POLITECNICO DI TORINO

Department of Environment, Land and Infrastructure Engineering

Master of Science in Petroleum Engineering

Investigation of oil viscosity modeling for non-isothermal transportation

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Abstract

As the global energy demand is growing, all hydrocarbon resources, particularly heavy and extra-heavy crude oil, need to be used. However, the decline in light crude oil reserves makes it attractive to use heavy and extra-heavy oil to meet energy requirements due to recoverable oil capacity. Despite the importance and high volumes of heavy crude oil reserves, development, production and refining are difficult due to its physico-chemical properties, mainly its high density and viscosity, low API gravity and high hydrocarbon content Heavy crude (HO) and extra-heavy crude (EHO) crude oils usually have a large percentage of heavy components such as resins and asphalt which reduce API gravity. In order to improve the transport of heavy crude oil to the surface, the conventional techniques used are heat pipes and pumping stations, dilution with less viscous solvents, emulsification and reduction of friction (annular flow). Such techniques, however, are expensive mainly because of the high raw material usage, heating of long tube lengths and additional processes for transporting crude oil. The changes in temperature across the line cause different oil properties changes and the system energy eventually changes. The study of oil transport under non-isothermal conditions underlines the significance of the change in properties such as viscosity and flow regimes in many environmental conditions, those properties are crucial and have triggered changes in the transport approach.

Laboratory measurement for heavy crude oil temperature ranges are 25 °C to 75 °C. The main purposes to analyses temperature below 25 °C for heavy oil viscosity until pour point. It used different model for prediction of viscosity of crude oil at lower temperature. Moreover, Light crude oil at different fraction boiling range, olive oil and water it used in order to choose best model for prediction. Using RheoStress RS100 from Haake, rheological properties of heavy crude oil have been studied.

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DEDICATION

This thesis is dedicated to my Parents

CHAPTER I

1. Introduction.

Problem Statement and Research Objectives:

The planned work could emphasis on several crucial points, so that the properties of heavy crude oil are understood and can be improved. Heavy crude oil viscosity has a data which is it start from 25 °C to 75 °C. Main purpose of this thesis is do describe viscosity of heavy oil below 25°C and due to this reason, it used three model. First model name is clarck, second one is Walther-Ubbelohde and last simple one exponential model in order to discover viscosity of oil under 25°C. Experimental research at chapter III it is clearly showing us that between 25° C to 75°C for three model error almost the same and not much big difference but below 25 °C have a big difference and it should proof that which model is best in order to identify oil viscosity which is prediction viscosity. Due to this problem it used low viscosity substances like water, olive oil and five different fraction of light crude oil because to make decision which model is best to predict heavy oil viscosity at lower temperature and rheological properties.Studying the rheological characteristics of heavy crude oil with the effect of shear stress τ, shear rate γ, yield stress τ_0 and thixotropic behavior. The analysis of the rheological properties of heavy crude oil, therefore, helps to determine the most effective method for viscosity reduction.

1.1 Organization of the Thesis:

The literature review is covered in Chapter II. The experimental setup and results of the work is discussed in Chapter III. The conclusions drawn from the project are summed up in Chapter IV.

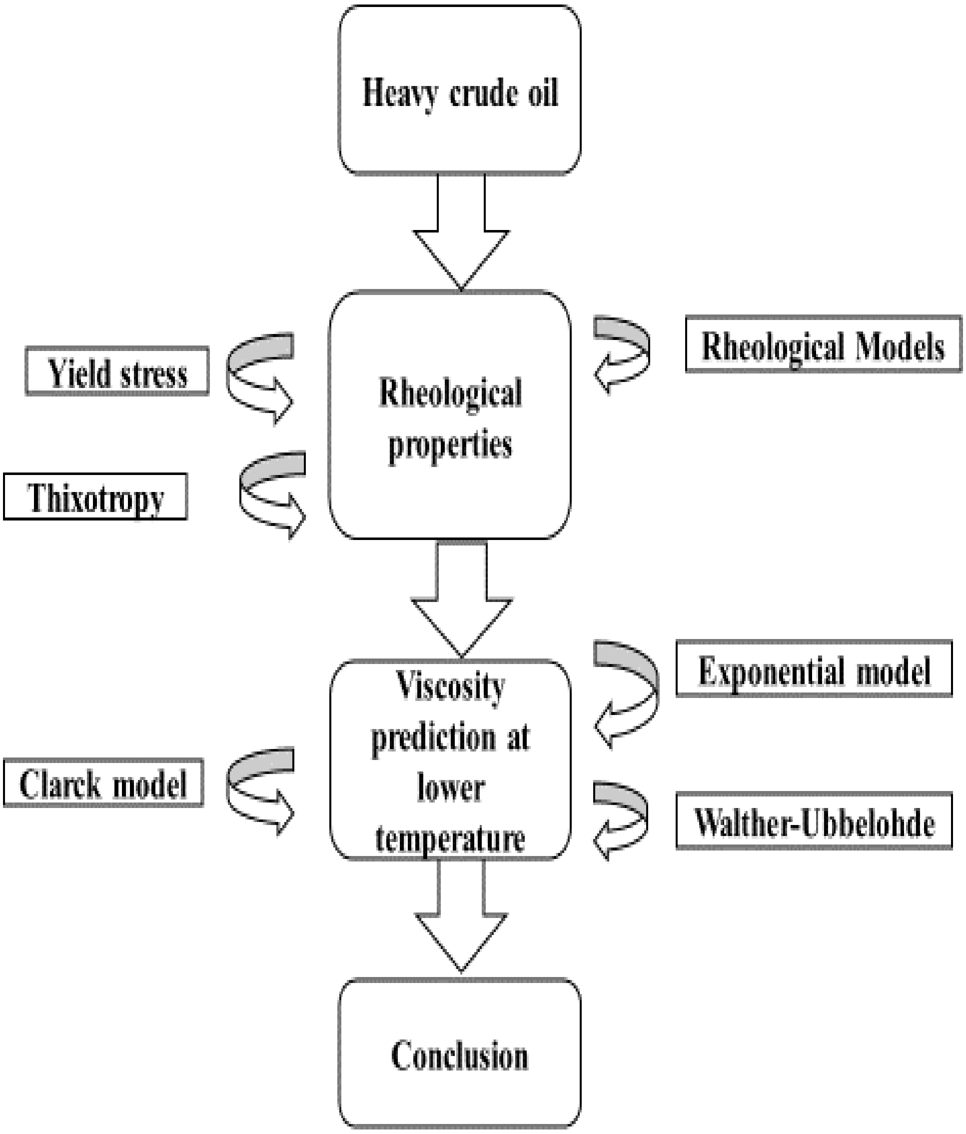


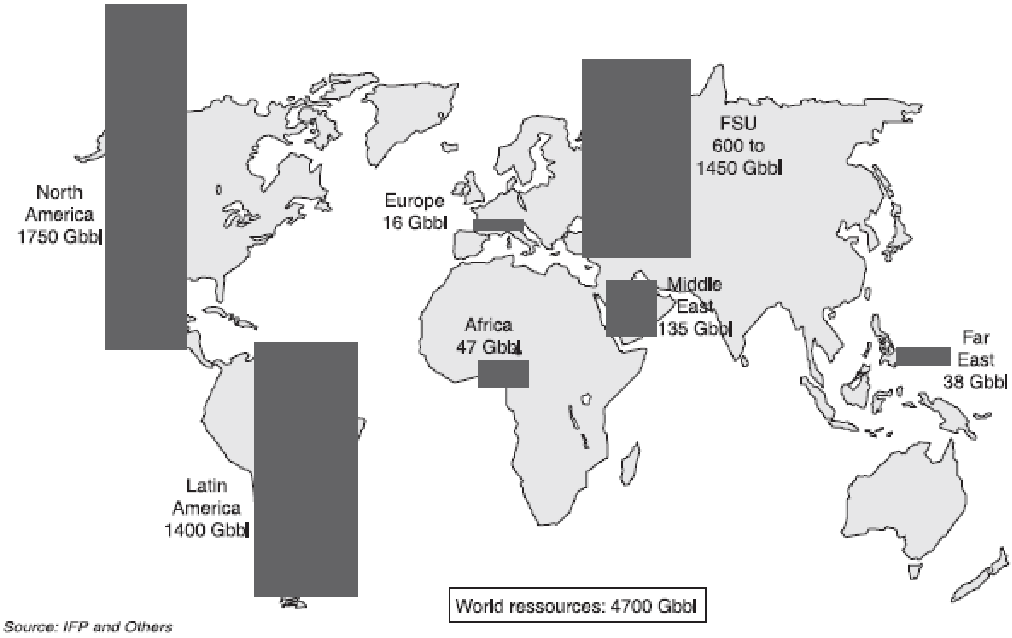
Fig. 1. Methodology of the study

CHAPTER II

2. Literature Review

2.1. Crude Oil:

Day-to-day fluctuations in oil prices, which affect both supply and demand.



Source: IFP and Others

Fig.2. Proven and recoverable oil reserves distributed by region in billions of barrels

The world demand for crude oil increased annually by an average of 1.76 percent over the 1994–2006 period, and during 2003–2004 by a high of 3.4 percent. In developing countries, such as China and India, demand growth is the highest, with dynamic economies that led to a significant 1,8% global increase in crude oil demand in 2009. The International Energy Agency's statistics state that heavy crude oil accounts for around 50 percent of the world's recoverable oil resources. Global demand for crude oil in the last twenty years has steadily increased, with world crude demand increasing to 84 million barrels daily, from 60 million barrels. Only about 1/2 the price of light crude oil is the market price, which is commonly quoted by the media. Oil transport have been an extremely technical and complex process. The high viscous fluids that require efficient and economic transfers of heavy crude is one of the major challenges in pipeline transport.

2.2 Heavy crude oils environmental challenges:

The high density of heavy crude oils is similar to or even above that of water. Due to high levels of sulfur and several metals, specially nickel and vanadium, heavy crude oils will not be easily pumped through the pipelines. Crude oils are complex fluids which trigger a number of challenges in oil production, separation, transport and refining. Nevertheless, the vast resources of such crude oils are becoming increasingly established. The oil industry and government energy agencies therefore create new cost-effective methods for the extraction of heavy oils from the reservoir, the improvement of heavy crude oil or synthesized crude oils at the source in the refinery and the refining of heavy oils and syncrudes to achieve high yields of valuable light and medium distillates.

There are two types of environmental concerns about heavy crude oil:

- Heavy crude oil production, upgrading and refinement of chemical waste and byproducts can cause severe ecological harm if released into the environment.
- Spills of heavy crude oils and sycrudes are difficult to purify and could result in long-term damage to the environment concerned.

Much of the in situ and wellhead equipment for upgrading and processing produce waste gasses and solids that may cause serious ecological damage. Nevertheless, problems with heavy oils are hard to remove. In fact, oil can be extremely persistent and can cause chronic damage to the environment concerned.[6]

2.3 Characterization and composition of crude oil:

Crude oil is not a pure substance; it is not even a mixture of two components which is contains different amounts of hydrocarbons. Crude oil hydrocarbons are primarily alkanes (paraffins), cycloalkanes and other aromatic hydrocarbons; other organic compounds include nitrogen, oxygen and sulfur and small amounts of metals including iron, nickel, copper and vanadium. The specific molecular composition varies significantly from formation to formation, but there is a fairly small difference between the proportion of chemical elements: Percent range of element are Metals lower that 0.1%,Sulfur 0.05 to 6 %, Oxygen 0.05 to 1.5%, Nitrogen 0.1 to 2%,Hdrogen 10 to 14%

and main part carbon are changing between 83 % up to 87%. The content of crude oil is defined by a variety of characteristics which influence the proportion of transport fuels and petroleum products produced when the oil is refined. Certain physical characteristics which influence primarily the behavior and persistence of crude oil are:

2.3.1. Specific Gravity or Density:

Crude oil quality based on SG (specific gravity), API (American Petroleum Institute) gravity and S% (Sulfur percentage). The most important of the commercial parameters is the specific gravity used to measure the quality of crude oils. The low specific gravity gives a great quality of the lighter fractions of crude oil and vice-versa. The crude oil is listed according to the gravity of measured API as light, medium or heavy [2]. Bitumen and extra heavy oil are characterized by API gravity below 10. API normally describes heavy oil from 10 ° to 22.3 °, medium oil from 22.3 ° to 31.1 ° and light oil higher than 31.1 °. The crude oil SG (Specific gravity) is reversed by the API values and provides a preliminary estimate of the types of hydrocarbons (heavy or light). As high-quality crude oil characterizes the lower the specific gravity and the higher API gravity. The total amount of sulfur in crude oil is composed of sulfur ingredients such as thiols, sulfides, disulfides and thiophenes, with sweet and sour oil classes based on sulfur percent. In general, the commercial ranking of crude oil was from very light to very heavy oil. The low-viscosity and SG of light hydrocarbon fractions are defined by a lower wax content and high API gravity. The API gravity formula can be stated as: [3]

$$API = \frac{141.5}{SG} - 131.5; \ Eq.1$$

2.3.2. Viscosity**:**

Viscosity is another sort of bulk property that has been described as fluid resistance to flow [4]. More technical definition is the shear stress required to cause a unit change in the rate of angular deformation and that is describe equation (2) below.

$$\tau = \mu \frac{du}{dy} \quad Eq.2.$$

Left of the equation which is τ shear stress or force per unit area. Force action on a fluid and then on the right part of the equation differential is the rate of angular deformation. Although, that also has several synonyms like velocity gradient or the rate of shearing strain. Velocity of the fluid is du and dy is direction. So, this equation describe that you apply force and you get certain amount of angular deformation and then that is all controlled viscosity (μ). More viscous fluid or fluid with a high viscosity it gets less angular deformation. Equation (2) illustrate for Newtonian fluid, is not for non-Newtonian fluid because some fluids, shear stress is not be linearly related to the velocity gradient.

