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A COMPUTATIONAL ANALYSIS OF OPERATIONS IN WAXY CRUDE OIL PIPELINES

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ABSTRACT

A COMPUTATIONAL ANALYSIS OF OPERATIONS IN WAXY CRUDE OIL PIPELINES

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In this thesis, a computational study is performed for the analysis of waxy crude oil in existing pipelines. The purpose of developing such software is to search Newtonian and non-Newtonian characteristics of the high pour point crude on the line and to find solutions to flow blockage problem. If it exists, the program performs modifications by changing some of the operational parameters such as flowrate, pump head, fluid parameters such as oil temperature at the beginning or at any location along the pipeline, chemical additives or combinations according to the users choice. This program can also be used for simple slurry pipeline problems since the same approach defined for waxy crude oil pipeline's hydraulics and analysis are used for slurry pipelines. This program is developed on a personal computer in Visual Basic 3.0 programming language.

This software is capable of evaluating and displaying temperature profile along the line for Newtonian and non-Newtonian analysis applied by this program and modified form of pipelines in case of flow blockage for normal operating condition and restart after a shutdown condition. Operating point of pumps at each modifications are also evaluated by this program. Data exchange can be done via predefined data files or directly from the screen. Various alternative cases may be stored in data files and the program may be executed for these data files.

Key Words: Waxy Crude Oil, Pour Point, Newtonian and Non-Newtonian Analysis, Hydraulic Grade Line, Pipeline Rheology, Pipeline Operations, Slurry Pipelines, Normal Operation, Restart After A Shutdown.

ÖZ

PARAFİNİK PETROL TAŞIYAN BORU HATLARI ÇALIŞMA ŞARTLARININ BİLGİSAYAR ANALİZİ

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Bu tezde parafinik ham petrolün mevcut bir boru hattında analiz edilmesine yönelik hesaplamalı bir çalışma yapılmıştır. Böyle bir yazılımın hazırlanmasındaki amaç, donma noktası yüksek olan ham petrolün Newtonian ve Newtonian olmayan özelliklerinin hat boyunca incelenmesi ve akışın bloke olması durumunda bazı çalışma parametrelerini ;debi, pompa basınç yükseklikleri, akışkan parametrelerini; petrol giriş sıcaklığı, herhangi bir noktada petrol sıcaklığı, kimyasal eklenmesi veya her ikisinide değiştirerek çözüm yolları bulmaktır. Bu program ayrıca parafinik ham petrolün incelenmesinde kullanılan yöntemlerle benzerlik göstermesi sebebiyle basit katı-sıvı akışların incelenmesinde de kullanılabilir. Yazılım, kişisel bir bilgisayarda Visual Basic 3.0 programlama dili kullanılarak yapılmıştır.

Yazılım, hattın sıcaklık profilini, bu program tarafından uygulanan Newtonian ve Newtonian olmayan analizler için ve akışın herhangi bir şekilde kesilmesi durumunda modifikasyonlar için normal çalışma şartlarında ve sistemin yeniden çalıştırılması durumunda gösterebilmektedir. Her bir modifikasyon için pompaların çalışma noktaları da bu program tarafından değerlendirilebilmektedir. Veri alışverişi önceden hazırlanan veri dosyaları üzerinden veya direkt ekrandan yapılmaktadır. Farklı uygulamalar birer veri dosyasına yüklenip program bu dosyalar için çalıştırılabilir.

Anahtar sözcükler: Parafinik ham petrol, Donma noktası, Newtonian ve Newtonian olmayan analiz, Manometrik Yükseklik Doğruları, Boru Hatları Reholojisi Boru hatları çalışmaları, Katı, sıvı boru hatları, Normal Çalışma şartları, Sistemin yeniden çalıştırılması.

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NOMENCLATURE

A	Cross-sectional area [m^2]
D	Diameter [m]
d	Particle diameter [micron]
f	Friction coefficient
g	Gravitational acceleration[m^2/s]
H	Head [m]
L	Length of pipe [km]
P	Pressure [Pa]
Q	Volumetric flowrate [m^3/h]
Q_s	Solid flowrate [m^3/h]
Q_l	Solid flowrate [m^3/h]
Q_{slurry}	Solid flowrate [m^3/h]
V	Velocity [m/s]
V_c	Critical velocity [m/s]
V_T	Transition velocity [m/s]
w	Settling velocity [m/s]
WP	Volume percent of solids
C_D	Drag coefficient
Cp	Oil specific heat [KJ/kg.K]
Cp_l	Liquid specific heat [KJ/kg.K]
Cp_s	Solid specific heat [KJ/kg.K]
Cp_{slurry}	Slurry specific heat [KJ/kg.K]
C_w	Concentration of solid by weight
f_f	Fanning friction factor

h	Convection heat transfer coefficients [W/m^2.K]
k_{ins}	Thermal conductivity of pipe insulation [W/m.K]
k_l	Thermal conductivity of liquid [W/m.K]
k_o	Thermal conductivity of oil [W/m.K]
k_s	Thermal conductivity of solid [W/m.K]
k_{slurry}	Thermal conductivity of slurry [W/m.K]
h_f	Frictional head loss [m]
P_g	Gel pressure [Pa]
Pr	Prandtl number
Re	Reynolds number
Re_p	Reynolds number based on plastic viscosity
Re_{mod}	Modified Reynols number for slurry pipelines
S	Plasticity number
t	Duration of shutdown [h]
T	Oil temperature at normal operation [°C]
T_i	Oil inlet temperature [°C]
Tr	Oil temperature at restart [°C]
U	Average overall heat transfer coefficients [W/m^2.K]
x	Distance from pipeline inlet [m]
γ	Shear rate [1/s]
μ_a	Apparent viscosity [Pa.s]
μ_p	Plastic viscosity [Pa.s]
ρ	Oil density [kg/m^3]
ρ_s	Solid density [kg/m^3]
ρ_l	Liquid density [kg/m^3]
ρ_{slurry}	Solid density [kg/m^3]
τ	Shear stress [Pa]
τ_o	Bingham yield stress [Pa]
τ_y	Yield strength [Pa]
$\Phi(S)$	Laminar flow parameter

ϕ	Solid volume fraction [%]
ν	Kinematic viscosity of slurry [m^2/s]
ΔP	Frictional pressure loss [Pa]

CHAPTER 1

INTRODUCTION

1.1 Waxy Crude Oil Problems

Until the early 1960's the crude oils generally showed normal characteristics in respect to pumping conditions such as viscosity and low pour point. The opening up of remote oil fields in North Africa and India in the 1960's to exploit low sulphur crudes (waxy crude oils) in these location, and the need to pump these oils through the much colder pipelines has lead oil producers to study the pumpability of waxy crude at temperatures below the pour point limit.

Most of the Middle East crude oils have pour point below 0°C and wax content less than 7 %, therefore pose no problems in pipeline transportation even at low temperatures. BOTAŞ first faced with this problems following the Gulf War. Low pour point Iraq crude oil was transported by pipelines such as Ceyhan-Kırıkkale pipeline to Central Anatolian Refinery. Following the war, BOTAŞ had to pumped crude oils imported from other countries due to the applied embargo to Irag. The new crudes, i.e. Nigeria, Egypt had high pour points and wax precipitation resulted in restricted flow, increased flowline pressure, more mechanical problems and higher handling cost in the existing pipelines.

The purpose of this thesis is to investigate the high pour point crude oils effect on the existing crude oils pipelines in Turkey and try to find out solutions of the pipeline blockage problem only changing the operating conditions of

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pumps, and alternatively study drag reducer chemical additives to the system.

1.2 General

Crude oils and petroleum products often contain waxy components which will crystallize during the production, transportation, and storage of the oils, forming an interlocking network of crystals which will effectively gel the oil, thus restricting the flow, forming surface deposits, and ultimately blocking pipelines and tanks.

The operation of the pipeline is most economical and efficient when a continuous constant flowrate is maintained. This minimizes storage volume, energy consumption, and investment in plant facilities. Pipelines that transport high-pour-point crude oil especially should be designed for continuous operation because of restart problems after shut-down. Since it is not always practical or possible to operate the entire pipeline system at a temperature above that at which the crude begins to form wax crystals, system components must be designed carefully and operating procedure must be selected accordingly.

The pipeline system should be tested to the design requirements prior to start-up. As restart pressures may approach the yield strength of the pipe, each component of the pipeline system will be required to perform to design capacity. Wax build up on the pipeline wall is also expected. As wax buildup occurs, throughput will decrease. Flow, temperatures, and pressures should be monitored closely for several weeks after start-up.

The analysis of an existing pipeline, all the data about the line are available to the users such as the topography, diameter and thickness of the pipe, its absolute roughness, location of pumping stations, characteristics of pipe at each station etc. Moreover, the variation of temperature versus viscosity, yield strength, Bingham yield stress, and plastic viscosity of crude oils must also be available. These properties change from crude to crude and extensive laboratory measurements are required to determine these variation.

The analysis software follows the procedure described below to predict the performance of a pipeline transporting congealing oil:

i. Determine the rheological properties of the oil under pipeline conditions such as variation of viscosity versus temperature etc.

ii. Calculate the oil temperature throughout the pipeline for given flow rates.

iii. Compute oil temperatures throughout the pipeline for the expected shut-down times.

iv. Calculate the pressure required to initiate flow by breaking the gel after a shut-down.

v. Determine the pressure losses for the pipeline under both normal operating conditions and restarting conditions at the desired restarting flowrate.

vi. Identify the maximum pressure which will be imposed on the pipeline as the greatest of

- Pressure required to maintain the desired flowrate for normal operating conditions
- Pressure require to break the gel when flow in the pipeline is restarted,
- Pressure required to maintain the desired flow rate under restarting conditions,

vii. Calculate the pump power for normal operations, and for restarting the flow after shut-down. Required power is the grater of these two values.

The most important parts of this procedure are the temperature variation along the line and pressure loss. The details of mathematical treatment can be found in further chapters. All the analysis throughout this thesis is based upon the fact that all the data related to physical conditions are available as input data. For that purpose, the related data can be stored in data files or entered to the program directly. These data files can be modified for various alternative cases and the program may be executed for these cases.

The aim of this study is to develop a computer program to analyse operation flexibility of existing crude oil pipelines in Turkey. Depending on the pour point of crude oil, the oil can be transported easily or the pumps capacity may not be enough to pump the desired amount of oils. If the pumps capacity is not enough, the flow can be achieved or not, by changing the operation condition of pumps, heating up the oil at the beginning of the pipeline or at an intermediate station, and adding a drag reducer by chemical injection or combinations. These are three important approaches in the analysis.

Last two approach is investigated throughout the pipeline when the first approach does not give any meaningful result with a given pump configurations. In analysing the existing crude oil pipelines, the capability of pumps to handle maximum expected volumes is so important that pumps should be selected to allow a parallel or series arrangement, which could transport early production volumes at slower rates and higher pressure when necessary. The piping could be manifolded so that parallel arrangement would be accommodated by re-positioning of valves to handle higher flow rates.

This program is applicable for any crude oil pipelines. Existing Ceyhan-Kırıkkale pipeline system is searched according to the criteria explained above. The details and results of this case is given in Chapter 7.

Chapter 2 gives basic aspects of liquid pipeline hydraulics and governing fluid flow equations. Chapter 3 explains the rheology of crude oils (crude oil properties, variation of viscosity with temperature) and mathematical treatment of heat transfer and pressure loss problems. Chapter 4 gives an information about the types of slurry pipelines and which type of slurries the waxy crude oils pipeline can be treated as. Chapter 5 deals with several methods used in transportation of high pour point crude oils and the effects of a chemical drag reducing in pipelines. Chapter 6 explains the details of the software. Chapter 7 summaries the results of an example case, namely Ceyhan-Kırıkkale pipeline system. Ceyhan-Kırıkkale is especially selected as a case study because several problems were encountered by BOTAŞ related to this system before. The crude oil's properties (viscosity vs. temperature, Bingham yield stress vs. etc) used in case study are either taken from literature or made up artificially by arranging hypothetical crudes.

1.3 Literature Survey

In the surface transportation of crude oils, high flowline pressure are encountered for a number of reasons. Basically these are a function of the rheological and depositional properties of the crude oil under the temperature profile and shear-rate conditions developed in the system. These problems can be categorized into these areas: paraffin deposition, asphaltene deposition, thixotropic crude oil, turbulent flow transmission and low-gravity asphaltic-based crude oils. Various laboratory and field tests, used to identify the key features of these problem crudes for the identification and chemical treatment purposes, are described by Newberry[1].

Ford, Ells and Russel[2] exhibit non-Newtonian viscosity behaviour at temperatures below about 6°C above the pour point. The lowered the temperature, the more marked is the deviation from a Newtonian behaviour. Viscosity is a function of both temperature and effective rate of shear. If the oil should cool statically, that is, under stagnant conditions with no shear to a temperature of a certain value below the pour point, then the oil will gel and a particular pressure will be required to initiate flow.

Ford, Ells and Russel[3] deal with the unsatisfactory result of repeated oil's shear stress(yield stress) test values. The yield values obtained by carefully repeated experiments, using the same apparatus, are subject to quite wide variations. These are not only dependent on the temperature to which the oil has cooled but, to a very large extend, on whether the oil has been cooled under static or flow conditions. While cooling, the rate of shear has only a minor influence on the yield values obtained.

Temperatures and burial depth and soil properties are critical factors in a pipeline. It is sometimes argued that there is an advantage in having it above ground so that heating of the sun's rays assist in degelling the line. However, in some regions, unless the line is lagged, the night ambient temperature conditions will often caused a marked reduction in throughput. In extreme cases, it would even stop the line completely. Ford, Ells and Russel[4] presents these effects.

Problems related with the transportation of two high pour point west African (Zaire and Cabinda) crudes are discussed by Irani and Zarac[5] . Relevant rheological parameters of untreated and treated (chemical additives for pour point depression) crude were determined in the laboratory and these results are presented. In both cases, low concentrations(30 to 50 ppmw) of the chemical additives improved the mobility and reduced the restarting pressure requirements for crude oil. On the basis of the successful laboratory program, a field test for Zaire was undertaken I June 1977. The treatment was implemented by preparing a batch solution of additive in crude oil and injecting the solution into the transfer line at the off shore platform. Field implementation of the Cabinda treatment presents a more difficult situation requiring injection of additive at the wellhead. On the basis of Cabinda crude, continuous circulation of the crude in the platform storage tank was suggested to field personnel as a means to partially alleviate the transportation problems.

Burger, Perkins and Striegler[6] presents the result of a study to investigate mechanisms of wax deposition and to determine the expected nature and thickness of deposits in Trans Alaska Pipeline system as a function of time and distance.

The parameters that effect the transportation of high-pour point crude are described by Smith and Crest[7]. One of them is the physical properties of crude. Pour point, density, specific heats, water and sediment, salt content and distillation summary the physical properties of crude oil. To determine the physical properties of a high-pour-point crude, samples of the crude must be tested in the laboratory. Such a determination of physical properties of waxy crude is fundamental to the safe and complete design of a pipeline system.

Design of heavy crude facilities is addressed by Smith and Crest[8]. Pump selection is of primary concern in facilities design.

Under stationary conditions, waxy oil congeals when it cools below the pour point. If this cooling takes place, a certain pressure is required to initiate flow of the gelled waxy crude. The starting pressure gradient is related to the rheological property known as the yield stress. Yield stress is the shear stress that must be developed in the oil to initiate flow. The maximum pressure buildup when a gelled pipeline is restarted occurs when the gel is sheared at the wall. To establish whether restart is possible for a given shutdown period, the available pumps must be evaluated for their ability to provide the required shear stress[9].

Heat transfer mechanism is one of the important parameter in pipeline design of waxy crude. Hydraulic calculation is straightforward with conventional crude oils. However, it becomes very complex with non-Newtonian crudes. Heat transfer calculation must be made to determine the type of flow[10].

Economides and, Chaney[11] deal basically with the heat losses from the pipeline considering a mare interruption of the flow that would derive from a variety of natural and/or man-made disasters at the pumping stations or at the marine terminal and a rupture in the pipeline that would expose a cross section of the pipeline to the ambient temperatures. A fundamental heat-transfer study and laboratory measurements were combined to forecast the rheological response and subsequent start-up requirements of Prudhoe Bay oil in gathering lines and in

Trans Alaska pipeline.

Kruka, Cadena, Long[12] explain possible methods of cloud point, the temperature at which wax or paraffin begins to precipitate from a hydrocarbon solution, determination of crude oils.

Khan, Dilawar, Nautiyal, Srivastava[13] explain a new method of pour point measurement of transparent fluids by determining wax appearance temperature.

The deposition of paraffin and asphaltenes in the reservoir rock tubulars, pumps, vessels and pipelines affect the production and transportation of oil. A wide range of solutions has been developed for the operating problems caused by these deposits. Examples of the field problems and the techniques chosen by Shell in the U.S. are cited by Tuttle[14].

Smith, Crest[15] present high pour point crude properties. If the crudes exhibit non-Newtonian viscosity behaviour, the effective viscosity is a function of both temperature and rate of shear. With each waxy crude discovery, extensive laboratory tests should be applied on this crude to determine exact crude behaviour under temperature variation. The exact behaviour under temperature is simply stated as crude's rheology. They also deals with " industry accepted" methods in pipelining high pour-point oil. Among these methods, only the effects of chemical as a drag reducer was investigated along the pipeline in the program.

Ajienka, Ikoku[16] present a new approach to the design of "power-law crude oil" pipelines. This method is based on the maximum pressure required in the handling of the power law crude for normal uninterrupted flow, restarted flow and pressure to break the gel. This method is different from Harvey[17] because non-Newtonian flow behaviour was assumed to be "power law model" instead of "Bingham plastic". Pipelines are assumed as a single phase waxy crude oil. This means that both Newtonian (inlet end) and non-Newtonian (discharge end) turbulent flow can occur along the pipeline depending on whether the flowing temperature is above or below cloud point. In this thesis, "Bingham plastic" model is used in non-Newtonian flow analysis. Moreover, the homogeneous or heterogeneous slurry characteristics of crude oils are investigated and some corrections are made on non-Newtonian pressure loss calculation to include the two face flow effects.

Design of a conventional pipeline presents a much more easy problem than that of a pipeline for a congealing oil. Heat transfer and fluid flow have to be considered, and performance must be determined not only for normal operating conditions but also for restarting after a shut-down. Harvey, Briller and Arnold[17] outlined a method for estimating system performance and pumping requirements for Newtonian and non-Newtonian laminar or turbulent flow. This procedure with minor changes was followed in the program for heat transfer analysis case. Harvey recommended that for Newtonian turbulent flow the Fanning equation can be used together with the Blasius friction factor and the Hagen-Poiseuille equation for laminar flow. The use of Chen and Colebrook-White equations together are preferred in the program. For non-Newtonian flow, the same equation can be used for turbulent flow but the apparent viscosity should be replaced with plastic viscosity. Hedstrom equation should be used for laminar flow. Non-Newtonian flow behaviour was assumed to be approximately Bingham Plastic.

The first Iraq-Turkey Crude Pipeline(ITP1) is studied while operating with chemical injection, to boost up the throughput in this report[18]. Most generally, the injected chemicals in small quantities, does not effect the crude's quality, but act as a drag reducer decreasing the frictional head loss. As a result, the existing pipeline is used at a higher capacity. In this program chemicals are used to decrease the non-Newtonian effects of crude oil if the pipeline does not operate due to high frictional loss.

The report[19] prepared by Eralp and Yahşi presents the hydraulic calculation and flow rate required to transport crudes from Batman to Dörtyol. The flowrate is compared with the design capacity of Batman-Dörtyol pipeline and the difference between them is taken as the base of energy loss. The gravity of crudes is very important when considering the pump power, its power increases with increasing gravity. Viscosity also shows the same effects on the pumps. So the loss during the transportation should be calculated by considering the flow rate loss.

Tullis[20] presents the use of centrifugal pumps and their relationship to the hydraulic characteristics of piping system. Pump characteristics covered include total dynamic head, efficiency, horsepower, net positive suction head, specific speed, suction specific speed, and similarity laws. The criterias effecting the selection of parallel and series pump combinations are discussed.

The centrifugal pump applications and several pump combination types are studied by Robert[21]. Importance of centrifugal pumps for pipelines are illustrated. There are various commercial catalogues available[22], [23], [24] which give empirical relations to various pump installation.

Statically cooled samples of waxy crude oil posses a complex yielding behaviour that can not be described by existing yield stress fluid models nor by the description and modelling of thixotropic materials. Three distinct characteristics of the yielding process, namely, a solid (Hookean) behaviour, a slow deformation (creep) and a sudden failure of the sample that closely resembles the brittle or ductile fracture of solids, have been identified by four different techniques- the vane technique, the cone and plate viscometer (constant rotation), constant stress rheometry, and oscilatory (dynamic) testing. A capillary viscometer or pilot scale pipeline presents technical difficulties which make it unsuitable for investigating the yielding behaviour of waxy crude oils. The shear stress at the fracture is the value of most interest to pipeline designers and the one most often taken s-as the yield point. Means of obtaining reproductible yield stress and fracture stress data are discussed by Wardhaugh, Boger[25].

A simple method needing the average boiling point (sometimes referred to as the 50% boiling point) as the only input, is found to predict viscosities of petroleum crude oils and their fractions, with comparable or better accuracy than other methods. Dutt[26] presents this method. Other crude oil viscosity prediction methods are Beal for dead oil and Chew and Connally for live or saturated oil. Beal correlated dead oil viscosity as a function of API gravity and temperature. Chew and Connally presented a correlation for the effect of dissolved gas on the oil viscosity[27]. Besharah, Salnan and Akashah[28] explains experimentally measured viscosities of light, medium, and heavy crude oils and their blends. These viscosity data can be used to develop a new method for predicting the viscosity of crude oil blends based on known component viscosity. Duhne[29] gives a general discussion of viscosity-temperature relationships, data sources, the accuracy of the correlations, and a comparison with nomograph methods.

Waxy crude oils are highly non-Newtonian materials known to cause handling and pipelining difficulties and whose flow properties are time and history dependent. Experimental techniques are described that enable reproducible steady-state flow property data to be obtained from rotational viscometers. The flow properties are shown to depend strongly on the shear rate applied during cooling (shear history effect). This leads to a definable minimum operating point below which flow in a waxy crude oil pipeline would cease. Modified pipeline design techniques are presented for both laminar and turbulent flow at temperatures below the pour point by Wardhaugh and Boger[30].

The design of subsea pipelines carrying waxy crude oil, especially in Norhern and artic areas, is largely controlled by start-up pressure requirements. The correct measurement of rheological parameters associated with start-up and line clearing of gelled crude oil pipelines, is thus important for proper design of pumping capacity and pipeline dimensions. The yielding behaviour of some waxy North Sea crude oils and the time dependent rheological properties of waxy crude oils are studied by Ronningsen[31].

Civil[32] performed a computational study for the simulation of batch operation of liquid pipelines. The aim of developing such a software is to manage to simulate the new operation schedule especially when the batching conditions are changed. Çakmanus[33] developed a software for full design of the steady state liquid pipelines. By the help of this software the optimum required pipe diameter, pipe wall thickness along the pipeline, number and spacing of pumping stations and corresponding first investment cost, operating cost and annual total cost are determined.

C. B. Lester and Associates, in cooperation with Tekfen Installation and Construction Company presented a proposal[34] for the application of ARCOFLO drag reducer to the Iraq-Turkey crude oil pipeline system. It includes a series of tests an the Iraq-Turkey system to establish the efficiency of the drag reducer, the quantities of drag reducer required to produce a certain drag reduction, the effects of chemicals on crude and pipeline system, the implementation such a chemical to the pipeline and quality assurance documentation.

Several implicit and explicit friction factors are compared by Round[35]. The friction factor equation used in this study is the relative friction factor.

The application of the extended Bernoulli equation and continuity equation to pipe flow, and pipe circuit, the flow regimes encountered in pipe flow are explained by Aksel[36], Sabersky,Acosta, Hauptmann[37], and Evett, Liu[38].

Recently, with the advent of microcomputers and enhanced programming technology, has permitted the pipeline design industry a new phase of performance and advancement of methodology as well as technology. The installation of microcomputer system, development and operation of a computer software is relatively inexpensive while the performance is just as effective as, and as reliable as, any of the more expensive systems. Kung, Mohitpour[39] deal with the application of microcomputer technology for hydraulic design and analysis of bitumen pipeline system in Alberta. They give an example pipeline hydraulics program with non-Newtonian flow characteristic incorporated.

Heywood, Cheng and Carleton[40] has considered the industrial and other practical experience in the application of correlations and methods available in the design of slurry pipelines. Four classes of fluids are discussed in terms of their relevant pipeline characteristics. The first is settling slurry, for which the pipeline characteristics are minimum transport velocity and pressure gradient. The second is nonsettling slurry, for which laminar/turbulent transition velocity and pressure gradient are relevant. The third is stabilized slurry, where non-settling slurry design equations can be used. The fourth is thixotropic fluid, for which start-up pressure and time required to clear the pipe of gelled material are of particular importance.

Smith[41] gives some numerical approaches to the numerical representation of pump characteristics. He also explains the advantages access of computer to pipeline technology.

Marks[42] gives a review of the most important computations in pipeline engineering. He present a pragmatic approach to these computations by utilizing programmable calculator programs. The handbook is divided into three principal parts. These present materials that are to be of use to the pipeline engineer engaged in feasibility studies, detailed design, and pipeline construction engineer.

Incropera and Dewitt[43] deal with the mechanisms of basic heat flow problems and their solution. Three modes of heat transfer mechanisms, conduction, convection and radiation are investigated in a more detailed form.

Karakan[44] developed a software for the design of steady state liquid pipelines similar to Çakmanus.

1.4 Objectives and Scope of Present Study

An analysis program about flow characteristics of crude oil pipeline system in Turkey is the subject of this thesis. Steady state design calculations are assumed to be performed previously. Its results are the input of this program. Hydraulic loading of the line satisfies the conditions of Maximum Allowable Operating Pressure (MAOP). Physical properties of the line such as pipe diameter, length of the line, pumping station characteristics, properties and configuration of fluids are stored in data file or entered to the program directly.

The main aim of the program is to operate high pour point crudes in existing pipelines by using the available conditions. In case of flow blockage due to the application of high pour point crude, the solutions are limited by the system. In other words, flowrate change, pump station head change heating of oil or any combinations of these are possible, if the pumps capacity or system allows these modifications. The crude oils transportation methods is not the scope of this thesis except for drag reducer chemicals.

Several assumptions are made in the program. These are as follows:

i. single phase steady state flow

ii. pipeline inlet and ambient temperatures as well as cloud- and pour-points are known

iii. the nature of waxy crude oil and expected handling problems have been determined

iv. the effect of temperature on the rheological parameters has been determined and thixotropy is ignored

v. the handling method has been decided upon the design throughput and other relevant information such as thoroughfare, etc., are known

vi. the minimum flow rate, Qmin, to initiate flow is 50 % of the desired throughput

vii. maximum advisable downtime is determined

viii. crude density, specific heat capacity, thermal conductivity are independent of temperature.

CHAPTER 2

HYDRAULIC ASPECTS IN LIQUID PIPELINES

2.1 Basic Equations

Continuity and extended Bernoulli equation are two basic equations used in the solutions of most pipeline fluid flow problem.

2.1.1 Continuity Equation

The simplest form of continuity equation is for one dimensional, incompressible($\partial\rho/\partial t=0$), steady flow in a closed conduit. Applying continuity between any two section gives

$$V_1 \times A_1 = V_2 \times A_2 = Q \tag{2.1}$$

in which A is the cross sectional area of the pipe, V is the mean velocity at the same location, and Q the flow rate. Equation 2.1 is valid for any rigid conduit as long as there is no addition or extraction of fluid between the sections.

2.1.2 Extended Bernoulli Equation

The extended Bernoulli Equation is very powerful equation in solving pipe flow problems. The most general form of this equation is as follows:

$$\frac{V_1^2}{2\times g}+\frac{P_1}{\rho\times g}+z_1+h_s-h_f=\frac{V_2^2}{2\times g}+\frac{P_2}{\rho\times g}+z_2 \qquad (2.2)$$

The term h_s refers to shaft work per unit weight and h_f refers to frictional work per unit weight. Thus P/ρ.g, called pressure head; z, called elevation head; and $V^2/2.g$, called velocity head. The sum of these three quantities is referred as the total energy head shown by energy grade line(EGL). The sum of elevation head and the pressure head is called piezometric head. The line showing the variation of the piezometric head is known as the hydraulic grade line (HGL).

2.2 Pumps in Pipelines

Centrifugal pumps are the most commonly used type of pumps in pipelines. Pumps transmit the required amount of hydraulic energy to the system when necessary.

Selecting a pump for a particular service requires the investigation of system requirements and pump capabilities. Centrifugal Pumps operate at the intersection of the head capacity curve and system characteristic curve which exhibit the head requirements of the system of pipe, valve, fittings etc. The proper selection of pump does not only provide the required head and discharge, but also it operates as close as the best efficiency point. The characteristics curves are generally provided by the manufacturer for centrifugal pumps and each of them may be represented by a polynomial at a given rpm. A quadratic polynomial can be used for head versus flowrate, cubic polynomial is used for power versus flowrate and fourth order polynomial is used for representing efficiency versus flowrate [41] at the nominal rpm. i.e.,

$$H=a_1+b_1\times Q+c_1\times Q^2 \qquad (2.3)$$

$$P=a_2+b_2\times Q+c_2\times Q^2+d_2\times Q^3 \qquad (2.4)$$

$$\eta = a_3 + b_3 \times Q + c_3 \times Q^2 + d_3 \times Q^3 + e_3 \times Q^4 \qquad (2.5)$$

where a_1, a_2, a_3, b_1, b_2, b_3, c_1, c_2, c_3, etc. are the constant coefficients of the respective polynomials. Curve fit is a must for computational work. There are various methods for curve fitting, but least square method is the simplest and most commonly used method among them all.

The head-flowrate curve of any pump changes with changing the rotational speed of the impeller. Typical characteristics of a centrifugal pump as shown in Figure2.1 is only valid for a given speed. To operate a centrifugal pump at a speed other than its design speed to meet the requirements of the particular duty is a common practice. In such a case, Affinity Laws described for pumps is applied to find new operating point for geometrically similar (D= constant) pumps, working at a different rotational speed. These relations can be expressed as follows:

$$\frac{H_1}{H_2} = \frac{N_1^2}{N_2^2} \qquad (2.6)$$

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \qquad (2.7)$$

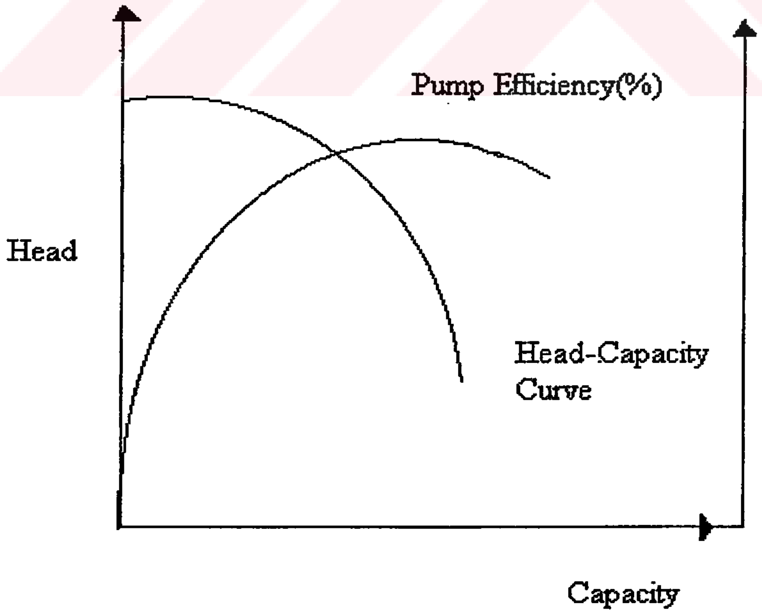

Figure 2.1 Typical Characteristic of a Centrifugal Pumps

Operating point explained above lies at the point of intersection between the pump curve and system characteristic. Similarity curve for the same pump operating at different rotational speeds has an equation in the form of $H= K.Q^2$, where K is the constant. Point 1 and 2 lie on two head curves at different speed are similar points. Graphical representation of this fact is given in Figure 2.2.

In crude oil pipelines, the pumps will be forced to handle crudes with a variety of viscosity due to the temperature dependence of viscosity. In this condition, considering the change of head requirement expected from the pump, the supplied head is adjusted by changing the rotational speed of the impeller.

Series or parallel combinations of pumps sometimes become inevitable due to varying demand, changes in reservoir elevation, or changes in friction or minor losses. According to the requirements of a particular duty, a single pump may not provide the necessary head or supply the required amount of discharge to the system. Series combination of pumps is a requirement for the former case and parallel for the latter case. In some cases, however, both of the principal combinations may be necessary.

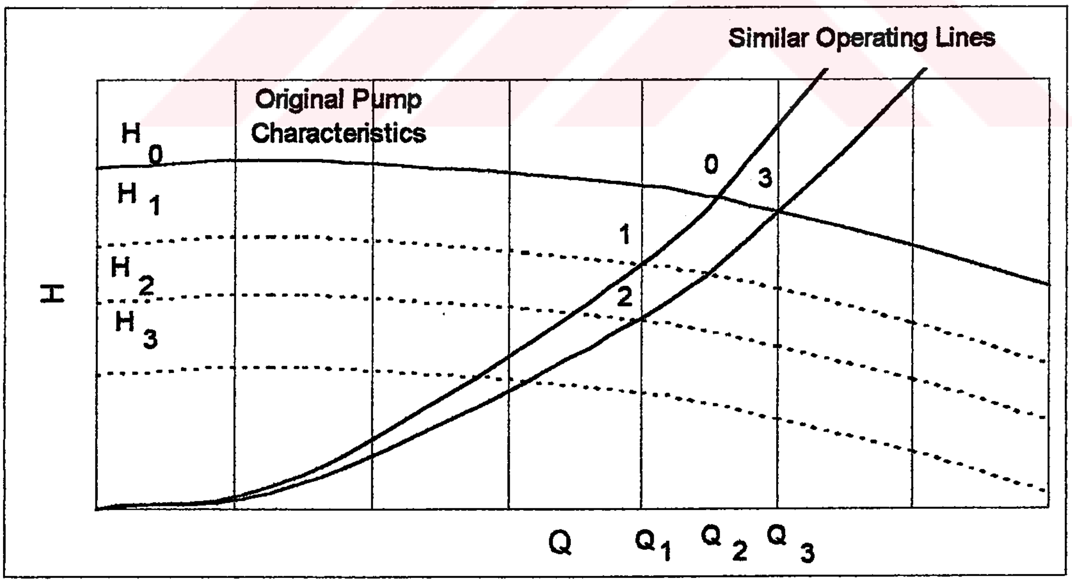

Figure 2.2 Similar Operating Points

2.2.1 Pumps Handling Viscous Liquids

As the viscosity of the fluid increases (for constant rotational speed), head, flowrate, efficiency of the pump fall. Generally, pump characteristics supplied by the manufacturer are proposed for water. In case, when pump handles a fluid other than water, its characteristics have to be corrected. Especially, if the viscosity of the fluid is relatively high; this become inevitable, because in such cases prediction of actual operating point is of primary importance.

Typical head-flowrate, power-flowrate and efficiency-flowrate characteristics corrected for a viscous flow are given in Figure 2.3. In this figure, subscript w denotes water and z denotes the viscous fluid handled. Especially for high flowrates and viscosity the correction is necessary because in these cases two curves for water and the viscous fluid deviate from each other considerably.

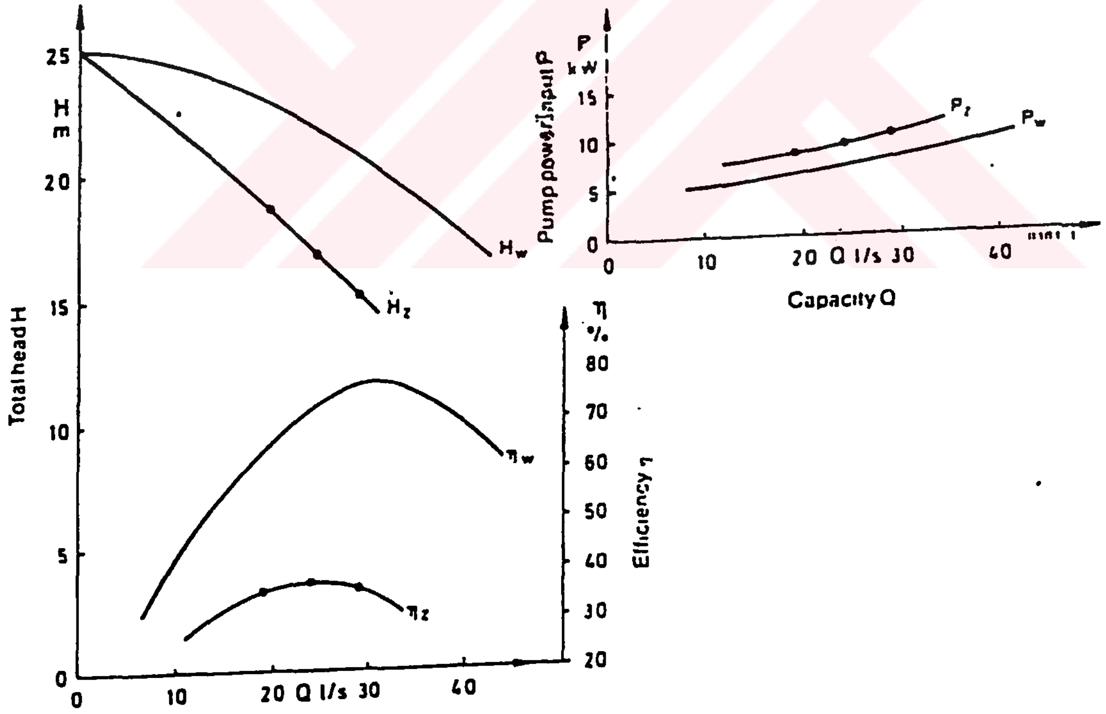

Figure 2.3 Characteristic Curve of a Centrifugal Pump for both Water(w) and Viscous Fluid(z) [22]

2.3.2.1 Viscosity Correction Procedure

The graphical form of viscosity correction is given in Figure 2.4. Because it is a tedious job to digitise these curves and storing them in a file due to the requirement of entrance thousands of data in the form of a database, it is converted into semi-analytical form by expressing the intermediate steps of nomograms analytically. Graphical procedure to find the intersection points at intermediate steps is replaced with direct analytical procedure in order to adopt viscosity correction over computational field. The procedure [32] is as follows:

i. Knowing H, Q, η for an operating point on the characteristics curves which is specified for water, one can directly find the intersection point (x_1) of logQ and H=constant lines by the aid of equation

$$X_1=-9.31\times\log Q+3.33\times\log H+34 \tag{2.8}$$

ii. The second step is to find the intersection point (x_2) of $y=X_1$ line and ν=constant line by the use of equation

$$X_2=0.069\times(X_1+9.16\times\log \nu) \tag{2.9}$$

iii. The last step is to find the correction factors (f_H, f_η) corresponding to X_2 and the specific speed (N_s) curve of the pump which is defined as

$$N_s=\frac{N\times\sqrt{Q}}{(g\times H)^{3/4}} \tag{2.10}$$

The curves for various specific speeds are digitized and the appropriate specific speed curve is used to find the correction factors. If the calculated specific speed curve falls between any two curves given in Figure 2.4 then the correction factors are to be found with interpolation.

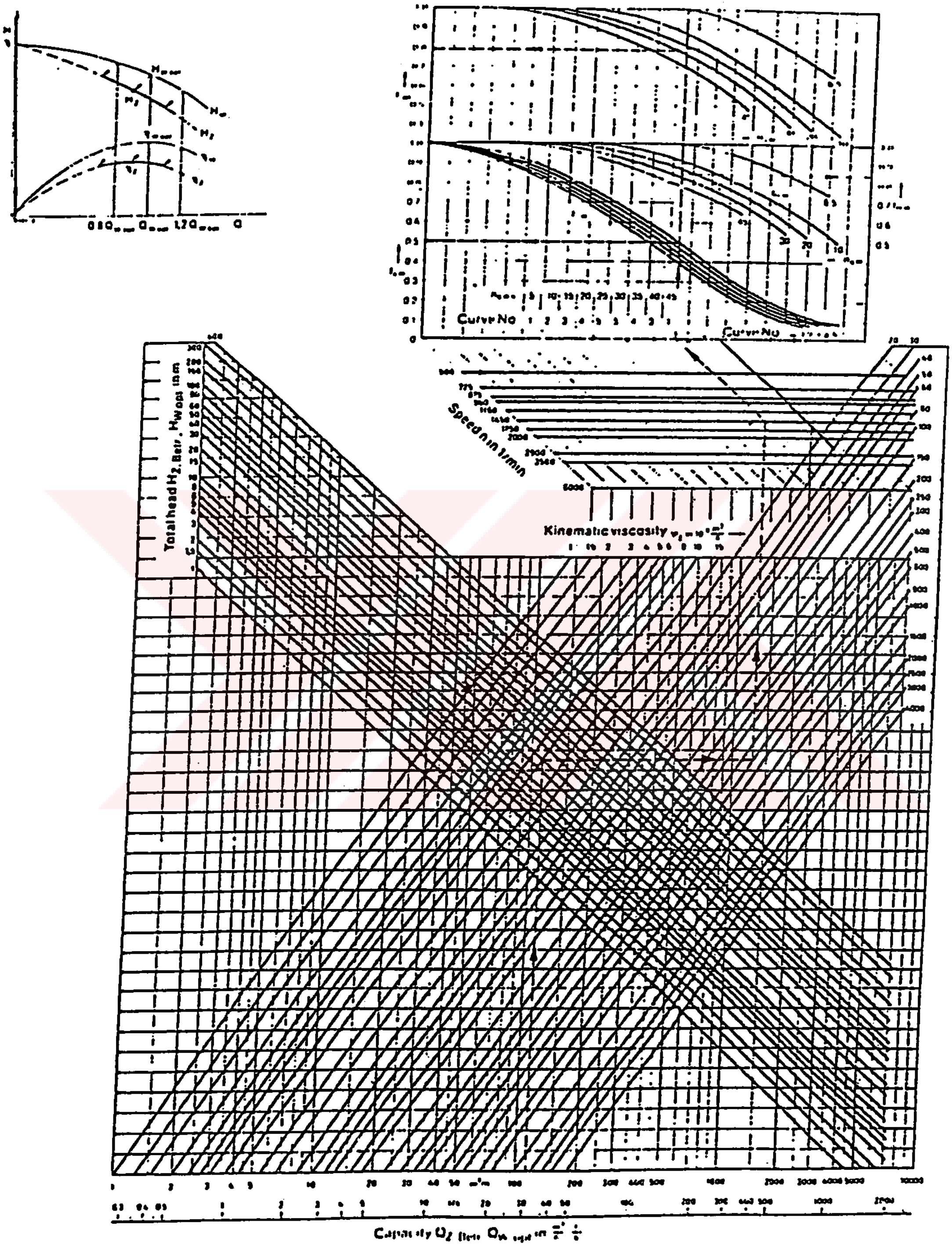

Figure 2.4 Head and Efficiency Correction Graph For Viscous Liquids[22]

If the nomograms are investigated carefully, the correction coefficients will appear not to be in negligible order of magnitude. In fact, if the viscosity is beyond 100 cst this coefficients will go down to 0.8, which is not of negligible importance.

2.3 Cavitation in Pumps

One of the serious problems with pump operation continues to be cavitation erosion. Turbomachines having liquid as the working fluid are susceptible to cavitation phenomenon which limits the performance under certain conditions. This phenomenon is defined as the local vaporization of the liquid due to dynamic conditions. Cavitation becomes visually apparent as vapour bubbles in the liquid both at the boundary and in the interior of the stream. Vaporization may occur when the local pressure reduces to the vapour pressure of the liquid at the local temperature. Cavitation, whenever occurring in pumps, generates noise, pressure fluctuations, vibrations, and eventually reduces the efficiency of the devices. Pumps can be forced to cavitate by reducing the suction pressure. Cavitation can exhibit two general effects on pump performance. First one is erosion damage, which wears away the impeller and other parts of the pump and degrades the pump performance. Second one is for advanced stages of the cavitation. The pump performance can be degraded by large quantities of vapour. The minimum amount of pressure required at the suction side of pump to prevent cavitation is referred to as the net positive suction head required. The net positive suction head available in the system must exceeds the net positive suction head required by the pump with a reasonable margin of safety to ensure the satisfactory operation. The net positive suction head available in pump stations of a pipeline can be stated as follows

$$\mathrm{NPSH_a}=\frac{P_s}{\gamma}+\frac{V_s^2}{2\times g}-H_v \qquad (2.11)$$

Where $\frac{P_s}{\gamma} = H_s$

H_v: absolute vapour pressure of the liquid

H_s: minimum elevation of hydraulic grade line from the land at each pumping stations to prevent cavitation problems in pumps

$\frac{V_s^2}{2 \times g}$: velocity head at the entrance of pumping stations

2.3.1 Suction Specific Speed

Another parameter used to describe the cavitation characteristics of an impeller is suction specific speed. This parameter relates the cavitation potential of a pump to its speed and discharge.

$$S = \frac{N \times Q^{0.5}}{(g \times NPSH_r)^{0.75}} \qquad (2.12)$$

where

N: speed of motor (rad/s)

Q: flow in m^3/s at the point of maximum efficiency

$NPSH_r$: NPSH at the point of maximum efficiency

Larger value of S shows more severe cavitation condition. Suction specific speed usually ranges between 1 an 7 depending on impeller design, speed, capacity, nature of fluid and service conditions and degree of cavitation. S ranging up to 5 or higher is generally used for the operation of pumps handling hydrocarbons.

CHAPTER 3

RHEOLOGY OF CRUDE OILS

3.1 Waxy Crude Oils

The majority of crude oils contain a certain proportion of heavy hydrocarbon compounds, which may precipitate as a waxy solid phase if the oil is cooled below a certain temperature. Wax precipitation may take place at temperatures far above the freezing point of water, and is therefore a potential problem when petroleum mixtures are transported in pipelines, e.g., underwater, or treated in process plant . Wax precipitation may result in plugging of pipes and process equipment. When designing pipelines and separation plants it is, therefore, of importance to be able to determine the conditions where wax precipitation takes place, and the amount of wax likely to form.

The wax present in petroleum crudes primarily consists of paraffin hydrocarbons (C18 - C36) known as paraffin wax and naphtenic hydrocarbons (C30 - C60). Hydrocarbon components of wax can exist in various states of matter (gas, liquid or solid) depending on their temperature and pressure. When the wax freezes, it forms crystals. The crystals formed of paraffin wax are known as macrocrystalline wax. Those formed from naphtenes are known as microcrystalline wax

Wax precipitated from oil mixtures consists of closed packed lattices of alligned paraffinic and naphthenic molecules. The most comprehensive waxcomposition analysis have been made on waxes extracted from petroleum mixtures. They can be divided in to two main categories: paraffinic waxes and microcrystalline waxes. The basic characteristic of each category are shown in Table 3.1.

Table 3.1 Typical Compositions and Properties of Paraffin and Microcrystalline Waxes

	Paraffin Waxes	Microcrystalline Waxes
Normal Paraffins (%)	80-95	0-15
Branched paraffins (%)	2-15	15-30
Cycloparaffins (%)	2-8	65-75
Melting point range (°C)	50-65	60-90
Average molecular weight range	350-430	500-800
Typical carbon number range	18-36	30-60
Crystallinity range (%)	80-90	50-65

A Waxy crude usually consists of a variety of light and intermediate hydrocarbons (paraffins, aromatics, naphtenic, etc.), wax and a variety of other heavy organic (non-hydrocarbon) compounds, even though at very low concentrations including resins, asphaltenes, diamondoids, mercaptdans, organo-metallics, etc. When the temperature of a waxy crude oil is lowered, first the heavier fractions of its wax content start to freeze out.

The crystallization of wax in crude oils causes several difficulties in pipelining storage with respect to low pour-point crude oil. As the waxy crude flows through a cold pipe or conduit (with a wall temperature below the cloud point of the crude), crystals of wax may be formed on the wall. Wax crystals could then grow in size until the whole inner wall is covered with the possibility of encapsulating oil inside the wax layers. As the wax thickness increases, pressure drop across the pipe shows an increasing trend continuously to maintain same flow rate of fully Newtonian case besides restriction in flow, increase in downtime, more mechanical problems and higher handling cost. As a result, the power requirement for the crude transport will increase. However, many pipelines around the world are now successfully transporting waxy crudes under conditions where the ambient temperature is lower than the pour point of the liquid.

3.2 Basic Properties of Crude Oils

Pour point temperature and cloud point temperatures are the most important properties of crude oils in determining the type of flow.

3.2.1 Pour Point Temperature

Pour point is the temperature at which the flow of crude oil, or other petroleum fluids, ceases. It is an important indicator of the transition of flow from Newtonian to non-Newtonian characteristic. Pour points provide to a good approximation, information about this transition temperature.

3.2.2 Cloud Point Temperature

The cloud point is the temperature at which paraffin particles begin to participate out of solution: the pour point is usually 3-6 °C lower than the cloud-point.

Waxy crude oils exhibit non-Newtonian flow behaviour below the cloud point temperature because of wax crystallisation. Above the cloud point flow is Newtonian.

3.2.3 Viscosity of Crude Oils

For most crudes, at sufficiently high temperatures, the viscosity at a given temperature is constant and the crude is a simple Newtonian liquid.The viscosity of oil can be defined by

$$\mu = \frac{\tau}{dv/dy} \tag{3.1}$$

where τ is the shear stress and dv/dy is the velocity gradient. The viscosity of crude oil is perhaps its most important physical property affecting the flow on a pipeline. As the temperature is reduced, the flow properties of a crude oil can readily change from the simple Newtonian to very complex flow behaviour due to the crystallisation of waxes and colloidal association of asphaltenes.

3.3 Rheology of Crude Oils

Rheology is the science of flow and deformation of matter and describes the interrelation between force, deformation and time. The term comes from Greek rheos meaning to flow. Rheology is applicable to all materials, from gases to solids.

Fluid rheology is used to describe the consistency of different products, normally by the two components viscosity and elasticity. By viscosity is usually meant resistance to flow or thickness and by elasticity usually stickiness or structure.

The flow properties of an oil containing crystallise wax are distinctly non-Newtonian. A yield stress (the minimum pressure required to restart flow, also termed gel strength) can be detected which, under some circumstances, can be many times higher than the normal pumping pressure.

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These crystals can entrap the oil in to a gel like structure that is capable of forming thick deposition in pipes and increasing pumping pressures to the point where flow ceases.

High pour point crudes require higher than normal temperatures before their pour points are reached (normally between 15 and 46 °C). Additionally, high pour point crudes exhibit non-Newtonian viscosity behaviour at temperatures below about 6 ° C above the pour point.

This means the effective viscosity is not a function of temperature alone, but it is also a function of the effective rate of shear in the pipeline. Shear stress and rate of shear must be determined to predict the pressure required delivering specified production volume.

Viscosity measurements would allow an investigation of the rheology of crude oils. With each waxy crude discovery extensive laboratory test should be made to determine the crude's rheology. A short review of rheological properties as follows:

3.3.1 Time Dependent Fluids

There are two types of time dependent non-Newtonian fluids. If the apparent viscosity decreases with time when the fluid is subjected to shear, the fluid is thixotropic. This property associated with high waxy crude oil separates it from normal crude. If the viscosity increases with time, then it is rheopectic.

3.3.2 Newtonian and Non-Newtonian Fluids

A Newtonian fluid is fluid whose deformation under laminar conditions is directly proportional to the stress. There are three types of non-Newtonian, time-dependent fluids:

- Bingham plastic
- Pseudoplastic
- Dilatant.

3.3.2.1 Bingham Plastic

A Bingham plastic, a material resisting flow much like any Hookenian solid until its yield strength is exceeded, behaves like a Newtonian fluid except that for flow to take place, a specific yield stress must be exceeded. Bingham plastic behaviour can be represented by the following equations. For $\tau > \tau_0$

$$\tau = \tau_o + B \times \frac{dv}{dy} \tag{3.2}$$

and for $\tau < \tau_0$,

$$\frac{dv}{dy} = 0 \tag{3.3}$$

where τ_0 is the yield stress that must be exceeded for the flow to be initiated and B is the coefficient of plastic viscosity.

3.3.2.2 Pseudoplastic Fluids

A pseudoplastic fluid is fluid whose apparent viscosity decreases with increasing shear rates. The behaviour can be expressed mathematically as

$$\tau = K \times \gamma^n \tag{3.4}$$

where K and n are constants.γ represents shear rate. This equation is often known as the power law relationship for non-Newtonian fluids.

3.3.2.3 Dilatant Fluids

A dilatant fluid displays rheological behaviour opposite to that of pseudoplastic fluids (apparent viscosity increases with increasing shear rates).

Table 3.2 Newtonian and Non-Newtonian Fluids

Fluid Type	Fluid Characteristics
Newtonian	Unaffected by magnitude and kind of motion to which they are subjected
Dilatant	Viscosity will increase as agitation is increased
Bingham Plastic	Have definite yield values, which must be exceeded before flow starts. After flow starts, viscosity decreases with increase in agitation
Pseudoplastic	Do not have a yield value, but do have decreasing viscosity with increase in agitation
Thixotropic	Viscosity will normally decrease upon increased agitation, but this depends upon duration of agitation and viscosity of fluid and rate of motion before agitation

3.4 Non-Newtonian Behaviour of Crude Oils

The crude may exhibit pseudoplastic or thixotropic behaviour and/or act as a Bingham plastic in the transition phase between the onset of wax crystallization and the fully gelled state.

A waxy crude may exhibit Bingham plastic behaviour after gelling. The behaviour of this type of crude varies from that of Newtonian fluids only in that its linear relationship between shear stress and shear rate does not go through the origin. A finite shear stress is required to initiate flow. Further, the viscosity or pumpability of a Bingham Plastic is both rate of shear and time dependent.

When waxy crude is allowed to cool below its cloud point under static conditions in a pipeline, the paraffin will crystallise causing the entire mass of crude oil to gel.

If a waxy crude pipeline being pumped below its cloud point via shut down for any reasons, resulting gelled state will require, upon restart, substantially more pressure to put it in motion. Several parameters must be investigated, such as

- Heat transfer
- Physical properties of crude oil
- Restart after shut-down
- Wax content

3.5 Hydraulic Calculations

Hydraulic calculations for Newtonian crude oils must be made using conventional hydraulic equations.

These calculations become more complex with non-Newtonian crude. Since the viscosity is both temperature and shear rate dependent. Pressure loss calculations for non-Newtonian liquids are made by dividing the pipeline into short segments and analyzing each segment separately as a result of variation of viscosity and the change of flow type depending on the temperature and viscosity.

3.5.1 Newtonian Pipe Flow

In crude oil pipelines, total frictional losses are given by Darcy-Weisbach equation:

$$h = f \times \frac{L}{D} \times \frac{V^2}{2 \times g} \tag{3.5}$$

For determining the correct friction coefficient, one has to first decide on the flow regime encountered inside the pipe. The only determining fact is the characteristic non-dimensional figure, i.e. Reynolds number, defined as

$$\mathrm{Re} = \frac{V \times D}{\nu} \tag{3.6}$$

Where V :Velocity
D :Characteristic length
ν :Kinematic viscosity of the fluid

For a pipe flow, characteristic length is the diameter of the pipe. As a general rule of thumb, flow is considered to be laminar if Re<2300, and it is in transition region up to Re<4000, and beyond this limit the flow is turbulent.

If Re<2300, flow inside the pipe is laminar and friction factor is simply equal to 64/Re.

If Re>4000, flow inside the pipe is turbulent. Chen and Colebrook-White equations are used to predict friction coefficient. The result of Chen equation is the initial assumption of Colebrook-White equation.

$$f = \left[-2 \times \log(\frac{\varepsilon}{3.7065} - \frac{5.0452}{\mathrm{Re}} \times \log(\frac{\varepsilon^{1.1098}}{2.8257} + (\frac{7.149}{\mathrm{Re}})^{0.8981})) \right]^{-2} \qquad (3.7)$$

$$\frac{1}{\sqrt{f}} = -2 \times \log(\frac{\varepsilon}{3.7 \times D} + \frac{2.51}{\mathrm{Re} \times \sqrt{f}}) \qquad (3.8)$$

This equation has been the basis for Moody diagram which is used commonly to determine the friction factor. The biggest obstacle of this equation is that it is an implicit function in f, so it requires an iterative solution procedure. However, it seldom necessitates enormous number of iterations and converges to a final value easily. This valuable advantage reduces the execution time and makes it very frequently used in computational work.

In transition region (2300<Re<4000) friction factor found from Colebrook-White equation can be improved:

$$f = \frac{64}{\mathrm{Re}} + 4 \times (f^{*} - 0.004) \times (\frac{\mathrm{Re}}{2000} - 1) \qquad (3.9)$$

3.5.2 Non-Newtonian Pipe Flow

Since the fluid properties are approximately Bingham Plastic, the method of Hedstrom[17] is applicable for non-Newtonian flow of crude oils. Using this calculation technique, the mode of flow is determined by two dimensionless parameters. These two terms, which may be described as a plasticity number and a Reynolds number based on plastic viscosity, are defined respectively as:

$$S = \frac{\tau_o \times D \times g}{\mu_p \times V} \qquad (3.10)$$

$$\mathrm{Re}_p = \frac{\rho \times V \times D}{\mu_p} \tag{3.11}$$

where τ_o : Bingham yield stress

μ_p: Plastic viscosity

The mode of flow is determined from Figure 3.1 with the help of plasticity number and Reynolds number based on plastic viscosity.

Calculation of pressure loss in turbulent flow can be accomplished by means of the conventional equations for Newtonian flow provided that plastic viscosity is used in the place of the Newtonian viscosity.

The calculation of laminar Non-Newtonian flow utilizes another dimensionless parameter, which is designated by $\phi(s)$. $\phi(s)$ is read from Figure 3.2 by using plasticity number. The pressure loss is calculated from Hedstrom's laminar flow relationship, which is

$$\Delta P_f = \frac{\phi(s).L\mu_p.V}{D^2.g} \tag{3.12}$$

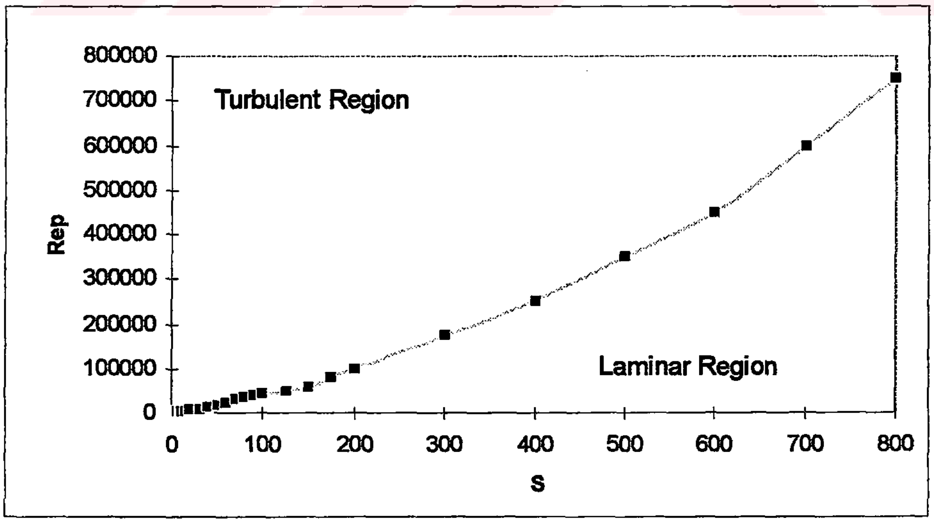

Figure 3.1 Mode of Flow for Bingham Plastics[17]

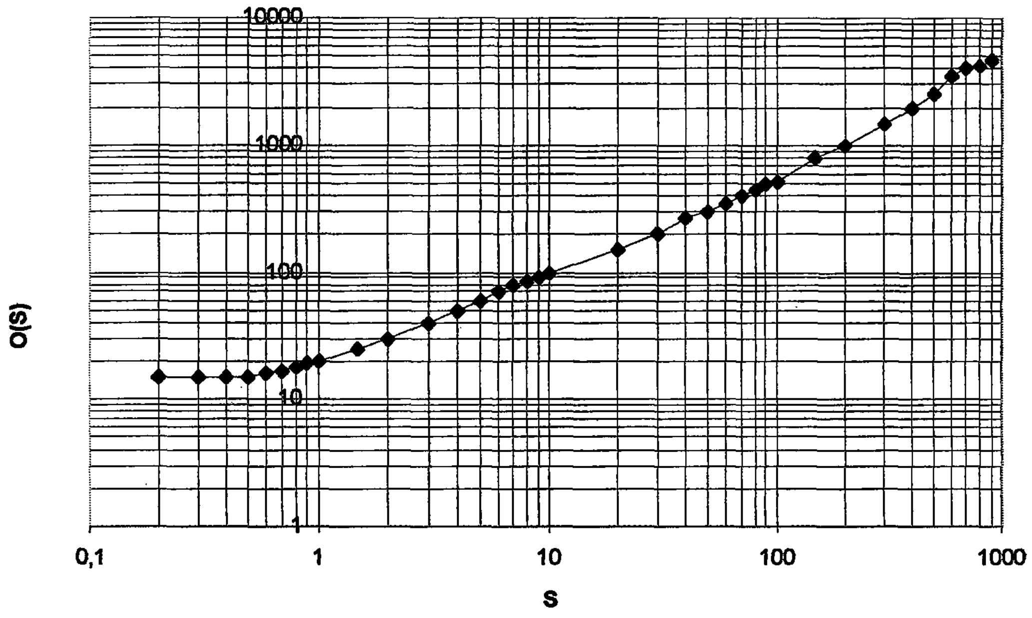

Figure 3.2 Laminar Flow for Bingham Plastics[17]

To analyse a segment efficiently, its inlet temperature and the temperature loss must be calculated. This involves an examination of the heat transfer from the oil to the surroundings environment.

3.6 Heat Transfer

Heat transfer has three distinct modes of heat transmission:

1.Conduction is the heat flow process from a region of higher temperature to a region of lower temperature within a medium (solid, liquid or gas) or between different mediums in direct physical contact.

2.Radiation is the heat flow process from a high temperature body to a lower temperature one when bodies are separated in space.

