IMPROVEMENT OF PIPELINE TRANSPORTATION OF FUEL OIL

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by

NAGHAM SALMAN HASSAN AL-MALIKY

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Ramadan 1425

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CERTIFICATION

We certify that this thesis entitled ***"Improvement of Pipeline Transportation of Fuel Oils"*** was prepared by **Nagham Salman Hassan Al-Maliky**, under our supervision at AL-Nahrain University, College of Engineering, in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering.

Signature: J. Shanshool
Prof. Dr.Jabir Shanshool
Date: 30/ 11/04

Signature: J. Kashmoula
Dr. Talib Kashmoula
Date:30 / 11 / 04

Signature:
Prof. Dr. Qasim J. Slaiman
Head of Chemical Engineering Department

Date: / /

CERTIFICATE

We certify that we have read this thesis, entitled ***"Improvement of Pipeline Transportation of Fuel Oils"*** and as examining committee examined the student **Nagham Salman Hassan Al-Maliky** in its content, and that in our opinion it is adequate for the partial fulfillment of requirements for the degree of Master of Science in Chemical Engineering.

Signature: J. Shanshool
Prof. Dr. Jabir Shanshool
(Supervisor)
Date: 30 / 11 / 04

Signature: T. Kashmoula
Dr. Talib Kashmoula
(Supervisor)
Date: 30 / 11 / 04

Signature: Latif
Dr. Mohammed N.Latif
(Member)
Date: 30 / 11 / 2004

Signature: Thoaib
Dr. Thoaib Abdul-Jabbar
(Member)
Date: 1 / 12 / 2004

Signature: Nada
Prof. Dr. Nada B.Nakkash
(Chairman)
Date : 1 / 12 / 2004

Approval of the College of Engineering

Signature: M Naima
Prof. Dr. Fawzi M. AL-Naima
Dean of the College of Engineering
Date: 20 / 12 / 2004

ABSTRACT

Reduced crude is considered usually as the main source for heating oils. Therefore, it was chosen in addition to, a commercial fuel oil in the present investigation, to improve their ability for pipelining.

Blending with low viscous fractions or heating are the major commercial applications for pipeline transportation of residual fuel oils. Accurate data on oil viscosity as function of temperature and composition are required for design of oil pipelines.

The effect of heating, up to 70 $^{\mathbf{o}}\mathbf{C}$ on the lowering viscosity of reduced crude and fuel oil and their mixtures with gas oil were studied. The viscosity of the considered oils undergoes significant reduction by temperature increase. Percentage reductions are 53% and 50% can be achieved by heating of reduced crude and fuel oil respectively at 40$^{\mathbf{o}}\mathbf{C}$.

It is practically possible to improve the viscosity of residual oils using the method of blending with gas oil. As it is expected, light gas oil effected more viscosity reduction than heavy gas oil.

The addition of methanol in low concentration to reduced crude and fuel oil leads to a reduction in their viscosities. The maximum decrease in viscosity (about 32% and 31% respectively) was obtained with addition of 3-4% by volume methanol.

The effect of viscosity lowering by heating and diluting on pumping horse power requirement and flow rate was tested. The calculation was done using operating data of two locally available fuel oil pipelines of 250m and 10Km distances were supplied from Daura Refinery in Baghdad. The results indicated reasonable decrease in power requirements or increase in oil output by diluting with gas oil or temperature increase.

A model was modified to estimate the kinematic viscosity of blended residual fuel oil at different temperatures. The method is based up also on the concentration (wt. %) of the diluting component as follows:

$$\left[\frac{\log(\upsilon)+K}{\log(\upsilon_0)+C}\right]=\left[\frac{T_0}{T}\right]^S$$

Comparison between measured and calculated viscosities of all studied mixtures of heavy petroleum fractions for different temperatures was found to be satisfactory, with an overall average absolute error of 2.12% for the 130 data points.

LIST OF CONTENTS

NOMENCLATURE

^{o}API	American Petroleum Institute gravity
a_1, a_2, and, a_3	Constants in equations (2.20), (2.21)
A, B	Constants in equations (2.9), (2.25)
b_1, b_2	Constants in equation (2.7)
$C_1$to C_6	Constants in equation (2.6)
C	Calibration constant of viscometer (Cst/s)
C, D	Constants in equation (2.19)
CI	Correlation index
d	Inside diameter of pipe (m)
h_f	Head loss due to fraction (m)
HP	Horse power required for pumping (W)
I_{bi}	Blend Refutas Index
I	Refutas function
K_w	Watson characterization factor
K,n	Constants in equation (2.18)
L	Length of pipe (m)
M	Molecular weight of each component in equation (2.24)
Mw	Molecular weight
m, b	Constants in equation (2.27)
P	Pressure (N/m^2)
P_c	Critical pressure (N/m^2)
Q	Volumetric flow rate (m^3/hr)
R_e	Reynold number

Sp. gr.	Specific gravity at 60^{o}F
T	Absolute temperature (K)
T_B	Mean average boiling point (^{o}R)
T_b	True boiling point (^{o}R)
T_r	Reduced temperature (K)
T_c	Critical temperature (K)
t	Time of flow (s)
u	Velocity of flow (m/s)
w	Weight fraction
W_t	Walter function
x	Mole fraction
Z	Compressibility factor

Greek Letters

μ	Dynamic viscosity (cP)
υ, η	Kinematic viscosity (cst)
ω_o	Centric factor
ρ	Density (kg/m^3)
$\Delta \mathbf{P}$	Pressure drop (Pa)
η_p	pump efficiency

Subscriptions

cal.	Calculate value
exp.	Experimental value

i	Component i
m, mix	Mixture
A, B	Component A and B

Superscripts

r	Reference fluid

Abbreviations

AAD	Average Absolute Deviation
ASTM	American Standard for Testing Materials
IP	Institute of Petroleum
ECN	Effective Carbon Number
RV	Relative Viscosity
%RC	Percentage Reduction Change
FO	Fuel Oil
RC	Reduced Crude
LGO	Light Gas Oil
HGO	Heavy Gas Oil

CHAPTER ONE

INTRODUCTION

Fuel oil is considered as heavy oil-stock, which is the most important source of industrial fuels used in boilers, furnaces, units of electrical energy generation, as a fuel to ships or trains, and many other industrial applications [1].

The main sources of industrial fuel oils are usually reduced crude or atmospheric residue and in some case the vacuum residue. These sources are usually blended with lighter fractions available within the refinery, such as heavy gas oil to improve their specifications.

The main properties of fuel oils are viscosity, pour point, flash point, ash content, water and sediment, carbon residue and heat of combustion.

There are different grades of fuel oils, which are classified usually according to their viscosities and densities into light, medium and heavy types for the different applications or number 1 up to number 6 due to their boiling range according to the American specifications.

Selling, storing or burning of commercial fuel oils encounter many difficulties, the majority of which arise because of the failure in meeting the required specifications. The high values of viscosity, pour point, sulfur content and carbon to hydrogen ratio, are the main reasons for the failure. However, it is possible to lower the high viscosity or pour point of the fuels through the process of visbreaking, which is a chemical upgrading process [2].

The major commercial applications for lowering the viscosity for pipeline transportation of heavy fuel oils are heating or diluting with low viscosity oil-stocks.

It is well known that the viscosity of heavy petroleum fractions decreases as temperature increases. Therefore, in oil industry the heavy petroleum fractions are heated in order to lower the viscosity, to improve its flow in pipeline. The disadvantages of this process are the added cost of heating devices, energy requirement and insulation of pipelines.

For cases of long distance transportation of such oils, stages of heating should be introduced, thus the cost becomes even higher. Therefore, it is preferable to perform the heating process inside the refineries. In certain cases where the quality to be transported is large, the heating process is carried out only at the beginning of pumping station [3].

The blending method for viscosity lowering is discussed as an alternative to hot oil pipeline transport of heavy petroleum fraction. The reduction in viscosity can be obtained also by blending heavy petroleum fractions with light petroleum cuts.

The dilution method would be acceptable when the cost of diluents is low and the heavy petroleum fractions are transported for long distances, provided that the diluents do not effect the other properties of fuel oils such as flash point.

Accurate values of viscosity of residual fuel oils and their mixtures as a function of temperature and composition are needed in engineering calculations, handling, pipeline transportation and burning of fuel oils [4, 5]. Numerous empirical or semi-empirical correlations were developed to describe the viscosity of heavy petroleum fraction dependence on the temperature and composition [4].

The aim of the present investigation was to improve the pumping behavior of residual fuel oil. The effect of heating and blending was studied on lowering the viscosity of reduced crude (atm. Residue) and vacuum fuel oil. These oil-stocks are considered as the main source for industrial fuels. Further more, experiments were carried out for lowering the viscosity by addition of methanol. Search was also made to derive a correlation to estimation the viscosity of fuel oil as a function of temperature and blending stock.

Further aim of this study was to use the results of viscosity lowering of residual fuel oils in increasing the pumping capacity (flow rate) or decreasing the power requirement of the pumps.

CHAPTER TWO

LITERATURE REVIEW

2.1 General Specifications of Oil-Stocks

Heavy crude oils and residual oils are characterized by their high viscosities, high pour point and low API gravity. The knowledge of the different properties of oil-stock is predominant for the production, handling, quality and uses of each type. Further processing or blending methods are usually taken to get the required specification of each fuel. The main individual properties for heavy oil-stock are as follows:
API gravity ,Characterization factors, Distillation curves, Viscosity, Pour point, flash point, carbon residue, Ash content, Calorific value, Sediment, water content and Sulphur content. The evaluation of petroleum fractions are carried out usually according to the standard methods, i-e IP or ASTM **[6, 7]**.

The density of petroleum fractions is expressed usually in term of $^{\mathbf{o}}$ **API** gravity, and can be calculated from specific gravity as follows:

$$^{o}\mathbf{API} = \frac{\mathbf{141.5}}{\mathbf{sp.gr.}} - \mathbf{131.5} \qquad (2\text{-}1)$$

Calculation of petroleum fractions density under varying temperatures and pressures is fundamental to all custody transfer operations. There are some methods for the calculating the densities of oil-stock mixtures:-

-The API standard 2540 [8] gives volume correlation factors and density reductions to 15 °C for petroleum fractions.

-The costald equation for LPG densities [9] was generalized to calculate the densities of petroleum fractions and their mixtures using critical temperature, critical pressure, characteristic volume, Soave-Redlich-Kwong a centric factor and molecular weight [10].

-Adaptation of costald equation with Hankinson-Brobst-Thomson technique [11] offers flexibility for estimating densities. This method provides accurate and computationally reliable prediction of petroleum fractions density.

There are several correlations between yield and the aromaticity and paraffincity of petroleum fractions, but the two most widely used are UOP or “Watson characterization factor” (K_w) and the U.S. Bureau of Mines “Correlation index” (CI), as given in equation (2-2) and (2-3), respectively [12].

$$\mathbf{K_w = (T_B)^{1/3} / Sp.gr.} \qquad (2\text{-}2)$$

$$CI = 473.7d - 456.8 + 48640/K_w \qquad (2\text{-}3)$$

Where:-

T_B= mean average boiling point, °R

Sp.gr. = specific gravity at 60 °F

The Watson characterization factor ranges from less than 10 for highly aromatics to almost 15 for highly paraffinic compounds. Crude oils show a narrow range of K_w and vary from 10.5 for highly naphthenic crude to 12.9 for paraffinic base crude [12].

Values for the correlation index, CI between 0 and 15 indicate a predominance of paraffinic hydrocarbons in the fractions, from 15 to 50 a predominance either of naphthenes or of mixtures of paraffines, naphthenes and aromatics; above 50 indicates predominantly aromatic character.

The distillation behaviors of petroleum fraction are carried out according to the standard method (i-e ASTM or IP) in a procedure of evaluating the percentage distillate with corresponding temperature. The most useful type of distillation is known as true boiling point (TBP) and generally refers to a distillation performed in equipment which gives higher degree of fractionation.

Distillation curves are of value in assessing the suitability of petroleum fractions for various applications, particularly in respect to volatility. Such information is also needed for the design and control of distillation columns. It is also useful, usually in conjunction with some other physical property such as density, in characterizing petroleum fractions to permit prediction of other property [13].

Viscosity, pour point, carbon residue flash point, calorific value, sediment and water content, sulphur content and ash content are predominant properties especially for heavy fractions and residual fuel oils.

2.2 Fuel Oils

2.2.1 Sources and Classifications

Many petroleum products are used as fuels, ranging from refinery gases and gasoline-type distillates to the heaviest residual oil and bitumen. However, it is generally accepted that the term “industrial fuels” refers to that range of products which includes the distillate oils known as gas oil and diesel fuel and light, medium and heavy fuel oils.

These oils may be either straight-run or cracked or they may be blends of both. Although the nomenclature light, medium, and heavy refers basically to the specific gravity of these oils. The terms are often used commercially as an indication of the viscosity of the oil [13].This range of fuel oils includes the heavy residual oils and residual oils blended with varying amounts of low viscosity stocks in order to obtain the desired viscosity.

The specific gravity will be of the order of 0.92 for the light fuel oil up to nearly 1.0 for the heavy residual oils. Commercially, these grades may be marketed according to a maximum viscosity limit, such as 75 Cst at 37.8 °C for light fuel oil, 150 Cst for medium fuel oil and over 225 Cst for heavy fuel oil. In practice, the heaviest grade marketed has a maximum viscosity of 1600 Cst at 37.8 °C.

An indication of the composition and some specifications of different types of fuel oils are given in table 2-1, [13].

Table 2-1: Typical specifications and analysis of Industrial fuel oils

Specifications	Light	medium	Heavy
Specific gravity at 15/15°C	0.922	0.948	0.977
Kinematic viscosity at 37.8 °C,Cst	170	400	640
Calorific value,gross,Btu/lb	18700	18500	18190
Ultimate analysis % wt			
C	84.9	84.9	84.5
H	12.0	11.4	11.1
S	2.57	3.19	3.84
Ash	0.06	0.11	0.12
N,O, etc. (by difference)	0.47	0.40	0.44
C: H ratio	7.1	7.4	7.6
Flash point, closed, Pensky-Martens, °C,min	66	66	66

Fuel oils are produced usually as the result of straight distillation of crude oil, it is referred to as a straight-run residue. Commercial fuel oils, however, usually contain appreciable proportions of residue resulting from cracking processes. These differ slightly from straight–run fuels in certain physical characteristics in that they are rather lower in pour point.

Most low viscosity fractions can serve as diluents provided their flash point is sufficiently high. Straight-run or cracked distillates from the naphtha range and heavier and the by-products of processes, such as the extracts from the production of lubricating oils and of premium grade kerosine, are all used for this purpose [13].

There is another wide American classification for fuel oil according to the viscosity, as shown in table 2-2, [15].

No.1 and No.2 fuel oils are called distillate oils, as they are capable of being distilled or vaporized at relatively low temperatures 150 to 345 °C at atmospheric pressure.No.1 oil is used almost exclusively for domestic heating and is just a little heavier than kerosine. No.2 distillate comes from the refinery fractionating tower after the No.1 oil. This oil is frequently called gas oil. No.4 fuel oil is variable and complex oil. No.5 and 6 fuel oils are called residual oils.

Table 2-2: detailed requirements for fuel oils according the American classification

Grade	Flash point °C	Pour point °C	Kinematic Viscosity Cst		API gravity	Sulphur Content %
			38 °C	50°C		
No.1	38		2.2		35	0.5
No.2	38	-7	3.6		30	0.7
No.4	55	-7	26.4			No limit
No.5 (light)	55		65.0			-
No.5 (heavy)	55		162.0	81		-
No.6	65		-	638		

2.2.2 Properties

Commercial fuel oils have to meet certain specifications to avoid any failures, which can be raised during pumping, storing or burning processes. The main limiting properties, which must be known for any fuel oil are, viscosity, specific gravity, pour and cloud point, flash point, sulfur content, sludge and sediment, and ash content.

Viscosity

Viscosity and viscosity-temperature relationship is considered as an important property when dealing with fuel oils during pumping, storage and atomization at burning.

Viscosity of heavy fuel oils can be usually reduced by heating, diluting with a low viscous oil-stock or the process of visbreaking. These are discussed in details in section 2-3.

The greater the viscosity, the greater it becomes the head loss along the pipeline of residual fuel oils, and therefore, more horsepower is required for pumping. These are under certain conditions, “Pseudoplastic fluid” which requires pressure to overcome yield stress to initiate flow or “Thixotropic” (Viscosity varies with respect to time and flow rate) [3].

Specific Gravity

Although the specific gravity of oil has no technical significance from the point of view of quality, it does give an idea of the grade of oil, i.e. whether it is a distillate or a residual oil. While an increase in specific gravity usually indicates an increase in the viscosity of fuel oil of the same origin, this may not apply if one fuel is straight-run and the other cracked.

In general, the API gravitates of distillate fuels are 26 to 39 °C and those of heavy fuel oils are 10 to 15 °C. Variations in specific gravity with temperature is an important factor in marketing and must also be taken into account when determining the fuel consumption of an appliance [13].

Pour and Cloud Point

The pour point is reported as the lowest temperature at which oil will flow under standardized test conditions in 3 °C increments. It is rough indicator of the relative paraffinicity of fuel oils. Pour point is considered as the lowest temperature at which oil could be stored or handled with out it congealing in the tanks or pipelines [15].

Cloud point is the temperature at which the incipient crystallization of wax in the oil results in an opacity or cloud, without necessarily complete solidification. This temperature will be higher than that of the pour point, since the fuel does not fail to pour until some of the wax crystals have coalesced. The purpose of quoting the cloud point is to indicate a temperature at which the blockage of fine filters may occur owing to the accumulation of waxy deposits.

Research is being carried out to determine the feasibility of using "Filterability" test as an alternative to a cloud point determination. The additions of pour point depressants are done some times to reduce pour and void wax crystallization [13].

Flash Point

The flash point of a fuel is the temperature at which the vapor given off will ignite when an external flame is applied under standardized condition. It is purpose is to ensure safety from fir risk during normal storage and handling. The flash point is an indication of the presence of a certain proportion of ignitable vapours in a specified set of circumstances and is not an indication of the general volatility or viscosity of a fuel. Flash point is considered as limiting property for blended or cracked fuel oils [13].

Sulphur

Sulphur is present in nearly all fuel oils in amounts above 2% as shows in table 2-1.Although commercially available residual fuel oils contain more than 4 wt% sulphur [13]. Sulphur in fuel oils is an undesirable consistent, causing pollution and corrosion effects, mainly due to sulphur oxides formation by burning of fuels.

-Sulphur oxides emitted from chimney stacks contaminate the atmosphere are proposing to have legislation or specifications to limit the amount of sulphur discharged into the atmosphere by limiting the sulphur content of industrial fuel oils.

- Sulphur oxides can also cause serious corrosion of air heaters in large boilers and of steel chimneys and other steel structures in temperatures below the acid dew point.
-In some industrial processes the presence of sulphur oxides in the products of combustion can adversely affect the product being heated.

The sulphur content of fuel oils can be reduced by hydrodesulphurization, but it is more difficult to produce low sulphur heavy fuel oils economically from sulphurous crude. Thus, when a low-sulphur heavy fuel is required, the refiner will use either low-sulphur crude or blend the residues with desulphurized cutter stock, or both.

Other Properties

There are other properties may be considered by the choice of fuel oils. Such properties influenced mainly the utilization of the fuel.

1-Sludge and Sediment Formation

These determine the possible life of the oil during storage. Unsatisfactory blending, or the presence of unstable, oxidizable, sediments, cause clogging of filters or nozzles and corrode storage tanks and pipelines. Cracked oils are particularly bad in this respect. Oxidation and corrosion inhibitors are sometimes added to reduce these troubles. When oils of different origins are mixed, an asphaltic sludge may be deposited, in such a case the oils are said to be incompatible. Asphaltic and waxy sludge can also be deposited from heavy fuel oils that are stored in heated storage tanks if serious over heating has occurred. The degree of sludging depends on a number of factors, including the nature of the oil and its thermal history, both before and after its delivery to customer's premises [13].

2-Carbon-Hydrogen Ratio

High carbon to hydrogen ratios fuels burn with more luminous flame than low ratio oils. High ratios causes an increase in the heat transfer by radiation, because of the high emissivity factor of such flames. The calorific value decreases and specific gravity increases with increasing carbon: hydrogen ratio. In general, also, the higher the C:H ratio, the greater the reduction in viscosity with increase in temperature [13].

3-Carbon Residue

Carbon residue is roughly related to the asphalt content of fuels. In most cases the lower the carbon residue the more valuable the fuel. This expressed in weight percent carbon residue by either the Ramsbottom (RCR) or Conradson (CCR) according to ASTM test procedures (D-524 and D-189) [13].

The maximum ash content in fuel oil is usually lower than 0.2%. Its composition is important, since certain constituents, such as sodium, vanadium and sulphur; cause severe corrosion of the surface and hot refractories of boilers and furnaces [13].

2.3 Viscosity Lowering of Residual Fuel Oils

2.3.1 Introduction

Viscosity of fuel oils is usually required in hydraulics calculations for surface facilities, pipeline transportation, handling and combustion devices. With the increased popularity of process and reservoir simulators, there is a need for a consistent, reliable and accurate analytical predictive method for viscosity calculations.

The high viscosity of residual fuel oils may be reduced usually by blending with less viscous products, heating, or by the process of visbreaking. Numerous information has been published on the variation of viscosity of oil-stocks with temperature and viscosity estimation for blends of oil-stocks.

2.3.2 Heating

It is well known that the viscosity of heavy petroleum fractions decreases as temperature increases. For short distance transportation of oil, through pipes the process of heating by steam would reduce the viscosity; making the flow easier. The disadvantages of this process are the added cost of heating devices, insulation of pipelines and energy requirement [16].