When there is a stronger inter-molecular attractiveness in a fluid, the viscosity is greater. The race between two fluids in a windshield is a perfect example. Which one will you expect quicker honey or water to rolls down the windshield. Naturally one could expect from experience that water will quickly pass over honey, a fact which shows that honey is viscosity much greater than water. Viscosity can be not only fluid flow resistant but also gas flow resistance, shape or motion resistance. It should also be remembered that the viscosity of fluids and gases is influenced by temperature but in comparison, the viscosity of a fluid decreases rapidly during heating, whereas gases flow more sluggishly. Because the total velocity of the molecules in fluid also increases when the temperature increases, and they are spending less time with their "neighbors." As a result, the average intermolecular force decreases when the temperature increases, and the molecules will interact without being "weighed down." Nevertheless, the viscosity of gas rises with the increased temperature as the likelihood of inter-molecular collisions at higher temperatures increases. Because the molecules are floating around in the void most of the time, any rise in the contact they have with each other will improve the intermolecular force that will ultimately lead to a disability for the whole substance to move around.

2.3. Classification of crude oil:

A process for characterizing heavy oils by a fractionation, which separate a heavy oil sample in smaller quantities or fractions, with a different composition for each fraction. That fraction is composed of a solubility class that contains a variety of molecular weight species [5]. The crude oil is classified into four solubility groups, collectively referred to as SARA; saturates, aromatics, resins, and asphaltenes. Saturates are iso- and cyclo-paraffin in general, and aromatic, resin and asphalt molecules form a continuum with a rising molecular weight, aromaticity and heteroatom contents.

Metals such as nickel and vanadium can also be present in asphalt. Sometimes this method is called an examination of deposition of asphaltene / wax / hydrate. The SARA separation scheme is shown in figure 3. Four different groups of saturates, aromatics, resin and asphalt are isolated into this crude oil system. Non-Polar hydrocarbons are saturated, which include straight and branched alkanes and compounds for cycloparaffins (naphthene). Wax consisting primarily of the long paraffin chain is considered to be a sub-class of saturates. Moreover, Aromatic products also include all of the compounds with one or more aromatic nuclei bound with naphthene rings and/or aliphatic side chains. The lightest of the crude oil are generally saturates and aromatics [6,7].

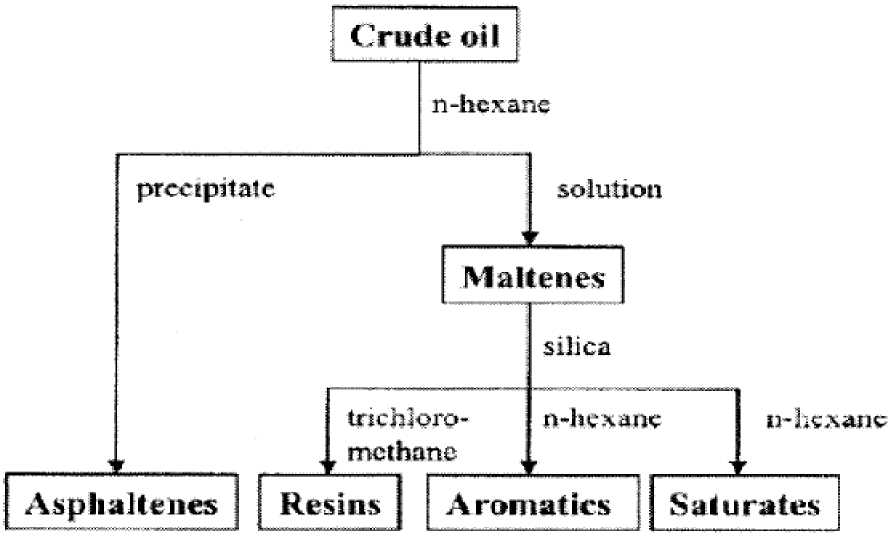


Fig. 3. Scheme for SARA separation [8]

Resin is another crude oil classification and is described as polar molecules that often contain heteroatom, such as nitrogen, oxygen and sulfur. This fraction appears to dissolve in light alkanes but has no ability to dissolve in liquid propane. Asphaltene are the heaviest aromatic or crude oil components with the highest heteroatom proportion (O, S and N) [6]. These components have a significant impact on oil production and transport by improving W/O emulsion stability. Nevertheless, asphaltene particle precipitation could pose serious problems for the pipeline and oil well [8,7].

2.4. Rheological behavior of crude oil

2.4.1. Theory:

Rheology is the analysis of deformation of substances and stress effects on flow. The force can be implemented in different ways: like compression, tension, shearing process or combination of three. Figure.6 is demonstrated with a simple type of deformation, shear [12]. The two parallel low plate is constantly maintained. In comparison to the lower one, the upper plate is pulled at a speed dv. The force of shear applied is F, which acts in x direction over area A. With regard to simple laminar flow, the basic parameters can be defined as follows:

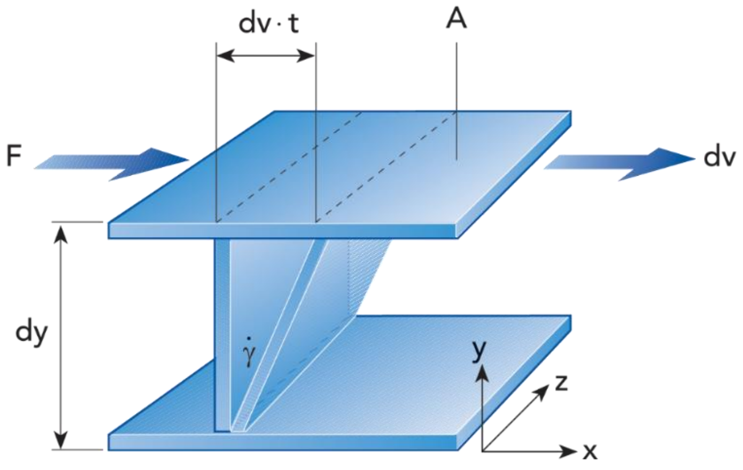


Fig. 6. Schematic representation of shearing flow [12]

The shear stress is a stress state in which the stresses are parallel or tangential. It is described as the force divided to the area which it is applied over [8].

$$\tau = \frac{dF}{dA} \qquad Eq.\ 3$$

The shear strain is the shifting of any plane relative to a second plane divided between planes by perpendicular distance [8].

$$\nu = \frac{dx}{dy} \qquad Eq.\ 4$$

Shear rate is the speed of deformation [8].

$$\gamma = \frac{dv}{dt} \qquad Eq.\ 5$$

2.4.2. Newtonian vs Non-Newtonian Liquids:

Newtonian fluids demonstrate a constant viscosity regardless of the shear rate and shear stress. Moreover, this type of fluid follow Newton's law of viscosity. Newtonian liquids equally have uniform flow resistance regardless of flow conditions. Example of Newtonian fluids are water, kerosene, diesel, mercury, glycerin etc.

The viscosity of non-Newtonian fluids varies with the shear rate and deformation process. In extensional flows, they exhibit elongational viscosities in no-apparent relation to their (shear) viscosities. Non-Newtonian fluids have varying flow resistance at various shear and extension rates and is nonlinear or does not transmit its origin flow curve (shear stress versus shear rate). Those materials can easily be categorized into three specific classes:

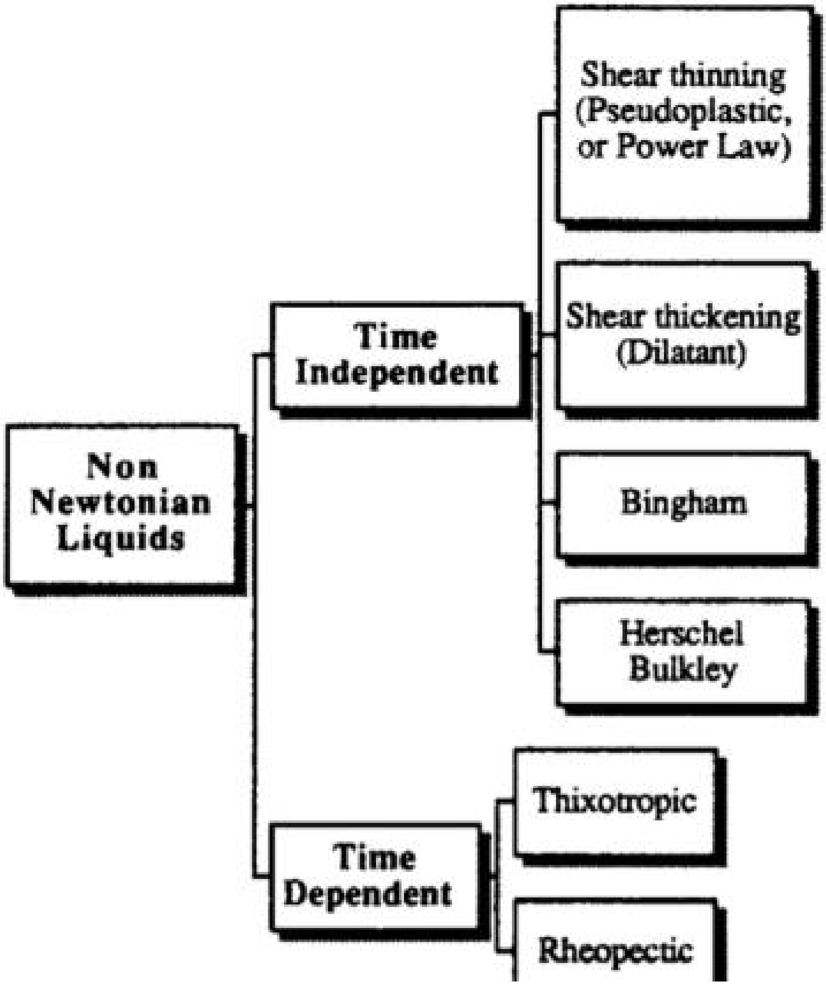


Fig. 7. Schematic representation of non-newton fluid

1. Time- independent fluids which is viscosity is independent of time; Viscosity is temperatures functions and $\frac{du}{dy}$ shear rate
2. Time-dependent fluids Viscosity is dependent on time;
3. Substances that display properties of ideal fluids; it is an imaginary fluid which has zero viscosity, zero surface tension, Incompressible [13].

