050	397.200
7.047	397.607
9.047	398.210
11.046	398.120
13.045	398.110
15.038	399.157
17.030	399.190
18.828	399.510
20.828	400.240
22.823	399.570
24.824	400.800
26.824	401.180
28.823	401.720
30.381	402.670
32.790	403.650
34.789	403.620
36.746	405.020
38.889	406.690
40.889	406.828
42.888	407.460
44.987	407.16

Table C-1: Pipeline distance-elevation data

(continue)

46.974	407.070
48.989	410.335
50.988	418.399
52.988	420.372
54.988	421.450
56.988	426.840
58.988	433.433
59.705	437.180
61.705	446.440
63.705	447.180
65.510	443.260
66.110	443.260
67.510	448.050
69.510	439.332
71.516	429.880
73.512	431.673
75.111	432.400
77.108	434.280
79.114	443.660
81.116	456.150
83.112	469.878
85.112	481.812
87.112	493.547
89.705	481.840
91.702	470.584
93.705	451.840
95.702	449.052
97.705	450.066
99.704	452.328
101.705	454.065

Table C-1: Pipeline distance-elevation data(continue)

103.705	456.923
105.704	460.148
107.703	462.714
109.706	465.285
111.705	467.946
113.710	471.275
115.706	473.646
117.704	476.205
119.706	479.652
121.705	496.639
124.299	504.711
124.451	504.653
125.214	497.500
125.394	494.199
127.394	491.846
129.392	501.406
131.347	498.049
132.949	500.839
134.948	504.585
136.548	510.658
138.426	517.482
140.081	518.786
142.093	524.710
144.018	532.579
146.018	542.088
148.018	537.746
150.119	546.475
152.117	560.094
154.048	576.109
156.125	590.522

Table C-1: Pipeline distance-elevation data(continue)

157.930	601.027
159.839	610.000
162.620	601.610
164.620	619.700
166.627	596.910
168.612	597.800
170.622	591.900
172.308	603.700
172.308	603.700
173.656	611.150
175.926	619.400
176.766	603.900
178.557	602.410
181.191	626.400
181.311	625.700
183.267	630.580
185.270	619.150
187.278	627.250
189.287	638.340
191.668	640.700
192.757	645.500
193.103	644.200
193.371	646.100
193.625	649.810
194.250	655.900
195.015	668.380
195.677	672.900
196.221	685.030
197.669	696.450
199.672	704.560

Table C-1: Pipeline distance-elevation data(continue)

200.673	702.290
201.706	701.110
202.758	704.480
203.710	708.270
204.713	709.040
205.667	708.440
206.704	710.080
209.168	709.320
210.139	706.300
211.085	721.075
212.201	713.650
214.219	714.660
216.250	717.440
218.205	717.060
220.171	732.705
221.477	741.800
223.475	724.600
225.426	713.200
227.486	730.470
228.456	721.790
231.456	715.000
233.215	717.170
235.224	714.500
237.231	718.269
239.424	708.219
241.300	711.374
243.282	701.440
245.226	686.435
246.704	683.755

Table C-1: Pipeline distance-elevation data(continue)

248.064	680.145
249.305	668.840
249.376	666.900
252.036	662.500
254.082	657.600
254.211	657.740
255.486	653.120
256.526	651.200
256.760	650.800
256.917	650.600
258.895	646.420
259.115	646.680
261.772	638.890
263.801	636.270
265.437	629.800
266.036	627.565
266.530	626.480
268.335	624.330
270.274	623.120
271.741	614.940
273.436	610.800
273.708	610.180
274.479	610.500
276.040	619.100
277.661	617.680
278.949	613.858
280.198	611.810
282.740	603.655
284.941	594.365
287.086	580.935

Table C-1: Pipeline distance-elevation data(continue)

289.227	578.070
291.304	585.200
293.733	578.400
295.955	600.600
298.019	593.900
300.247	577.200
302.242	580.700
304.277	584.000
306.424	585.000
308.302	579.000
310.104	576.700
311.375	575.960
312.892	576.211
313.000	575.770
313.475	573.890
313.601	574.680
315.928	565.759
318.190	576.982
320.825	576.847
323.139	575.610
325.160	572.825
327.148	579.541
329.157	577.542
331.101	565.612
332.979	573.019
335.034	582.301
337.149	585.536
339.188	579.922
339.188	579.619
341.258	579.265

Table C-1: Pipeline distance-elevation data(continue)