To minimize tube size a by-pass stream, taken from the main flow, is heated to a higher temperature than the required. When it re-enters the main flow, it mixes with the remainder of the oil and the resultant temperature is that which is required. The temperature to which the oil is raised in the heater must obviously be kept below the cooking range.

To achieve an economic “optimum” with respect to pipeline size pumping, and cost, the temperature and viscosity profile for the line must be established. An upper limit about 93 °C is usually set to protect the insulation from damaged due to steam generation at the pipe surface [3].

2.3.3 Blending

The blending method for viscosity lowering is discussed as alternative to hot oil pipeline transports of heavy petroleum fractions. The blending of oil-stocks in pipeline is usually a continuous and controlled process.

The problem which confronted the engineers in this case is that of designing a system in which each component is individually regulated to maintain a fixed amount of the total flow to match the pipeline requirements [17].

The blending process is carried out in many methods. These methods are agitation by air, propeller or paddle, circulation and gravitation using proportionate pumps and meters. Heating is usually necessary in case of blending of residual fuel oils to obtain good blends. Heat sets up circulation with in the tank and this circulation results in the desired mixing. The higher temperature reduces the viscosity, which makes blending easier [15].

Agitation by air, propeller or paddle are used but not too extensively, although this methods, plus heating, well give a very good blend.

Circulation is accomplished by pumping the blending oils into a tank and pumping from the bottom and back into the top. This method is used together with heating and the results are satisfactory. Gravity blending is used mostly for blending in trucks and small bulk plants where equipment is limited. This method is the cheapest of any, and there are two procedures as follows:

1-The heavier oil is pumped into the tank first and the lighter oil is then pumped into the bottom, where it mixed with the oil as it moves upward.

2-The light oil is pumped in firstly into the tank and then the heavier oil pumped through the top, where mixing occur as it moves downward.

Another method of blending is using meters and pumps. In this type of blending, the correct amount of diluents or distillate is metered. The volume of heavier oil is controlled by a constant rate pump. These two products enter a common line. In compatibility, one of the problems raised from mixing processes, it is defined as the ability of fuel residue to form participates when mixed with another fuel oil. The most important mixing problem appears when the fuel oil contains asphalt higher than 3-5% is mixed with another one of paraffinic base, which causes asphalt to participation [18].

2.3.4 Other Methods

Visbreaking operation at different temperatures and LHSV's was used in order to improve the main physical specifications of residual fuel oil. The viscosity, pour point and sulpher content of Vacuum residue were lowered noticeably by the process of visbreaking [1].

An attempt has been made to produce fuel oil from two Iraqi residues using a soaker and coil visbreaking. The continuous experiments were carried out under mild conditions, namely 420−480 °C and 43−109 sec in the coil and 151−397 sec in the soaker. Stable fuel oils with acceptable viscosity, pour point and flash point were produced [19].

The degree of viscosity and pour point reduction is a function of the composition of the residual feed to the visbreaker. Waxy feed stocks achieve pour point reductions from−9 to −1.7° C and final viscosities up to 75% of the original value.

Coil cracking uses high furnace outlet temperature 474−499° C and reaction times from one to three minutes, while soaker cracking uses lower furnace outlet temperatures 427−443 °C and longer reaction times [12].

Marsden, et al. [20] described a method of transporting crude oils at low temperature by dispersion in methanol. Those containing 50 to 80 volume percent of the oils, which are stabilized by presence of a small amount of an effective surface-active dispersant, which can readily be pumped through buried pipelines at temperature below 0 °C.

The addition of both methanol and ethanol in a low concentration to heavy petroleum fractions lead in a reduction of their apparent viscosity. The maximum decrease in viscosity was obtained by the addition of about 3% by volume alcohol [21].

A method has been developed to make homogenous and stable blends of residual oil and ethanol in the presence of Kerosine as a coupling agent [22]. This blend exhibits much lower viscosity and better combustion characteristics.

Killesriete [23] suggested the use of gas mixtures like the refinery gas or liquefied petroleum gas for an enhanced oil recovery. All these gases have a positive effect on viscosity lowering and swelling.

There are other methods for viscosity lowering of heavy residual oils, which have less commercial applications. One of these methods is the use of additive to modify the wax crystals so they do not agglomerate or stick to surfaces, hence preserving the fluidity of the oil.

Mixing water with oil to form a lower viscosity, unstable emulsion, has been also proposed for transport of heavy petroleum fractions [3].

One of the solutions of an oil capacity increases problems is to inject a drag reducing additive. The additives that have been used successfuly are solutions of certain types of high molecular weight long chain polymers in hydrocarbon solvents [24,25]. The performance of the drag reducing polymer, namely CDR (Conoco Drag reducer) for two Iraqi crude oil was evaluated. The data presented should be useful in possible application of drag reduction additives for flow capacity increase for crude oil [26].

Drag reducing additives were prepared locally and studied in flowing Kerosine and gas oil at concentrations up to 50 ppm. Drag reduction up to 28% and 20% was achieved for Kerosine and gas oil respectively [27].

2.4 Viscosity Correlations

2.4.1 Effect of Temperature on Viscosity of Oil-Stocks

Numbers correlations are available in the literature on the effect of temperature on viscosity of petroleum fractions.

De-Guzman [28] proposed firstly a simple exponential relationship for viscosity-temperature correlation for undefined petroleum fractions. Then many investigators, such as Arrhenious [29], Madge [30], Andrade [31] and Velzen et al. [32] have contributed in developing various forms of exponential relations.

Watson et al. [33] presented figures related to kinematic viscosity as a function of API gravity data and Watson characterization factor (Kw). The API technical data book [34] replaced these figures with monographs to relate the kinematic viscosity as a function of temperature. This has proven useful over the years and it is at present accepted as an industry-wide standard for predicting viscosities of light to moderately heavy oils.

Abbott et al. [35] reduced the API monographs to equations with reasonable accuracy but these were found to be subject to singularities [36]. Therefore, the correlation can not be extrapolated into the regions where no experimental data are available.

Baltatu [37] proposed the use of modified corresponding-state reported by Ely and Hanley [38] to predict the viscosity of petroleum fractions. The input data required are the pseudo critical parameters, the molecular weight and centric factor for each fraction of interest. The centric factor, which is the key parameter in the proposed correlation, brings considerable uncertainties concerning its estimation for petroleum fractions. This is primarily a result of the compounded inaccuracies introduced by the estimation of the intermediate correlating parameters such as critical temperature, critical pressure and the choice, from the several values of the boiling point. The alternative approach has been used to develop generalized correlation that based on the experimental kinematic viscosity.

Twu [39] proposed the following equation to estimate the viscosity of oil-stock based on API gravitates:

$$\mathbf{ln(\nu) = ln(\nu^{(r_1)}) + \frac{API - API^{(r_1)}}{API^{(r_2)} - API^{(r_1)}} * \left[ln(\nu)^{(r_2)} - ln(\nu)^{(r_1)}\right]} \qquad (2\text{-}4)$$

Where v is the kinematic viscosity of the petroleum fraction in Cst at either 372.04 or 310.93 K. $\nu, \nu^{(r1)}$ and $\nu^{(r2)}$ are evaluated at the same boiling point. The superscripts (r_1) and (r_2) again refer to two reference fluids. Since all the calculations are made at the same boiling point. Equation (2-4) can be simplified based on the definition of Watson characterization factor and ^{o}API gravity as follows:

$$\nu = \nu^{\mathbf{(r1)}} \left[\frac{\nu^{(\mathbf{r}_2)}}{\nu^{(\mathbf{r}_1)}} \right]^{\mathbf{(1/2)(K_w - 10)}} \qquad (2\text{-}5)$$

Twu [39] showed that, the viscosity of the reference fluid can be obtained from plots of Watson correlation [40]. These data had been correlated as a function of the boiling point temperature of petroleum fraction by means of the following equation:

$$\ln\left(\nu^{(r)}\right) = C_1 + \frac{C_2}{T_b} + C_3 \ln(T_b) + C_4 T_b + C_5 T_b^3 + C_6 T_b^6 \qquad (2\text{-}6)$$

Where:-

$\nu^{(r)}$ is the reference viscosity in Cst at either 372.04 or 310.93 K.

The Walther equation [41] is used commonly for correlating the viscosity temperature behavior of petroleum products, as follows:

$$\text{Log}\log(\eta+0.7) = b_1 + b_2 \text{Log}(T) \qquad (2\text{-}7)$$

Singh, Miadonye and Puttagunta [42] developed a simple and generalized correlation for predicting temperatures effect on the absolute viscosity of unrefined bitumens and heavy oils as follows:

$$\left[\frac{\text{Log}(\mu) + C}{\log(\mu_0) + C}\right] = \left[\frac{T_0}{T}\right]^s \qquad (2\text{-}8)$$

Where:-

μ= absolute viscosity, Pas.s

C=3.0020, when the log bas is 10

S=0.0066940 log (μ_0) +3.5565, when T_0 is 303.15K (30 °C)

The correlation allows for prediction of the viscosity of bitumens and heavy oils over a wide range of temperatures by making only a single viscosity measurement μ_0, on the sample at any convenient temperature, T_0. The overall AAD with this correlation was 4.23% for 125 data points.

Amin and Maddox [43] and Beg et al. [45] carried out extensive research work on a correlative procedure. For predicting the viscosity of petroleum fractions. They used several modifications of Eyring's [44] equation and the one which is the best correlated viscosity data was found to be of the following form:

$$\eta = \mathbf{A\,exp}\left(\frac{\mathbf{B}}{\mathbf{T}}\right) \tag{2-9}$$

Beg et al. [45] formulated A and B to be functional to 50% boiling point and API gravity at 15 °C as follows:

$$B=\exp\,(5.471+0.00342T_b) \tag{2-10}$$

$$A=-0.0339\,(API)^{0.188}+0.241(T_b/B) \tag{2-11}$$

Substitution of expressions for parameters A and B into Eyring's equation gives the following generalized Kinematic viscosity correlation:

$$\eta = \left\{-\mathbf{0.0339(API)^{0.188}}+\mathbf{0.241(\frac{T_b}{B})}\right\}+\mathbf{exp}\left[\frac{\mathbf{exp(5.471+0.00342T_b)}}{\mathbf{T}}\right] \tag{2-12}$$

Where:-

T_b=50% boiling point, K

Equation (2-12) gave an overall AAD of 7% for 156 viscosity measurements as compared with the overall AAD of 17.5% given by API method [34]. Further, this correlation fitted the data from 102 experimental measurement of kinematic viscosity made on 34, other world crud oil fractions with an overall AAD of 7.4% while the corresponding error for the API method was 19.1%.

Amin et al. [46] extended that work by introducing molecular weight as an additional parameter beside the other two parameters of ^{o}API gravity and 50% boiling point. The final form is:

$$\eta = [-1.954*10^{-3} + 0.0906 \exp(-7.773+10^{-3}Mw)] \exp\{[67.45 + \exp(5.329 + 0.00329T_b)(Mw/API)]/T\} \qquad (2\text{-}13)$$

Mehrotra [47] suggested a correlation for the viscosity of pure hydrocarbons at different temperature, as follows:

$$\text{Log}(\mu+0.8) = 100(0.01T)^{b} \qquad (2\text{-}14)$$

Where:-

$$b = -5.745 + 0.616\ln(ECN) - 40.468(ECN)^{-1.5} \qquad (2\text{-}15)$$

μ=Viscosity of pure liquid hydrocarbon, Mpa.s

Mehrotra tabulated ECN for 65 components. A modified Mehrotra equation (2-14) had been considered for the development of a new generalized correlation for viscosity-temperature prediction [48].The modification had been done by replacing μ by ν; Kinematic viscosity of petroleum fraction in cst and changing the constant 0.8 by 0.7, so as to have equation of the following form:

$$\text{Log}\,(\nu+0.7) = 100(0.01T)^{b} \qquad (2\text{-}16)$$

b can be calculated by equation (2-15), while ECN for petroleum fractions was calculated by equation (2-17).

$$ECN(T_b,API) = -1799.8195 - 0.0403386T_b + 8.19416*10^{-5}T_b^{2} - 352.5229(T_b/API)^{0.1} + 2158(T_b/API)^{0.02} \qquad (2\text{-}17)$$

Where: - API at 15 °C and T_b =50% boiling point in15 °F.

2.4.2 Effect of Pressure on Viscosity of Oil-Stocks

Block [49] reviewed different approaches to describe the viscosity temperature-pressure relationship of lubricating oils in terms of empirical formulas and their predictions from correlation's based on properties that are easily accessible at atmospheric pressure. An approach proposed in which viscosity-temperature-pressure relationship was first studied individually for "similar group" of natural lubricating oils originating from a similar source and refined in a similar way and was used to examine several correlations, such as Heresy and Lowdenslager [50] formula:

$$\boldsymbol{\eta(p) = \eta_a (1 + P / K)^n} \tag{2-18}$$

Where:-

η_a is the viscosity at atmospheric pressure

η (P) is the viscosity at the required pressure

Sanderson [51] presented a formula to calculate the Kinematic viscosity as function of pressure, as follows:

$$\text{Log Log } [\nu(P) +0.6] =C\ P^{1/2} +D \tag{2-19}$$

Where:-

ν (P) is the kinematic viscosity at the required pressure.

Mehrotra and Svrcek [52] presented new data for the effect of pressure and temperature on a gas-free Athabasca bitumen viscosity covering a temperature of 43-120°C and pressure up to 10 Mpa (1450 Psi). Two correlations were developed to describe the effect of pressure and temperature on the viscosity of bitumen:-

Model 1:

$$\ln \mu=\exp [a_1+a_2+\ln T] +a_3P \tag{2-20}$$

Model 2:

$$\ln \mu = [a_1 + a_2 \ln T] + a_3 P \qquad (2\text{-}21)$$

Where:-
T in K
P in Mpa

The AAD was 1.8% with model 2 compared to 2.8% with model 1. An increase of pressure to 10 Mpa resulted in a 49% increase in the bitumen viscosity at 43 °C compared with a 33% at 120 °C. Thus, the effect of pressure is more significant at lower temperature where the viscosity of bitumen is high. Graphical representation of the increase of viscosity with pressure demonstrated a nonlinear relationship, while a linear relationship of lnμ with pressure over the whole range of temperatures was noticed.

Kouzel [53] presented an equation to calculate the effect of pressure on the viscosity of high molecular weight hydrocarbons, as follows:-

$$\mathbf{Log}\left(\frac{\mu}{\mu_0}\right) = \frac{\mathbf{P}}{\mathbf{1000}}\left[\mathbf{0.0239 - 0.01632}\mu_0^{\mathbf{0.278}}\right] \qquad (2\text{-}22)$$

Where:-
μ at T and P, in cP
μ_0 at T and 1atm, in cP
P in Psi

The deviations between calculated and experimental viscosities of high molecular weight hydrocarbon were reported as approximately 5% for pressure,< 5000 Psi and approximately 8% for pressure up to 10000 Psi. [54].

Ahrabi et al. [55] measured the viscosities for crude oil and natural gas liquid (NGL) at different pressures. Measured viscosities for liquid phase crude oil increased with an increase in pressure, with a pronounced break at the bubble point at all temperatures.

Generally pressure exhibits a linear relationship with Log viscosity of liquids [56].

2.4.3 Effect of Composition on Viscosity of Oil-Stocks

It is advantageous to be able to predict the physical properties of petroleum fraction mixtures from the properties of the components. The theory of the viscosity of mixture based upon molecular interaction has been discussed by Eyring et al. [57, 58]. Gemant [59] considered Eyring's theory to be most complete, but many modifications have recently been proposed. In practice, the viscosities of blends always bear non-components. Therefore, numbers empirical correlations had been developed to predict the viscosities of blends.

Rybak[60] Kosakov[61], Gurevich [62] and Nelson[63], proposed methods for calculating the viscosity of petroleum product blends, based on some properties of individual blend components.

Reid et al. [64] defined the kinematic viscosity ν_m of mixture of two components A and B by equation (2-23).

$$\ln\nu_m = x_A^3 \ln\nu_A + 3x_A^2 x_B \ln\nu_{AB} + x_A x_B \ln\nu_{BA} + x_B^3 \ln\nu_B + R^0 \qquad (2\text{-}23)$$

Where:-

$$\mathbf{R^o = x_B^3 \ln \frac{M_B}{M_A} + 3x_A^2 x_B^2 \ln \frac{1 + 2M_B/M_A}{3} + 3x_A^2 x_B \ln \frac{2 + M_B/M_A}{3} - \ln x_A + x_B \frac{M_B}{M_A}} \qquad (2\text{-}24)$$

and

x =mole fraction of each component

M=molecular weight of each component

ν=kinematic viscosity, Cst

ν_{AB}, ν_{BA}=constant determined by the least squares method.

Wright [65, 66] used the standard viscosity-temperature charts to predict the viscosities of blends of petroleum products and the following equation was proposed.

Log Log Z=A-B Log T (2-25)

Where:-

T in R°

Z= compressibility factor

A, B are constants

Z=ν+0.7+C-D+E-F+G-H (2-26)

And

C =exp (f-1.14883-2.65868ν)

E=exp (5.4649-37.62889ν)

G=exp (37.4619-192.643ν)

D=exp (0.0038138-12.5645ν)

$F=\exp(13.0458-74.6851\nu)$

$H=\exp(80.4945-400.468\nu)$

The limits of applicability are:-

$Z=(\nu+0.7)$	$2*10^7$ to 2 (Cst)
$Z=(\nu+0.7+C)$	$2*10^7$ to 0.9 (Cst)
$Z=(\nu+0.7+C+D+E)$	$2*10^7$ to 0.3 (Cst)
$Z=(\nu+0.7+C+D+E-F+G)$	$2*10^7$ to 0.24 (Cst)
$Z=(\nu+0.7+C+D+E-F+G-H)$	$2*10^7$ to 0.21 (Cst)

To improve Wright's method, a modified Walther's equation [67] was used.

$$\ln\ln(\nu+0.7)=m\ln T+b \qquad (2\text{-}27)$$

Where:-

ν=kinematic viscosity in (Cst)

T=absolute temperature (R°)

m,b =constant

This equation enables the viscosity to be obtained at any desired temperature, if m and b are known and b can be deduced from two viscosity observations [68].

The most widely used approach in calculating the viscosity of product blends is the ASTM-D341 method [69], which is based on the additive quantity log log $(\nu_t+0.8)$, as follows:

$$\mathbf{LogLog(\nu_b + 0.8) = \sum \frac{x_i}{100} LogLog(\nu_i + 0.8)} \qquad (2\text{-}28)$$

Where:-

ν_i and ν_b the kinematic viscosities, at a given temperature, of the blend components, and of the blend; in (Cst), respectively

x_i is the percentage of the given component in the blend.

Walter suggested equation (2-29), [63, 70], to predict the viscosity of oil blends.

$W_t = \log \log (\nu_t + 0.8) = A - B \log T$ (2-29)

W_t=Walter function, the additive quantity function, which appears in equation (2-29), has a number of remarkable properties [71-74] and its additive is consistent.

The Refutas viscosity blending function [75] was widely used to predict the kinematic viscosity of petroleum products blend. This method considers blending indices, provided in special tables, which are aggregated on a weight basis. The Refutas function I can be calculated from the equation (2-30):

$I = f(\nu) = 23.097 + 33.468 \mathrm{LogLog}\,(\nu + 0.8)$ (2-30)

The Refutas indices of the components, of known viscosities at the same temperature as the mixture, were first determined, and the index of the blend was then calculated, based on the weight fraction of each component.

$$\mathbf{I_{bi}} = \sum_{i}^{n} \mathbf{I_i w_i} \qquad (2\text{-}31)$$

Where:-

I_{bi} is the blend Refutas index

w_i is the weight fraction of component i, the viscosity of the blend was hence computed from equation (2-30). This method had been reported for petroleum products but it was less for extreme blends such as gasoline and residues. The percentage deviations of the predicted viscosity from experimental values were of the order of 2% for middle distillates.

Letsou and Stiel [76] proposed a corresponding state approach that uses the centric factor (ω_o), as given in equation (2-32) through equation (2-35):

$$\eta\varepsilon = (\eta\varepsilon)^{0} + (\eta\varepsilon)' \qquad (2\text{-}32)$$

Where:-

$$(\eta\varepsilon)^{o} = 0.015174 - 0.012135T_r + 0.0075T_r^2 \qquad (2\text{-}33)$$

$$(\eta\varepsilon)' = 0.042552 - 0.07674T_r + 0.0340T_r^2 \qquad (2\text{-}34)$$

$$\varepsilon = \mathbf{T_c^{1/6} / M^{1/2} P_c^{2/3}} \qquad (2\text{-}35)$$

$\eta\varepsilon$ is reduced viscosity of two substances at the same reduced temperature (T_r)

T_c, M and P_c are the critical temperature, molecular weight, and critical pressure, respectively.

2.5 Pipeline Transportation

Crude oils and their fractions are often transported by pipelines over long distances from fields and storage to marketing and processing units. During the pumping a substantial drop in pressure may be take in account in both the pipeline and in the individual units themselves. Many intermediate products are pumped from one factory site to another, and raw materials such as natural gas and petroleum products may be pumped very long distances to domestic or industrial consumers. It is necessary, therefore, to consider the problems concerned with calculating the power requirements for pumping, with designing the most suitable flow systems, and frequently with controlling the flow at a steady rate. The oil-stocks may consist of one or more phases and contain suspended solids; and considered sometimes as non-Newtonian properties, these often complicate the analysis. The design and layout of pipe systems are an important factor in the planning of modern plants and may represent a significant part of the total cost.