2.4.3. Time-independent fluid behavior:

Time-independent fluid is classified into three types;

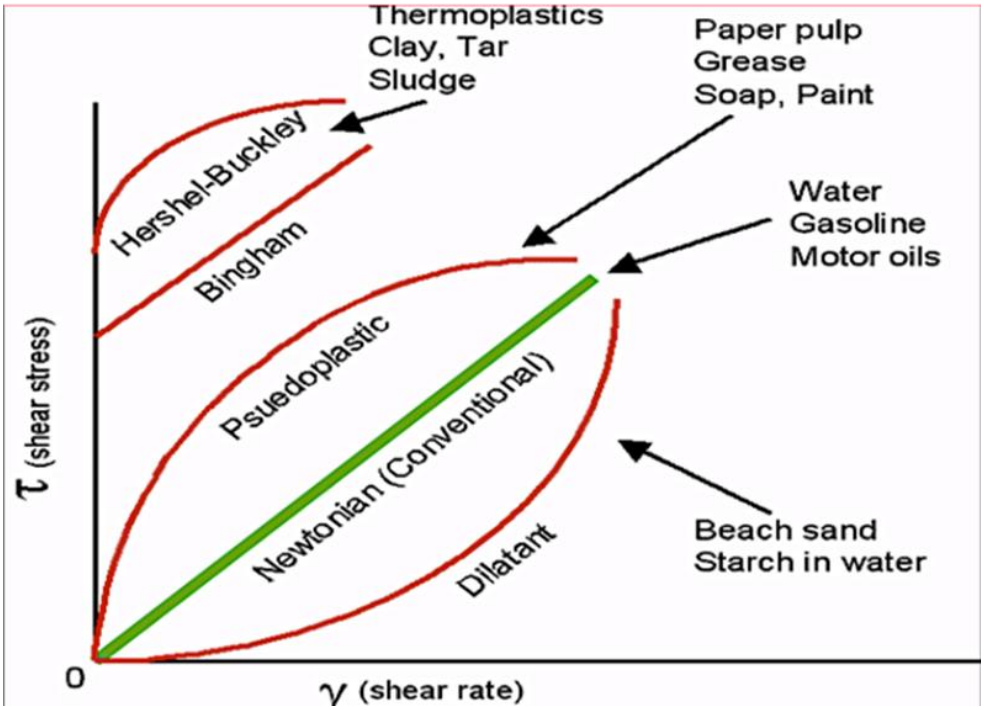


Fig.8. Types of time -independent flow behavior

- ***Shear-thinning or pseudoplastic,*** $\tau_y = 0$ and n<1 When $\frac{du}{dy}$ increases, viscosity decreases. Pseudoplasticity is observed as the most prevalent type of non-Newtonian fluid behavior, distinguished by an apparent viscosity reducing as the shear rate increased. The thinner shear becomes a particular case of thixotropic behavior, because a microstructure recovery in its initial condition often needs a non-zero time where viscosity recovery is very fast after disruption. Example for this kind of fluid is polymer solution as well as solution of large molecular weight substances. There is no yield point for pseudoplasty fluids, and their consistency curves pass through the origin.

- ***Dilatant flow*** these are also called shear thickening systems, because with the increased shearing stress, the system become more viscous or thick or the system show increase in resistance between layers of fluid. $\tau_y = 0$ and n>1 When $\frac{du}{dy}$ shear rate increases, viscosity increases. These kinds of system usually increase their volume when gets sheared, hence called dilatant. Continuous shear thickening of concentrated hard particle suspensions can occur, which is linked to an amount of unusual solid characteristics, such as striking. For example, a person to walk on a fluid surface leads to an important question of how the application of small particles to fluid qualitatively interferes with new properties as a result of a large number of particle interactions. Special shear thicknesses are described by a strong increase in shear resistance with a rising shear rate. Continuous thickening could be interpreted as a reply to dilatation. Because if a thick granular substance is sheared, it expands or dilates so that the particles run around each other. System deformation allows the powers of surface tension to repress the particles. These forces are transmitted from particle to particle through bulk through friction contacts. Such forces are responsible for the large increase in shear resistance which is it classify with discontinuous shear thickening. The explanation of this kind of flow is at the resting condition, the particles are closely packed with lesser void space between them. In shearing condition, the space between

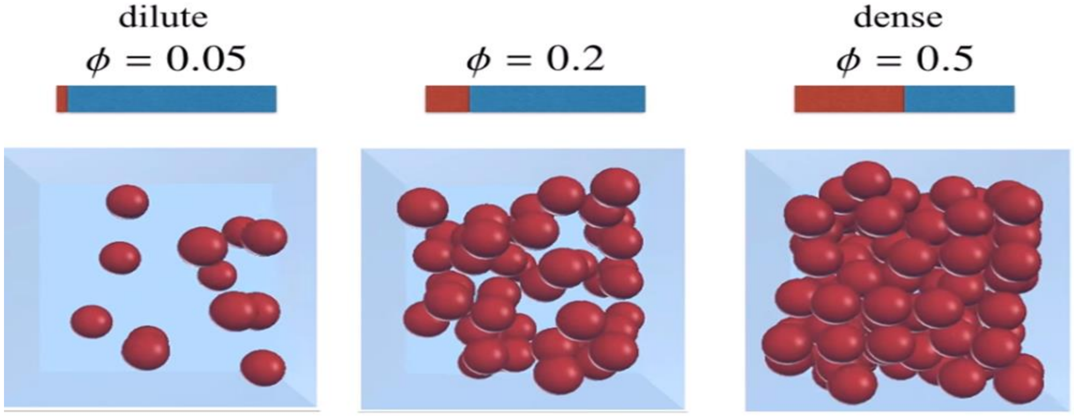


Fig. 9. Solid volume fractions

particles get increased and the system gets expands or dilates. When the space between particles gets increased, the vehicle or the medium, become unable to fill that gap or space. Due to this particle not getting wet properly by vehicle of medium, generates more friction between particles. This situation viscosity is increasing, and system become thick. Example of this system is corn starch suspension in water.

- ***Viscoplastic or Bingham plastics*** the interesting thing about Bingham plastic is that this behavior is neither solid nor fluid. Example of this fluid is toothpaste or mayonnaise. From figure (8) Bingham plastic has no shear stress unto a certain yield stress is rich and as soon as this shearing stress is greater than yield stress. Bingham plastic acts as fluid and it starts having a rate of shearing. This model requires two parameters the yield stress and the slope of the line known as the plastic viscosity.

2.4.5. Time-dependent fluid behavior:

The apparent viscosity in practice depend on the shear rate but also time when the fluid is sharing. Further, time-dependent fluid behavior, thixotropy or rheopexy can be divided into two categories: [14,15].

1. **Thixotropy** is isothermal and slow recovery of material which is

removed from the applied shear stress.

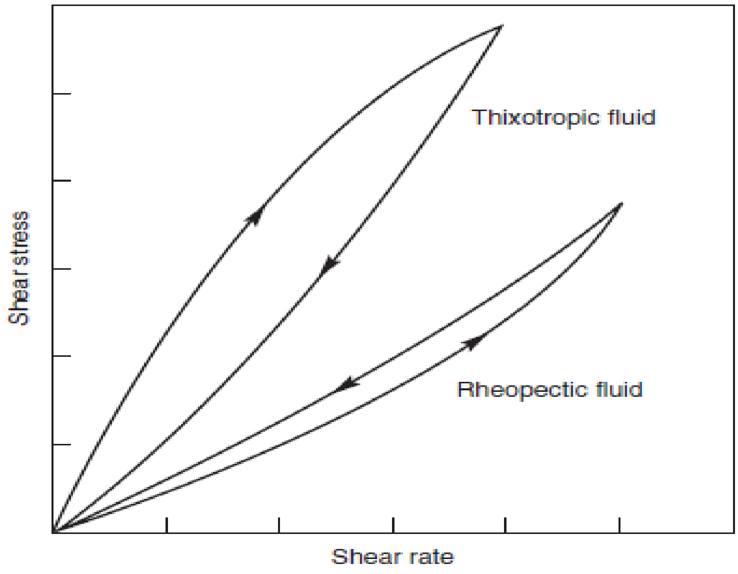


Fig.10. Time dependent fluids.

Shear stress on the x- axis and y-axis is rate of shear for a pseudo plastic material or shear thinning material. When apply shear stress the rate of shear slowly increases. This increase in rate of shear is due to the decrease in viscosity when remove the shear stress the shear thinning systems comes back to its initial position very slowly. Figure (6) illustrate shear thinning systems. The upward curve and the downward curve. Upward curve during application of shear stress and downward curve during removal of shear stress. The downward curve is always shifted to left side of the up curve. This is due to decrease in recovery speed and this decrease in recover is due to increase in viscosity. This phenomenon of slow recovery is thixotropic. For example. if takes a gel with high viscosity and apply shear stress its viscosity decreases and forms like a solution or a little less viscous. When remove the shear stress the solution will go back to its a gel. In case of anti-thixotropy increase the shear stress rate of shear slowly increases like thinning systems or pseudo plastic systems. Anti-thixotropy the shifting is towards right side and recovery is very slow. It observes that is in case of thixotropic the shifting is towards lefts side and recovery is slow but anti- thixotropic the shifting is towards right side and recovery is very slow. If continuously apply the shearing stress and anti-thixotropic systems, there is always certain amount of permanent loss in its shape. Applying this force, a certain point the material become from gel state to solid state.

2. **Rheopectic fluid** is conversion of is same as that of thixotropic

behavior but in thixotropic gel becomes a solid whereas rheopexy a solid becomes gel. Stiff solid material upon application of shear stress it becomes gel. When remove stress again from gel state it will go to solid state. Saturation point for Rheopectic material is gel [16].

2.4.6. Rheometer:

It's the rheological experimental part. This describes how to calculate the deformation under applied stress and vice versa, for the formulation of a constitutive working equation. Work on viscosity, normal stresses, relaxation times and elongational viscosity has provided several commercially available rheometers. The cone and plate, the concentric cylinder, the capillary and parallel plate rheometers are some broadly utilized rheological tools [17].

- *Concentric cylinder:* The sample is positioned between two concentrated cylinders. The inner cylinders are operated by a constant torque (angular force), with the strain (angular deflection) or strain rate (speed at which the inner cylinders rotate). The fluid's viscosity between plates determines the inner cylinder's rotational speed: The more spins at a particular time the greater the viscosity of the studied material. The torque can be adjusted to calculate the (apparently) elastic modulus or viscosity according to shear stress. This device could be used for viscosity calculation of non-Newtonian fluids, semisolid viscoelastic and solids elasticity.

- *Parallel plate*: The sample is mounted in this instrument on two

panels: the base is stationary and the top side rotates On the upper plate is applied a constant torque that calculates angular deflection or strain rate depending on whether a mainly solid or liquid sample is examined .With this sort of experimental method, the primary problem is that the shear strain is variable throughout the sample. In the center of the sample the shear strain is lower than on the edges. Parallel plate configurations are therefore only appropriate for samples when the rheological characteristics are independent from shear rate therefore, they are not appropriate for non-Newtonian fluids or solids.

- *Cone and plate:* The concept of the parallel plate method is

exactly the same, just that a cone substitutes the top plate. The cone has a slight angle particularly designed to ensure a constant strain across the sample. This makes the study of non-Newtonian materials

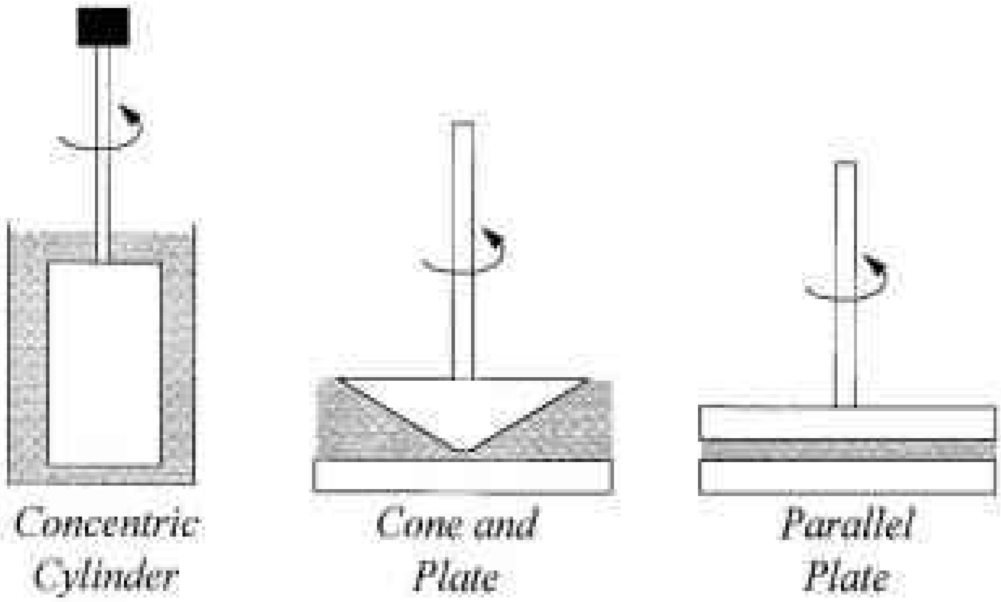


Fig.11. Different types of rheometers [17]

Any of these tests can be used by calculating variance in shear stress with shear rate to carry out basic viscosity measurements of liquid. Some of them can however also be used for costlier applications, including the transient rheological and dynamic rheological purpose [54].