3.Convection, the heat flow process by fluid motion between regions of unequal density caused by non-uniform heating, is the mechanism of energy transfer between a solid and a liquid or a gas. As all the pipelines investigated in this thesis are burial, the radiation heat transfer effect is neglected. Total amount of heat loss in a pipeline can be calculated by using following formula.

$$Q = \frac{(T_i - T_a) \times \pi \times d}{\frac{d}{h_i \times d_i} + \frac{d \times \ln(d_e / d_i)}{2 \times k_{pipe}} + \frac{d \times \ln(d / d_e)}{2 \times k_{ins}} + \frac{1}{h_o}} \tag{3.13}$$

Where

Q : heat flow

h_i : inside convective heat transfer coefficient

h_o: outside convective heat transfer coefficients

d_i: inside diameter of pipe

d_e: outside diameter of pipe

d: diameter of pipe with insulation

k_{pipe}: thermal conductivity of pipe

k_{ins}: thermal conductivity of insulation

T_i: temperature of crude oil at the center of the pipe

T_a: ambient soil temperature

Heat loss also can be calculated by using thermal conductivity of soil.

$$Q = S_f \times k_s \times (T_1 - T_2) \tag{3.14}$$

Where:

S_f: Shape factor

k_s: Soil thermal conductivity

T_1: Pipe surface temperature

T_2: Surface Temperature

The values of S_f worked out for several geometrise can be found in many reference books[43]. If the pipes are assumed as isothermal cylinder of radius r buried in semi-infinite medium having isothermal surface, shape factors are calculated according to the geometric conditions.

$$S_f = \frac{2 \times \pi \times L}{Cosh^{-1}(D/r)} \qquad \text{L>>r, D>3.r} \qquad (3.15)$$

$$S_f = \frac{2 \times \pi \times .L}{\ln(2 \times D/r)} \qquad \text{L>>R, D<3.r} \qquad (3.16)$$

$$S_f = \frac{2 \times \pi \times L}{\ln(L/r) \times \left[1 - \frac{\ln(L/2 \times D)}{\ln(L/r)}\right]} \qquad \text{D>>r, L>>D} \qquad (3.17)$$

Where:

L: Length of cylinder
r: Radius of cylinder
D: Depth of burial

Heat losses from the pipeline is calculated using transient temperature analysis. To develop the differential equation that is satisfied by the temperature profile in a pipeline with stagnant oil, the density and the specific heat remain unchanged during cooling process. In addition, the resistance through pipeline insulation controls the heat loss to the surroundings. Thus, the reciprocal of this controlling resistance can be set as equal to the overall heat transfer coefficient.

$$U = \frac{1}{\frac{d}{h_i \times d_i} + \frac{d \times \ln(d_e/d_i)}{2 \times k_{pipe}} + \frac{d \times \ln(d/d_e)}{2 \times k_{ins}} + \frac{1}{h_o}} \qquad (3.18)$$

Temperature losses must be calculated for two cases: Normal operating conditions and Restart after a shut down.

In order to calculate heat transfer from equation, the convection coefficients must be known according to the type of flow (Laminar, turbulent). In literature empirical correlations pertinent to laminar and turbulent flow exist[43].

Laminar Flow:

$$h_i = \frac{k_o}{d} \times \left[3.66 + \frac{0.0668 \times (d/L) \times \mathrm{Re}_d \times \mathrm{Pr}}{1 + 0.04 \times \left(d/(L \times \mathrm{Re}_d \times \mathrm{Pr})\right)^{2/3}} \right] \tag{3.19}$$

Turbulent Flow (Dittus-Boelter) :

$$h_i=(k_o/d)\times 0.023\times(\mathrm{Re})^{0.8}\times(\mathrm{Pr})^n \tag{3.20}$$

This equation can be applied for the range of conditions

$0.7 \leq \mathrm{Pr} \leq 160$

$\mathrm{Re}_D \geq 10000$

$L/d \geq 10$

where

$$\mathrm{Re} = \frac{\rho \times V \times D}{\mu_a} \tag{3.21}$$

$$\mathrm{Pr} = \frac{C \times \mu_a}{k_o} \tag{3.22}$$

k_o : thermal conductivity of oil

ρ : density of oil

C: specific heat of oil

μ_a : apparent viscosity of the oil

3.6.1 Temperature Distribution of Flowing Oil for Normal Operating Conditions

A heat balance is made between the loss of internal energy of the oil and heat flux through the pipe wall. The overall heat transfer coefficient is generally controlled by k_{ins}, so the other terms are neglected.

$$U = \frac{1}{\dfrac{d \times \ln(d/d_e)}{2 \times k_{ins}}} \tag{3.23}$$

$$\frac{(T - T_a)}{(T_i - T_a)} = e^{\left(-\frac{4 \times U \times X}{3600 \times \rho \times C \times V \times D}\right)} \tag{3.24}$$

Where

T: temperature of oil at a distance x

T_a: soil temperature

T_i: oil inlet temperature

C: specific heat of oil

V: flow velocity

3.6.2 Temperature Distribution of Oil for Re-start after a Shut-Down

Oil temperature at any point of pipeline subsequent to a shut-down may be computed by balancing the heat flux through the pipe with the rate of heat loss of the oil.

$$Tr = T_a + (T_i - T_a) \times e^{-\frac{4 \times U \times t}{\rho \times C \times D^2}} \tag{3.25}$$

where T_i: temperature of oil found using equation (3.24)

t: estimated shutdown time

3.7 Restart after a Shut-down

Under stationary conditions, waxy oil congeals when it cools below the pour point. If this cooling takes place, a certain pressure required to initiate flow of the gelled waxy crude.

The starting pressure gradient is related to the rheological property known as yield stress. Yield stress is the shear stress that must be developed in the oil to initiate flow.

$$P_g \times \frac{\pi}{4} \times D^2 = \tau_Y \times \pi \times D \tag{3.26}$$

For waxy crude yield stress is an inverse function of temperature and increases with decreasing temperature. It is also a function of the rate of shear. Start-up pressure, for instance, depends to a large extent whether the oil is cooled under static or dynamic conditions.

The maximum pressure build up when a gelled pipeline is restarted occurs when the gel is sheared at the wall. To establish whether restart is possible for a given shut-down period, the available pumps must be evaluated for their ability to provide the required shear stress.

$$P_g = \frac{4 \times \tau_y \times L}{D} \tag{3.27}$$

Where

P_g: Pressure required to break gel

τ_y: Yield strength of gelled crude (determined in laboratory tests) is different for dynamic and static cooling

D: Internal diameter of the pipe

L: length of pipe segment

Experiments have shown that restart pressure can be 5 to 10 times higher for statically cooled pipelining than for one that has been dynamically cooled.

The pressure required to initiate flow is considered to be sum of pressure difference required to break gel in each section of the pipeline.

CHAPTER 4

SLURRY SYSTEM AND PIPELINES

4.1 Slurry Characteristics

Slurry pipeline system are an efficient and reliable transportation mode. Flow of mixture of solids and liquids in pipes differs from flow of homogenous liquids in several important ways. With liquids, the complete range of velocities is possible, and the nature of the flow (laminar, transition and turbulent) is defined the physical properties of the fluid and system. With slurries, two additional distinct flow regimes(homogeneous and heterogeneous) and several more physical properties are superimposed on the liquid system.

Design of equipment for handling slurries is based on the type of slurry involved. The four basic kinds are:

i.Settling slurries (heterogeneous)
ii.Nonsettling slurries that behave as homogeneous non-Newtonian fluids (homogeneous)
iii.Stabilized slurries
iv.Slurries that show thixotropic properties (generally nonsettling)

For settling slurries, design methods are used to determine the minimum transport velocity and to predict the pressure gradient. For slurries that behave as homogenous non-Newtonian fluids, design methods predict the laminar/turbulent transition and the pressure gradient. Stabilized slurries contain large particles to be conveyed. These particles are supported by a dense or heavy medium which consists of flocculated, much finer particles and which impart non-Newtonian shear thining flow behaviour to the heavy medium. Shear-thinning media are highly suitable for transporting coarse particles.

For slurries with thixotropic properties, methods are also required for predicting the start-up pressures after shutdown.

If the solid particles are homogenously distributed in the liquid media, such slurries often exhibit non-Newtonian rheology (i.e., the effective viscosity is not constant, but varies with the applied rate of shear strain).

Concentration gradients exist along the vertical axis of a horizontal pipe even at high flow rates; i.e. the fluid phase and solid phase retain their separate identities. Thus, the designer will often be faced with defining the dominant characteristic of a slurry. Evaluation of the complex mixed regime is outside the scope of this thesis.

4.1.1 Critical Velocity

Slurries are broadly classified as being in the homogeneous or heterogeneous regime, each regime having a distinctive character. Like homogeneous liquids, the flow of slurries are defined in three different regions according to a new Reynolds number described below:

$$\mathrm{Re}_{\mathrm{mod}} = \frac{w \times d}{\upsilon} \tag{4.1}$$

where w: settling velocity

d: particle diameter

ν: slurry kinematic viscosity

The calculation of settling velocity changes with the flow regime. If the Re_{mod} is less than 1, this regime is described by Stoke's law[42].

If $Re_{mod} < 1$ then,

$$w = 0.0169 \times g \times \frac{(\rho_s - \rho_l)}{\rho_l \times \upsilon} \times d^2 \tag{4.2}$$

$$C_D = \frac{24}{Re_{mod}} \tag{4.3}$$

where ρ_s: solid density

ρ_l: liquid density

C_D: drag coefficients

If the Re_{mod} is greater than 1and less than 1000, this regime is described by Intermediate Law[42]. Settling velocity calculation is same with Stoke's Law.

$$\frac{C_D}{Re} = \frac{4 \times g \times (\rho_s - \rho_l) \times \upsilon}{3 \times \rho_l \times w^3} \tag{4.4}$$

If the Re_{mod} is greater than 1000 and less than 2.10^5, this regime is described by Newton's Law[42].

$$w = \left(\frac{0.3094 \times (\rho_s - \rho_l) \times d}{\rho_l} \right)^{1/2} \tag{4.5}$$

C_D=0.4

Both homogeneous and heterogeneous slurries have entirely different critical-velocity characteristics, as seen in Figure 4.1. On the chart, Curve A illustrates the deposition critical velocity typical of heterogeneous slurries. The depositional critical velocity is directly related to the settling velocity of the coarser particles in a heterogeneous slurry and the degree of turbulence in the pipe: it therefore increases with increasing particle size or specific gravity, and with increasing slurry concentration or viscosity. Deposition velocity generally exhibits an increase proportional to the square root of pipe diameter.

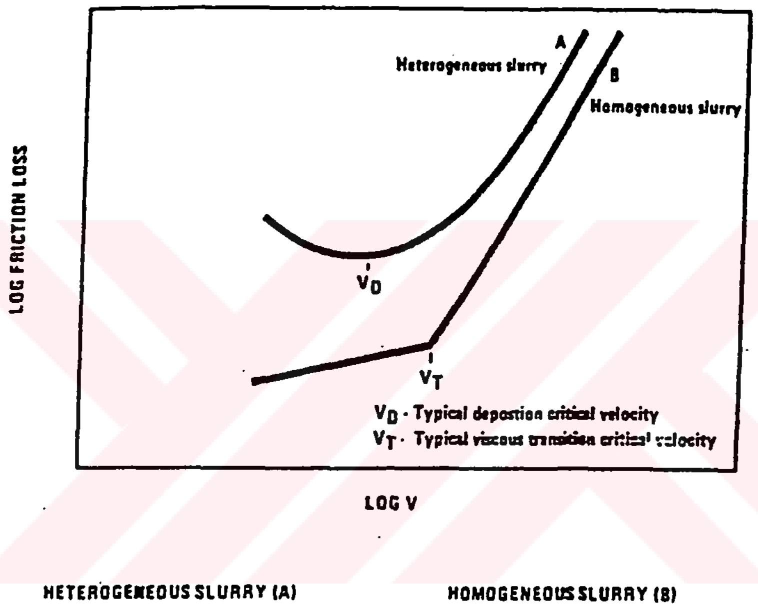

Figure 4.1 Critical velocity characteristics depend on whether slurry is heterogeneous or homogeneous[40]

Curve B shows viscous-transition critical velocity, which is characteristic of homogeneous slurries. While the design of a system for operation below the transition critical velocity is acceptable for truly homogeneous slurries, no turbulent flow exist to suspend even trace amounts of heterogeneous particles.

There are many correlations found in literature about determination of homogeneous or heterogeneous flow. Two new velocities are described as a function of solid concentration, pipe diameter, and one or two particle parameters[40,42].

$$V_c = F_L \times (2 \times g \times D \times (S-1))^{1/2} \tag{4.6}$$

where

V_c: Critical velocity

F_L: Durand and Condolios factor[42]

D: Inside diameter of pipe

S: Ratio of solid density to liquid density

If our transport velocity is less than the critical velocity (Durand correlation), there is no flow in the pipe. That is, V_c is the minimum velocity to maintain flow in the pipe. The slurry transport velocity must always be grater than the critical velocity

$$V_T = (50.97 \times g \times D \times w)^{1/3} \tag{4.7}$$

where

V_T: Transition velocity

w: Settling velocity

Equation (4.7) (Newitt correlation[42]) describes the transition from heterogeneous to homogeneous flow. If transport velocity of slurry is grater or equal to the transition velocity, the flow is homogeneous. Othewise, the flow is heterogeneous.

4.1.2 Solids Concentration

The slurry volume concentration and specific gravity are directly related, depending only on the solids specific gravity and the liquid specific gravity. Various properties of the slurry can be calculated as follows[42]:

Flowrate of solids:

Slurry flowrate is the summation of liquid and solid parts flowrate. Solid flowrate is as follows:

$$Q_S=Q_{slurry}\times WP \tag{4.8}$$

where

WP: Volume percent of solids

Q_{slurry}: Flowrate of slurry

Q_S: Solid part flowrate

Flowrate of liquids

$$Q_L=Q_{slurry}-Q_S \tag{4.9}$$

where Q_L: Liquid part flowrate

Density of Slurry

$$\rho_{slurry}=\rho_s\times WP+\rho_l\times(1-WP) \tag{4.10}$$

where ρ_s: solid density

ρ_l: solid density

ρ_{slurry}: slurry density

Concentration of solid by weight (C_w):

$$C_w = \frac{WP \times \rho_s}{\rho_{slurry}} \tag{4.11}$$

Solid volume fraction(ϕ):

$$\phi = \frac{WP}{100} \tag{4.12}$$

Solid viscosity to suspension viscosity ratio:

$$\frac{\mu_m}{\mu_o} = 1.25 \times \phi + 10.05 \times \phi^2 + 0.00273 \times \exp(16.6 \times \phi) \tag{4.13}$$

where μ_m: Solid absolute viscosity

μ_o: Slurry absolute viscosity

Specific heat of slurry:

$$Cp_{slurry} = \frac{Cp_s \times C_w + Cp_l \times (100 - C_w)}{100} \tag{4.14}$$

where Cp_s: Solid specific heat

Cp_l: Liquid specific heat

Cp_{slurry}: Slurry specific heat

Thermal conductivity of slurry:

$$k_{slurry} = k_l \times \left[\frac{2 \times k_l + k_s - 2 \times \phi \times (k_l - k_s)}{2 \times k_l + k_s + \phi \times (k_l - k_s)} \right] \tag{4.15}$$

where k_l: Liquid thermal conductivity

k_s: Solid thermal conductivity

k_s: Slurry thermal conductivity

4.1.3 Slurry Rheology, Viscosity

Solid concentration is based on consideration of the slurry rheology (or viscosity). The rheological properties of a slurry determine the viscosity used for friction loss calculation and for transition critical velocity of fine, thick slurries(heterogeneous). The following two rheological cases adequately cover homogeneous slurries.

Newtonian slurries are described by the simple rheological property of viscosity, and can be treated as true fluids, provided the following velocity is high enough to suspend the solids.

Bingham Plastic slurries require a knowledge of shear stress as a function of shear rate to determine the parameters of yield strength and Bingham yield stress. Bingham Plastic slurries are characteristically composed of fine solids at higher concentrations. This was explained in a more detailed form in Chapter 3.

4.2 Settling Slurries

When handling settling slurries, the main design problem is predicting a design velocity high enough so that there is no possibility of blockage, but not so high that the pressure gradient and wear rates are not excessive.

The flow of settling slurries in horizontal pipes can be classified into various flow regimes. These flow regimes refer to the in-situ vertical solid concentration profile and whether all solids are suspended or a proportion are conveyed as a bed sliding along the pipe bottom. At high mean velocities it may be possible to convey some coarse slurries, but it is usually uneconomic to operate pipelines carrying settling velocities at high velocity. For predicting design velocities for horizontal pipe flow, there are a number of definitions of design velocity. These are:

Sliding-bed velocity: This is the velocity at which the shearing forces in liquid are just sufficient to move particles that lie on the floor of the pipe. This normally is an inefficient method of transporting the solids, but it may be used as a mechanism by which solids are carried in high concentration.

Saltating velocity: At this velocity, particles are repeatly picked up by the liquid and deposited further along the pipe.

Suspending velocity: This is the lowest velocity at which all the particles are picked up and remain in suspension. This velocity is used for designing most pipelines.

Deposit velocity: The velocity at which particles start to settle out as the flow is lowered. This particles may settle to a static or a sliding bed. This velocity is not same as the suspending velocity.

Velocity for homogeneous flow: This is the velocity at which the particles become evenly distributed throughout the pipe.

4.2.1 Friction Losses and Hydraulic Gradients

Friction losses are calculated using the familiar f versus Re

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DOKÜMANTASYON MERKEZİ

relationship, with appropriate overpressure corrections for heterogeneous distribution of more dense particles in horizontal pipes.

Heterogeneous slurries flowing in horizontal pipes have higher friction loses due to nonuniform distribution of particles across the pipe. Durand's emprical relationship corrects the friction factor as follows[40]:

$$f = f_l\left[1 + 82 \times \left(\frac{g \times D \times \rho_s - \rho_l}{V^2 \times \rho_l}\right)^{3/2} \times \frac{WP}{C_D^{3/4}}\right] \tag{4.16}$$

where

f, f_l: Fanning friction factor
WP: Volume percent solids
C_D: Drag coefficient

$$\Delta P = \frac{2 \times \rho \times f \times V^2 \times L}{g \times D} \tag{4.17}$$

In a vertical pipe, the solids are uniformly distributed, so the pressure losses are calculated as described for homogeneous slurry.

4.3 Non Settling Slurries

Solid-liquid mixtures that settle (when not in flow) can be treated as nonsettling, if the settling rate is low. These slurries can be treated as single-phase homogeneous fluids, they can be characterized in a laboratory viscometer with the rheological parameters obtained being used for full scale design. The method that have been developed for waxy crude oil pipelines calculation was explained in Chapter 3.

4.4 Stabilized Slurries

For the hydraulic transport of settling slurries containing large particles, relatively high flow velocities are required to prevent pipe blockage. In addition, pipe wall wear rates are high and specific energy requirements (the energy consumption per unit mass of solid transported per unit distance) are usually much in excess of those for the hydraulic transport of nonsettling slurries. There are a number of ways in which this specific energy requirement may be reduced. Two important methods are ‘dense phase conveying’ or alternatively, by both increasing the density of carrier fluid and imparting the non-Newtonian shear thinning property to the suspending medium through the presence of flocculated fine particles.

Dense Phase Conveying: By increasing the solid concentration in the pipe to such an extent that the flow within the pipe resembles that of a sliding bed occupying practically the entire pipe cross-section. The mean slurry velocity can be over a wide range because the coarse particles are not being supported by numerous particle-particle contact throughout slurry.

Use of a Heavy Medium: Large particles, which would normally settle out rapidly in low viscosity carrier liquid such as water, can be incorporated in to a ‘heavy medium’ which is usually a homogeneous suspension of colloidal particles in liquid. These colloidal particles may often be flocculated, resulting in the carrier medium possessing shear-thining non-Newtonian flow property. Such property can reduce or almost eliminate the settling of large particles as result of high high carrier the medium viscosity at the relevant low shear rates, while, at the high shear rates close the pipe wall, the viscosity of the carrier liquid and of the slurry as a whole (including the large particles) is reduced because of shear-thinning behaviour.

4.5 Thixotropic Slurries

For slurries that poses strong interparticle attraction and form a gel when left to stand in a pipeline, the start-up pressures are very much grater than normal operation pressure. A method for predicting start-up pressure and the time taken for the gelled material to be expelled from the pipeline has been developed according to the generalized Bingham fluid.

CHAPTER 5

TRANSPORTATION OF WAXY CRUDE OILS

5.1 Transportation of Waxy Crude Oil

Oil producers have long been aware of the difficulties of pipelining waxy crude oil and fuel oils. Traditionally the answer has been to avoid the problem by heating the crude and/or the pipelines, thus holding the the wax in solution, or by frequently emptying and clearing the lines.

To exploit the low sulfur waxy crude oils, the pumpability characteristics of waxy crudes at temperatures below the pour point limit have been studied by Simith and Crest[15]. It has been found possible to improve the flow of waxy crude oils by a number of methods. Pipelining the crude as an oil-in-water (O/W) emulsion reduces the flow properties to nearly the viscosity of continuous water phase. Blending with a less waxy crude oil or distillate improves the flow properties by altering the wax solubility relationships. Both of these methods have the disadvantage of reducing the crude oil carrying capacity of the pipeline. Note that seperation at the well head to include more condensate in the crude oil (if available) has the same effect as dilutation. More recently, pour point depressants/flow improvers have been developed that, in small concentration, affect the crystal growth and as a result improve the flow properties.

Of the various methods developed, the use of pour point depressants /flow improvers is found to be more attractive. The main attraction of this method is its relative cheapness and variability of dosage with respect to the temperature and desired viscosity requirements.

The injection of pour point depressant/flow improver additives appears to hold the greatest promise of achieving the desired overall objectives of:

1.Operational safety, i.e., protection of the line against blockage by the setting of the oil into a storage gel.

2.Operating economy, i.e., maintenance of reasonable flowing viscosity with resulting economical level of power consumption.

Flow improvers should have the capacity to:

1.Reduce the pour point (the temperature at which the flow of crude oil, or other petroleum fluids, ceases) viscosity, and yield stress under dynamic conditions.

2.Restart the pumping after a shutdown with the available shear stress and aid in fast clearance.

One of the following methods for pipelining waxy crude oils may be considered:

1. Select pumps to allow a parallel/series arrangement which could transport at slower rates and higher pressures when required. The piping could be manifold so that parallel arrangement would be accommodated by repositioning of valves to handle higher flow rates

2. Use of separate low flow high head pumps for restarting.

3. Side traps at frequent intervals to allow short sections to be started separately.

4. Reverse pumping to create back and forth pumping sequence which prohibits static cool-down.

5. Use of pour point depressants/ flow improvers.

6. Adding hydrocarbon diluent such as a less waxy crude or light

distillute.

7. Injection of water to form a layer between pipe wall and crude.

8. Mixing water with crude to form an emulsion.

9. Displacement with water or light hydrocarbon liquid in the case of shut-down of pipeline.

10. Separation at higher than normal pressure to allow as much gas and light hydrocarbons as possible to remain in the crude.

11. Conditioning the crude before pipelining to change the wax crystal structure and to reduce pour point and viscosity.

12. Further subdivision of pipeline into smaller segments or reducing batch length of waxy crude to increase maximum shear stress available.

13. Combination of above methods.

5.2 Drag Reduction with Chemical Injection

Pipelines can be operateted with chemical injection to boost up the throughput. Most generally, the injected chemicals in small quatities virtually does not effect the quality of the crude oil transported, but acts a drag reducer decreasing the frictional head loss. As a result, the existing pipeline is used at higher capacity if necessary.

The drag reducer chemicals are high molecular weight co-polymers . These are hydrocarbons which distill according to the volatility of its fractions and will not be distinquishable from the hydrocarbons originally present in the crude oil. It has been shown by laboratory and refinery scale test that these chemicals have no adverse effect on refined oil products or desalting, coking or foaming characteristics of crude oil.

These chemical boosters injected into a pipeline, reduces turbulence substantially, causing a significant decrease in pressure drop due to hydraulic friction. Thus the pumping efficiency is increased, enabling higher flow rates without the need for additional pump hardware or pipeline looping. As the chemical is injected, hydraulic friction decreased, and flow rate begins to increase reaching a maximum level when all of the crude in the pipeline has been treated. Conversly, when injection is discontinued, the flow rate begins to decrease as untreated oil replaces the treated one.

At very low concentrations the effect of drag reducer is difficult to predict. At very low flow rates the effect of drag reducer is negligible. The effect is pronounced at higher flow rates where turbulent flow conditions exists. The effect generally increases with increasing flow rates. At very high flow rates, due to high shears involved, the effect is diminished going downstream from the point of injection. This is due to the fact that the drag reducers consume a high percentage of their drag reducing ability when subjected to high shears, and higher shear rates. The fluid passing through a pump, the drag reducing ability is lost due to high shears involved. Thus drag reducers must be introduced to a pipeline on the discharge sides of existing pumps. Conversly, unless shears and shear rates in pipelines are very large, the efficiency of drag reducer is not diminished.

Maximum flow rate is established by the limiting conditions from the bottlenecking section of the pipeline. The "bottleneck" is the section at which has the minimum throughput capability in a pipeline.

Figure 5.1 a exhibits the chemical ARCOFLO II application to Iraq-Turkey crude oil pipeline system during 1987-1988. In this chart, point A is the original outlet pressure head at fifth station of Iraq-Turkey pipeline without chemical additives. At that point, the flowrate is 768.000 barrel per day. B,C and D are the application points of different amount of chemicals. The slope of the hydraulic grade line decreases with the injection of increasing amount of chemicals. Moreover, pressure head requirement to reach the pigtrap at the elevation of 1014 m declines at each increase of chemicals .On the other hand, drag reduction in percentage and flowrate at that points increase within a certain range. Drag reduction can be calculated by using the following expression:

$$\text{Drag Reduction(\%)}=\frac{100\times\left(\mathrm{Pr}\,essure\cdot drop_{untreated}-\mathrm{Pr}\,essure\cdot drop_{treated}\right)}{\mathrm{Pr}\,essure\cdot drop_{untreated}} \qquad (5.1)$$

The drag reduction with the chemical additives can be seen more clearly in Figure 5.1 b. In this figure, vertical axis represents the pressure head at fifth station of Irag Turkey pipeline and horizontal axis represents the duration of chemical in hours. The chemicals move in the line with a velocity of crude oils. Therefore, it takes certain time to show the effects of additives on the line completely. For example, 28 hours is required to display the pressure decrease to 117.6 kg/cm^2 at a distance 80 km after the addition of 6.7 ppm chemical to system. Like treatment level 1, 42 hours for treatment level 2 and 56 hours for treatment level 3 can be read from the figure. At the end of 56 hours, the application is discontinued. Since pressure drop starts to increase and reaches to its initial value at 70 hours.

These effects of drag reducers have been reduced to a set of complex correlation relationships requires to access to a computer to produce a meaningful results in a reasonable time. Such a work had been performed for ARCOFLO II. After an extensive laboratory measurements, the variation of injection amount-percentage throughput increase and drag reduction percentage were obtained in graphical forms witin a minimum and maximum range. Figure 5.2[34] exhibits the variation of injection amount with percentage throughput increase. Figure 5.3[34] shows the variation of injection amount with drag reduction percentage. These curves are represented analytically instead of digitizing them. The maximum amount of chemicals injected by the program is limited up to 50% drag reduction. Above this limit, chemical injection is meaningless and effect the quality of crude oil. In the case study, ARCOFLOW II is used as a chemical. However, if the users want to apply other chemicals, it's possible to enter their own data or correlations.The result of chemical injrction range(minimum-maximum level) at each station with duration time can be seen as an output of the program.

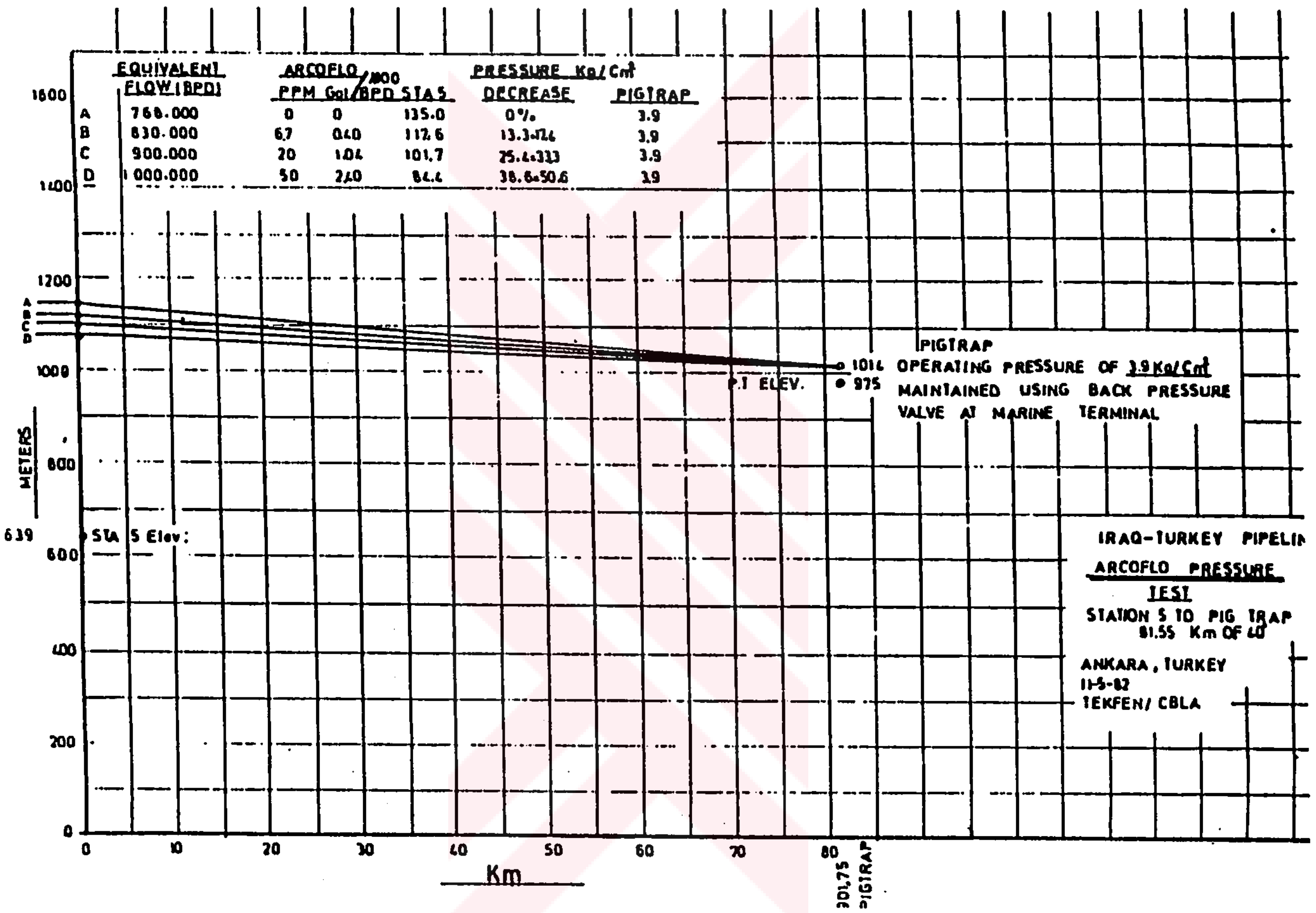

Figure 5.1-a The Effects of Chemical as a Drag Reducer[34]

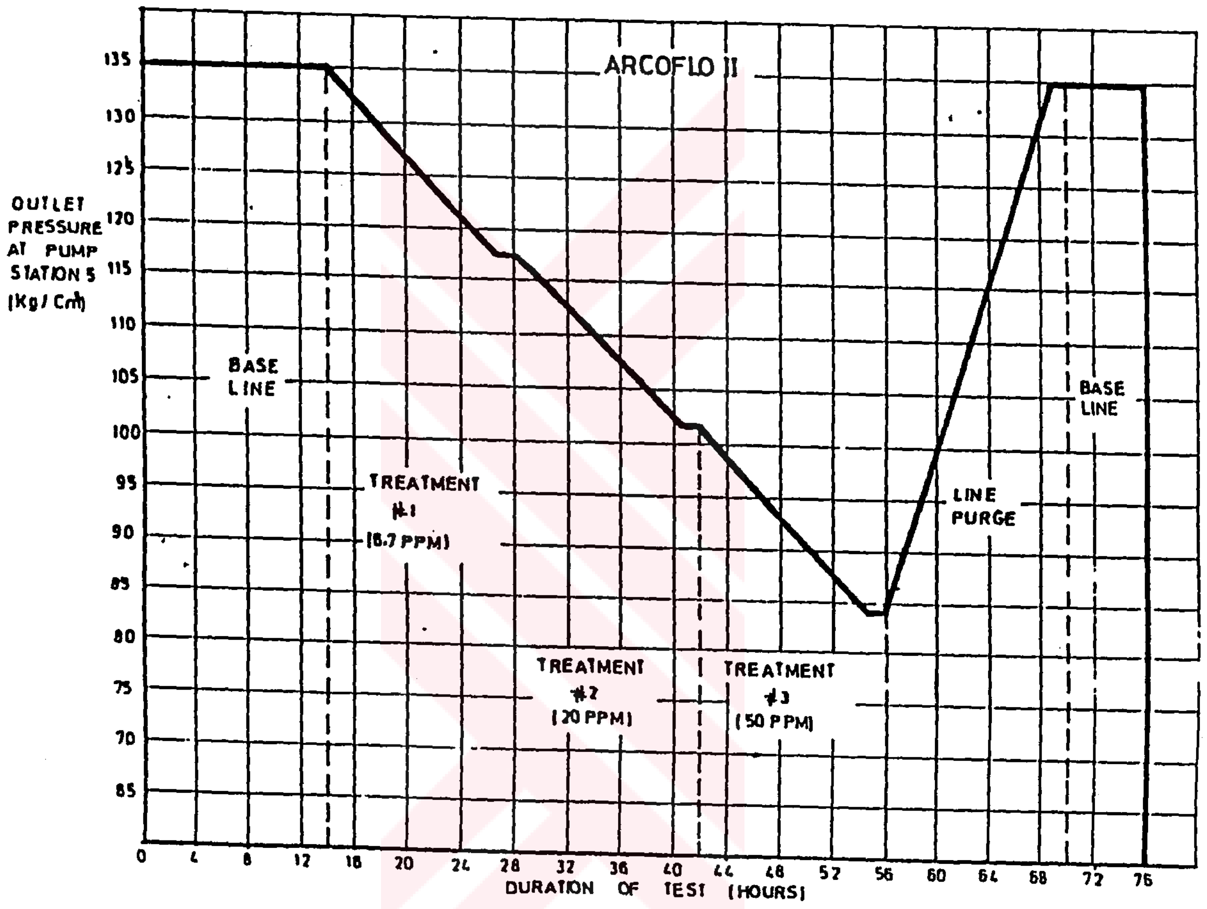

Figure 5.1-b The Effects of Chemical as a Drag Reducer[34]

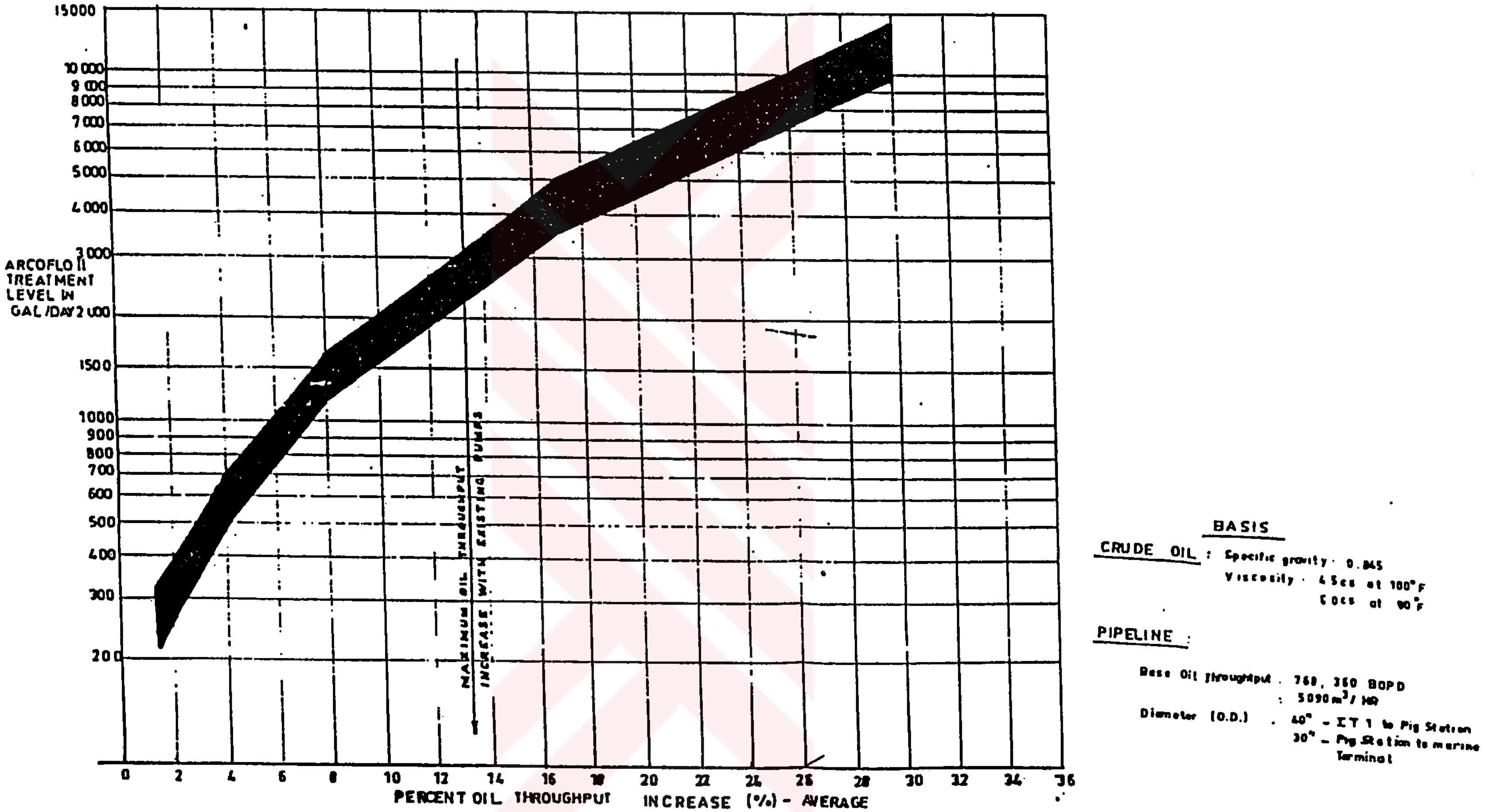

Figure 5.2 The Variation of Chemical Injection with Percentage Throughput Increase[34]

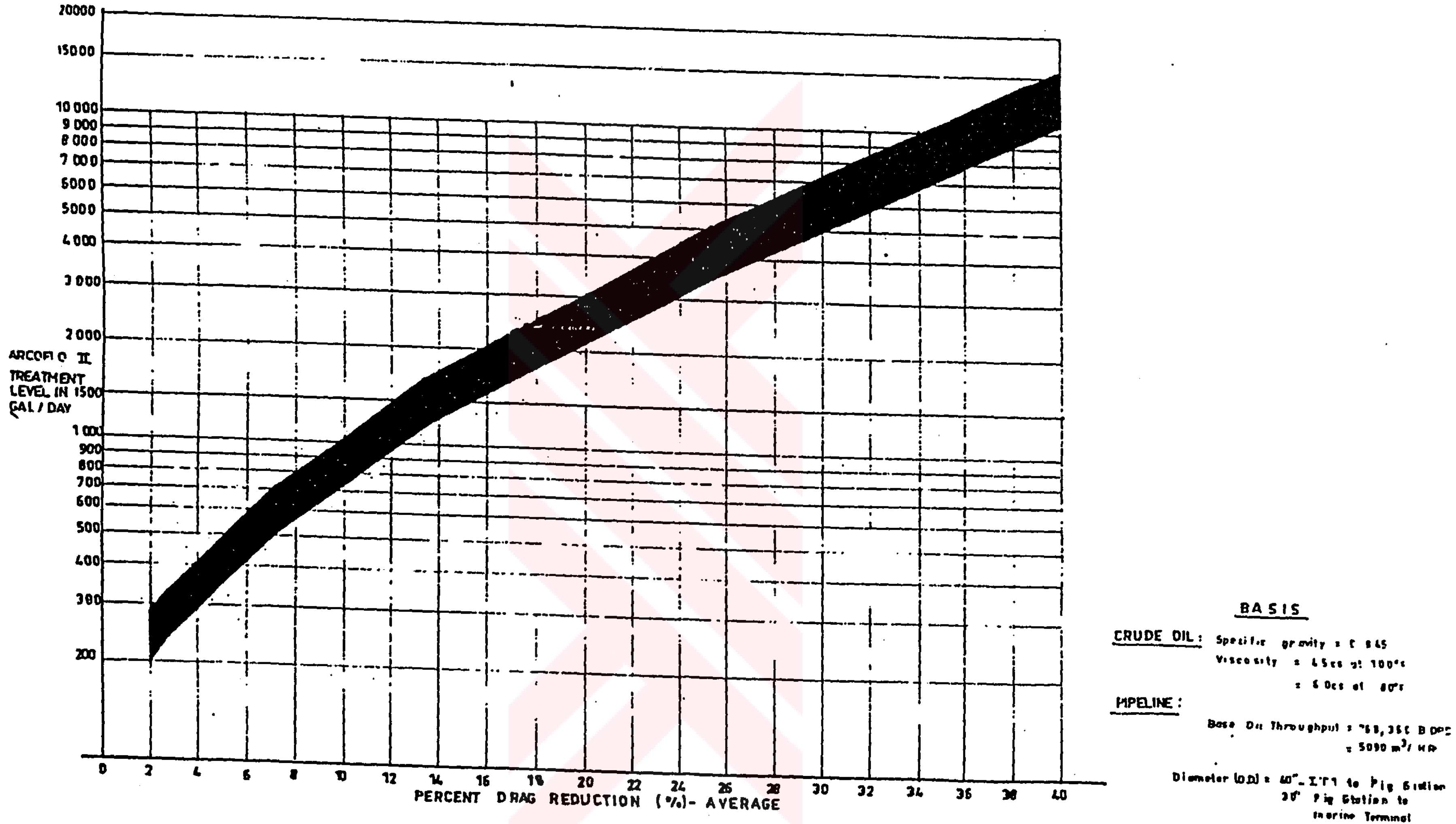

Figure 5.3 The Variation of Chemical Injection with Percentage Drag Reduction[34]

CHAPTER 6

COMPUTER MODELLING OF THE PROBLEM

6.1 General

A computer software is developed in Visual Basic (3.0) Professional Edition programming language to analyse the flow behaviour of existing crude oil pipeline against high pour point crude oil. The selection of an optimum pipeline diameter with conventional method does not take into consideration the peculiarities of waxy crude oils. This may have resulted in pipelines being lost through gelling by allowing downtimes beyond the permissible level and the available pump capacity not being sufficient to restart flow. This program is mainly based on data input directly and data transfer from a previously prepared data file. The previously prepared data file brings the full advantage of time saving.

The software takes the physical constraints of an already installed pipeline with rheological properties of crude oil and searches its Newtonian and non-Newtonian flow characteristics together. In conventional pipeline design, a pipe diameter is chosen based on the required flow rate and pipe length considering only turbulent or laminar Newtonian flow. However, the worst design conditions are non-Newtonian turbulent flow, when flow is completely initiated and non-Newtonian restarted laminar flow at the lowest ambient temperatures with the restart flowrate being below the design throughput.

The method of study is to predict the temperature along the pipeline, to determine those segments where temperature indicate Newtonian and non-Newtonian flows, to evaluate the total pressure drop for turbulent and laminar flows as well as for gelled flowline, and then to display the hydraulic profile of line for normal operating condition and restart after a shut-down. If there is a blockage of the flow due to high frictional losses or pressure level beyond the permissible level of pipes, the system is tried to be modified by increasing or decreasing the flowrate step by step up to a point of acceptable flow level neither less than half of the design flowrate nor grater than one and half of it, heating the oil at the beginning or an intermediate section, changing the pump head without exceeding the maximum allowable operating pressure of pipes and combination of these. The other possibility is to apply drag reducer chemicals at the discharge side of pumps to satisfy such a flow. Afterwards the pump capacities are investigated to pump such a flow by changing the speed of the pump. If they are appropriate, the system can be worked in more flexible conditions. If not, the system will be stoped with the application of high pour point crude to the system, or the pump capacity will not be enough to restart such a flow due to an interruption of flow by any reasons.

The other important point is the heterogeneous slurry consideration for non-Newtonian flow. In general, the waxy crudes are assumed to be homogeneous and the procedure given in Chapter 3 is followed. However, if wax percent is very high, the flow can show heterogeneous behaviour. Therefore, the slurry characteristics is searched at the beginning of the program and pressure losses are corrected if flow is heterogeneous.

This program also performs hydraulic calculations, net pump head calculations taking viscosity correction into account between input of all data and output stage.

6.2 Flowchart of the Software

The overall algorithm of the software is given in Figure 6.4. The input data of the program can be classified in three groups: fluid properties, field data and pumping station data. Such fluid properties include:

i. pour-point, cloud-point temperatures
ii. variation of temperature with yield strength, Bingham Yield stress, plastic viscosity, viscosity
iii. density, specific heat, thermal conductivity
iv. wax percent, slurry characteristics of crude

Field data include:

i. soil and ambient temperatures and seasonal variations, inlet temperature of oil
ii. type of pipeline surface buried or insulated; if buried, depth of burial;
iii. elevation profile, pipe diameter, total length of the line, and locations of pumping stations

Pumping station data includes required pump head, speed, flowrate and pump characteristics at each station. An interactive program guides to users to enter and specify the data correctly. Hence, program user interaction features are the most important fact which eliminate misunderstandings and lead to the culminating result.

There are two possibility of users while entering the viscosity variation with temperature. It can be stated as the empirical equations found in the literature or given as direct measurement. Since viscosity of the fluid is one of the most important parameters of Reynolds number in determining the type of flow and one of the dominant parameters of pressure loss calculations, it should be inserted as exact variation as possible. Therefore, direct measurement of viscosity with temperature is preferred, if possible. In determining the variation of viscosity at an intermediate points, linear interpolation and extrapolation are used. Since if the data points are enough to exhibit the variation behaviour exactly, this methods are the easiest way.

Among the inputs, the new parameters which haven't been described with conventional pipeline design exist. These are yield strength, Bingham yield stress and plastic viscosity. All of them reflect the rheological behaviour of crude oil and do not have any standard empirical correlations. An extensive laboratory measurement can only represent their exact variation. It is very difficult to find such data for different types of crudes used in Ceyhan –Kırıkkale pipeline, so rheological data for a hypothetical crude[17] is used in case studies. Data presented by Figure 6.1 and by table 6.1 indicate that the oil behaves as non Newtonian fluid at temperatures below approximately 24 °C. In this temperature range shear stress is not proportional to shear rate, and and the oil has a significant yield strength. The yield strength is assumed virtually constant after 20 hr of shutdown time. Therefore, the values of τ_y which are presented by Table 6.1 are applicable of shutdown times which exceed 20 hr. These data are stored in a special form in the computer and linear interpolation or extrapolation are performed at the intermediate points. Alternatively, the users can enter their own data.

In this figure 6.1, Bingham yield stress and Yield strength decreases with increasing temperature and drops to 0 after 24 °C. This means that certain pressure(Bingham yield stress) must be exceeded to initiate flow below cloud point temperature. This parameter is zero for Newtonian flow. Apparent viscosity shows approximately the similar variation behaviour but never drops to zero. On the other hand plastic viscosity is entirely different from each other. Two different trends in variation characteristic exist depending on the temperature above or below the cloud point. This indicates that different mechanisms are dominant on the cooling characteristics of crude. Up to 20 °C, the plastic viscosity shows very steep decrease with increasing temperature. Then it changes slowly with temperature.

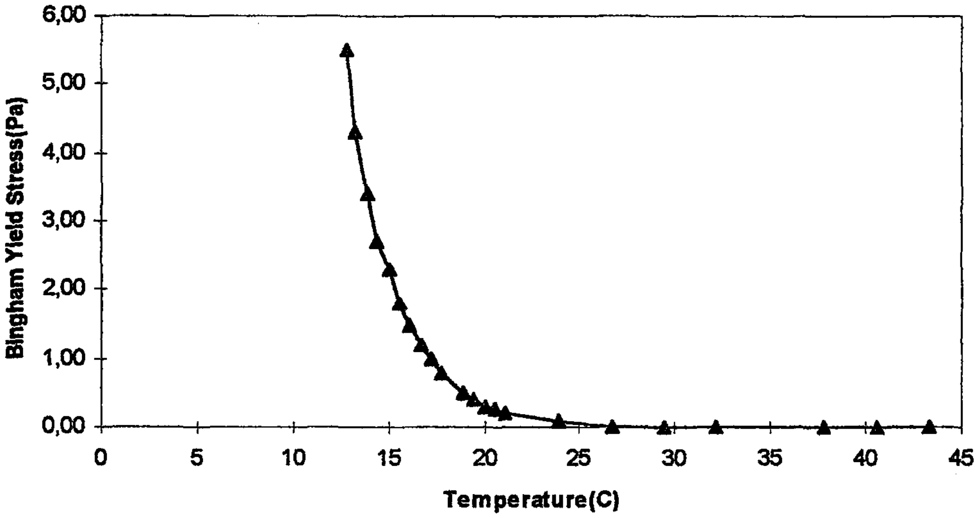

Figure 6.1(a) Bingham Yield Stress versus Temperature for the Hypothetical Crude Oil(17)

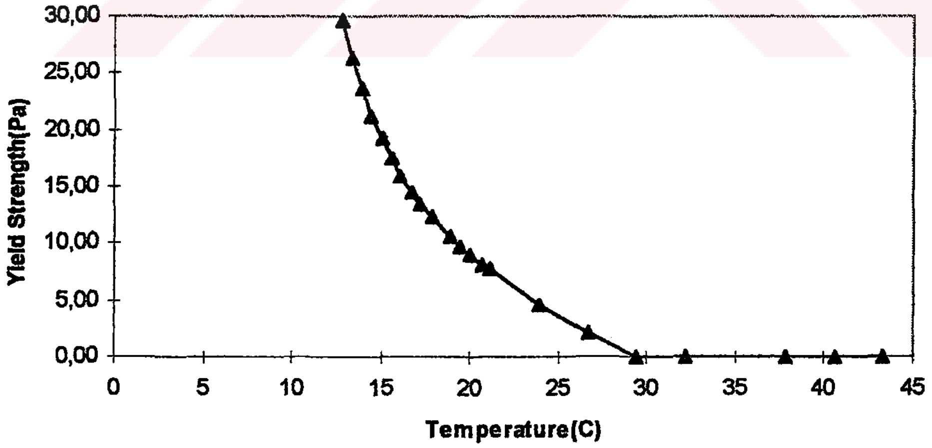

Figure 6.1(b) Yield Strength versus Temperature for the Hypothetical Crude Oil (17)

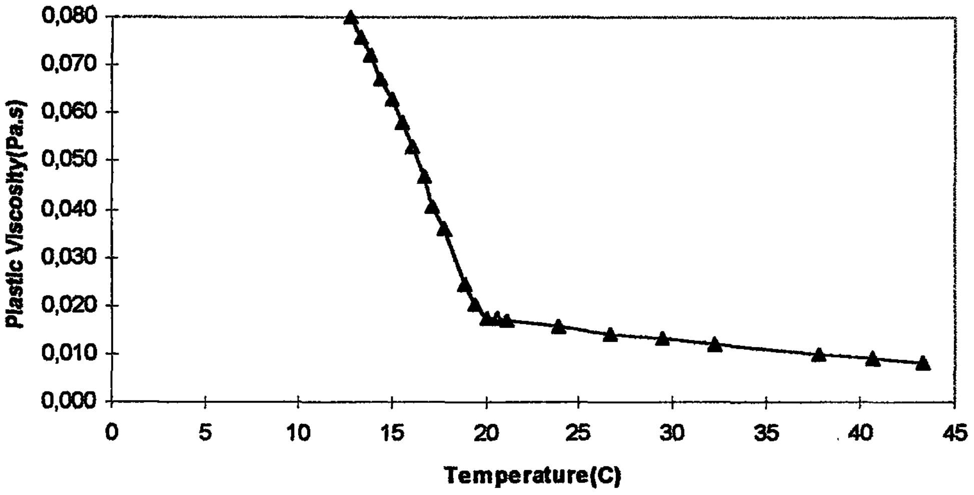

Figure 6.1 (c) Plastic Viscosity versus Temperature for the Hypothetical Crude Oil(17)

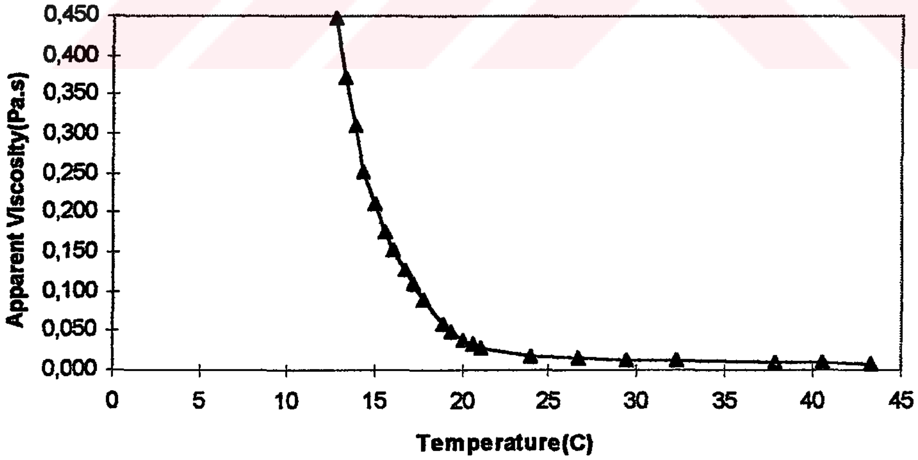

Figure 6.1 (d) Apparent Viscosity versus Temperature for the Hypothetical Crude Oil(17)

Table 6.1 Rheological Data for a Hypothetical Crude[17]

(Shear rate=16 1/sec)				
Temperature C	Bingham yield stress Pa	20 hr yield strength Pa	Plastic viscosity Pa.s	Apparent viscosity Pa.s
12,8	5,52	29,63	0,079	0,4464
13,3	4,30	26,33	0,076	0,3720
13,9	3,39	23,58	0,072	0,3109
14,4	2,70	21,17	0,066	0,2514
15,0	2,30	19,31	0,062	0,2112
15,6	1,79	17,39	0,058	0,1755
16,1	1,49	15,88	0,052	0,1532
16,7	1,19	14,50	0,047	0,1282
17,2	0,99	13,40	0,040	0,1087
17,8	0,79	12,30	0,036	0,0877
18,9	0,49	10,51	0,024	0,0590
19,4	0,39	9,69	0,020	0,0483
20,0	0,29	8,93	0,017	0,0391
20,6	0,24	8,18	0,017	0,0330
21,1	0,19	7,74	0,016	0,0276
23,9	0,09	4,53	0,015	0,0186
26,7	0	2,13	0,014	0,0142
29,4	0	0	0,013	0,0131
32,2	0	0	0,011	0,0119
37,8	0	0	0,010	0,0099
40,6	0	0	0,009	0,0091
43,3	0	0	0,008	0,0084

This program can also perform the hydraulic calculations of Newtonian pipeline design. If the number of pump stations, locations, required pump head at each stations and pump station configurations are not available for a specified pipeline system, these can be calculated by the program to be used in non-Newtonian calculations. One of the most important limitation in non-Newtonian analysis is not to change the locations of pumping stations described by Newtonian design and exceed the maximum allowable operating pressure of the pipes.

In heat transfer part of this program, first the pipeline is divided into small and equal segments. It is assumed that the temperature is constant at each segment. Then the temperature distributions at each part are calculated by using equations mentioned in Chapter 3 for normal operating condition and restart after a shutdown. These temperatures are the key points in determining the Newtonian and non-Newtonian characteristics of the flow. If the temperature is less than cloud point temperature, the flow is said to be non-Newtonian otherwise Newtonian. Next step is to calculate frictional loss at each segment. Total frictional loss is equal to the addition of each segment. Pressure required to break gel at restart condition is another important consideration for waxy crude oil analysis. This value must be lower than the maximum allowable operating pressure of the pipe. Like normal operating pressure and restart after a shutdown, it is calculated segment by segment and then added together.

The yield strength of the crude oil, the parameter used in the calculation of pressure required to break the gel after a shut down, τ_y, is very sensitive to small temperature variations. Maximum shut down for each type of crude oil must be such a value that the gel pressure does not exceed the maximum allowable operating pressure of the pipe. The downtime can be increased a certain amount step by step until gel pressure grater than or equal to maximum allowable operating pressure. This value approximately reflects the critical downtime. The recommended maximum downtimes must be between 3 and 10 days depending on the pour point and ambient temperature. The downtime is not standard for every crude and is longer than the critical downtimes hazardous. Any method were found in literature related to the critical downtime calculation but a rough idea about this value can be obtained by using the above approach.

The nature of the problem necessitates a single-phase assumption for waxy crude oil pipeline. Both Newtonian (inlet end) and non-Newtonian (discharge end) turbulent flow can occur along the pipeline on whether the flowing temperature is above or below the cloud point. However, for the possibility of the two phase flow, the crude characteristic is searched at the beginning of the program and some corrections are made on friction factors. In hydraulic calculations, Chen equation is used with Colebrook-White equation for Newtonian turbulent flow and Hagen-

Poiseuille friction factor for Newtonian laminar flow. The flow behaviour is assumed to be approximately Bingham Plastic for non-Newtonian flow. The same flow equations are used for turbulent flow but plastic viscosity is replaced with viscosity and the Hedestrom equation[17] for laminar flow.

Slope of hydraulic grade line for each operating case is calculated by the use of following formula:

$$\text{Slope of HGL (m/km)} = 1000 \times f \times \frac{V^2}{2 \times g \times D} \tag{6.1}$$

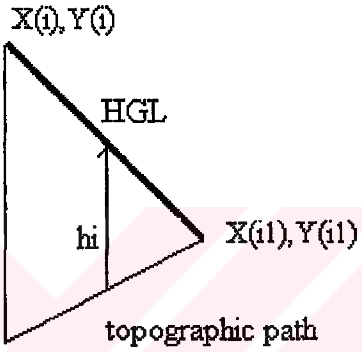

Figure 6.2 Graphical Representation of Total Head Requirement between Two Successive Points

$$h_i = -(Y(i1) - Y(i)) \times \frac{X(i1) - X}{X(i1) - X(i)} \tag{6.2}$$

Where

$$\frac{Y(i1) - Y(i)}{X(i1) - X(i)} = 1000 \times f \times \frac{V^2}{2 \times g \times D}$$

This can be applied for Newtonian flow easily. When the slope of hydraulic grade line is determined, the rest is to calculate head required overcoming the frictional losses and static elevation difference between two successive pumping stations. Figure 6.5 displays head calculation at an intermediate point between two known points. The total head is equal to:

$$H(i)= h_i+ (Y(i1)-Y(i)) \qquad (6.3)$$

In this program, the use of pressure loss values at each segment dividing by ρ.g instead of equation (6.1) is much more meaningful. In non-Newtonian case, the slope can not easily calculated like Newtonian case. Moreover, the slope of hydraulic grade line is not constant along the system.

The next step is to control the possibility of intersection of hydraulic grade line with maximum allowable operating pressure and land profile. Depending on the intersection, the program tries to reach an optimum point by changing the flowrate (increase or decrease). This is a trial and error procedure and shown in Figure 6.6. Pump head changes, oil inlet temperature changes, sectional heating of the crude and any combinations of these are the other options of the program offered to users.

The flow along the line can also be achieved by using drag reducing agents in case of hydraulic grade line intersection with land profile. These can substantially reduce frictional loss in most pipelines. The slope of the hydraulic grade line decreases and flow can take place easily. The small amount injected to the line does not have an adverse effect on the crude oil. The procedure followed in this part is to consider whether the flow of the line can be achieved by chemical or not, maximum and minimum amount of chemicals required and percentage throughput increase due to drag reduction.

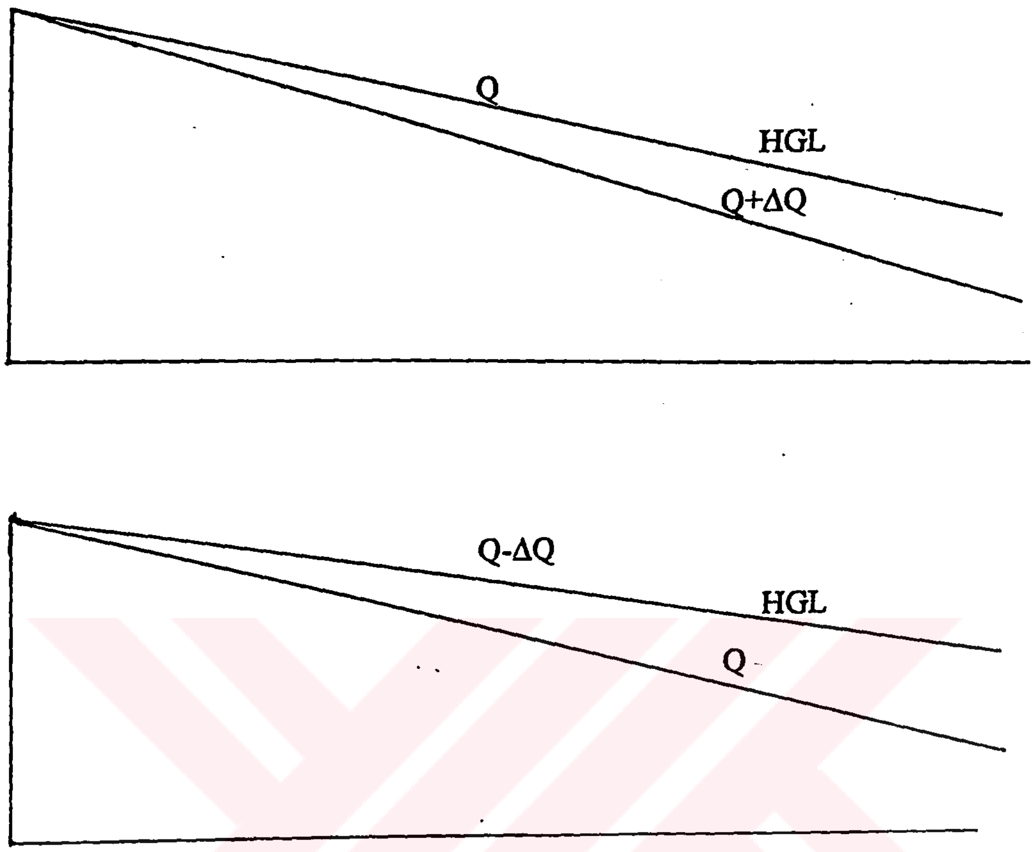

Figure 6.3 The Effects of Flowrate Change on Hydraulic Gradelines

Then, the capacities of the pump stations are investigated considering each station separately. The pumps are corrected according to the viscosity variation. The restart effect on pumping equipment are also investigated by the program.

6.3 Overview of Subprograms

In Visual Basic programming language, there are two types of procedure: subprograms and functions. This program is the combination of subprograms and functions, which are efficient tools to control the program. Modular structure is achieved by the use of subprograms. Basic subprograms and their brief descriptions are given below.

ACI is the tool to calculate the frictional head losses along the each section of pipeline, equally divided into small segments.

AIJENKACOR enables the user to calculate viscosity as a function of APIDEG, pour point and temperature. This is one of the empirical correlations used in viscosity calculation depending on the temperature.

ANTOINECOR is the other viscosity versus temperature equation found in literature. In this case, the boiling temperature of the oil is the second parameter in the calculation.

BEALCOR calculates the viscosity and density of crude oil as a function of temperature and APIDEG.

BINLAMFLOW determines the type of flow (laminar or turbulent) for non-Newtonian liquids. It is an application of Hedestrom's method to computer.

BURIAL calculates the shape factor used in heat transfer calculations according to the depth of burial.

CHEWCOR is one of the methods of viscosity calculations as a function of APIDEG and dissolved gas amount.

EFFICIENCY1 is the tool to obtain a fourth degree correlation between efficiency and flowrate by using polynomial regression method.

EFFICIENCYCAL preserves the constants obtained by EFFICIENCY1 and provide necessary data during the pump characteristics drawing.

HEAD1 is a way of obtaining a second degree correlation between efficiency and flowrate by using polynomial regression method.