343.183	577.382
345.318	581.166
347.160	577.272
349.294	580.210
351.290	576.431
353.321	567.438
355.299	569.392
357.274	569.680
359.301	558.367
360.132	552.576
360.444	551.251
362.639	550.700
364.793	547.300
367.043	561.400
369.178	564.900
371.402	566.250
373.542	565.150
375.946	570.200
378.189	582.550
380.511	588.600
383.330	590.600
384.029	589.875
384.154	589.889
385.623	587.826
385.775	586.284
388.501	577.178
388.812	577.692
389.079	577.601
393.170	564.400
396.886	558.186

Table C-1: Pipeline distance-elevation data(continue)

399.284	552.867
401.395	555.683
404.685	542.285
408.383	541.600
410.990	528.300
413.000	540.100
415.663	535.754
417.597	518.539
419.491	523.045
421.935	524.760
424.501	515.965
426.696	506.020
428.801	504.210
431.421	503.710
432.599	501.900
433.894	498.185
435.895	495.830
438.110	494.420
440.195	491.745
442.098	488.810
444.264	483.855
446.730	480.815
448.659	480.815
450.771	477.745
452.875	479.500
455.081	476.115
456.690	477.950
459.097	475.875
461.268	470.760
463.614	468.630

Table C-1: Pipeline distance-elevation data(continue)

466.486	466.855
469.088	464.915
471.140	467.695
473.509	467.540
475.655	465.890
477.623	466.270
479.498	466.009
479.498	466.009
481.705	463.702
483.758	463.180
485.730	463.863
487.698	464.675
489.788	462.113
490.970	461.614
492.408	462.706
493.918	460.756
495.937	461.022
498.307	458.939
499.935	456.118
501.885	454.679
504.085	455.160
505.839	453.793
507.927	452.640
509.724	453.264
511.844	453.731
513.820	455.169
515.775	450.872
517.767	452.914
519.935	449.975
521.752	445.960

Table C-1: Pipeline distance-elevation data(continue)

523.726	447.768
525.812	442.584
527.805	441.668
529.825	440.880
531.891	436.394
533.928	438.455
535.890	434.291
537.908	433.446
540.033	432.367
542.116	431.668
544.013	427.060
545.955	426.456
548.373	421.471
550.693	420.699
553.189	415.621
555.378	414.044
557.439	413.536
559.522	414.239
561.886	412.595
564.089	412.404
566.143	414.214
568.291	417.035
570.296	418.786
572.294	420.958
574.262	423.196
576.305	423.511
578.298	420.823
580.345	421.251
582.849	423.250
585.315	419.783

Table C-1: Pipeline distance-elevation data(continue)

587.889	418.315
590.619	419.286
593.394	417.234
596.259	417.408
599.138	419.891
601.836	420.012
604.037	421.834
606.374	429.436
609.542	432.627
612.431	444.302
615.471	438.535
618.170	429.549
620.918	425.787
623.390	419.742
626.157	418.138
628.873	415.271
631.620	417.400
634.890	426.457
637.497	428.333
639.629	433.141
642.080	444.003
644.486	460.438
647.063	457.494
650.044	450.928
652.400	455.342
654.994	470.897
657.103	471.520
657.103	471.490
658.993	476.770
660.895	471.370

Table C-1: Pipeline distance-elevation data(continue)

662.585	465.470
664.293	466.990
666.481	469.900
667.895	462.360
669.348	459.940
669.681	458.350
670.758	451.260
671.859	442.930
672.896	430.660
674.263	426.220
675.361	419.500
676.698	424.640
678.393	433.740
679.581	430.090
681.141	431.560
682.137	431.920
683.601	429.790
684.846	436.100
686.383	443.750
686.963	440.390
689.585	444.610
691.070	447.370
693.798	444.570
696.628	448.940
700.156	457.960
703.670	472.370
706.923	471.510
709.038	477.800
712.172	473.070
715.890	470.950

Table C-1: Pipeline distance-elevation data(continue)

718.988	449.610
721.865	443.750
724.004	436.730
725.882	428.730
728.421	422.860
730.514	422.660
732.741	412.630
735.383	400.970
738.221	398.590
738.221	399.070
740.672	401.860
742.307	403.000
744.456	405.870
745.601	408.670
746.536	409.020
747.015	409.620
749.019	409.290
749.345	408.915
750.513	407.740
751.928	407.345
752.968	406.160
753.790	406.445
755.116	407.665
757.074	412.385
758.268	428.520
760.168	416.735
762.175	408.230
764.277	407.030
766.401	423.455
768.878	429.445

Table C-1: Pipeline distance-elevation data(continue)