2.4.7. Rheology Applications:

The application of rheology in many areas is significant. For example, in the engineering field, geophysics and physiology it is applied. Hemorheology, the blood flow research, has huge medical significance. Throughout geology, solid earth structures with long-term viscous fluids are known as rheids. In the field of engineering, rheology has predominately extended itself to the production and use of polymer materials (plasticity theory is also significant in the design of processes of metal-forming, but often not part of rheology in the engineering community). Rheology regulators are also a key element for paint development in order for paints to be levelled but not sag on vertical surfaces.

Rheological tests are important for the study of the properties of the material analyzed in the field of fluid mechanics, so that fluid scientists have analytical techniques to determine those properties. The majority of rheological tests involve using a force to measure its flow or change in shape. In various fields of fluid science, rheology is significant. The fluid movement through pipes or the ease with which it is stored is generally identified by their rheology [18,19].

2.4.8. Rheological Models:

Several equations define various rheological models; they are briefly described as follows.

- *Power law Equation:*

$$\tau = K\gamma^{n-1} \quad Eq.6$$

In equation (6) K is flow consistency index, and n is the power law index
According to the flow behavior index, n:

When $0<n<1$, the pseudoplastic or shear-thinning is shown in this solution. In this case, a smaller value of n is more shear-thinning.

When n=1: the fluid illustrates Newtonian behavior

When 1<n: fluid exhibits a behavior of dilatant and shear thickening with a greater value of n, resulting in more thickening. Power law model approximating non-Newtonian fluid behavior. The k and n values therefore depend on the shear rate range. However, power law is the most widely used model for applications in process engineering.

- *Bigham Model*

A rheological two-parameter model commonly utilize in the drilling sector to characterize flow features of several kinds of muds. Mathematically it can be defined in equation (7)

$$\tau = \tau_B + \eta_p \gamma \quad Eq.7$$

Bingham plastic fluid illustrate a linear shear stress. Viscosity in plastic is a slope and the threshold stress are the yielding point. The yield point needs to be as high as possible in order to clean the hole. A judicious choice of mud treatment is adjusted for the yield point. The Bingham plastic fluid model was specifically designed for the direct-indication rotation Rheometer. The plastic behavior with a linear equation can be described, where η_p is the plastic viscosity and τ_B is the yield stress and is a key factor in restarting transportation [20].

- *Casson Model:*

Furthermore, the Casson equation(8)is commonly used to describe the non-Newtonian behavior of activated sludge (Casson, 1956):

$$(\tau)^{0.5} = (\tau_0)^{0.5} + K(\gamma)^{0.5} \qquad Eq.\ 8$$

2.4.9. Definition of pour point or solidification temperature:

Crude oils with huge amounts of waxes can be built into crystalline networks, creating problems in flows in production storage and uploading lines in conditions where the temperature rapidly decreases. Eventually, the amount of n-alkane-low concentrations of aromatic compounds in oil will improve the pour point

Pour points are the minimum level at which flow of oil are still possible. crude oil cannot flow in a certain manner under Pour Point. This refers to a measure of oil content and an approximation of the quantity of paraffin waxes at lower temperatures.

Whether the oil does not contain paraffin waxes, the amount of pour point depends on the viscosity of crude oil. Although the temperature of solidification is the temperature where oil is started to be solid, these components present a significant threat not just to the pipeline's activity as well as to the well itself. At low temperature, because of the precipitant, disorderly molecules the flow curve of shear rate is very steep. It indicates that the shear stress would not be enough to disturb such solid particles and that they increase their resistance to flow with their increasing size, which leads to a high-pressure drop. If the energy of the flow pressures is not sufficient to overcome this friction, the pipeline stops carrying the fluid as well as the liquid will stuck, which can lead to an increase in a solid plug inside the pipe. Then an expensive and complex work-over has to be carried out to repair the tube. In addition, the well should be shut down to prevent the production, and heavy crude oil could also solidify in the tube without appropriate treatment. For this reason, it should prevent cooling of oil and temperature must be kept above the pour point. The solidification temperature of crude oil changing between 3-5°C and in this thesis research it took 4°C.

2.5. Flow profiles:

Flow profiles primarily have two flow behaviors: first laminar and second one turbulent flow. Flow in a laminar system typically involves high viscosity fluids. Moreover, it is important to clarify turbulence as these turbulent patterns of flows are quite different than the laminar flow. These two models will be compared soon in this chapter, as the flow system affects the heat exchange, the velocity allocation as well as the liquid mixture.

2.5.1. Laminar flow:

The movement of laminar is that in which there is no eddies, current and swirls and flow should be a parallel layer. The viscous forces overpower then the inertial forces in a simple way in the laminar flow and the model of laminar flow is Reynolds below the 2300 number.

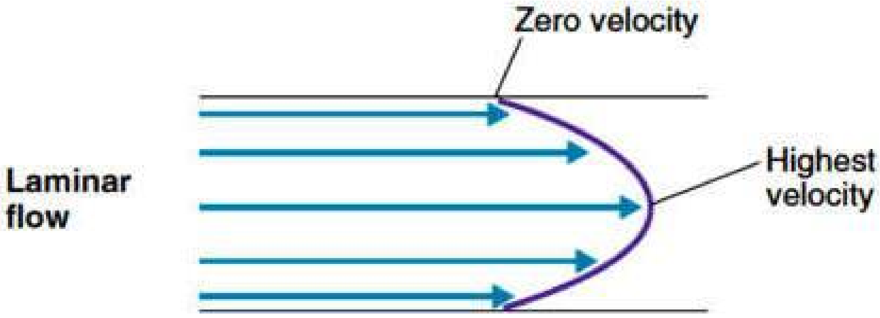


Fig. 12. Laminar flow pattern

2.5.2. Turbulent Flow:

Turbulent flow takes place in higher speed, light fluids, causing irregular flow patterns and swirls and the turbulent flow is characterized by the number Reynolds greater than 2300.

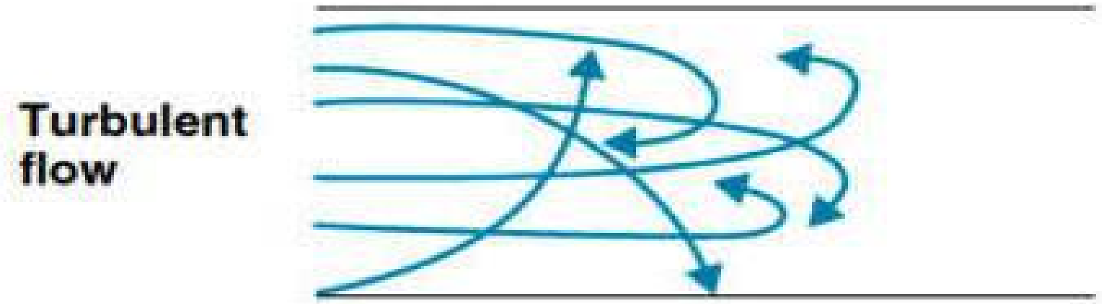


Fig. 13. Turbulent flow pattern

In this speed of turbulent flow, Reynolds broke down velocity of stream into two different components, constant and varying component:

$$u = \bar{u} + u'$$

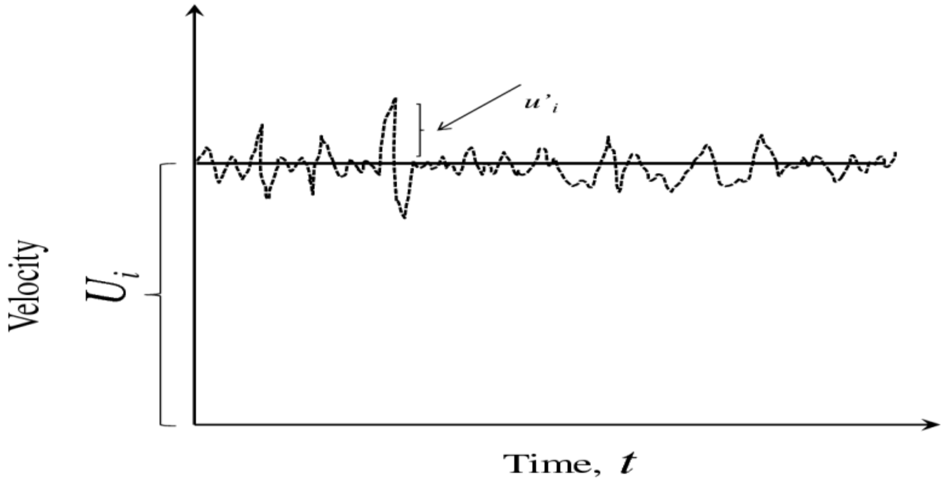


Fig. 14. Turbulent Flow velocity

2.5.3 Reynolds Number:

Reynold numbers play a major part in the estimation of the pattern of the behavior of a liquid. Throughout all viscous streams, this is one of the most relevant parameters where a numerical model is chosen by pre-calculated Reynolds numbers.

Even though the Reynolds number includes both static and kinematic fluid properties, it's defined as a flow property, when dynamic circumstances are examined. The Reynolds number is theoretically the ratio of inertial forces and viscous forces.

Whether the force of inertia resists to a shift of object's velocity and causes the motion of the fluid is prominent, the stream is turbulent. Hence, the viscous forces are predominant, known as the flow resistance, then the stream is laminar.

The dimensionless amount of Reynolds calculates whether liquid flows are laminar or turbulent, referring to many properties, including speed, length, viscosity and also flow kinds. Reynold numbers are given as the following:

$$Re.N = \frac{v*d_i}{\nu} \quad \text{or} \quad Re.N = \frac{\rho*v*d_i}{\mu} \quad ; \; Eq.9$$

Equation μ is the fluid's dynamic viscosity and ν is the kinematic viscosity which is equal to $\nu = \frac{\mu}{\rho}$. In the case of circular tubes, the shift from laminar into turbulent flow range around 2,300 to 4,000 Reynolds ' numbers, despite fluid nature and pipe dimensions or average speeds. Result of the chapter about Reynolds number, laminar flow below 2,300 and turbulent above 4,000.

CHAPTER III

3. Experimentations

3.1. Heavy crude oil viscosity identification at lower temperature:

Oil viscosity depends on numerous parameters, such as pressures, temperatures and chemical force. Nevertheless, it concentrated only on temperature-dependent viscosity variations [25].

Temperature [°C]	Density $[kg/m^3]$	Kinematic viscosity $[\frac{10^{-6}m^2}{s}]$
25	990.75	9774.41
35	986.5	8545.36
45	982.25	7590.74
55	978	6914.1
65	973.75	6223.34
75	969.5	5631.10

Table .1. Results for Crude Oil density and viscosity at different temperature range.

In the case of reservoir situations, this change must be understood attributable to increased pressure levels. On the other side, when the pressure is measured on the pipeline, it typically does not reach 20 bar.

According to the Table.1 the viscosity of crude oil is very vulnerable to temperature rise and the range between 25-75 ° C. The temperature for fluid in this work is almost 0 ° C in a worst-case. Figure 15. It is clearly seen that density versus temperature have linear relationship [23].