HEADCAL preserves the constants obtained by HEAD1 and provide necessary data during the pump characteristics drawing.

MAOP calculates the amount of pressure exerted by the fluid on the pipe. This is a design limitation and won't be exceeded during the transportation and restart.

MAXLEV calculates maximum amount of drag reducer to be added to provide necessary drag reduction for normal operating conditions and restart after a shutdown at each station.

MINLEV exhibits the same work of MAXLEV. In this procedure, minimum limits are calculated.

NEWTONIANNOR divides the pipelines into short segments. For each segment, first it calculates the temperature, compares with cloud point temperature, determines the type of flow (laminar or turbulent) and mode of flow (Newtonian or non-Nwtonian), finally calculates the frictional pressure loss for normal operating condition case.

NEWTONIANRES repeats the same procedure followed by NEWTONIANNOR for restart after a shutdown case. The results of heat transfer analysis for normal operating condition case are used as an input of heat transfer for restart after a shutdown. Moreover, the amount of gel pressure at each section of pipeline and total amount is calculated in this procedure as well as restart pressure.

PARALLEL determines whether the head and flowrate requirement of the system is satisfied with parallel configuration of pump or not.

PARALLELCAL calculates the operating points of each pump to satisfy the flowrate requirement determined by PARALLEL.

PERRYCOR is another method of viscosity calculations as a function of temperature.

POMPAMODEFF performs the calculation method of efficiency correction due to appliaction of viscous liquids to pumps.

POMPAMODH calculates the correction factor of head for viscous liquids.

POMPAMODQ enables to users to perform the calculation of flowrate correction factor.

PUMPHEAD determines the amount of head requirement at each station considering the maximum allowable operating pressure.

RESIM represents the hydraulic grade line in graphical form for normal operating condition and restart after a shutdown.

RESIMLIK enables to make some modifications on the slope of the HGL. The flowrate is increased or decreased to reach a satisfactory result. The final solutions are displayed in graphical form. The effects of chemical injection are also performed.

SERIES determines whether the head and flowrate requirement of the system is satisfied with series configuration of pump or not.

SERIESCAL calculates the operating points of each pump to satisfy the flowrate requirement determined by SERIES.

STSTEMCHARAC calculates the system characteristic curves at each station for given flowrate and elevation change.

TANALFA calculates the slope of hydraulic grade line at each section.

YIELD calculates the yield stress, Bingham yield strength and plastic viscosity by applying linear interpolation technique.

The programs listed above are directly related to computational and graphical work. There are some other procedures, which serve in control of data entry and loop progress etc.

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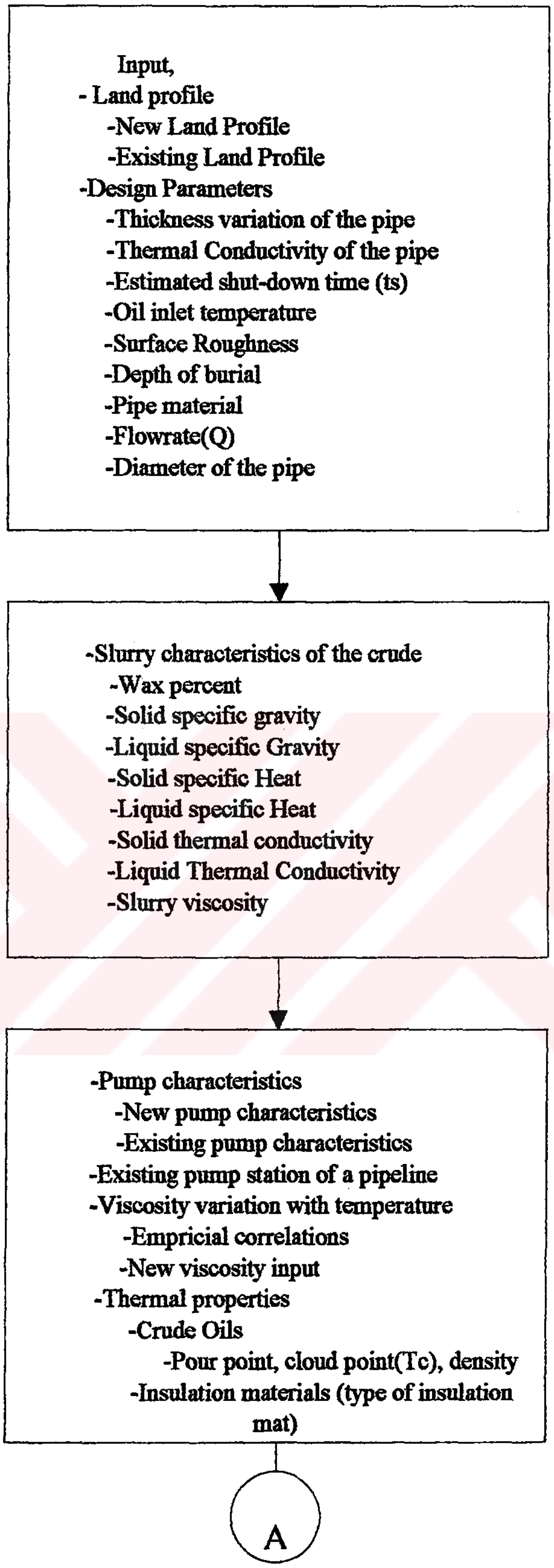


Figure 6.4(a) Overall Algorithm of the Software

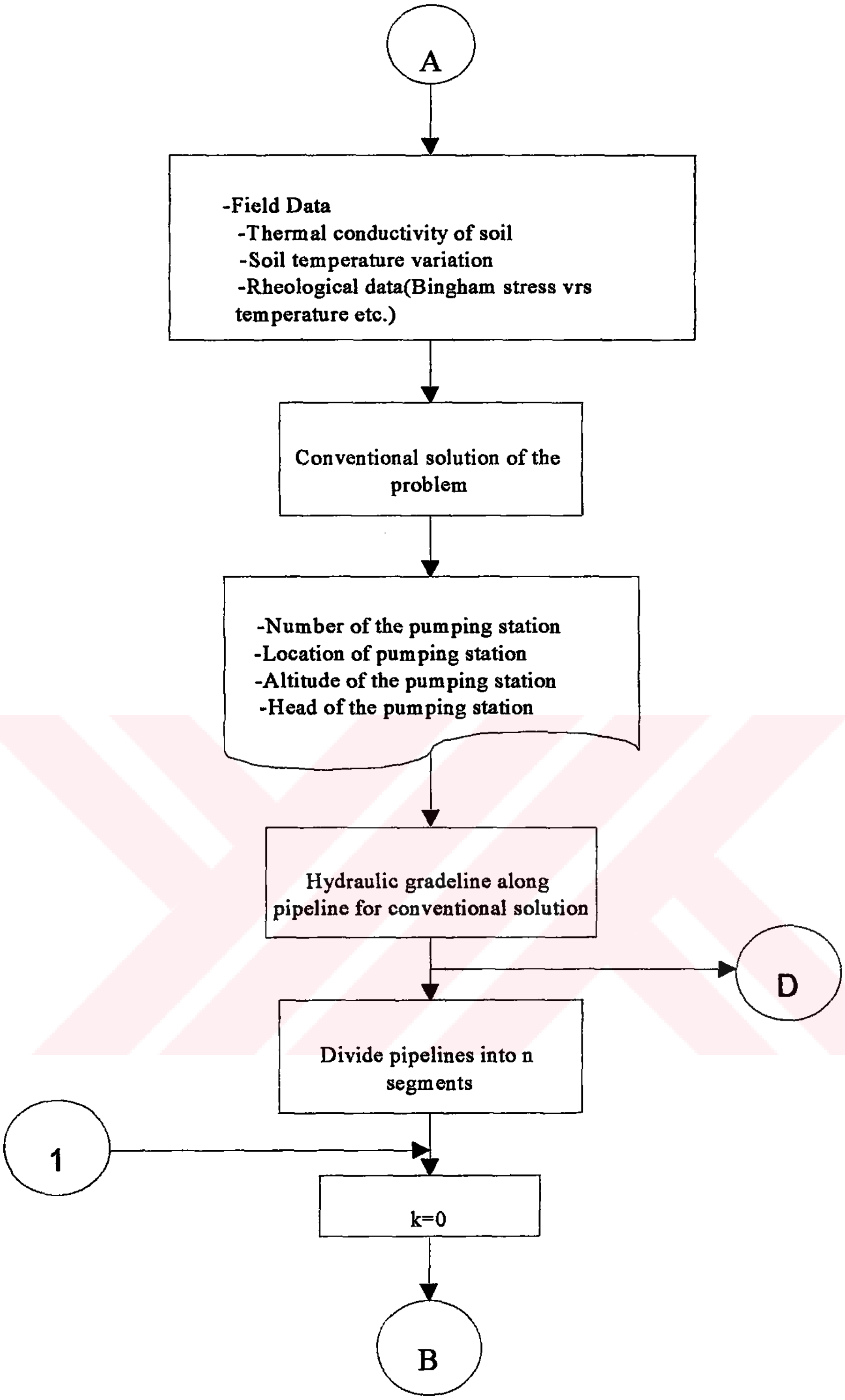


Figure 6.4 (b) Overall Algorithm of the Software

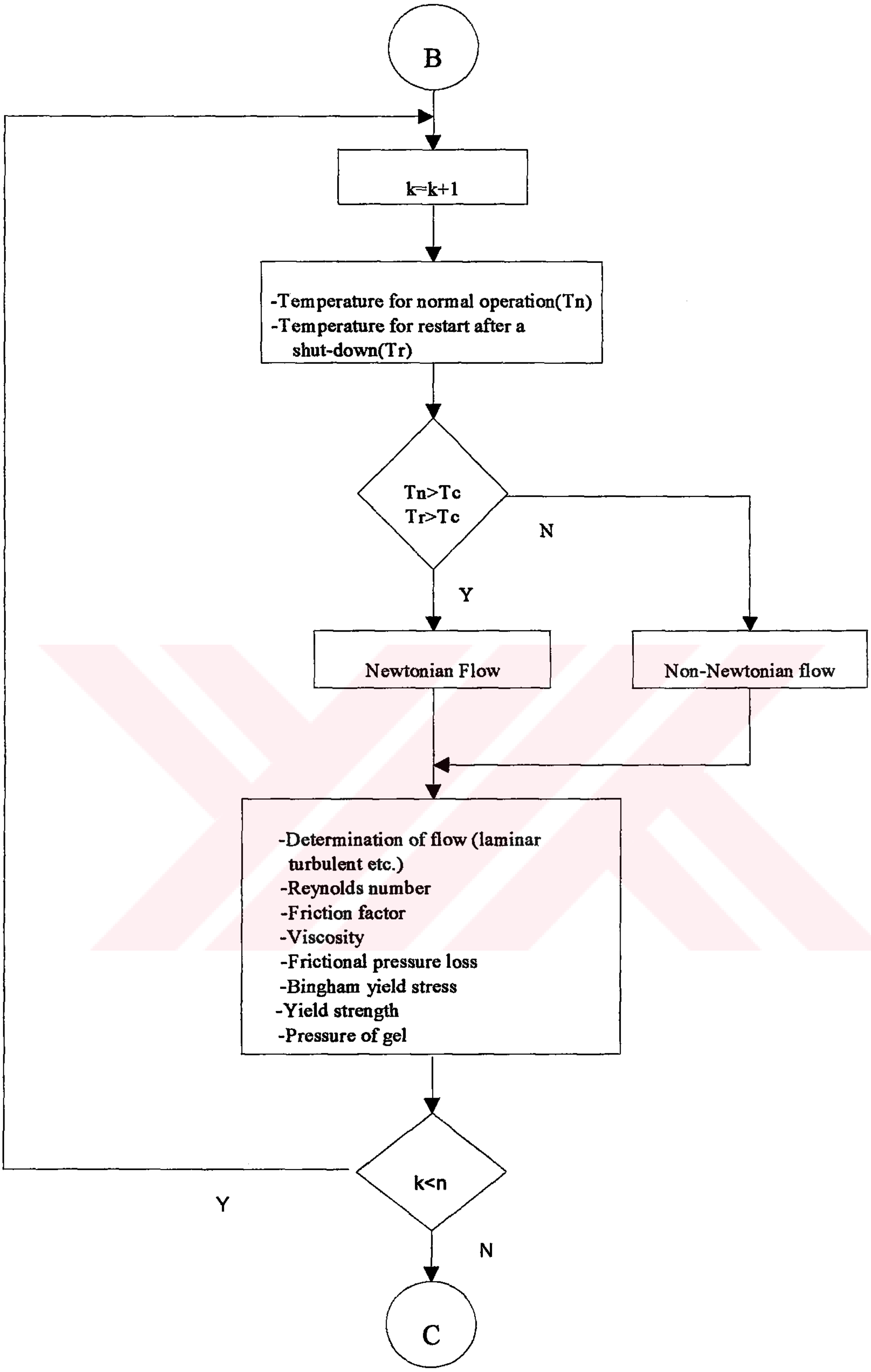


Figure 6.4 (c) Overall Algorithm of the Software

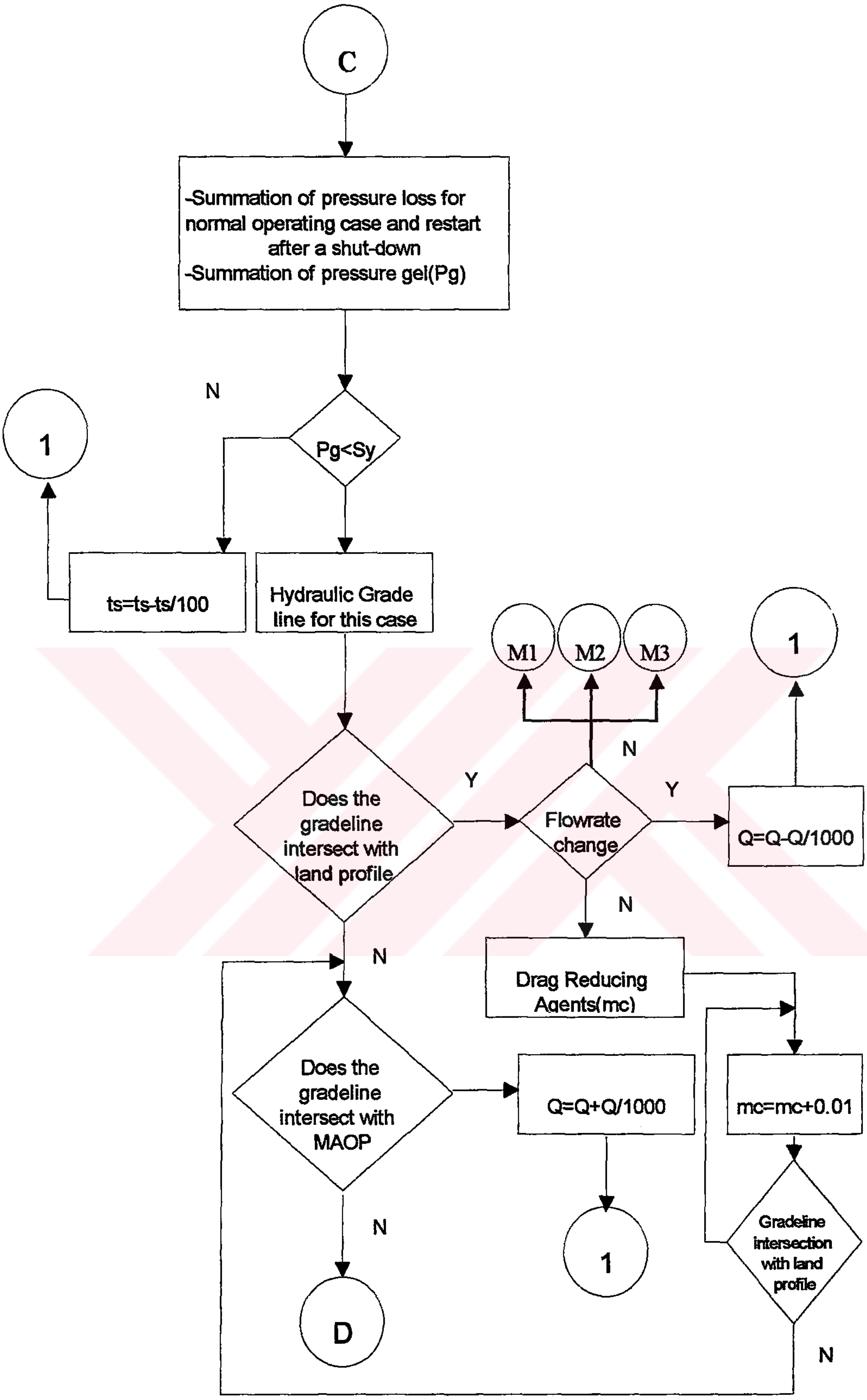


Figure 6.4 (d) Overall Algorithm of the Software

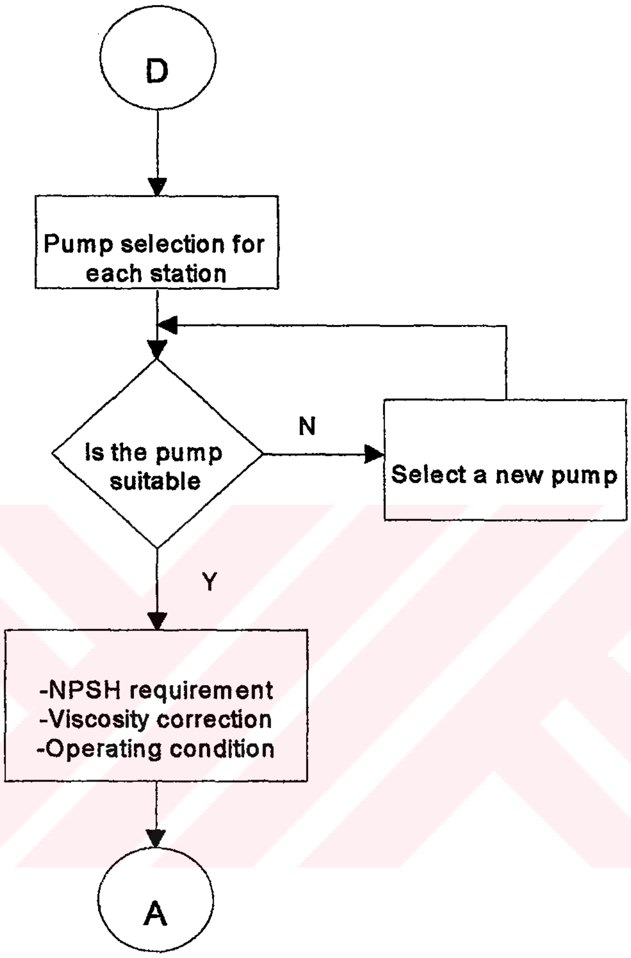


Figure 6.4 (e) Overall Algorithm of the Software

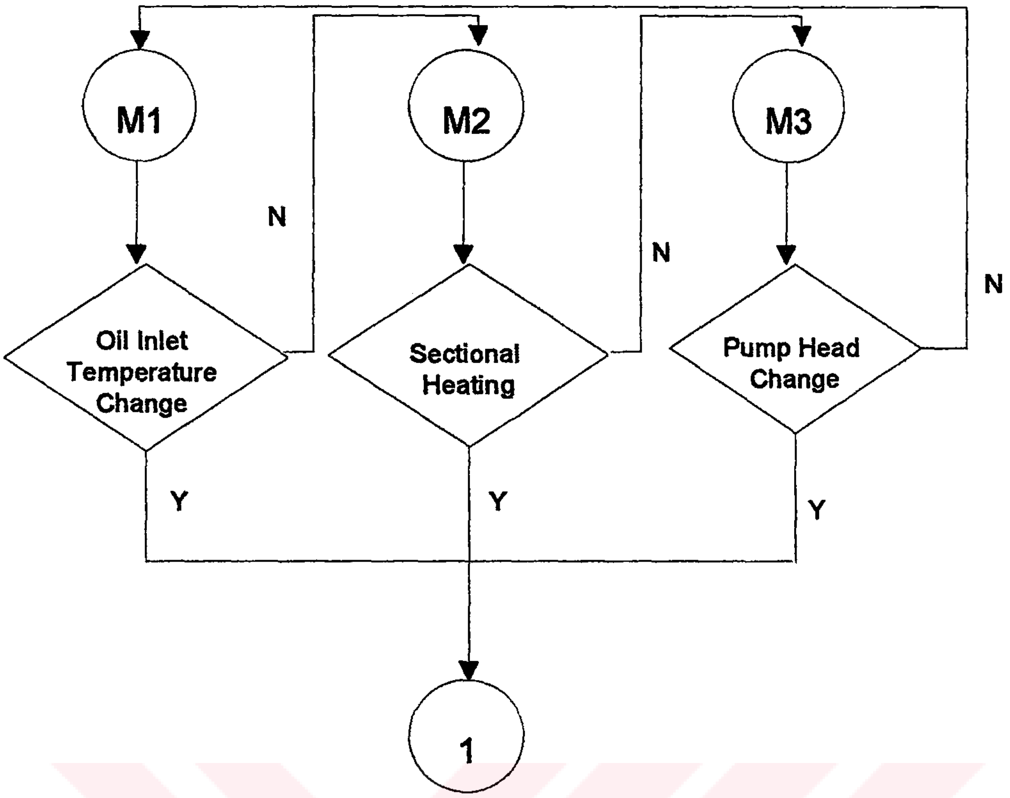


Figure 6.4 (f) Overall Algorithm of the Software

CHAPTER 7

CASE STUDIES

7.1 General

Ceyhan-Kırıkkale pipeline is investigated to test the software about the effects of waxy crude oil on pipeline operation. Ceyhan-Kırıkkale pipeline system is preffered for such a search because several problems were encountered on this line due to the application of high pour crude oil to system instead of Iraq crude after the Gulf War. Besides the problems related to this line, land profile exhibits very steep changes along the Toros Mountains. This profile increases the diffuculty of crude flow for both normal and restart after a shut-down cases.

Newtonian and non-Newtonian analysis and the details of application for Ceyhan-Kırıkkale system are given in the following sections. Inputs of the program are listed in Appendix A.

7.2 Case I (Ceyhan-Kırıkkale Pipeline System)

7.2.1 General

Ceyhan-Kırıkkale system delivers crude oil at 1200 m^3/h to the Central Anatolian Refinery at Kırıkkale from the tank farm at Ceyhan. Ceyhan is also the end terminal of Iraq-Turkey Crude Oil Pipeline System. The system has two pumping stations: First pumping station is located at Yumurtalık, and second one is located at 96th km. There is a third pumping station which is inactive and that is located near Aksaray at 276th km.

The pipeline has a diameter of 24 inches with a wall thickness ranging between 0.25 inch (6.35 mm) and 0.47 inch (11.92 mm)(Table 7.2). Pipe material is made of API 5L grade X60 (minimum yield strength 410 MPa). The length of the system is 447 m. The characteristic of the design crude oil is the same as that of the Iraq-Turkey Pipeline System. Some of the design parameters are given below:

Nominal Capacity:	5,000,000 tons/year
Viscosity:	10.7 cst
Density:	845 kg/m^3
Pipe Roughness:	$4.57.10^{-5}$ m
Design Capacity:	158,000 bbl/day
Vapour pressure:	0.02 bar
Pipeline Availability	90%

9 line valves along the pipeline at the river crossings and 4 venting valves at high points are installed to the system.

The oil inlet temperature is approximately 30 °C. The variation of soil temperature along the line as considered in the design is as follows:

Table 7.1 Variation of Soil Temperature along the Line

Location (km)	Soil Temperature (°C)
0-98	13
98-114	12.5
114-137	12
137-277	11
277-383	10
383-447	10.5

The rheological properties of crude are shown in Table 7.3.

Table 7.2 Wall Thickness Distribution for Kırıkkale-Ceyhan Pipeline System

Distance (km)	Wall Thickness (mm)
0	6.35
104	7.14
107.5	6.35
108.5	7.92
109.5	9.52
110	10.31
111	10.31
112	7.14
113	8.74
114	10.31
119	8.74
120	9.52
125	9.52
126	8.74
130	8.74
134.9	7.92
136	7.92
137	7.14
138	6.35
447	6.35

Table 7.3 Rheological data for hypothetical crude [17]

(Shear rate=16 1/sec)				
Temperature C	Bingham yield stress Pa	20 hr yield strength Pa	Plastic viscosity Pa.s	Apparent viscosity Pa.s
12,8	5,52	29,63	0,079	0,4464
13,3	4,30	26,33	0,076	0,3720
13,9	3,39	23,58	0,072	0,3109
14,4	2,70	21,17	0,066	0,2514
15,0	2,30	19,31	0,062	0,2112
15,6	1,79	17,39	0,058	0,1755
16,1	1,49	15,88	0,052	0,1532
16,7	1,19	14,50	0,047	0,1282
17,2	0,99	13,40	0,040	0,1087
17,8	0,79	12,30	0,036	0,0877
18,9	0,49	10,51	0,024	0,0590
19,4	0,39	9,69	0,020	0,0483
20,0	0,29	8,93	0,017	0,0391
20,6	0,24	8,18	0,017	0,0330
21,1	0,19	7,74	0,016	0,0276
23,9	0,09	4,53	0,015	0,0186
26,7	0	2,13	0,014	0,0142
29,4	0	0	0,013	0,0131
32,2	0	0	0,011	0,0119
37,8	0	0	0,010	0,0099
40,6	0	0	0,009	0,0091
43,3	0	0	0,008	0,0084

7.2.2 Newtonian Normal Operation Solutions of Ceyhan-Kırıkkale Pipeline

Table 7.4 displays the Newtonian solution of Kırıkkale-Ceyhan pipeline system and Figure 7.1 shows the hydraulic loading of this solution performed by the program. According to this solution, the system has two pumping stations at 0, and 96th km.

7.2.3 Non-Newtonian Operations Solutions of Ceyhan-Kırıkkale Pipeline

If the method described in the previous sections is applied to the system, the mode of flow changes from Newtonian to non-Newtonian at approximately 266th km for normal operation case and completely non-Newtonian for restart after 36 h shutdown time. The results of this method are shown in Table B.1 for normal operation and Table B.2 for re-start after 36 h shutdown. In this tables, S represents the factor $\phi(s)$ described for non-Newtonian laminar flow in Chapter 3. Therefore, it's 0 for Newtonian (laminar or turbulent) and non-Newtonian turbulent flow.

Figure 7.2 and 7.3 shows the variation of temperature along the line for normal operating conditions and re-start after 36 h shutdown. If these graphics are investigated carefully, both temperatures shows sudden small increases or decreases at certain locations. Soil temperature variations shown in Table 7.1 cause these changes at described locations. In hydraulic loading graphs, the area shown by dots exhibits non-Newtonian (laminar or turbulent) flow behaviour. The hydraulic loading of the line found by the program (Figure 7.4 for normal operation and Figure 7.5 for re-start after 36 hour shutdown) displays that the application of high pour point crude causes the blockage of the line at both operation case.. At that condition, the users have 6 basic solution possibilities to prevent blockage: flowrate change, pumphead change, chemical injection, oil inlet temperature change, partial heating, blending; or combinations of these basic solutions..

7.2.4 System Modifications for Ceyhan Kırıkkale Pipeline System

7.2.4.1 Flowrate Modifications

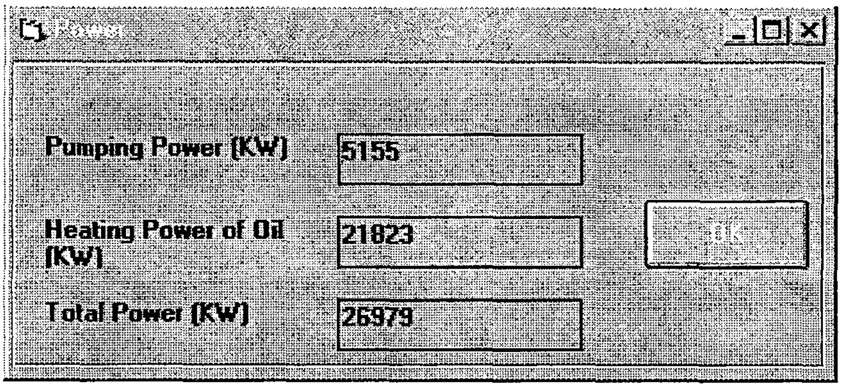
Hydraulic grade lines intersect with land profile for both normal operation (Figure 7.4) and restart after 36 h shutdown condition (Figure 7.5). This means that the slope of hydraulic grade line is so high that no flow takes place in the pipe. The slope of the hydraulic grade line can be decreased only changing the amount of flowrate. The program limits the flowrate modifications between half of the design flowrate and one and half of the flowrate. Within these limitations, the flowrate is dropped from 1200 m^3/h to 1018 m^3/h for normal operating condition with trial and error methods. Hydraulic loading of the Ceyhan-Kırıkkale pipeline can be seen in Figure 7.6. However the program couldn't obtain any satisfactory result for restart after 36 h shutdown. As a result, flowrate modifications solution is not suitable choice for the described system to prevent flow blockage problem because it didn't give any meaningful result for restart condition. If the flowrate is decreased, the beginning location of non-Newtonian flow moves from 266th km to 225th km approximately.

7.2.4.2 Pump Head Modifications

The change of pump heads at each station without exceeding maximum allowable operating pressure of the pipes and intersecting with land profile can satisfy such a flow in the line. The program didn't find any results for two operating conditions.

7.2.4.3 Oil Inlet Temperature Change

The oil temperature is increased 0.5 °C step by the program up to the point of flow in the pipe. Figure 7.7 exhibits that the oil inlet temperature must be 71 °C to allow such a flow at design capacity for normal operating conditions. At that temperature, flow is completely Newtonian. Figure 7.8 (a) displays the variation of temperature for normal operating conditions and Figure 7.8.(b) for restart after 36 hours shutdown. Figure 7.9 shows the result of oil inlet temperature change for restart operation case. The completely non-Newtonian flow becomes partially non-Newtonian, which begins at 148th km. The variation of temperature along the line for normal operating condition can be seen in Figure 7.10(a) and for restart operating condition in Figure 7.10(b) depending on the variation in Figure 7.10(a). The oil inlet temperature must be 45 °C at restart condition. Normal operating condition is much more critical than restart conditions. The increase of oil temperature to 71 °C provides flow for both conditions but oil inlet temperature over 60 °C is not a practical and cheapest operation for most oil producers. Therefore, heating at the pump stations or any other location is searched by the program. The possibility of non-Newtonian flow decreases with increasing temperature. The power requirement of the system due to the increase of oil inlet temperature to 71 °C can be summarised as follows.



Pumping Power (KW) 5155

Heating Power of Oil (KW) 21823

Total Power (KW) 26979

7.2.4.4 Partial Heating

Figure 7.11 shows that if oil is heated at second pumping station, it is also possible to enhance flow in the line for normal operating conditions. Figure 7.12(a) and 7.12(b) are the temperature distributions of the pipeline. In Figure 7.12 (a), the oil temperature increases to 51 °C at 96th km(second pump station). The effect of this increase on the temperatures at restart case is shown in Figure 7.12(b). At the same location, the temperature of oil increases to 33 °C. Figure 7.13 is the hydraulic loading of the line after 36 h shutdown if oil is heated at 96th km to obtain flow only restart conditions. The maximum oil temperature is 33 °C for normal operating condition (Figure 7.14(a)) and 22 °C for restart case (Figure 7.14(b)). Similar to oil inlet temperature increase to 71 °C, the increase of oil temperatures at 96th km to 51 °C is the solution of flow blockage problem at two operating conditions. The power requirement of the system as a result of heating oil to 51 °C at second pumping station is as follows:

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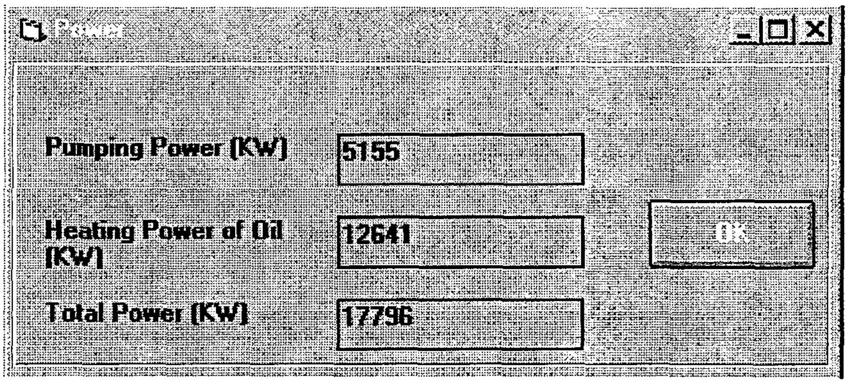


Pumping Power [KW] 5155

Heating Power of Oil [KW] 12641

Total Power [KW] 17796

7.2.4.5 Chemical Injection

At the discharge side of pumping stations, the chemicals can be used to decrease the frictional pressure loss. Figure 7.15 displays the amount of chemical within the maximum and minimum range, drag reduction percentage and the duration of chemical applications at each station. In order to show the effects of chemicals completely on the line, 85 hours is required. Hydraulic loading of the profile displays the state of the line at the end of this 85 hours for normal operation. Chemical injection couldn't give any satisfactory results for restart after 36 h shutdown case.

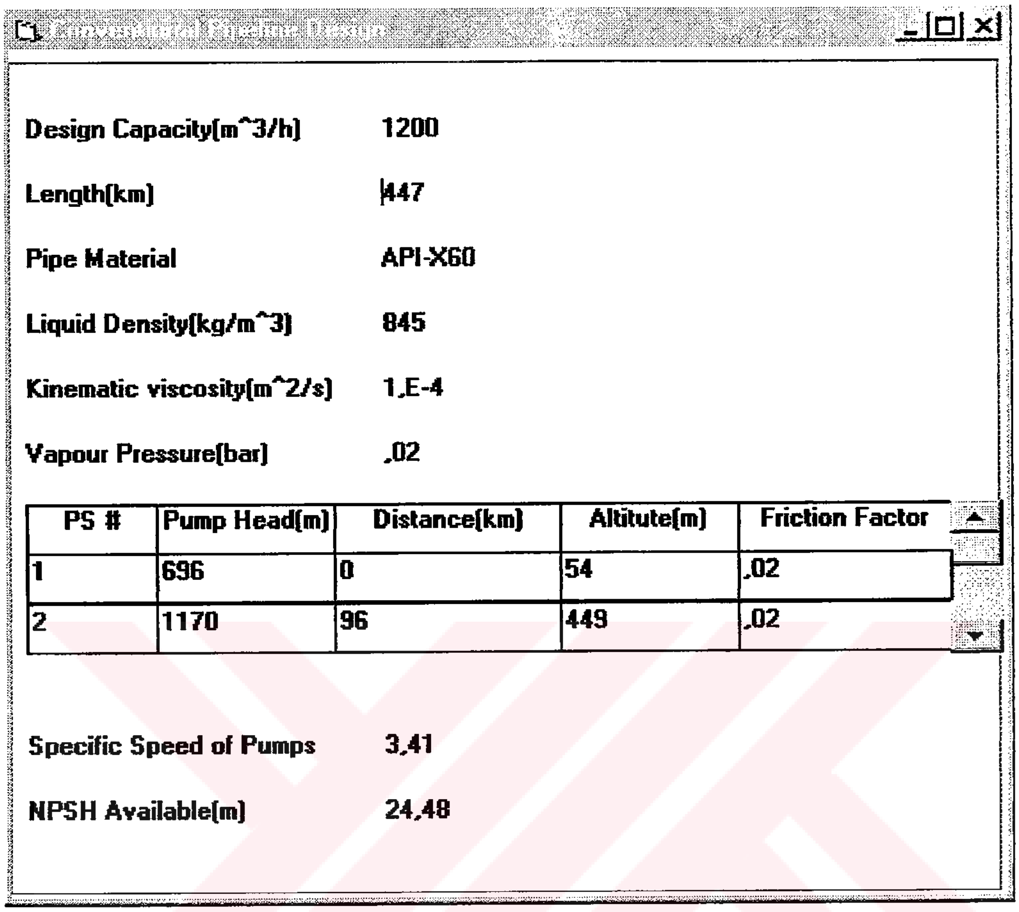
7.2.3.6 Combinations of Operational Modifications

The effects of pumphead, flowrate, oil inlet temperature and partial heating are searched on the system separately up to now. However, it is possible to combine the effects of any of two. Figure 7.16.shows the effects of oil inlet temperature change and flowrate change at the same time on the system for normal operation case. Figure 7.17(a) and 7.17(b) display the temperature distribution of system for normal operation case and restart after 36 h shutdown case at that condition. The oil inlet temperature 32 °C and the flowrate of 1037 m^3/h are the results of the program for normal operation case. The temperature distribution of the system is very similar to its original temperature distribution (Figure 7.2 and 7.3). If the same approach is applied only considering the flow at restart after 36 h shutdown case, Figure 7.18 is the result hydraulic loading of the system.

Flowrate decreases to 1042 m^3/h and oil inlet temperature increases to 48 °C. The temperature distribution of the systems are shown in Figure 7.19(a) for normal operations and in Figure 7.19(b) for restart after 36 h shutdown. The two results of the flowrate must be satisfied by the system.

In making modifications, two basic parameters of the system change: fluid parameters and operational parameters. When changing fluid parameters, the most critical result of the normal operation and restart operation of the system is the overall solution of the normal operation and restart operation. Conversely, each solution must be considered individually when changing operational parameters. The pump configuration of the system must satisfy the necessary flowrate and pump head at two operation conditions. The results of pump configuration for Newtonian solution can be seen in Figure 7.20 (a) and (b). Figure 7.21 (a) and (b) are the results of new pump operating points for normal operating conditions if the flowrate and oil temperatures are modified together. Figure 7.22 (a) and (b) are the results of pump operating points at restart condition. It is assumed that the flowrate at restart condition is equal to the 5/8 of design flowrate (1042 m^3/h).

Table 7.4 Newtonian Solution of Ceyhan Kırıkkale Pipeline System obtained from the program



Design Capacity(m^3/h) 1200

Length(km) 447

Pipe Material API-X60

Liquid Density(kg/m^3) 845

Kinematic viscosity(m^2/s) 1,E-4

Vapour Pressure(bar) ,02

PS #	Pump Head(m)	Distance(km)	Altitute(m)	Friction Factor
1	696	0	54	,02
2	1170	96	449	,02

Specific Speed of Pumps 3,41

NPSH Available(m) 24,48

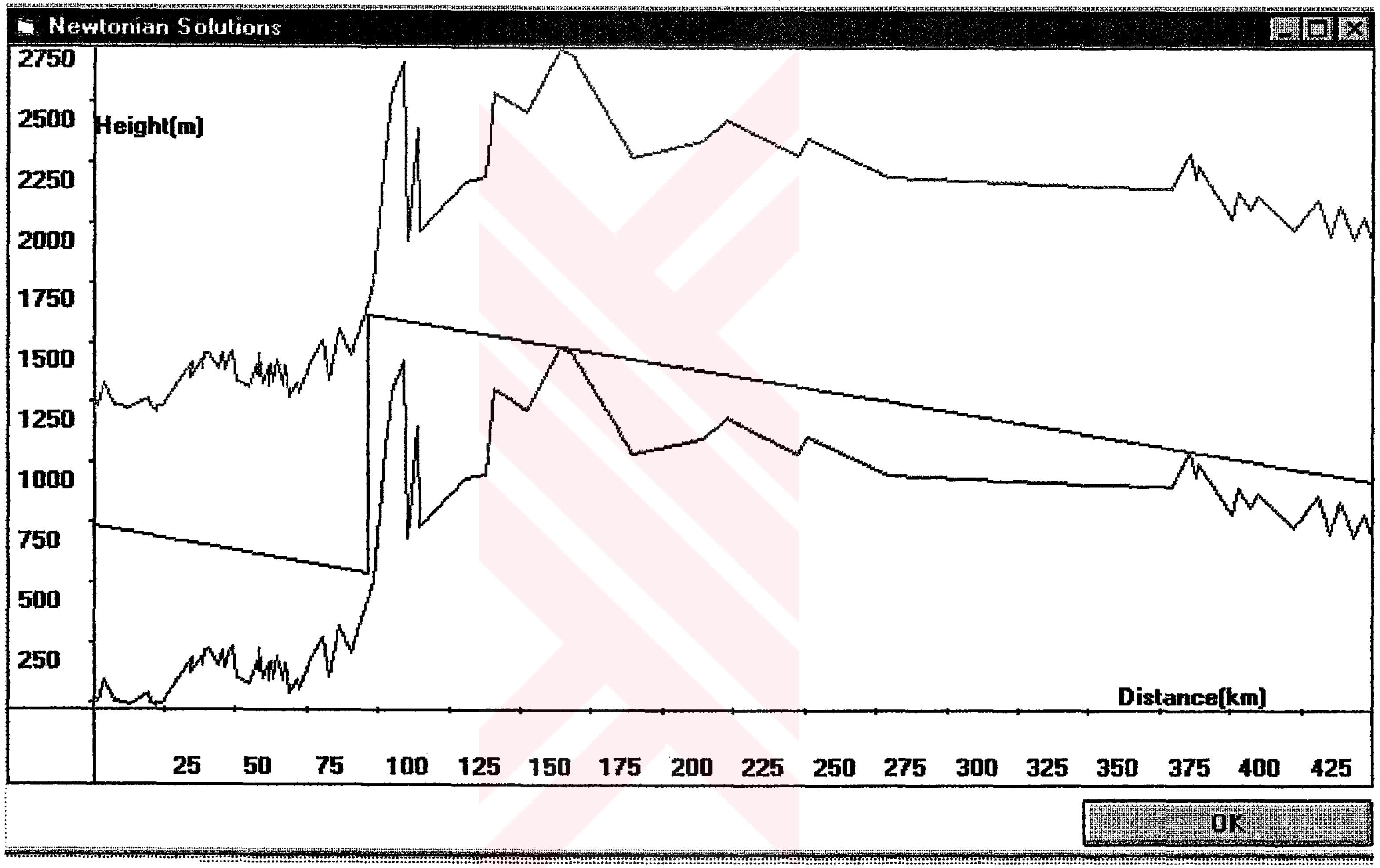


Figure 7.1 Hydraulic Loading of Kırıkkale-Ceyhan Pipeline System for Conventional Solution

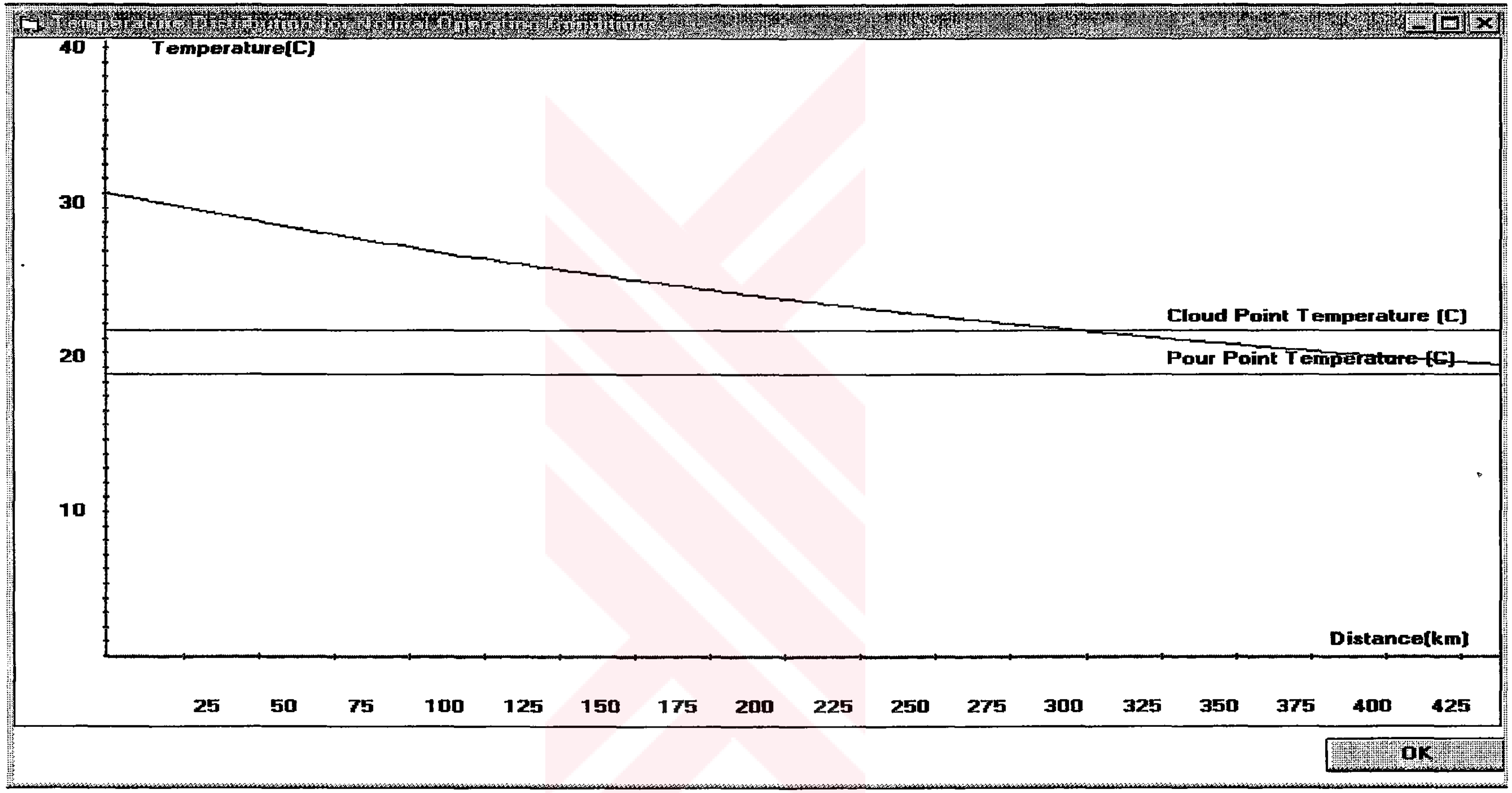


Figure 7.2 Temperature Distribution along the Line for Normal Operating Condition

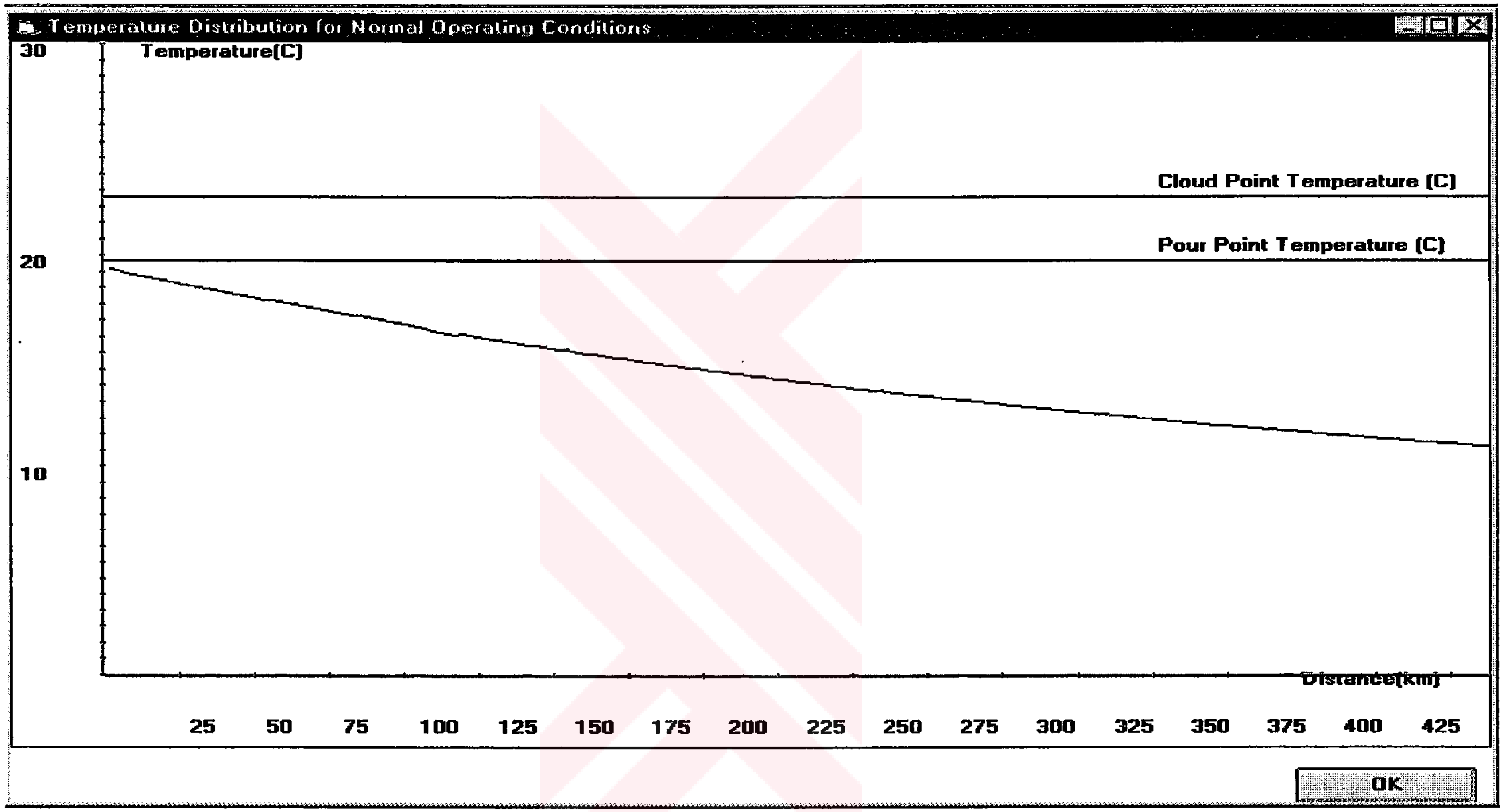
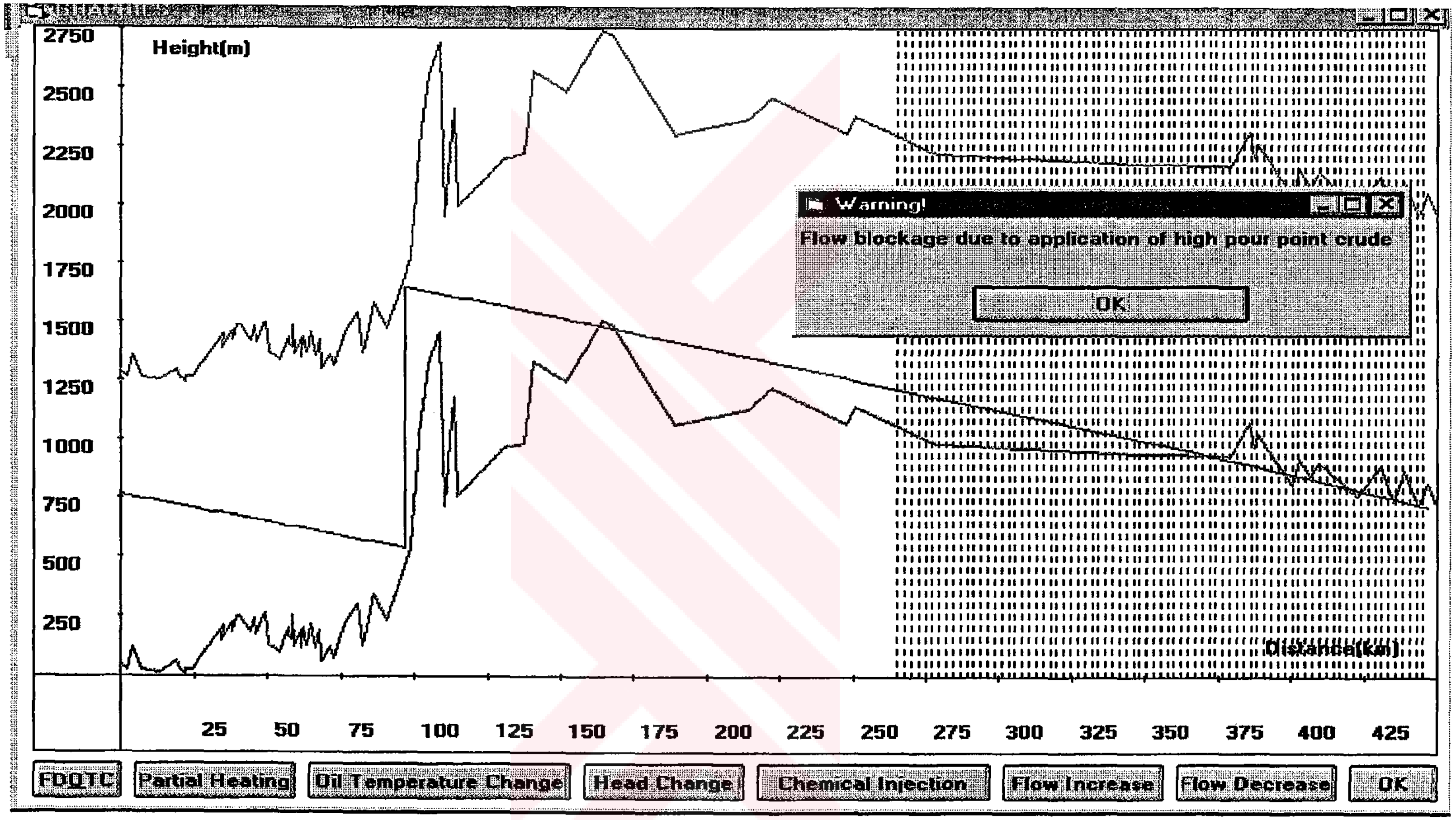
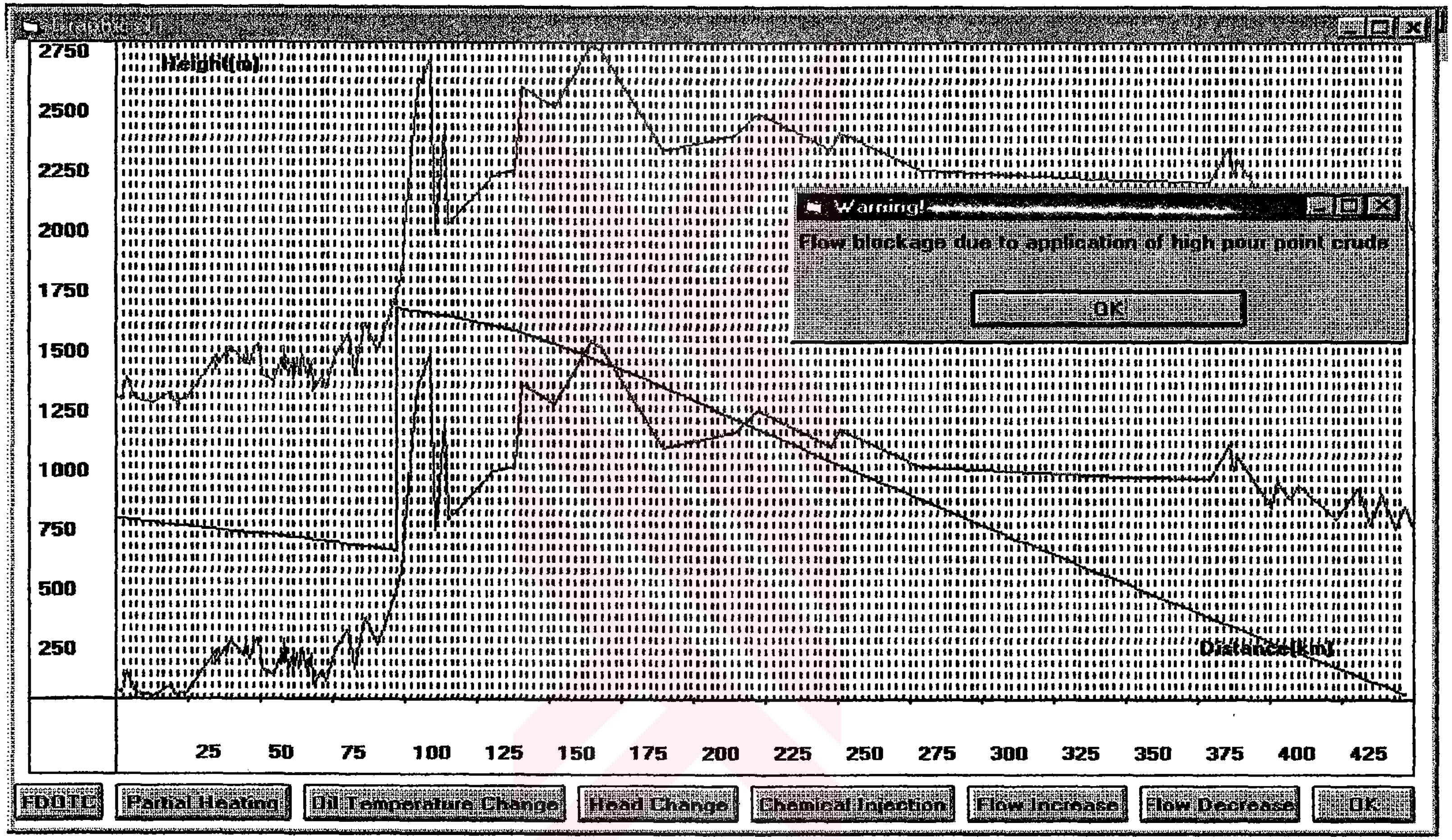


Figure 7.3 Temperature Distribution along the Line for Re-start after 36 h shutdown


Warning!