The energy required by the pump will depend on the height through which the fluid is raised, the pressure required on delivery, the length and diameter of the pipe, the rate of flow, together with the physical properties of the fluids, particularly its viscosity and density [77].

Heavy oils, characterized by their high viscosities, high pour point, and low API gravitates, are currently being transported to a limited extent by pipelines. Many of these pipeline are transporting the residual product (residual fuel oil) from the refining to consumers. Although there are some pipelines used for the transport of heavy crude oils.

Heavy oils present problems of pipeline transport usually because of one of the two characteristics:-

-Pour point (wax crystallization)

-Viscosity (the ability to flow)

The pour point is the temperature at which wax crystals in the oil inhibit its ability to flow; at pour point temperature the liquid will gel and behave like a solid material. Waxy crude will form wax sediment in storage tanks and thick wax deposits on the walls of pipelines sufficient, in time, to block the pipeline. Generally, pipelines are designed and operated at temperatures above the pour point .The relationship between viscosity and temperature is important in the design of pipelines. This relationship is shown in figure 2-1 for a number of crude oils, both heavy and light [3]. Viscosity relates to the shear stress and shear rate. The greater the viscosity, the greater becomes the head loss along the pipeline, and therefore, more horse power is required for pumping. Generally, the economic range of viscosities at pipeline temperatures is 10−1000Cst, depending on pipeline length. The effect of viscosity on pipeline size and pumping power requirement are shown in table 2-3, [3]. The data developed do not necessarily represent an economically" optimum" design for each case, but serve to illustrate the effect of viscosity.

Note that above approximately 100Cst there are large incremental increases in pipeline size and pumping HP. It is for this reason that most existing large and long oil pipelines have been designed for viscosities in the region of 100Cst. However, it is feasible to consider designs for viscosities in the region of 1000Cst if the economics are favorable.

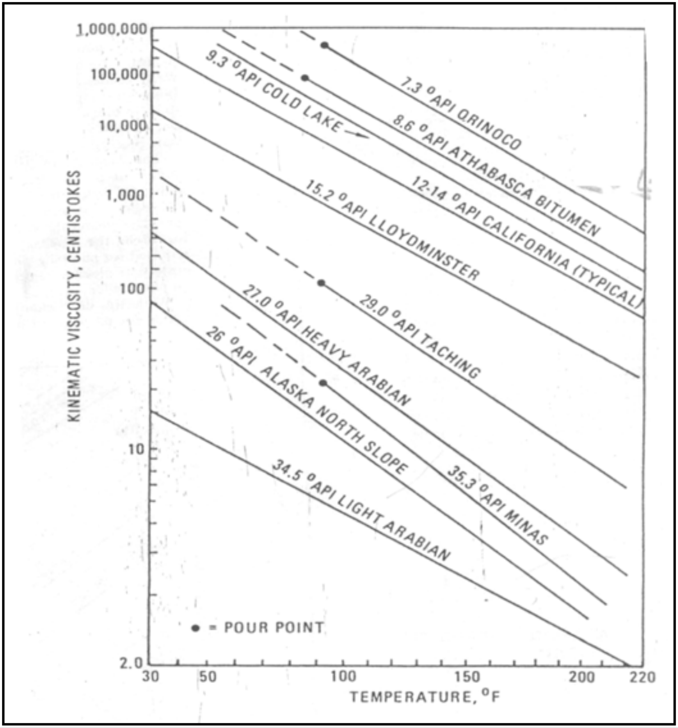

Figure 2-1: Effect of temperature on Viscosity of various crude oils and a bitumen [3]

Table 2-3: Effect of viscosity on pipeline size and pumping HP [3]

Viscosity Cst	Gravity ^{o}API	Pipeline I.D., in	Psi/Mile	HP per Mile	Station spacing, Miles
50,000 BPD capacity					
1	45	10.3	16	17	75
10	26	11.2	17.4	18.5	70
100	17	12.5	19.4	20.5	60
1000	10	17.0	26.5	28	45
100.000BPD capacity					
1	45	14.4	11.2	24	105
10	26	15.6	12.1	26	100
100	17	17.3	13.5	29	90
1000	10	22.2	17.3	37	70

To achieve an economic "Optimum" with respect to pipeline size, pumping HP and cost, the temperature (and viscosity) profile for the line must be established. (An upper limit of $93\,^{\mathbf{o}}\mathbf{C}$ is usually set to protect the insulation from damage due to steam generation at the pipe surface). As the oil moves down the line, heat is lost, the oil temperature drops, and therefore the viscosity increases, and pressure drop increases. However, friction serves to impart some heat to the oil, and may provide a substantial heat contribution in the case of a large diameter, high capacity pipelines.

The method used to establish the temperature profile considers the line divided into sections, for of which heat loss, friction heat, temperature drop (or rise), viscosity, and soil conductivity must be taken into account for the heat loss calculation. The results of this calculation can be shown in figure 2-2 as a graphic profile [3].

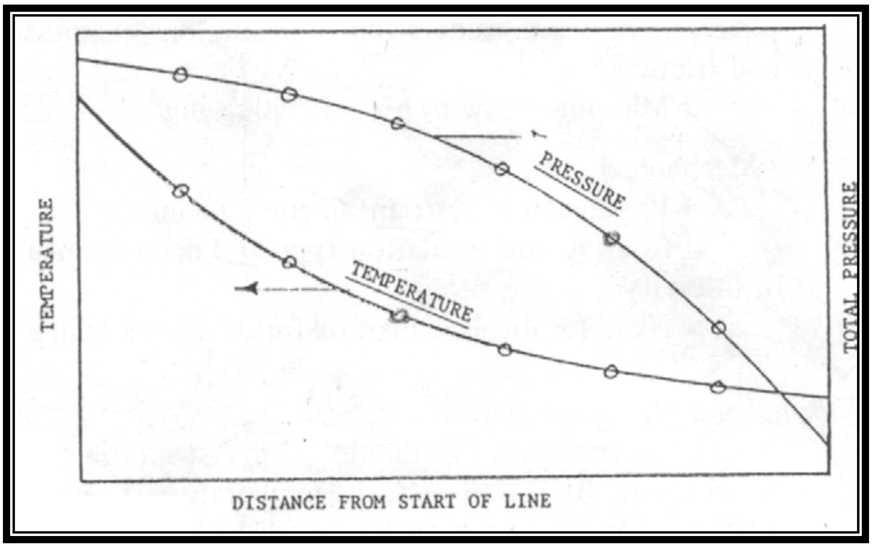

Figure 2-2: Temperature profile in pipe flow

The analysis of temperature loss and pressure drop must also consider the economic impact of intermediate reheating. Reheating will serve to increase the temperature, reduce the viscosity and reduce the line size and pumping HP, but these savings must be weighed against the cost of reheating [3].

Pipelines designed to convey fuel oils at temperatures considerably higher than ambient require to be thermally insulated so that the heat cost during transit can be kept to a minimum. The insulating material currently in common use is foamed polyurethane. This material may be obtained in pre-formed sections, applied directly to the pipe or applied to an annulus between the pipe and an outer polyethylene sheath.

The fuel oil is usually heated to about, $95^{\circ}\mathbf{C}$ before being delivered to the pipeline, and insulated pipelines have hitherto been confined to comparatively short distances of less than 30 miles, or greater if en-route re heating stations are provided. An insulated pipeline runs from Fawley to west London, a distance of 64 miles. This pipeline was designed to handle between 1.5 and 2 million tons/year without intermediate pumping or heating stations [14].

An alternative to hot oil pipeline transport of heavy oils at ambient temperature, pipeline transport by reducing the viscosity of the heavy crude oil with low viscosity oil-stocks such as condensate, natural gasoline, or naphtha.

Figure 2-3 shows the reduction in viscosity that can be obtained by blending of condensation with heavy crude oils. While table 2-4 shows the effect of dilution on pipeline size, pumping HP, and costs for pipeline transport of 1000 Cst oil with and without dilution [3].

Note that in this case use of 10–20 percent diluents approximates an “Optimum” pipeline design [3], table 2-4.

Table 2-4 Effect of Dilution on pipeline Sizes and Transportation Costs [3]

Blend Stock Added to Crude Oil, parts P/100	Total Capacity MBD	Blend		Pipe line I.D., in	Psi. per Mile	HP per Mile	Relative Investment cost per mile	Station Spacing Miles
		ν Cst	API					
0	100	1000	10	22.2	17.3	37	100	70
1	101	838	11	21.5	16.6	36	97	75
5	105	445	13	19.2	14.2	32	86.7	85
10	110	123	15	18.5	13.1	31	83.7	90
20	120	85	18	18.7	12.1	31	84.58	100
30	130	41	23	18.7	11.2	31	84.58	105
40	140	23	28	18.9	10.5	31	85.42	115

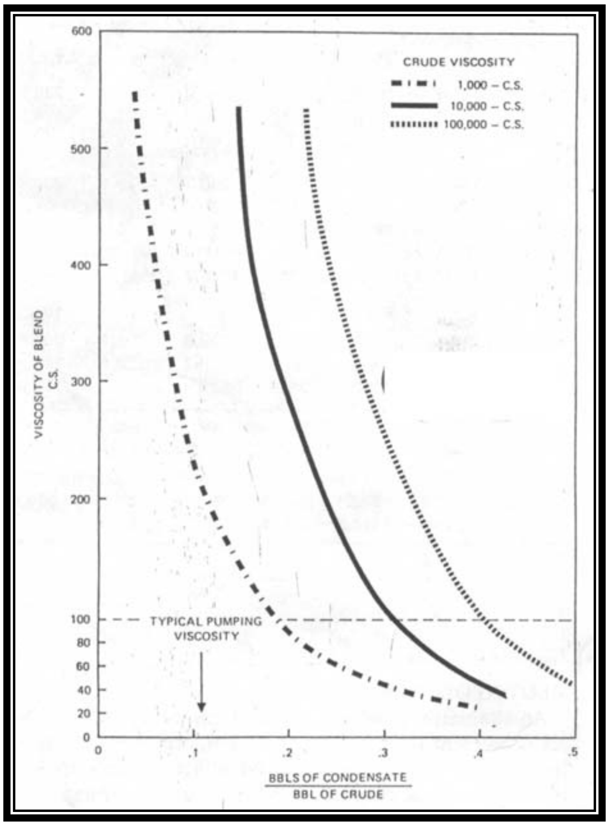

Figure 2-3: Effect of dilution with condensate on viscosity of crude oils

The following discussions will be confined to normal situations met in actual practice that is, steady state (isothermal) conditions, and exclude problems of moving non-Newtonian oils or those which require heating [77]. Fundamentally, Darcy's equation is expressed as follows:

$$\mathbf{h_f = 8\phi \frac{L}{d} \frac{u^2}{2g}} \qquad (2\text{-}36)$$

The Darcy equation is far more useful in a form employed conventional pipeline units.

$$\Delta P = 4\phi \frac{L}{d} \rho u^2 \qquad (2\text{-}37)$$

$$Re = \frac{\rho u d}{\mu} \qquad (2\text{-}38)$$

For turbulent flow and smooth pipe, equation (2-37) can be adapted by substituting the value of $\phi = \frac{0.04}{Re^{0.25}}$ and the value of Re in equation (2-38)

$$\frac{\Delta P}{L} = \frac{0.16\rho^{0.75}u^{1.75}\mu^{0.25}}{d^{1.25}} \qquad (2\text{-}39)$$

The oil velocity is calculated by equation (2-40)

$$\mathbf{u = \frac{Q}{A} = \frac{Q}{(\frac{\pi}{4})d^2} = 1.27\frac{Q}{d^2}} \qquad (2\text{-}40)$$

The pressure drop is estimated by

$$\frac{\Delta P}{L} = 0.244\frac{Q^{1.75}\mu^{0.25}\rho^{0.75}}{d^{4.75}} \qquad (2\text{-}41)$$

The power required for pumping will be given by the product of the volumetric flow rate and the pressure difference between the pump and the discharge and of the pipeline.

$$HP = \Delta PQ/\eta_p \qquad (2\text{-}42)$$

The required horse power can be calculated by assuming constant volumetric flow rate, as follows:

$$\mathbf{HP} = \frac{\mathbf{0.244Q^{2.75}L}}{\mathbf{d^{4.75}}\eta_\mathbf{p}}\rho^{\mathbf{0.75}}\mu^{\mathbf{0.25}} \tag{2-43}$$

While, the volumetric flow rate is calculated by constant pumping horse power, as follows:

$$\mathbf{Q} = \left[\frac{\mathbf{d^{4.75}}\eta_\mathbf{P}\mathbf{HP}}{\mathbf{0.244}\mu^{\mathbf{0.25}}\rho^{\mathbf{0.75}}\mathbf{L}}\right]^{\mathbf{0.3637}} \tag{2-44}$$

CHAPTER THREE

EXPERIMENTAL WORK

3.1 Petroleum Fractions

The considered oil-stocks, fuel oil, reduced crude, light gas oil and heavy gas oil are supplied from Al-Daura Refinery in Baghdad. The significant specifications of the oil-stocks are given in table 3-1 while, the effect of temperature up to 70 ^{o}C on their viscosities are listed in table 3-2.

Pour point, flash point and 50% distilled were measured in laboratory of Daura refinery according to the IP standards. Analar grade methanol was supplied by BDH England.

Table 3-1: Significant properties of petroleum fractions

Specification	Light gas oil	Heavy gas oil	Fuel oil	Reduced crude
API gravity at 15.5 ^{o}C	41.27	31.29	17.85	17.74
Viscosity at 30 ^{o}C,Cst	4.01	10.45	584.64	648.49
50% distilled, ^{o}C	290	325	370	410
Flash point, ^{o}C	82	140	168	180
Pour point, ^{o}C	-10	9	16	20

Table 3-2: Kinematic viscosity variation with different temperatures for petroleum fractions

Petroleum Fractions	Viscosity(Cst) at temperature, ^{o}C				
	30	40	50	60	70
Light gas oil	4.01	2.87	2.45	2.15	1.85
Heavy gas oil	10.45	6.89	5.47	4.32	3.67
Fuel oil	584.64	289.5	151.35	85.95	55
Reduced crude	648.49	303.78	156.38	89.33	57.05

3.2 Blending

The composition of each oil mixture was prepared as volume percentage and then transferred to the weight percent, for more accuracy. Measurements were taken by using a graduated 100 and 25 ml cylinders for blends above 10%, while 100 and 10 ml cylinders for lower blends.

The blended samples were shaken inside closed bottles at room temperature $18-23^{o}C$ using magnetic stirrer set during the winter season. Viscosity and density measurements were completed immediately, after preparing the mixtures to avoid deposit formation or vaporizing the light ends. All the viscosity and density measurements are carried out at atmospheric pressure.

The following mixtures were prepared in this study to investigate the reduction of the viscosity of commercial fuel oil and reduced crude:

1. Binary mixtures of fuel oil with light or heavy gas oil over range of 1−25vol. % of low viscous stock at different temperatures ranging between 30 −70^{o}C.
2. Binary mixtures of reduced crude with light or heavy gas oil over range of 1−25vol. % of low viscous stock at different temperatures ranging between 30 −70^{o}C.
3. Addition of methanol over range between 1−10 vol. % to each fuel oil or reduced crude at different temperatures ranging between 30 – 50^{o}C.

3.3 Density Measurements

Density determination of petroleum fractions and their blends were carried out using pyknometer with size 25 cm^3 according to the standard method (IP. 190) [78]. The calibration of pyknometer was done by determining the density of distillate water, with a good degree of purity at 15^{o}C.

The density of all binary mixtures and petroleum fractions were measured at six different temperatures, namely 30, 40, 50, 60, 70^{o}C. The density measurements of methanol blends were carried out at 30 – 50^{o}C since methanol itself has a boiling point of about 60^{o}C. A constant temperature bath type (Julabo HC) was used to achieve the required temperature within µ 0.1^{o}C. Each experiment was repeated at least twice times in order to get confident results.

3.4 Viscosity Measurements

Viscosity measurements at different temperatures were performed by using different types and size of cannon-fenske routine viscometers. These viscometers are suitable for kinematic viscosity ranges 1−400mm^2/s according to the standard method (IP.71) [78]. The selection of type and size of viscometers was depending on the type and density of petroleum fraction.

The viscometer was placed in a water bath type Julabo, which was capable of maintaining the temperature within µ $0.1^{o}C$ of the selected temperature. A measurement of kinematic viscosity was determined by the international standard ISO 3105. The viscosity of petroleum fractions and all binary mixtures were measured at five different temperatures, namely 30, 40, 50, 60, $70^{o}C$ and up to $50^{o}C$ when dealing with methanol. Kinematic viscosity was calculated from the measured flow time, t, and the viscometer calibration constant, c, by the equation (3-1):

$$\upsilon = \mathbf{ct} \qquad (3\text{-}1)$$

Where:-

υ is the kinematic viscosity in cst/s.

c is the calibration constant of the viscometer in cst/s.

t is the flow time in second.

Each experiment was repeated at least three times in order to get confident result.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

Viscosity is considered as the main single parameter effecting the pipeline transportation of heavy oil-stocks. Reduced crude is considered as the main source for fuel oils, therefore, reduced crude in addition to a commercial fuel oil were chosen to study the possible improvement for pipeline transportation of such heavy oil-stocks.

Fuel oils are characterized by their high viscosities; high pour points and low API gravities are currently being transported to a limited extent by pipelines. There are many short distance pipelines around the world were designed for the transport of heated residual fuel oils.

Heating or diluting with low viscous fractions are the major application for pipeline transport of heavy residual oils[3]. The data of viscosity lowering by heating, dilution or addition of methanol may be utilized to improve the pumping capacity and reduce the horse power requirement by pipeline transportation of fuel oil or reduced crude.

4.2 Heating

Figure 4-1 shows the effect of temperature increase in the range 30-70°C on the lowering the viscosity of the considered oil-stocks. The sensitivity of viscosity with temperature variations depends on the value of viscosity. Thus the viscosity of reduced crude and fuel oil undergo significant reduction by temperature increase.

The viscosities of reduced crude and fuel oil at 30°C were 648.5 and 584.6Cst, which dropped to 156.4 and 151.4Cst at 50°C respectively. These were about 76% and 74% respectively as percent lowering, while the reduction at 40°C were about 53% and 50%. The viscosities at temperature 40°C are considered as acceptable for pipeline transportation of such heavy oils.

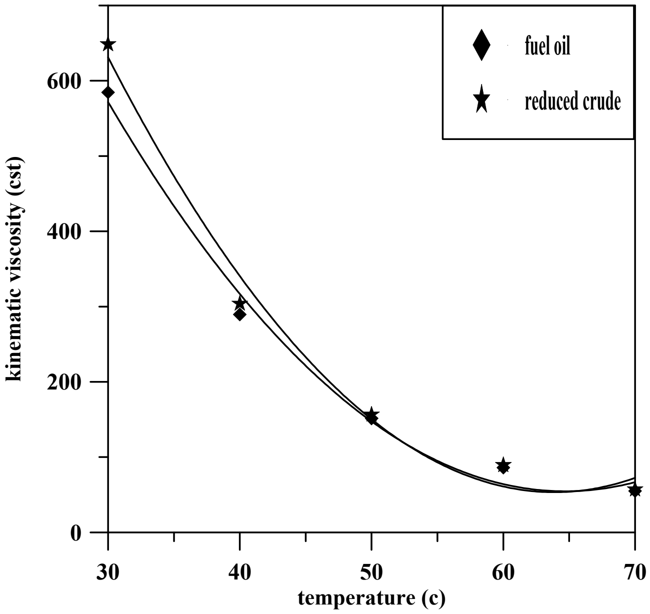

Figure 4-1: Effect of temperature on the viscosity of RC and FO

4.3 Blending

Light and heavy gas oil were chosen as blending components to reduce the viscosities of residual fuel oils. The temperature dependence on viscosities of gas oils are shown in figure 4-2.

The high viscous, reduced crude and fuel oil were blended with different concentrations in the range up to 25 vol. % of low viscous, light gas oil and heavy gas oil at different temperatures, as shown in figures 4-3 through 4-6.The blending of reduced crude and fuel oil with heavy gas oil and light gas oil resulted in a noticeable reduction in the viscosity when the weight percent of light gas oil or heavy gas oil increased.