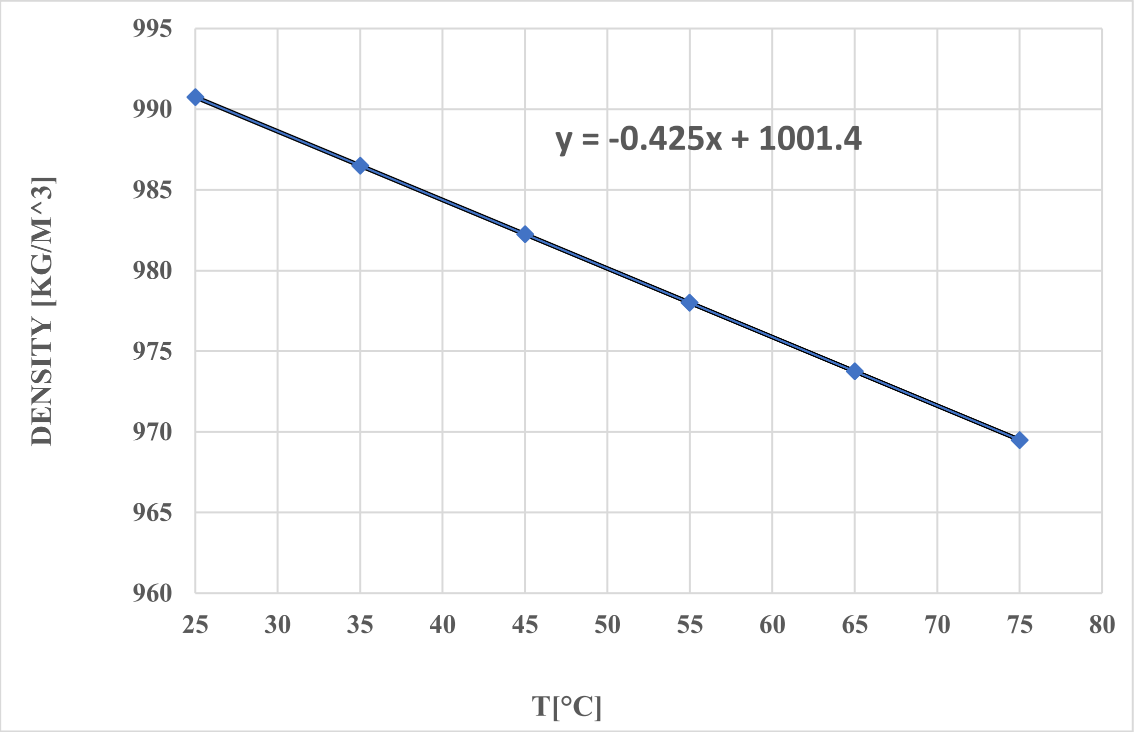


Fig. 15. Density vs temperature of examined crude oil

Oil density is highly dependent on pipeline temperature and varies with temperature variations drastically.

$$SG_{25^\circ C} = \frac{\rho_{20^\circ C}}{\rho_{water}} = \frac{990.75}{1000} = 0.990751; \ Eq.10$$

Extrapolating outside the range, which can lead to a major mistake, should take into account the temperature levels below minimum measurement points 25 ° C. Three different temperature viscosity model are studied in order to find viscosity of oil at lower temperature.

1. First and simplest one is the *exponential model.* This equation reported by Amin and Maddox at 1980 years.

$$\nu = a * e^{b(T+273)}\ ; \quad Eq.11$$

ν is kinematic viscosity, temperatures are in Celsius and a and b are constants at equation11. It is clearly seen from figure.16 that constant a is equal to 12598 and constant b is equal to -0.011numbers.

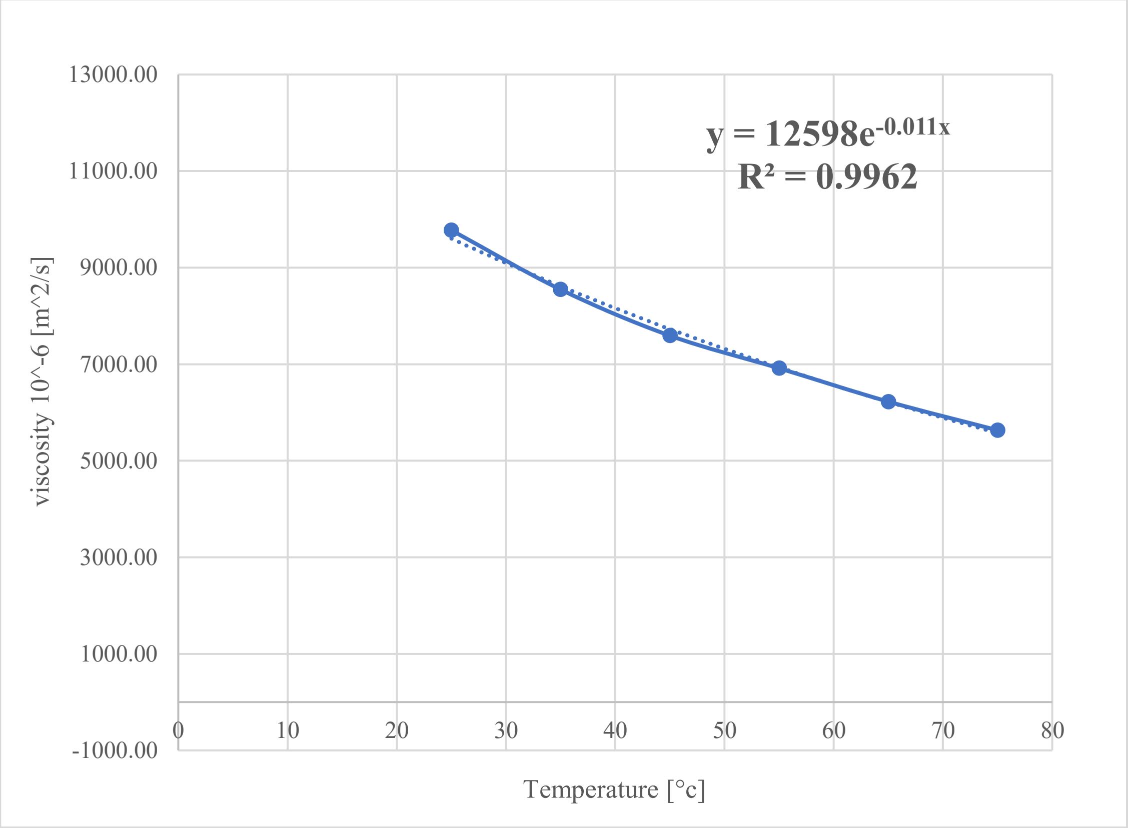


Fig.16. Exponential model graphical representation

Crude oil kinematic viscosity at 4 °C which is solidification point is 12055.7 $*10^{-6}\,\frac{m^2}{s}$

2. *Walther -Ubbelohde* which provides the following relation between kinematic viscosity and temperature.

$$log^{Log(10^6 * \nu + C_1)} = C_2 + C_3 * log^{(T+273)} \;\; ; \; Eq.\ 12$$

Practically C_1 is equal to 0.8 and after making simplification of equation (12) it can get equation (13).

$$\nu = \frac{10^{10^{C2+C3*\log(T+273)}} - 0.8}{10^6} \quad ; \quad Eq.\ 13$$

With the help of graphical solution can find $\mathrm{C_2}$and $\mathrm{C_3}$ constants and based on equation (12) tow time of logarithm of viscosity is a linear function of log(T+273).

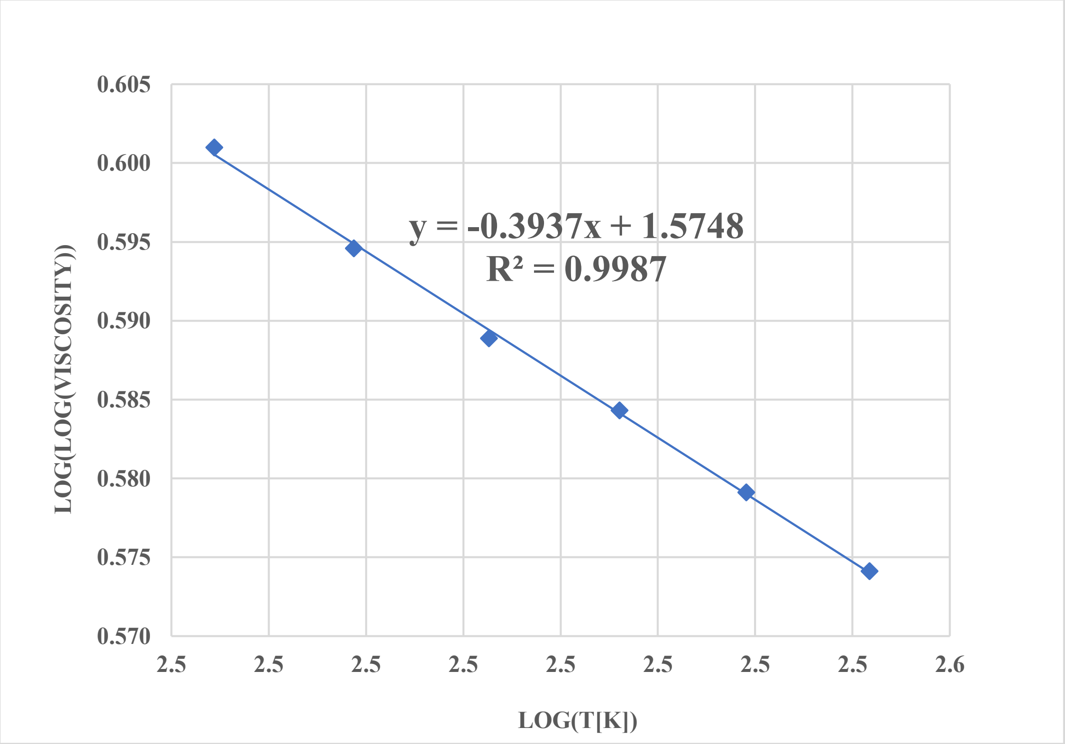


Fig. 17. Walther-Ubbelohde model graphical representation.

Kinematic Viscosity value at pour point with the help of Walther -Ubbelohde model is $12636.5 * 10^{-6}\,\frac{m^2}{s}$

3. Third model name is *Clarck* model.

In this model it can predict viscosity of crude oil at solidification temperature like previous two model.

$$Ln\mu(T) = C_1 + \frac{C_2}{(T+273)^2} + C_3\rho^2 * ln\rho \; ; \quad Eq.14$$

In order to make calculation and graphical model, should know $C_{1,}C_2, C_3$ constants. Due two Table (1) have six equation and 3 unknowns. If use first three equation, it will get three unknown which is not true approach because must do it regression for all possible cases. If it uses six equation, will get 20 different value of constants

$\frac{6!}{3!(6-3)!} = 20$ and best approach to use regression which is right value will give less value of error. After calculation with Clarck model pour point or solidification point of crude oil kinematic viscosity is $13706.3 * 10^{-6}\frac{m^2}{s}$.

As we can see for three model, crude oil viscosity is not the same at solidification point. We can see also from Figure (17) all the three line coincides temperature range 25 - 75 °C but our main research is below 25 °C which is viscosity of crude oil changed significantly.

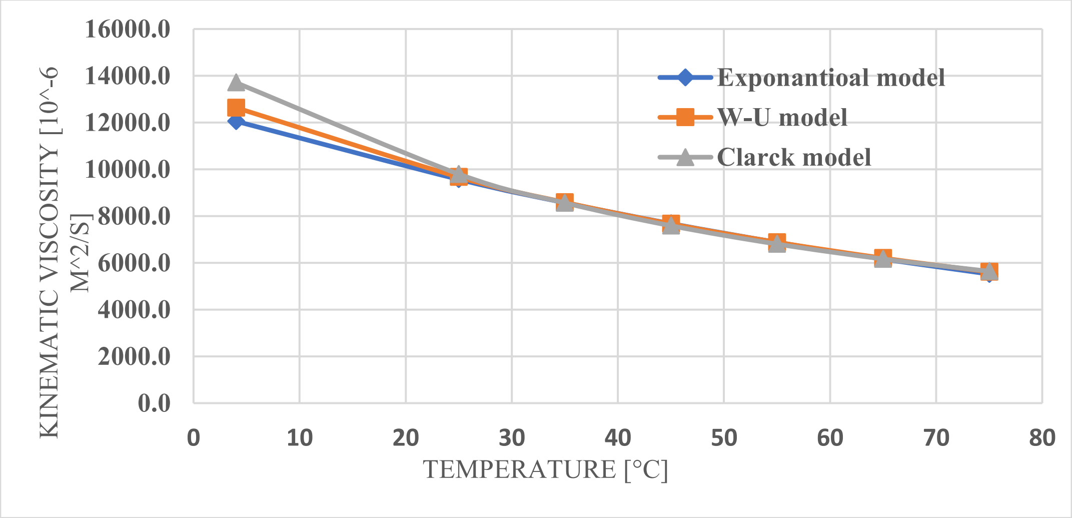


Fig. 18. Viscosity vs temperature models for heavy crude oil

Three model illustrate in graph, and it should choose best model to make approximation when temperature below 25 °C. Due to this reason it takes light crude oil fraction, water and olive oil viscosity versus at lower temperature to make compression or to choose right model.

3.1.1. Study of light crude oil viscosity model:

At five different fraction range light crude oil viscosity versus temperature analysis in order to predict best viscosity model.[24]

- **Fraction boiling range: 100-125 °C.**

Compression with real and predicted value of light crude oil at boiling range 100-125◦C, W-U model cumulative error is 301.49, Clarck model is 132.93 and exponential model cumulative error is 1423.85. Cumulative error is real value minus predicted value square sum for all different temperature. Due to the error value best model is clarck model for prediction of viscosity and worst case is exponential model. Figure (19) it is representing three model viscosity versus temperature and it is clearly seen all the line is not coincide at lower temperature specially.