769.635	432.000
771.676	412.460
773.935	400.150
775.895	402.910
778.037	402.500
780.535	399.870
782.661	395.375
784.461	394.140
786.734	395.325
787.502	397.380
788.605	396.840
790.223	397.770
791.251	395.590
791.903	392.195
792.354	391.610
792.890	390.625
793.503	387.865
795.421	373.000
795.801	382.100
796.714	383.400
798.084	387.000
798.324	387.400
800.581	392.500
802.775	391.800
805.025	402.200
807.300	398.400
809.523	406.400
811.789	412.100
813.763	413.000
815.562	407.045

Table C-1: Pipeline distance-elevation data(continue)

816.579	405.697
816.901	406.900
817.918	412.630
817.918	412.600
818.034	412.400
818.137	412.400
818.173	412.200
819.888	410.100
821.993	413.900
822.709	411.300
824.872	417.500
826.567	425.000
828.354	427.230
830.217	425.200
831.917	431.400
833.661	431.300
835.513	423.400
837.386	427.500
838.003	430.400
839.654	429.800
842.097	427.450
843.174	424.480
845.166	427.180
846.764	429.600
848.397	433.600
849.428	433.100
850.444	435.370
851.023	431.290
851.864	426.400
854.117	416.800

Table C-1: Pipeline distance-elevation data(continue)

856.070	410.400
858.252	405.400
860.092	404.000
862.387	400.570
863.990	398.830
865.852	394.400
868.284	393.700
870.078	387.100
872.279	380.100
873.822	382.000
874.600	379.700
876.048	377.000
876.961	377.900
878.562	380.060
879.717	378.350
880.123	376.460
881.024	386.550
882.615	395.340
884.919	386.470
886.076	376.130
886.202	376.670
887.486	385.800
889.682	397.910
892.046	393.870
894.636	385.313
896.195	386.700
898.952	385.300
901.525	385.490
903.937	393.470
906.655	395.544

Table C-1: Pipeline distance-elevation data(continue)

908.897	395.290
911.922	388.678
914.918	390.807
916.999	385.920
919.371	380.640
921.499	379.290
923.460	378.960
924.942	376.700
926.444	374.150
928.109	372.780
929.751	374.580
932.198	372.370
934.260	374.810
935.960	373.930
937.861	375.580
939.753	382.620
942.135	374.050
944.161	378.480
945.401	375.430
947.939	374.680
949.974	374.060
950.368	374.300
952.397	374.350
954.328	370.450
955.899	371.580
957.849	368.757
960.261	366.806
962.382	370.387
964.000	372.233
967.082	374.172

Table C-1: Pipeline distance-elevation data(continue)

967.757	376.935
969.079	377.574
969.911	374.514
971.946	373.700
973.293	377.282
975.342	374.594
975.976	374.356
978.509	402.385
978.646	415.895
979.032	414.220
981.067	423.468
983.953	411.160
984.562	406.850
986.208	395.586
986.711	387.158
987.970	381.315
991.549	373.620
993.356	379.000
995.374	379.666
996.980	368.985
997.926	368.500
1000.117	366.113
1000.400	364.515
1001.727	366.007
1002.978	367.705
1005.426	370.557
1007.774	381.200
1011.172	379.505
1012.999	372.500
1015.173	368.900

Table C-1: Pipeline distance-elevation data(continue)

1017.163	365.405
1017.163	365.402
1019.194	363.491
1021.438	363.453
1022.702	364.519
1024.982	363.780
1027.212	364.018
1029.240	363.680
1031.224	368.293
1031.930	369.474
1034.177	370.325
1036.226	372.153
1038.388	371.682
1040.418	371.400
1042.384	367.548
1044.493	365.877
1046.586	370.437
1048.576	370.924
1050.754	371.142
1052.894	371.365
1055.225	367.801
1057.954	365.817
1058.908	362.481
1059.457	362.433
1059.596	362.379
1059.620	362.525
1060.067	362.588
1060.092	362.633
1060.430	362.457
1062.566	365.595

Table C-1: Pipeline distance-elevation data(continue)

1064.683	368.089
1066.539	370.788
1068.614	369.665
1070.585	371.669
1072.573	372.395
1074.659	374.052
1076.698	376.468
1078.643	374.954
1080.809	375.157
1082.909	374.707
1084.869	375.350
1086.746	376.530
1086.782	376.586
1086.941	376.334
1086.964	376.185
1088.874	376.025
1091.018	376.174
1092.961	376.216
1093.061	376.148
1095.014	376.698
1096.649	377.452
1098.676	378.613
1101.024	380.304
1103.154	380.999
1105.104	381.239
1107.150	382.388
1109.140	384.176
1111.208	385.123
1113.233	386.300
1115.215	388.112

Table C-1: Pipeline distance-elevation data(continue)