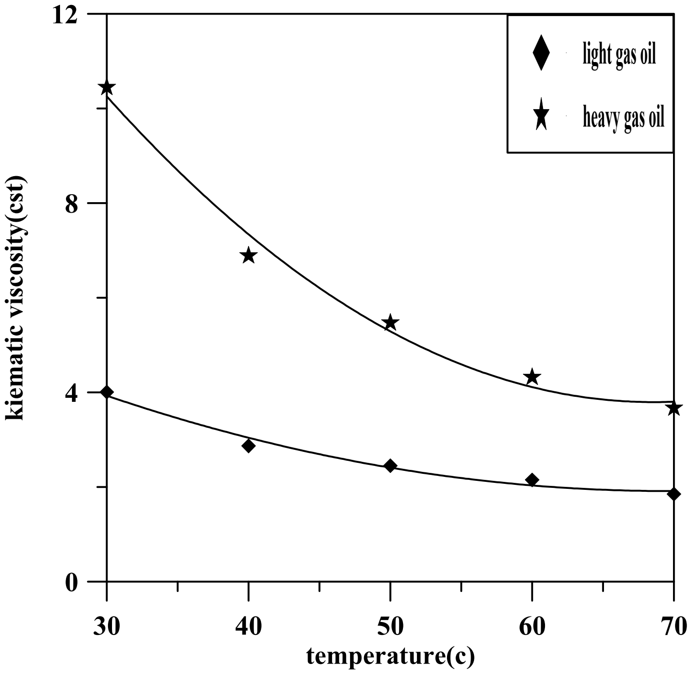

Figure 4-2: Effect of temperature on the viscosity of LGO and HGO

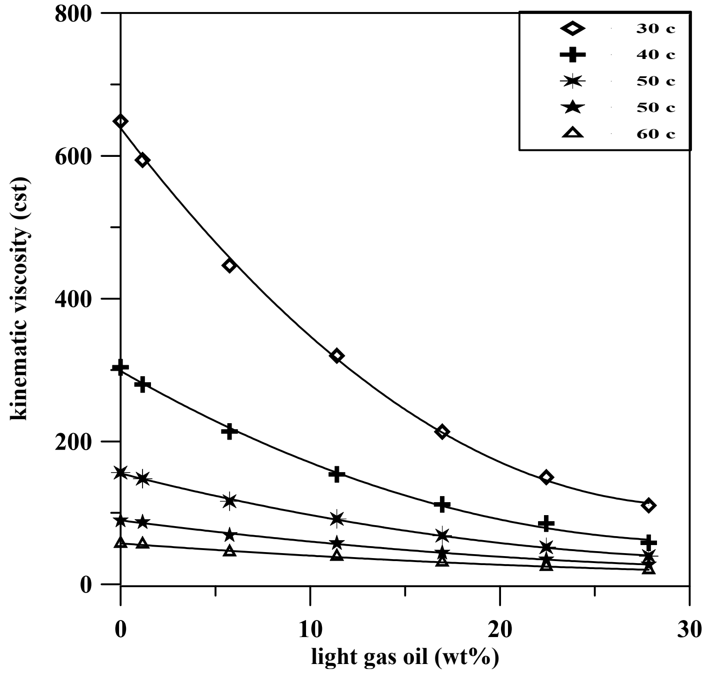

Figure 4-3: Effect of temperature and composition on the viscosity of RC blended with LGO

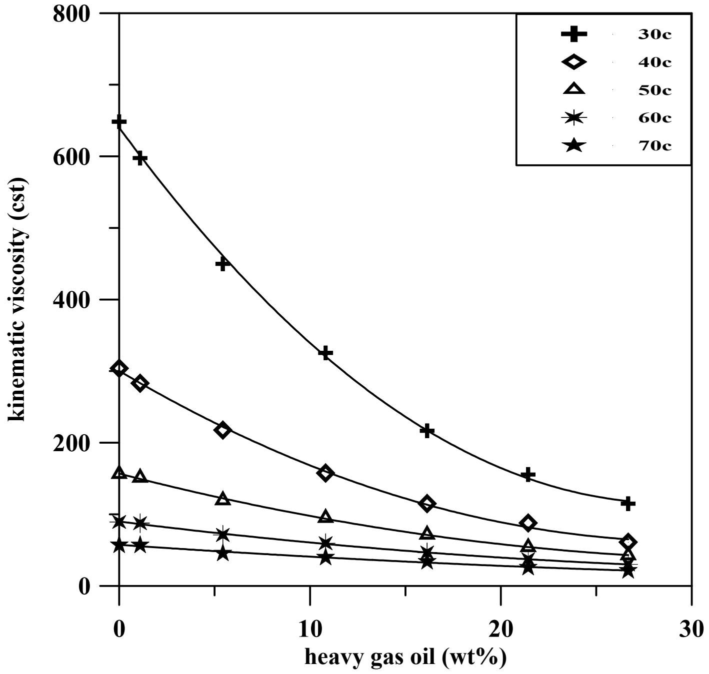

Figure 4-4: Effect of temperature and composition on the viscosity of RC blended with HGO

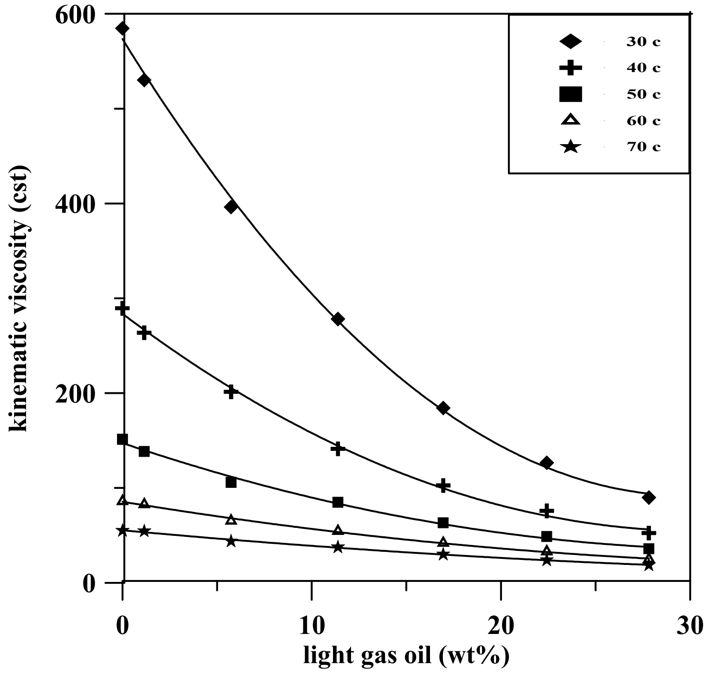

Figure 4-5: Effect of temperature and composition on the viscosity of FO blended with LGO

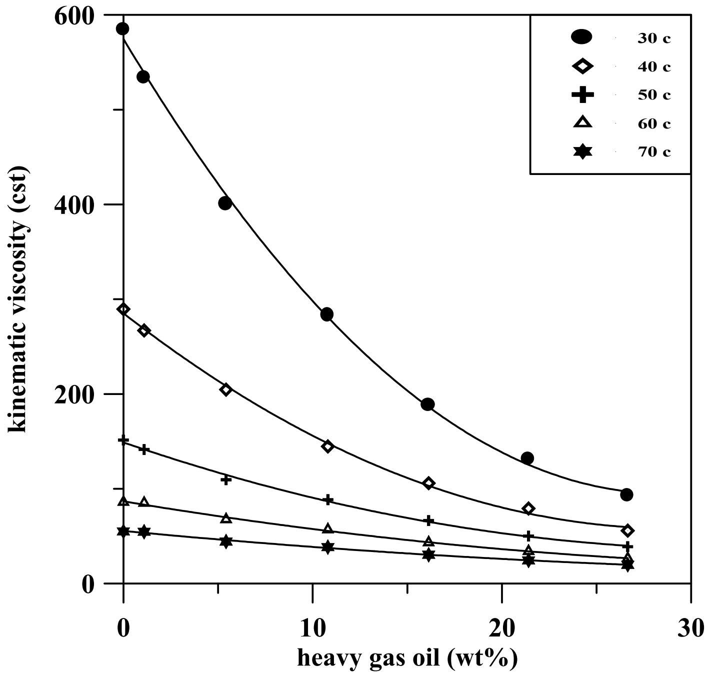

Figure 4-6: Effect of temperature and composition on the viscosity of FO blended with HGO

Those, the viscosity of reduced crude and fuel oil can be reduced to about 50%and 52% respectively by blending with 10 vol. % heavy gas oil at $30^{o}C$ as shown in figures 4-7 through 4-10, while the reductions were about 82% and 84% by blending with 25 vol. % heavy gas oil at the same temperature $30^{o}C$. 10 vol.% blended reduced crude or fuel oil achieved approximately 76% and 75% viscosity lowering respectively when the blends were heated at $40^{o}\mathbf{C}$, while the reduction in viscosity were 91% and 90% at $60^{o}\mathbf{C}$.

The percentage reduction in viscosity of blends with gas oil was calculated by equation (4-1) and these results are demonstrated in figures 4-7 through 4-10.

$$(\%RC) = \frac{\upsilon_F - \upsilon_B}{\upsilon_F} \tag{4-1}$$

Where:-

%RC=Percentage reduction change of viscosity

υ_B = kinematic viscosity of the blend (Cst)

υ_F = kinematic viscosity of reduced crude or fuel oil (Cst)

As shown in figures 4-7 through 4-10, the effect of heating on percent reduction of viscosities of fuel blends is significant at low temperatures, as $30^{o}\mathbf{C}$. While this reduction at higher temperatures, as 60-$70^{o}\mathbf{C}$ is noticeable low.

As it is expected light gas oil has more effect on the viscosity reduction of heavy oil-stock than heavy gas oil.

Reduced crude is usually used for production of commercial fuel oils. The viscosity of reduced crude at 30°**C** is about 648.5Cst and can be reduced to about 324.3Cst, which is 50% of the original value by the following alternatives.

- Heating at 39°**C**.
- Blending with 10 vol. % heavy gas oil or 9 vol. % light gas oil, both at 30°**C**.
- Blending with 5 vol. % light gas oil plus heating at 36°**C** or blending with 5 vol. % heavy gas oil plus heating at 35°**C**.

The above-mentioned methods produce fuel oil with acceptable physical properties and improved their pipeline transportation.

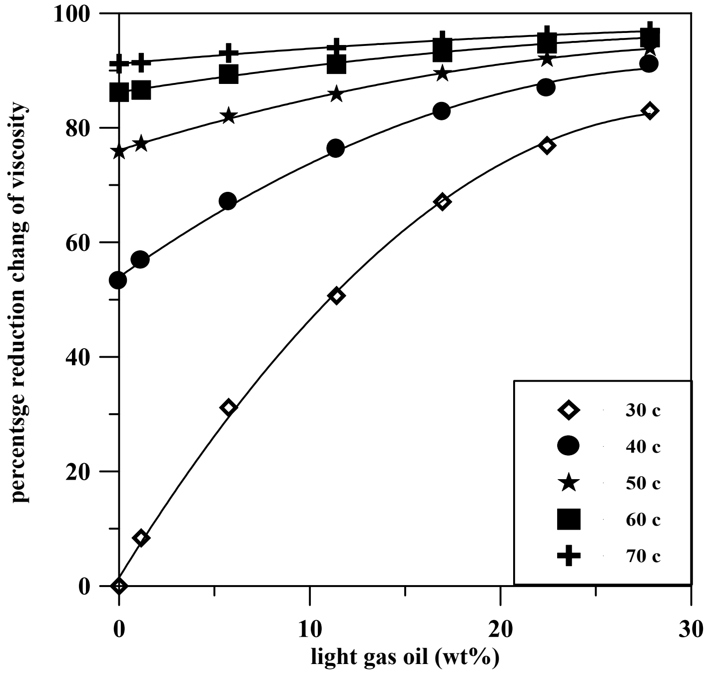

Figure 4-7: Effect of temperature and composition on the percentage reduction of viscosity of RC blended with LGO

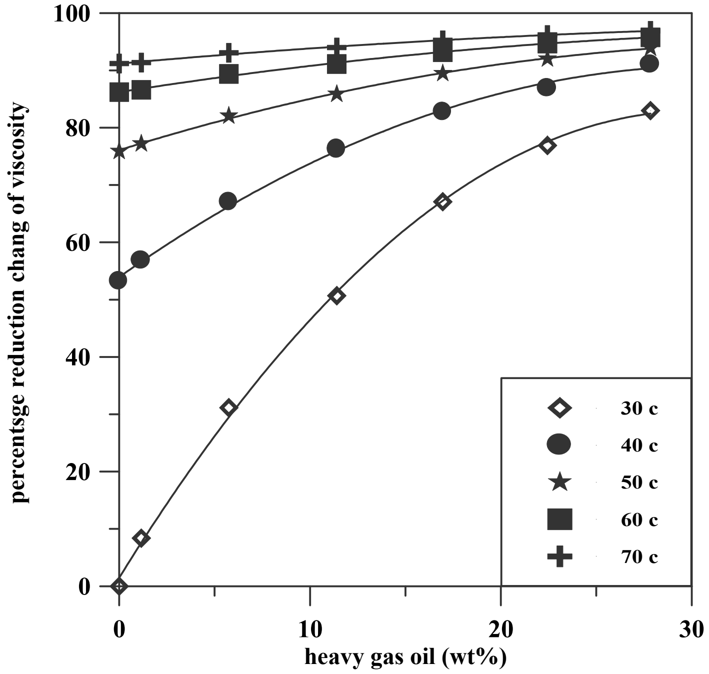

Figure 4-8: Effect of temperature and composition on the percentage reduction of viscosity of RC blended with HGO

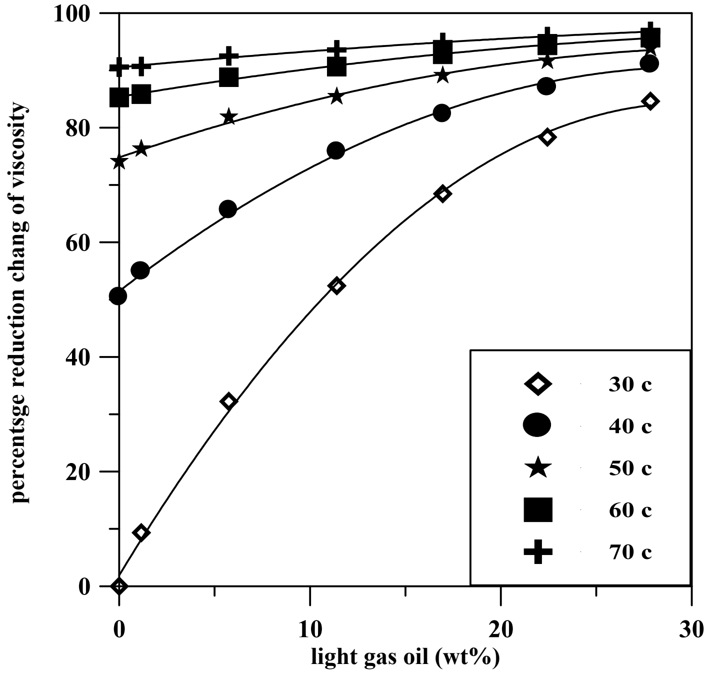

Figure 4-9: Effect of temperature and composition on the percentage reduction of viscosity of FO blended with LGO

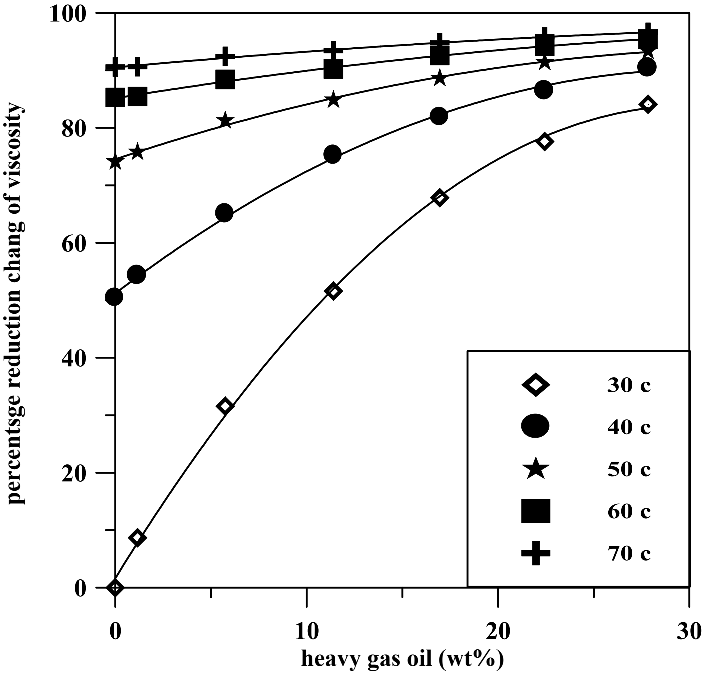

Figure 4-10: Effect of temperature and composition on the percentage reduction of viscosity of FO blended with HGO

4.4 Addition of Methanol

Reduced crude and fuel oil were mixed with different concentrations in the range of 1-10 vol. % of methanol. The results of viscosity lowering by methanol addition are illustrated in table 4-1, for reduced crude and fuel oil respectively. The maximum reduction in viscosities of heavy petroleum fractions was obtained by the blending with 3-4% by volume methanol, as shown in figures 4-11 and 4-12. Those were 32% and 31% reduction for reduced crude and fuel oil respectively. Higher percentages of methanol resulted in a lower reduction in the viscosities due to the fact that methanol was not compatible with heavy oils and made unstable, unhomogenous dispersion at high concentrations. [79, 80]

The results of the viscosity variation of the blends were reported as relative change of viscosity (RV), as follows:

$$(RV)= \frac{\upsilon_{\mathbf{B}}}{\upsilon_{\mathbf{F}}} \tag{4-2}$$

Where:-

$\upsilon_{\mathbf{B}}$ = kinematic viscosity of the blend (Cst)

$\upsilon_{\mathbf{F}}$ = kinematic viscosity of reduced crude or fuel oil (Cst)

The results are demonstrated in figures 4-11 and 4-12, for fuel oil and reduced crude respectively by addition up to 10 vol. %.

The low methanol concentration in such blends did not effect the other physical properties of heavy fractions studied. At the same time such blends exhibited much lower viscosity and better ignition and combustion characteristics [81]. Further more the reduction of viscosity lead to the decrease of the shear stress and shear rate, therefore, it was expected that easier oil transportation by pipelines be achieved by the addition 3-4 vol. % of methanol to residual fuel oils.

Table: 4-1 Effect of methanol concentration on viscosity of reduced crude and fuel oil at different temperatures

VOL.% OF METHANOL	T(K)	υ(Cst) of RC	υ(Cst) of FO
1	303	590.83	526.55
	313	274.30	260.05
	323	139.83	135.13
1.5	303	586.75	523.13
	313	270.23	255.625
	323	136.15	133.13
2	303	583.08	519.35
	313	267.55	252.85
	323	131.73	124.08
3	303	510.45	440.20
	313	225.93	210.70
	323	112.98	105.53
5	303	570.73	514.33
	313	262.20	246.83
	323	127.13	119.68
7	303	512.60	445.30
	313	228.08	212.80
	323	115.05	107.83
10	303	568.25	511.83
	313	257.30	244.33
	323	117.30	109.78

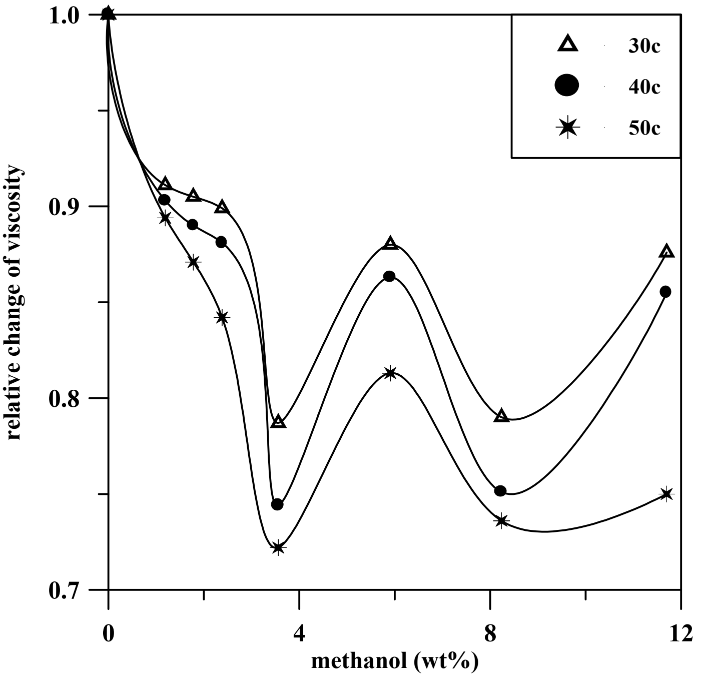

Figure 4-11: Effect of methanol addition to RC on the relative viscosity at different temperatures

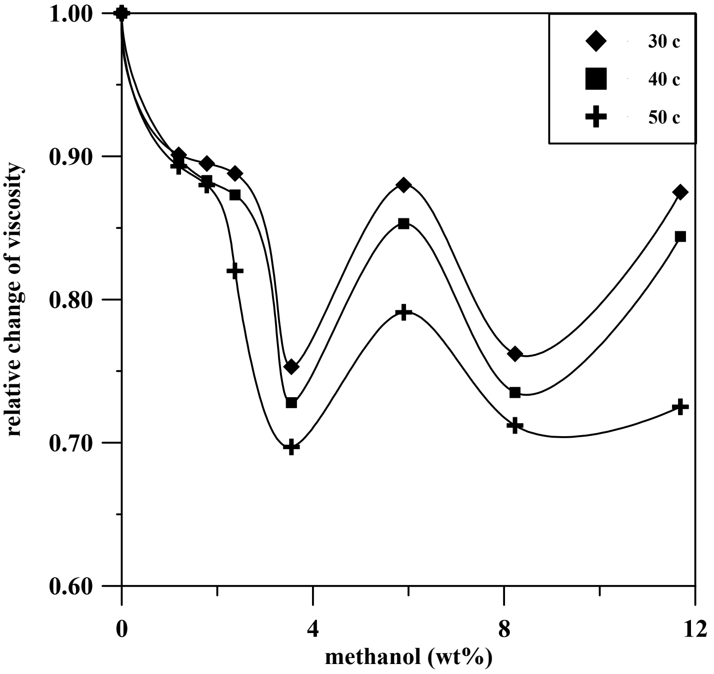

Figure 4-12: Effect of methanol addition to FO on the relative viscosity at different temperatures

4.5 Pipeline Transportation of Heavy Oils

4.5.1 Pipelining

Heavy oils, characterized by their high viscosities, high pour points and low API gravities are currently being transported to a limited extend by pipelines. Heavy oils present problems of pipeline transport usually because there high viscosities causing less ability to flow. The greater the viscosity becomes the greater head loss a long the pipeline. Therefore, more horse power is required for pumping or causing less pipeline capacities for high viscous fuels.