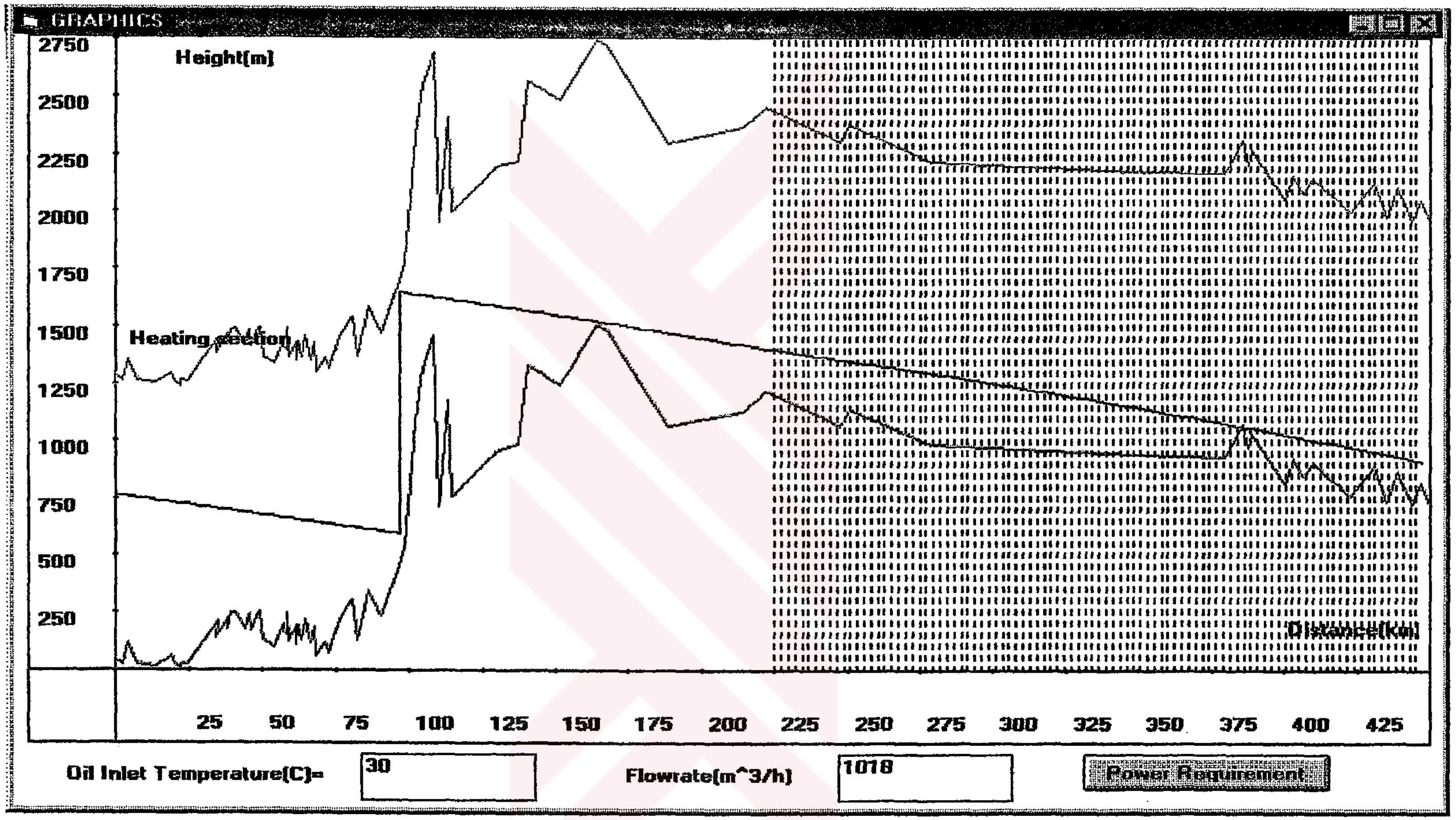
Flow blockage due to application of high pour point crude

Figure 7.4 Hydraulic Loading of Kırıkkale Ceyhan Pipeline System due to Application of High Pour Point Crudes (normal operation)



Flow blockage due to application of high pour point crude

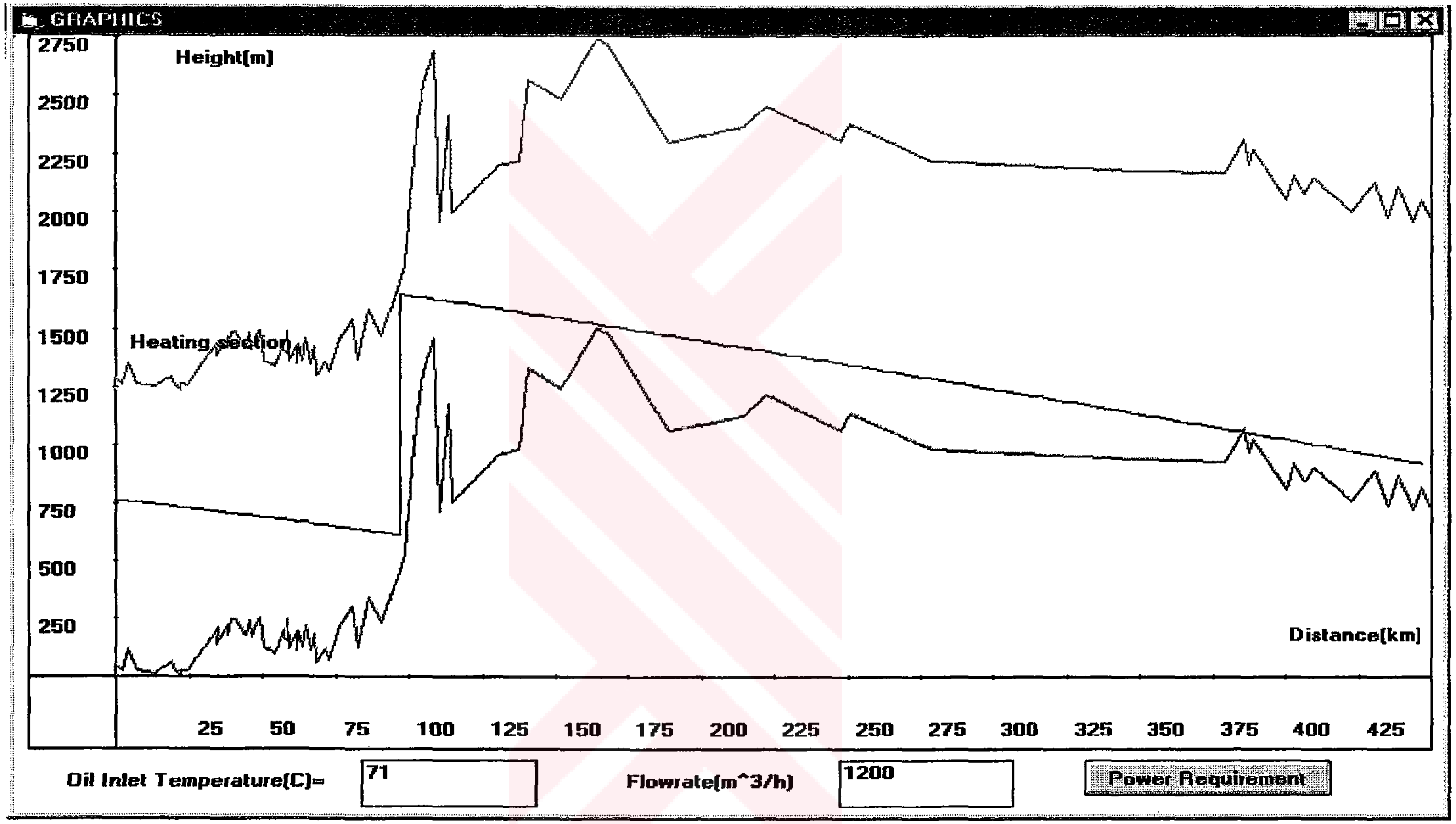
Figure 7.5 Hydraulic Loading of Kırıkkale Ceyhan Pipeline System due to Application of High Pour Point Crudes (re-start operation)



Oil Inlet Temperature(C)= 30

Flowrate(m^3/h) 1018

Figure 7.6 Hydraulic Loading of Kırıkkale Ceyhan When Flowrate is decreased to Satisfy such a Flow(normal operation)



Oil Inlet Temperature(C)= 71

Flowrate(m^3/h) 1200

Figure 7.7 Hydraulic Loading of Kırıkkale Ceyhan When oil inlet temperature is increased to Satisfy such a Flow(normal operation)

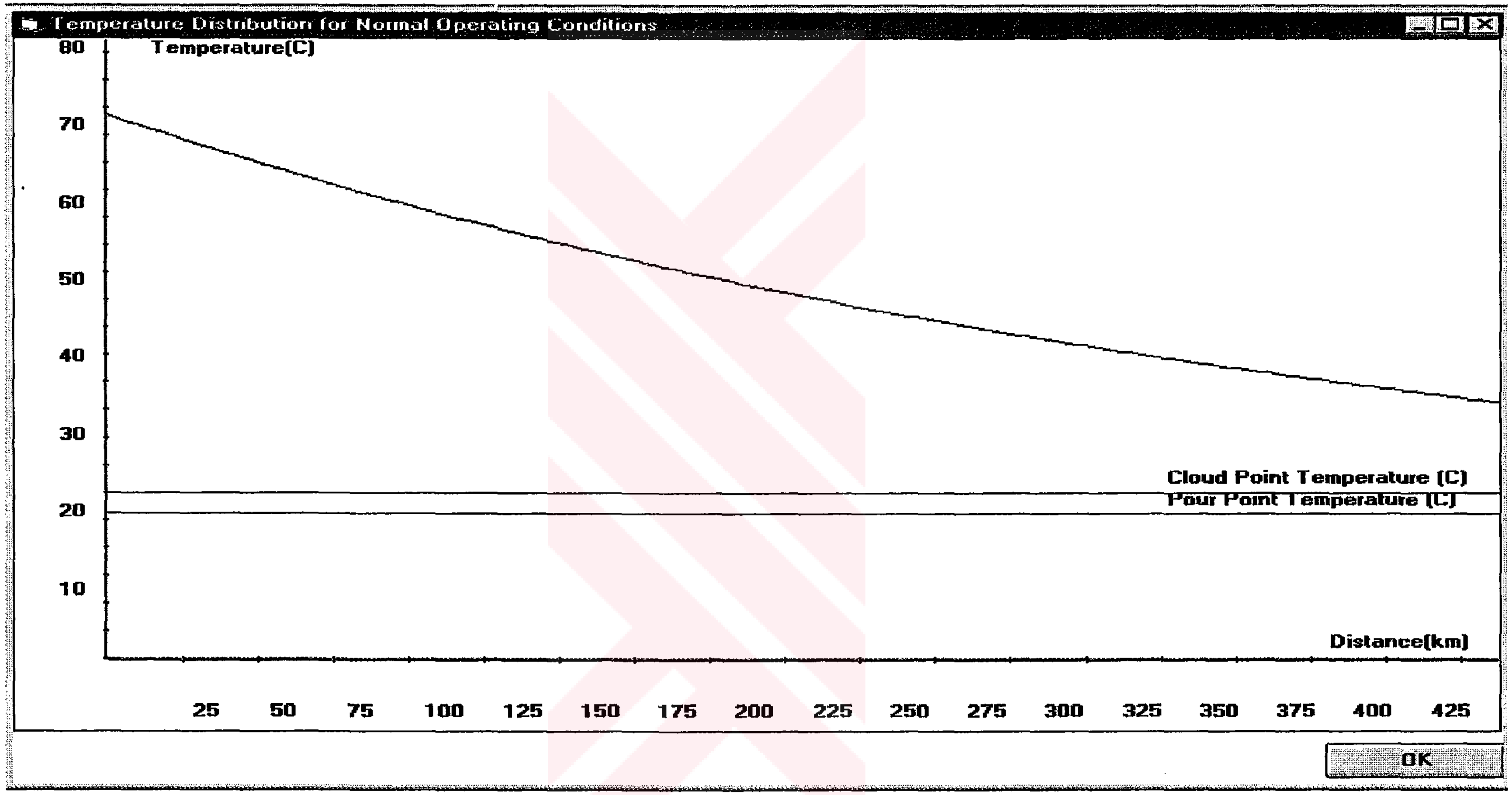


Figure 7.8 (a) Temperature Distribution of the system after an increase of Oil Inlet Temperature to 71 °C (Normal Operation)

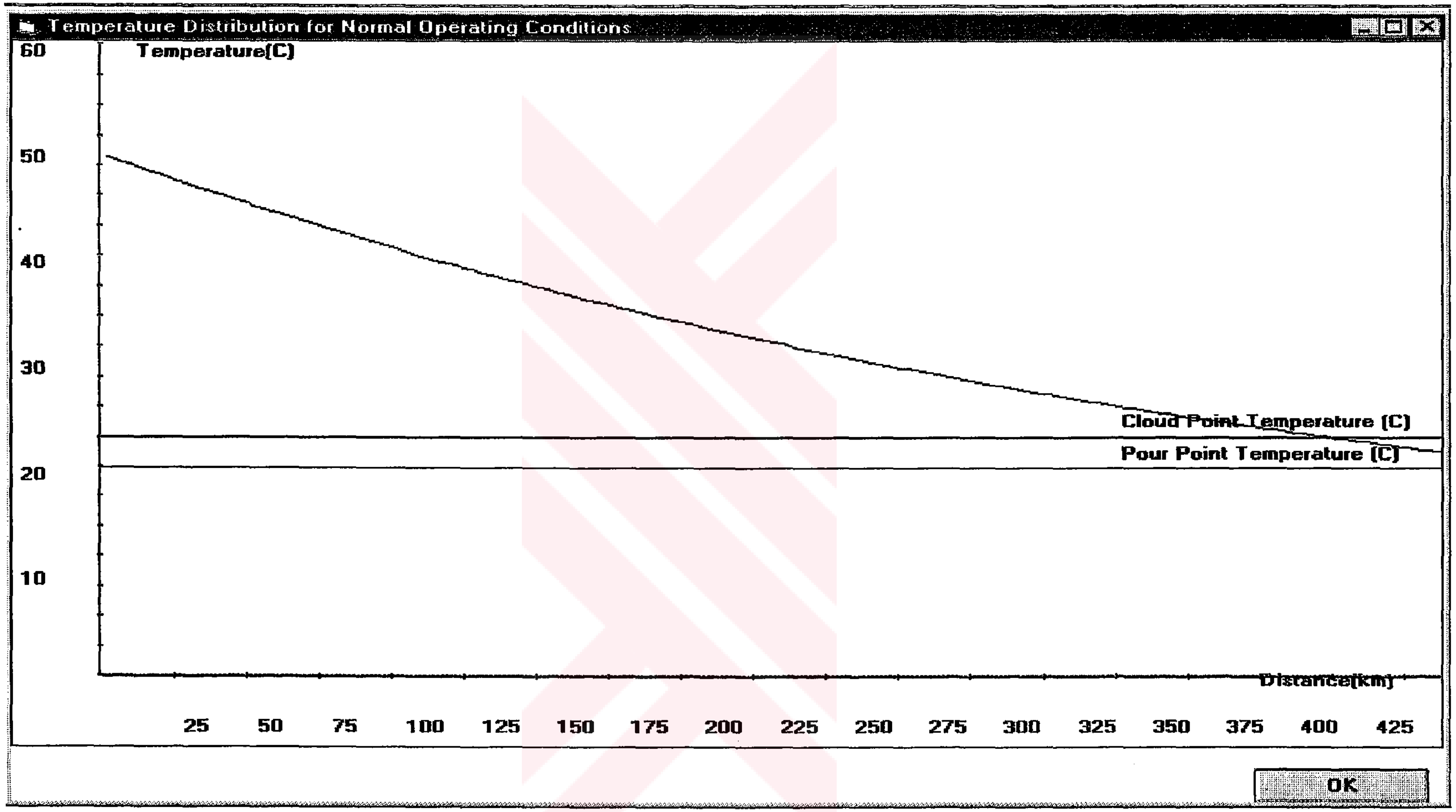
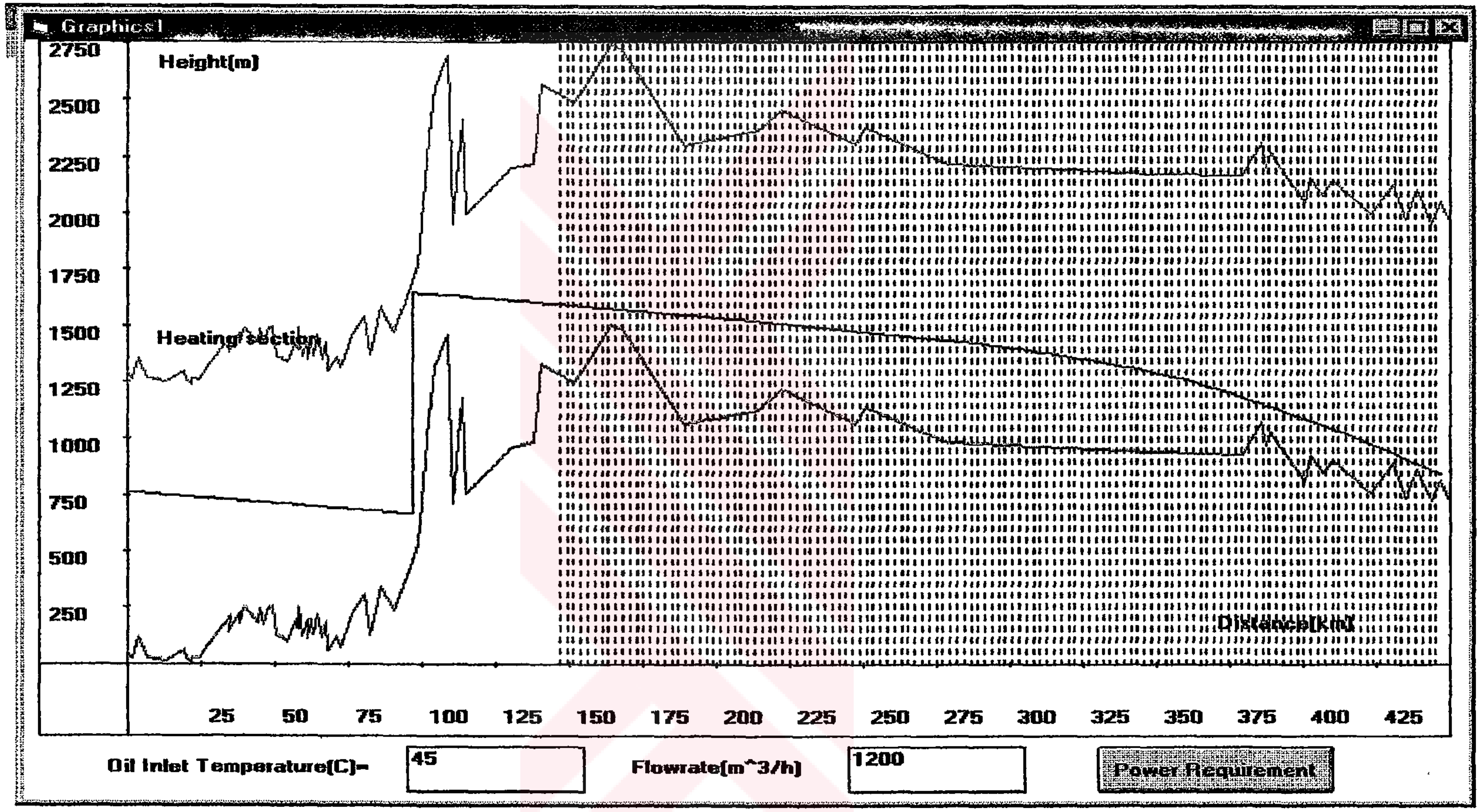


Figure 7.8 (b) Temperature Distribution of the system after an increase of Oil Inlet Temperature to 71 °C (Restart after 36 h Shutdown)



Oil Inlet Temperature(C)= 45

Flowrate(m^3/h) 1200

Figure 7.9 Hydraulic Loading of Kırıkkale Ceyhan When oil inlet temperature is increased to Satisfy such a Flow

(Re-start after36 hour shutdown)

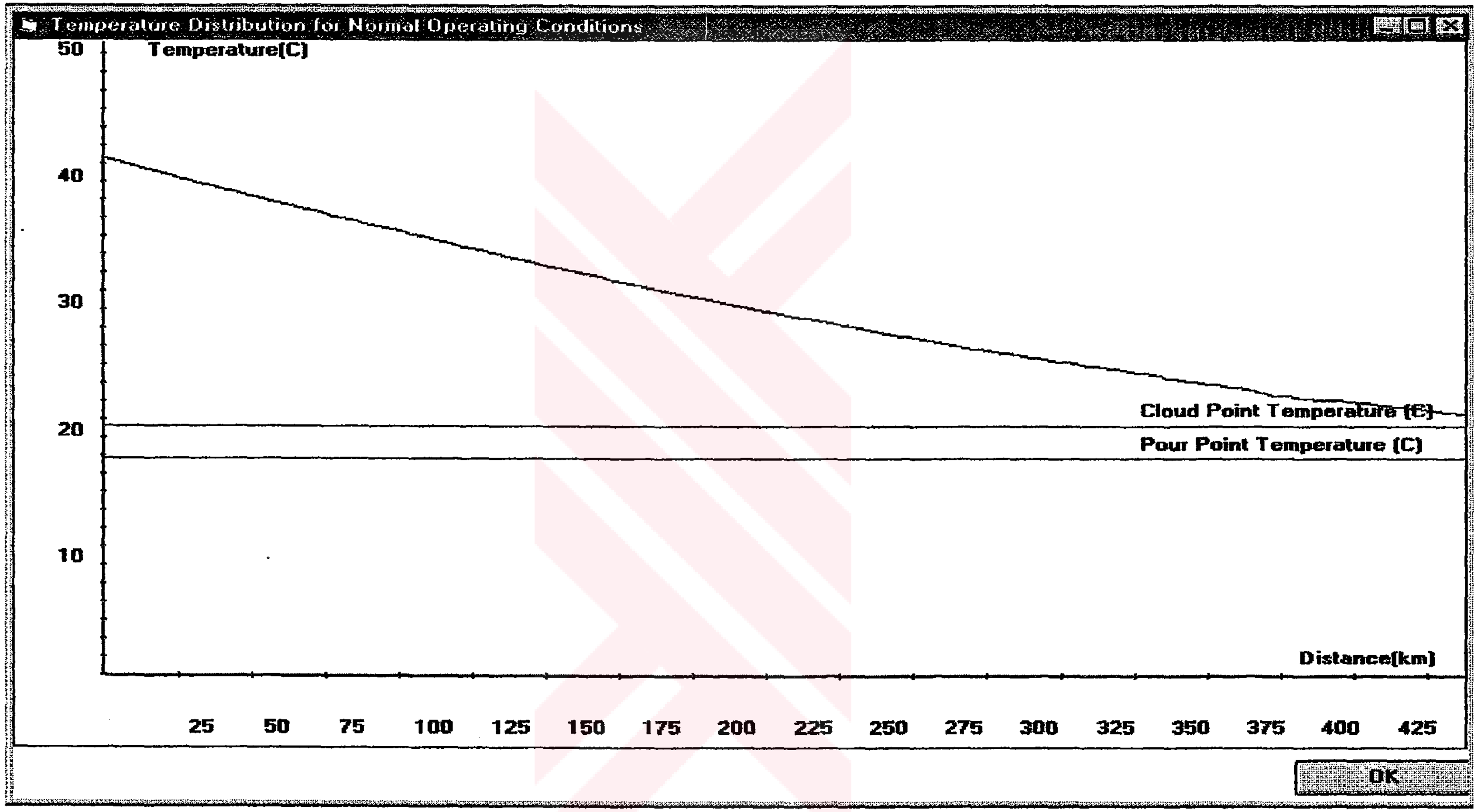


Figure 7.10 (a) Temperature Distribution of the system after an increase of Oil Inlet Temperature to 45 °C (Normal Operation)

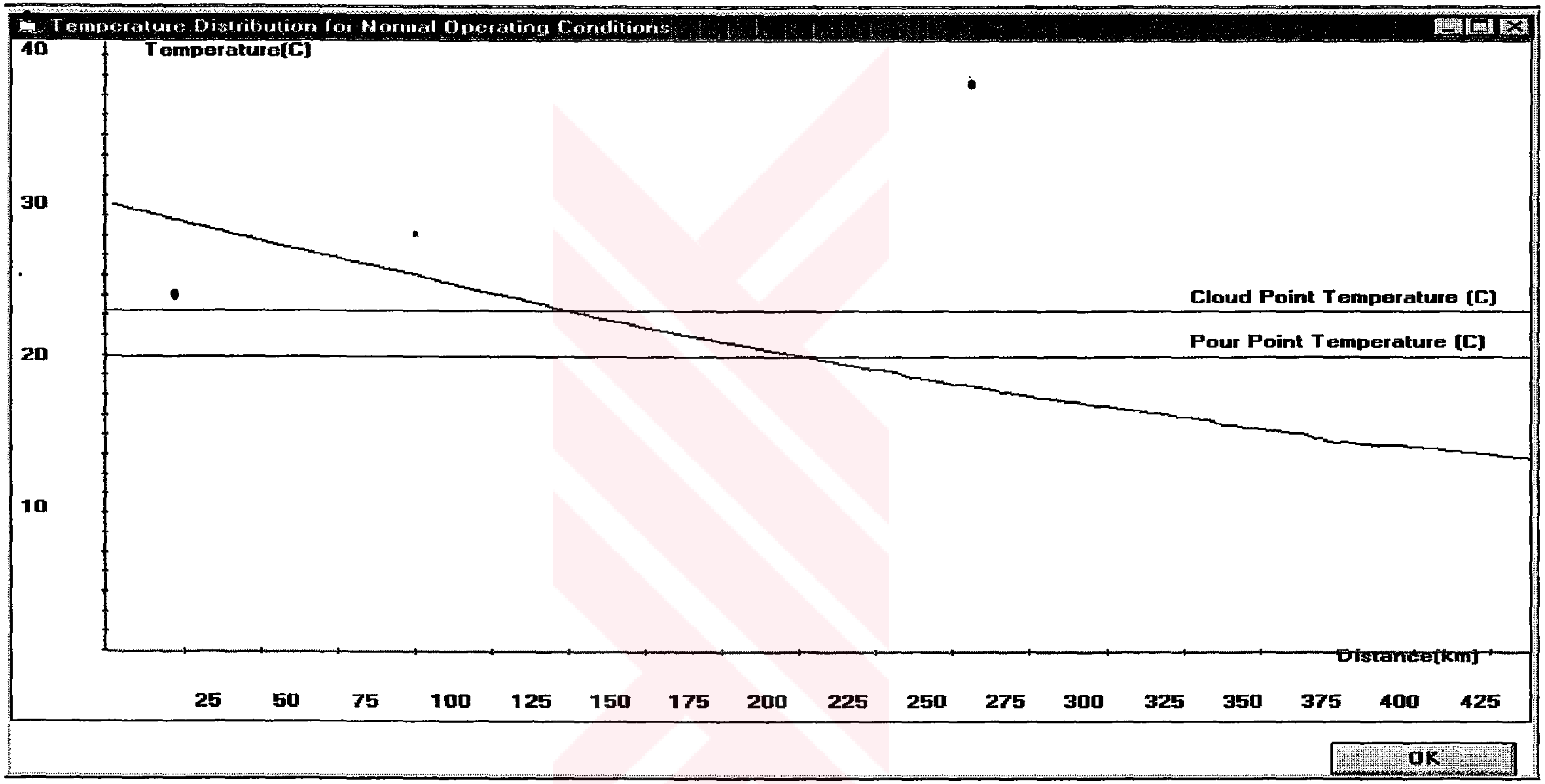
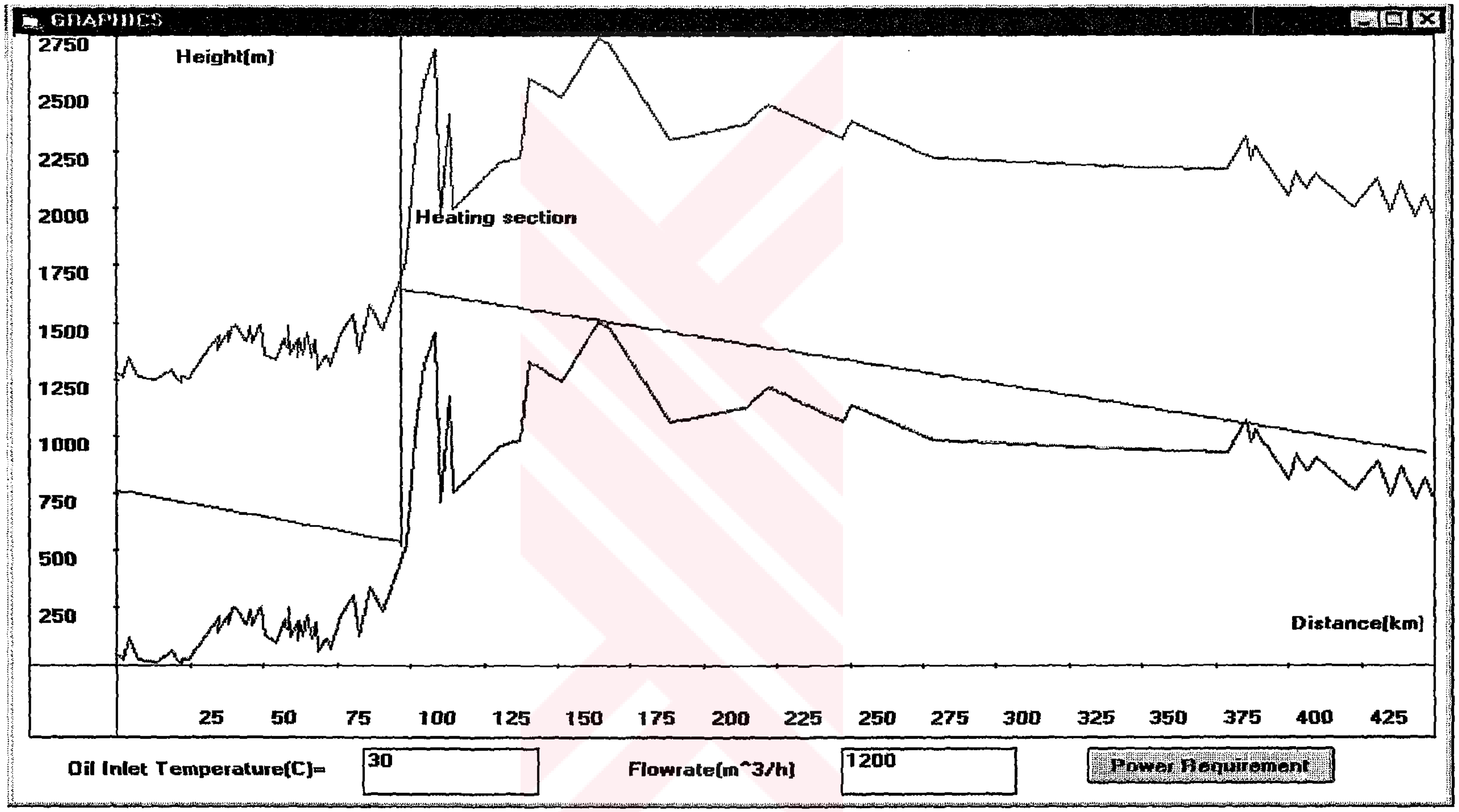


Figure 7.10 (b) Temperature Distribution of the system after an increase of Oil Inlet Temperature to 45 °C

(Re-start after 36 hour shutdown)



Oil Inlet Temperature(C)= 30

Flowrate(m^3/h) 1200

Figure7.11 Hydraulic Loading of the System with Partial Heating (Normal Operation)

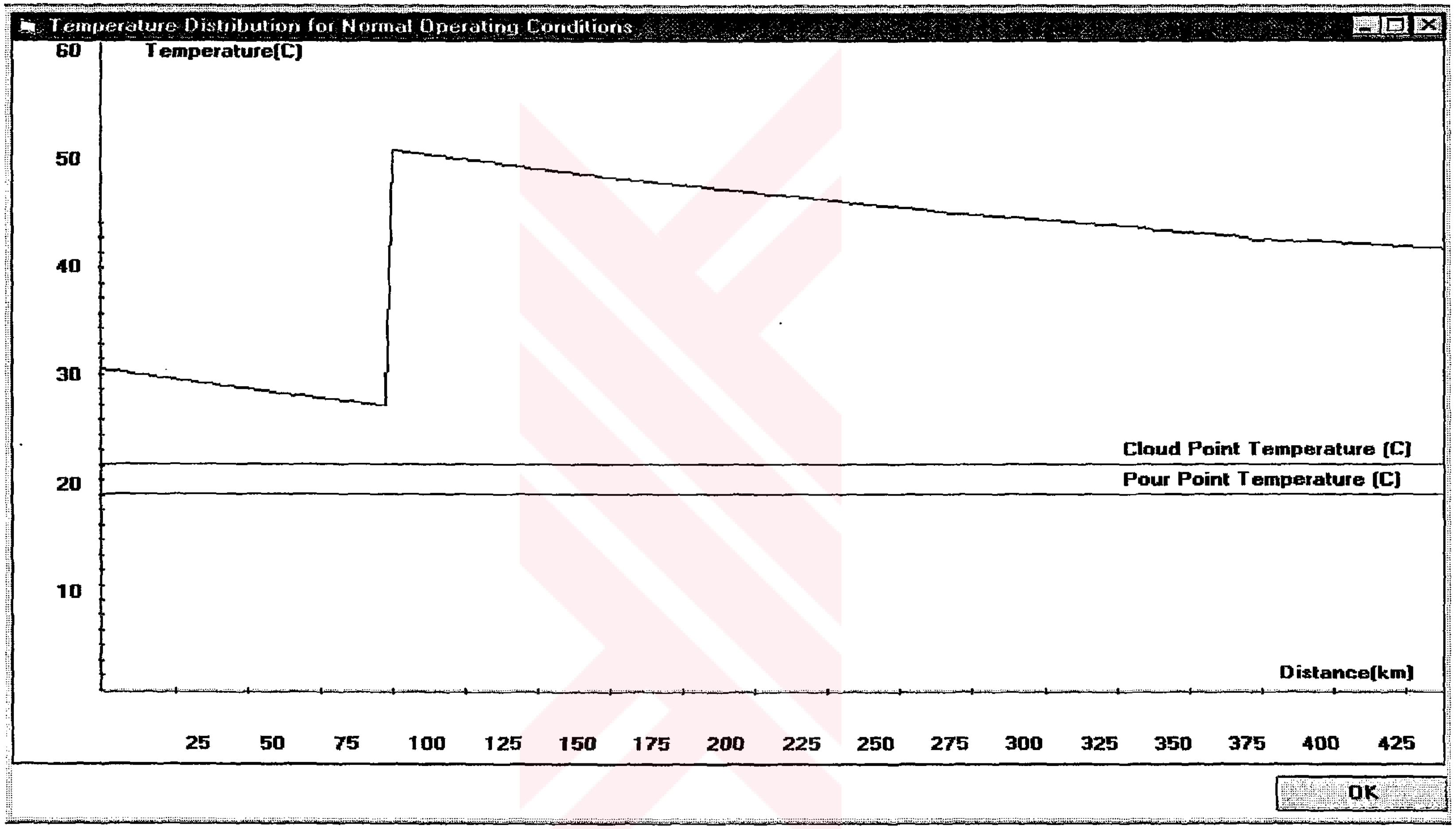


Figure 7.12(a) Temperature Distribution of the System after Partial Heating (Normal Operation)

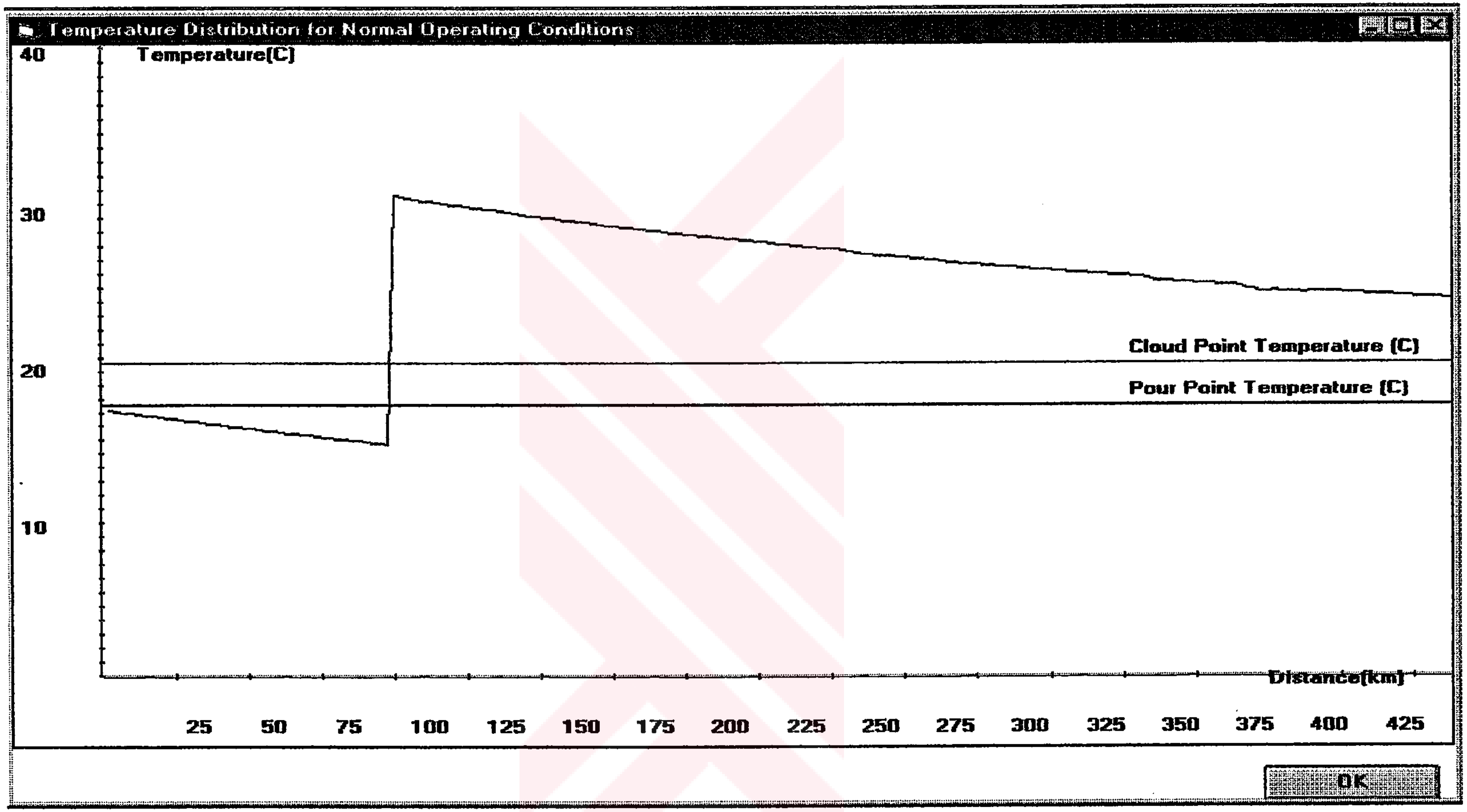
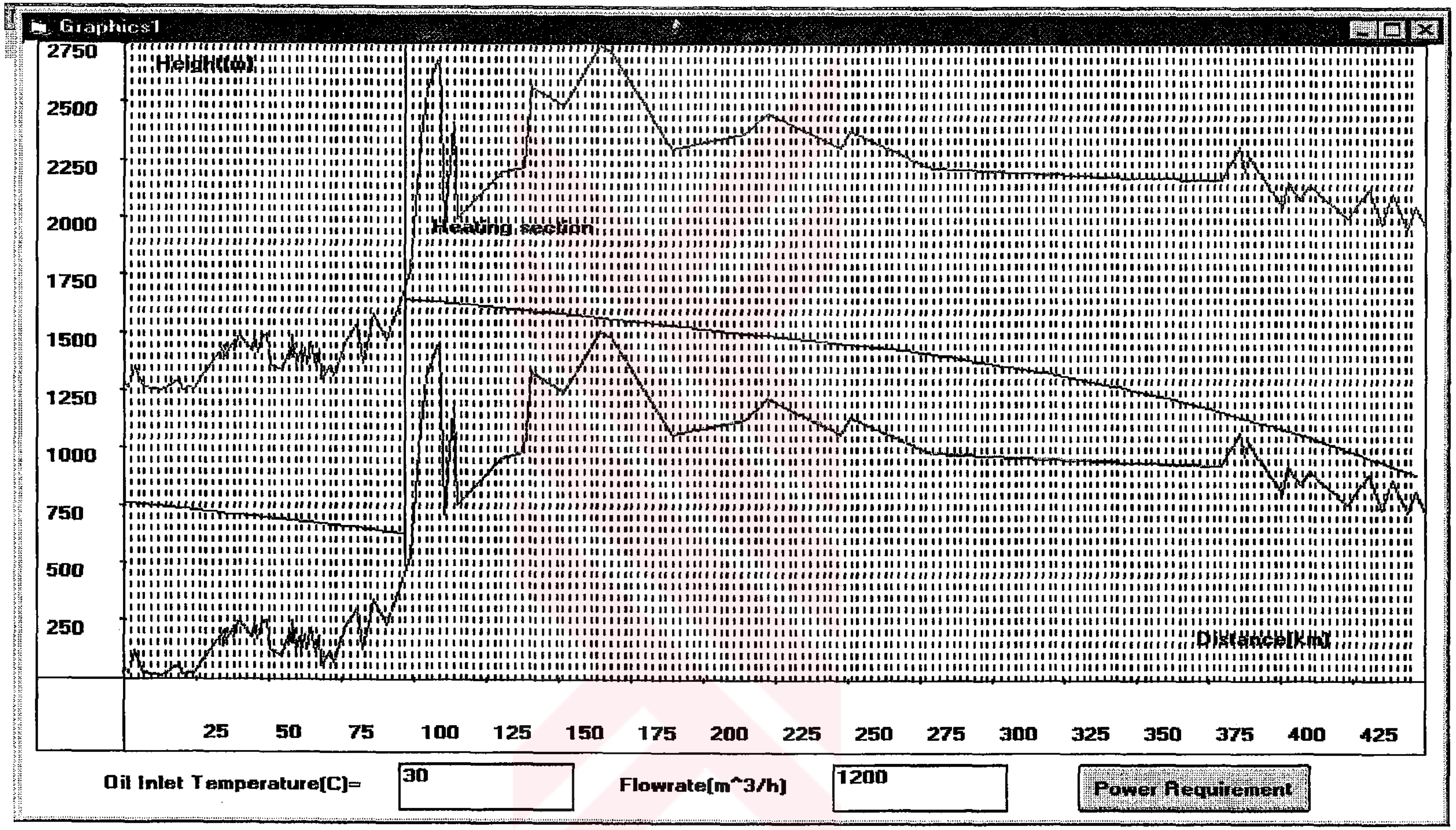


Figure 7.12(b) Temperature Distribution of the System after Partial Heating (Restart after 36 hours Shutdown)



Oil Inlet Temperature[C]= 30

Flowrate[m^3/h] 1200

Figure7.13 Hydraulic Loading of the System with Partial Heating (Re-start after 36 hours shutdown)

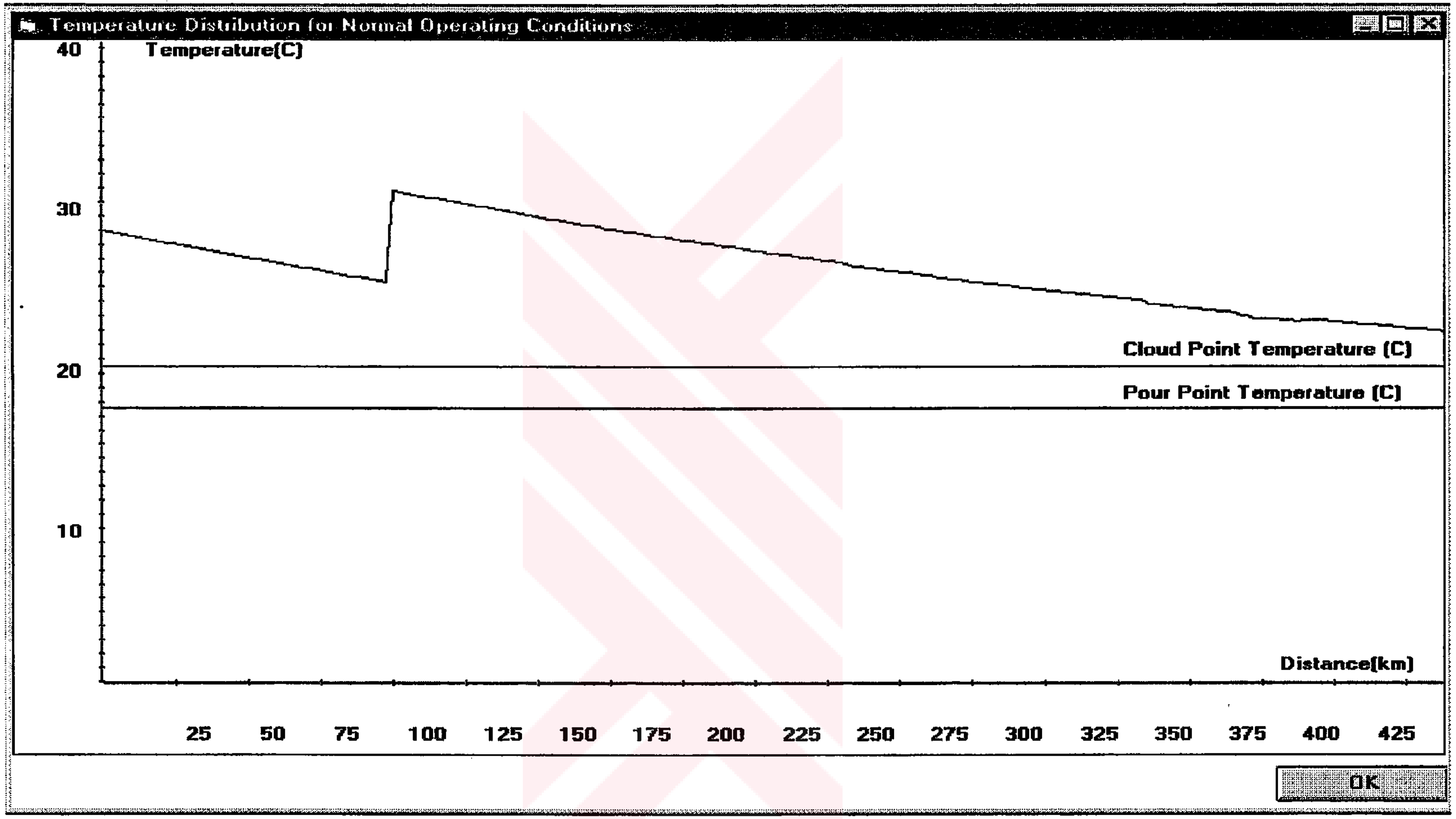


Figure 7.14(a) Temperature Distribution of the System after Partial Heating (Normal Operation)

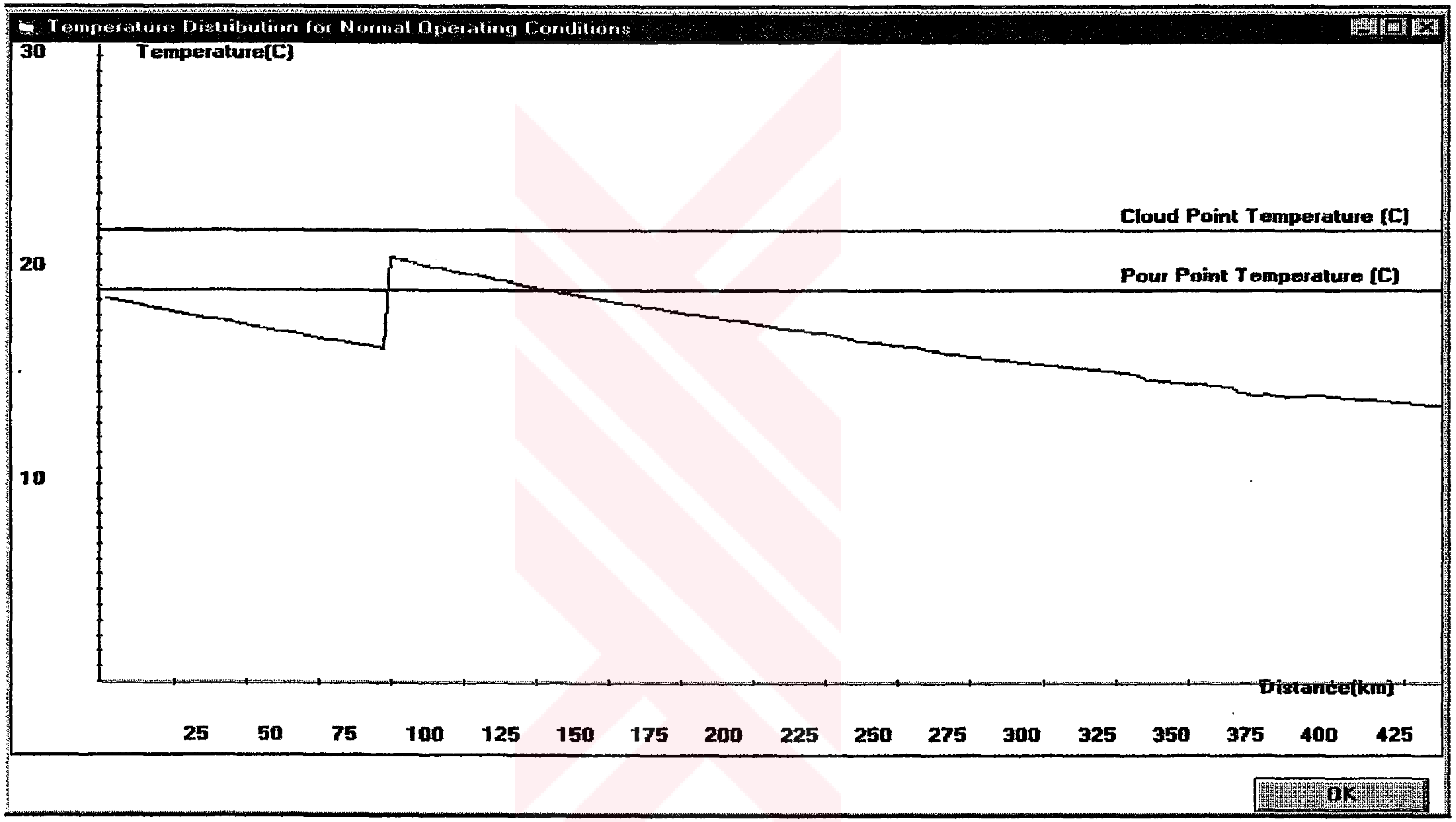
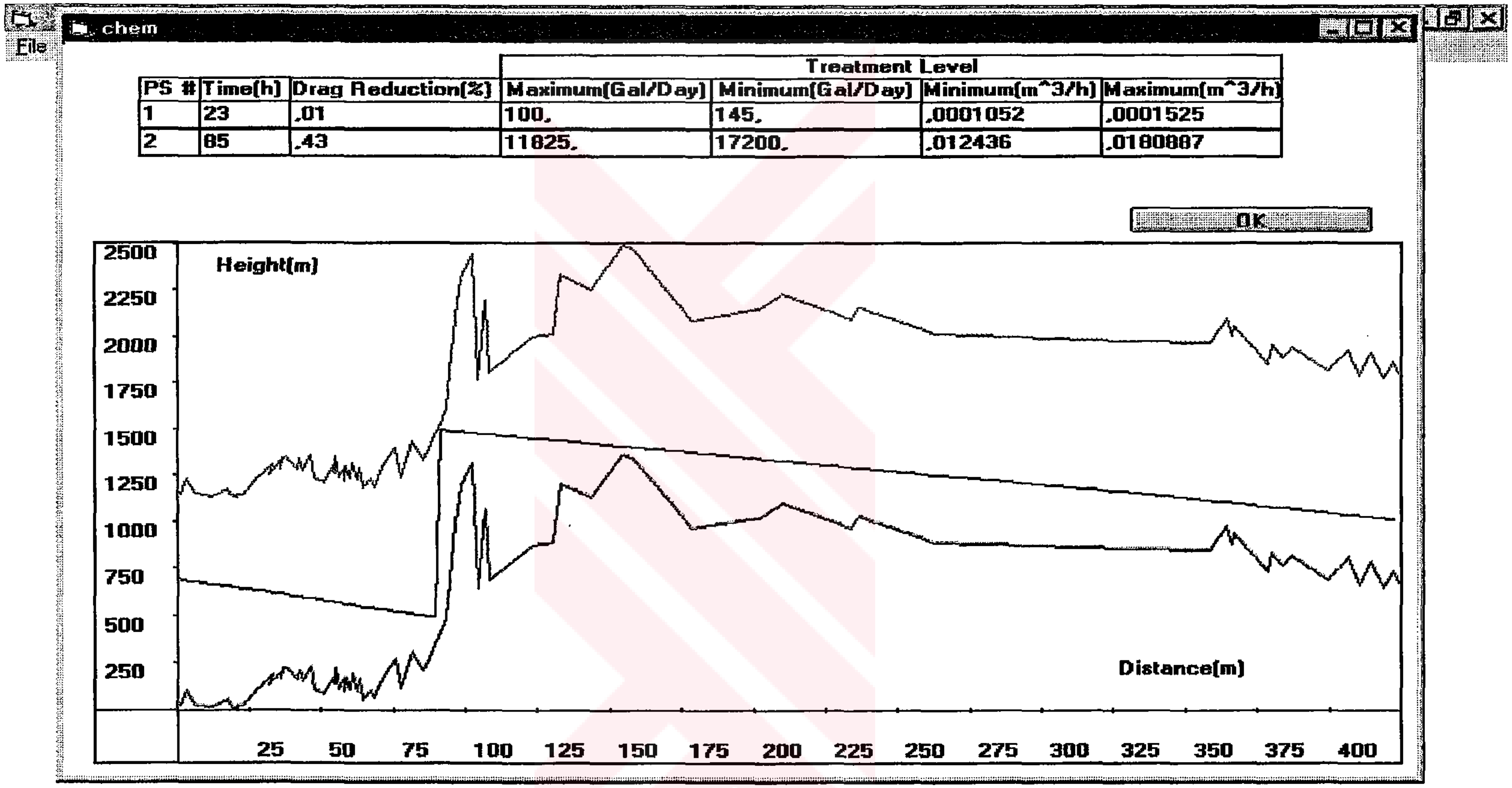
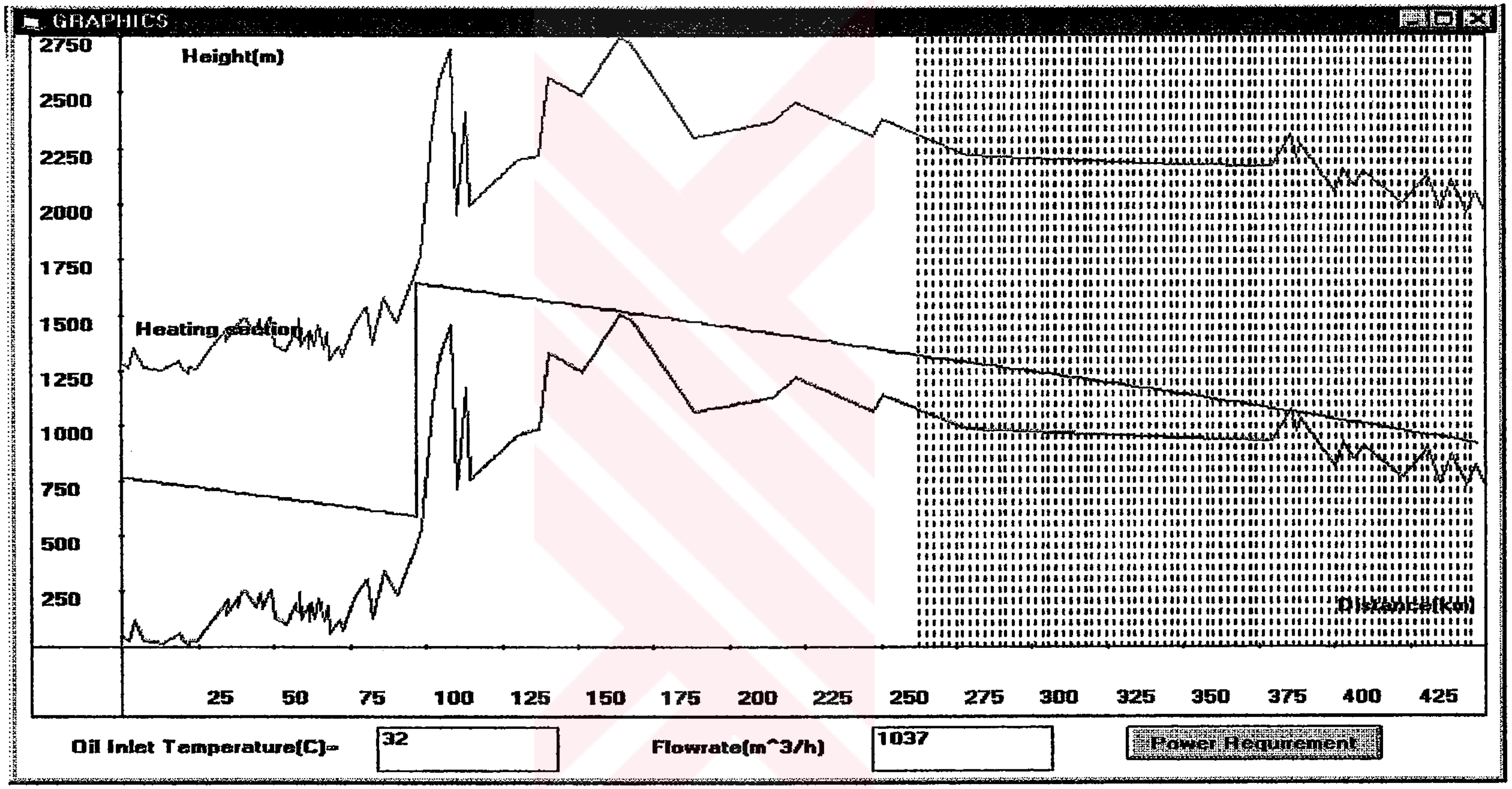


Figure 7.14(b) Temperature Distribution of the System after Partial Heating (Restart after 36 hours Shutdown)



			Treatment Level			
PS #	Time(h)	Drag Reduction(%)	Maximum(Gal/Day)	Minimum(Gal/Day)	Minimum(m^3/h)	Maximum(m^3/h)
1	23	.01	100.	145.	.0001052	.0001525
2	85	.43	11825.	17200.	.012436	.0180887

Figure7.15 Hydraulic loading of the system when chemicals are injected to the system(Normal Operation)



Oil Inlet Temperature(C)= 32

Flowrate(m^3/h) 1037

Figure 7.16 Hydraulic Loading of the System If Oil Inlet Temperature and Flowrate are Changed at the Same Time(Normal Operation)

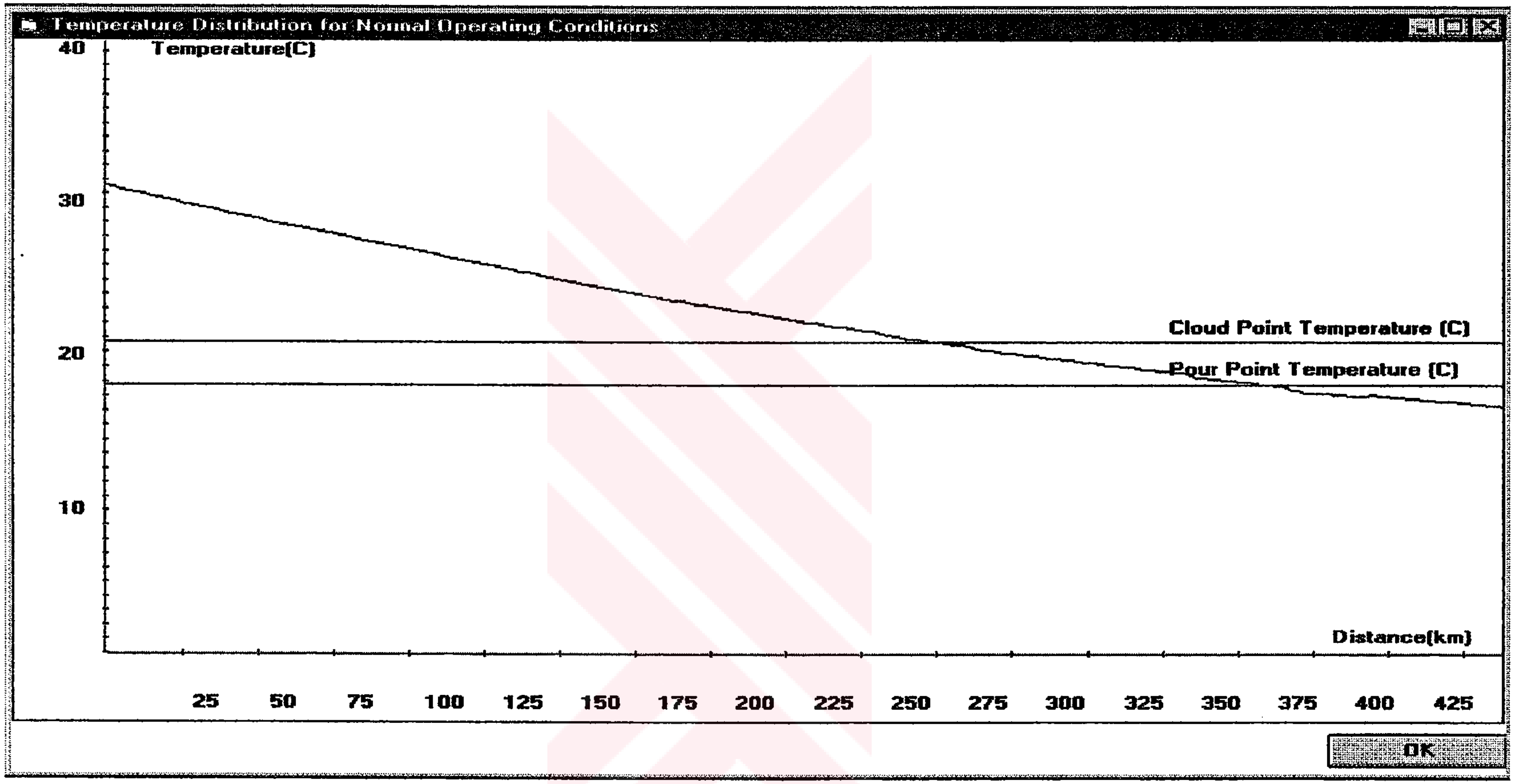


Figure 7.17(a) Temperature Distribution of the System after Combination of Flowrate Change Oil Inlet Temperature Changes

(Normal Operation)

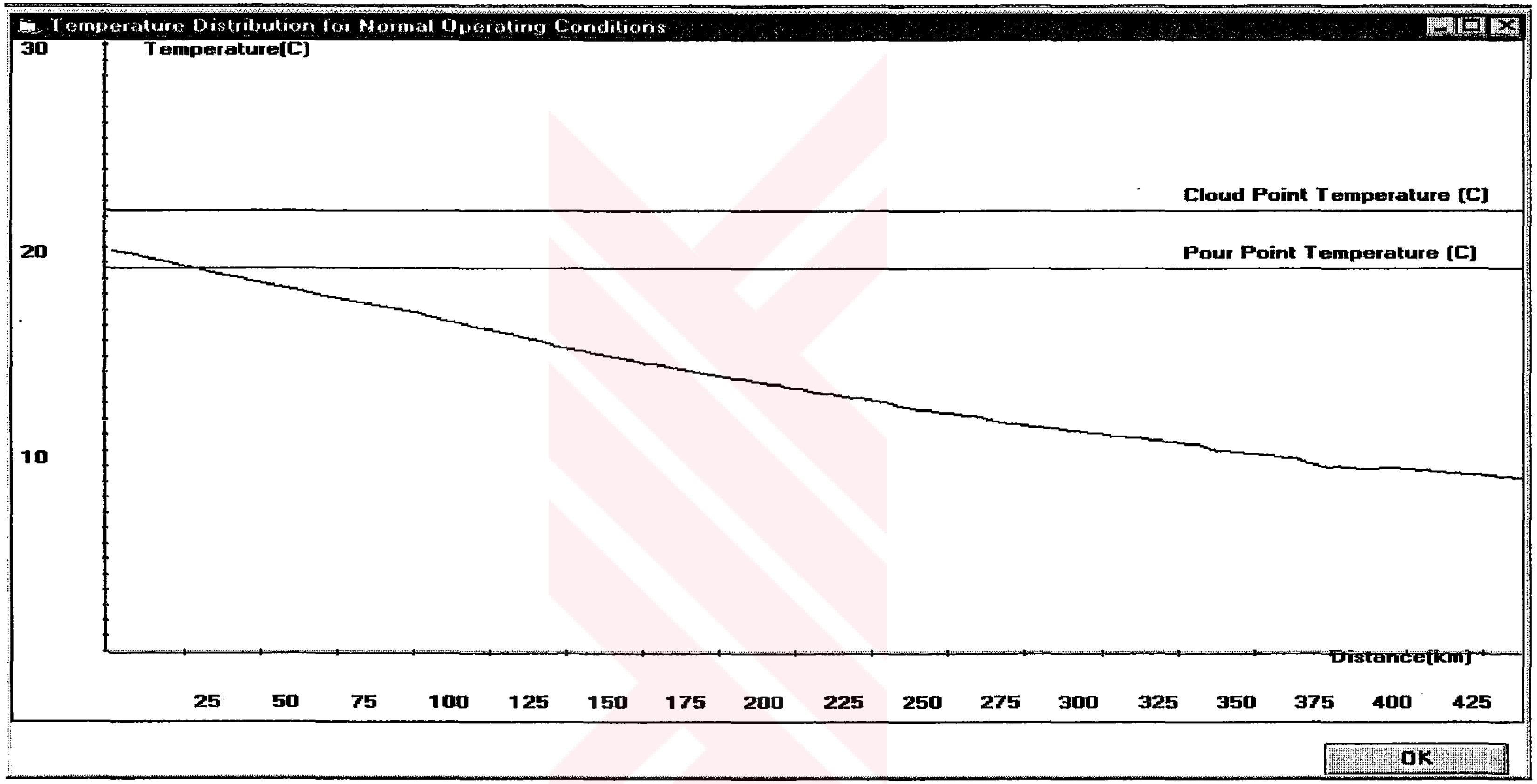
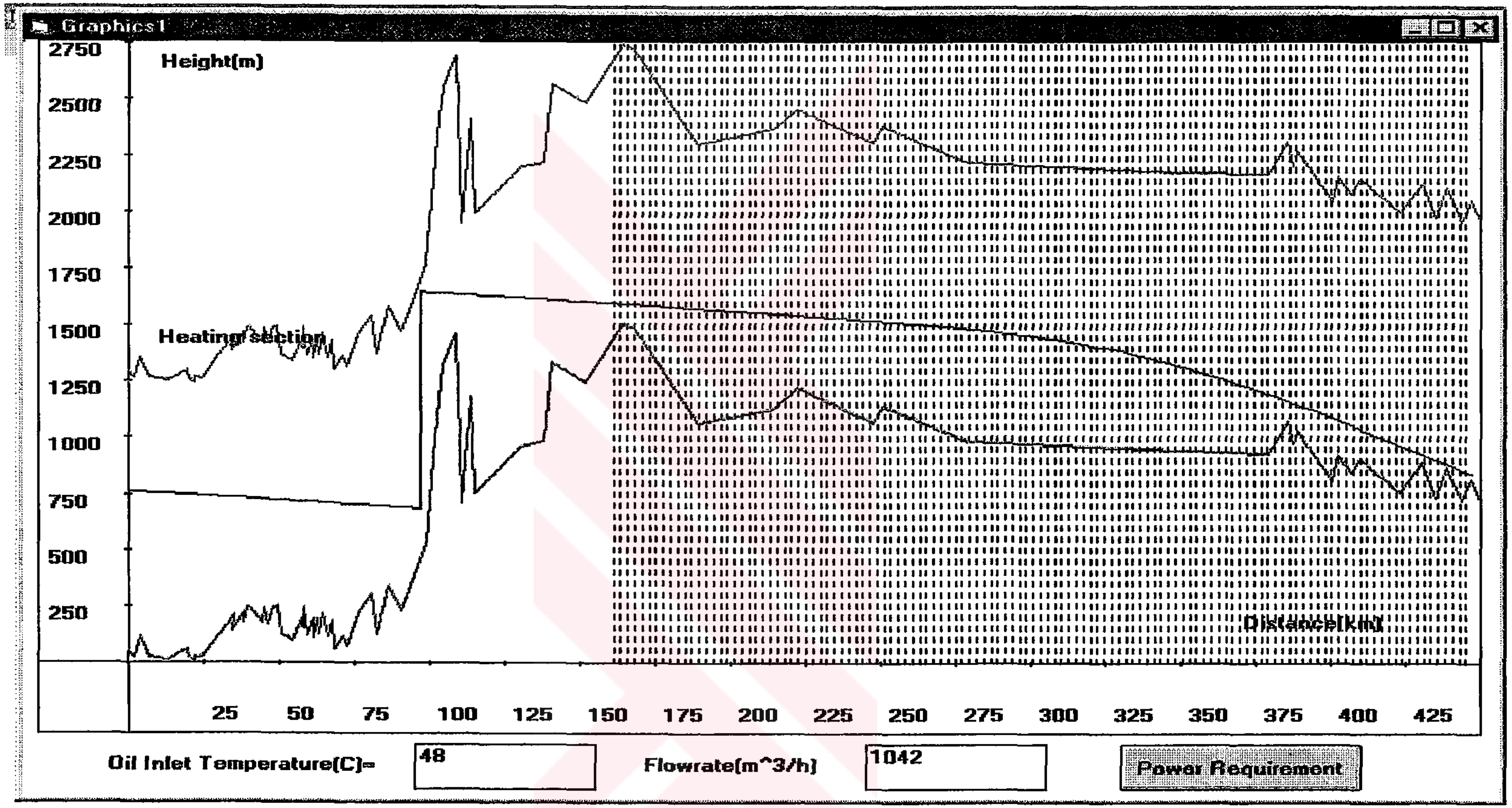