1117.309	390.176
1119.322	393.603
1121.623	394.414
1123.644	395.254
1125.625	397.361
1127.618	398.646
1129.664	400.842
1131.597	401.843
1133.655	402.965
1135.557	404.990
1137.631	405.593
1139.679	409.937
1141.541	412.415
1143.738	411.294
1146.033	412.749
1147.019	411.853
1149.208	413.372
1151.468	415.352
1153.880	418.555
1155.376	421.375
1155.523	421.372
1157.055	420.771
1157.287	420.605
1159.554	421.354
1161.801	421.651
1165.564	424.591
1167.507	426.602
1169.408	428.318
1171.468	430.288
1173.324	432.126

Table C-1: Pipeline distance-elevation data(continue)

1175.429	435.154
1177.468	438.537
1179.685	452.862
1181.446	456.624
1183.402	458.671
1185.376	468.008
1187.063	456.075
1188.647	456.563
1190.516	455.924
1192.525	458.332
1194.578	459.762
1197.155	461.480
1197.622	462.402
1199.247	464.403
1202.107	467.581
1204.110	469.864
1206.886	472.886
1209.537	475.623
1212.551	477.484
1214.559	479.421
1216.586	482.637
1218.779	486.273
1221.401	489.362
1223.693	491.554
1225.845	493.450
1228.121	496.387
1230.888	498.697
1233.262	501.569
1235.810	504.996
1238.005	507.914

Table C-1: Pipeline distance-elevation data(continue)

1239.426	509.913
1240.887	511.078
1243.330	514.132
1246.637	518.524
1248.539	520.405
1249.743	526.583
1251.033	525.711
1252.620	527.534
1253.769	537.628
1255.439	537.658
1255.973	536.047
1256.828	541.537
1257.832	544.013
1260.427	539.798
1262.563	542.076
1263.797	542.876
1265.940	545.689
1267.085	547.453
1269.300	551.748
1271.563	555.496
1272.826	557.658
1274.954	561.625
1276.249	563.924
1278.086	566.583
1279.858	569.125
1280.968	571.354
1282.132	573.534
1282.642	573.715
1283.907	575.824
1284.144	576.432

Table C-1: Pipeline distance-elevation data(continue)

1285.362	578.170
1286.719	580.547
1287.152	581.533
1287.357	581.198
1288.072	583.254
1289.097	588.501
1289.686	586.784
1289.968	587.663
1290.500	588.364
1292.506	589.266
1292.666	590.324
1294.387	593.589
1296.553	597.365
1297.992	602.319
1298.337	605.994
1299.546	603.153
1304.662	619.323
1308.586	628.924
1312.169	639.163
1312.983	640.913
1314.043	644.920
1314.345	646.346
1314.524	645.170
1315.080	645.911
1315.327	647.149
1317.819	657.395
1319.777	661.209
1321.850	671.239
1323.652	674.032
1325.939	682.529

Table C-1: Pipeline distance-elevation data(continue)

1326.310	680.588
1327.534	684.911
1330.429	693.831
1332.550	699.109
1335.535	710.494
1336.997	716.416
1338.508	719.758
1339.352	722.621
1340.069	725.032
1342.794	737.668
1345.308	746.796
1347.939	756.676
1350.025	765.032
1352.044	770.628
1354.040	778.490
1355.950	785.472
1357.520	790.820
1358.923	797.780
1360.923	801.901
1362.402	808.170
1363.749	813.790
1365.452	820.135
1367.984	828.758
1371.198	843.061
1373.628	852.738
1373.949	853.926
1375.887	863.672
1375.887	863.672
1378.189	873.436
1380.724	884.668

Table C-1: Pipeline distance-elevation data(continue)

1382.774	894.000
1385.573	903.671
1386.214	905.413
1388.858	917.598
1391.368	923.015
1392.274	917.347
1394.167	908.351
1394.837	907.997
1395.735	899.828
1397.177	892.873
1398.591	884.442
1399.261	881.657
1399.648	880.136
1400.631	875.969
1401.649	870.112
1402.593	865.600
1404.812	858.706
1407.103	841.664
1408.550	832.298
1410.852	820.324
1411.036	819.720
1413.332	803.944
1413.865	801.647
1415.494	791.584
1416.863	783.390
1416.964	782.780
1417.887	775.674
1420.270	761.380
1422.383	748.992
1423.372	743.285

Table C-1: Pipeline distance-elevation data(continue)