To show the effect of viscosity lowering by heating and blending on pumping requirements, two pipeline systems for fuel oil were chosen. These pipelines are available by Daura refinery and having 250m and 10000m lengths. Further characteristics of the pipelines are shown in table 4-2.

Table 4-2: Characteristics the fuel oil piping system[Daura]

Specification	First pipeline	Second pipeline
Length , m	250	10000
Diameter , inch	2	5
Flow rate , m^3/hr	46.789	72
Temperature , ^{o}C	325	54
Pump	Centrifugal	Centrifugal
Pumping powers , hp	40	160
Pump efficiency	0.4757	0.77

4.5.2 Power Requirement

The appropriate equations to relate the required horse power to the viscosity of liquids were discussed in chapter two, section 2.5. Equation 2-43 was used to evaluate the required horse power for pipeline pumping.

$$\mathbf{HP = \frac{0.244Q^{2.75}L}{d^{4.75}\eta_p}\rho^{0.75}\mu^{0.25}} \tag{2-43}$$

The appropriate data in table 4-2 were substituted into equation (2-43) to estimate the required power by pumping of fuel oil and reduced crude at different viscosities, resulting equation (4-3) and equation (4-4) for 250m and 10000m pipelines respectively.

$$HP = 1170.072\,\rho^{.75}\,\mu^{.25} \tag{4-3}$$

$$HP = 1218.047\,\rho^{.75}\,\mu^{.25} \tag{4-4}$$

The lowering of viscosities of these fuels by heating, blending with gas oils or addition of methanol was discussed previously in this chapter.

The effect of heating on power requirements for pumping of reduced crude and fuel oil through 250m and 10Km pipelines are summarized in tables 4-3 and 4-4 and represented graphically in figures 4-13 and 4-14 respectively.

Table 4-3: Power requirement for pumping of reduced crude at different temperatures

T(k)	υ (Cst)	ρ(kg/m^3)	HP(kw) pipeline, 250m	HP(kw) pipeline, 10000m
303	648.49	940.64	175.635	182.837
313	303.775	935.18	144.459	150.382
323	156.375	929.29	121.592	126.578
333	89.325	920.97	104.761	109.057
343	57.05	914.25	92.9697	96.782

Table 4-4: Power requirement for pumping of fuel oil at different temperatures

T(k)	υ (Cst)	ρ(kg/m^3)	HP(kw) pipeline, 250m	HP(kw) pipeline, 10000m
303	584.64	940.45	171.108	178.124
313	289.5	935.16	142.729	148.581
323	151.35	929.09	120.577	125.521
333	85.95	920.80	103.738	107.992
343	55	913.69	92.067	95.841

The results in figure 4-13 indicate that an increase in the temperature of heavy petroleum fractions results in a decrease in power requirement due to decrease in the viscosity. The power requirements for reduced crude and fuel oil at $30^{o}\mathbf{C}$ in a 250m pipeline were 175.6 and 171.1 Kw, which dropped to 121.6 and 120.6 Kw at $50^{o}\mathbf{C}$ respectively; achieving 30.8% and 29.5% power reduction. The power requirements in a 10 Km pipeline were 182.8 and 178.1 Kw at $30^{o}\mathbf{C}$, which were dropped to 126.6 and 125.5 Kw for reduced crude and fuel oil at 50°C. These are about 30.8% and 29.5% power reduction, as shown in figure 4-13.

The power reduction by pipelining of reduced crude and fuel oil in 10 Km pipeline is about similar as in 250m pipeline. It is noticeable that the length of pipeline has no significant influence on the percentage power reduction, as shown in figure 4-14.

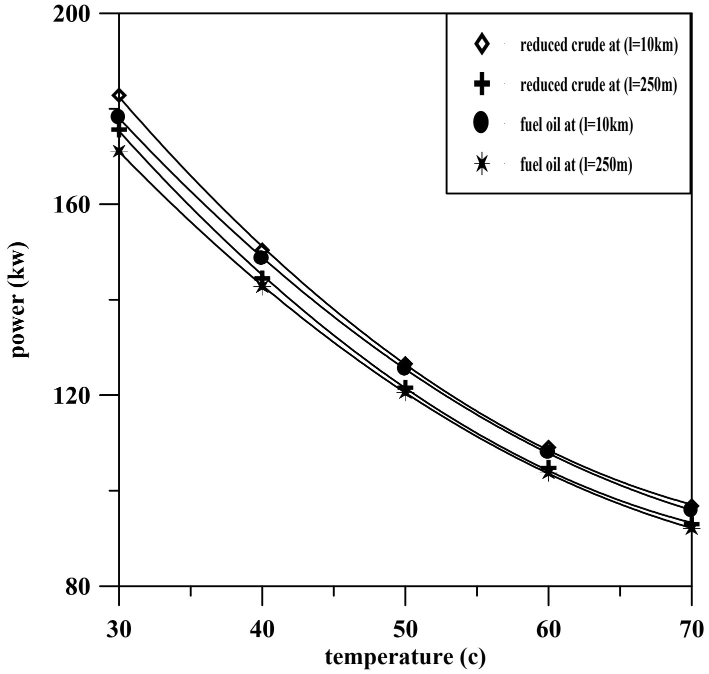

Figure 4-13: Effect of temperature on the power requirement for pumping of RC and FO

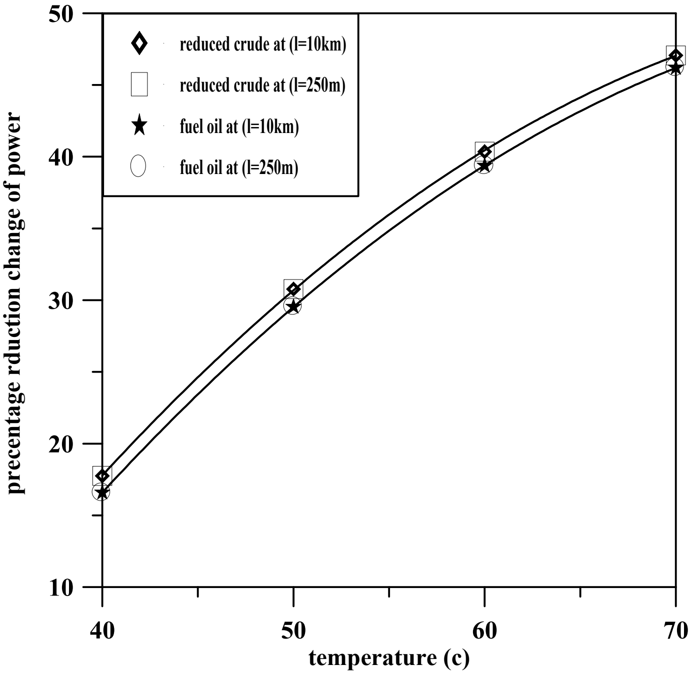

Figure 4-14: Effect of temperature on the percentage reduction of power for pumping of RC and FO

The second applicable method for pipelining of heavy fuels was the blending with gas oil. These blends cause noticeable viscosity lowering of reduced crude. Those permit an economic pipelining as it is expected.

The effects of both heating and dilution with gas oil on the power requirements for pumping of reduced crude and fuel oil through 250m and 10Km pipelines are represented graphically in figures 4-15 through 40-22 and listed in the appendix, tables A-1 through A-8.

The blending of reduced crude and fuel oil with heavy gas oil and light gas oil resulted in a noticeable reduction in the power requirement due to decrease their viscosities when the weight percent of light gas oil and heavy gas oil increased. Approximate linear relationship was achieved for power reduction in case of reduced crude and fuel oil diluted with gas oil at different temperatures.

The power requirements for 250m pipelining unblended reduced crude and fuel oil were 175.6 and 171.1 Kw respectively at 30°C. Those were dropped to about 171.6 and 166.7 Kw respectively when these fuels were blended with 10 vol. % light gas oil at the same temperature 30°C. Further more the required power was about 145 and 140 Kw for 10 vol. % blended fuels at 50°C. Those indicate that heating has more effect on power reduction than the blending. The power reduction by pipelining of both fuels blended with gas oil in a 10 Km pipeline was about similar to 250m pipeline.

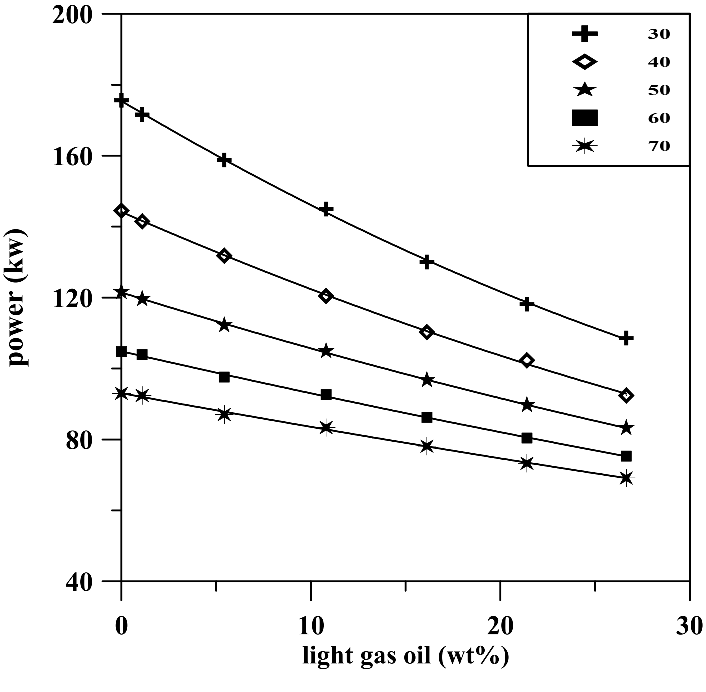

Figure 4-15: Power requirements by pumping of RC blended with LGO at different temperatures, in 250m pipeline

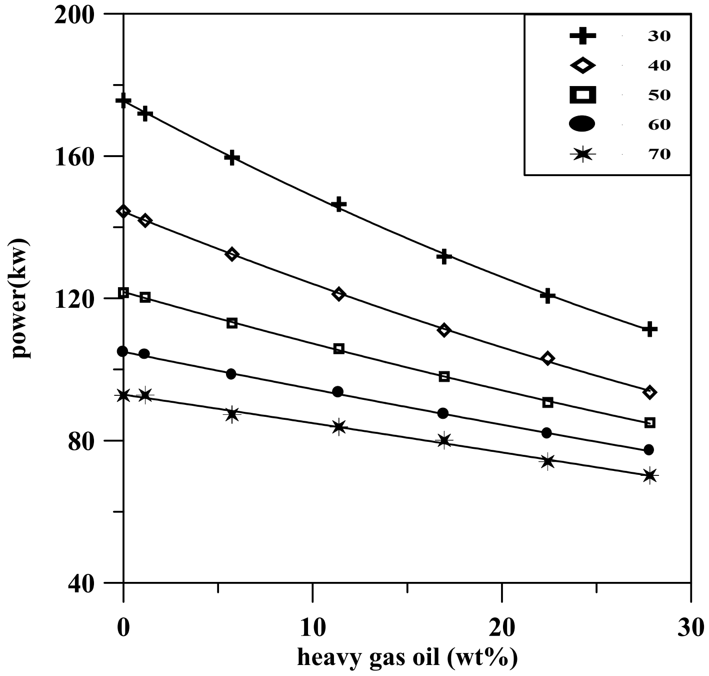

Figure 4-16: Power requirements by pumping of RC blended with HGO at different temperatures, in 250m pipeline

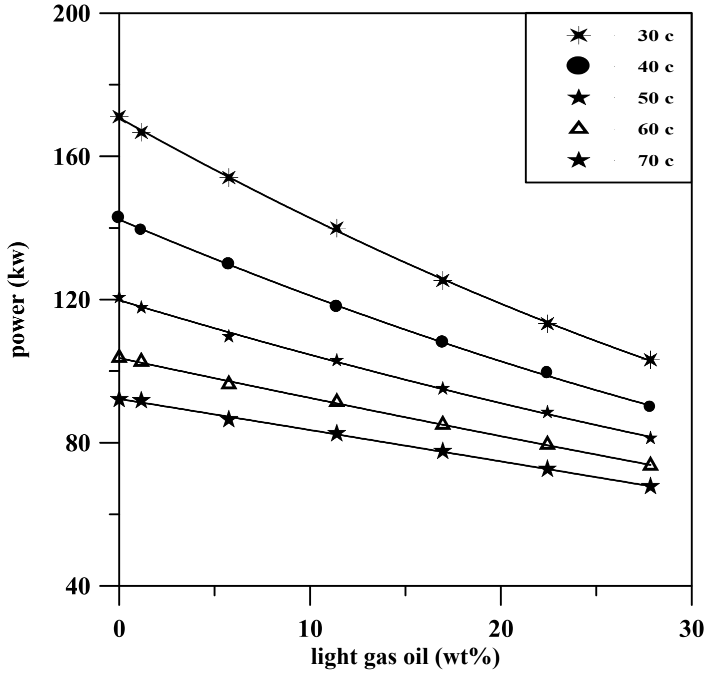

Figure 4-17: Power requirements by pumping of FO blended with LGO at different temperatures, in 250m pipeline

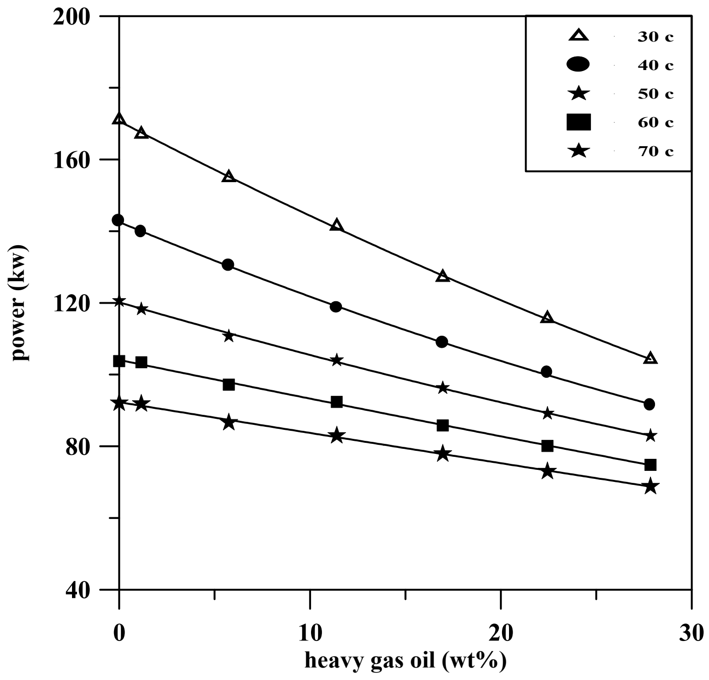

Figure 4-18: Power requirements by pumping of FO blended with HGO at different temperatures, in 250m pipeline

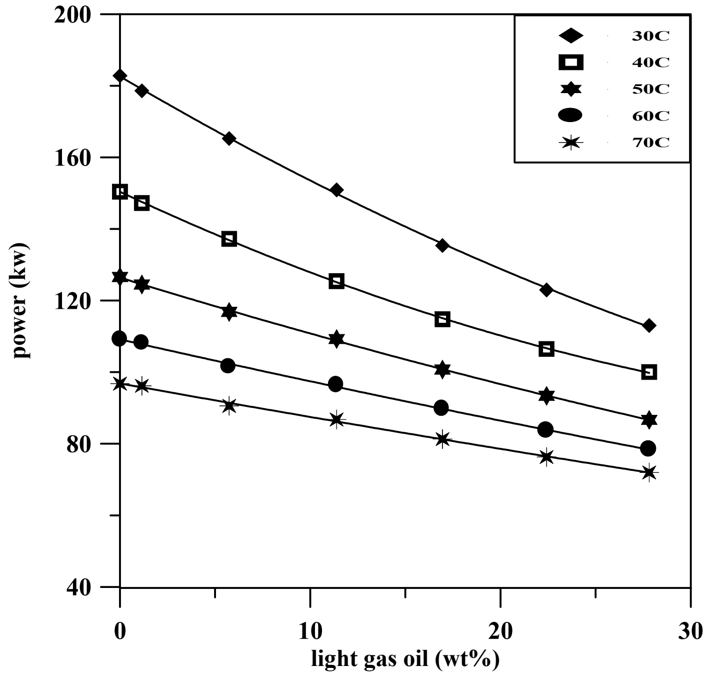

Figure 4-19: Power requirements by pumping of RC blended with LGO at different temperatures, in 10Km pipeline

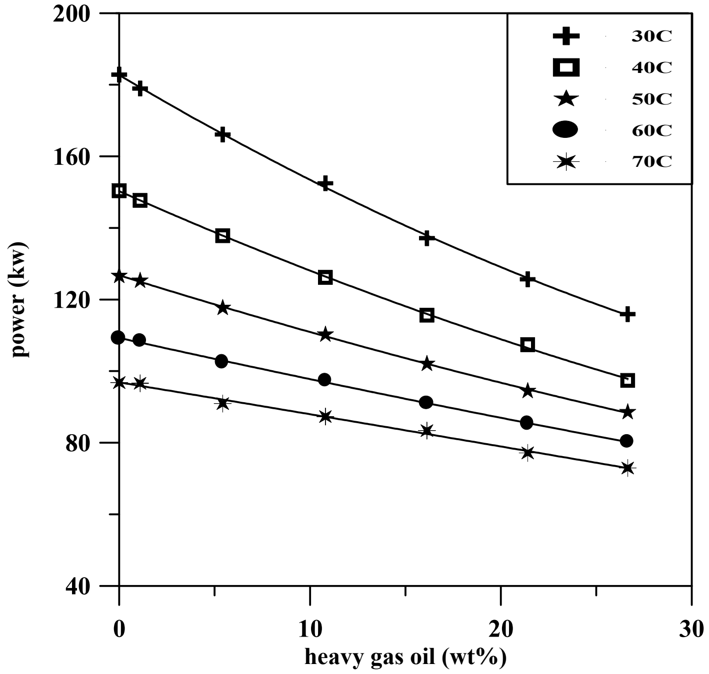

Figure 4-20: Power requirements by pumping of RC blended with HGO at different temperatures, in 10Km pipeline

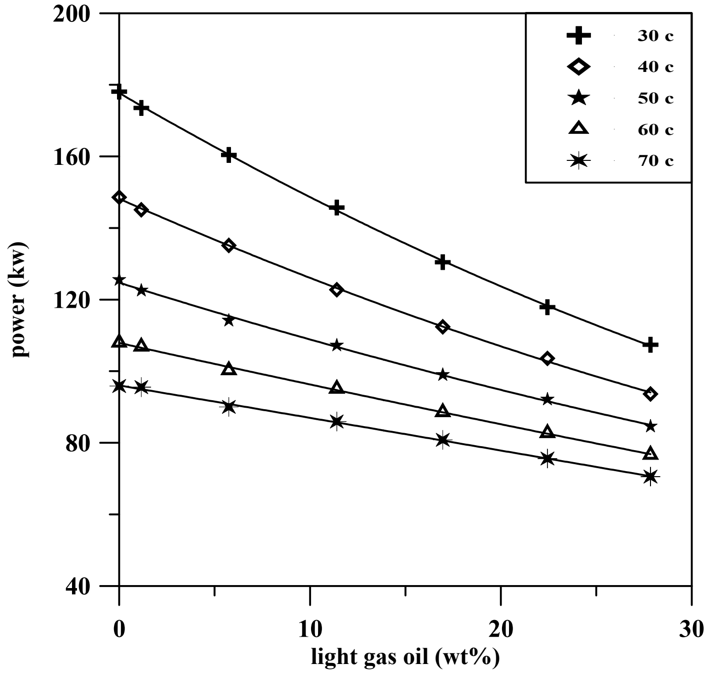

Figure 4-21: Power requirements by pumping of FO blended with LGO at different temperatures, in 10Km pipeline

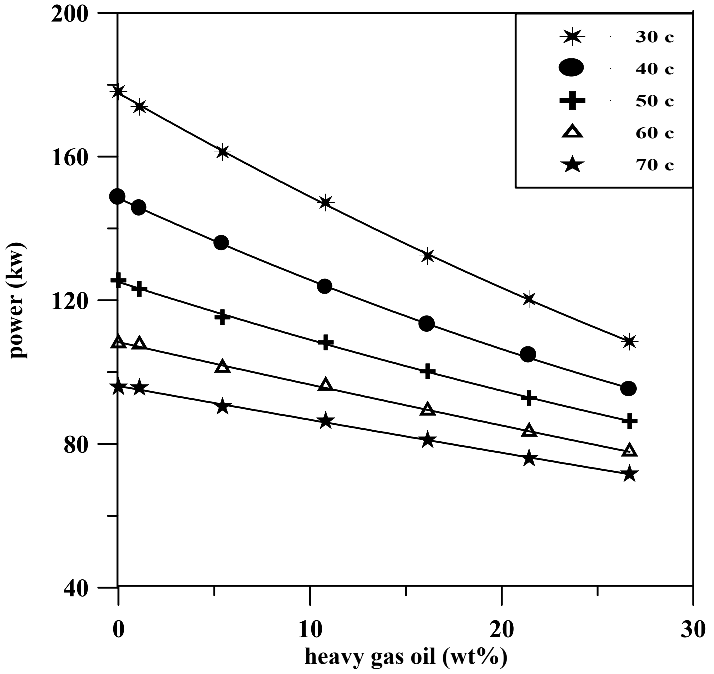

Figure 4-22: Power requirements by pumping of FO blended with HGO at different temperatures, in 10Km pipeline

Figures 4-23 through 4-27 show the achieved percentage reduction of power by diluting of reduced crude and fuel oil with both light gas oil and heavy gas oil at different temperatures.