Figure 7.17(b) Temperature Distribution of the System after Combination of Flowrate Change Oil Inlet Temperature Changes

(Restart after 36 hours Shutdown)



Oil Inlet Temperature(C)= 48

Flowrate(m^3/h) 1042

Figure 7.18 Hydraulic Loading of the System If Oil Inlet Temperature and Flowrate are Changed at the same Time

(Re-start after 36 hour shutdown)

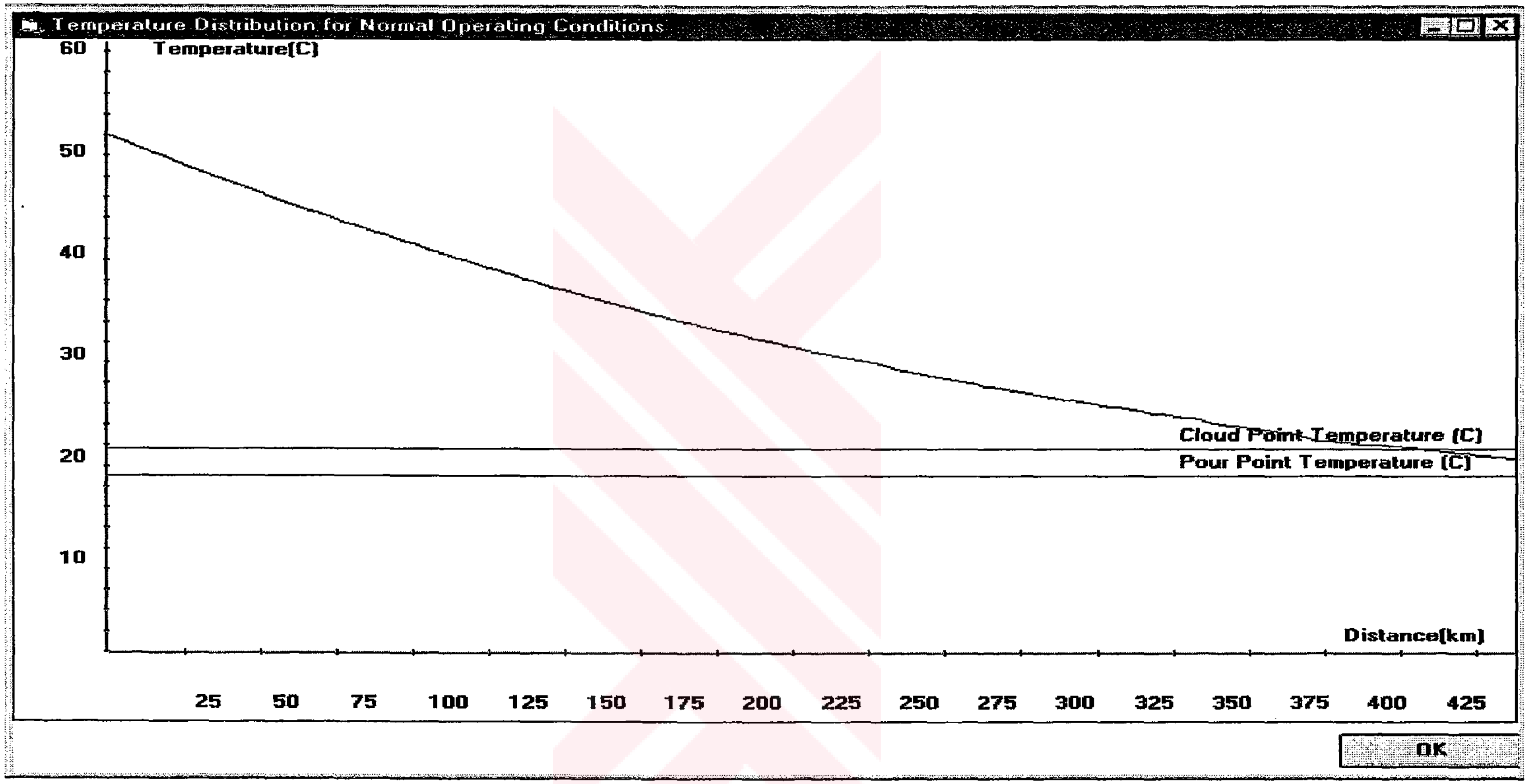


Figure 7.19(a) Temperature Distribution of the System after Combination of Flowrate Change Oil Inlet Temperature Changes

(Normal Operation)

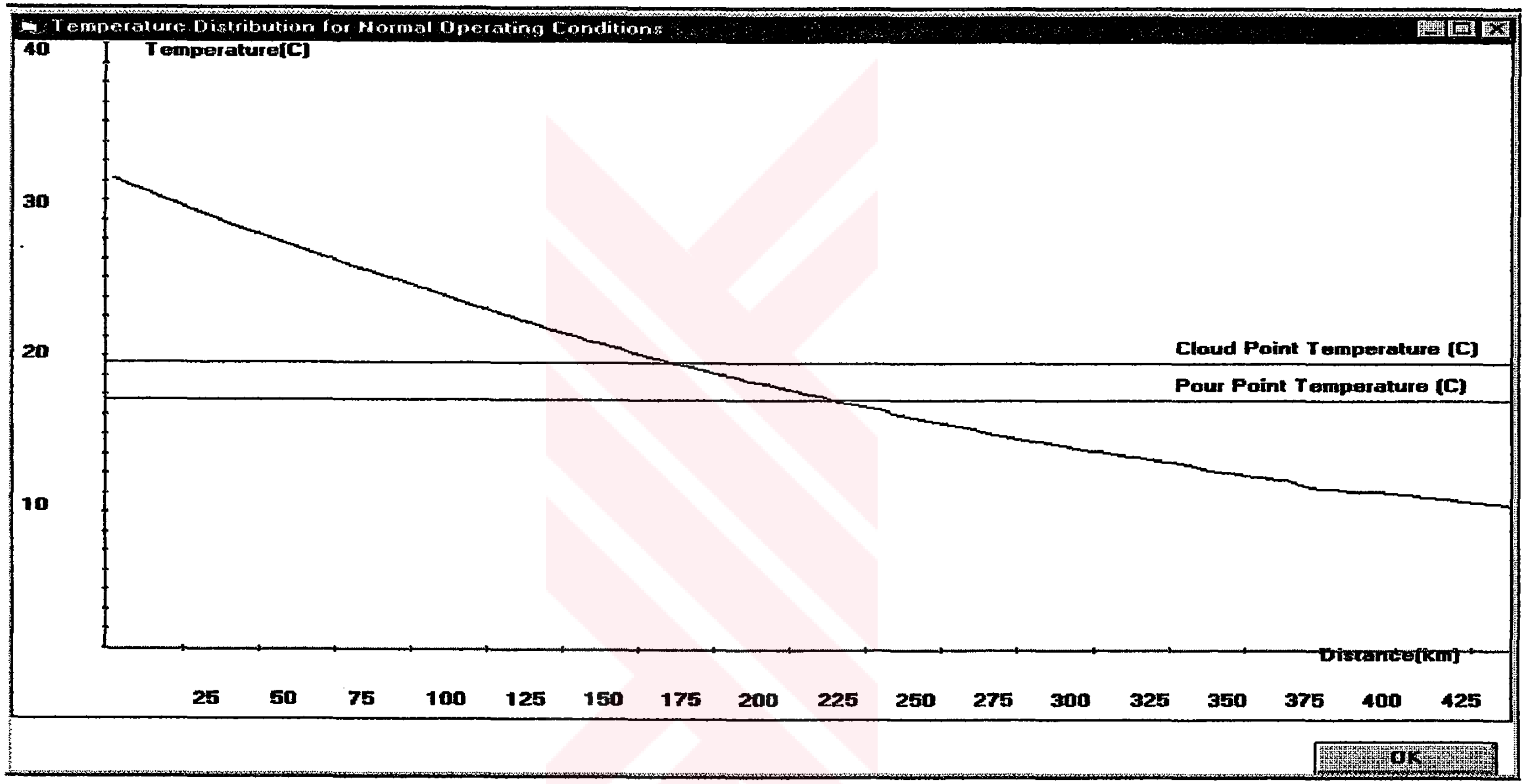
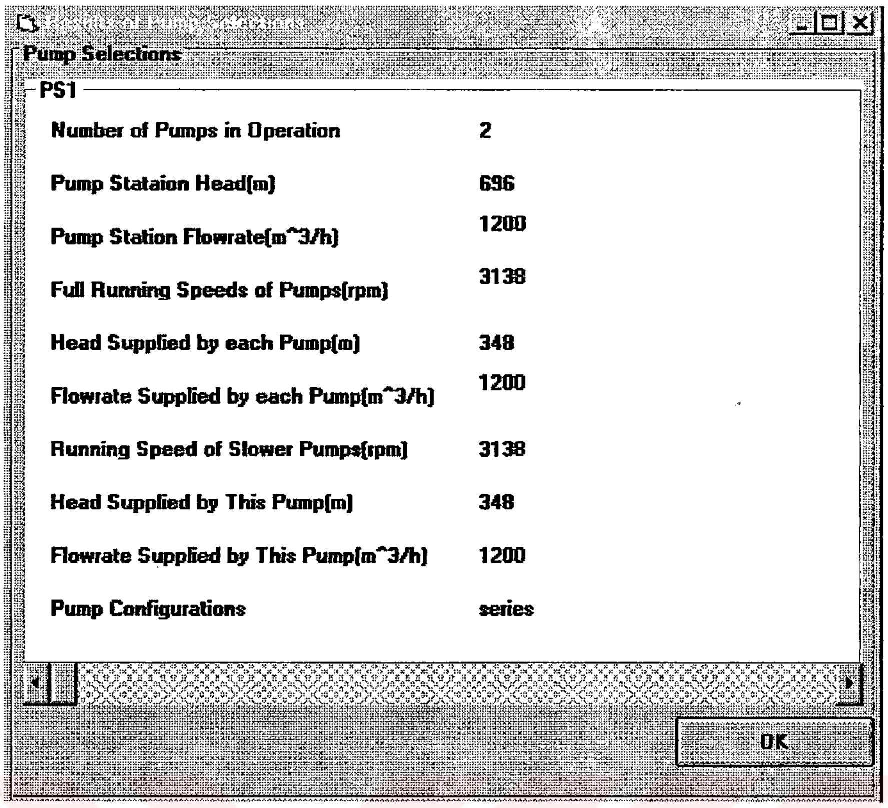


Figure 7.19(b) Temperature Distribution of the System after Combination of Flowrate Change Oil Inlet Temperature Changes

(Restart after 36 hours Shutdown)

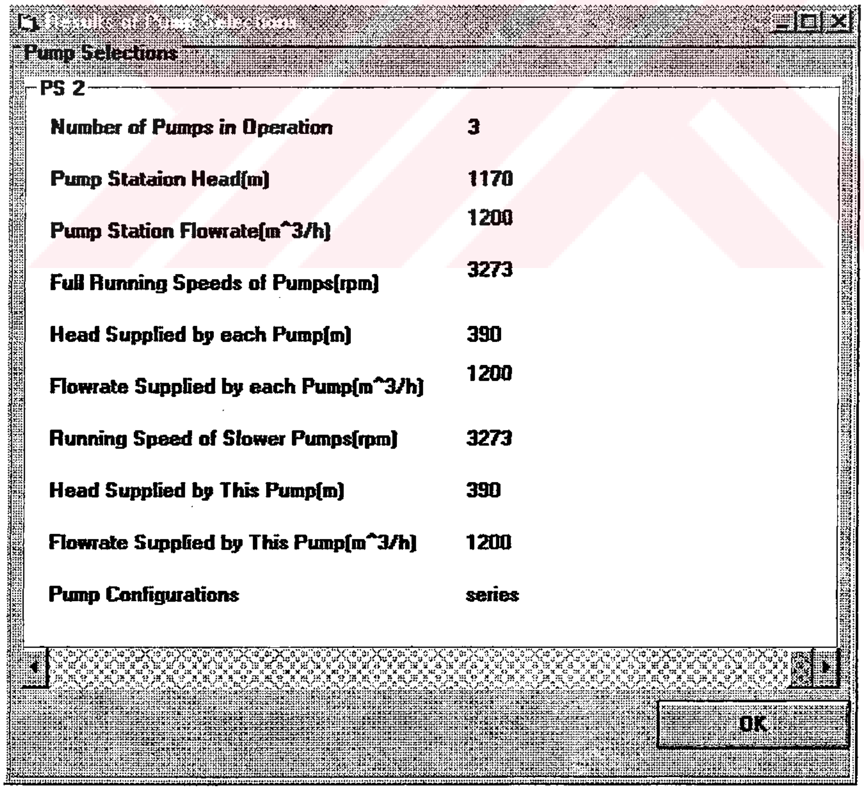


Pump Selections

PS1

Number of Pumps in Operation	2
Pump Stataion Head(m)	696
Pump Station Flowrate(m^3/h)	1200
Full Running Speeds of Pumps(rpm)	3138
Head Supplied by each Pump(m)	348
Flowrate Supplied by each Pump(m^3/h)	1200
Running Speed of Slower Pumps(rpm)	3138
Head Supplied by This Pump(m)	348
Flowrate Supplied by This Pump(m^3/h)	1200
Pump Configurations	series

Figure 7.20 (a) Results of pump selection for Newtonian Solutions

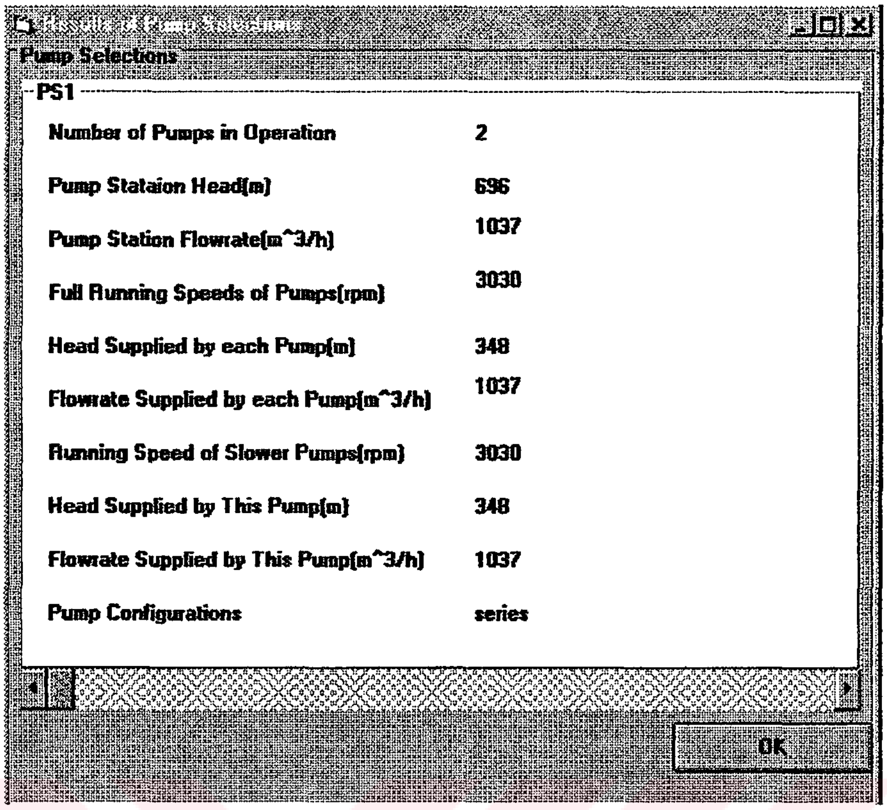


Pump Selections

PS 2

Number of Pumps in Operation	3
Pump Stataion Head(m)	1170
Pump Station Flowrate(m^3/h)	1200
Full Running Speeds of Pumps(rpm)	3273
Head Supplied by each Pump(m)	390
Flowrate Supplied by each Pump(m^3/h)	1200
Running Speed of Slower Pumps(rpm)	3273
Head Supplied by This Pump(m)	390
Flowrate Supplied by This Pump(m^3/h)	1200
Pump Configurations	series

Figure 7.20 (b) Results of pump selection for Newtonian Solutions



Number of Pumps in Operation 2

Pump Stataion Head(m) 696

Pump Station Flowrate(m^3/h) 1037

Full Running Speeds of Pumps(rpm) 3030

Head Supplied by each Pump(m) 348

Flowrate Supplied by each Pump(m^3/h) 1037

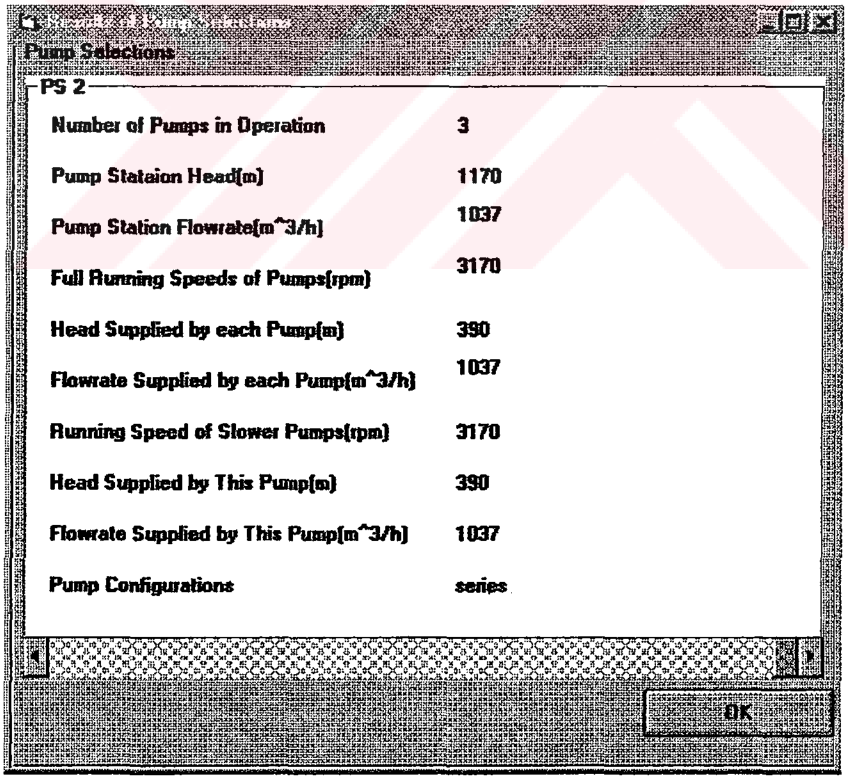
Running Speed of Slower Pumps(rpm) 3030

Head Supplied by This Pump(m) 348

Flowrate Supplied by This Pump(m^3/h) 1037

Pump Configurations series

Figure 7.21 (a) Results of pump selection for Non-Newtonian Solutions



Number of Pumps in Operation 3

Pump Stataion Head(m) 1170

Pump Station Flowrate(m^3/h) 1037

Full Running Speeds of Pumps(rpm) 3170

Head Supplied by each Pump(m) 390

Flowrate Supplied by each Pump(m^3/h) 1037

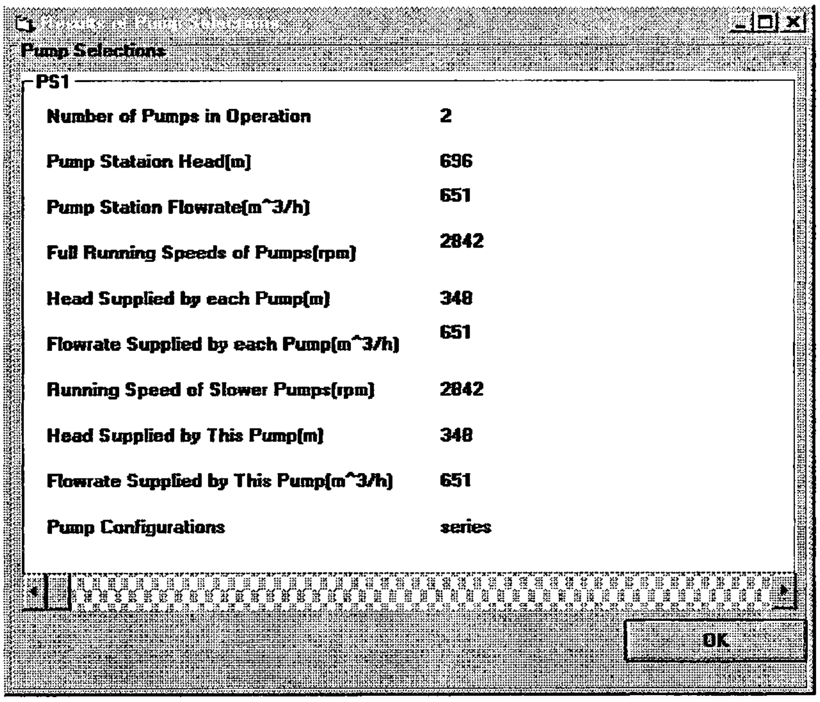
Running Speed of Slower Pumps(rpm) 3170

Head Supplied by This Pump(m) 390

Flowrate Supplied by This Pump(m^3/h) 1037

Pump Configurations series

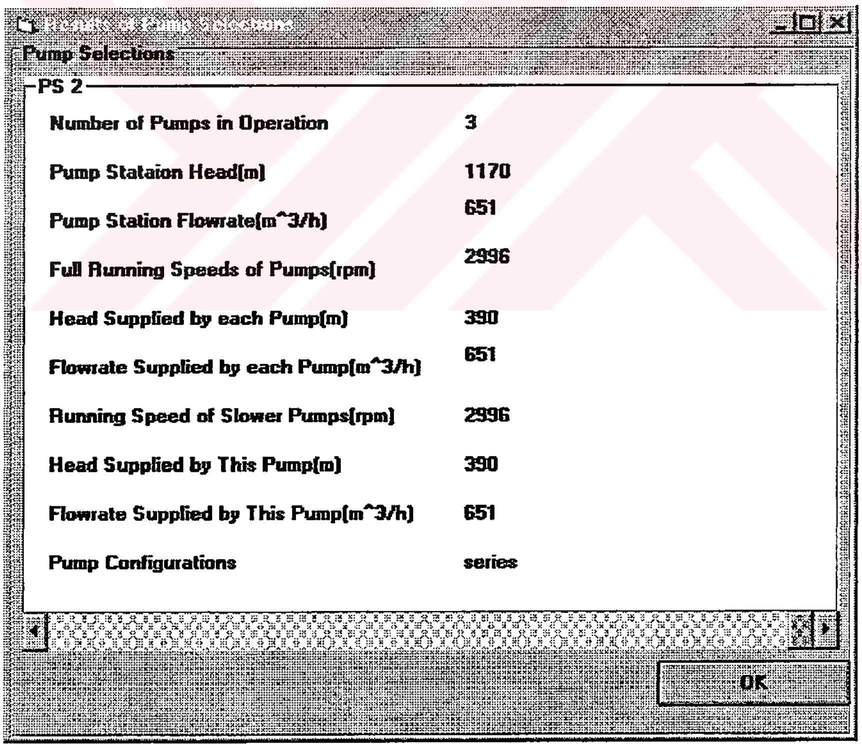
Figure 7.21 (b) Results of pump selection for Non-Newtonian Solutions



PS1

Number of Pumps in Operation	2
Pump Stataion Head[m]	696
Pump Station Flowrate[m^3/h]	651
Full Running Speeds of Pumps[rpm]	2842
Head Supplied by each Pump[m]	348
Flowrate Supplied by each Pump[m^3/h]	651
Running Speed of Slower Pumps[rpm]	2842
Head Supplied by This Pump[m]	348
Flowrate Supplied by This Pump[m^3/h]	651
Pump Configurations	series

Figure 7.22 (a) Results of pump selection for Non-Newtonian Solutions (Re-start Operation)



PS 2

Number of Pumps in Operation	3
Pump Stataion Head[m]	1170
Pump Station Flowrate[m^3/h]	651
Full Running Speeds of Pumps[rpm]	2996
Head Supplied by each Pump[m]	390
Flowrate Supplied by each Pump[m^3/h]	651
Running Speed of Slower Pumps[rpm]	2996
Head Supplied by This Pump[m]	390
Flowrate Supplied by This Pump[m^3/h]	651
Pump Configurations	series

Figure 7.22 (b) Results of pump selection for Non-Newtonian Solutions (Re-start Operation)

7.3 Case II (Batman-Dörtyol Pipeline System)

7.3.1 Batman-Dörtyol Pipeline System

The existing Batman Dörtyol pipeline system was constructed and began operation in 1967. It has three pumping stations: Batman, Diyarbakır and Saril pumping stations.

The diameter of a pipe is 18 inches with a wall thickness of 0.281 inches (7.14 mm). The pipe material is made of API-5L Grade X 46. The existing pipeline length has been extended by approximately 16 km for the Atatürk Dam between the Diyarbakır and Saril Station and approximately 1.5 km for the Bahçe rerouting between Saril and Dörtyol.The length of the pipeline is 511 km. The pipeline ends at the Dörtyol Marine Terminal, which has a tank farm loading facilities.

At each pumping station three centrifugal pumps driven by electric motors (two operating in series, one as stand by). After implementation of the expansion Step I, the maximum inherent system capacity theoretically consists of approximately 76000 b/d.

Although the system has been designed for a single crude and a fixed flowrate through the pipeline, the number of crudes have been increased in the course of time and now five different types of crude has been transported in two batches. since 1984.

Batman-Dörtyol is a typical example of multi-injection point batch operation but it is modified as a simple slurry pipeline to test the program. It is assumed that single crude and a fixed flowrate through the pipeline exist. The characteristics of the design crude oil used in this case are as follows:

Viscosity: 85 cst

Density: 845 kg/m^3

Pipe Roughness: 0.00043 m

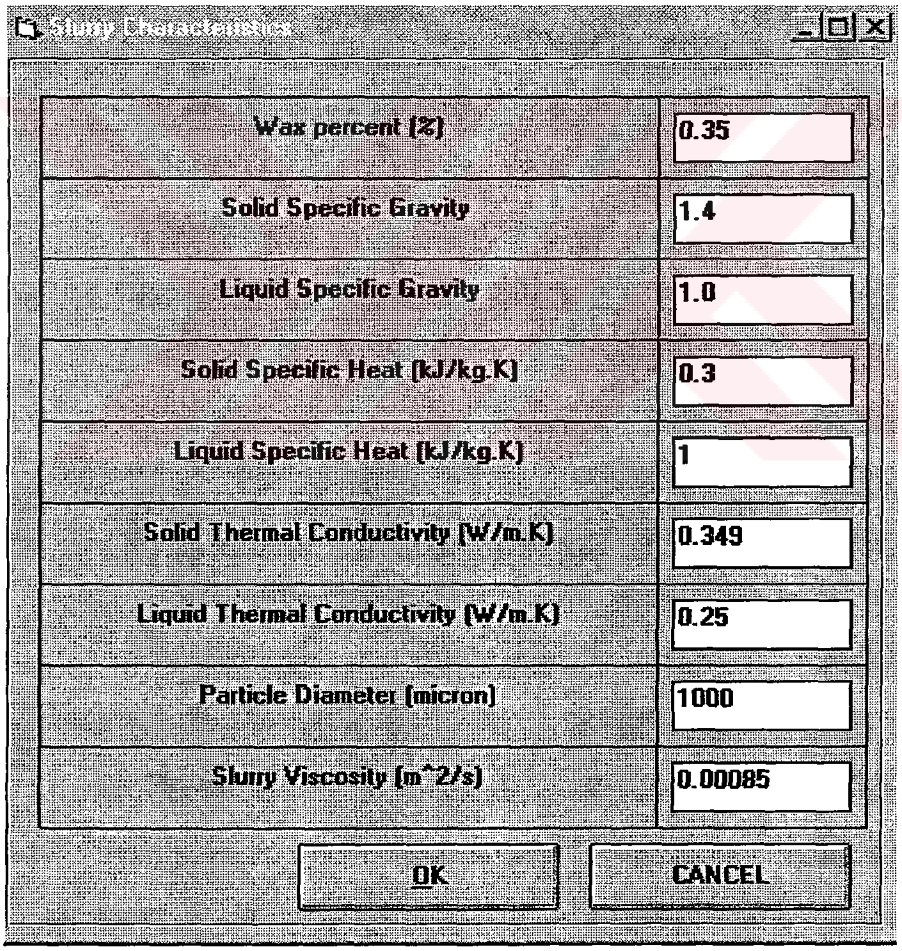
Design Capacity: 76.000 bbl/day

Vapor pressure: 0.2 bar

Pipeline Availability: 90 %

The characteristics of the slurry considered in the analysis can be described as follows:

Table 7.5 Characteristics of Slurry



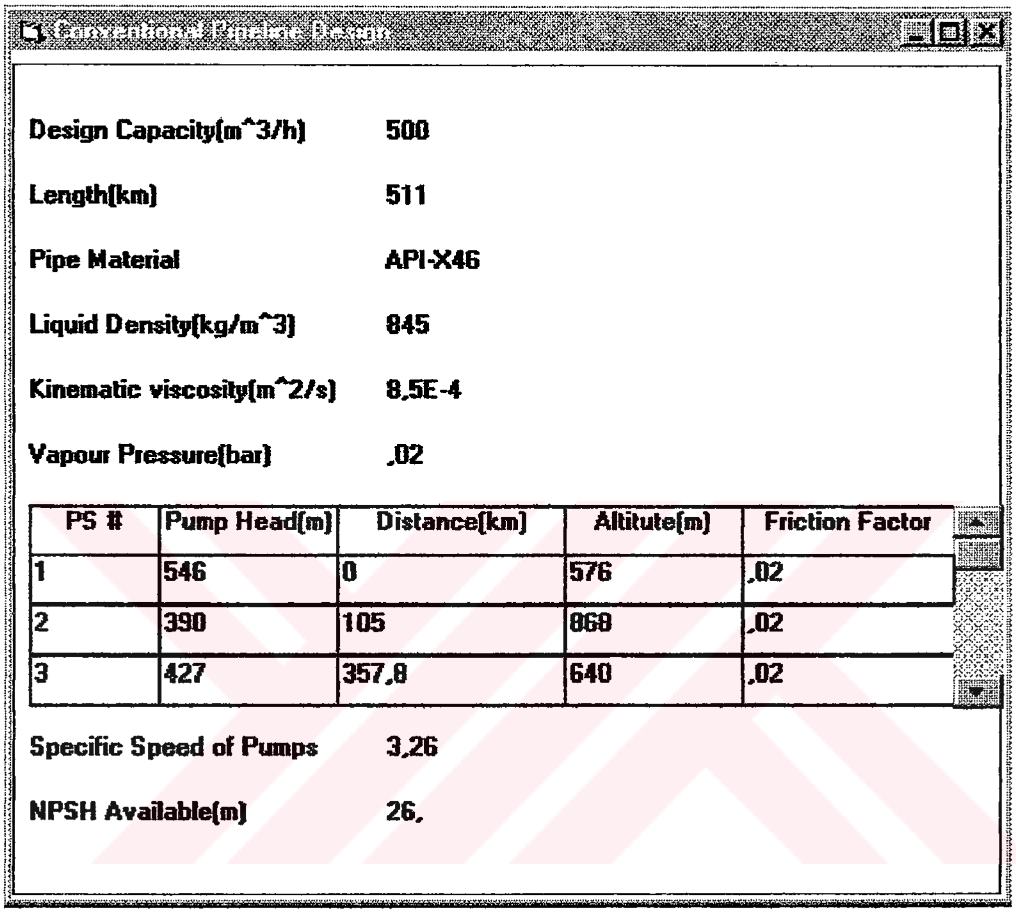
Wax percent [%]	0.35
Solid Specific Gravity	1.4
Liquid Specific Gravity	1.0
Solid Specific Heat [kJ/kg.K]	0.3
Liquid Specific Heat [kJ/kg.K]	1
Solid Thermal Conductivity [W/m.K]	0.349
Liquid Thermal Conductivity [W/m.K]	0.25
Particle Diameter [micron]	1000
Slurry Viscosity [m^2/s]	0.00085

7.3.2 Newtonian and Non-Newtonian Solutions of Batman-Dörtyol Pipeline

The oil inlet temperature as considered in design is approximately 30 °C and also soil temperature is assumed to be 10 °C along the line. The rheological properties of the crude's used in Case I is also applicable to this system. Similar to this, the solutions of the line are as follows:

Figure 7.23 is the hydraulic loading of the Batman-Dörtyol pipeline for Newtonian solution. Figure 7.24 and 7.25 is the temperature distributions of the system at normal operation and at restart after 36 h shutdown condition. If the method described in this thesis is applied to the hydraulic calculations, the hydraulic loading of the system for normal operation condition in Figure 7.26 and restart operation in Figure 7.27 are obtained. At each conditions, the flow is blocked with the application of high pour point crude oil. In contrast to previous case study, the restart condition is much more critical than normal operation. All the methods except for partial heating at pump stations or anywhere didn't find any solutions to the system. Figure 7.28 is the solutions of system for normal operation by increasing pump head but it is not possible to satisfy such a flow in the line by changing the amount of pump head at restart case. If the oil is heated at the beginning of the pipeline, not at 1st pumping station, to 40 °C, it is enough to obtain flow in the line for normal operation(Figure 7.29 for hydraulic loading, Figure 7.30(a) temperature distribution for normal operation, Figure 7.30(b) the effect of temperature increase at normal operation to restart case). Figure 7.31 is the result of hydraulic loading only if the restart condition is considered individually. The heating temperature of oil is approximately 50 °C (Figure 7.32(a)). The effects of this temperature increase on restart condition is shown in Figure 7.32(b). All the dotted area on hydraulic loading profile represents the non-Newtonian flow behaviour at that locations.

Table 7.6 Newtonian Solution of Batman-Dörtyol Pipeline System obtained from the program



Design Capacity(m^3/h) 500

Length(km) 511

Pipe Material API-X46

Liquid Density(kg/m^3) 845

Kinematic viscosity(m^2/s) 8,5E-4

Vapour Pressure(bar) ,02

PS #	Pump Head(m)	Distance(km)	Altitute(m)	Friction Factor
1	546	0	576	,02
2	390	105	868	,02
3	427	357,8	640	,02

Specific Speed of Pumps 3,26

NPSH Available(m) 26,

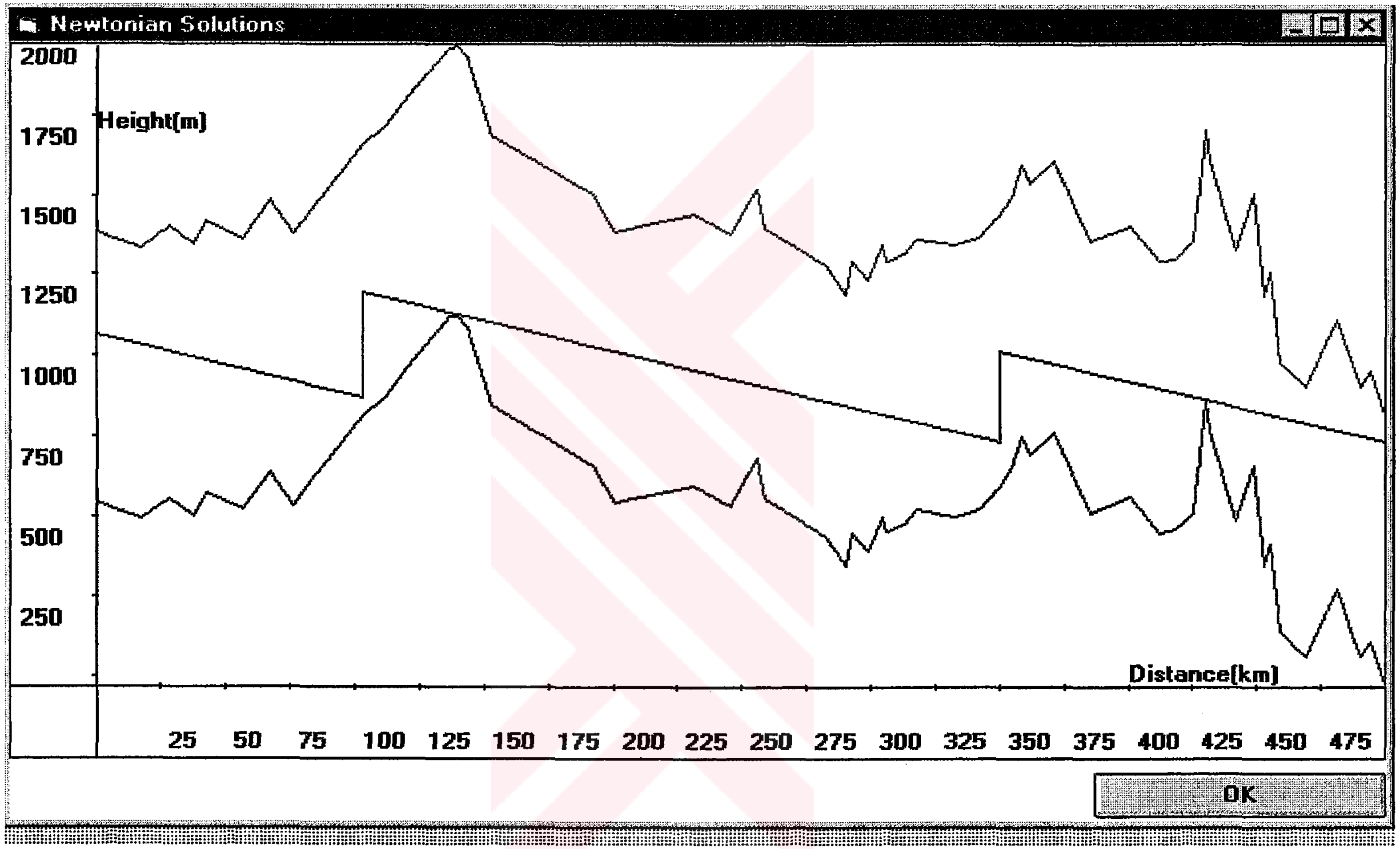


Figure 7.23 Hydraulic Loading of Batman-Dörtyol Pipeline System for Conventional Solution

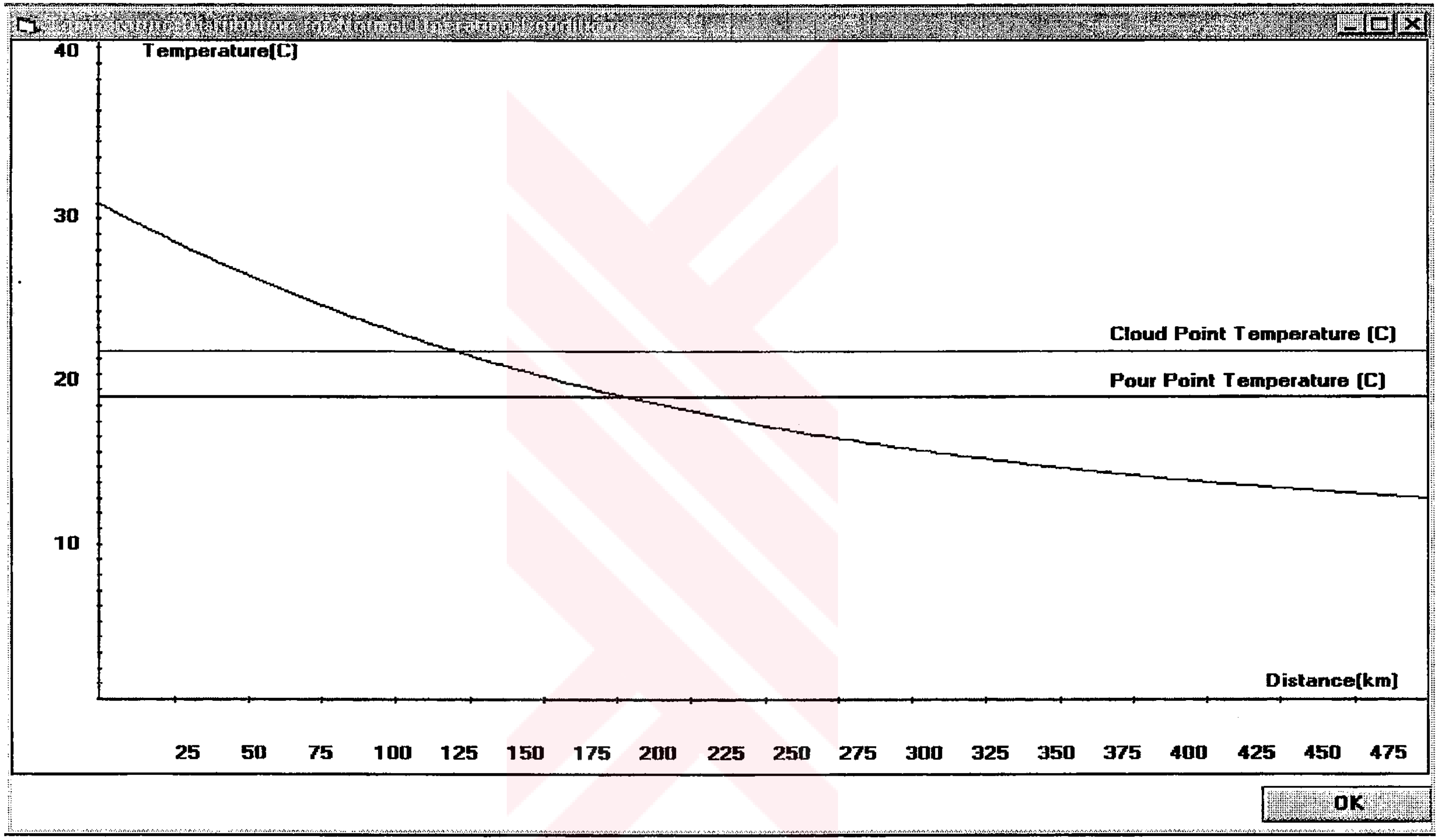


Figure 7.24 Temperature Distribution along the Line for Normal Operating Condition

T.C. YÜKSEKÖĞRETİM KURULU
DOKÜMANTASYON MERKEZİ

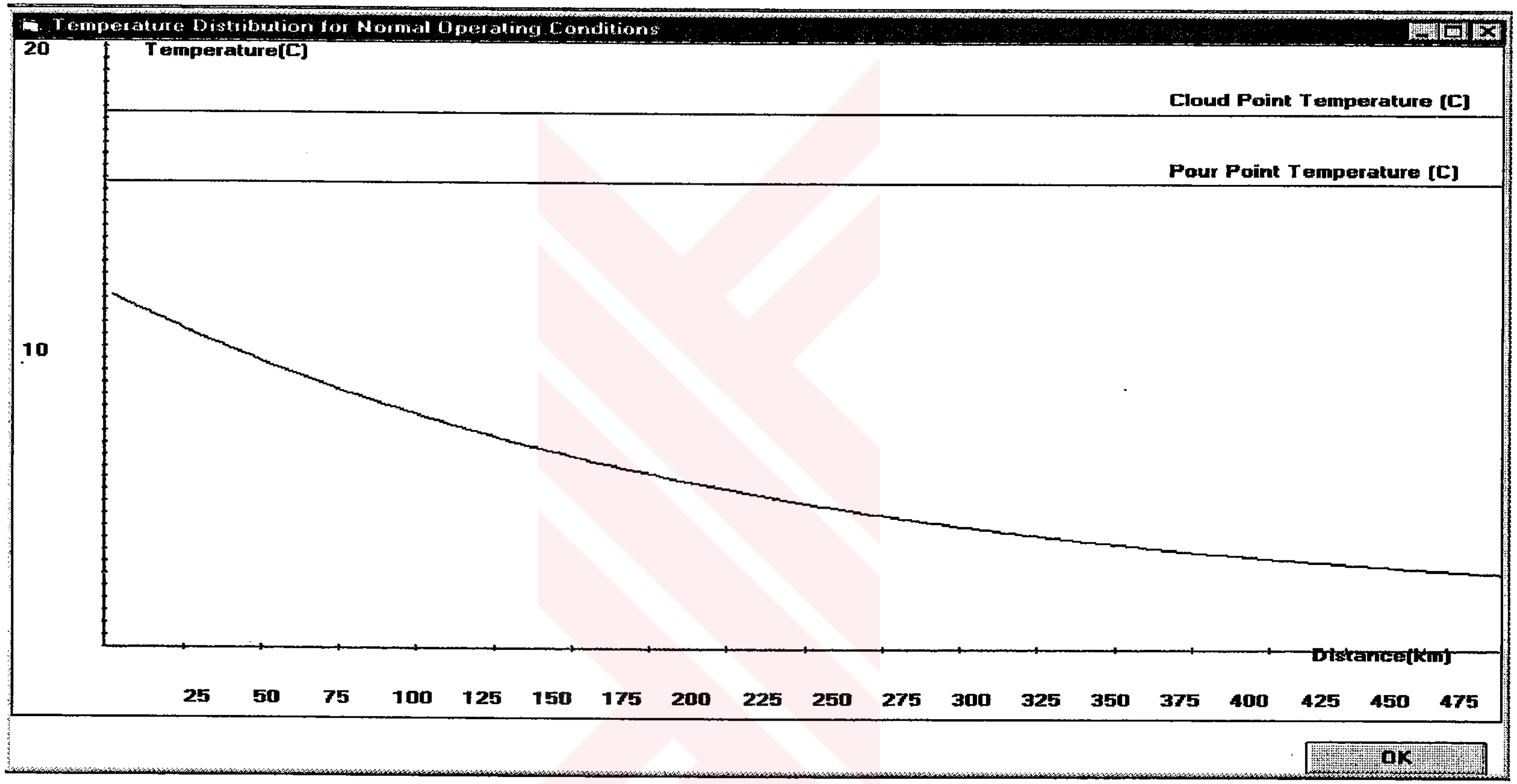
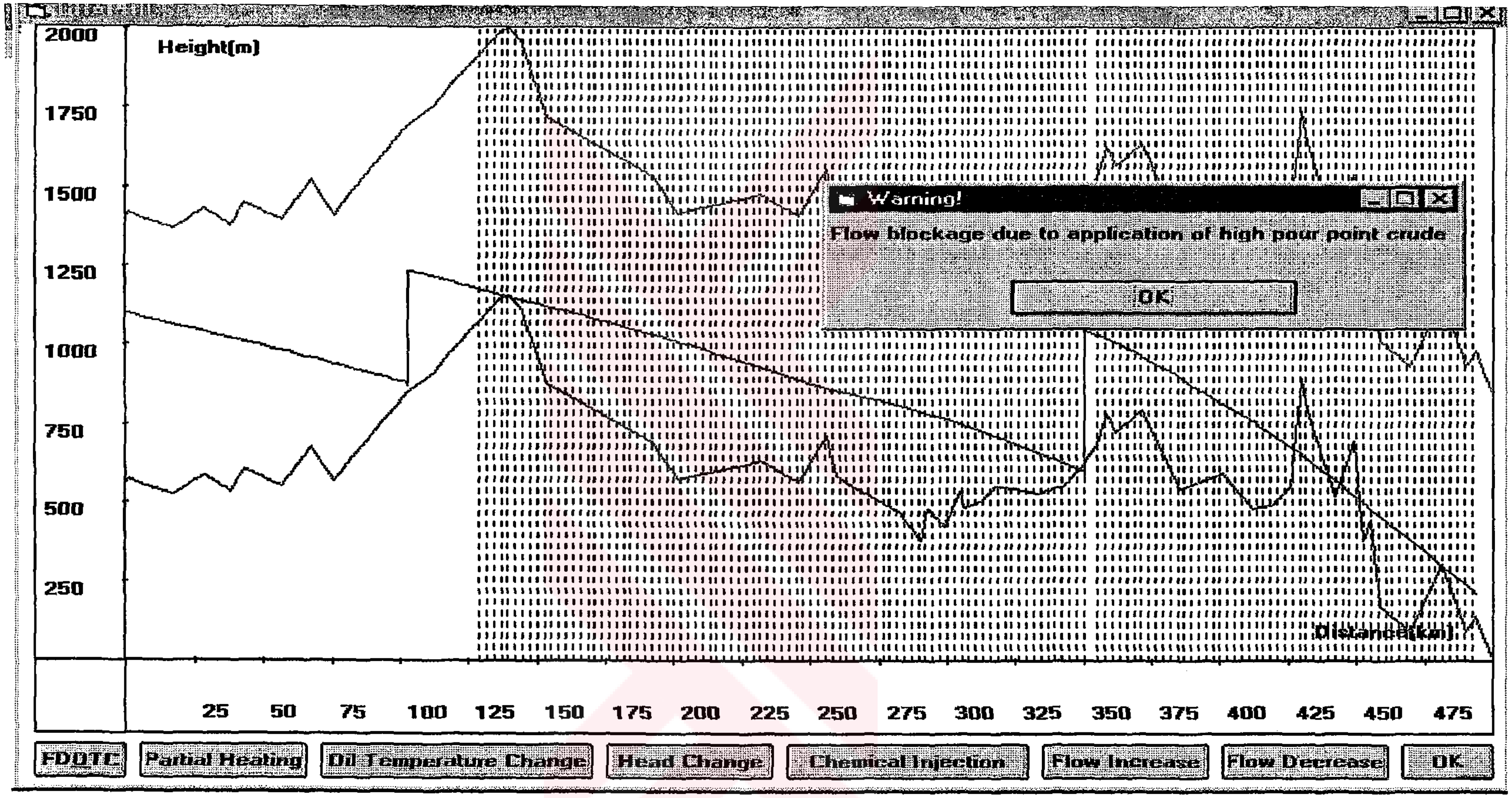


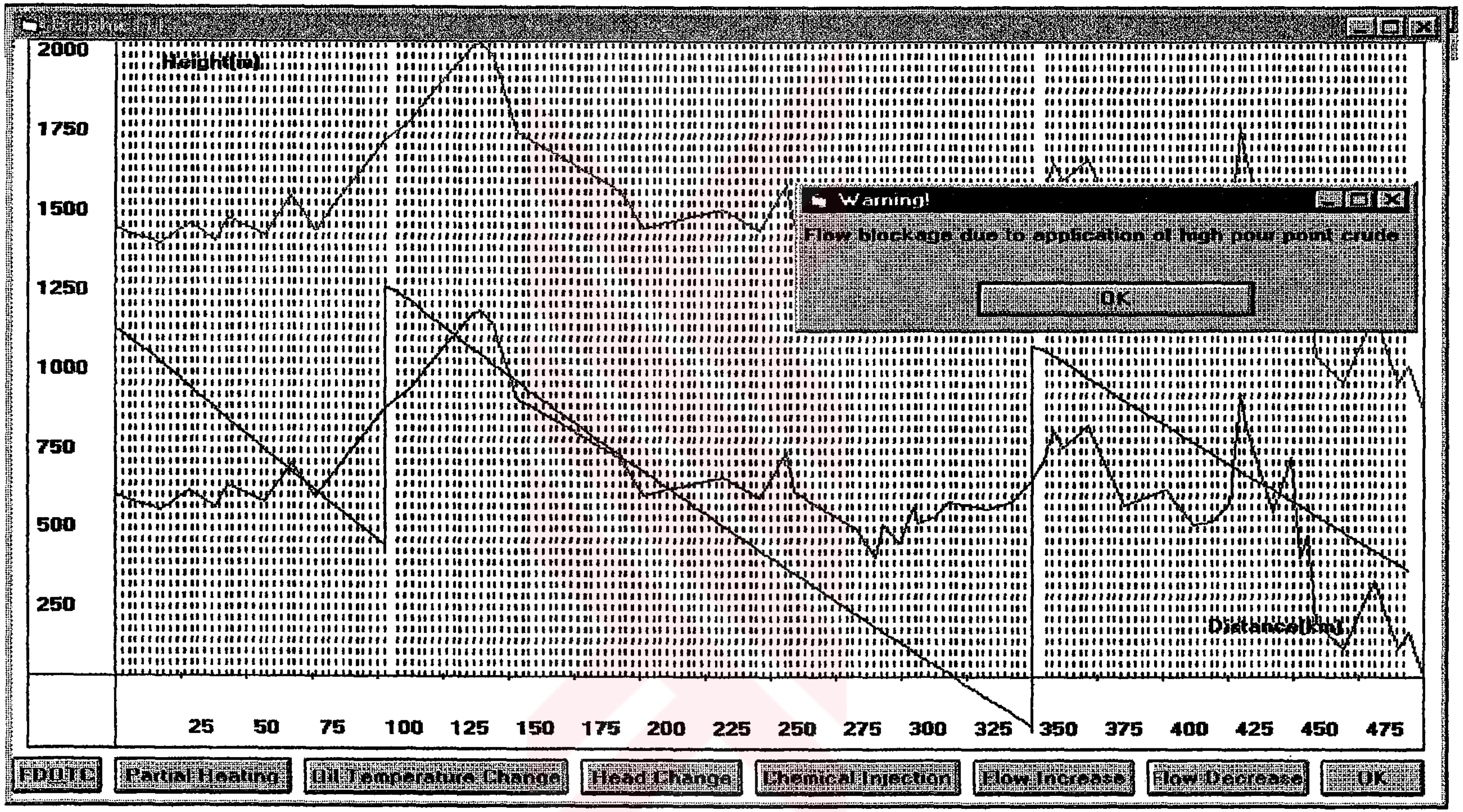
Figure 7.25 Temperature Distribution along the Line for Re-start after 36 h shutdown



Warning!

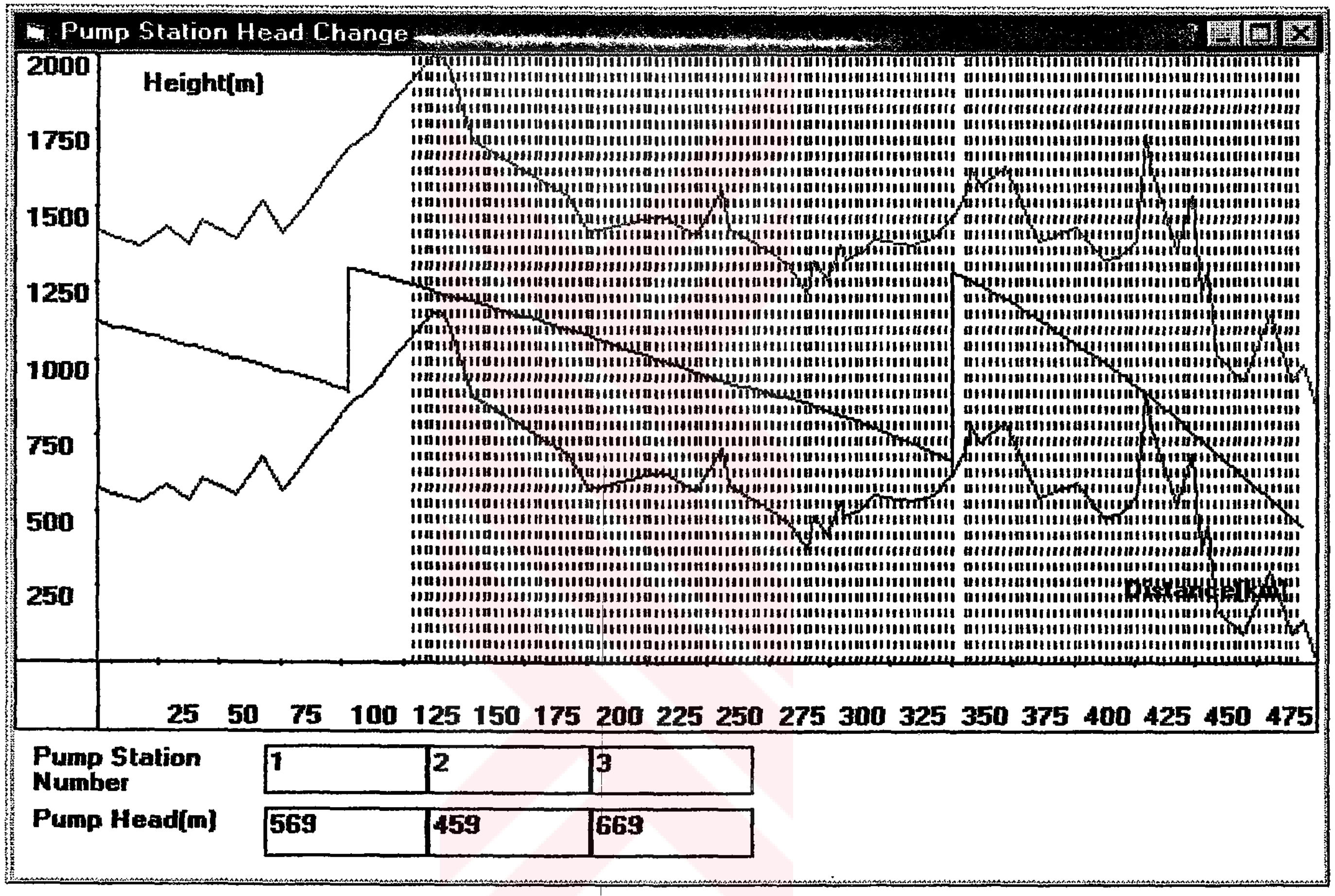
Flow blockage due to application of high pour point crude

Figure 7.26 Hydraulic Loading of Batman-Dörtyol Pipeline System due to Application of High Pour Point Crude's (normal operation)



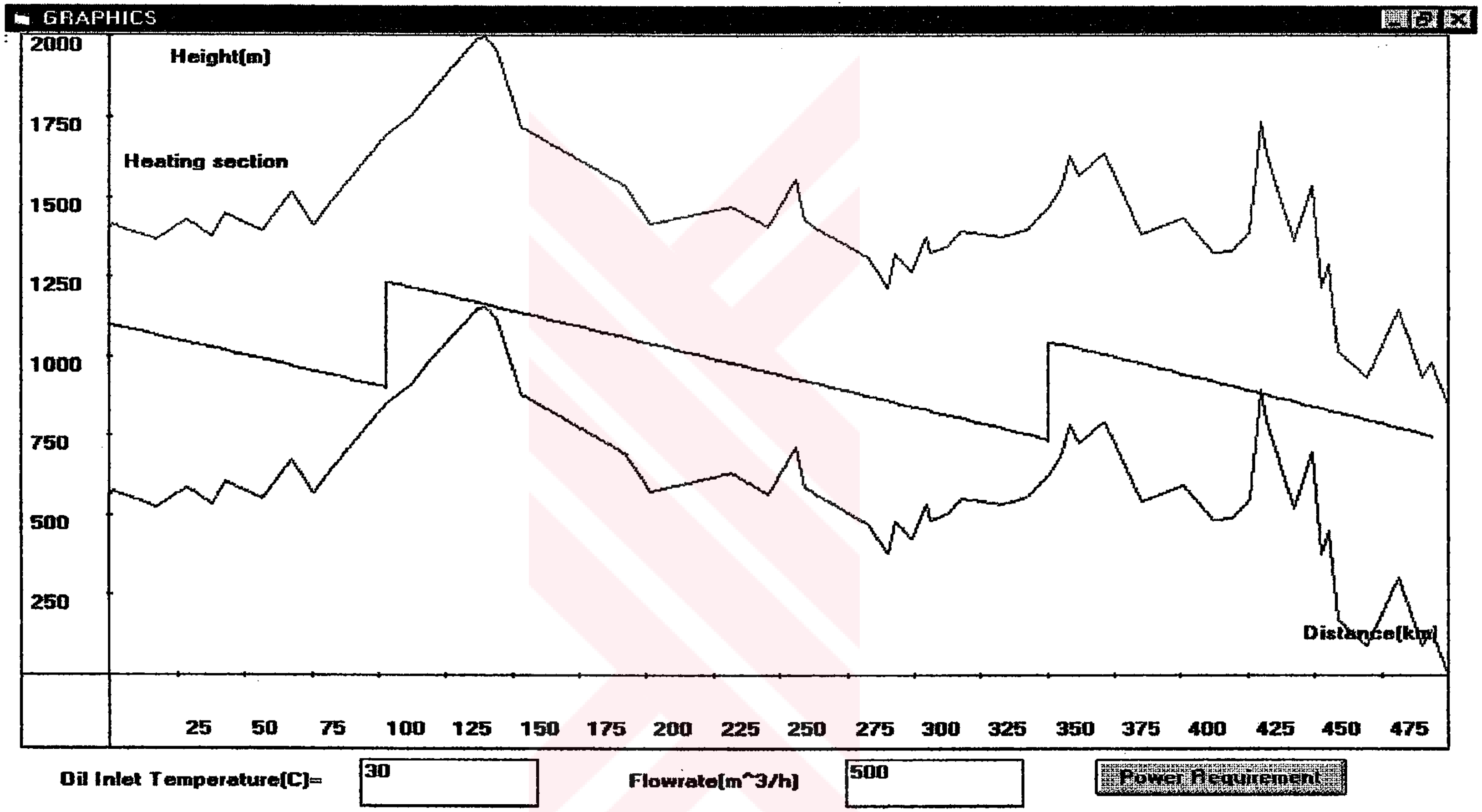
Flow blockage due to application of high pour point crude

Figure 7.27 Hydraulic Loading of Batman-Dörtyol Pipeline System due to Application of High Pour Point Crude (re-start operation)



Pump Station Number	1	2	3
Pump Head(m)	569	459	669

Figure 7.28 Hydraulic Loading of Batman-Dörtyol When Pump Head is changed to Satisfy such a Flow(normal operation)



Oil Inlet Temperature(C)= 30

Flowrate(m^3/h) 500

Figure7.29 Hydraulic Loading of the System with Partial Heating (Normal Operation)