1423.550	746.472
1425.231	734.268
1427.431	717.606
1427.957	711.430
1428.142	711.530
1428.523	710.789
1429.248	705.057
1429.617	702.590
1430.832	694.510
1431.407	690.386
1432.682	681.288
1434.698	662.714
1434.871	661.010
1435.259	662.140
1436.816	656.351
1438.321	638.073
1439.058	629.600
1439.866	622.262
1441.182	630.121
1442.930	613.430
1443.441	604.323
1443.512	605.407
1443.969	588.450
1444.254	581.145
1444.884	571.860
1445.416	576.350
1446.458	588.447
1446.969	581.002
1447.358	576.700
1447.432	576.534

Table C-1: Pipeline distance-elevation data(continue)

1448.024	570.810
1449.310	557.102
1451.288	516.313
1453.276	480.449
1454.912	454.382
1456.610	422.514
1456.610	422.514
1458.871	378.946
1460.868	345.465
1461.516	337.185
1461.869	333.252
1463.288	313.230
1465.576	287.601
1466.510	276.763
1469.476	237.254
1472.026	208.812
1474.562	181.597
1477.241	152.174
1479.769	125.139
1482.567	96.008
1485.363	69.814
1487.940	47.011
1489.982	30.211
1490.140	29.399
1491.810	18.031
1493.902	16.548
1495.839	17.864
1496.614	17.368
1498.029	16.785
1500.303	19.389

Table C-1: Pipeline distance-elevation data(continue)

1502.524	21.788
1504.324	19.233
1504.888	17.058
1505.412	14.928
1505.566	16.630

Appendix (D)

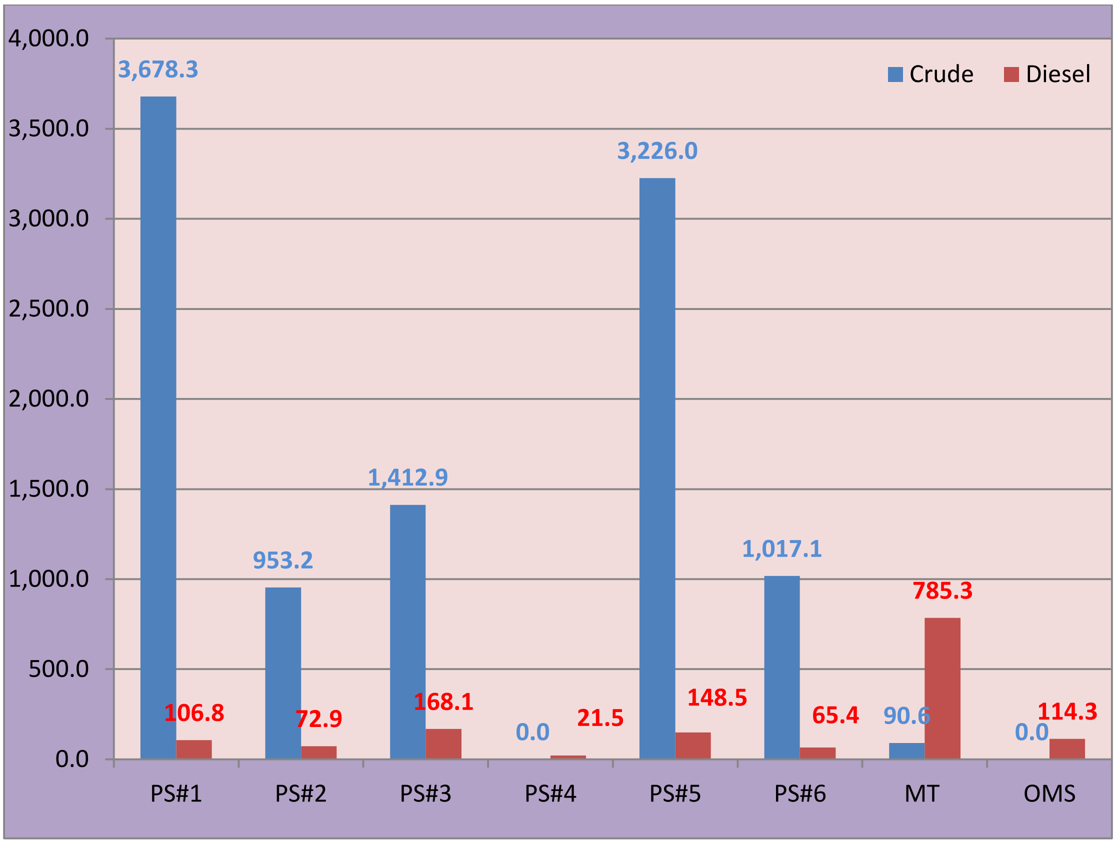

Figure D-1: Diesel and crude consumption during year 2013, m^3/ station