The results in figures 4-23 through 4-26 indicate that the magnitude of percentage power reduction would be increased when the concentration of heavy petroleum fractions in the blend is increased. Fuel oil undergoes nearly similar power requirement as reduced crude due to the similarity in viscosity behaviors.

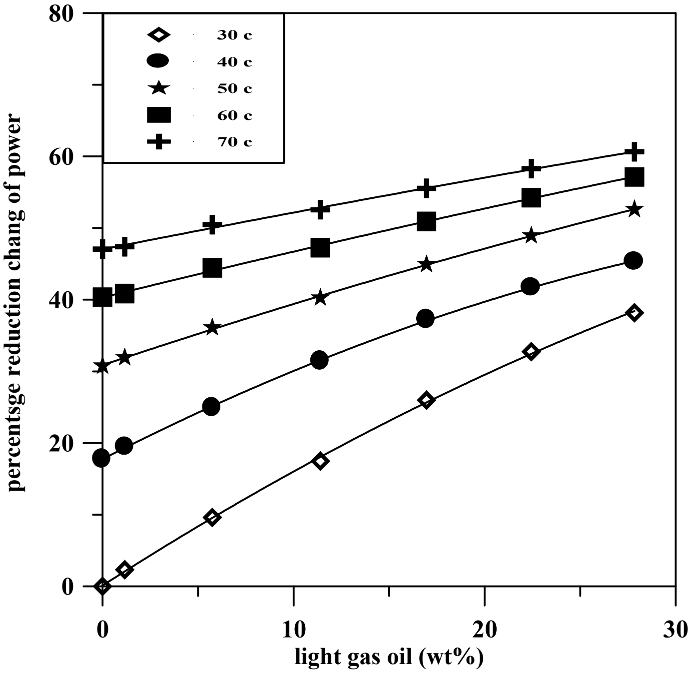

Figure 4-23: Effect of temperature and composition on the percentage reduction of power by pumping of RC blended with LGO in=250m pipeline

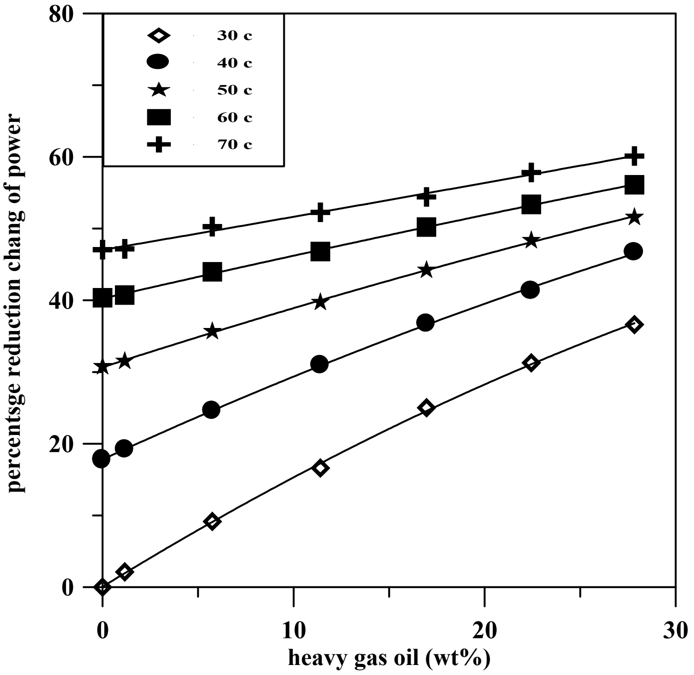

Figure 4-24: Effect of temperature and composition on the percentage reduction of power by pumping of RC blended with HGO in=250m pipeline

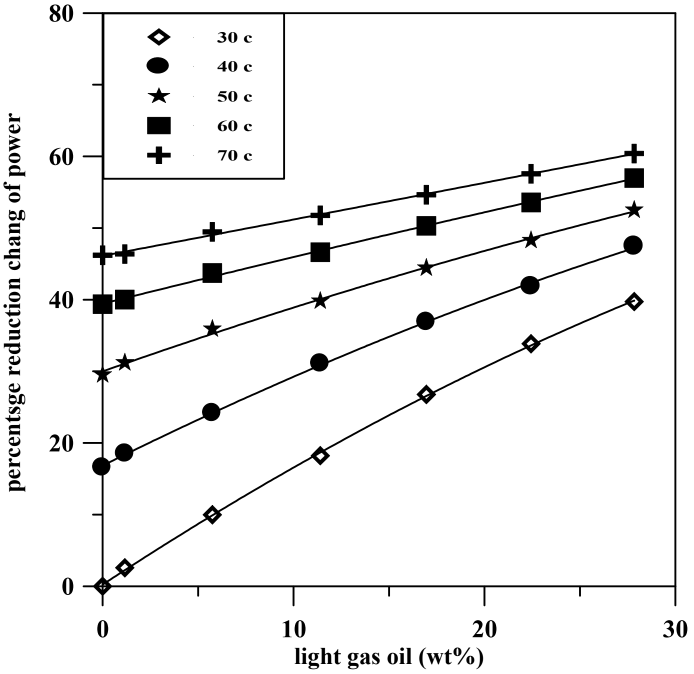

Figure 4-25: Effect of temperature and composition on the percentage reduction of power by pumping of FO blended with LGO in=250m pipeline

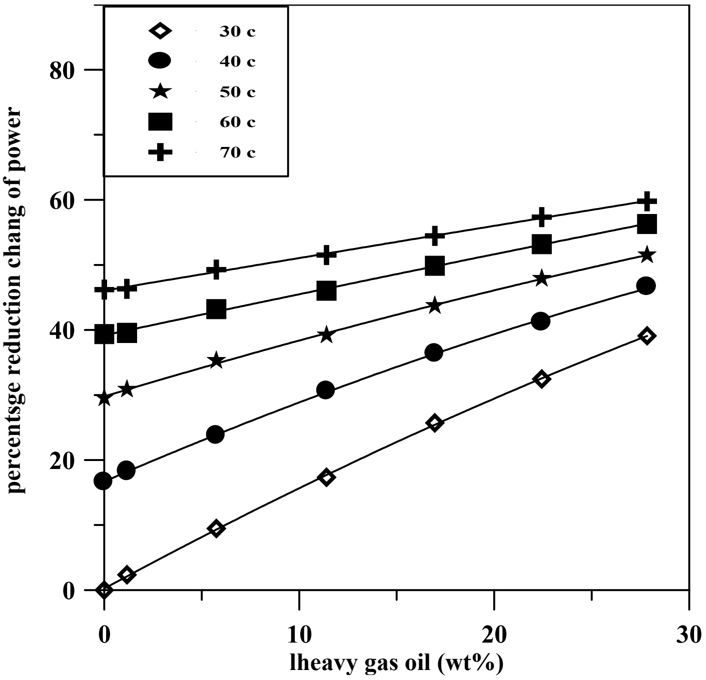

Figure 4-26: Effect of temperature and composition on the percentage reduction of power by pumping of FO blended with HGO in=250m pipeline

It is noticeable that the length of pipeline has no significant influence on the percentage power reduction, as shown in figure 4-27.

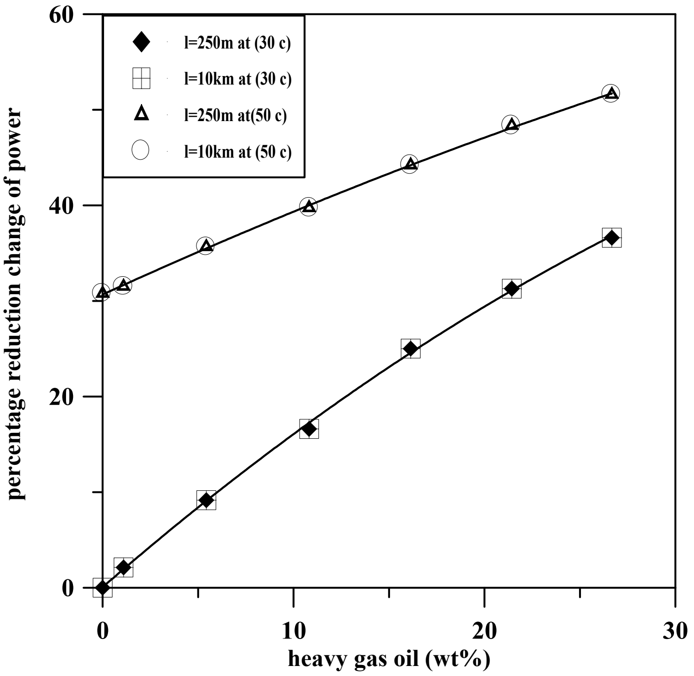

Figure 4-27: Effect of temperature and composition on the percentage reduction of power by pumping of RC blended with HGO

As shown in part 4.4 of this chapter, the addition of methanol in a low concentrations, 3-4 vol. % to reduced crude or fuel oil lead to 32% and 31% reduction of their viscosities. The pipelines given in table 4-2 were again used to examine the effect of achieved low viscosities of such fuels by the addition of methanol, on power requirements. The results are demonstrated in figures 4-28 through 4-31 and presented in appendix A-9 through A-12, indicating that the addition of methanol in a low concentration resulted in reduction of power requirements of residual fuel oils. The achieved reduction is lower when compared with gas oil blends.

Furthermore the results indicate that heating has more effect on power reduction than the addition of methanol. The power reduction by pipelining of both fuels blended with methanol in 10Km pipeline was about similar to 250m pipeline, as shown in figure 4-32.

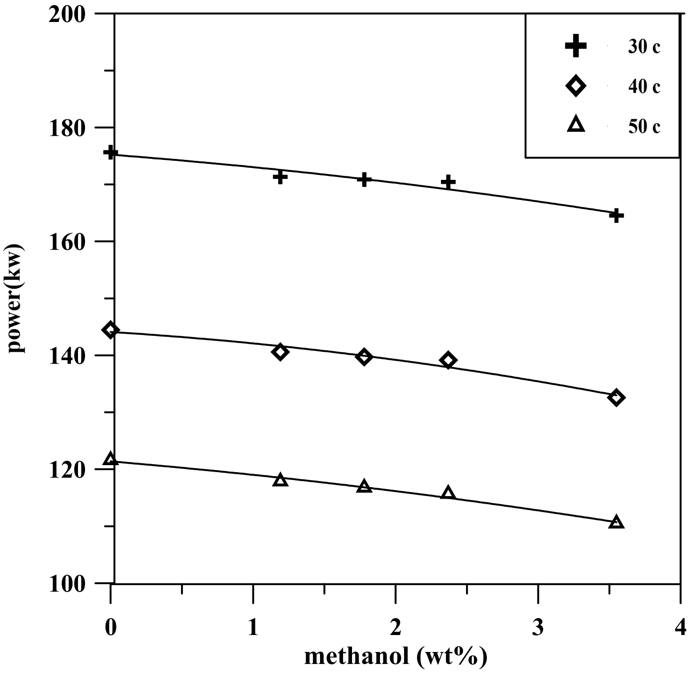

Figure 4-28: Effect of methanol addition to RC on the power requirement at different temperatures in 250m pipeline

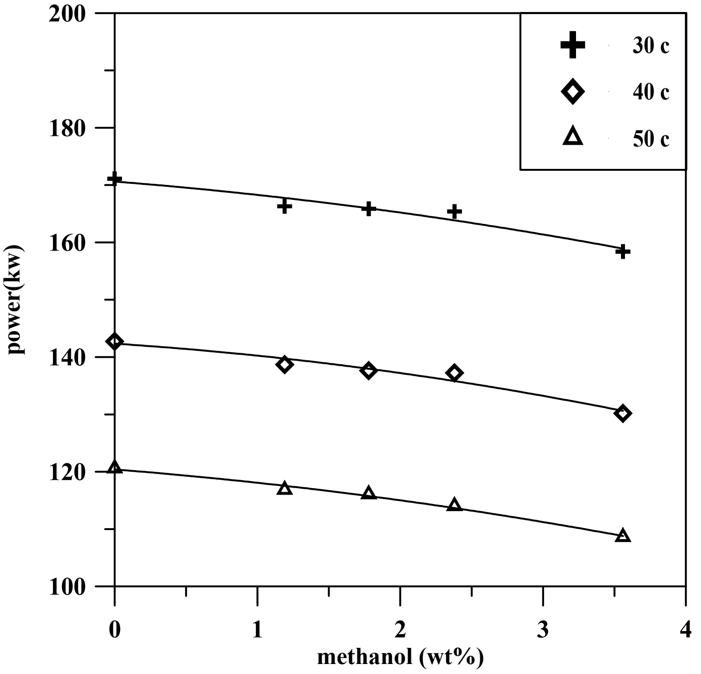

Figure 4-29: Effect of methanol addition to FO on the power requirement at different temperatures in 250m pipeline

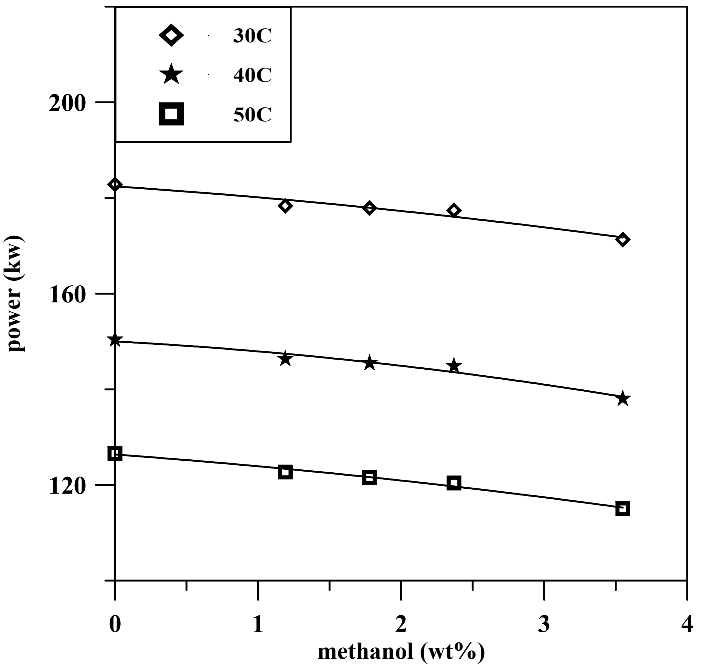

Figure 4-30: Effect of methanol addition to RC on the power requirement at different temperatures in 10Km pipeline

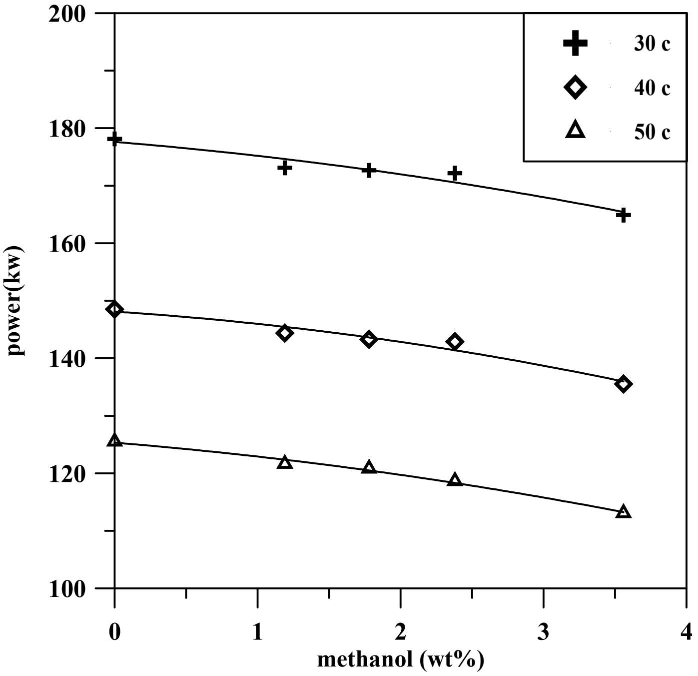

Figure 4-31: Effect of methanol addition to FO on the power requirement at different temperatures in 10Km pipeline

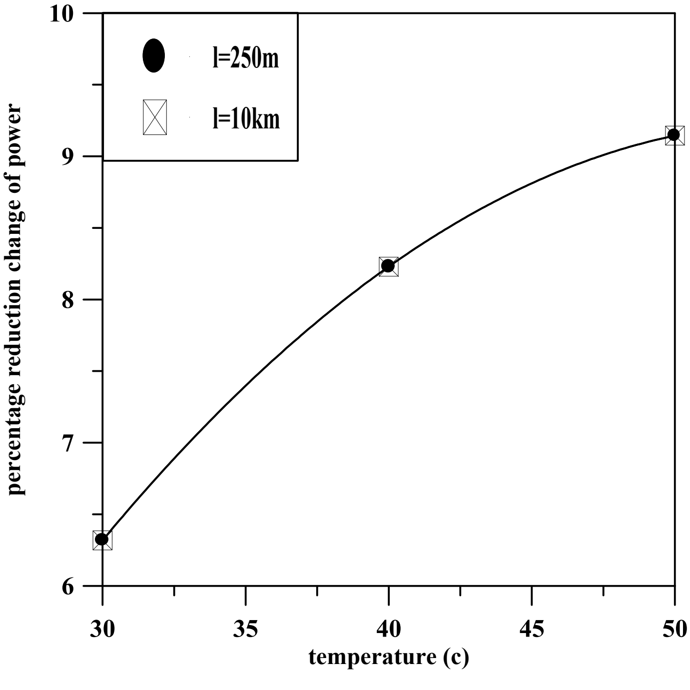

Figure 4-32: Effect of temperature on the percentage reduction of power by pumping of RC with 3.6wt% of methanol addition

4.5.3 Flow Rate

The characteristics of residual fuel oils had been altered by heating or dilution to make them pipelineable. Therefore, the effect of heating on flow rate was estimated using the pipeline systems given in table 4-2 with a constant pumping horse power. The results are graphically demonstrated in figure 4-33 and summarized in tables 4-5 and 4-6 for reduced crude and fuel oil through 250m and 10Km pipelines. The results show a linear increase in flow rate of oils by decreasing the viscosity due to increase the temperature. Nearly 14.3% and 13.6% increase in flow rate was achieved by heating the oils at about 50°C.

Table 4-5: Flow rate by pipelining of reduced crude at different temperatures

T(k)	VIS(cst)	$\rho(kg/m^3)$	$Q(m^3/hr)$ Pipeline, 250m	$Q(m^3/hr)$ Pipeline, 10000m
303	648.49	940.64	24.556	61.648
313	303.775	935.18	26.363	66.188
323	156.375	929.29	28.069	70.468
333	89.325	920.97	29.632	74.391
343	57.05	914.25	30.949	77.692

Table 4-6: Flow rate by pipelining of fuel oil at different temperatures

T(k)	VIS(cst)	ρ(kg/m^3)	Q(m^3/hr) in 250m, pipeline	Q(m^3/hr) in 10000m, pipeline
303	584.64	940.45	24.789	62.236
313	289.5	935.16	26.478	66.478
323	151.35	929.09	28.105	70.683
333	85.95	920.80	29.736	74.657
343	55	913.69	31.057	77.968

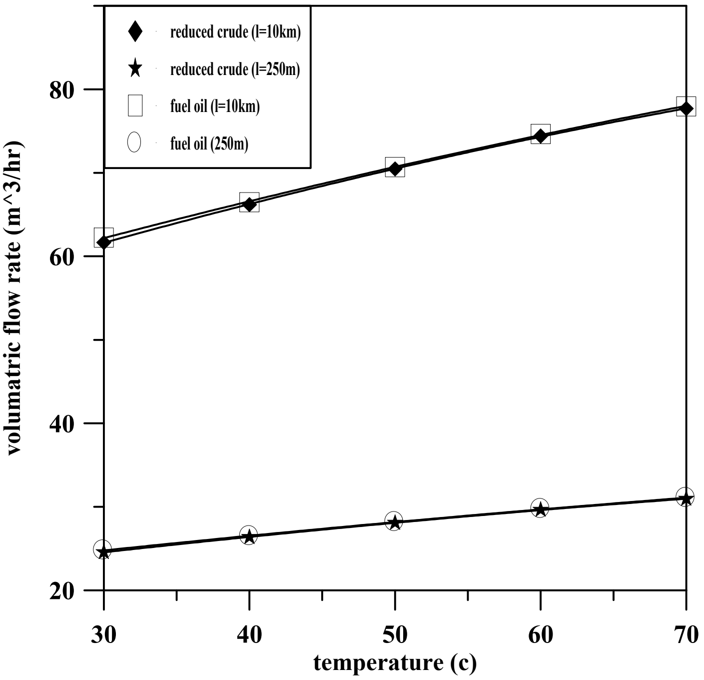

Figure 4-33: Effect of temperature on the volumetric flow rate by pipelining of RC and FO

The second method for pipelining of heavy fuels is by blending them with gas oil since the blending method can be considered as a suitable and economical method. The effects of both dilution and heating on the flow rate by a constant horse power and by using the pipeline systems are listed in table 4-2.

Reduced crude and fuel oil show a similar viscosity behavior therefore, reduced crude was taken as an example to test the effect of diluting on flow rate. Figures 4-34 through 4-37 illustrate a graphical representation of the effects of both temperature and concentration of gas oil on the flow rate by pipelining of reduced crude through 250m and 10Km pipeline, more details are given in appendix, A-1 to A-8. The results show a linear increase in flow rate of reduced crude with increase of gas oil concentration, due to decrease of the viscosities of blends.