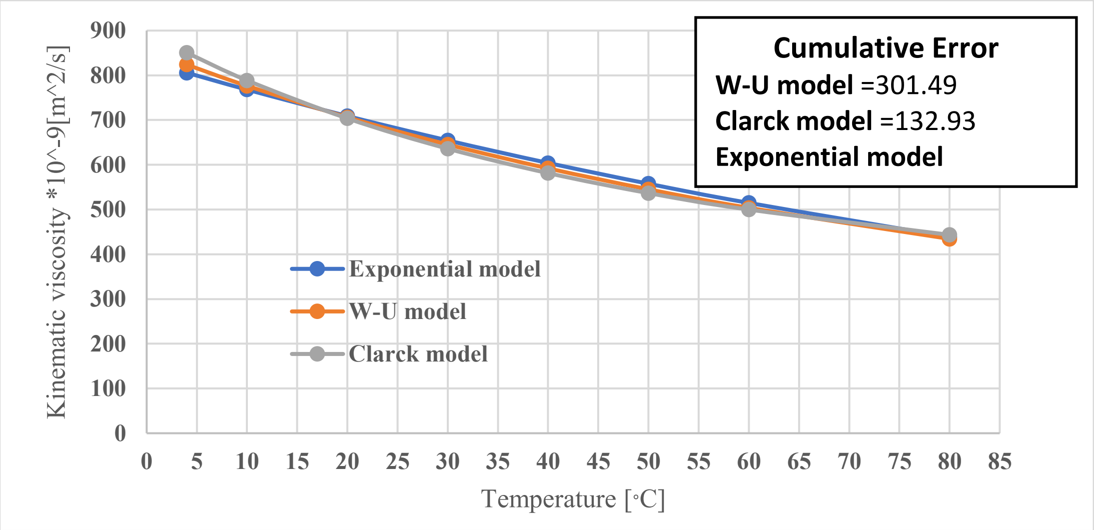


Fig.19. Viscosity versus temperature of light crude oil at fraction boiling range 100-125 ◦C

- **Fraction boiling range: 125-150 °C.**

Fraction boiling range 125-150 ◦C Cumulative error value for W-U model is 1790.1, Clarck model is 61.3 and Exponential is 2151.3. Second example proofed that Clarck model cumulative error is less than other two model and exponential model is not good model at all to predict viscosity due to real and predicted value comparison.

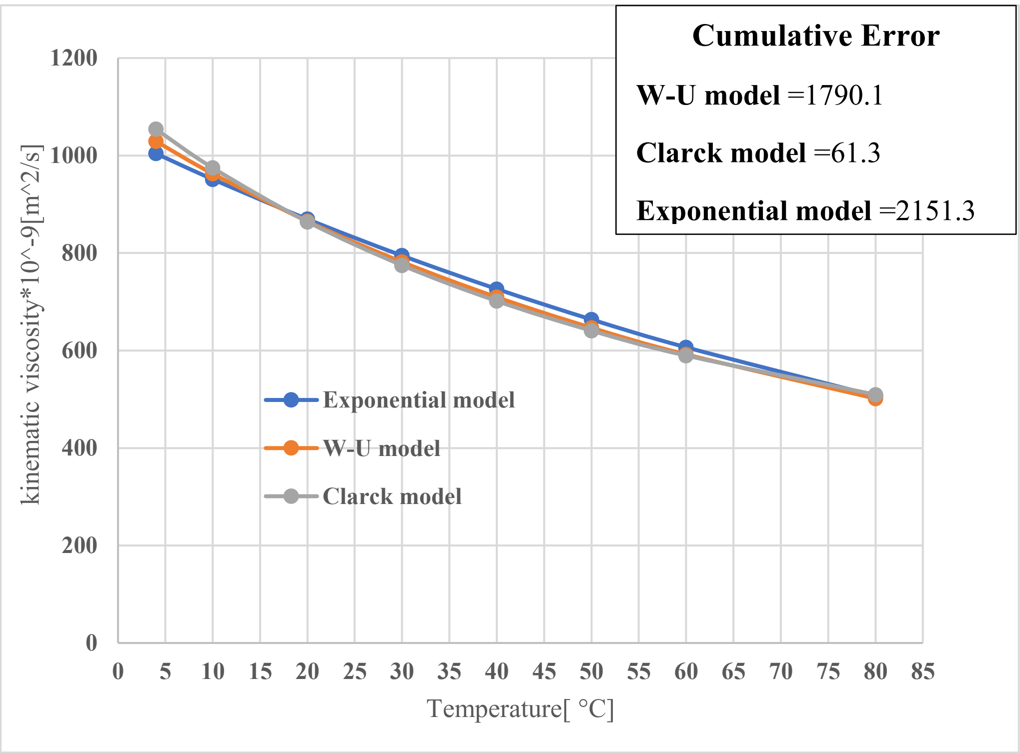


Fig.20. Viscosity versus temperature of light crude oil at fraction boiling range 125-150 °C

- **Fraction boiling range: 150-175 °C.**

Clarck model cumulative error is 256.6, W-U model 1061.51 and exponential model is equal to2428812.08 which is much more difference than other two model. Fraction boiling range 150-175 ◦C Clarck model is best.

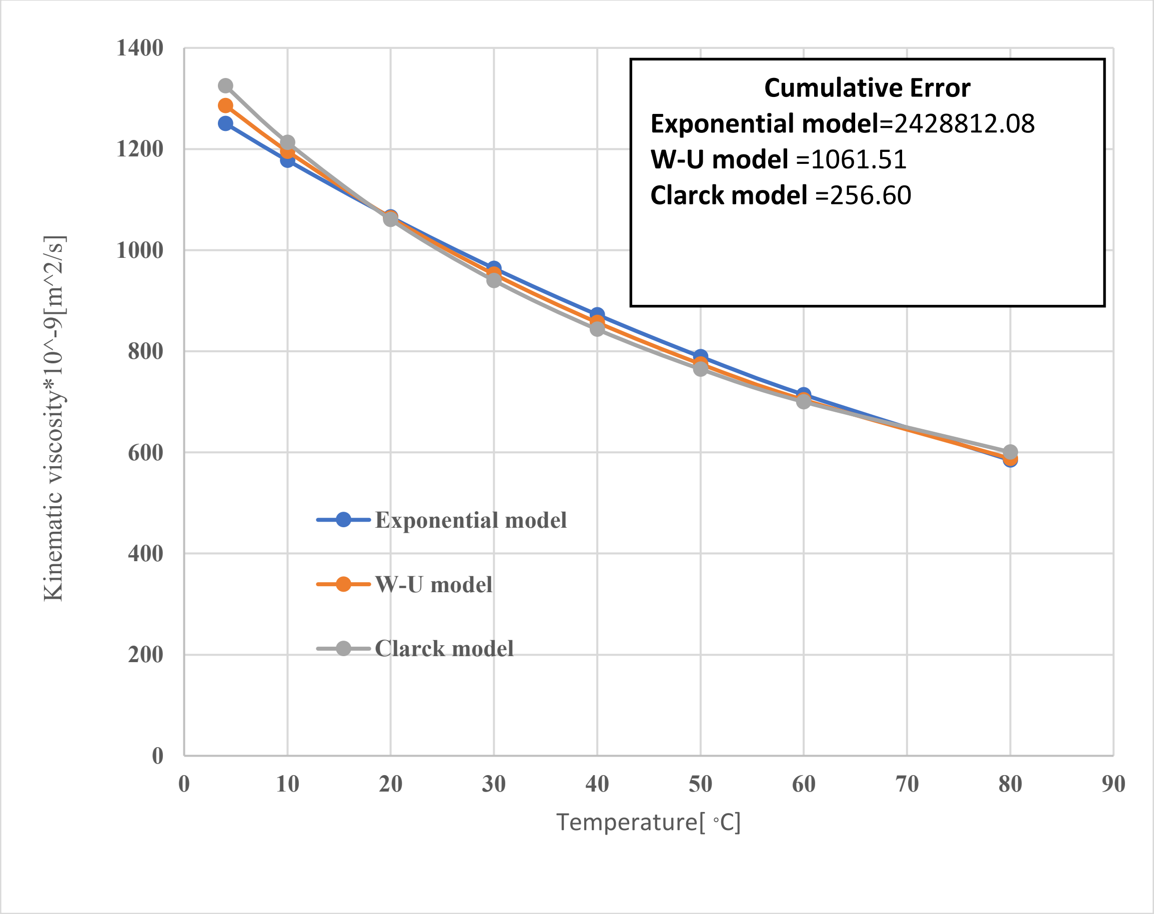
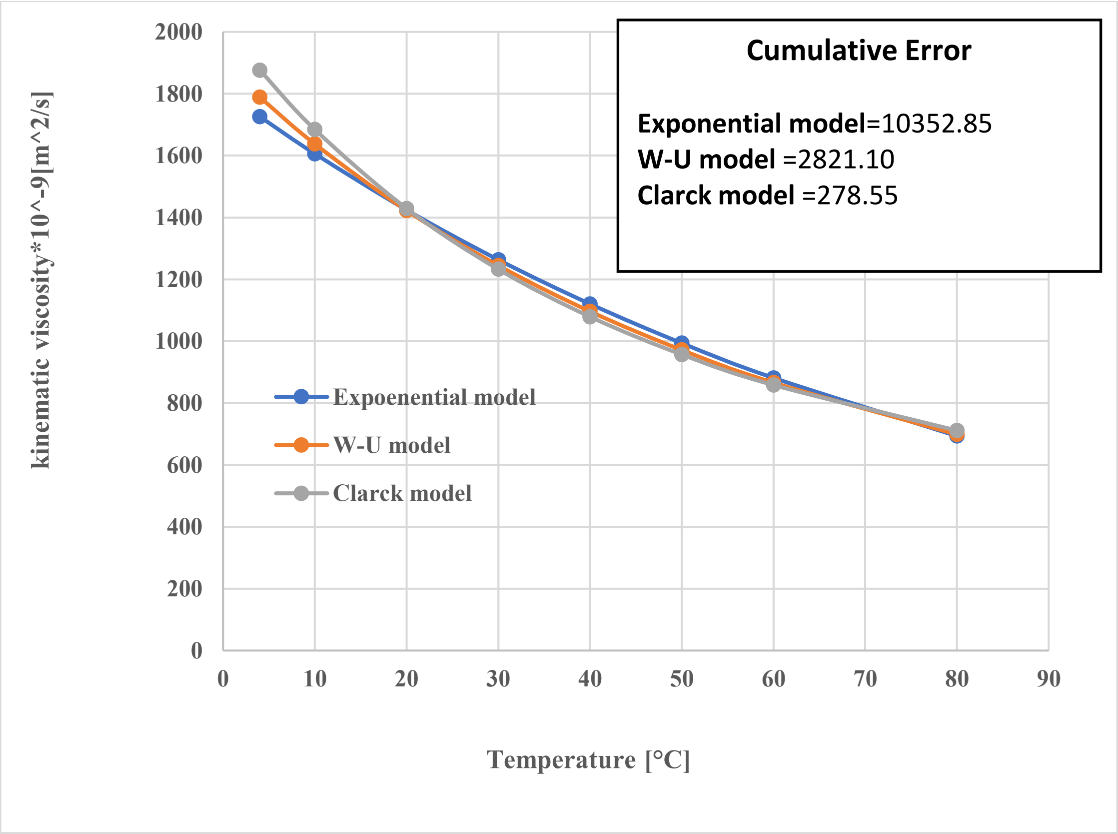


Fig.21. Viscosity versus temperature of light crude oil at fraction boiling range 150-175 °C

- **Fraction boiling range:175-200 °C.**

From the Figure (22) it is clearly seen that until 20 ◦C almost all the line coincides and have less error but compare to error temperature lower than 20 ◦C have significant difference for three model and less error observe at Clarck model again.



Cumulative Error

Exponential model=10352.85
W-U model =2821.10
Clarck model =278.55

Fig.22. Viscosity versus temperature of light crude oil at fraction boiling range 175 -200°C.

- **Fraction boiling range:200-225 °C**

Temperature between 4 ◦C and 20 ◦C three model seen much more difference than rest of 4 Fraction boiling range. Cumulative error for clarck model is significant less than other two models.