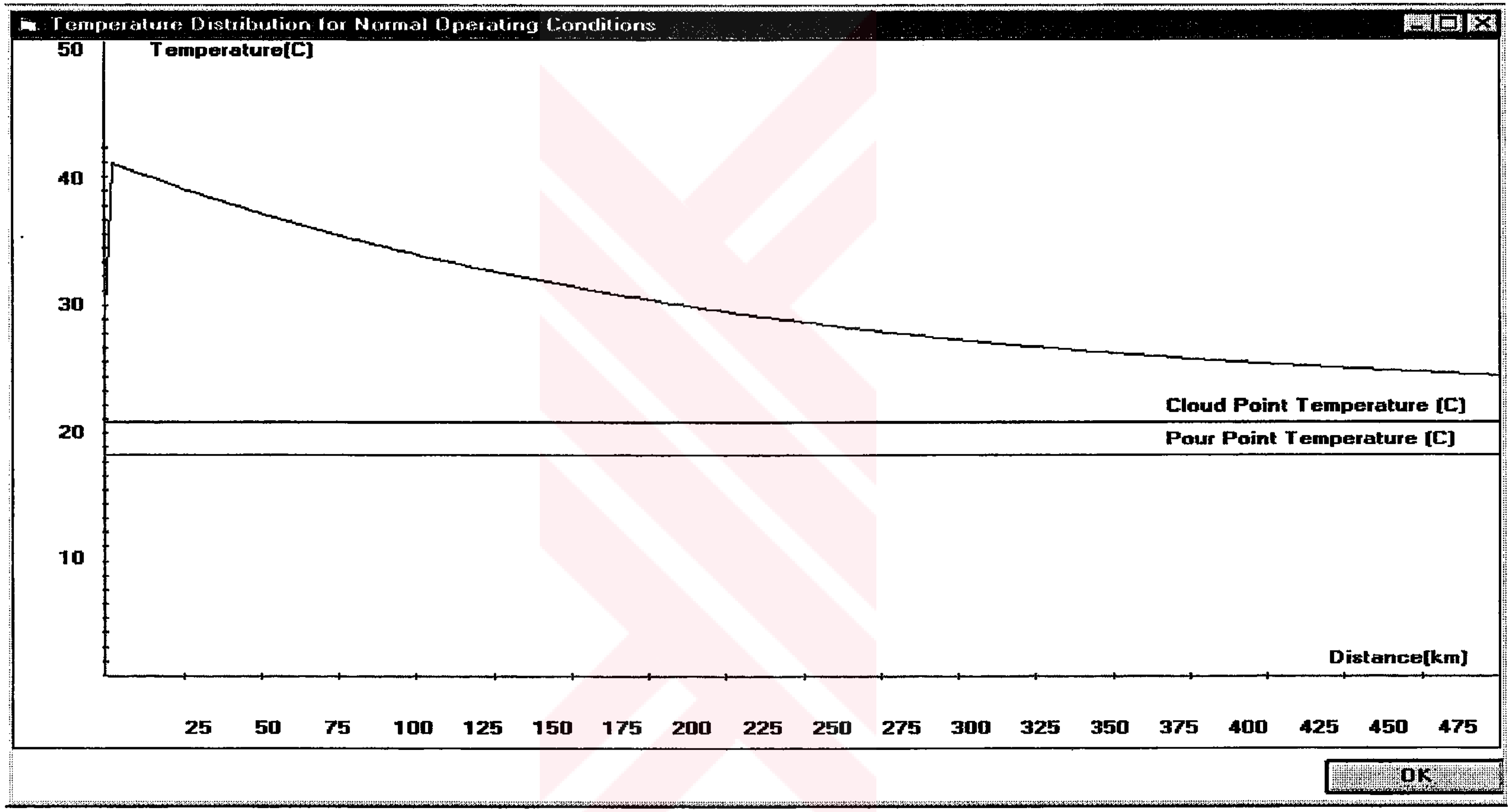


Figure 7.30(a) Temperature Distribution of the System after Partial Heating (Normal Operation)

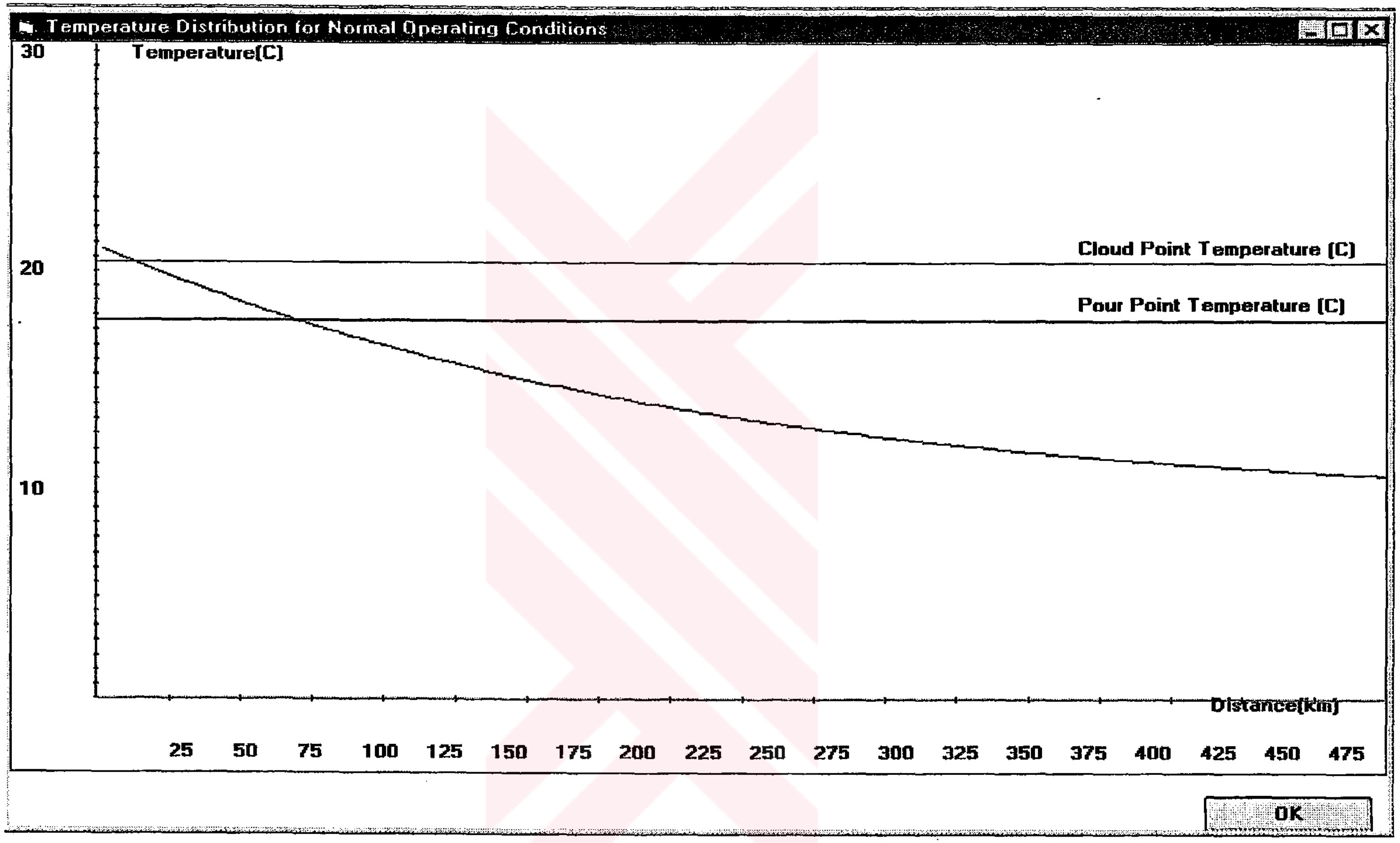
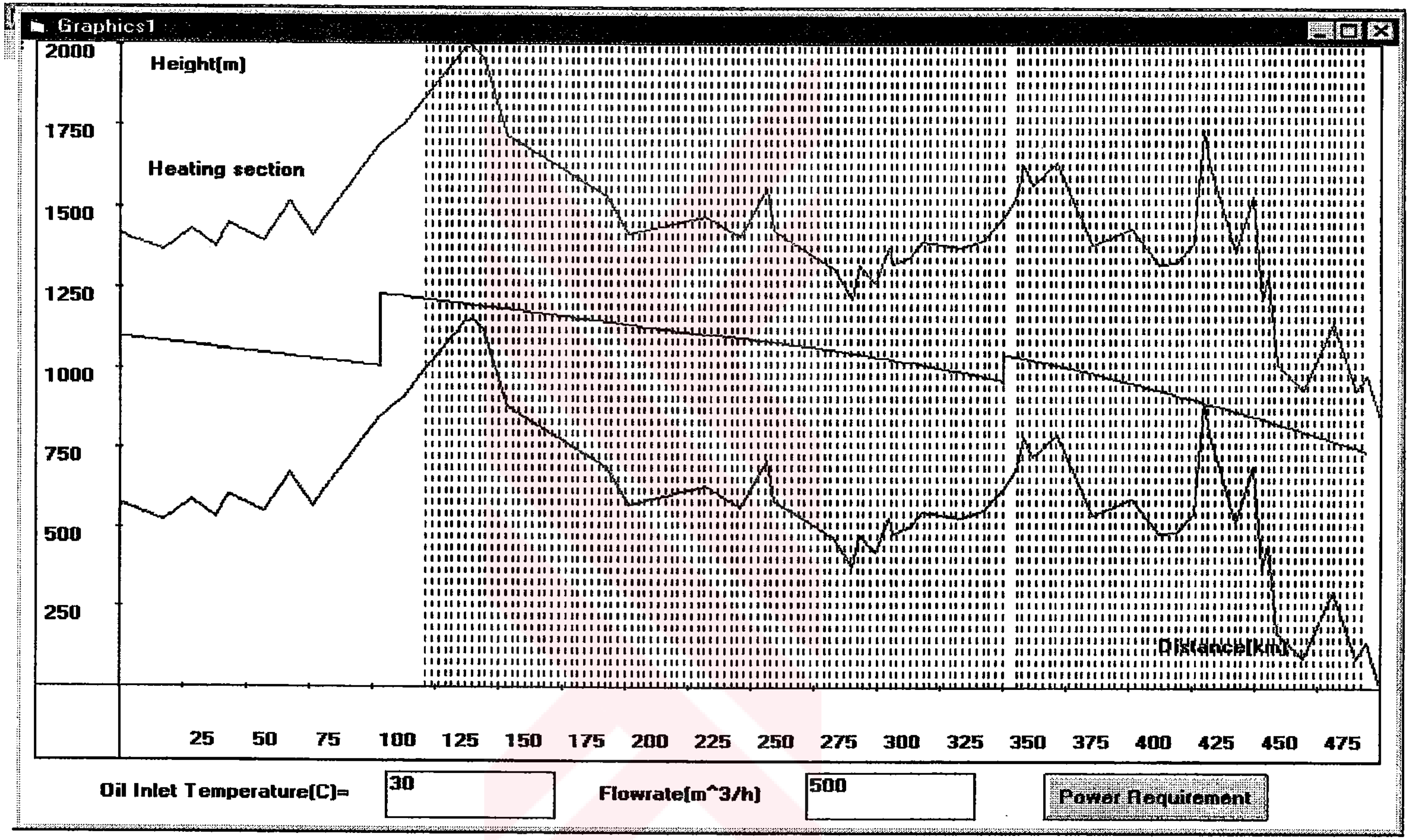


Figure 7.30(b) Temperature Distribution of the System after Partial Heating (Restart after 36 hours Shutdown)



Oil Inlet Temperature(C)= 30

Flowrate(m^3/h) 500

Figure 7.31 Hydraulic Loading of the System with Partial Heating (Re-start after 36 hours shutdown)

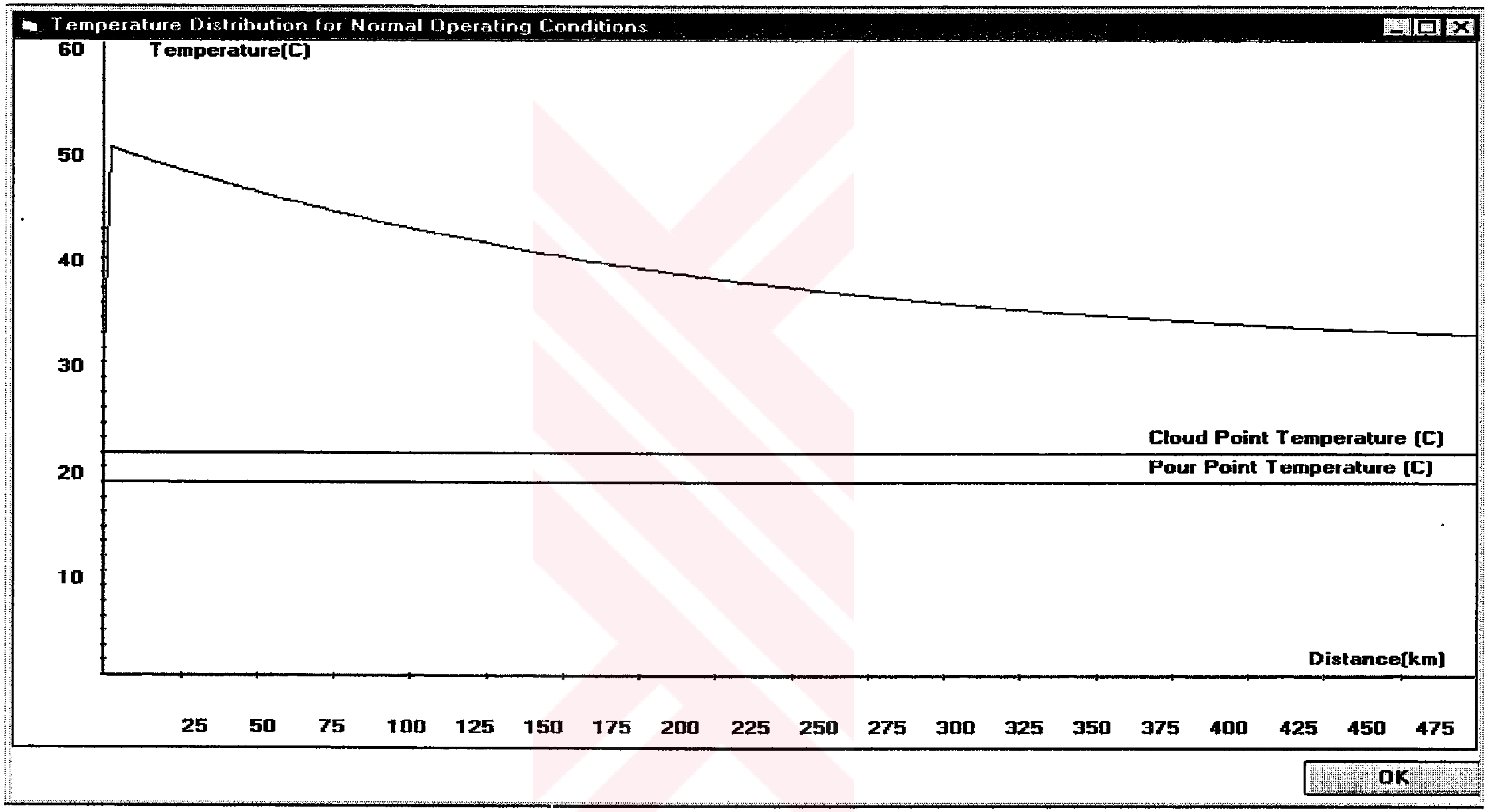


Figure 7.32(a) Temperature Distribution of the System after Partial Heating (Normal Operation)

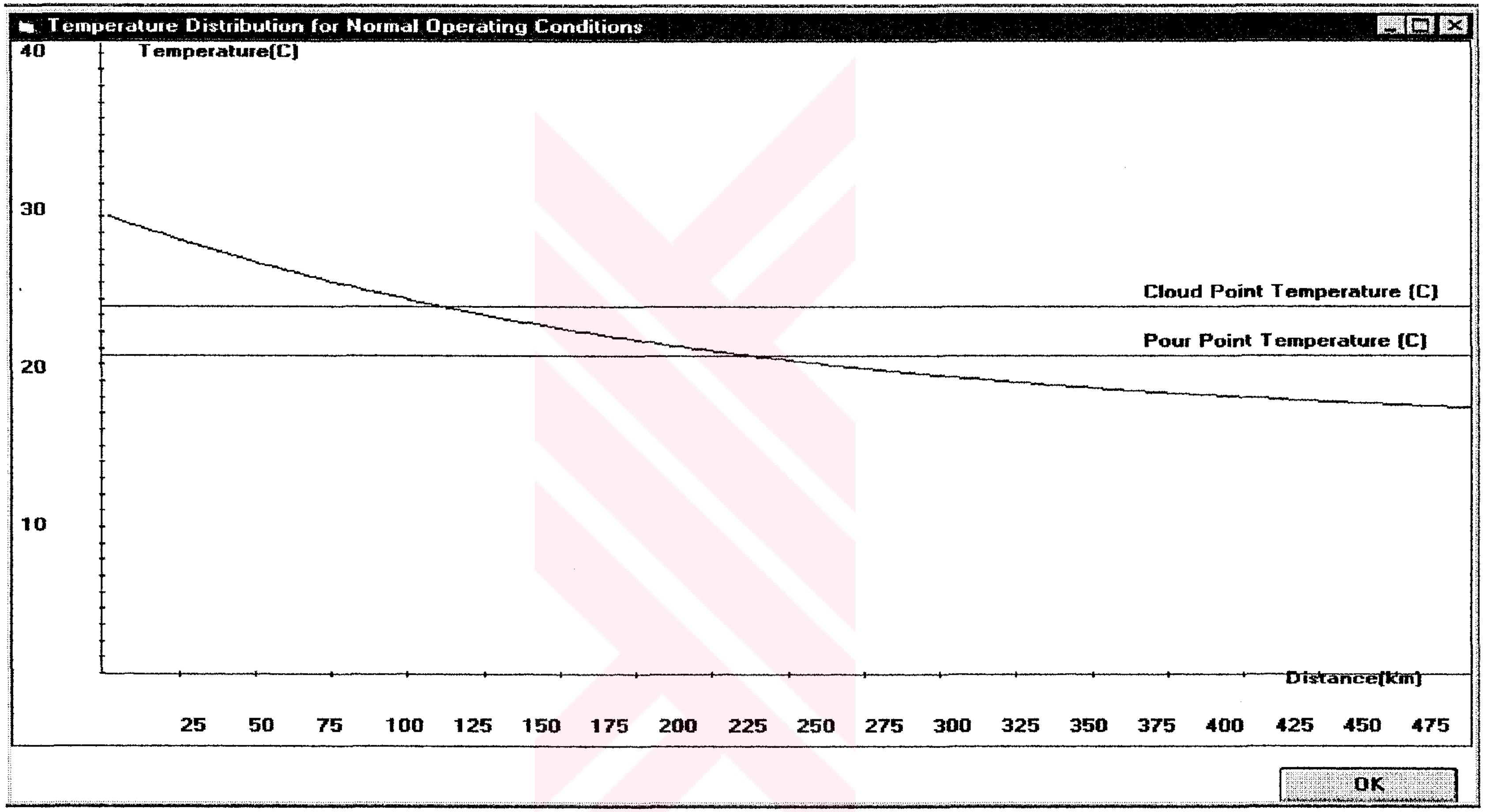


Figure 7.32(b) Temperature Distribution of the System after Partial Heating (Restart after 36 hours Shutdown)

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

8.1 Conclusions

Generally, crude oil pipelines are designed according to the conventional methods. However, waxy crudes are distinguished, as far as pipelines are concerned, by the fact that they exhibit non-Nerwtonian viscosity behaviour at temperatures below cloud point. This software is prepared to fill the gap in the design stage of pipelines by analysing existing crude oil pipelines considering the non-Newtonian effects. In this software, crude oil properties (crude's rheology) and variation of soil temperatures along the line are the key points of the analysis. In previous analysis (Civil[32], Çakmanus[33], Karakan[44]), heat transfer from the line does not influence the flow properties of crude oils. If non-Newtonian effects are considered, viscosity changes with temperature and the type of flow can change from point to point depending on the temperature of the crude oils and the value of viscosity. Therefore, the line is divided into small segments and each segment is analysed separately.

A non-Newtonian fluid is one whose viscosity at a given temperature is dependent on the rate of shear. The viscosity may increase or decrease, depending the type of flow. Non-Newtonian fluids can be classed as time-independent, and time dependent. A non-Newtonian fluid is time-independent if the shear stress at any rate of shear is constant with time- that is, the properties of the fluid depend only on the magnitude of the imposed shear stresses and not on the duration of the stresses. A non-Newtonian fluid is said to be time-dependent if the shear stress changes with the duration of shear –in other words, the viscosity at any time depends on the previous shearing of the liquid. There is no straightforward method for determining the pressure drop of time dependent non-Newtonian liquids. The variation of viscosity with time is neglected and only temperature variation is considered due to the difficulties encountered controlling the variation of viscosity with time.

The rheology of crude oils is highly temperature dependent so heat transfer is considered for normal uninterrupted operations, as well as for restarting flow after downtime. Temperature change shows an increase during shutdown. Thus static cooling is much more problematic than dynamic cooling during uninterrupted flow. The worst design conditions may be non-Newtonian turbulent flow, and non-Newtonian restarted laminar flow when flow is completely initiated at the lowest ambient temperatures. The pour point can be considered as the critical design point if pour point is lower than ambient temperature. Restart flow rate is the minimum design flow rate to initiate flow after shutdown in a cold flowline full of oil. For cold flowline, flow can be non-Newtonian and very high pressure is required to break gel and initiate flow. Such pressures could be higher than the burst pressure of the pipeline, thus low flow rates are required to minimise the pressure requirements.

Temperature, and its effects on the mechanical and rheological properties, is generally quite different from crude to crude. With each waxy crude discovery, extensive laboratory tests should be made to determine its exact behaviour under temperature variation.

When waxy crude oil pipeline is considered, as well as the crude characteristics, a through understanding of pipeline system is a requirement of pump selection for the mainline units. Figure 8.1 displays what can be a typical waxy crude pump pressure versus flow curve.

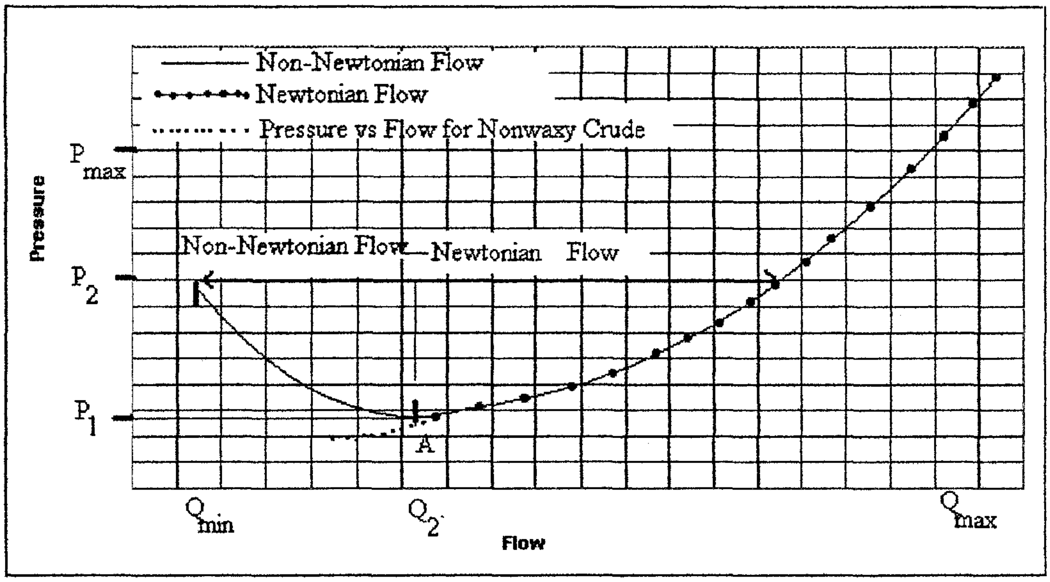


Figure 8.1 Pump pressure vs. flow curve for typical waxy crude oils

The given characteristic shows that, as flow decreases from point A, the pressure requirements will increase, since the longer the oil in the line, the more it cools and the more its viscosity increases. Moreover, as the flow decreases, so does the velocity, thus decreasing the rate of shear.

As the rate of the shear decreases in non-Newtonian flow, the viscosity increases. When the flow increase past point A, Newtonian characteristics dominate, and pressure again increases because, increased pressure is required to off-set the increased friction losses caused by the additional flow.

In selecting a main pump for the system curve, the operating point P_{max}, Q_{max} must be met. If P_2, Q_{min} can not be met by the mainline because of temperature restrictions at the low flow rate, or P_2 can be grater than P_{max}, special start-up/restart pumps (high pressure, low flow) pumps might be considered.

Generally, high volume, low to moderate pressure requirements can be met by centrifugal pumps. Positive displacement pumps handle low volume, high pressure requirements. Flows between Q_{min} and Q_2, if it is found that P_2 is grater than P_{max}, P_2 would be handled by positive displacement start/restart pumps.

Once the properties of the crude oils, its temperature variation along the line and restart pressure requirements are determined mainline pump selection will not be much different for high-pour-point crudes than it would for Newtonian crudes.

If the flow is blocked, 6 basic modifications are performed by the program. Some of them relate to operational parameters and rest to fluid parameters. Different solutions must exist at the same time for two operating conditions. If the fluid parameters are improved, one of the operating conditions is much severe with respect to other and it can be stated as the overall solution of the problem by the users. However, this is not true for operational parameters because these effects the operating points of pumps and pump configurations (parallel, series, single or stand by pumps). Existing pump configuration and capacities must satisfy flow at each case separately. It is not possible to mention about the overall solution for two conditions. Overall solution means that the fluid parameter or parameters are changed once to operate system completely for normal and restart operating case. If the users want to apply each solution separately, they can do it. Actually, the most important consideration is to find a meaningful solutions to both operating conditions.

If the flowrate of the pipeline is decreased, the possibility of the non-Newtonian flow increases. Conversely, if temperature of oil at any location is increased, non-Newtonian flow decreases. The modifications of pump head do not have any effect on non-Newtonian flow. The chemical injection process is very complex and decreases the frictional pressure loss but noting can be said about the effect on the viscosity. Partial heating of oil is more cheaper than increasing the oil temperature at the beginning. The combinations of operational parameters and fluid parameters give more realistic and cheaper results with respect to cases in which all of them are considered separately.

This program can also be used for the analysis of slurry pipeline as long as the slurry parameters(rheological, operational) are loaded to the program. Therefore, Batman-Dörtyol pipeline is evaluated as a slurry pipeline considering the rheological properties of hypothetical crude [17].

This thesis is one of the continuing studies made on pipelines in more. Several studied thesis have been made on the energy optimisation of pipelines, design optimisation, and batch operation [32,33,44]. This work brings a new approach to liquid pipelines by considering the possibility of non-Newtonian flow in pipes. Up to this research, viscosity is generally taken as a constant. The constant viscosity doesn't give meaningful results for high-pour-point liquids.

8.2 Recommendations For Future Work

In the future, this program can be upgraded to improve design and operation condition of pipelines.

i. This program can be combined with a design optimisation program to consider the non-Newtonian effects at the design stage of pipelines.
ii. Non-Newtonian flow behaviour was assumed to be approximately Bingham Plastic. This work can be re-examined by using other non-Newtonian flow model i.e, Power Law.
iii. The rheological data used in this thesis are for a hypothetical crude oil. This study can be performed with an original data after investigating the real characteristics of crude in a laboratory.
iv. The interactive nature of the program can be extended by converting it into Visual Basic 5.0.

v. Slurry considerations can be improved and a special program which is related to all kinds of slurry can be added.

vi. The pump performance characteristics data files reads the individual characteristics of the pumps and searches the combinations of the pumps and combined characteristics. A sub-program which reads combined characteristics of the pumps may be added as an another option.

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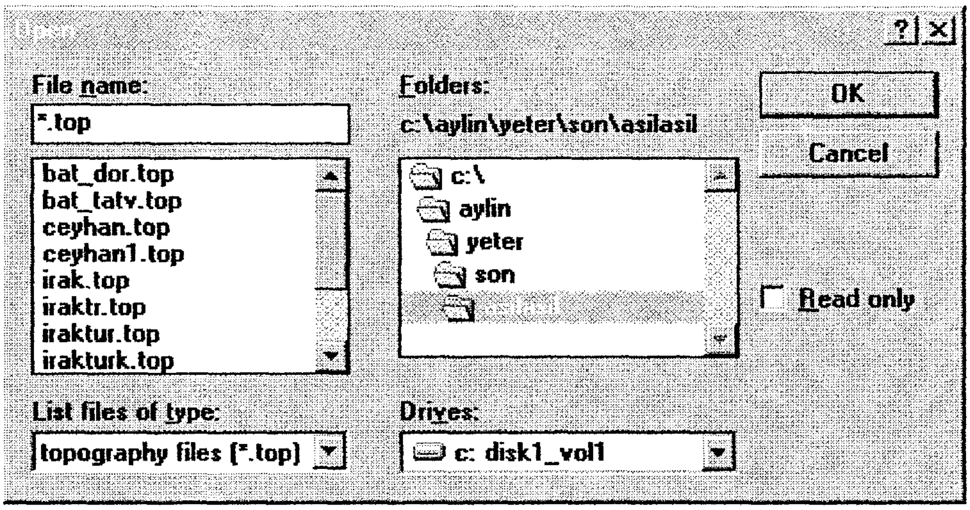
APPENDIX A

INPUT FORMS OF THE PROGRAM



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- bat_dor.top
- bat_tatv.top
- ceyhan.top
- ceyhan1.top
- irak.top
- iraktr.top
- iraktur.top
- irakturk.top

Folders: c:\aylin\yeter\son\asilasil

- c:\
  - aylin
    - yeter
      - son
        - asilasil

☐ Read only

List files of type: topography files (*.top)

Drives: c: disk1_vol1

Figure A.1 Input form of existing land profile

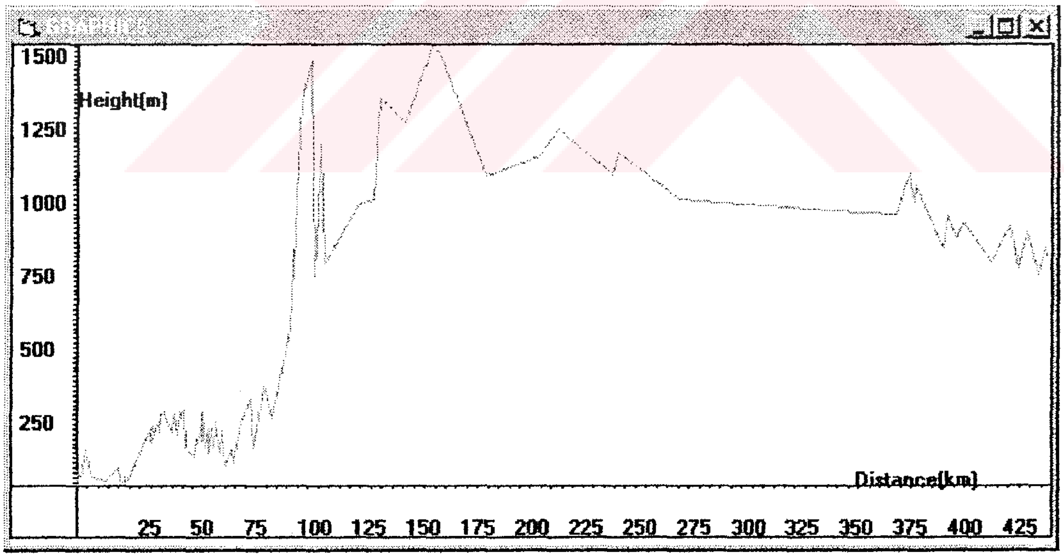


Figure A.2 Land profile for Kırıkkale-Ceyhan pipeline

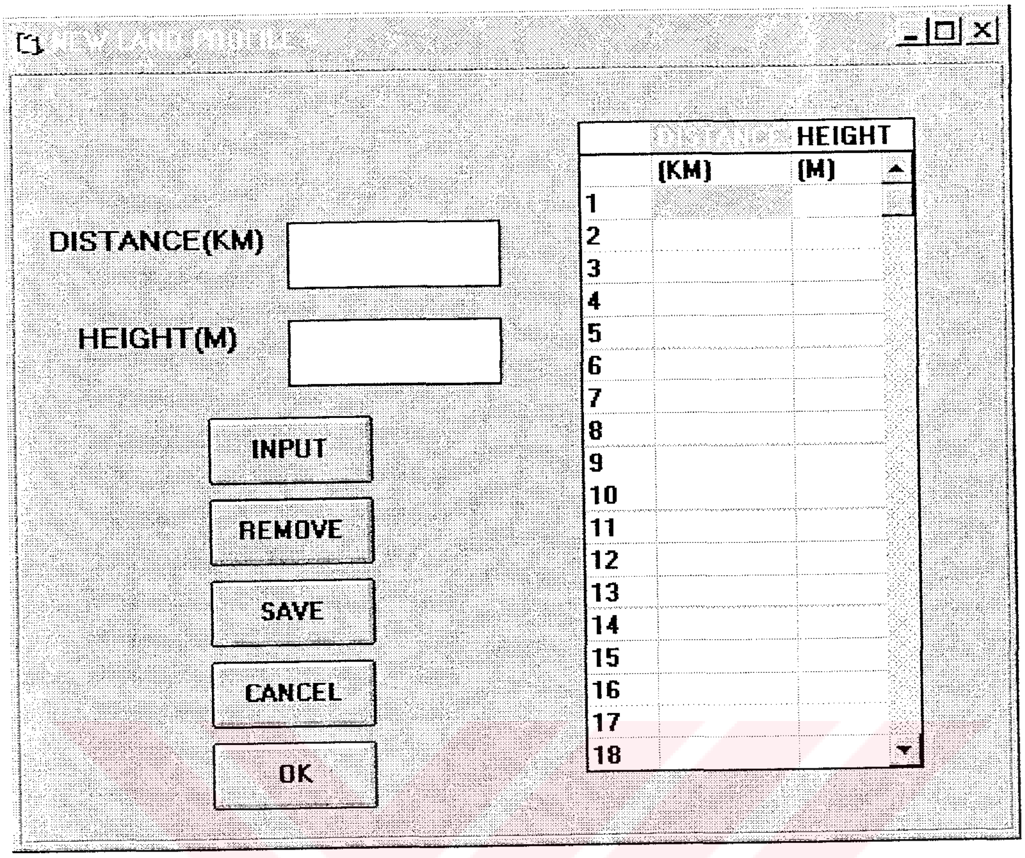
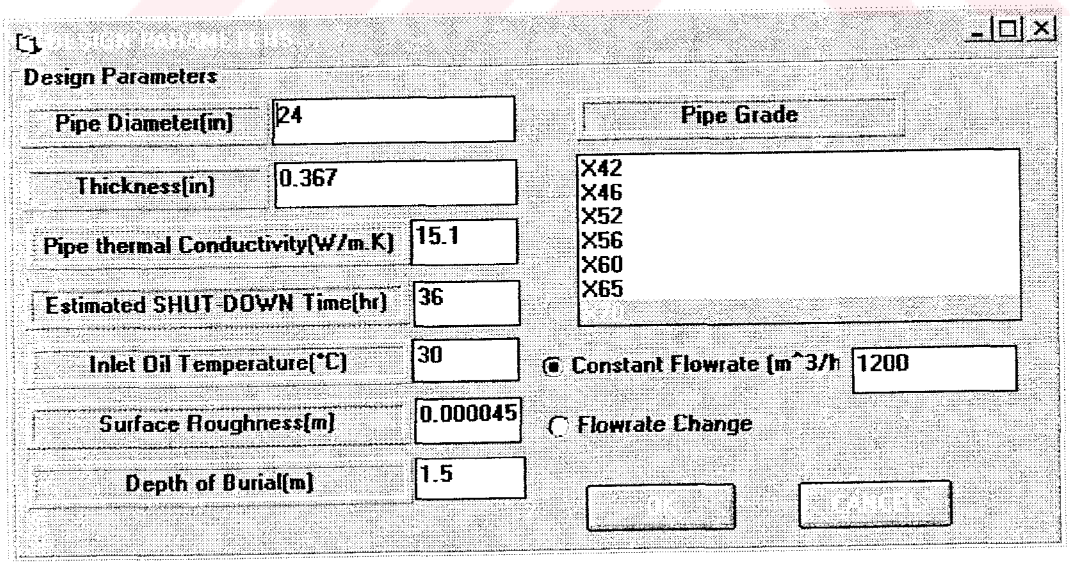


Figure A.3 Input form of new land profile



Pipe Diameter(in) 24

Thickness(in) 0.367

Pipe thermal Conductivity(W/m.K) 15.1

Estimated SHUT-DOWN Time(hr) 36

Inlet Oil Temperature(°C) 30

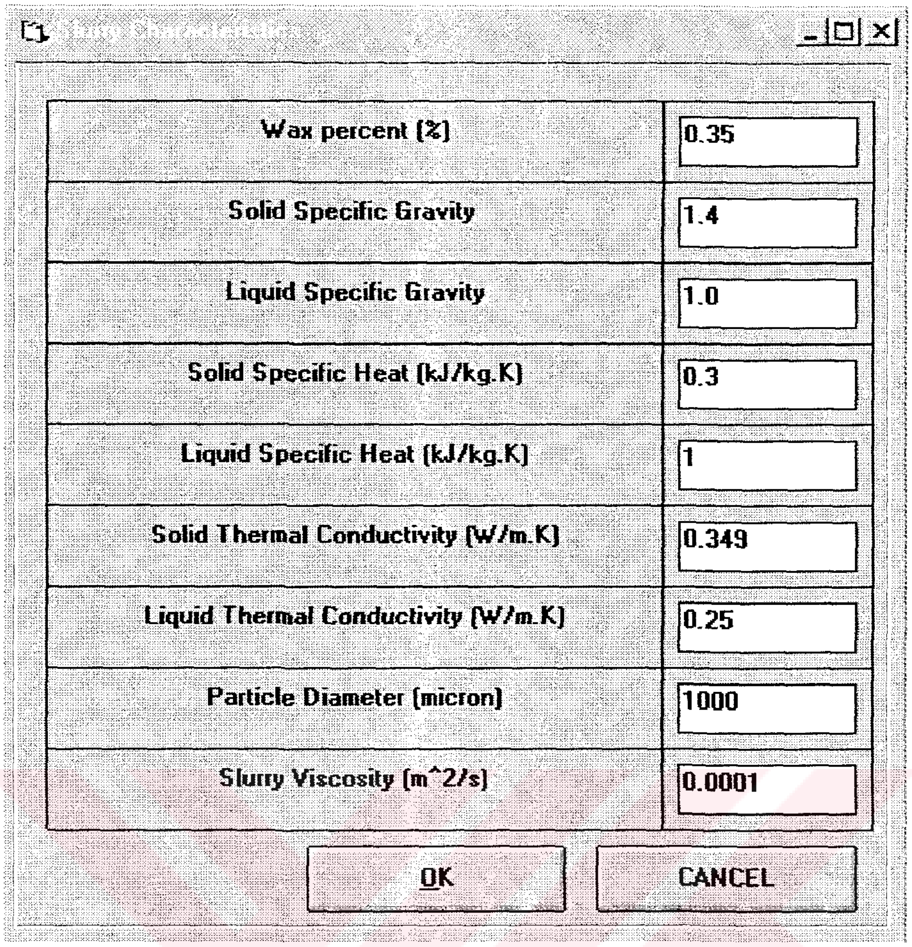
Surface Roughness(m) 0.000045

Depth of Burial(m) 1.5

● Constant Flowrate (m^3/h 1200

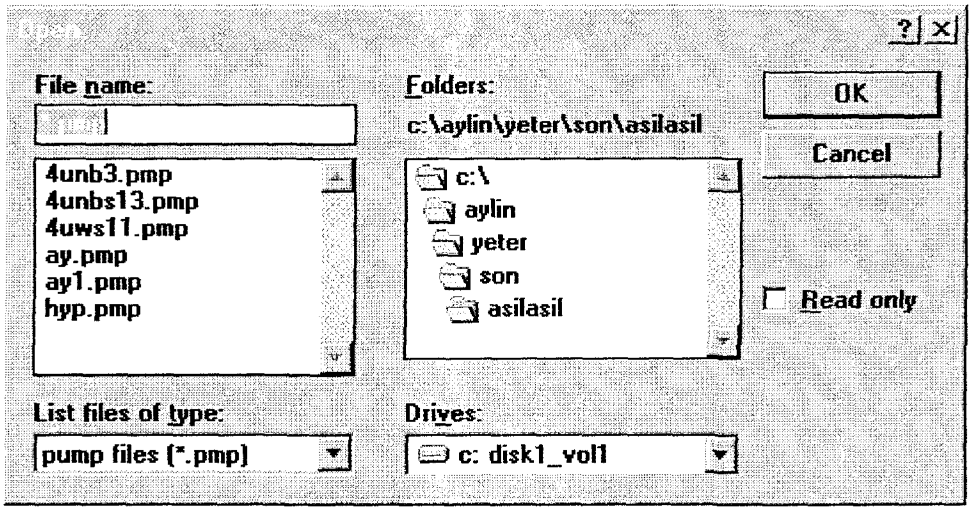
○ Flowrate Change

Figure A.4 Input form of design parameters



Wax percent (%)	0.35
Solid Specific Gravity	1.4
Liquid Specific Gravity	1.0
Solid Specific Heat (kJ/kg.K)	0.3
Liquid Specific Heat (kJ/kg.K)	1
Solid Thermal Conductivity (W/m.K)	0.349
Liquid Thermal Conductivity (W/m.K)	0.25
Particle Diameter (micron)	1000
Slurry Viscosity (m^2/s)	0.0001

Figure A.5 Input form of slurry characteristics of crude oil



File name:

4unb3.pmp
4unbs13.pmp
4uws11.pmp
ay.pmp
ay1.pmp
hyp.pmp

Folders:
c:\aylin\yeter\son\asilasil

c:\
aylin
yeter
son
asilasil

List files of type:
pump files (*.pmp)

Drives:
c: disk1_vol1

Figure A.6 Input form of existing pump characteristics

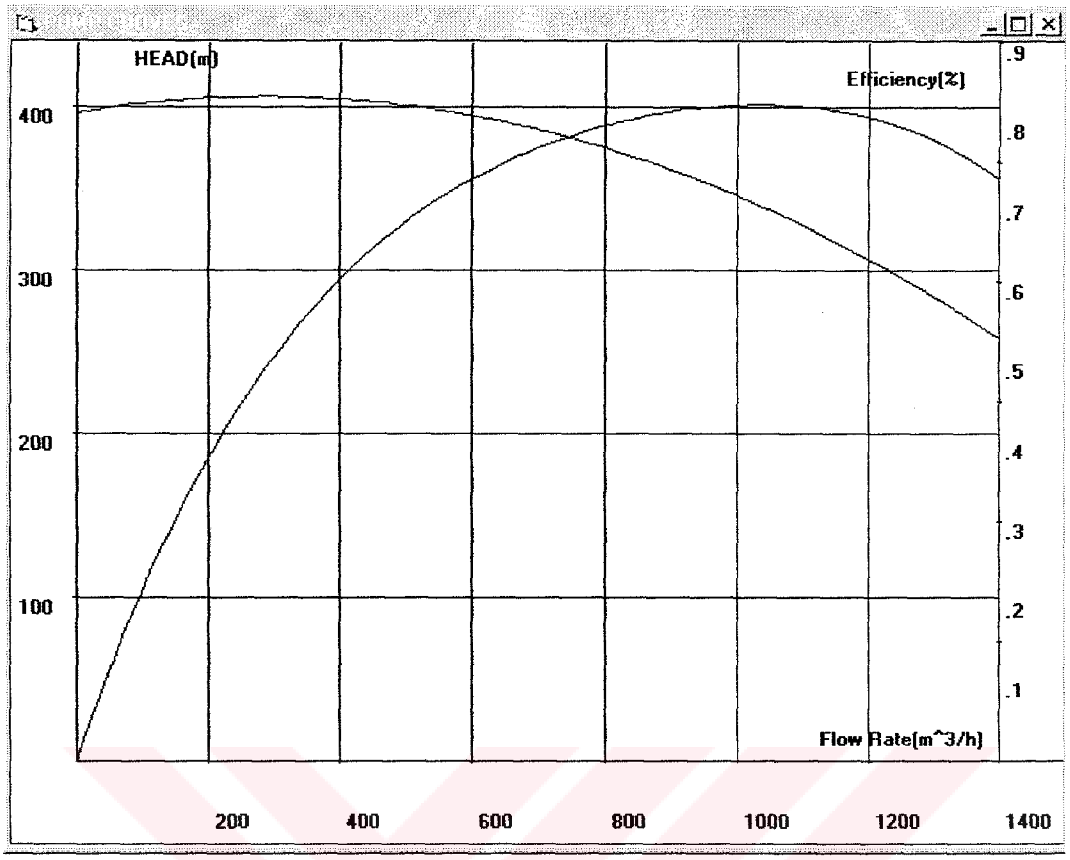


Figure A.7 Pump characteristic of case study

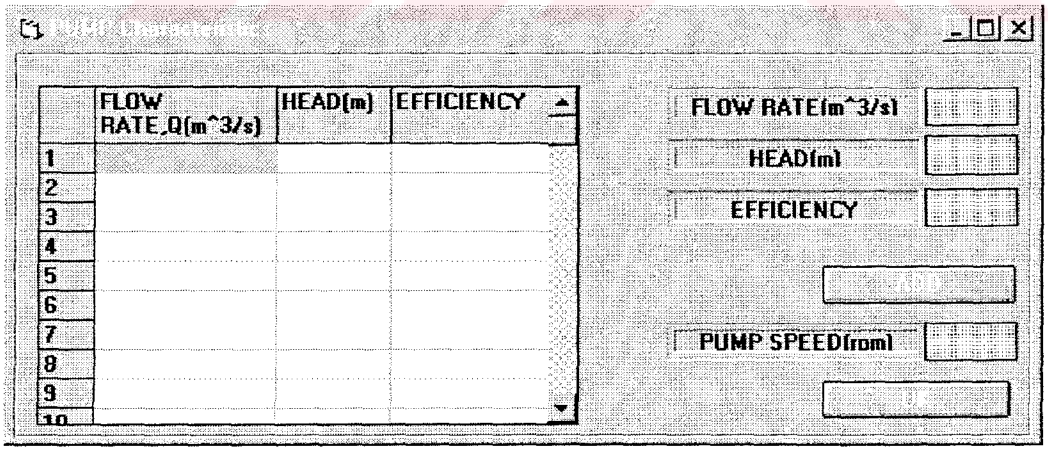
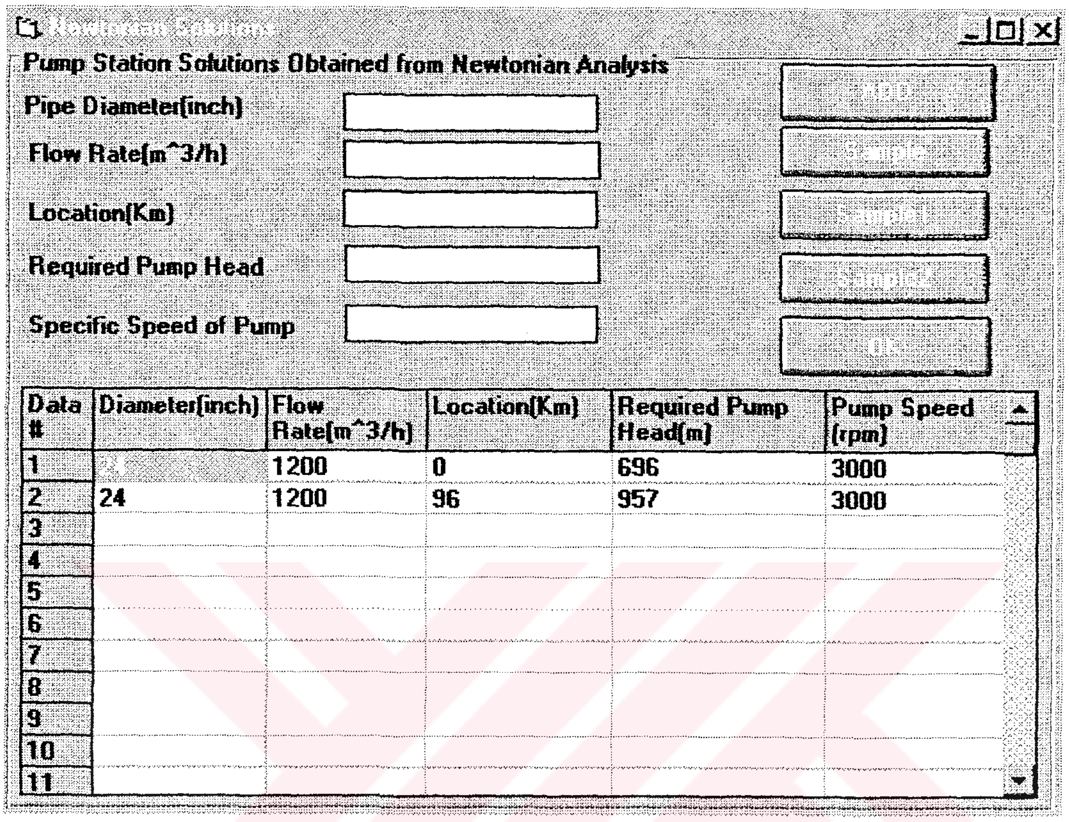


Figure A.8 Input form of new pump characteristics



Pump Station Solutions Obtained from Newtonian Analysis

Pipe Diameter(inch)

Flow Rate(m^3/h)

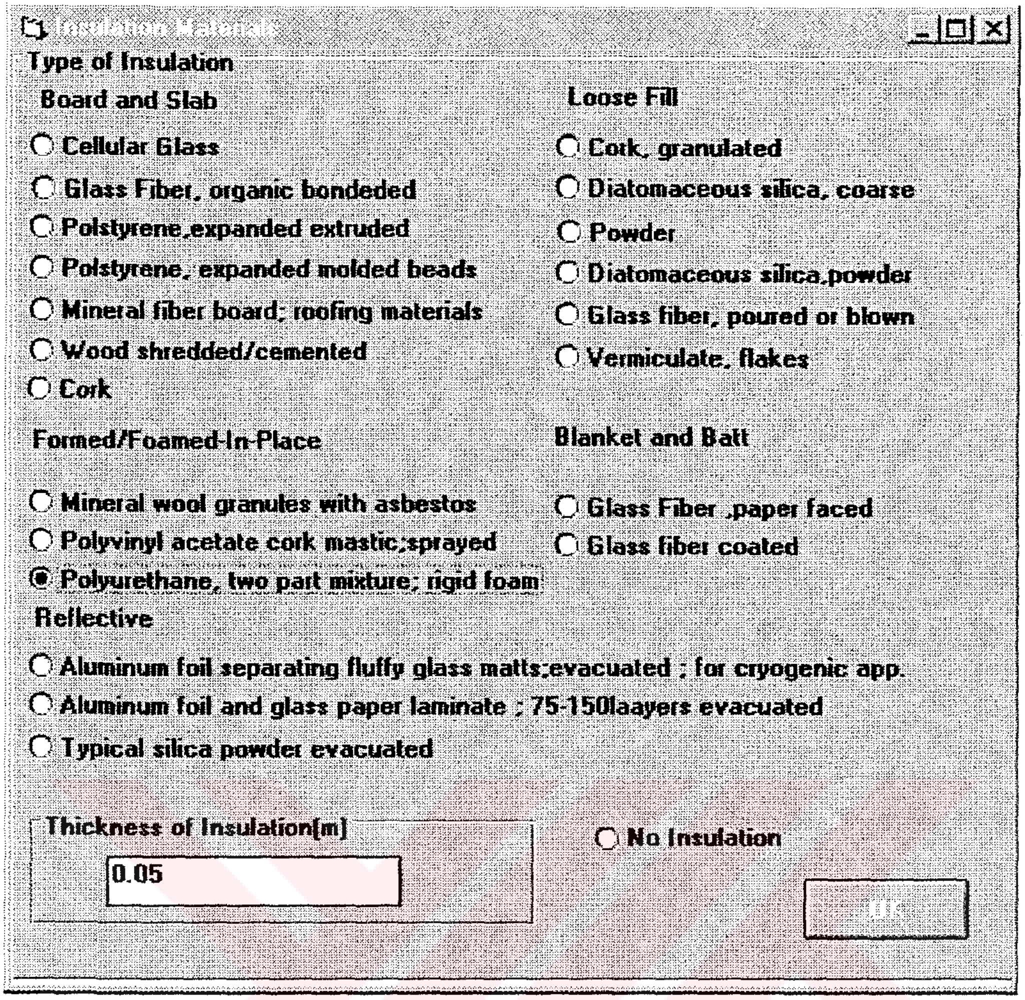
Location(Km)

Required Pump Head

Specific Speed of Pump

Data #	Diameter(inch)	Flow Rate(m^3/h)	Location(Km)	Required Pump Head(m)	Pump Speed (rpm)
1	24	1200	0	696	3000
2	24	1200	96	957	3000
3					
4					
5					
6					
7					
8					
9					
10					
11					

Figure A.9 Input form of Newtonian solutions



Insulation Materials

Type of Insulation

Board and Slab

○ Cellular Glass
○ Glass Fiber, organic bondeded
○ Polstyrene,expanded extruded
○ Polstyrene, expanded molded beads
○ Mineral fiber board; roofing materials
○ Wood shredded/cemented
○ Cork

Loose Fill

○ Cork, granulated
○ Diatomaceous silica, coarse
○ Powder
○ Diatomaceous silica,powder
○ Glass fiber, poured or blown
○ Vermiculate, flakes

Formed/Foamed-In-Place

○ Mineral wool granules with asbestos
○ Polyvinyl acetate cork mastic;sprayed
● Polyurethane, two part mixture; rigid foam

Blanket and Batt

○ Glass Fiber ,paper faced
○ Glass fiber coated

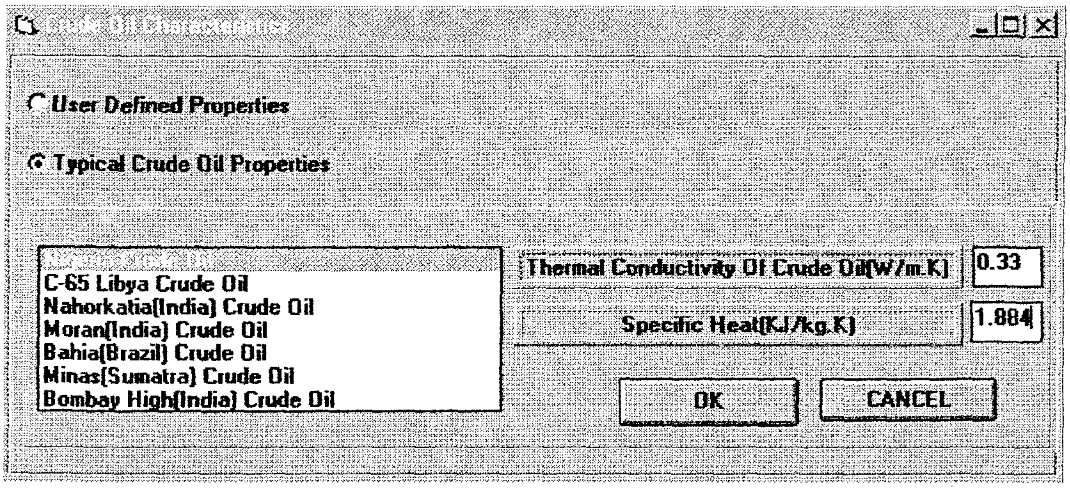
Reflective

○ Aluminum foil separating fluffy glass matts;evacuated ; for cryogenic app.
○ Aluminum foil and glass paper laminate ; 75-150laayers evacuated
○ Typical silica powder evacuated

Thickness of Insulation[m]: 0.05

○ No Insulation

Figure A.10 Input form of insulation materials



Crude Oil Characteristics

○ User Defined Properties

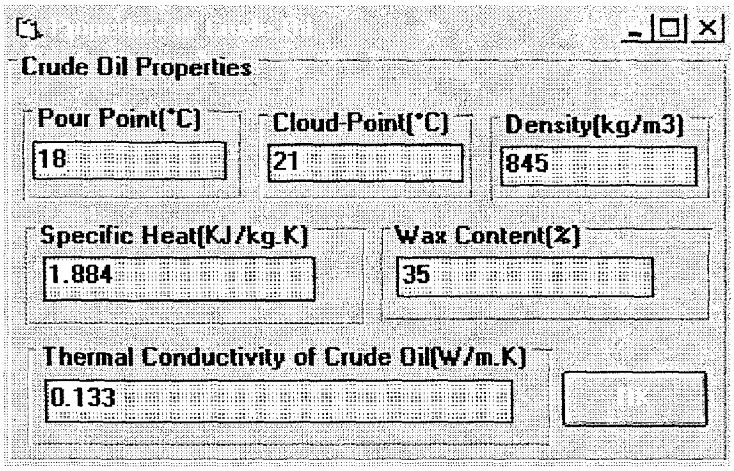
● Typical Crude Oil Properties

Nigerian Crude Oil
C-65 Libya Crude Oil
Nahorkatia(India) Crude Oil
Moran(India) Crude Oil
Bahia(Brazil) Crude Oil
Minas(Sumatra) Crude Oil
Bombay High(India) Crude Oil

Thermal Conductivity Of Crude Oil[W/m.K]: 0.33

Specific Heat[KJ/kg.K]: 1.884

Figure A.11 Input form of crude oil properties



Crude Oil Properties

Pour Point(°C): 18

Cloud-Point(°C): 21

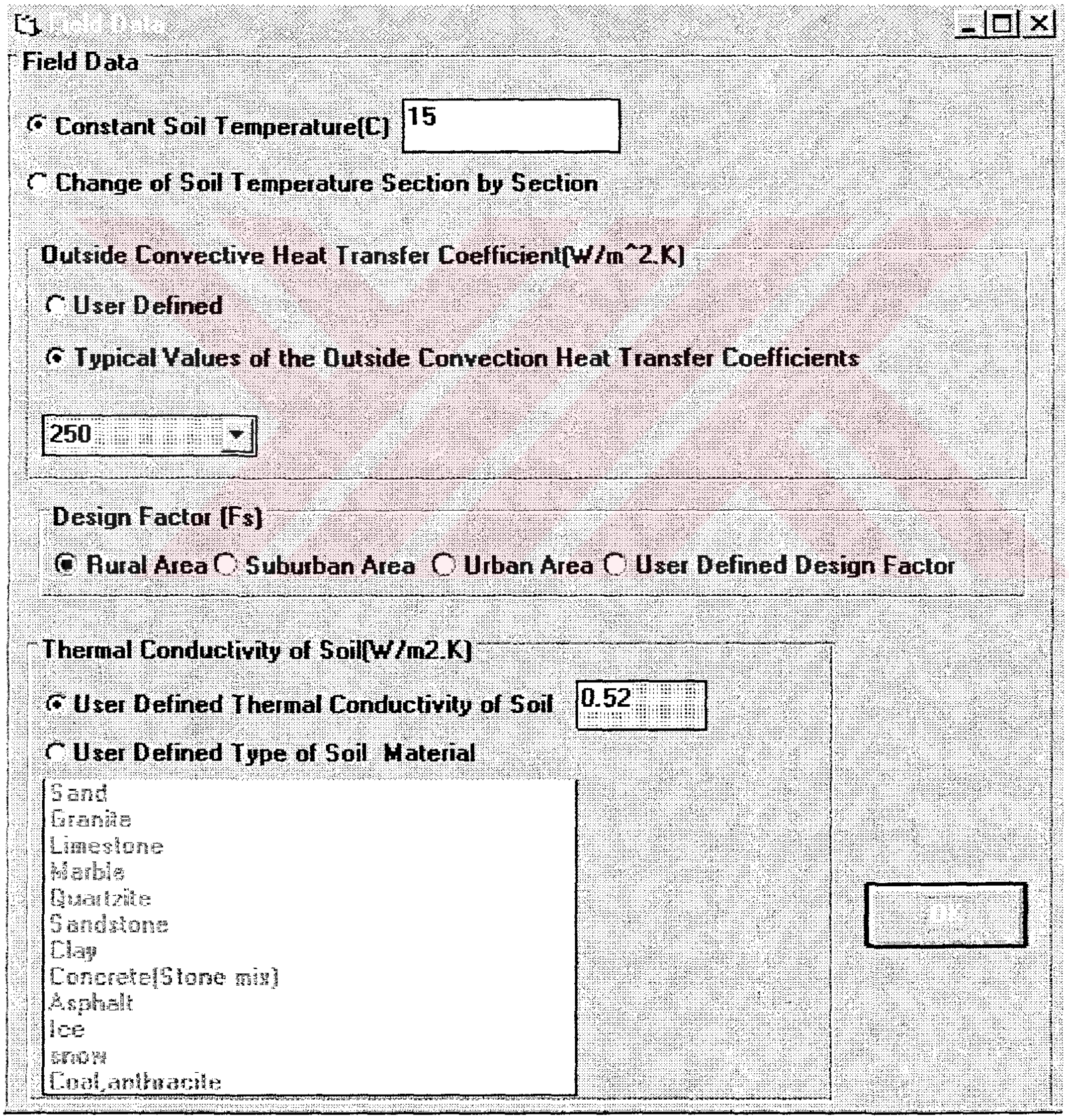
Density(kg/m3): 845

Specific Heat(KJ/kg.K): 1.884

Wax Content(%): 35

Thermal Conductivity of Crude Oil(W/m.K): 0.133

Figure A.12 Input form of user defined crude oil properties



Field Data

● Constant Soil Temperature(C) 15

○ Change of Soil Temperature Section by Section

Outside Convective Heat Transfer Coefficient(W/m^2.K)

○ User Defined

● Typical Values of the Outside Convection Heat Transfer Coefficients

250

Design Factor (Fs)

● Rural Area ○ Suburban Area ○ Urban Area ○ User Defined Design Factor

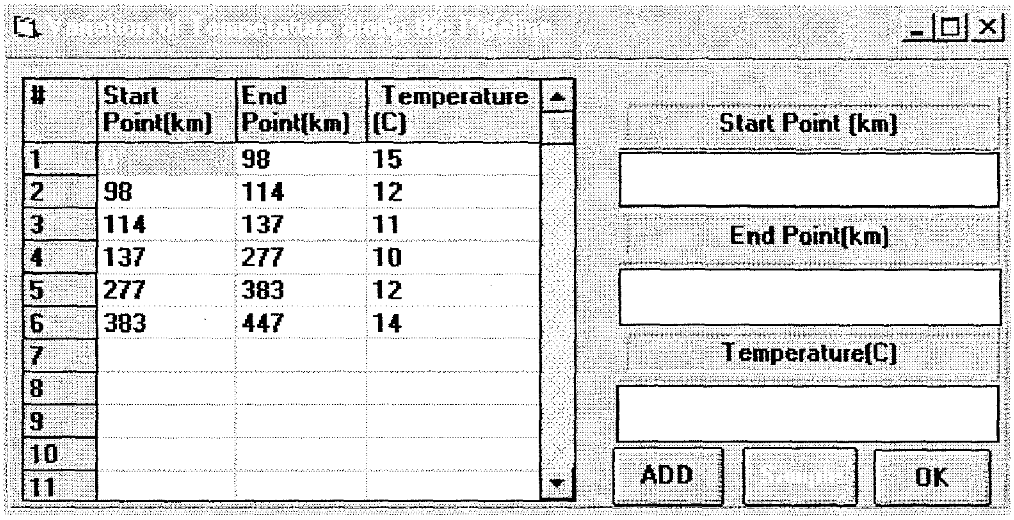
Thermal Conductivity of Soil(W/m2.K)

● User Defined Thermal Conductivity of Soil 0.52

○ User Defined Type of Soil Material

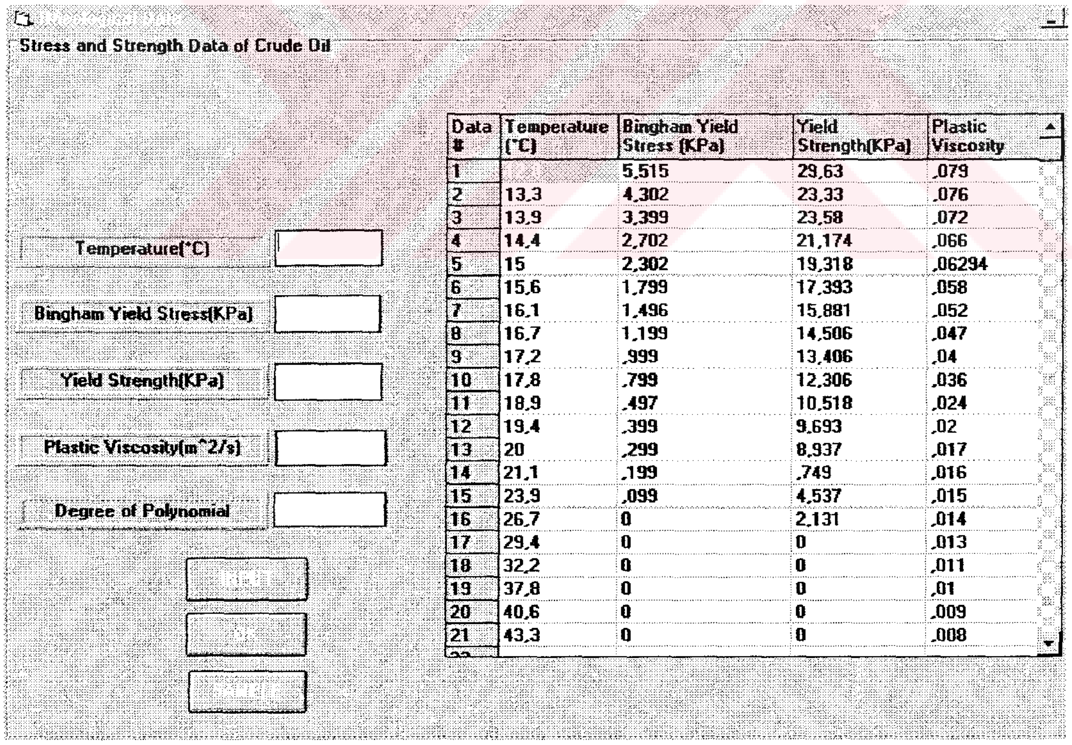
- Sand
- Granite
- Limestone
- Marble
- Quartzite
- Sandstone
- Clay
- Concrete(Stone mix)
- Asphalt
- Ice
- snow
- Coal,anthracite