The flow rate for 250m pipelining of reduced crude was 24.5m^3/hr at 30°C which increased to 26.3m^3/hr when reduced crude was blended with 10 vol. % heavy gas oil at the same of temperature 30°C. The flow rate was about 29.5m^3/hr for 10 vol. % blended reduced crude at 50°C.Those indicate that heating has more effect on the flow rate increase than the blending.

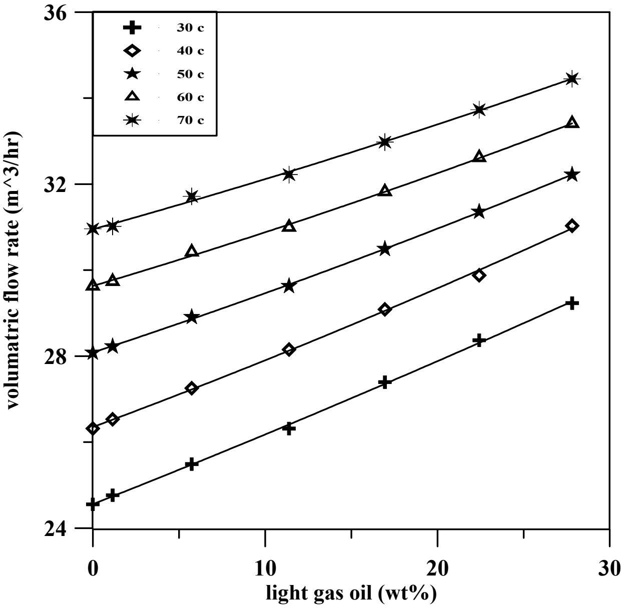

Figure 4-34: Effect of temperature and composition on the flow rate of RC blended with LGO in 250m pipeline

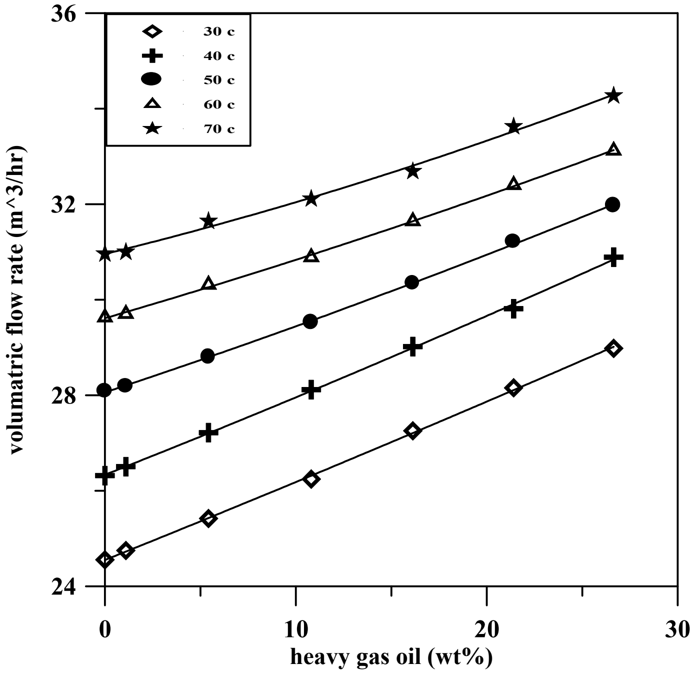

Figure 4-35: Effect of temperature and composition on the flow rate of RC blended with HGO in 250m pipeline

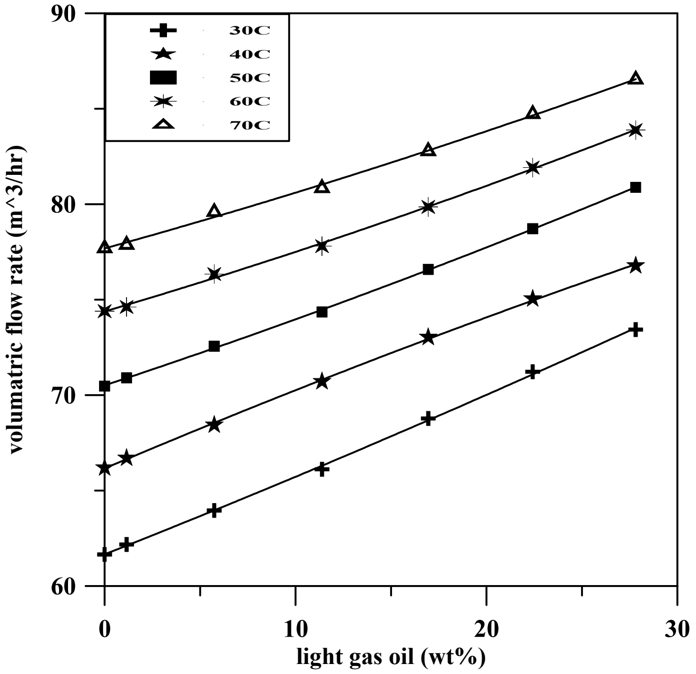

Figure 4-36: Effect of temperature and composition on the flow rate of RC blended with LGO in 10Km pipeline

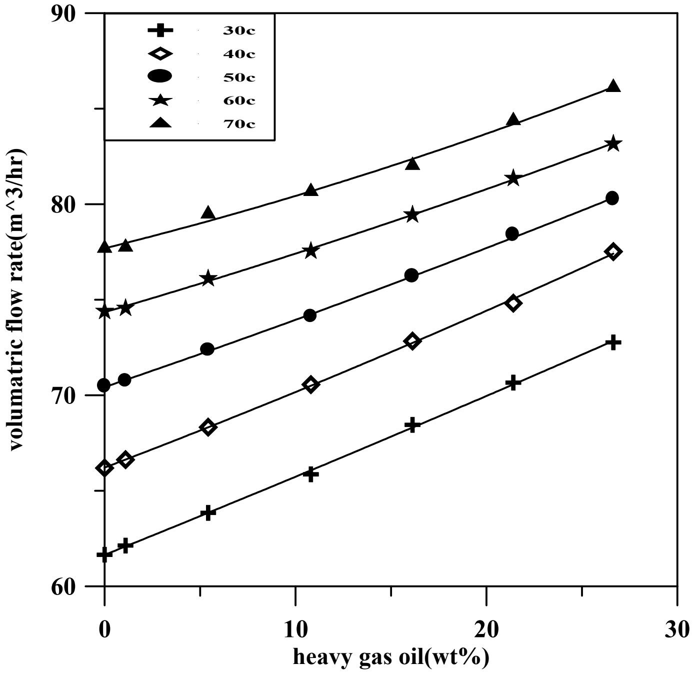

Figure 4-37: Effect of temperature and composition on the flow rate of RC blended with HGO in 10Km pipeline

As shown previously the addition of methanol in a low concentration to reduced crude or fuel oil leads to decrease in their viscosities. The pipelines system, shown in table 4-2, was used again, to evaluate the effect of methanol addition on pipelining of these fuels.

The results achieved for reduced crude are demonstrated, due to the similarity between reduced crude and fuel oil, as shown in figures 4-38 and 4-39 for 250m and 10Km pipelines respectively. The results are listed also in appendix; table A-9 through A-12 for both fuels.

The flow rate for 250m pipelining unblended reduced crude was 24.6m^3/hr at 30°C . It was increased to about 25.2m^3/hr when reduced crude was blended with 3 vol. % methanol at the same temperature 30°C .The flow rate was about 29m^3/hr for 3 vol. % blended reduced crude at 50°C .

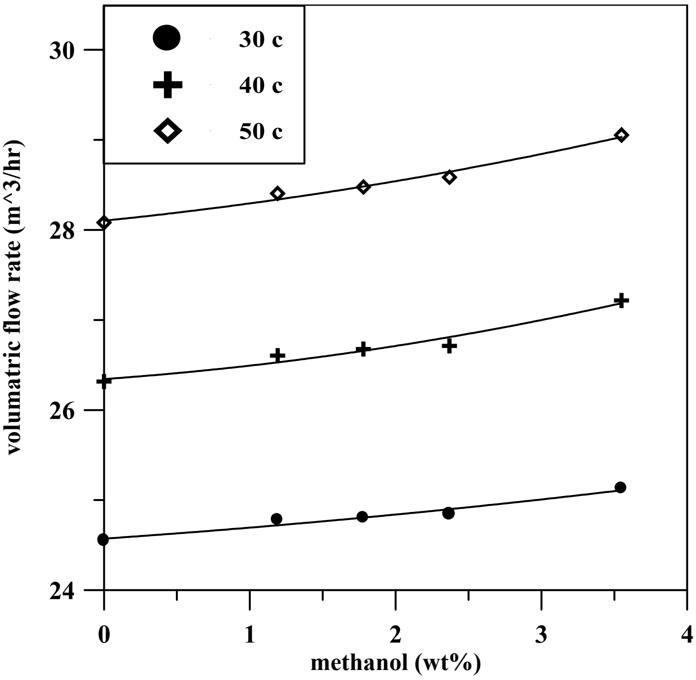

Figure 4-38: Effect of methanol addition to RC on the flow rate at different temperatures in 250m pipeline

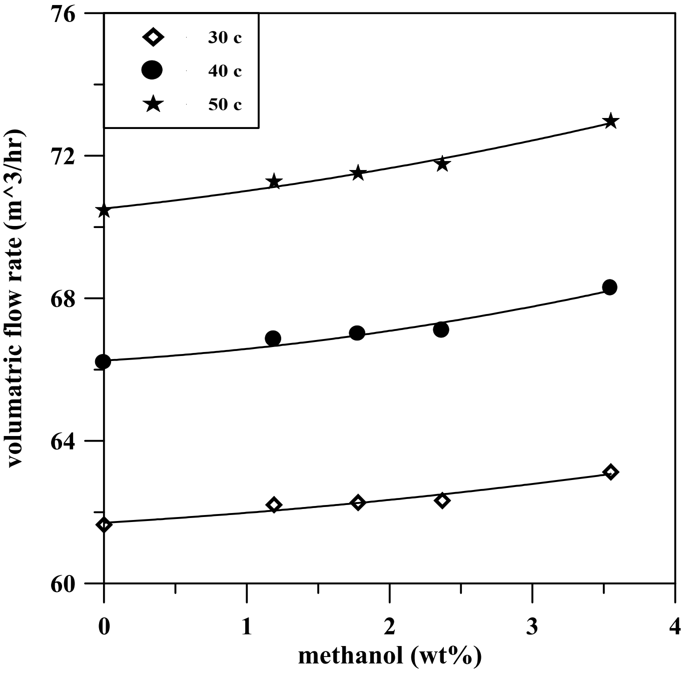

Figure 4-39: Effect of methanol addition to RC on the flow rate at different temperatures in 10Km pipeline

4.6 Viscosity-Temperature Correlations

Accurate data on oil viscosity as a function of temperature and composition are required for reservoir studies, process design, or the solution of oil pipelining problems. Numerous investigations had been reported for oils and fractions to develop correlations, which describe the viscosity-temperature behavior, as mentioned in chapter 2, section 2.4.1.

The following viscosity-temperature correlation is particularly relevant to the present study:

$$\left[\frac{\mathbf{Log}(\mu)+\mathbf{C}}{\mathbf{log}(\mu_0)+\mathbf{C}}\right]=\left[\frac{\mathbf{T_0}}{\mathbf{T}}\right]^{\mathbf{s}} \qquad (2\text{-}8)$$

Where:-

μ= dynamic viscosity, Pas.s

T= absolute temperature, K

C=3.0020, when the log base is 10

S=0.0066940 log (μ_0) +3.5565, when T_0 is 303.15K (30 °C)

Equation (2-8) was originally proposed as generalized dynamic viscosity-temperature correlation for bitumen and heavy oils [42]. A modification has been done on equation (2-8) in order to use it to predict the viscosities of fuel oils and their blends at different temperatures.

The procedure of the modified correlation was achieved by changing the dynamic viscosity in equation (2-8) to kinematic viscosity and take the fraction of blending component in account so as to have an equation of the form:-

$$\left[\frac{\log(\upsilon)+K}{\log(\upsilon_o)+C}\right]=\left[\frac{T_0}{T}\right]^S \qquad (4\text{-}5)$$

Where:-

$K = (E^* Wt_b + B)$ (4-6)

$S = D \log(\upsilon_o) + A^* Wt_b$ (4-7)

υ= the kinematic viscosity of blends in Cst at different temperatures (T)

Wt_b= weight fraction of blends

υ_o= the kinematic viscosity of the blends in Cst at T_o=303.15K

C= constant

Equation (4-5) correlates the kinematic viscosity as function of composition of blending component and temperature.

Regression analysis had been used to evaluate the parameters in equation (4-5). A computer program package (statistica) was used to develop the necessary correlation. The program performs an onlinear least square fitting of a proposed function for given set of data. The final constants of equations (4-5), (4-6) and (4-7) are listed in table 4-7.

Table 4-7: constants of equations (4-5), (4-6) and (4-7)

A	B	C	D	E
5.1054	-0.3708	-0.3755	1.5986	0.0043

The new formula of equation (4-5) was used to predict the viscosity of reduced crude and fuel oil or their blends at different temperatures. The results are listed in tables 4-8 through 4-11.

The analysis shown that the proposed correlation fits the experimental data consisting of 130 viscosity measurements (for reduced crude, fuel oil and their blends with gas oils) with an over all absolute error of 2.1%. The corresponding overall absolute error for the original correlation given in equation (2-8) was about 7%. All four systems shown in the table gives an average absolute error not greater than 2.4%, this value was for the blends of fuel oil with heavy gas oil.

The similarities of overall absolute error for all four systems are probably due to the fact that reduced crude and fuel oil have some what the same viscosity behavior.

Table 4-8: Comparison between measured and calculated kinematic viscosity values for the blends of reduced crude with light gas oil

Weight Fraction	Viscosity (cst)	Temperature °C					Av.Abs %erroe
		30	40	50	60	70	
0	υ exp	648.49	303.775	156.375	89.325	57.05	1.921
	υ calc	649.58	303.698	159.52	92.932	58.78	
	Error%	0.1681	0.355	2.011	4.038	3.026	
0.0116	υ exp	594.125	279.6	147.75	86.85	55.9	0.549
	υ calc	594.937	280.627	149.4	87.784	55.927	
	Error%	0.137	0.367	1.117	1.076	0.048	
0.05742	υ exp	446.5	213.75	116.25	68.75	44.95	2.696
	υ calc	446.667	217.892	119.4	71.928	46.825	
	Error%	0.037	1.938	2.71	4.622	4.171	
0.114	υ exp	319.89	153.875	91.575	5.55	38.875	1.83
	υ calc	319.638	151.93	91.686	56.824	37.92	
	Error%	0.0789	5.235	0.121	1.261	2.456	
0.1696	υ exp	213.5	111.675	68.1	44.1	30.725	1.222
	υ calc	213.021	114.097	67.686	43.629	30.098	
	Error%	0.224	2.169	0.608	1.068	2.039	
0.2244	υ exp	149.825	84.988	51.75	34.55	24.725	0.859
	υ calc	149.299	83.664	51.571	34.346	24.366	
	Error%	0.351	1.558	0.345	0.591	1.452	
0.2784	υ exp	110.27	58.1	39.45	27.35	20.075	2.946
	υ calc	109.761	63.766	40.545	27.737	20.14	
	Error%	0.462	9.752	2.776	1.413	0.324	
Av.Abs %erroe	1.718						

Table 4-9: Comparison between measured and calculated kinematic viscosity values for the blends of reduced crude with heavy gas oil

Weight Fraction	Viscosity (cst)	Temperature °C					Av.Abs %erroe
		30	40	50	60	70	
0.0109	υ exp	597.57	283.05	151.2	87.55	56.825	0.635
	υ calc	598.399	282.019	150.034	88.105	56.103	
	Error%	0.138	0.364	0.779	0.634	1.269	
0.0543	υ exp	449.75	217.475	119.55	71.125	45.525	1.478
	υ calc	449.926	219.626	120.382	72.525	47.211	
	Error%	0.039	0.984	0.696	1.969	3.703	
0.1081	υ exp	325.34	157.475	94.8	59.55	39.85	2.52
	υ calc	325.1	164.73	93.256	57.773	38.531	
	Error%	0.073	4.607	1.628	2.983	3.308	
0.1614	υ exp	216.612	114.8	71.5	46.575	33.95	3.841
	υ calc	216.136	116	68.895	44.433	30.656	
	Error%	0.219	1.045	3.642	4.598	9.7	
0.2143	υ exp	155.55	87.8	54.062	37.2	25.825	2.136
	υ calc	155.024	86.67	53.308	35.423	25.076	
	Error%	0.338	1.277	1.395	4.775	2.897	
0.2667	υ exp	114.67	61.05	42.775	29.875	21.3	3.444
	υ calc	114.156	66.187	41.995	28.666	20.77	
	Error%	0.447	8.415	1.823	4.047	2.487	
Av.Abs %erroe	2.342						

Table 4-10: Comparison between measured and calculated kinematic viscosity values for the blends of fuel oil with light gas oil

Weight Fraction	Viscosity (cst)	Temperature °C					Av.Abs %erroe
		30	40	50	60	70	
0	υ exp	584.64	289.5	151.35	85.95	55	2.247
	υ calc	585.373	279.765	150.381	88.978	56.97	
	Error%	0.1253	3.363	0.64	3.523	3.582	
0.0115	υ exp	530.125	263.625	138.5	82.625	54.45	1.121
	υ calc	530.602	257.302	139.982	83.661	54.017	
	Error%	0.0901	2.398	1.07	1.254	0.7945	
0.0574	υ exp	396.2	201.3	105.875	65.3	43.75	2.812
	υ calc	396.159	198.814	111.396	68.2889	45.072	
	Error%	0.0105	1.235	5.215	4.577	3.022	
0.1138	υ exp	278.13	141.25	85	54.475	37.55	1.865
	υ calc	277.758	145.372	84.439	53.378	36.2	
	Error%	0.1336	2.918	0.66	2.013	3.595	
0.1695	υ exp	184.3	102.7	63.35	41.95	29.95	2.177
	υ calc	183.784	101.738	61.941	40.754	28.575	
	Error%	0.28	0.936	2.223	2.852	4.591	
0.2242	υ exp	126.6	75.8	48.725	32.925	23.9	3.242
	υ calc	126.078	73.295	46.508	31.692	22.897	
	Error%	0.413	3.305	4.551	3.744	4.197	
0.2782	υ exp	89.89	52.4	35.925	25	18.625	1.018
	υ calc	89.409	54.252	35.702	25.098	18.624	
	Error%	0.535	3.535	0.622	0.391	0.007	
Av.Abs %erroe	2.069						

Table 4-11: Comparison between measured and calculated kinematic viscosity values for the blends of fuel oil with heavy gas oil

Weight Fraction	Viscosity (cst)	Temperature °C					Av.Abs %erroe
		30	40	50	60	70	
0.0109	υ exp	533.78	267	141.5	85.05	54.625	1.16
	υ calc	534.274	258.777	140.65	83.994	54.197	
	Error%	0.093	3.08	0.601	1.242	0.783	
0.0542	υ exp	400.15	204.55	109.45	67.625	44.3	1.852
	υ calc	400.12	200.808	112.497	68.945	45.49	
	Error%	0.008	1.829	2.784	1.952	2.686	
0.108	υ exp	282.98	144.7	88.5	56.925	38.213	2.785
	υ calc	282.617	147.918	85.894	54.288	36.783	
	Error%	0.128	2.224	2.945	4.633	3.993	
0.1613	υ exp	188.11	105.813	66.45	43.3	30.4	2.96
	υ calc	187.596	103.914	63.272	41.617	29.165	
	Error%	0.273	1.794	4.783	3.887	4.063	
0.2141	υ exp	130.9	79.125	50.1	33.975	24.4	3.312
	υ calc	130.375	75.691	47.954	32.624	23.531	
	Error%	0.401	4.34	4.284	3.976	3.562	
0.2665	υ exp	92.88	55.8	38.875	26.55	19.8	2.401
	υ calc	92.395	56.026	36.83	25.857	19.16	
	Error%	0.523	0.404	5.262	2.61	3.234	
Av.Abs %erroe	2.412						

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

From the results of the present work, the following conclusions are dram:

1. The viscosity of residual fuel oils can be improved either by increasing the temperature (heating) or blending with gas oil. The viscosities of reduced crude and fuel oil can be reduced to about 53% and 50% at $40^{\circ}C$.

2. The blending method can be considered as a suitable and economical method for improving the viscosity of heavy petroleum fraction especially for transportation of a long distances and discarding of the heating of heavy petroleum fractions. The viscosities of reduced crude and fuel oil can be reduced to about 52% and 50% respectively by blending with 10% heavy gas oil at $30^{\circ}C$.

3. The addition of methanol in low concentration to reduced crude or fuel oil causes a reduction in there viscosities. The maximum decrease in viscosity (about 32% and 31%rsspectivly) was achieved by 3-4 vol. % of methanol.

4. The reduction of viscosity of commercial fuel oil and reduced crude lead to decrease of power requirements for pumping and increase of the pumping

capacity through pipelines. The power of reduced crude can be reduced to about 30.8%, while the flow rate is increased by 14.3% also at $50^{o}C$ for both lines or blending with 10% heavy gas oil at $40\ ^{o}C$.

5. A modified model has been used to predict the viscosity of heavy petroleum fractions blended with gas oil, based on temperature and concentration (wt. %). The overall average absolute error obtained by this correlation is 2.1%.