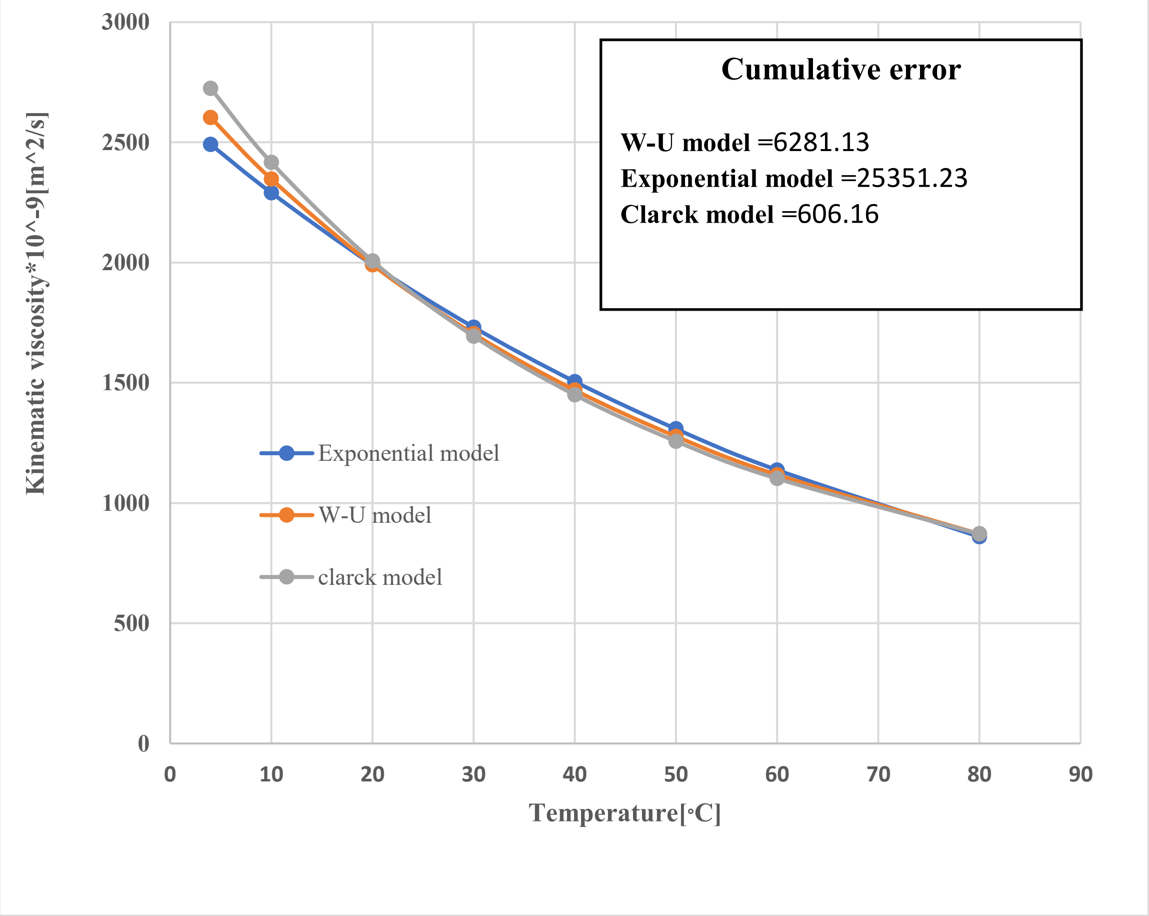


Fig.23. Viscosity versus temperature of light crude oil at fraction boiling range 200-225°C.

3.1.1. Olive oil viscosity model:

Experimental measurement of Olive oil viscosity at temperature range are 7-50 °C. It used the same calculation and the same model name is Exponential, W-U model and Clarck model which is done for light and heavy crude oil viscosity. Pour point or solidification point of Olive oil at range of 39 F or 3.88 °C. Olive oil viscosity is lower and illustrating Newtonian behavior. At lower temperature also it is best data to predict best viscosity model. Due to calculation cumulative error exponential model is which is simple one is much higher and Clarck model is best model.

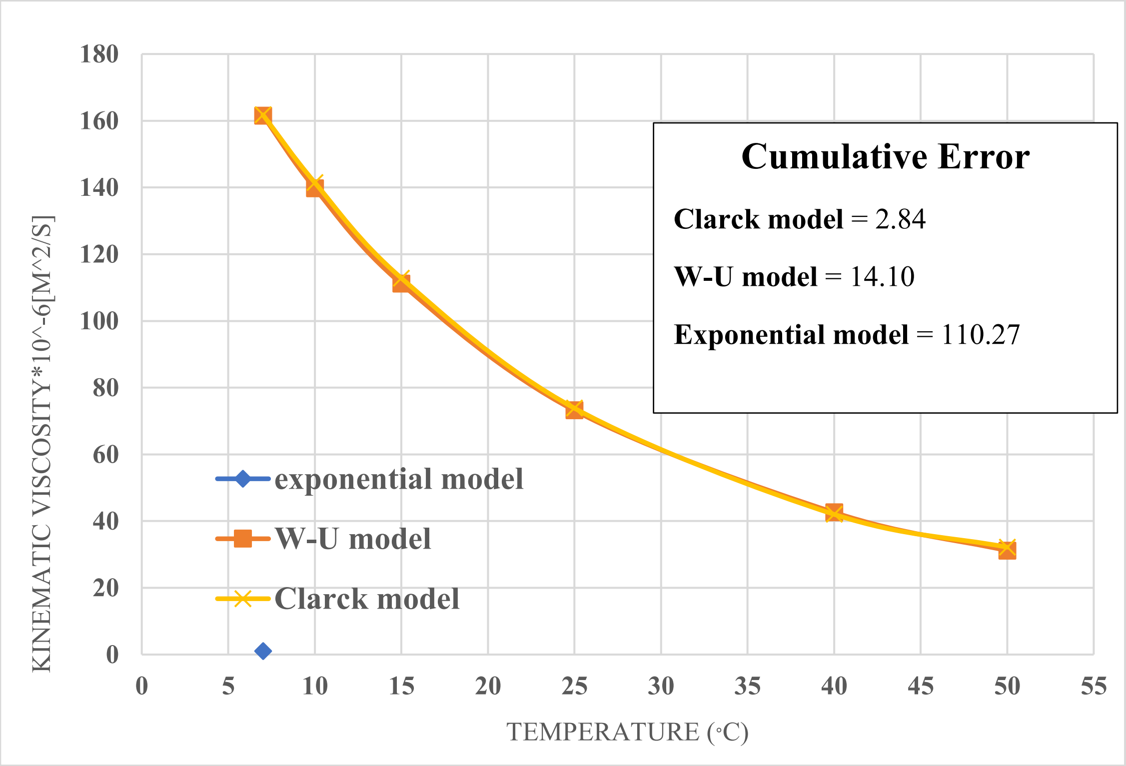


Fig. 24. Viscosity vs temperature models for Olive oil

3.1.2. Water viscosity model:

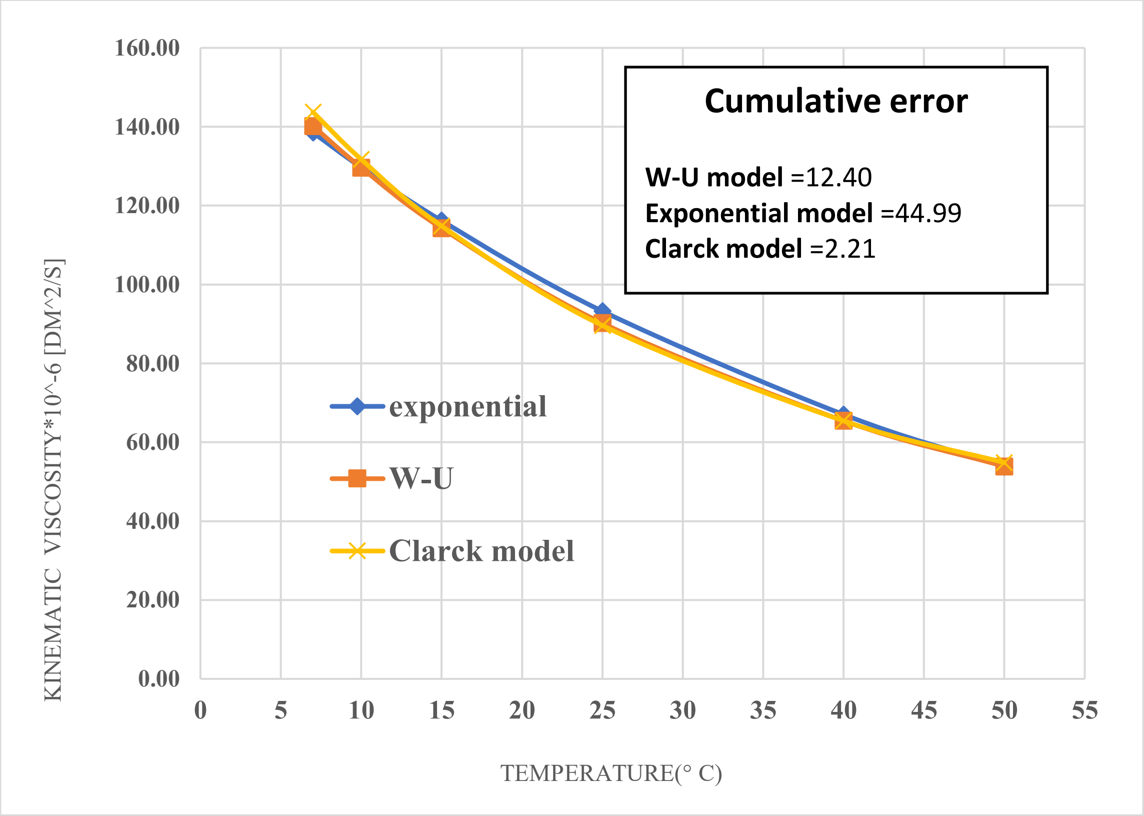


Fig.25. Viscosity vs temperature model for Water

It is clear from five light crude oil fraction at different boiling range, Olive oil and water kinematic viscosity versus temperature graph and Error table, best model is Clarck model [26].

3.2. Experimental set -up:

The Test was made utilizing RheoStress RS100 Haake and this rheometer has a number of running experiment modes [21]. The CS mode uses very low inertia to apply shear stress to a sample group. The controlled shaft of the RS100 has an air bearing centered to guarantee that the applied stress can be transferred to the test fluid almost without friction A digital encoder can identify the corresponding deformation with the test, and processing 10^6 impulses per revolutions. The resolution enables low yield values, strain or shear rates to be measured. It's possible to directly transfer computer-controlled rheometers between CS and CR modes and to provide oscillations stresses input and auto strain. To place the cone on the plate, a regulated variable lift rate is used, and a thermal gap is regulated to balance any heat produced by the sensor. The "Haake Windows" software system manages the testing procedures and data assessment. The cone and plate sensors is fitted for the rheometers and a sensor with a 4° cone angle, a 35 mm cone diameter, and a 0.137 mm gap on the cone tip were used. Figure (26) demonstrates the study set-up.

Fig. 26. RheoStress RS100 Haake

3.3. Rheological Model:

Various rheological models are tested in order to choose the good model for the measurements. The procedure is performed in CR mode at room temperature 25 °C and hence the shear stress and shear rate values are recorded. Such details are collected to create the most fitting model. Among this research Power-law, Bingham, and Casson models have been analyzed and its formulas are utilized to quantify the calculated amounts of shear stress, shear rate as well, discussed earlier throughout section 2. Figure 27 to 29 it is seems that power-low linear regression is higher than Casson and Bingham model. Best model for heavy crude oil rheological model is Power law model. This conclusion agrees with other works.