Figure A.13 Input form of field data



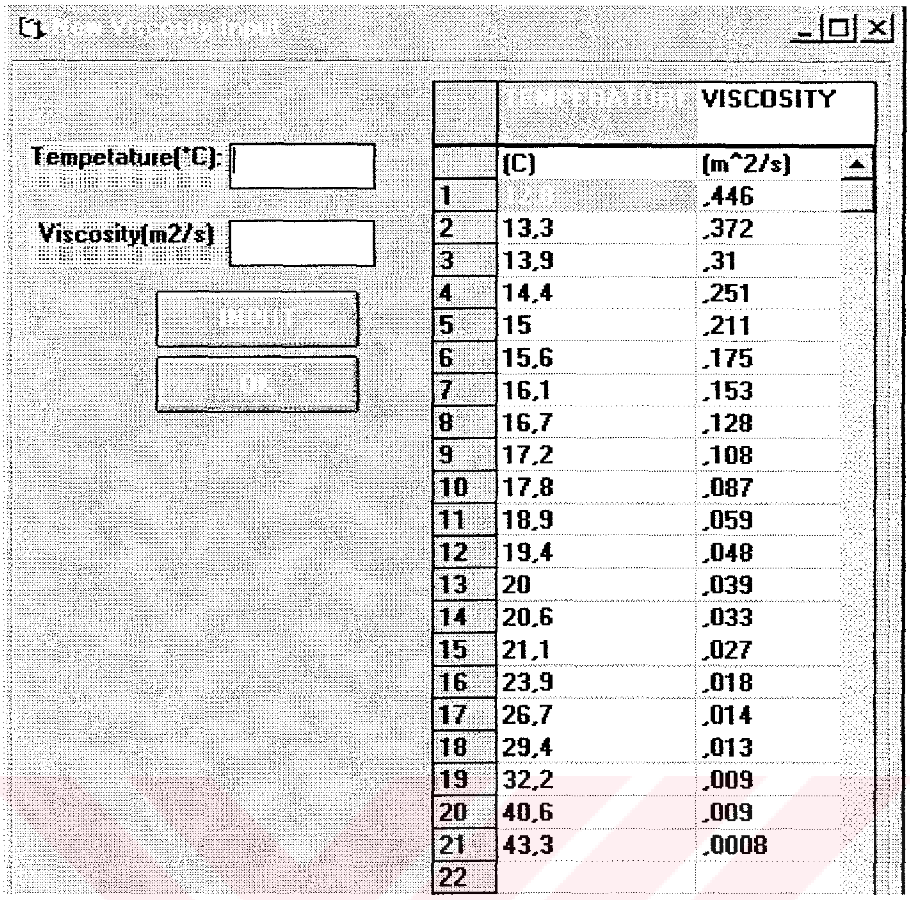
#	Start Point(km)	End Point(km)	Temperature (C)
1	0	98	15
2	98	114	12
3	114	137	11
4	137	277	10
5	277	383	12
6	383	447	14
7			
8			
9			
10			
11			

Figure A.14 Input form of soil temperature variation along the pipeline



Data #	Temperature (°C)	Bingham Yield Stress (KPa)	Yield Strength(KPa)	Plastic Viscosity
1		5,515	29,63	,079
2	13,3	4,302	23,33	,076
3	13,9	3,399	23,58	,072
4	14,4	2,702	21,174	,066
5	15	2,302	19,318	,06294
6	15,6	1,799	17,393	,058
7	16,1	1,496	15,881	,052
8	16,7	1,199	14,506	,047
9	17,2	,999	13,406	,04
10	17,8	,799	12,306	,036
11	18,9	,497	10,518	,024
12	19,4	,399	9,693	,02
13	20	,299	8,937	,017
14	21,1	,199	,749	,016
15	23,9	,099	4,537	,015
16	26,7	0	2,131	,014
17	29,4	0	0	,013
18	32,2	0	0	,011
19	37,8	0	0	,01
20	40,6	0	0	,009
21	43,3	0	0	,008

Figure A.15 Input form of rheological properties of crude oil

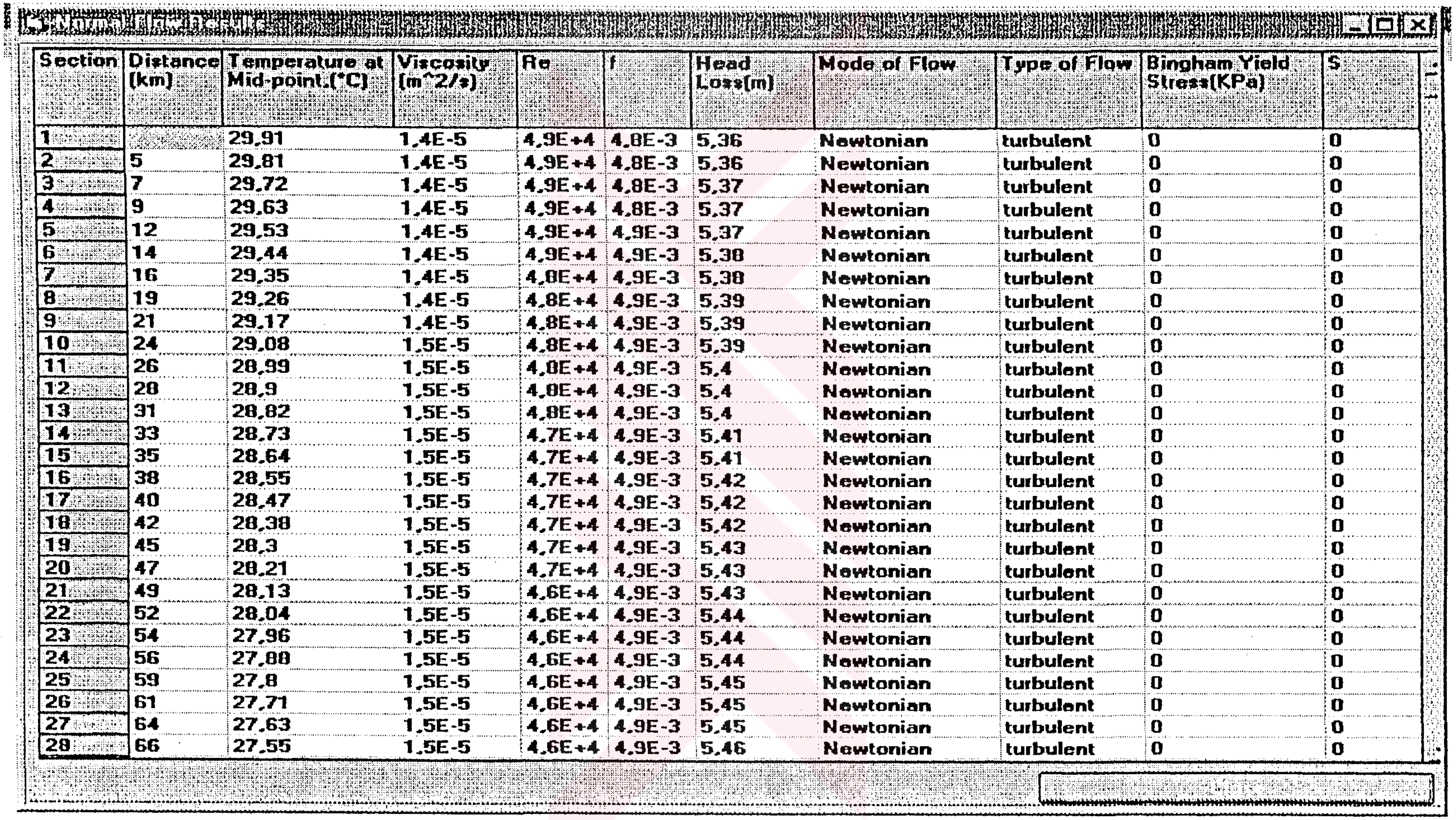


	TEMPERATURE	VISCOSITY
	(C)	(m^2/s)
1	12,8	,446
2	13,3	,372
3	13,9	,31
4	14,4	,251
5	15	,211
6	15,6	,175
7	16,1	,153
8	16,7	,128
9	17,2	,108
10	17,8	,087
11	18,9	,059
12	19,4	,048
13	20	,039
14	20,6	,033
15	21,1	,027
16	23,9	,018
17	26,7	,014
18	29,4	,013
19	32,2	,009
20	40,6	,009
21	43,3	,0008
22		

Figure A.16 Input form of viscosity variation with temperature

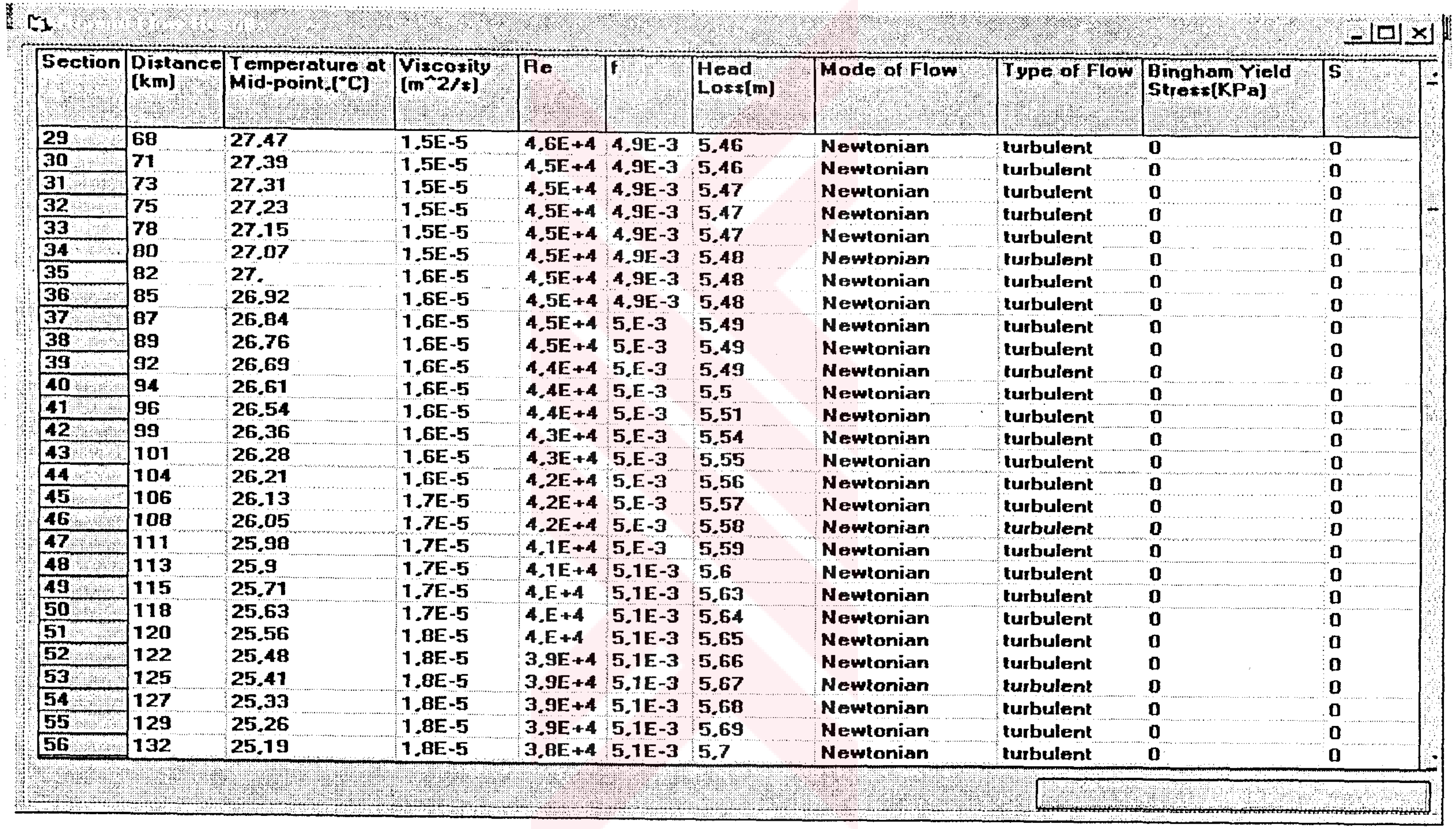
APPENDIX B
EXAMPLE NON-NEWTONIAN ANALYSIS RESULTS OF THE PROGRAM

Table B.1 Newtonian and Non-Newtonian Characteristics of Ceyhan-Kırıkkale Pipeline System for Normal Operating Conditions



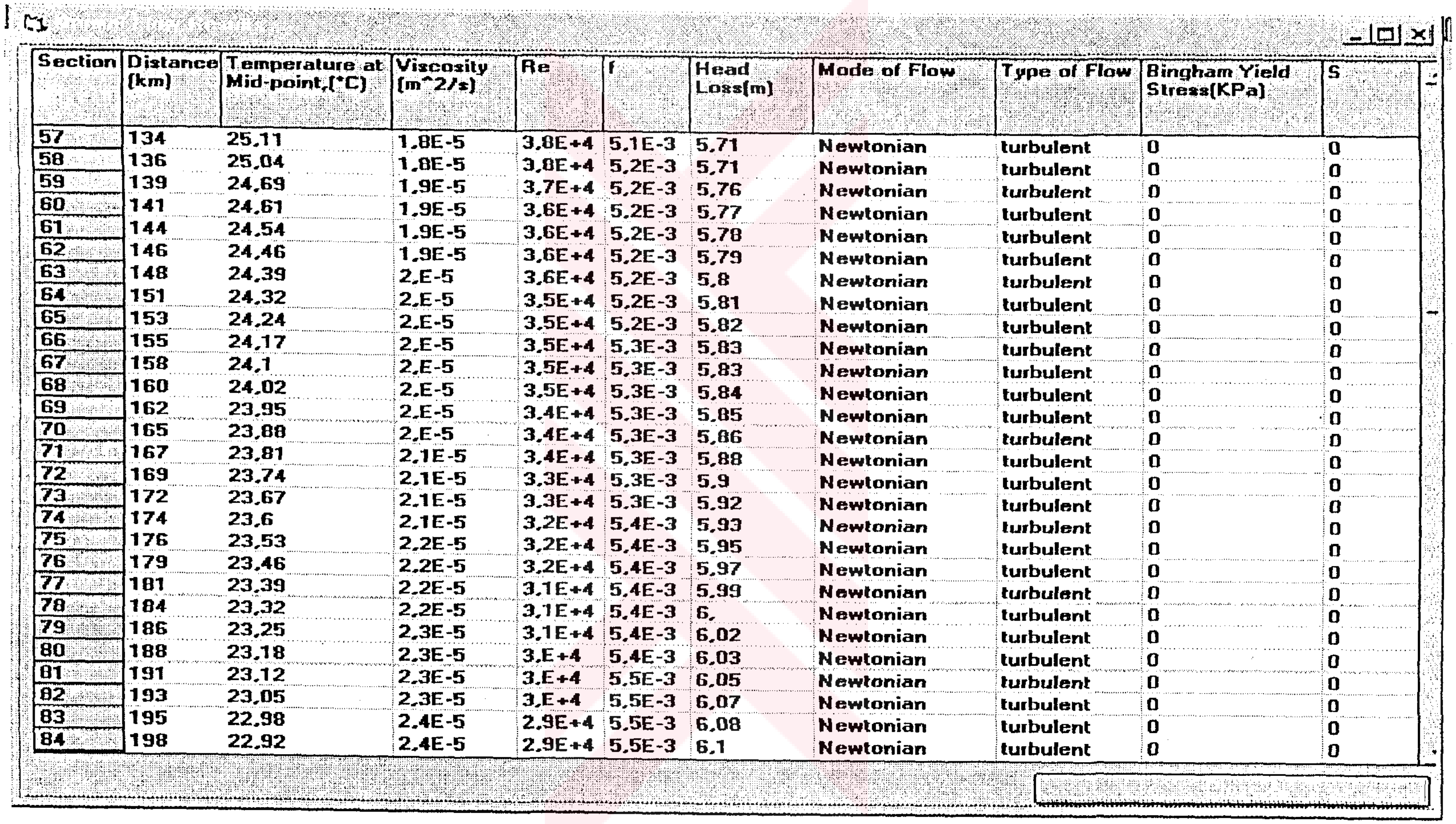
Section	Distance (km)	Temperature at Mid-point.(°C)	Viscosity (m^2/s)	Re	f	Head Loss(m)	Mode of Flow	Type of Flow	Bingham Yield Stress(KPa)	S
1		29,91	1,4E-5	4,9E+4	4,8E-3	5,36	Newtonian	turbulent	0	0
2	5	29,81	1,4E-5	4,9E+4	4,8E-3	5,36	Newtonian	turbulent	0	0
3	7	29,72	1,4E-5	4,9E+4	4,8E-3	5,37	Newtonian	turbulent	0	0
4	9	29,63	1,4E-5	4,9E+4	4,8E-3	5,37	Newtonian	turbulent	0	0
5	12	29,53	1,4E-5	4,9E+4	4,9E-3	5,37	Newtonian	turbulent	0	0
6	14	29,44	1,4E-5	4,9E+4	4,9E-3	5,38	Newtonian	turbulent	0	0
7	16	29,35	1,4E-5	4,8E+4	4,9E-3	5,38	Newtonian	turbulent	0	0
8	19	29,26	1,4E-5	4,8E+4	4,9E-3	5,39	Newtonian	turbulent	0	0
9	21	29,17	1,4E-5	4,8E+4	4,9E-3	5,39	Newtonian	turbulent	0	0
10	24	29,08	1,5E-5	4,8E+4	4,9E-3	5,39	Newtonian	turbulent	0	0
11	26	28,99	1,5E-5	4,8E+4	4,9E-3	5,4	Newtonian	turbulent	0	0
12	28	28,9	1,5E-5	4,8E+4	4,9E-3	5,4	Newtonian	turbulent	0	0
13	31	28,82	1,5E-5	4,8E+4	4,9E-3	5,4	Newtonian	turbulent	0	0
14	33	28,73	1,5E-5	4,7E+4	4,9E-3	5,41	Newtonian	turbulent	0	0
15	35	28,64	1,5E-5	4,7E+4	4,9E-3	5,41	Newtonian	turbulent	0	0
16	38	28,55	1,5E-5	4,7E+4	4,9E-3	5,42	Newtonian	turbulent	0	0
17	40	28,47	1,5E-5	4,7E+4	4,9E-3	5,42	Newtonian	turbulent	0	0
18	42	28,38	1,5E-5	4,7E+4	4,9E-3	5,42	Newtonian	turbulent	0	0
19	45	28,3	1,5E-5	4,7E+4	4,9E-3	5,43	Newtonian	turbulent	0	0
20	47	28,21	1,5E-5	4,7E+4	4,9E-3	5,43	Newtonian	turbulent	0	0
21	49	28,13	1,5E-5	4,6E+4	4,9E-3	5,43	Newtonian	turbulent	0	0
22	52	28,04	1,5E-5	4,6E+4	4,9E-3	5,44	Newtonian	turbulent	0	0
23	54	27,96	1,5E-5	4,6E+4	4,9E-3	5,44	Newtonian	turbulent	0	0
24	56	27,88	1,5E-5	4,6E+4	4,9E-3	5,44	Newtonian	turbulent	0	0
25	59	27,8	1,5E-5	4,6E+4	4,9E-3	5,45	Newtonian	turbulent	0	0
26	61	27,71	1,5E-5	4,6E+4	4,9E-3	5,45	Newtonian	turbulent	0	0
27	64	27,63	1,5E-5	4,6E+4	4,9E-3	5,45	Newtonian	turbulent	0	0
28	66	27,55	1,5E-5	4,6E+4	4,9E-3	5,46	Newtonian	turbulent	0	0

Table B 1 Continued



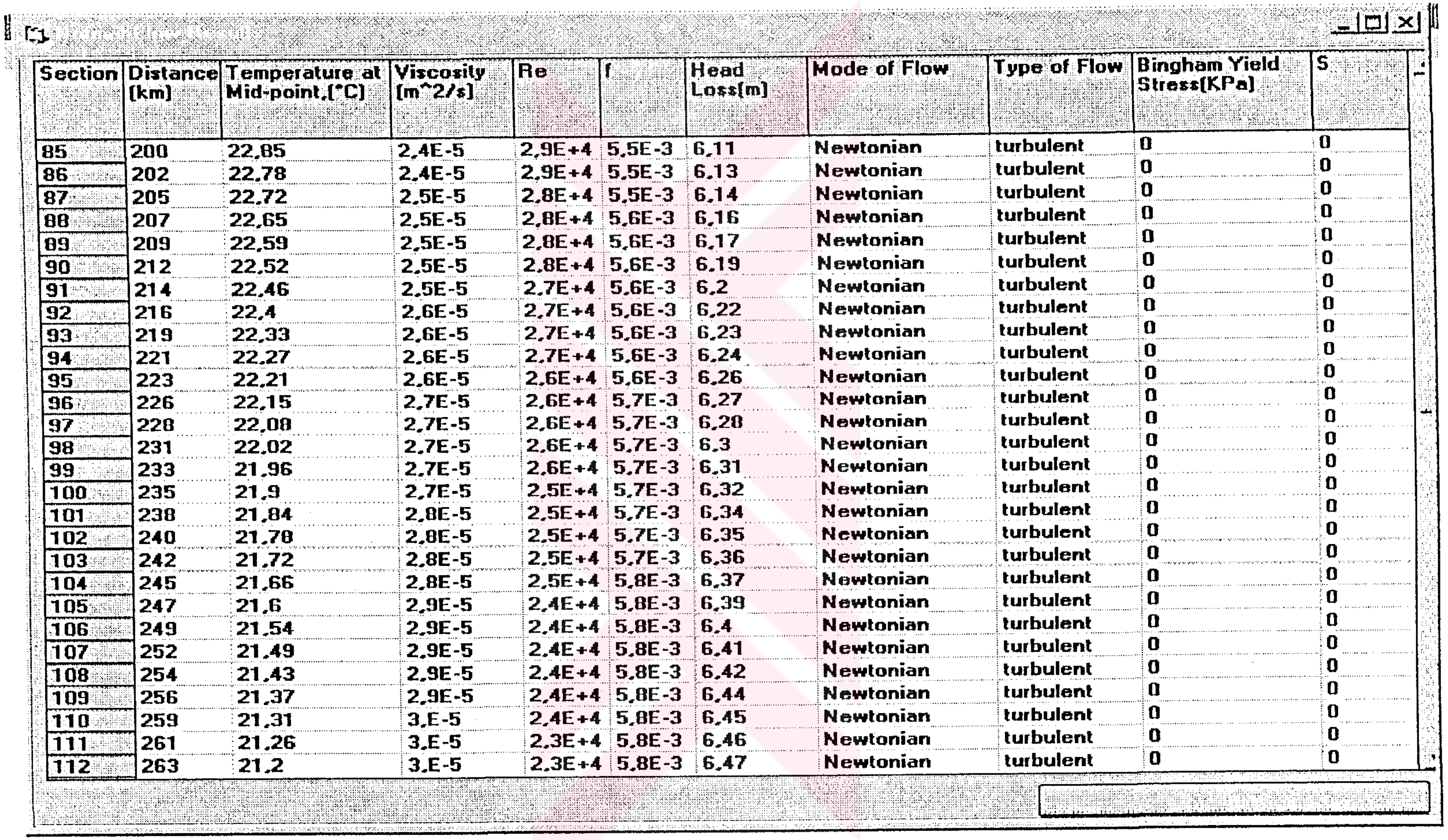
Section	Distance (km)	Temperature at Mid-point,(°C)	Viscosity (m^2/s)	Re	f	Head Loss(m)	Mode of Flow	Type of Flow	Bingham Yield Stress(KPa)	S
29	68	27,47	1,5E-5	4,6E+4	4,9E-3	5,46	Newtonian	turbulent	0	0
30	71	27,39	1,5E-5	4,5E+4	4,9E-3	5,46	Newtonian	turbulent	0	0
31	73	27,31	1,5E-5	4,5E+4	4,9E-3	5,47	Newtonian	turbulent	0	0
32	75	27,23	1,5E-5	4,5E+4	4,9E-3	5,47	Newtonian	turbulent	0	0
33	78	27,15	1,5E-5	4,5E+4	4,9E-3	5,47	Newtonian	turbulent	0	0
34	80	27,07	1,5E-5	4,5E+4	4,9E-3	5,48	Newtonian	turbulent	0	0
35	82	27,	1,6E-5	4,5E+4	4,9E-3	5,48	Newtonian	turbulent	0	0
36	85	26,92	1,6E-5	4,5E+4	4,9E-3	5,48	Newtonian	turbulent	0	0
37	87	26,84	1,6E-5	4,5E+4	5,E-3	5,49	Newtonian	turbulent	0	0
38	89	26,76	1,6E-5	4,5E+4	5,E-3	5,49	Newtonian	turbulent	0	0
39	92	26,69	1,6E-5	4,4E+4	5,E-3	5,49	Newtonian	turbulent	0	0
40	94	26,61	1,6E-5	4,4E+4	5,E-3	5,5	Newtonian	turbulent	0	0
41	96	26,54	1,6E-5	4,4E+4	5,E-3	5,51	Newtonian	turbulent	0	0
42	99	26,36	1,6E-5	4,3E+4	5,E-3	5,54	Newtonian	turbulent	0	0
43	101	26,28	1,6E-5	4,3E+4	5,E-3	5,55	Newtonian	turbulent	0	0
44	104	26,21	1,6E-5	4,2E+4	5,E-3	5,56	Newtonian	turbulent	0	0
45	106	26,13	1,7E-5	4,2E+4	5,E-3	5,57	Newtonian	turbulent	0	0
46	108	26,05	1,7E-5	4,2E+4	5,E-3	5,58	Newtonian	turbulent	0	0
47	111	25,98	1,7E-5	4,1E+4	5,E-3	5,59	Newtonian	turbulent	0	0
48	113	25,9	1,7E-5	4,1E+4	5,1E-3	5,6	Newtonian	turbulent	0	0
49	115	25,71	1,7E-5	4,E+4	5,1E-3	5,63	Newtonian	turbulent	0	0
50	118	25,63	1,7E-5	4,E+4	5,1E-3	5,64	Newtonian	turbulent	0	0
51	120	25,56	1,8E-5	4,E+4	5,1E-3	5,65	Newtonian	turbulent	0	0
52	122	25,48	1,8E-5	3,9E+4	5,1E-3	5,66	Newtonian	turbulent	0	0
53	125	25,41	1,8E-5	3,9E+4	5,1E-3	5,67	Newtonian	turbulent	0	0
54	127	25,33	1,8E-5	3,9E+4	5,1E-3	5,68	Newtonian	turbulent	0	0
55	129	25,26	1,8E-5	3,9E+4	5,1E-3	5,69	Newtonian	turbulent	0	0
56	132	25,19	1,8E-5	3,8E+4	5,1E-3	5,7	Newtonian	turbulent	0	0

Table B 1 Continued



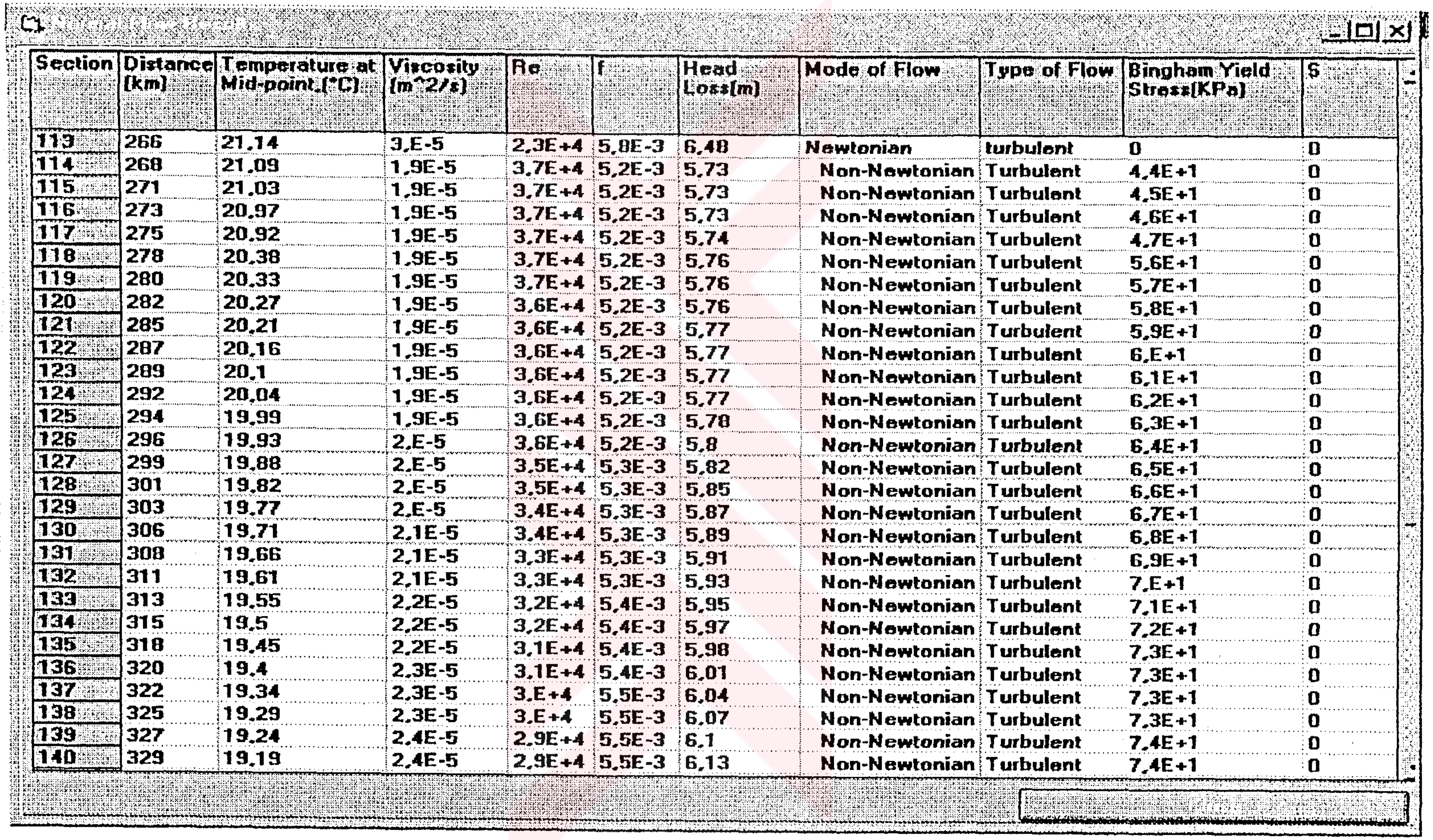
Section	Distance (km)	Temperature at Mid-point,(°C)	Viscosity (m^2/s)	Re	f	Head Loss(m)	Mode of Flow	Type of Flow	Bingham Yield Stress(KPa)	S
57	134	25,11	1,8E-5	3,8E+4	5,1E-3	5,71	Newtonian	turbulent	0	0
58	136	25,04	1,8E-5	3,8E+4	5,2E-3	5,71	Newtonian	turbulent	0	0
59	139	24,69	1,9E-5	3,7E+4	5,2E-3	5,76	Newtonian	turbulent	0	0
60	141	24,61	1,9E-5	3,6E+4	5,2E-3	5,77	Newtonian	turbulent	0	0
61	144	24,54	1,9E-5	3,6E+4	5,2E-3	5,78	Newtonian	turbulent	0	0
62	146	24,46	1,9E-5	3,6E+4	5,2E-3	5,79	Newtonian	turbulent	0	0
63	148	24,39	2,E-5	3,6E+4	5,2E-3	5,8	Newtonian	turbulent	0	0
64	151	24,32	2,E-5	3,5E+4	5,2E-3	5,81	Newtonian	turbulent	0	0
65	153	24,24	2,E-5	3,5E+4	5,2E-3	5,82	Newtonian	turbulent	0	0
66	155	24,17	2,E-5	3,5E+4	5,3E-3	5,83	Newtonian	turbulent	0	0
67	158	24,1	2,E-5	3,5E+4	5,3E-3	5,83	Newtonian	turbulent	0	0
68	160	24,02	2,E-5	3,5E+4	5,3E-3	5,84	Newtonian	turbulent	0	0
69	162	23,95	2,E-5	3,4E+4	5,3E-3	5,85	Newtonian	turbulent	0	0
70	165	23,88	2,E-5	3,4E+4	5,3E-3	5,86	Newtonian	turbulent	0	0
71	167	23,81	2,1E-5	3,4E+4	5,3E-3	5,88	Newtonian	turbulent	0	0
72	169	23,74	2,1E-5	3,3E+4	5,3E-3	5,9	Newtonian	turbulent	0	0
73	172	23,67	2,1E-5	3,3E+4	5,3E-3	5,92	Newtonian	turbulent	0	0
74	174	23,6	2,1E-5	3,2E+4	5,4E-3	5,93	Newtonian	turbulent	0	0
75	176	23,53	2,2E-5	3,2E+4	5,4E-3	5,95	Newtonian	turbulent	0	0
76	179	23,46	2,2E-5	3,2E+4	5,4E-3	5,97	Newtonian	turbulent	0	0
77	181	23,39	2,2E-5	3,1E+4	5,4E-3	5,99	Newtonian	turbulent	0	0
78	184	23,32	2,2E-5	3,1E+4	5,4E-3	6,	Newtonian	turbulent	0	0
79	186	23,25	2,3E-5	3,1E+4	5,4E-3	6,02	Newtonian	turbulent	0	0
80	188	23,18	2,3E-5	3,E+4	5,4E-3	6,03	Newtonian	turbulent	0	0
81	191	23,12	2,3E-5	3,E+4	5,5E-3	6,05	Newtonian	turbulent	0	0
82	193	23,05	2,3E-5	3,E+4	5,5E-3	6,07	Newtonian	turbulent	0	0
83	195	22,98	2,4E-5	2,9E+4	5,5E-3	6,08	Newtonian	turbulent	0	0
84	198	22,92	2,4E-5	2,9E+4	5,5E-3	6,1	Newtonian	turbulent	0	0

Table B 1 Continued



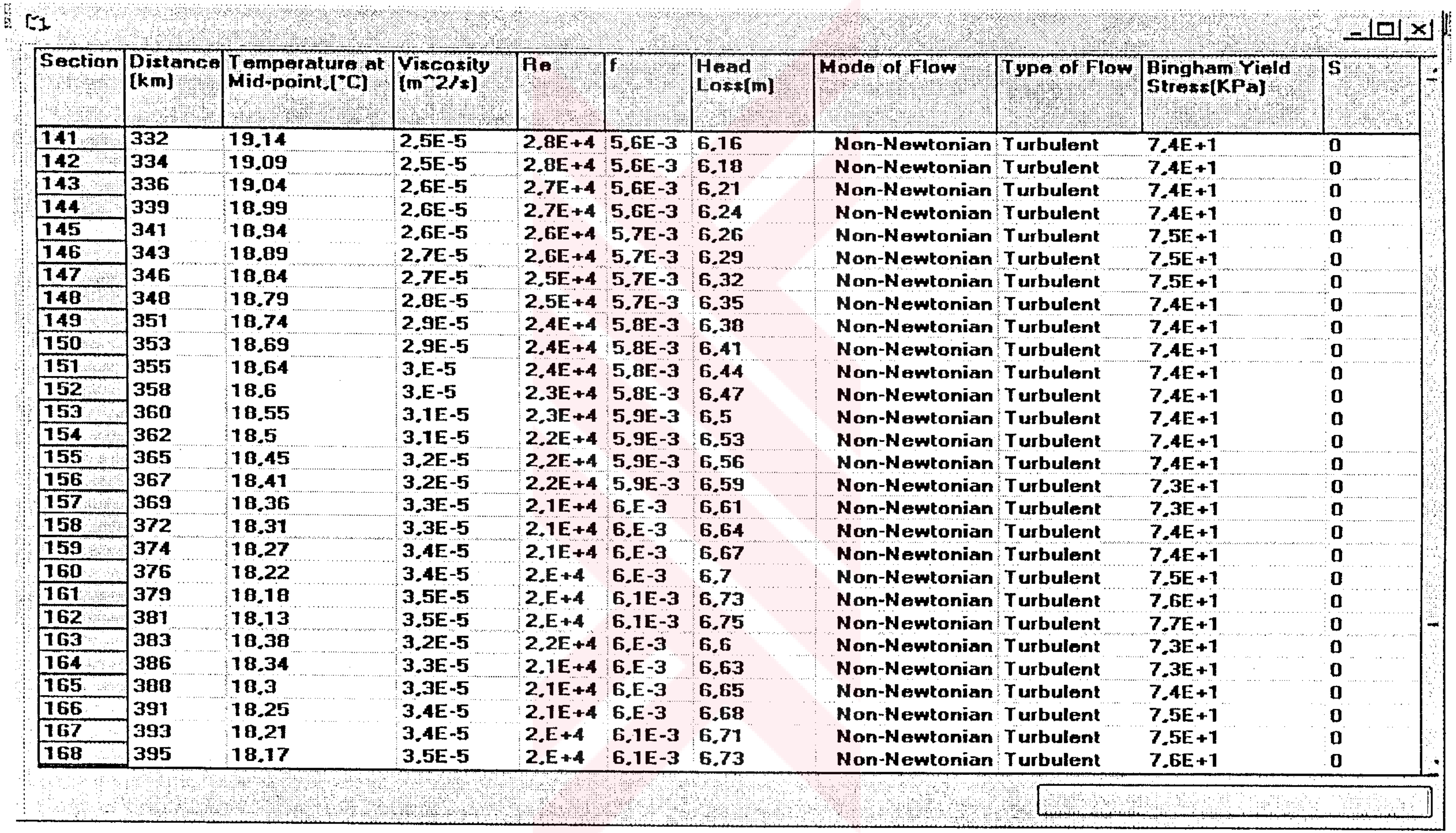
Section	Distance [km]	Temperature at Mid-point,[°C]	Viscosity [m^2/s]	Re	f	Head Loss[m]	Mode of Flow	Type of Flow	Bingham Yield Stress[KPa]	S
85	200	22,85	2,4E-5	2,9E+4	5,5E-3	6,11	Newtonian	turbulent	0	0
86	202	22,78	2,4E-5	2,9E+4	5,5E-3	6,13	Newtonian	turbulent	0	0
87	205	22,72	2,5E-5	2,8E+4	5,5E-3	6,14	Newtonian	turbulent	0	0
88	207	22,65	2,5E-5	2,8E+4	5,6E-3	6,16	Newtonian	turbulent	0	0
89	209	22,59	2,5E-5	2,8E+4	5,6E-3	6,17	Newtonian	turbulent	0	0
90	212	22,52	2,5E-5	2,8E+4	5,6E-3	6,19	Newtonian	turbulent	0	0
91	214	22,46	2,5E-5	2,7E+4	5,6E-3	6,2	Newtonian	turbulent	0	0
92	216	22,4	2,6E-5	2,7E+4	5,6E-3	6,22	Newtonian	turbulent	0	0
93	219	22,33	2,6E-5	2,7E+4	5,6E-3	6,23	Newtonian	turbulent	0	0
94	221	22,27	2,6E-5	2,7E+4	5,6E-3	6,24	Newtonian	turbulent	0	0
95	223	22,21	2,6E-5	2,6E+4	5,6E-3	6,26	Newtonian	turbulent	0	0
96	226	22,15	2,7E-5	2,6E+4	5,7E-3	6,27	Newtonian	turbulent	0	0
97	228	22,08	2,7E-5	2,6E+4	5,7E-3	6,28	Newtonian	turbulent	0	0
98	231	22,02	2,7E-5	2,6E+4	5,7E-3	6,3	Newtonian	turbulent	0	0
99	233	21,96	2,7E-5	2,6E+4	5,7E-3	6,31	Newtonian	turbulent	0	0
100	235	21,9	2,7E-5	2,5E+4	5,7E-3	6,32	Newtonian	turbulent	0	0
101	238	21,84	2,8E-5	2,5E+4	5,7E-3	6,34	Newtonian	turbulent	0	0
102	240	21,78	2,8E-5	2,5E+4	5,7E-3	6,35	Newtonian	turbulent	0	0
103	242	21,72	2,8E-5	2,5E+4	5,7E-3	6,36	Newtonian	turbulent	0	0
104	245	21,66	2,8E-5	2,5E+4	5,8E-3	6,37	Newtonian	turbulent	0	0
105	247	21,6	2,9E-5	2,4E+4	5,8E-3	6,39	Newtonian	turbulent	0	0
106	249	21,54	2,9E-5	2,4E+4	5,8E-3	6,4	Newtonian	turbulent	0	0
107	252	21,49	2,9E-5	2,4E+4	5,8E-3	6,41	Newtonian	turbulent	0	0
108	254	21,43	2,9E-5	2,4E+4	5,8E-3	6,42	Newtonian	turbulent	0	0
109	256	21,37	2,9E-5	2,4E+4	5,8E-3	6,44	Newtonian	turbulent	0	0
110	259	21,31	3,E-5	2,4E+4	5,8E-3	6,45	Newtonian	turbulent	0	0
111	261	21,26	3,E-5	2,3E+4	5,8E-3	6,46	Newtonian	turbulent	0	0
112	263	21,2	3,E-5	2,3E+4	5,8E-3	6,47	Newtonian	turbulent	0	0

Table B 1 Continued



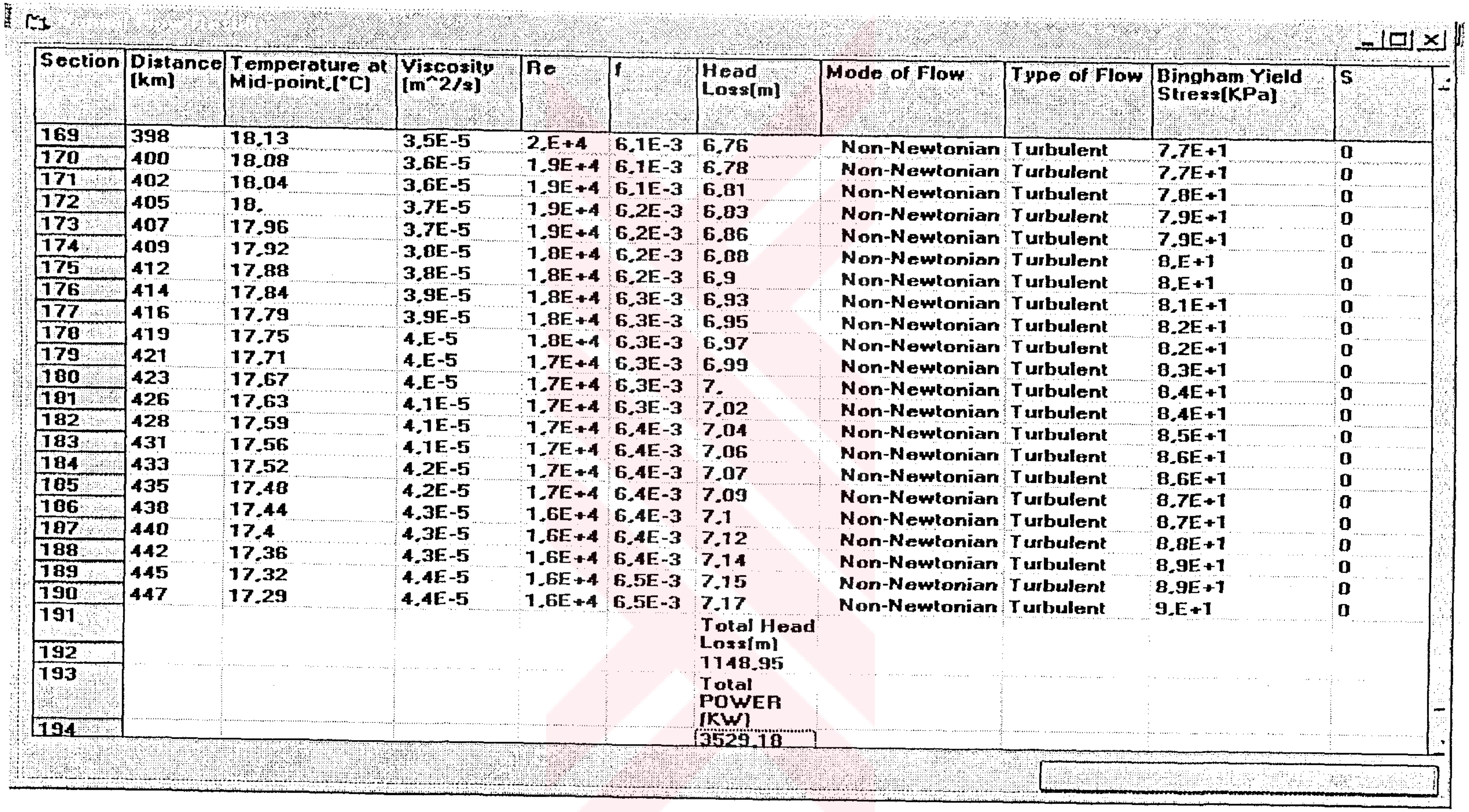
Section	Distance [km]	Temperature at Mid-point.[°C]	Viscosity [m^2/s]	Re	f	Head Loss[m]	Mode of Flow	Type of Flow	Bingham Yield Stress[KPa]	S
113	266	21,14	3,E-5	2,3E+4	5,8E-3	6,48	Newtonian	turbulent	0	0
114	268	21,09	1,9E-5	3,7E+4	5,2E-3	5,73	Non-Newtonian	Turbulent	4,4E+1	0
115	271	21,03	1,9E-5	3,7E+4	5,2E-3	5,73	Non-Newtonian	Turbulent	4,5E+1	0
116	273	20,97	1,9E-5	3,7E+4	5,2E-3	5,73	Non-Newtonian	Turbulent	4,6E+1	0
117	275	20,92	1,9E-5	3,7E+4	5,2E-3	5,74	Non-Newtonian	Turbulent	4,7E+1	0
118	278	20,38	1,9E-5	3,7E+4	5,2E-3	5,76	Non-Newtonian	Turbulent	5,6E+1	0
119	280	20,33	1,9E-5	3,7E+4	5,2E-3	5,76	Non-Newtonian	Turbulent	5,7E+1	0
120	282	20,27	1,9E-5	3,6E+4	5,2E-3	5,76	Non-Newtonian	Turbulent	5,8E+1	0
121	285	20,21	1,9E-5	3,6E+4	5,2E-3	5,77	Non-Newtonian	Turbulent	5,9E+1	0
122	287	20,16	1,9E-5	3,6E+4	5,2E-3	5,77	Non-Newtonian	Turbulent	6,E+1	0
123	289	20,1	1,9E-5	3,6E+4	5,2E-3	5,77	Non-Newtonian	Turbulent	6,1E+1	0
124	292	20,04	1,9E-5	3,6E+4	5,2E-3	5,77	Non-Newtonian	Turbulent	6,2E+1	0
125	294	19,99	1,9E-5	3,6E+4	5,2E-3	5,78	Non-Newtonian	Turbulent	6,3E+1	0
126	296	19,93	2,E-5	3,6E+4	5,2E-3	5,8	Non-Newtonian	Turbulent	6,4E+1	0
127	299	19,88	2,E-5	3,5E+4	5,3E-3	5,82	Non-Newtonian	Turbulent	6,5E+1	0
128	301	19,82	2,E-5	3,5E+4	5,3E-3	5,85	Non-Newtonian	Turbulent	6,6E+1	0
129	303	19,77	2,E-5	3,4E+4	5,3E-3	5,87	Non-Newtonian	Turbulent	6,7E+1	0
130	306	19,71	2,1E-5	3,4E+4	5,3E-3	5,89	Non-Newtonian	Turbulent	6,8E+1	0
131	308	19,66	2,1E-5	3,3E+4	5,3E-3	5,91	Non-Newtonian	Turbulent	6,9E+1	0
132	311	19,61	2,1E-5	3,3E+4	5,3E-3	5,93	Non-Newtonian	Turbulent	7,E+1	0
133	313	19,55	2,2E-5	3,2E+4	5,4E-3	5,95	Non-Newtonian	Turbulent	7,1E+1	0
134	315	19,5	2,2E-5	3,2E+4	5,4E-3	5,97	Non-Newtonian	Turbulent	7,2E+1	0
135	318	19,45	2,2E-5	3,1E+4	5,4E-3	5,98	Non-Newtonian	Turbulent	7,3E+1	0
136	320	19,4	2,3E-5	3,1E+4	5,4E-3	6,01	Non-Newtonian	Turbulent	7,3E+1	0
137	322	19,34	2,3E-5	3,E+4	5,5E-3	6,04	Non-Newtonian	Turbulent	7,3E+1	0
138	325	19,29	2,3E-5	3,E+4	5,5E-3	6,07	Non-Newtonian	Turbulent	7,3E+1	0
139	327	19,24	2,4E-5	2,9E+4	5,5E-3	6,1	Non-Newtonian	Turbulent	7,4E+1	0
140	329	19,19	2,4E-5	2,9E+4	5,5E-3	6,13	Non-Newtonian	Turbulent	7,4E+1	0

Table B 1 Continued



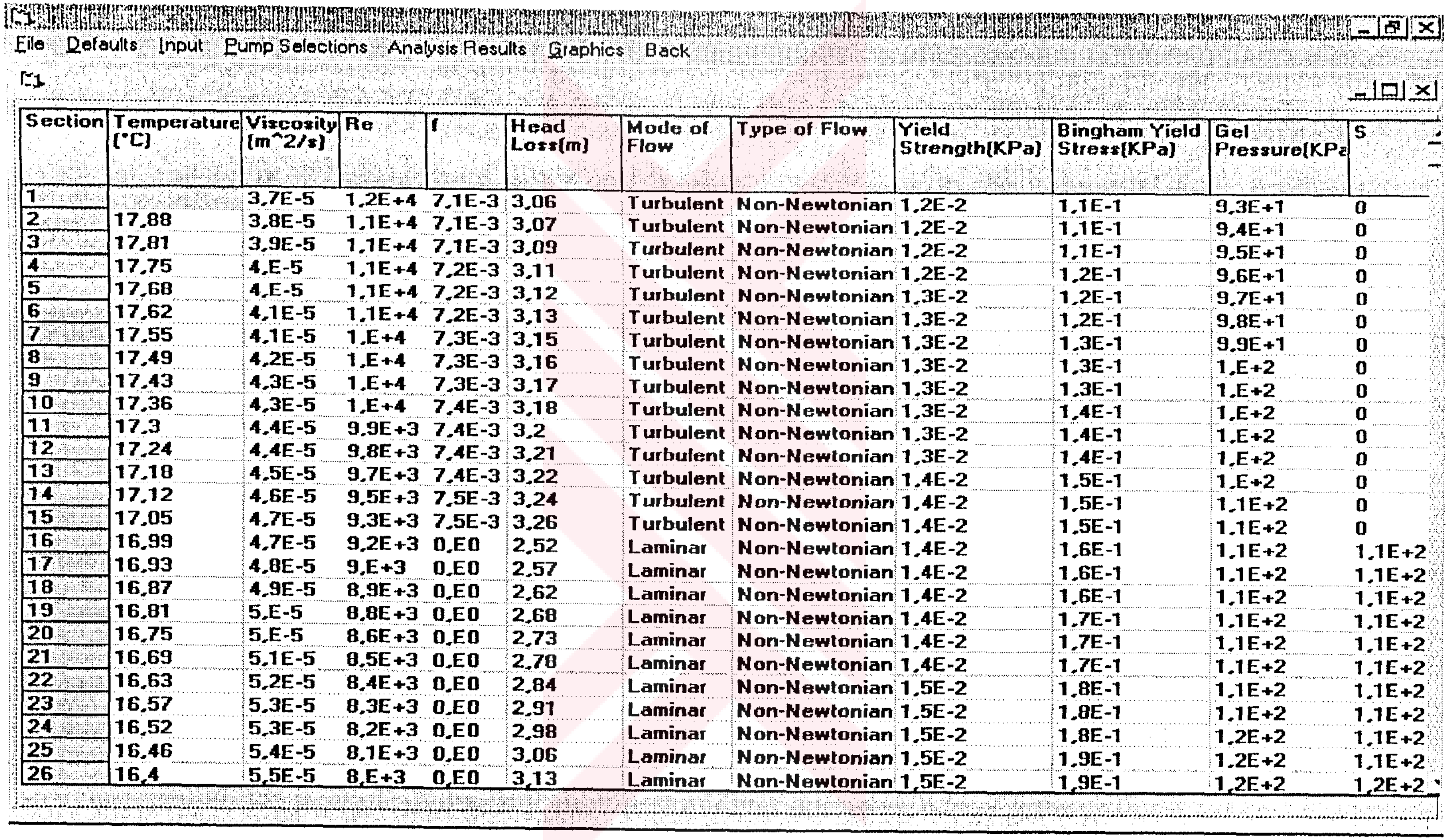
Section	Distance (km)	Temperature at Mid-point,[°C]	Viscosity (m^2/s)	Re	f	Head Loss(m)	Mode of Flow	Type of Flow	Bingham Yield Stress(KPa)	S
141	332	19,14	2,5E-5	2,8E+4	5,6E-3	6,16	Non-Newtonian	Turbulent	7,4E+1	0
142	334	19,09	2,5E-5	2,8E+4	5,6E-3	6,18	Non-Newtonian	Turbulent	7,4E+1	0
143	336	19,04	2,6E-5	2,7E+4	5,6E-3	6,21	Non-Newtonian	Turbulent	7,4E+1	0
144	339	18,99	2,6E-5	2,7E+4	5,6E-3	6,24	Non-Newtonian	Turbulent	7,4E+1	0
145	341	18,94	2,6E-5	2,6E+4	5,7E-3	6,26	Non-Newtonian	Turbulent	7,5E+1	0
146	343	18,89	2,7E-5	2,6E+4	5,7E-3	6,29	Non-Newtonian	Turbulent	7,5E+1	0
147	346	18,84	2,7E-5	2,5E+4	5,7E-3	6,32	Non-Newtonian	Turbulent	7,5E+1	0
148	348	18,79	2,8E-5	2,5E+4	5,7E-3	6,35	Non-Newtonian	Turbulent	7,4E+1	0
149	351	18,74	2,9E-5	2,4E+4	5,8E-3	6,38	Non-Newtonian	Turbulent	7,4E+1	0
150	353	18,69	2,9E-5	2,4E+4	5,8E-3	6,41	Non-Newtonian	Turbulent	7,4E+1	0
151	355	18,64	3,E-5	2,4E+4	5,8E-3	6,44	Non-Newtonian	Turbulent	7,4E+1	0
152	358	18,6	3,E-5	2,3E+4	5,8E-3	6,47	Non-Newtonian	Turbulent	7,4E+1	0
153	360	18,55	3,1E-5	2,3E+4	5,9E-3	6,5	Non-Newtonian	Turbulent	7,4E+1	0
154	362	18,5	3,1E-5	2,2E+4	5,9E-3	6,53	Non-Newtonian	Turbulent	7,4E+1	0
155	365	18,45	3,2E-5	2,2E+4	5,9E-3	6,56	Non-Newtonian	Turbulent	7,4E+1	0
156	367	18,41	3,2E-5	2,2E+4	5,9E-3	6,59	Non-Newtonian	Turbulent	7,3E+1	0
157	369	18,36	3,3E-5	2,1E+4	6,E-3	6,61	Non-Newtonian	Turbulent	7,3E+1	0
158	372	18,31	3,3E-5	2,1E+4	6,E-3	6,64	Non-Newtonian	Turbulent	7,4E+1	0
159	374	18,27	3,4E-5	2,1E+4	6,E-3	6,67	Non-Newtonian	Turbulent	7,4E+1	0
160	376	18,22	3,4E-5	2,E+4	6,E-3	6,7	Non-Newtonian	Turbulent	7,5E+1	0
161	379	18,18	3,5E-5	2,E+4	6,1E-3	6,73	Non-Newtonian	Turbulent	7,6E+1	0
162	381	18,13	3,5E-5	2,E+4	6,1E-3	6,75	Non-Newtonian	Turbulent	7,7E+1	0
163	383	18,38	3,2E-5	2,2E+4	6,E-3	6,6	Non-Newtonian	Turbulent	7,3E+1	0
164	386	18,34	3,3E-5	2,1E+4	6,E-3	6,63	Non-Newtonian	Turbulent	7,3E+1	0
165	388	18,3	3,3E-5	2,1E+4	6,E-3	6,65	Non-Newtonian	Turbulent	7,4E+1	0
166	391	18,25	3,4E-5	2,1E+4	6,E-3	6,68	Non-Newtonian	Turbulent	7,5E+1	0
167	393	18,21	3,4E-5	2,E+4	6,1E-3	6,71	Non-Newtonian	Turbulent	7,5E+1	0
168	395	18,17	3,5E-5	2,E+4	6,1E-3	6,73	Non-Newtonian	Turbulent	7,6E+1	0

Table B 1 Continued



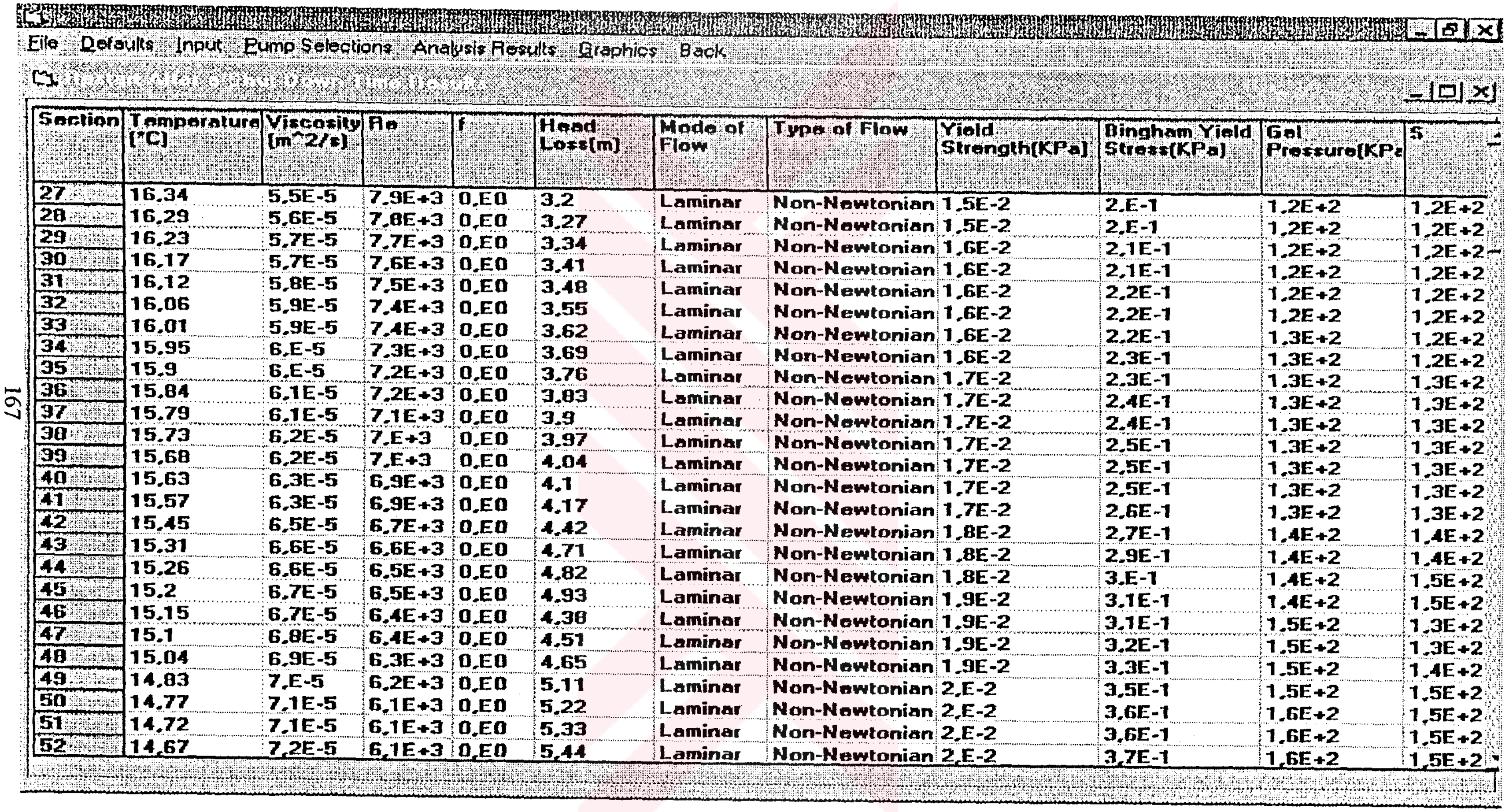
Section	Distance [km]	Temperature at Mid-point,[°C]	Viscosity [m^2/s]	Re	f	Head Loss[m]	Mode of Flow	Type of Flow	Bingham Yield Stress[KPa]	S
169	398	18,13	3,5E-5	2,E+4	6,1E-3	6,76	Non-Newtonian	Turbulent	7,7E+1	0
170	400	18,08	3,6E-5	1,9E+4	6,1E-3	6,78	Non-Newtonian	Turbulent	7,7E+1	0
171	402	18,04	3,6E-5	1,9E+4	6,1E-3	6,81	Non-Newtonian	Turbulent	7,8E+1	0
172	405	18,	3,7E-5	1,9E+4	6,2E-3	6,83	Non-Newtonian	Turbulent	7,9E+1	0
173	407	17,96	3,7E-5	1,9E+4	6,2E-3	6,86	Non-Newtonian	Turbulent	7,9E+1	0
174	409	17,92	3,8E-5	1,8E+4	6,2E-3	6,88	Non-Newtonian	Turbulent	8,E+1	0
175	412	17,88	3,8E-5	1,8E+4	6,2E-3	6,9	Non-Newtonian	Turbulent	8,E+1	0
176	414	17,84	3,9E-5	1,8E+4	6,3E-3	6,93	Non-Newtonian	Turbulent	8,1E+1	0
177	416	17,79	3,9E-5	1,8E+4	6,3E-3	6,95	Non-Newtonian	Turbulent	8,2E+1	0
178	419	17,75	4,E-5	1,8E+4	6,3E-3	6,97	Non-Newtonian	Turbulent	8,2E+1	0
179	421	17,71	4,E-5	1,7E+4	6,3E-3	6,99	Non-Newtonian	Turbulent	8,3E+1	0
180	423	17,67	4,E-5	1,7E+4	6,3E-3	7,	Non-Newtonian	Turbulent	8,4E+1	0
181	426	17,63	4,1E-5	1,7E+4	6,3E-3	7,02	Non-Newtonian	Turbulent	8,4E+1	0
182	428	17,59	4,1E-5	1,7E+4	6,4E-3	7,04	Non-Newtonian	Turbulent	8,5E+1	0
183	431	17,56	4,1E-5	1,7E+4	6,4E-3	7,06	Non-Newtonian	Turbulent	8,6E+1	0
184	433	17,52	4,2E-5	1,7E+4	6,4E-3	7,07	Non-Newtonian	Turbulent	8,6E+1	0
185	435	17,48	4,2E-5	1,7E+4	6,4E-3	7,09	Non-Newtonian	Turbulent	8,7E+1	0
186	438	17,44	4,3E-5	1,6E+4	6,4E-3	7,1	Non-Newtonian	Turbulent	8,7E+1	0
187	440	17,4	4,3E-5	1,6E+4	6,4E-3	7,12	Non-Newtonian	Turbulent	8,8E+1	0
188	442	17,36	4,3E-5	1,6E+4	6,4E-3	7,14	Non-Newtonian	Turbulent	8,9E+1	0
189	445	17,32	4,4E-5	1,6E+4	6,5E-3	7,15	Non-Newtonian	Turbulent	8,9E+1	0
190	447	17,29	4,4E-5	1,6E+4	6,5E-3	7,17	Non-Newtonian	Turbulent	9,E+1	0
191						Total Head Loss[m]				
192						1148,95				
193						Total POWER [KW]				
194						3529,18				