5.2 Recommendations for Future Work

1. Further work can be carried out to study the pressure effect on kinematic viscosity of fuel oils.

2. An attempt can be made to formulate a correlation to predict the kinematic viscosity as a function API gravity and pour point of the mixtures.

3. Studying the effect of temperature and concentration on the viscosity change for ternary and quaternary mixtures of heavy petroleum fraction.

4. Study the effect of blending and methanol addition on pipeline requirements of crude oils.

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APPENDIX A

Table A-1: Flow rate, power, density and kinematic viscosity of reduced crude blended with light gas oil at different temperature and l=250m

WT% OF L.G.O	T(K)	υ(Cst)	ρ(Kg/m^3)	HP(Kw)	Q(m^3/hr)
1.16	303	594.125	939.19	171.57	24.766
	313	279.6	934.88	141.45	26.567
	323	147.75	926.85	119.57	28.241
	333	86.85	919.82	103.9	29.721
	343	55.9	913.17	92.388	31.017
5.742	303	446.5	933.41	158.76	25.474
	313	213.75	931.6	131.8	27.258
	323	116.25	923.59	112.21	28.9
	333	68.75	915.75	97.568	30.408
	343	44.95	908.22	87.013	31.701
11.4	303	319.89	926.3	144.95	26.332
	313	153.875	924.31	120.45	28.165
	323	91.575	916.71	104.93	29.614
	333	57.55	908.9	92.628	30.988
	343	38.875	902.01	83.338	32.202
16.96	303	213.5	919.28	130.02	27.393
	313	111.675	916.51	110.24	29.087
	323	68.1	910.07	96.733	30.503
	333	44.1	904.25	86.221	31.806
	343	30.725	896.51	78.098	32.972
22.44	303	149.825	912.38	118.11	28.367
	313	84.988	910.42	102.28	29.891
	323	51.75	903.71	89.685	31.354
	333	34.55	896.03	80.38	32.628
	343	24.725	888	73.267	33.746
27.84	303	110.27	905.59	108.58	29.248
	313	58.1	940.39	96.065	30.58
	323	39.45	897.75	83.249	32.215
	333	27.35	889.98	75.306	33.411
	343	20.075	882.67	69.131	34.467

Table A-2: Flow rate, power, density and kinematic viscosity of reduced crude blended with heavy gas oil at different temperature and l=250m

WT% OF H.G.O	T(K)	υ(Cst)	ρ(Kg/m^3)	HP(Kw)	Q(m^3/hr)
1.09	303	597.57	939.78	171.92	24.747
	313	283.05	934.9	141.89	26.537
	323	151.2	927.15	120.3	28.178
	333	87.55	919.84	104.11	29.699
	343	56.825	913.36	92.788	30.969
5.43	303	449.75	936.35	159.55	25.428
	313	217.475	931.72	132.39	27.214
	323	119.55	923.71	113.01	28.826
	333	71.125	915.82	98.408	30.313
	343	45.525	908.61	87.328	31.659
10.81	303	325.34	932.09	146.47	26.232
	313	157.475	924.65	121.2	28.102
	323	94.8	916.82	105.85	29.52
	333	59.55	909.19	93.452	30.888
	343	39.85	902.05	83.859	32.129
16.14	303	216.6125	927.88	131.71	27.265
	313	114.8	916.98	111.06	29.009
	323	71.5	910.81	97.998	30.359
	333	46.575	904.66	87.445	31.644
	343	33.95	896.62	80.081	32.672
21.43	303	155.55	923.7	120.7	28.144
	313	87.8	910.68	103.15	29.799
	323	54.0625	904.17	90.717	31.224
	333	37.2	896.43	81.915	32.404
	343	25.825	888.18	74.084	33.61
26.67	303	114.67	919.56	111.34	28.982
	313	61.05	904.65	93.565	30.875
	323	42.775	898.62	85.033	31.967
	333	29.875	891.44	77.114	33.124
	343	21.3	881.3	70.054	34.301

Table A-3: Flow rate, power, density and kinematic viscosity of fuel oil blended with light gas oil at different temperature and l=250m

WT% OF L.G.O	T(K)	υ(Cst))	ρ(Kg/m^3)	HP(Kw)	Q(m^3/hr)
1.15	303	530.125	939	166.71	25.026
	313	263.625	934.72	139.36	26.711
	323	138.5	927.39	117.72	28.401
	333	82.625	920.22	102.66	29.851
	343	54.45	913.1	91.776	31.092
5.74	303	396.2	933.25	154.06	25.754
	313	201.3	931.23	129.79	27.411
	323	105.875	923.9	109.66	29.143
	333	65.3	915.58	96.302	30.553
	343	43.75	908.67	86.47	31.773
11.38	303	278.13	926.14	139.94	26.67
	313	141.25	924.29	117.9	28.385
	323	85	916.6	102.98	29.817
	333	54.475	908.59	91.333	31.147
	343	37.55	901.29	82.552	32.313
16.95	303	184.3	919.15	125.31	27.763
	313	102.7	916.65	107.97	29.308
	323	63.35	910.74	95.07	30.696
	333	41.95	903.32	85.062	31.963
	343	29.95	896.71	77.618	33.046
22.42	303	126.6	912.26	113.22	28.806
	313	75.8	911.3	99.493	30.193
	323	48.725	905.15	88.485	31.508
	333	32.925	896.53	79.462	32.765
	343	23.9	887.6	72.616	33.856
27.82	303	89.89	905.29	103.14	29.8
	313	52.4	903.31	89.925	31.323
	323	35.925	896.86	81.243	32.502
	333	25	889.86	73.624	33.687
	343	18.625	881.58	67.764	34.718

Table A-4: Flow rate, power, density and kinematic viscosity of fuel oil blended with heavy gas oil at different temperature and l=250m

WT% OF H.G.O	T(K)	υ (Cst))	ρ(Kg/m^3)	HP(Kw)	Q(m^3/hr)
1.09	303	533.78	939.359	167.06	25.006
	313	267	934.84	139.82	26.679
	323	141.5	926.8	118.27	28.353
	333	85.05	920.36	103.42	29.771
	343	54.625	913.22	91.862	31.082
5.42	303	400.15	936.17	154.93	25.702
	313	204.55	931.65	130.37	27.367
	323	109.45	925.1	110.71	29.042
	333	67.625	916.06	97.199	30.45
	343	44.3	909.48	86.817	31.727
10.8	303	282.98	931.93	141.43	26.568
	313	144.7	924.62	118.66	28.319
	323	88.5	916.62	104.03	29.708
	333	56.925	908.83	92.368	31.02
	343	38.3125	901.36	82.975	32.253
16.13	303	188.11	927.73	127.13	27.618
	313	105.8125	916.82	108.8	29.227
	323	66.45	911.3	96.272	30.556
	333	43.3	903.85	85.789	31.864
	343	30.4	896.82	77.918	32.999
21.41	303	130.9	923.66	115.6	28.589
	313	79.125	911.47	100.59	30.073
	323	50.1	905.38	89.126	31.425
	333	33.975	896.63	80.097	32.67
	343	24.4	887.7	73.001	33.791
26.65	303	92.88	907.31	104.22	29.687
	313	55.8	903.69	91.388	31.14
	323	38.875	897.83	82.952	32.257
	333	26.55	890.68	74.808	33.492
	343	19.8	881.77	68.823	34.523

Table A-5: Flow rate, power, density and kinematic viscosity of reduced crude blended with light gas oil at different temperature and l=10Km

WT% OF L.G.O	T(K)	υ(Cst)	ρ(Kg/m^3)	HP(Kw)	Q(m^3/hr)
1.16	303	594.125	939.19	178.6	62.175
	313	279.6	934.88	147.25	66.696
	323	147.75	926.85	124.47	70.899
	333	86.85	919.82	108.16	74.615
	343	55.9	913.17	96.176	77.869
5.742	303	446.5	933.41	165.27	63.954
	313	213.75	931.6	137.21	68.432
	323	116.25	923.59	116.81	72.555
	333	68.75	915.75	101.57	76.340
	343	44.95	908.22	90.581	79.586
11.4	303	319.89	926.3	150.89	66.106
	313	153.875	924.31	125.39	70.709
	323	91.575	916.71	109.23	74.348
	333	57.55	908.9	96.425	77.796
	343	38.875	902.01	86.755	80.844
16.96	303	213.5	919.28	135.35	68.771
	313	111.675	916.51	114.76	73.025
	323	68.1	910.07	100.7	76.579
	333	44.1	904.25	89.756	79.851
	343	30.725	896.51	81.3	82.776
22.44	303	149.825	912.38	122.95	71.216
	313	84.988	910.42	106.47	75.042
	323	51.75	903.71	93.362	78.715
	333	34.55	896.03	83.676	81.914
	343	24.725	888	76.271	84.721
27.84	303	110.27	905.59	113.03	73.428
	313	58.1	940.39	100	76.772
	323	39.45	897.75	86.662	80.876
	333	27.35	889.98	78.394	83.879
	343	20.075	882.67	71.966	86.529

Table A-6: Flow rate, power, density and kinematic viscosity of reduced crude blended with heavy gas oil at different temperature and l=10Km

WT% OF H.G.O	T(K)	υ(Cst))	ρ(Kg/m^3	HP(Kw)	Q(m^3/hr)
1.09	303	597.57	939.78	178.97	62.128
	313	283.05	934.9	147.7	66.621
	323	151.2	927.15	125.23	70.743
	333	87.55	919.84	108.38	74.559
	343	56.825	913.36	96.592	77.748
5.43	303	449.75	936.35	166.09	63.839
	313	217.475	931.72	137.82	68.321
	323	119.55	923.71	117.65	72.367
	333	71.125	915.82	102.44	76.103
	343	45.525	908.61	90.908	79.481
10.81	303	325.34	932.09	152.48	65.855
	313	157.475	924.65	126.17	70.551
	323	94.8	916.82	110.19	74.111
	333	59.55	909.19	97.283	77.546
	343	39.85	902.05	87.297	80.661
16.14	303	216.6125	927.88	137.11	68.449
	313	114.8	916.98	115.61	72.828
	323	71.5	910.81	102.02	76.218
	333	46.575	904.66	91.031	79.442
	343	33.95	896.62	83.365	82.025
21.43	303	155.55	923.7	125.65	70.657
	313	87.8	910.68	107.38	74.812
	323	54.0625	904.17	94.436	78.388
	333	37.2	896.43	85.274	81.352
	343	25.825	888.18	77.121	84.379
26.67	303	114.67	919.56	115.91	72.761
	313	61.05	904.65	97.402	77.512
	323	42.775	898.62	88.519	80.255
	333	29.875	891.44	80.276	83.159
	343	21.3	881.3	72.926	86.114

Table A-7: Flow rate, power, density and kinematic viscosity of fuel oil blended with light gas oil at different temperature and l=10Km

WT% OF L.G.O	T(K)	υ(Cst)	ρ(Kg/m^3)	HP(Kw)	Q(m^3/hr)
1.15	303	530.125	939	173.55	62.827
	313	263.625	934.72	145.07	67.058
	323	138.5	927.39	122.54	71.303
	333	82.625	920.22	106.86	74.942
	343	54.45	913.1	95.539	78.058
5.74	303	396.2	933.25	160.38	64.657
	313	201.3	931.23	135.11	68.816
	323	105.875	923.9	114.15	73.166
	333	65.3	915.58	100.25	76.704
	343	43.75	908.67	90.015	79.767
11.38	303	278.13	926.14	145.68	66.956
	313	141.25	924.29	122.74	71.262
	323	85	916.6	107.2	74.857
	333	54.475	908.59	95.078	78.196
	343	37.55	901.29	85.937	81.123
16.95	303	184.3	919.15	130.45	69.701
	313	102.7	916.65	112.4	73.579
	323	63.35	910.74	98.968	77.064
	333	41.95	903.32	88.55	80.245
	343	29.95	896.71	80.801	82.962
22.42	303	126.6	912.26	117.87	72.319
	313	75.8	911.3	103.57	75.799
	323	48.725	905.15	92.113	79.102
	333	32.925	896.53	82.72	82.257
	343	23.9	887.6	75.593	84.996
27.82	303	89.89	905.29	107.37	74.814
	313	52.4	903.31	93.612	78.639
	323	35.925	896.86	84.574	81.596
	333	25	889.86	76.643	84.571
	343	18.625	881.58	70.542	87.161

Table A-8: Flow rate, power, density and kinematic viscosity of fuel oil blended with heavy gas oil at different temperature and l=10Km

WT% OF H.G.O	T(K)	υ (Cst)	ρ(Kg/m^3	HP(Kw)	Q(m^3/hr)
1.09	303	533.78	939.359	173.91	62.779
	313	267	934.84	145.56	66.977
	323	141.5	926.8	123.12	71.180
	333	85.05	920.36	107.66	74.741
	343	54.625	913.22	95.628	78.032
5.42	303	400.15	936.17	161.28	64.525
	313	204.55	931.65	135.71	68.705
	323	109.45	925.1	115.25	72.911
	333	67.625	916.06	101.18	76.445
	343	44.3	909.48	90.377	79.651
10.8	303	282.98	931.93	147.23	66.699
	313	144.7	924.62	123.52	71.097
	323	88.5	916.62	108.29	74.582
	333	56.925	908.83	96.155	77.876
	343	38.3125	901.36	86.377	80.973
16.13	303	188.11	927.73	132.34	69.336
	313	105.8125	916.82	113.26	73.374
	323	66.45	911.3	100.22	76.713
	333	43.3	903.85	89.306	79.997
	343	30.4	896.82	81.112	82.846
21.41	303	130.9	923.66	120.34	71.775
	313	79.125	911.47	104.71	75.499
	323	50.1	905.38	92.78	78.894
	333	33.975	896.63	83.381	82.019
	343	24.4	887.7	75.994	84.833
26.65	303	92.88	907.31	108.49	74.531
	313	55.8	903.69	95.135	78.178
	323	38.875	897.83	86.353	80.981
	333	26.55	890.68	77.876	84.082
	343	19.8	881.77	71.645	86.670

Table A-9: Flow rate, power, density and kinematic viscosity of reduced crude blended with methanol at different temperature and l=250m

WT% OF METHANOL	T(K)	υ (Cst)	ρ(Kg/m^3)	HP(Kw)	Q(m^3/hr)
1.19	303	590.825	939.18	171.327	24.778
	313	274.3	933.5	140.567	26.627
	323	139.83	926.34	117.865	28.388
1.78	303	586.75	938.26	170.863	24.803
	313	270.225	931.32	139.715	26.686
	323	136.15	923.93	116.777	28.484
2.38	303	583.075	937.36	170.432	24.826
	313	267.55	929.95	139.163	26.724
	323	131.725	922.72	115.664	28.584
3.56	303	510.45	935.55	164.539	25.145
	313	225.925	924.16	132.572	27.200
	323	112.975	915.8	110.474	29.065

Table A-10: Flow rate, power, density and kinematic viscosity of fuel oil blended with methanol at different temperature and l=250m

WT% OF METHANOL	T(K)	υ (Cst))	ρ(Kg/m^3)	HP(Kw)	Q(m^3/hr)
1.19	303	526.55	938.19	166.289	25.049
	313	260.05	933.33	138.679	26.758
	323	135.125	926.25	116.849	28.478
1.78	303	523.125	937.29	165.859	25.072
	313	255.625	930.26	137.632	26.832
	323	133.125	923.48	116.066	28.548
2.37	303	519.35	936.39	165.4	25.098
	313	252.85	930.08	137.23	26.861
	323	124.075	923.05	113.988	28.736
3.55	303	440.2	934.59	158.397	25.496
	313	210.7	923.36	130.167	27.382
	323	105.525	916	108.629	29.243

Table A-11: Flow rate, power, density and kinematic viscosity of reduced crude blended with methanol at different temperature and l=10Km

WT% OF METHANOL	T(K)	ʋ (Cst))	ρ(Kg/m^3)	HP(Kw)	Q(m^3/hr)
1.19	303	590.825	939.18	178.352	62.207
	313	274.3	933.5	146.33	66.848
	323	139.83	926.34	122.697	71.270
1.78	303	586.75	938.26	177.869	62.268
	313	270.225	931.32	145.444	66.996
	323	136.15	923.93	121.565	71.511
2.38	303	583.075	937.36	177.42	62.325
	313	267.55	929.95	144.869	67.093
	323	131.725	922.72	120.407	71.760
3.56	303	510.45	935.55	171.285	63.128
	313	225.925	924.16	138.007	68.287
	323	112.975	915.8	115.003	72.968

Table A-12: Flow rate, power, density and kinematic viscosity of fuel oil blended with methanol at different temperature and l=10Km

WT% OF METHANOL	T(K)	ʋ (Cst))	ρ(Kg/m^3)	HP(Kw)	Q(m^3/hr)
1.19	303	526.55	938.19	173.107	62.886
	313	260.05	933.33	144.366	67.178
	323	135.125	926.25	121.64	71.495
1.78	303	523.125	937.29	172.659	62.945
	313	255.625	930.26	143.275	67.363
	323	133.125	923.48	120.825	71.669
2.37	303	519.35	936.39	172.181	63.008
	313	252.85	930.08	142.857	67.435
	323	124.075	923.05	118.662	72.142
3.55	303	440.2	934.59	164.891	64.007
	313	210.7	923.36	135.504	68.743
	323	105.525	916	113.083	73.417

الخلاصة

يعد "متبقي التقطير الجوي" المصدر الرئيسي والمهم لانتاج الوقود الصناعي.لذا تم أعتمادة في هذا البحث بالاضافة الى زيت الوقود التجاري وذلك لتطوير عملية الضخ عبر نقل ألانابيب.

هنالك طريقتان رئيسيتان لتسهيل عملية ضخ المشتقات النفطية الثقيلة الاولى تتم عن طريق المزج مع مشتقات نفطية خفيفة ذات لزوجة قليلة والثانية تتم بواسطة تسخين المنتج المراد نقلة.أن القيم الدقيقة التي تربط اللزوجة بدرجة الحرارة ونسب التركيب مهمةً جداً في الحسابات التصميمية لانابيب الضخ.

تم دراسة عملية التسخين، الى درجة ٧٠ درجة مئوية وتأثيرها على تقليل لزوجة متبقي التقطير الجوي وزيت الوقود وخلائطهما مع زيت الغاز. وقد لوحظ نقصان كبير في قيمة اللزوجة يتناسب طرديا مع زيادة درجة الحرارة. حيث تم تحقيق ٥٣٪ , ٥٠٪ تقليل في لزوجة متبقي التقطير الجوي وزيت الوقود على التوالي عند درجة ٤٠ درجة مئوية.

وقد لوحظ من الممكن عمليا تطوير لزوجة متبقي التقطير الجوي بأستخدام طريقة مزجة مع زيت الغاز. وكانت النتائج كما متوقع حيث أن زيت الغاز الخفيف أثر بصورة أكبر في تقليل اللزوجة من زيت الغاز الثقيل.

أن أضافة المثانول بتراكيز قليلة لكل من متبقي التقطير الجوي وزيت الوقود أدى الى تقليل لزوجتهما. أقصى خفض للزوجة تم الحصول علية عند أضافة ٣-٤٪ حجماً من الميثانول.

تم كذلك دراسة تأثير تقليل اللزوجة لكلا الطريقتين (التسخين والمزج) على القدرة الحصانية اللازمة للضخ وعلى معدل الجريان. تم أجراء الحسابات بالاستناد الى البيانات المتوفرة محليا لانابيب نقل زيت الوقود لمسافات ٢٥٠متر, ١٠٠٠٠متر. وقد بينت النتائج نقصان ملحوظ بالقدرة اللزمة للضخ وزيادة حجم ضخ عند التخفيف مع زيت الغاز أو الميثانول وعند زيادة درجة الحرارة.

تم تطوير نموذوج رياضي لحساب اللزوجة الديناميكية لخلائط زيت الوقود ومتبقي التقطير الجوي بدرجات حرارة مختلفة ,كما مبين آدناة:

$$\left[\frac{\log(\upsilon)+K}{\log(\upsilon_o)+C}\right]=\left[\frac{T_0}{T}\right]^S$$

عند أجراء مقارنة بين قيم اللزوجة المحسوبة من المعادلة وتلك التي تم الحصول عليها بالقياس للمشتقات النفطية الثقيلة وخلائطها ولدرجات حرارة مختلفة, وجد أن نتائج المقارنة كانت مرضية وبنسبة خطأ كلية مقدارها ٢,١٢٪ أخذت لـ ١٣٠ حالة مختلفة.

شكر وتقدير

أود أن اعبر عن خالص شكري وتقديري وامتناني العميق للمشرف الدكتور جابر شنشول جمالي لما قدمه لي من توجيهات قيمة ونصائح سديدة طوال فترة إنجاز البحث.

أود أيضاً أن اشكر المشرف الدكتور طالب بهجت كشمولة وجميع أساتذة وموظفي قسم الهندسة الكيمياوية في جامعة النهرين لإبدائهم المساعدة اللازمة أثناء هذا العمل.

ولا أنسى أن أتقدم بالشكر والامتنان إلى من لازمني طوال فترة البحث وخلال اصعب الظروف إلى أعز من في الوجود إلى أبى وأمي وجميع أفراد عائلتي فلهم جزيل الشكر والتقدير.

نغم سلمان حسن المالكي

تحسين نقل زيت الوقود بواسطة خطوط الانابيب

رسالة

مقدمة الى كلية الهندسة في جامعة النهرين كجزء من متطلبات نيل درجة ماجستير

علوم في الهندسة الكيمياوية

من قبل

نغم سلمان حسن المالكي

(بكالوريوس في الهندسة الكيمياوية ٢٠٠١)

شهر رمضان ١٤٢٥هـ

تشرين الاول ٢٠٠٤م