Table B 2 Newtonian and Non-Newtonian Characteristics of Ceyhan-Kırıkkale Pipeline System for Re-start after 36 h Shutdown



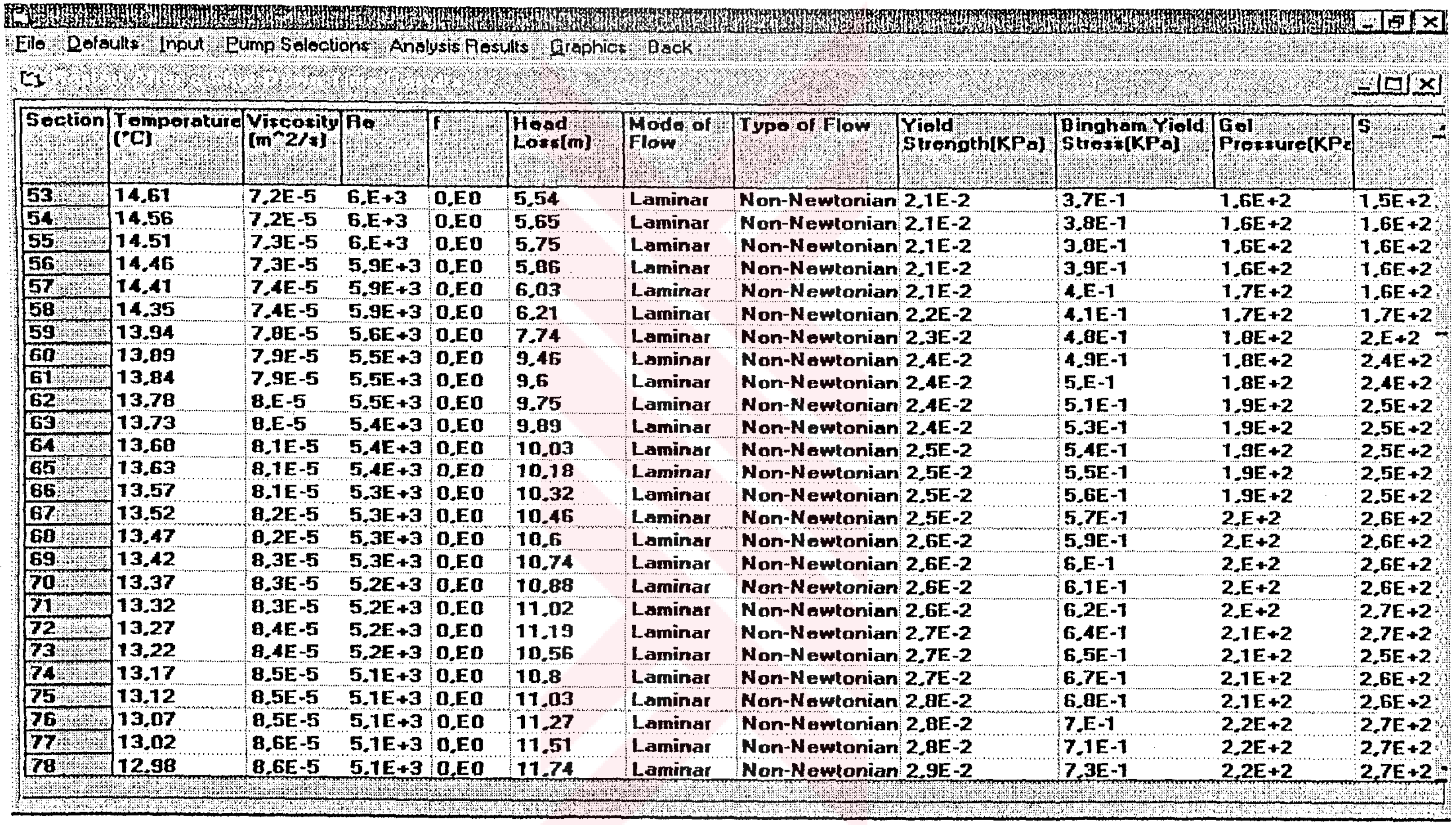
Section	Temperature (°C)	Viscosity (m^2/s)	Re	f	Head Loss(m)	Mode of Flow	Type of Flow	Yield Strength(KPa)	Bingham Yield Stress(KPa)	Gel Pressure(KPa	S
1		3,7E-5	1,2E+4	7,1E-3	3,06	Turbulent	Non-Newtonian	1,2E-2	1,1E-1	9,3E+1	0
2	17,88	3,8E-5	1,1E+4	7,1E-3	3,07	Turbulent	Non-Newtonian	1,2E-2	1,1E-1	9,4E+1	0
3	17,81	3,9E-5	1,1E+4	7,1E-3	3,09	Turbulent	Non-Newtonian	1,2E-2	1,1E-1	9,5E+1	0
4	17,75	4,E-5	1,1E+4	7,2E-3	3,11	Turbulent	Non-Newtonian	1,2E-2	1,2E-1	9,6E+1	0
5	17,68	4,E-5	1,1E+4	7,2E-3	3,12	Turbulent	Non-Newtonian	1,3E-2	1,2E-1	9,7E+1	0
6	17,62	4,1E-5	1,1E+4	7,2E-3	3,13	Turbulent	Non-Newtonian	1,3E-2	1,2E-1	9,8E+1	0
7	17,55	4,1E-5	1,E+4	7,3E-3	3,15	Turbulent	Non-Newtonian	1,3E-2	1,3E-1	9,9E+1	0
8	17,49	4,2E-5	1,E+4	7,3E-3	3,16	Turbulent	Non-Newtonian	1,3E-2	1,3E-1	1,E+2	0
9	17,43	4,3E-5	1,E+4	7,3E-3	3,17	Turbulent	Non-Newtonian	1,3E-2	1,3E-1	1,E+2	0
10	17,36	4,3E-5	1,E+4	7,4E-3	3,18	Turbulent	Non-Newtonian	1,3E-2	1,4E-1	1,E+2	0
11	17,3	4,4E-5	9,9E+3	7,4E-3	3,2	Turbulent	Non-Newtonian	1,3E-2	1,4E-1	1,E+2	0
12	17,24	4,4E-5	9,8E+3	7,4E-3	3,21	Turbulent	Non-Newtonian	1,3E-2	1,4E-1	1,E+2	0
13	17,18	4,5E-5	9,7E+3	7,4E-3	3,22	Turbulent	Non-Newtonian	1,4E-2	1,5E-1	1,E+2	0
14	17,12	4,6E-5	9,5E+3	7,5E-3	3,24	Turbulent	Non-Newtonian	1,4E-2	1,5E-1	1,1E+2	0
15	17,05	4,7E-5	9,3E+3	7,5E-3	3,26	Turbulent	Non-Newtonian	1,4E-2	1,5E-1	1,1E+2	0
16	16,99	4,7E-5	9,2E+3	0,E0	2,52	Laminar	Non-Newtonian	1,4E-2	1,6E-1	1,1E+2	1,1E+2
17	16,93	4,8E-5	9,E+3	0,E0	2,57	Laminar	Non-Newtonian	1,4E-2	1,6E-1	1,1E+2	1,1E+2
18	16,87	4,9E-5	8,9E+3	0,E0	2,62	Laminar	Non-Newtonian	1,4E-2	1,6E-1	1,1E+2	1,1E+2
19	16,81	5,E-5	8,8E+3	0,E0	2,68	Laminar	Non-Newtonian	1,4E-2	1,7E-1	1,1E+2	1,1E+2
20	16,75	5,E-5	8,6E+3	0,E0	2,73	Laminar	Non-Newtonian	1,4E-2	1,7E-1	1,1E+2	1,1E+2
21	16,69	5,1E-5	8,5E+3	0,E0	2,78	Laminar	Non-Newtonian	1,4E-2	1,7E-1	1,1E+2	1,1E+2
22	16,63	5,2E-5	8,4E+3	0,E0	2,84	Laminar	Non-Newtonian	1,5E-2	1,8E-1	1,1E+2	1,1E+2
23	16,57	5,3E-5	8,3E+3	0,E0	2,91	Laminar	Non-Newtonian	1,5E-2	1,8E-1	1,1E+2	1,1E+2
24	16,52	5,3E-5	8,2E+3	0,E0	2,98	Laminar	Non-Newtonian	1,5E-2	1,8E-1	1,2E+2	1,1E+2
25	16,46	5,4E-5	8,1E+3	0,E0	3,06	Laminar	Non-Newtonian	1,5E-2	1,9E-1	1,2E+2	1,1E+2
26	16,4	5,5E-5	8,E+3	0,E0	3,13	Laminar	Non-Newtonian	1,5E-2	1,9E-1	1,2E+2	1,2E+2

Table B 2 Continued



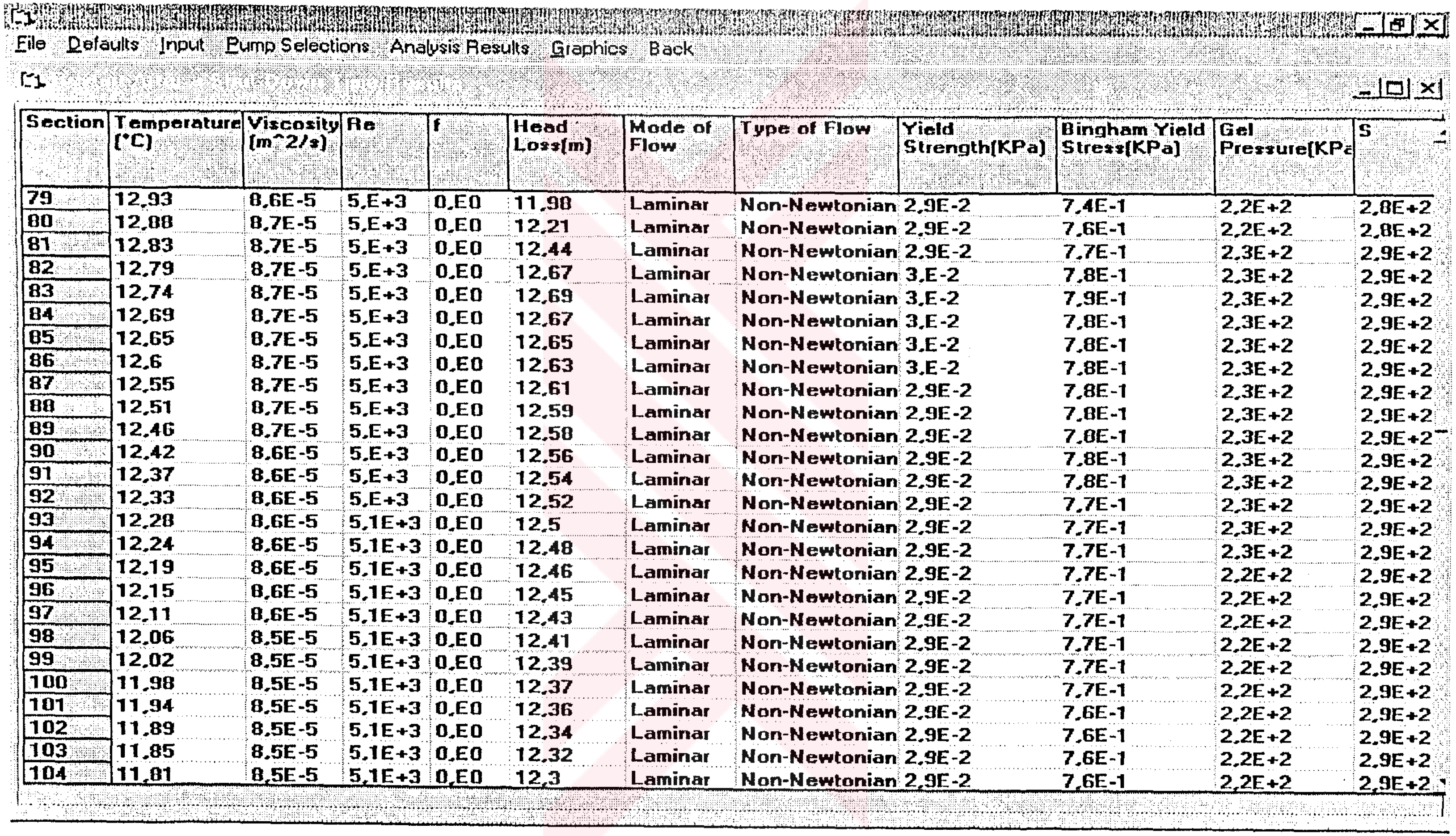
Section	Temperature (°C)	Viscosity (m^2/s)	Re	f	Head Loss(m)	Mode of Flow	Type of Flow	Yield Strength(KPa)	Bingham Yield Stress(KPa)	Gel Pressure(KP	S
27	16,34	5,5E-5	7,9E+3	0,E0	3,2	Laminar	Non-Newtonian	1,5E-2	2,E-1	1,2E+2	1,2E+2
28	16,29	5,6E-5	7,8E+3	0,E0	3,27	Laminar	Non-Newtonian	1,5E-2	2,E-1	1,2E+2	1,2E+2
29	16,23	5,7E-5	7,7E+3	0,E0	3,34	Laminar	Non-Newtonian	1,6E-2	2,1E-1	1,2E+2	1,2E+2
30	16,17	5,7E-5	7,6E+3	0,E0	3,41	Laminar	Non-Newtonian	1,6E-2	2,1E-1	1,2E+2	1,2E+2
31	16,12	5,8E-5	7,5E+3	0,E0	3,48	Laminar	Non-Newtonian	1,6E-2	2,2E-1	1,2E+2	1,2E+2
32	16,06	5,9E-5	7,4E+3	0,E0	3,55	Laminar	Non-Newtonian	1,6E-2	2,2E-1	1,2E+2	1,2E+2
33	16,01	5,9E-5	7,4E+3	0,E0	3,62	Laminar	Non-Newtonian	1,6E-2	2,2E-1	1,3E+2	1,2E+2
34	15,95	6,E-5	7,3E+3	0,E0	3,69	Laminar	Non-Newtonian	1,6E-2	2,3E-1	1,3E+2	1,2E+2
35	15,9	6,E-5	7,2E+3	0,E0	3,76	Laminar	Non-Newtonian	1,7E-2	2,3E-1	1,3E+2	1,3E+2
36	15,84	6,1E-5	7,2E+3	0,E0	3,83	Laminar	Non-Newtonian	1,7E-2	2,4E-1	1,3E+2	1,3E+2
37	15,79	6,1E-5	7,1E+3	0,E0	3,9	Laminar	Non-Newtonian	1,7E-2	2,4E-1	1,3E+2	1,3E+2
38	15,73	6,2E-5	7,E+3	0,E0	3,97	Laminar	Non-Newtonian	1,7E-2	2,5E-1	1,3E+2	1,3E+2
39	15,68	6,2E-5	7,E+3	0,E0	4,04	Laminar	Non-Newtonian	1,7E-2	2,5E-1	1,3E+2	1,3E+2
40	15,63	6,3E-5	6,9E+3	0,E0	4,1	Laminar	Non-Newtonian	1,7E-2	2,5E-1	1,3E+2	1,3E+2
41	15,57	6,3E-5	6,9E+3	0,E0	4,17	Laminar	Non-Newtonian	1,7E-2	2,6E-1	1,3E+2	1,3E+2
42	15,45	6,5E-5	6,7E+3	0,E0	4,42	Laminar	Non-Newtonian	1,8E-2	2,7E-1	1,4E+2	1,4E+2
43	15,31	6,6E-5	6,6E+3	0,E0	4,71	Laminar	Non-Newtonian	1,8E-2	2,9E-1	1,4E+2	1,4E+2
44	15,26	6,6E-5	6,5E+3	0,E0	4,82	Laminar	Non-Newtonian	1,8E-2	3,E-1	1,4E+2	1,5E+2
45	15,2	6,7E-5	6,5E+3	0,E0	4,93	Laminar	Non-Newtonian	1,9E-2	3,1E-1	1,4E+2	1,5E+2
46	15,15	6,7E-5	6,4E+3	0,E0	4,38	Laminar	Non-Newtonian	1,9E-2	3,1E-1	1,5E+2	1,3E+2
47	15,1	6,8E-5	6,4E+3	0,E0	4,51	Laminar	Non-Newtonian	1,9E-2	3,2E-1	1,5E+2	1,3E+2
48	15,04	6,9E-5	6,3E+3	0,E0	4,65	Laminar	Non-Newtonian	1,9E-2	3,3E-1	1,5E+2	1,4E+2
49	14,83	7,E-5	6,2E+3	0,E0	5,11	Laminar	Non-Newtonian	2,E-2	3,5E-1	1,5E+2	1,5E+2
50	14,77	7,1E-5	6,1E+3	0,E0	5,22	Laminar	Non-Newtonian	2,E-2	3,6E-1	1,6E+2	1,5E+2
51	14,72	7,1E-5	6,1E+3	0,E0	5,33	Laminar	Non-Newtonian	2,E-2	3,6E-1	1,6E+2	1,5E+2
52	14,67	7,2E-5	6,1E+3	0,E0	5,44	Laminar	Non-Newtonian	2,E-2	3,7E-1	1,6E+2	1,5E+2

Table B 2 Continued



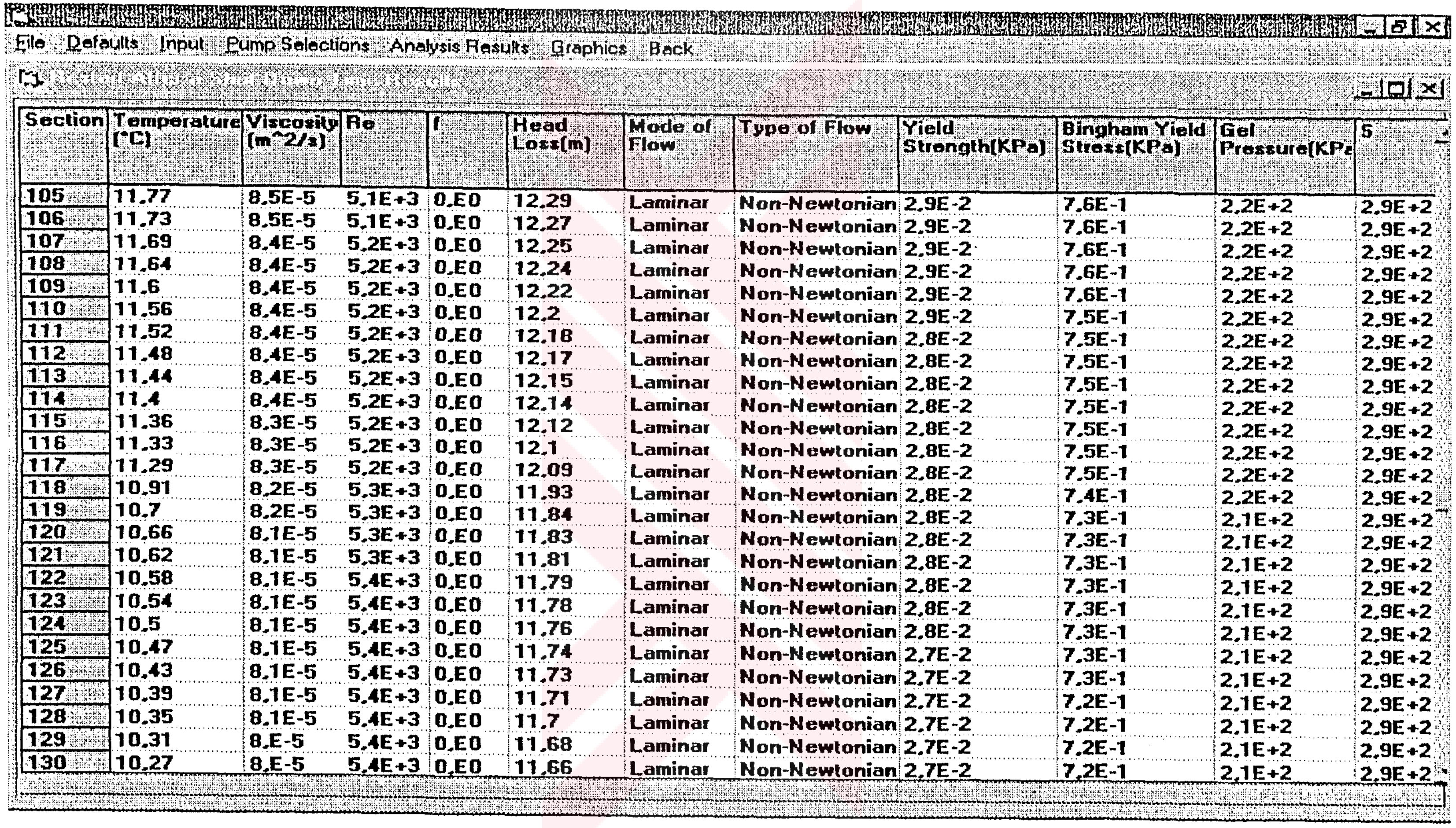
Section	Temperature (°C)	Viscosity (m^2/s)	Re	f	Head Loss(m)	Mode of Flow	Type of Flow	Yield Strength(KPa)	Bingham Yield Stress(KPa)	Gel Pressure(KPa	S
53	14,61	7,2E-5	6,E+3	0,E0	5,54	Laminar	Non-Newtonian	2,1E-2	3,7E-1	1,6E+2	1,5E+2
54	14,56	7,2E-5	6,E+3	0,E0	5,65	Laminar	Non-Newtonian	2,1E-2	3,8E-1	1,6E+2	1,6E+2
55	14,51	7,3E-5	6,E+3	0,E0	5,75	Laminar	Non-Newtonian	2,1E-2	3,8E-1	1,6E+2	1,6E+2
56	14,46	7,3E-5	5,9E+3	0,E0	5,86	Laminar	Non-Newtonian	2,1E-2	3,9E-1	1,6E+2	1,6E+2
57	14,41	7,4E-5	5,9E+3	0,E0	6,03	Laminar	Non-Newtonian	2,1E-2	4,E-1	1,7E+2	1,6E+2
58	14,35	7,4E-5	5,9E+3	0,E0	6,21	Laminar	Non-Newtonian	2,2E-2	4,1E-1	1,7E+2	1,7E+2
59	13,94	7,8E-5	5,6E+3	0,E0	7,74	Laminar	Non-Newtonian	2,3E-2	4,8E-1	1,8E+2	2,E+2
60	13,89	7,9E-5	5,5E+3	0,E0	9,46	Laminar	Non-Newtonian	2,4E-2	4,9E-1	1,8E+2	2,4E+2
61	13,84	7,9E-5	5,5E+3	0,E0	9,6	Laminar	Non-Newtonian	2,4E-2	5,E-1	1,8E+2	2,4E+2
62	13,78	8,E-5	5,5E+3	0,E0	9,75	Laminar	Non-Newtonian	2,4E-2	5,1E-1	1,9E+2	2,5E+2
63	13,73	8,E-5	5,4E+3	0,E0	9,89	Laminar	Non-Newtonian	2,4E-2	5,3E-1	1,9E+2	2,5E+2
64	13,68	8,1E-5	5,4E+3	0,E0	10,03	Laminar	Non-Newtonian	2,5E-2	5,4E-1	1,9E+2	2,5E+2
65	13,63	8,1E-5	5,4E+3	0,E0	10,18	Laminar	Non-Newtonian	2,5E-2	5,5E-1	1,9E+2	2,5E+2
66	13,57	8,1E-5	5,3E+3	0,E0	10,32	Laminar	Non-Newtonian	2,5E-2	5,6E-1	1,9E+2	2,5E+2
67	13,52	8,2E-5	5,3E+3	0,E0	10,46	Laminar	Non-Newtonian	2,5E-2	5,7E-1	2,E+2	2,6E+2
68	13,47	8,2E-5	5,3E+3	0,E0	10,6	Laminar	Non-Newtonian	2,6E-2	5,9E-1	2,E+2	2,6E+2
69	13,42	8,3E-5	5,3E+3	0,E0	10,74	Laminar	Non-Newtonian	2,6E-2	6,E-1	2,E+2	2,6E+2
70	13,37	8,3E-5	5,2E+3	0,E0	10,88	Laminar	Non-Newtonian	2,6E-2	6,1E-1	2,E+2	2,6E+2
71	13,32	8,3E-5	5,2E+3	0,E0	11,02	Laminar	Non-Newtonian	2,6E-2	6,2E-1	2,E+2	2,7E+2
72	13,27	8,4E-5	5,2E+3	0,E0	11,19	Laminar	Non-Newtonian	2,7E-2	6,4E-1	2,1E+2	2,7E+2
73	13,22	8,4E-5	5,2E+3	0,E0	10,56	Laminar	Non-Newtonian	2,7E-2	6,5E-1	2,1E+2	2,5E+2
74	13,17	8,5E-5	5,1E+3	0,E0	10,8	Laminar	Non-Newtonian	2,7E-2	6,7E-1	2,1E+2	2,6E+2
75	13,12	8,5E-5	5,1E+3	0,E0	11,03	Laminar	Non-Newtonian	2,8E-2	6,8E-1	2,1E+2	2,6E+2
76	13,07	8,5E-5	5,1E+3	0,E0	11,27	Laminar	Non-Newtonian	2,8E-2	7,E-1	2,2E+2	2,7E+2
77	13,02	8,6E-5	5,1E+3	0,E0	11,51	Laminar	Non-Newtonian	2,8E-2	7,1E-1	2,2E+2	2,7E+2
78	12,98	8,6E-5	5,1E+3	0,E0	11,74	Laminar	Non-Newtonian	2,9E-2	7,3E-1	2,2E+2	2,7E+2

Table B 2 Continued



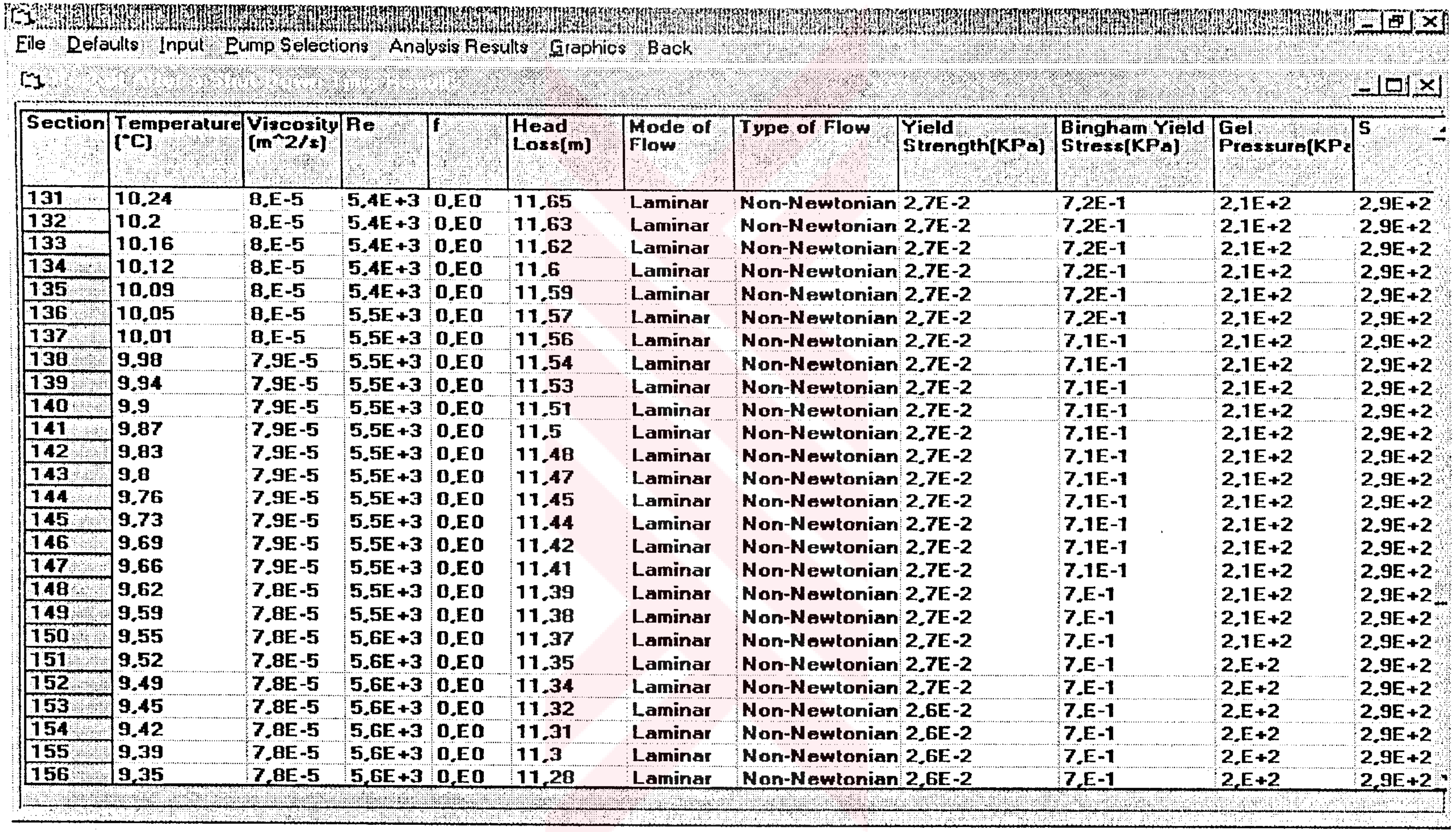
Section	Temperature (°C)	Viscosity (m^2/s)	Re	f	Head Loss(m)	Mode of Flow	Type of Flow	Yield Strength(KPa)	Bingham Yield Stress(KPa)	Gel Pressure[KPa	S
79	12,93	8,6E-5	5,E+3	0,E0	11,98	Laminar	Non-Newtonian	2,9E-2	7,4E-1	2,2E+2	2,8E+2
80	12,88	8,7E-5	5,E+3	0,E0	12,21	Laminar	Non-Newtonian	2,9E-2	7,6E-1	2,2E+2	2,8E+2
81	12,83	8,7E-5	5,E+3	0,E0	12,44	Laminar	Non-Newtonian	2,9E-2	7,7E-1	2,3E+2	2,9E+2
82	12,79	8,7E-5	5,E+3	0,E0	12,67	Laminar	Non-Newtonian	3,E-2	7,8E-1	2,3E+2	2,9E+2
83	12,74	8,7E-5	5,E+3	0,E0	12,69	Laminar	Non-Newtonian	3,E-2	7,9E-1	2,3E+2	2,9E+2
84	12,69	8,7E-5	5,E+3	0,E0	12,67	Laminar	Non-Newtonian	3,E-2	7,8E-1	2,3E+2	2,9E+2
85	12,65	8,7E-5	5,E+3	0,E0	12,65	Laminar	Non-Newtonian	3,E-2	7,8E-1	2,3E+2	2,9E+2
86	12,6	8,7E-5	5,E+3	0,E0	12,63	Laminar	Non-Newtonian	3,E-2	7,8E-1	2,3E+2	2,9E+2
87	12,55	8,7E-5	5,E+3	0,E0	12,61	Laminar	Non-Newtonian	2,9E-2	7,8E-1	2,3E+2	2,9E+2
88	12,51	8,7E-5	5,E+3	0,E0	12,59	Laminar	Non-Newtonian	2,9E-2	7,8E-1	2,3E+2	2,9E+2
89	12,46	8,7E-5	5,E+3	0,E0	12,58	Laminar	Non-Newtonian	2,9E-2	7,8E-1	2,3E+2	2,9E+2
90	12,42	8,6E-5	5,E+3	0,E0	12,56	Laminar	Non-Newtonian	2,9E-2	7,8E-1	2,3E+2	2,9E+2
91	12,37	8,6E-5	5,E+3	0,E0	12,54	Laminar	Non-Newtonian	2,9E-2	7,8E-1	2,3E+2	2,9E+2
92	12,33	8,6E-5	5,E+3	0,E0	12,52	Laminar	Non-Newtonian	2,9E-2	7,7E-1	2,3E+2	2,9E+2
93	12,28	8,6E-5	5,1E+3	0,E0	12,5	Laminar	Non-Newtonian	2,9E-2	7,7E-1	2,3E+2	2,9E+2
94	12,24	8,6E-5	5,1E+3	0,E0	12,48	Laminar	Non-Newtonian	2,9E-2	7,7E-1	2,3E+2	2,9E+2
95	12,19	8,6E-5	5,1E+3	0,E0	12,46	Laminar	Non-Newtonian	2,9E-2	7,7E-1	2,3E+2	2,9E+2
96	12,15	8,6E-5	5,1E+3	0,E0	12,45	Laminar	Non-Newtonian	2,9E-2	7,7E-1	2,2E+2	2,9E+2
97	12,11	8,6E-5	5,1E+3	0,E0	12,43	Laminar	Non-Newtonian	2,9E-2	7,7E-1	2,2E+2	2,9E+2
98	12,06	8,5E-5	5,1E+3	0,E0	12,41	Laminar	Non-Newtonian	2,9E-2	7,7E-1	2,2E+2	2,9E+2
99	12,02	8,5E-5	5,1E+3	0,E0	12,39	Laminar	Non-Newtonian	2,9E-2	7,7E-1	2,2E+2	2,9E+2
100	11,98	8,5E-5	5,1E+3	0,E0	12,37	Laminar	Non-Newtonian	2,9E-2	7,7E-1	2,2E+2	2,9E+2
101	11,94	8,5E-5	5,1E+3	0,E0	12,36	Laminar	Non-Newtonian	2,9E-2	7,6E-1	2,2E+2	2,9E+2
102	11,89	8,5E-5	5,1E+3	0,E0	12,34	Laminar	Non-Newtonian	2,9E-2	7,6E-1	2,2E+2	2,9E+2
103	11,85	8,5E-5	5,1E+3	0,E0	12,32	Laminar	Non-Newtonian	2,9E-2	7,6E-1	2,2E+2	2,9E+2
104	11,81	8,5E-5	5,1E+3	0,E0	12,3	Laminar	Non-Newtonian	2,9E-2	7,6E-1	2,2E+2	2,9E+2

Table B 2 Continued



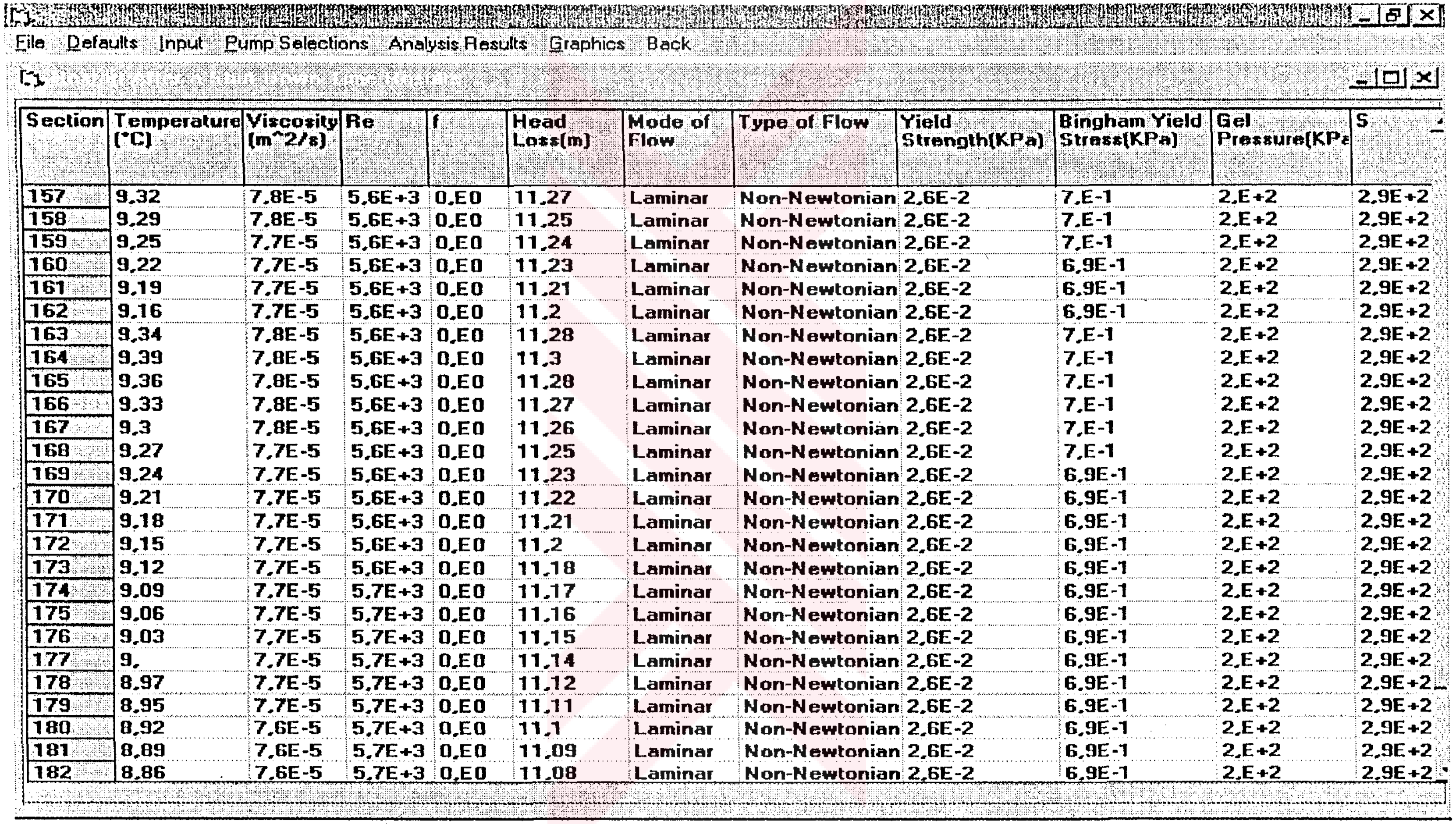
Section	Temperature (°C)	Viscosity (m^2/s)	Re	f	Head Loss(m)	Mode of Flow	Type of Flow	Yield Strength(KPa)	Bingham Yield Stress(KPa)	Gel Pressure(KP	S
105	11.77	8.5E-5	5.1E+3	0.E0	12.29	Laminar	Non-Newtonian	2.9E-2	7.6E-1	2.2E+2	2.9E+2
106	11.73	8.5E-5	5.1E+3	0.E0	12.27	Laminar	Non-Newtonian	2.9E-2	7.6E-1	2.2E+2	2.9E+2
107	11.69	8.4E-5	5.2E+3	0.E0	12.25	Laminar	Non-Newtonian	2.9E-2	7.6E-1	2.2E+2	2.9E+2
108	11.64	8.4E-5	5.2E+3	0.E0	12.24	Laminar	Non-Newtonian	2.9E-2	7.6E-1	2.2E+2	2.9E+2
109	11.6	8.4E-5	5.2E+3	0.E0	12.22	Laminar	Non-Newtonian	2.9E-2	7.6E-1	2.2E+2	2.9E+2
110	11.56	8.4E-5	5.2E+3	0.E0	12.2	Laminar	Non-Newtonian	2.9E-2	7.5E-1	2.2E+2	2.9E+2
111	11.52	8.4E-5	5.2E+3	0.E0	12.18	Laminar	Non-Newtonian	2.8E-2	7.5E-1	2.2E+2	2.9E+2
112	11.48	8.4E-5	5.2E+3	0.E0	12.17	Laminar	Non-Newtonian	2.8E-2	7.5E-1	2.2E+2	2.9E+2
113	11.44	8.4E-5	5.2E+3	0.E0	12.15	Laminar	Non-Newtonian	2.8E-2	7.5E-1	2.2E+2	2.9E+2
114	11.4	8.4E-5	5.2E+3	0.E0	12.14	Laminar	Non-Newtonian	2.8E-2	7.5E-1	2.2E+2	2.9E+2
115	11.36	8.3E-5	5.2E+3	0.E0	12.12	Laminar	Non-Newtonian	2.8E-2	7.5E-1	2.2E+2	2.9E+2
116	11.33	8.3E-5	5.2E+3	0.E0	12.1	Laminar	Non-Newtonian	2.8E-2	7.5E-1	2.2E+2	2.9E+2
117	11.29	8.3E-5	5.2E+3	0.E0	12.09	Laminar	Non-Newtonian	2.8E-2	7.5E-1	2.2E+2	2.9E+2
118	10.91	8.2E-5	5.3E+3	0.E0	11.93	Laminar	Non-Newtonian	2.8E-2	7.5E-1	2.2E+2	2.9E+2
119	10.7	8.2E-5	5.3E+3	0.E0	11.84	Laminar	Non-Newtonian	2.8E-2	7.4E-1	2.2E+2	2.9E+2
120	10.66	8.1E-5	5.3E+3	0.E0	11.83	Laminar	Non-Newtonian	2.8E-2	7.3E-1	2.1E+2	2.9E+2
121	10.62	8.1E-5	5.3E+3	0.E0	11.81	Laminar	Non-Newtonian	2.8E-2	7.3E-1	2.1E+2	2.9E+2
122	10.58	8.1E-5	5.4E+3	0.E0	11.79	Laminar	Non-Newtonian	2.8E-2	7.3E-1	2.1E+2	2.9E+2
123	10.54	8.1E-5	5.4E+3	0.E0	11.78	Laminar	Non-Newtonian	2.8E-2	7.3E-1	2.1E+2	2.9E+2
124	10.5	8.1E-5	5.4E+3	0.E0	11.76	Laminar	Non-Newtonian	2.8E-2	7.3E-1	2.1E+2	2.9E+2
125	10.47	8.1E-5	5.4E+3	0.E0	11.74	Laminar	Non-Newtonian	2.7E-2	7.3E-1	2.1E+2	2.9E+2
126	10.43	8.1E-5	5.4E+3	0.E0	11.73	Laminar	Non-Newtonian	2.7E-2	7.3E-1	2.1E+2	2.9E+2
127	10.39	8.1E-5	5.4E+3	0.E0	11.71	Laminar	Non-Newtonian	2.7E-2	7.2E-1	2.1E+2	2.9E+2
128	10.35	8.1E-5	5.4E+3	0.E0	11.7	Laminar	Non-Newtonian	2.7E-2	7.2E-1	2.1E+2	2.9E+2
129	10.31	8.E-5	5.4E+3	0.E0	11.68	Laminar	Non-Newtonian	2.7E-2	7.2E-1	2.1E+2	2.9E+2
130	10.27	8.E-5	5.4E+3	0.E0	11.66	Laminar	Non-Newtonian	2.7E-2	7.2E-1	2.1E+2	2.9E+2

Table B 2 Continued



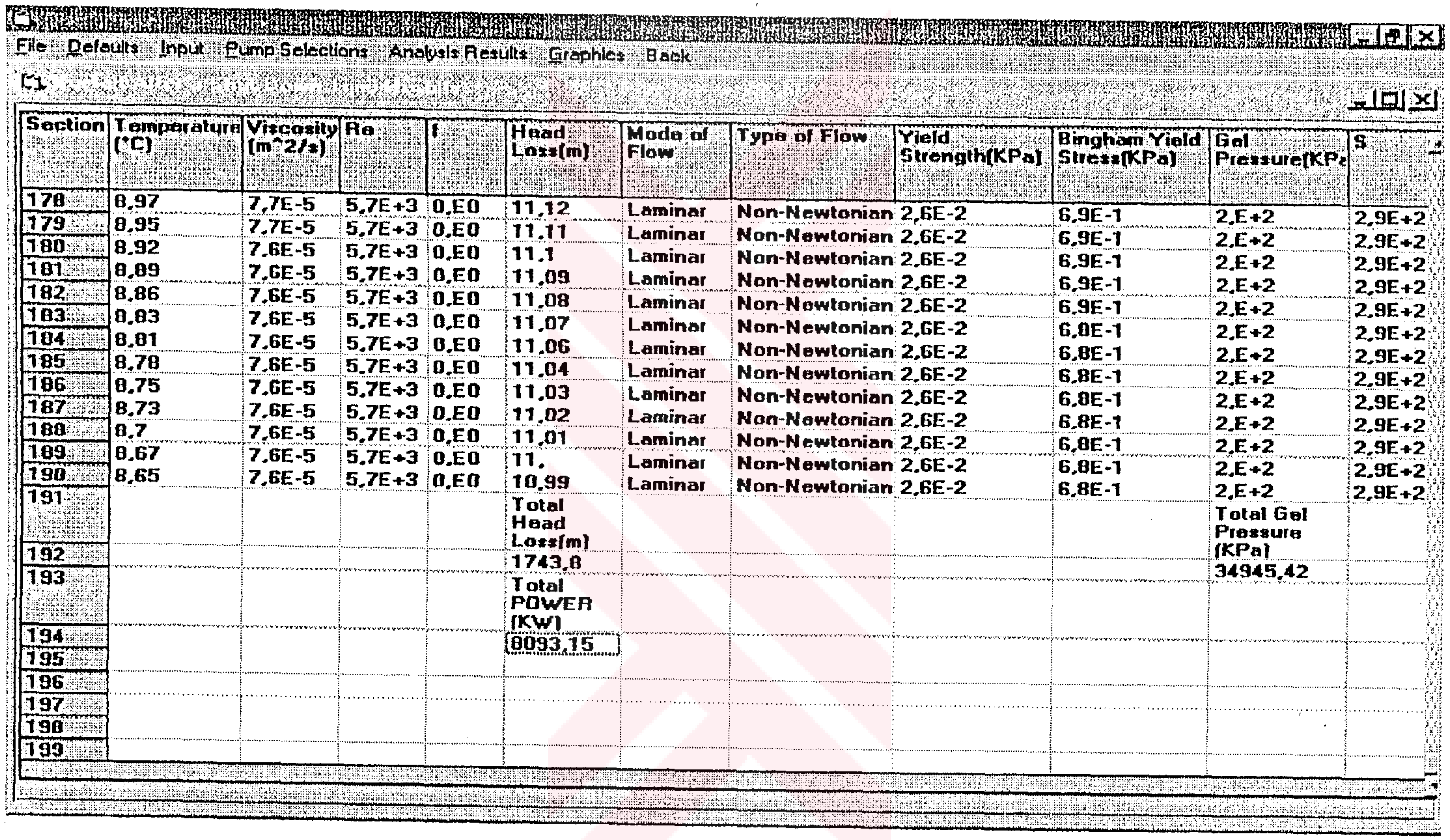
Section	Temperature (°C)	Viscosity (m^2/s)	Re	f	Head Loss(m)	Mode of Flow	Type of Flow	Yield Strength(KPa)	Bingham Yield Stress(KPa)	Gel Pressure(KPa	S
131	10,24	8,E-5	5,4E+3	0,E0	11,65	Laminar	Non-Newtonian	2,7E-2	7,2E-1	2,1E+2	2,9E+2
132	10,2	8,E-5	5,4E+3	0,E0	11,63	Laminar	Non-Newtonian	2,7E-2	7,2E-1	2,1E+2	2,9E+2
133	10,16	8,E-5	5,4E+3	0,E0	11,62	Laminar	Non-Newtonian	2,7E-2	7,2E-1	2,1E+2	2,9E+2
134	10,12	8,E-5	5,4E+3	0,E0	11,6	Laminar	Non-Newtonian	2,7E-2	7,2E-1	2,1E+2	2,9E+2
135	10,09	8,E-5	5,4E+3	0,E0	11,59	Laminar	Non-Newtonian	2,7E-2	7,2E-1	2,1E+2	2,9E+2
136	10,05	8,E-5	5,5E+3	0,E0	11,57	Laminar	Non-Newtonian	2,7E-2	7,2E-1	2,1E+2	2,9E+2
137	10,01	8,E-5	5,5E+3	0,E0	11,56	Laminar	Non-Newtonian	2,7E-2	7,1E-1	2,1E+2	2,9E+2
138	9,98	7,9E-5	5,5E+3	0,E0	11,54	Laminar	Non-Newtonian	2,7E-2	7,1E-1	2,1E+2	2,9E+2
139	9,94	7,9E-5	5,5E+3	0,E0	11,53	Laminar	Non-Newtonian	2,7E-2	7,1E-1	2,1E+2	2,9E+2
140	9,9	7,9E-5	5,5E+3	0,E0	11,51	Laminar	Non-Newtonian	2,7E-2	7,1E-1	2,1E+2	2,9E+2
141	9,87	7,9E-5	5,5E+3	0,E0	11,5	Laminar	Non-Newtonian	2,7E-2	7,1E-1	2,1E+2	2,9E+2
142	9,83	7,9E-5	5,5E+3	0,E0	11,48	Laminar	Non-Newtonian	2,7E-2	7,1E-1	2,1E+2	2,9E+2
143	9,8	7,9E-5	5,5E+3	0,E0	11,47	Laminar	Non-Newtonian	2,7E-2	7,1E-1	2,1E+2	2,9E+2
144	9,76	7,9E-5	5,5E+3	0,E0	11,45	Laminar	Non-Newtonian	2,7E-2	7,1E-1	2,1E+2	2,9E+2
145	9,73	7,9E-5	5,5E+3	0,E0	11,44	Laminar	Non-Newtonian	2,7E-2	7,1E-1	2,1E+2	2,9E+2
146	9,69	7,9E-5	5,5E+3	0,E0	11,42	Laminar	Non-Newtonian	2,7E-2	7,1E-1	2,1E+2	2,9E+2
147	9,66	7,9E-5	5,5E+3	0,E0	11,41	Laminar	Non-Newtonian	2,7E-2	7,1E-1	2,1E+2	2,9E+2
148	9,62	7,8E-5	5,5E+3	0,E0	11,39	Laminar	Non-Newtonian	2,7E-2	7,E-1	2,1E+2	2,9E+2
149	9,59	7,8E-5	5,5E+3	0,E0	11,38	Laminar	Non-Newtonian	2,7E-2	7,E-1	2,1E+2	2,9E+2
150	9,55	7,8E-5	5,6E+3	0,E0	11,37	Laminar	Non-Newtonian	2,7E-2	7,E-1	2,1E+2	2,9E+2
151	9,52	7,8E-5	5,6E+3	0,E0	11,35	Laminar	Non-Newtonian	2,7E-2	7,E-1	2,E+2	2,9E+2
152	9,49	7,8E-5	5,6E+3	0,E0	11,34	Laminar	Non-Newtonian	2,7E-2	7,E-1	2,E+2	2,9E+2
153	9,45	7,8E-5	5,6E+3	0,E0	11,32	Laminar	Non-Newtonian	2,6E-2	7,E-1	2,E+2	2,9E+2
154	9,42	7,8E-5	5,6E+3	0,E0	11,31	Laminar	Non-Newtonian	2,6E-2	7,E-1	2,E+2	2,9E+2
155	9,39	7,8E-5	5,6E+3	0,E0	11,3	Laminar	Non-Newtonian	2,6E-2	7,E-1	2,E+2	2,9E+2
156	9,35	7,8E-5	5,6E+3	0,E0	11,28	Laminar	Non-Newtonian	2,6E-2	7,E-1	2,E+2	2,9E+2

Table B 2 Continued



Section	Temperature (°C)	Viscosity (m^2/s)	Re	f	Head Loss(m)	Mode of Flow	Type of Flow	Yield Strength(KPa)	Bingham Yield Stress(KPa)	Gel Pressure(KPa	S
157	9,32	7,8E-5	5,6E+3	0,E0	11,27	Laminar	Non-Newtonian	2,6E-2	7,E-1	2,E+2	2,9E+2
158	9,29	7,8E-5	5,6E+3	0,E0	11,25	Laminar	Non-Newtonian	2,6E-2	7,E-1	2,E+2	2,9E+2
159	9,25	7,7E-5	5,6E+3	0,E0	11,24	Laminar	Non-Newtonian	2,6E-2	7,E-1	2,E+2	2,9E+2
160	9,22	7,7E-5	5,6E+3	0,E0	11,23	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
161	9,19	7,7E-5	5,6E+3	0,E0	11,21	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
162	9,16	7,7E-5	5,6E+3	0,E0	11,2	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
163	9,34	7,8E-5	5,6E+3	0,E0	11,28	Laminar	Non-Newtonian	2,6E-2	7,E-1	2,E+2	2,9E+2
164	9,39	7,8E-5	5,6E+3	0,E0	11,3	Laminar	Non-Newtonian	2,6E-2	7,E-1	2,E+2	2,9E+2
165	9,36	7,8E-5	5,6E+3	0,E0	11,28	Laminar	Non-Newtonian	2,6E-2	7,E-1	2,E+2	2,9E+2
166	9,33	7,8E-5	5,6E+3	0,E0	11,27	Laminar	Non-Newtonian	2,6E-2	7,E-1	2,E+2	2,9E+2
167	9,3	7,8E-5	5,6E+3	0,E0	11,26	Laminar	Non-Newtonian	2,6E-2	7,E-1	2,E+2	2,9E+2
168	9,27	7,7E-5	5,6E+3	0,E0	11,25	Laminar	Non-Newtonian	2,6E-2	7,E-1	2,E+2	2,9E+2
169	9,24	7,7E-5	5,6E+3	0,E0	11,23	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
170	9,21	7,7E-5	5,6E+3	0,E0	11,22	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
171	9,18	7,7E-5	5,6E+3	0,E0	11,21	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
172	9,15	7,7E-5	5,6E+3	0,E0	11,2	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
173	9,12	7,7E-5	5,6E+3	0,E0	11,18	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
174	9,09	7,7E-5	5,7E+3	0,E0	11,17	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
175	9,06	7,7E-5	5,7E+3	0,E0	11,16	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
176	9,03	7,7E-5	5,7E+3	0,E0	11,15	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
177	9,	7,7E-5	5,7E+3	0,E0	11,14	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
178	8,97	7,7E-5	5,7E+3	0,E0	11,12	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
179	8,95	7,7E-5	5,7E+3	0,E0	11,11	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
180	8,92	7,6E-5	5,7E+3	0,E0	11,1	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
181	8,89	7,6E-5	5,7E+3	0,E0	11,09	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
182	8,86	7,6E-5	5,7E+3	0,E0	11,08	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2

Table B 2 Continued



Section	Temperature (°C)	Viscosity (m^2/s)	Re	f	Head Loss(m)	Mode of Flow	Type of Flow	Yield Strength(KPa)	Bingham Yield Stress(KPa)	Gel Pressure(KP	S
178	8,97	7,7E-5	5,7E+3	0,E0	11,12	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
179	8,95	7,7E-5	5,7E+3	0,E0	11,11	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
180	8,92	7,6E-5	5,7E+3	0,E0	11,1	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
181	8,89	7,6E-5	5,7E+3	0,E0	11,09	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
182	8,86	7,6E-5	5,7E+3	0,E0	11,08	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
183	8,83	7,6E-5	5,7E+3	0,E0	11,07	Laminar	Non-Newtonian	2,6E-2	6,9E-1	2,E+2	2,9E+2
184	8,81	7,6E-5	5,7E+3	0,E0	11,06	Laminar	Non-Newtonian	2,6E-2	6,8E-1	2,E+2	2,9E+2
185	8,78	7,6E-5	5,7E+3	0,E0	11,04	Laminar	Non-Newtonian	2,6E-2	6,8E-1	2,E+2	2,9E+2
186	8,75	7,6E-5	5,7E+3	0,E0	11,03	Laminar	Non-Newtonian	2,6E-2	6,8E-1	2,E+2	2,9E+2
187	8,73	7,6E-5	5,7E+3	0,E0	11,02	Laminar	Non-Newtonian	2,6E-2	6,8E-1	2,E+2	2,9E+2
188	8,7	7,6E-5	5,7E+3	0,E0	11,01	Laminar	Non-Newtonian	2,6E-2	6,8E-1	2,E+2	2,9E+2
189	8,67	7,6E-5	5,7E+3	0,E0	11,	Laminar	Non-Newtonian	2,6E-2	6,8E-1	2,E+2	2,9E+2
190	8,65	7,6E-5	5,7E+3	0,E0	10,99	Laminar	Non-Newtonian	2,6E-2	6,8E-1	2,E+2	2,9E+2
191					Total Head Loss(m)					Total Gel Pressure (KPa)	
192					1743,8					34945,42	
193					Total POWER (KW)						
194					8093,15						
195											
196											
197											
198											
199											

Table

APPENDIX C

USER'S MANUAL

- Select land profile option under data sub-menu. There are two possibility for land profile entrance: opening a data file with an extension *.top(Figure A.1), entering directly from the screen(Figure A.3).

- Under the same menu, select design parameters option. This provides the entrance of pipe diameter, thickness, thermal conductivity of the pipe material, pipe grade, surface roughness of the pipe, depth of burial, flowrate and its change locations(Figure A.4).

- Slurry characteristics of the crude or any slurry pipeline can be entered with slurry characteristics option under data menu(Figure A.5).

- Similar to land profile options under data sub-menu, Pump Characteristics menu has two options: opening a data file with an extension *.pmp(Figure A.6), entering from the screen(Figure A.8).

- Select Existing Pump Station of a Pipeline menu to enter the results of Newtonian solutions of the pipe diameter, flowrate, required pump head, speed of pump and station locations(Figure A.9).

- If the results of the Newtonian solutions don't exist, Next menu provides to enter second screen. The Newtonian solution is performed by this software using the Locations of Pump Stations option under Pump Selection menu. If Newtonian solutions are entered from the Existing Pump Station of a Pipeline, Locations of Pump Stations option under Pump Selection menu in the second screen becomes disabled.

- In the second screen, first select Viscosity Correlation options under Input menu. The variation of viscosity with temperature can be entered as a empirical correlations (Beal, Chew and Cannolly, Perry, Ajienka, Antoine) or as a direct measurement(Figure A.16).

- Then, select Thermal Properties option under Input menu. Thermal Properties option is divided into two: Insulation Materials to enter the type of insulation and its thickness(Figure A.10) and Crude Oil Properties(Figure A.11). Under the Crude Oil Properties part, standard crude oil types can be selected or the users can define their own crude's properties(Figure A.12).

- Select Field Data under Input menu. This menu procures the entrance of soil temperature or variations along the pipeline, outside convective heat transfer coefficient, design factors, and thermal conductivity of the soil(Figure A.13, A.14).

- Finally Stress and Strength Data under Input menu is selected to finish data input. The rheological properties of the crude are entered to program. If the properties of hypothetical crude are used as a data, click sample options in this screen to perform analysis mentioned in Chapter 3.

- The results of the Newtonian solutions can be seen by selecting Conventional Pipeline Design option under Analysis Results menu.

- The results of the analysis performed by this program can be seen by selecting Normal Operating Conditions and Re-start After Shut-Down Conditions options under Analysis Results menu.

- The results of the analysis in graphical form can be seen under graphics menu. Non-Newtonian Hydraulic Grade Line Solutions and Temperature Distributions options provides solutions for both normal operating conditions and restart after a shutdown.

- If the analysis gives unsatisfactory results for the line, the modifications are presented in optional state in the non-Newtonian hydraulic grade line form. Any one is selected by clicking the option and the results in the graphical form is loaded directly by the program. Other information related to this modification can be seen by using Analysis menu and Temperature Distributions option under Graphics menu.

- The results of pumps operating point at each station can be displayed with Results of Pump Selection option for Newtonian solutions and Non-Newtonian Pump Selection option for modifications related to the design parameters.

APPENDIX D

ESTIMATING THE VISCOSITY OF CRUDE OIL SYSTEM

Viscosity of crude oils are required in various pipeline engineering problems. In evaluation of fluid flow in a reservoir, the viscosity of the liquid is required at various values of reservoir pressure and at reservoir temperature. There are cases, however, when the viscosity is needed at other temperatures. The most common situation requiring viscosities at various pressures and temperatures occurs in the calculation of two-phase, gas liquid flowing pressure traverses. Calculation these pressure traverses involves dividing the flow string into a number of length increments and calculating the pressure gradient at average conditions of temperature and pressure in the increment. Calculation of pressure gradients requires knowledge of oil viscosity. The most popular methods used for predicting oil viscosity are Beal[27] for dead oil and Chew and Connally [27] for live or saturated oil. Beal correlated dead oil viscosity as a function of API gravity and temperature. Chew and Connally presented a correlation for the effect of dissolved gas on the oil viscosity.The correlation developed for dead oil viscosity is

$$\mu_{OD}=10^{x}-1 \qquad (D.1)$$

Where

$X=y\times T^{-1.163}$

$Y=10^{z}$

$Z=3.0324-0.02023\times\gamma_{o}$

The correlation of the dead oil viscosity for dissolved gas is

$$\mu=A\times\mu_{OD}^{B} \qquad (D.2)$$

Where

$A=10.715\times(R_s+100)^{-0.515}$

$B=5.44\times(R_s+100)^{-0.338}$

R_s=dissolved gas oil ratio

T= temperature

μ_{OD}= viscosity of gas-free oil at T

μ=viscosity of gas saturated oil at T

γ_o=oil gravity, ° API

t_b=normal boiling point

γ=kinematic viscosity

N. V. K. Dutt [26] developed a simple method needing the average boiling point as the only input. This method, when tested on 15 world crude oils (and their fractions) at 250 data points, yielded an overall deviation of 6%. The correlation of kinematic viscosity is:

$$\ln \nu = -3.0171 + \frac{442.78 + 1.645.t_b}{T + (239 - 0.19.t_b)} \qquad \text{(D.3)}$$

where

t_b: boiling temperature of oil

Ajienka correlation for calculation of oil viscosity [16]:

$$\nu=35.7223\times\exp[0.02008\times(T-T_{pour})]+0.03132\times \gamma_o \qquad \text{(D.4)}$$

Perry correlation [29]:

$$\nu=9.6717\times10^{12}\times T^{-5.0931} \qquad \text{(D.5)}$$

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APPENDIX E

TEMPERATURE INCREASE OF OIL DUE TO FRICTIONAL PRESSURE LOSS ALONG THE LINE

Temperature increase per km along the line due to frictional pressure loss or viscous dissipation along the line can be calculated by balancing the loss of internal energy of oil with frictional power.

$$P = \dot{m} \times C \times \Delta T$$

For Ceyhan-Kırıkkale Pipeline system

P=5155 KW

ρ=850 kg/m^3

Q=1200 m^3/h

C=1884 J/kg.K

L=447 km

$$\Delta T = \frac{5155 \times 10^3 W}{(1200 \frac{m^3}{h} \times 850 \frac{kg}{m^3} \times \frac{h}{3600 \times s} \times 1884 \frac{J}{kg \times K})} \times \frac{1}{447 km}$$

ΔT= 0.021 °C/ km

If this temperature change per km is compared with oil temperature variation given in Table B1 and B2, it sometimes compensates with the temperature decrease and sometimes it is so small with respect to temperature decrease that it doesn't take into consideration.