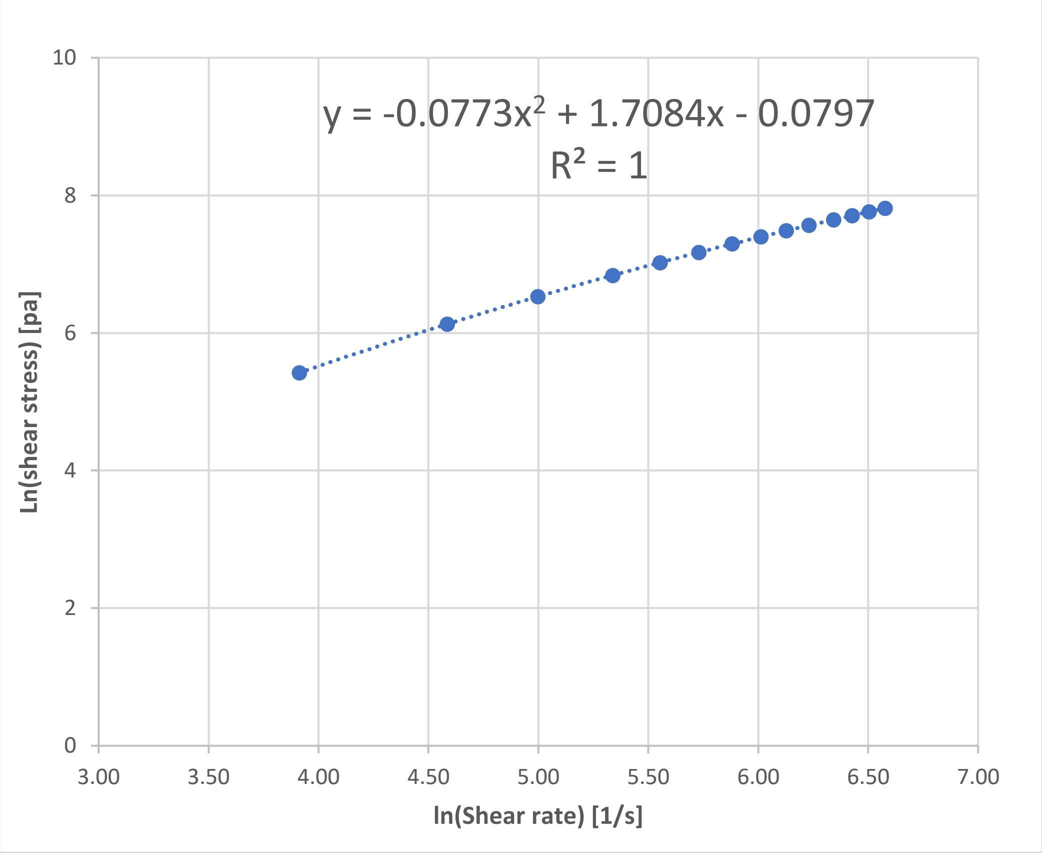


Fig.27. Power law model.

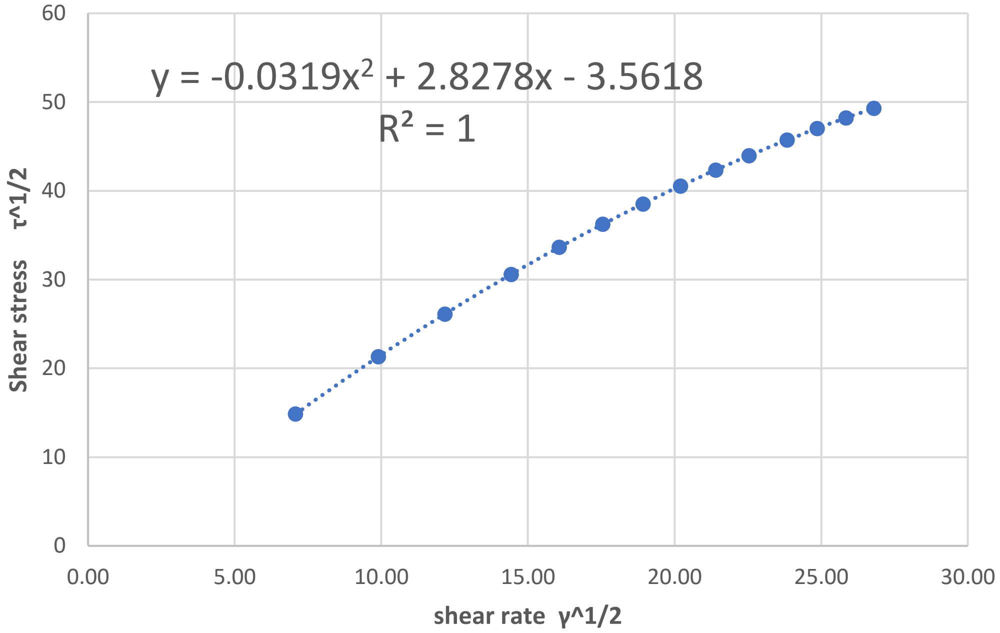


Fig.28. Casson model.

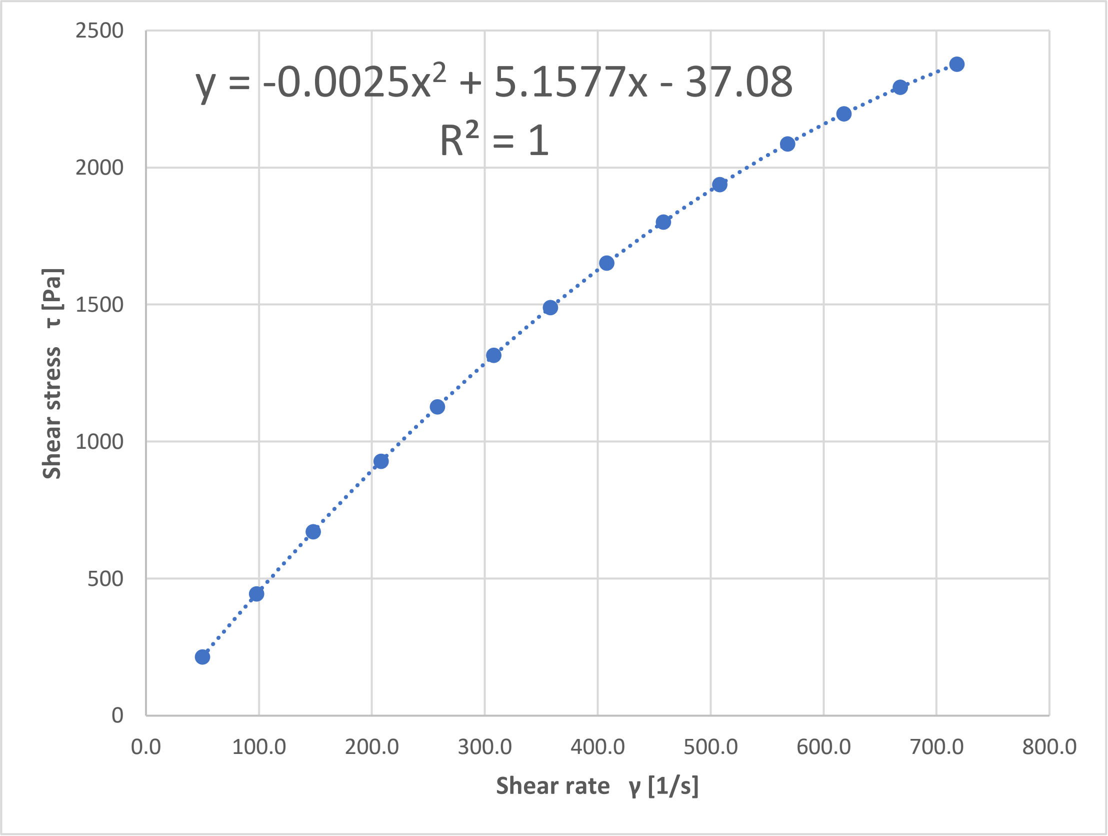


Fig.29. Bingham model

3.4. Temperature effect to viscosity versus shear rate:

The flow curve for viscosity- shear rate relationships are given by this experiment. The temperature's effects on the viscosity of crude oil shear-rate are shown in figure 30, by a rise of 10 degrees from 25 to 75 ° C. The analysis takes place in CR mode. Crude oil indicates a non-Newtonian shear dilution of the range of shear rate between 0.8 and 762 s^{-1}, where the apparent viscosity reduces significantly with temperature, and declines by half from 25 to 75 ° C. Although, heated viscosity variations have been shown to be greater at lower shear levels than at large shear rates. With the rising temperature, heavy crude oil compounds (e.g. asphaltenes, resins, waxes, etc.) break the bonds between solid particles and thus decrease the oil viscosity. Degree of viscosity reduction (DVR) it calculated by equation (15) [2].

$$DVR\% = \frac{\mu_r - \mu_c}{\mu_r} * 100 \qquad Eq.\ 15$$

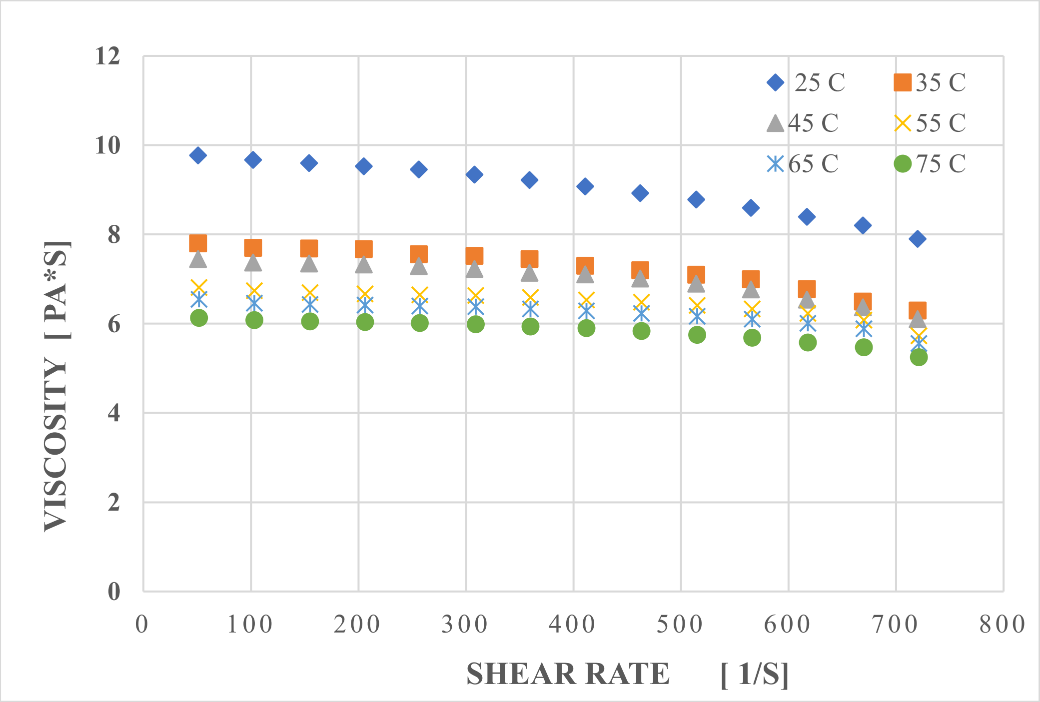


Fig. 30. Heavy crude oil viscosity vs shear rate at different temperatures.

Where μ_r is the reference viscosity and μ_c is the corresponding viscosity at shear rate 51.7 s^{-1}. When the temperature increases from 25 ° C to75 ° C, table 4 records the DVR level from 0 to 37 percent. This could be due to several causes. The first factor is that heavy components of raw oil (i.e., asphaltene and wax) are strongly affected by temperature. The second issue is that the chemical product configurations of heavy component have high temperatures that lead to the destruction and thus reduction of oil viscosity of the orderly structures of heavy components in the crude oil phase [22].

Temperature (°C)	DVR %
25	0
35	20
45	24
55	30
65	33
75	37

Table 2. Heavy crude oil DVR% at different temperature.

Hence, heavy crude oil viscosity also depends on shear rate. At large shear rates the viscosity approaches low numbers. This indicates the flow is less resistant at generally higher shear rate and this circumstance related to chemical chain in crude oil [2,21].

3.5. Yield stress Measurements:

The yield stresses are characterized as limiting stress under which a material acts like a solid. The elastic deformations occur at low stress and goes away if the stresses are released. There are a linear relationships betweens elastic deformations and stresses. But the imposed stress results in a limitless deformation beyond the yield stress level, which lets the material continue to flow. The relationship between shear stress and the shear rate in which heavy crude oil yield tests are carried out. at Figure (31). The heavy crude oil is exposed, within a certain duration of 150 seconds, to a continuous shear stress range around 0,08 to 3,98 Pa [21]. The analysis is performed in CS mode and From figure .31 is derived also the shift in the yield stress with the oil content and the temperature The yield point reduces to begin the flow when the temperature is increases which means that ,at room temperature 25 °C, the yield point for heavy crude oil was 0.6 Pa and dropped to 0.3 Pa when it raised temperature around 25to 65 °C.

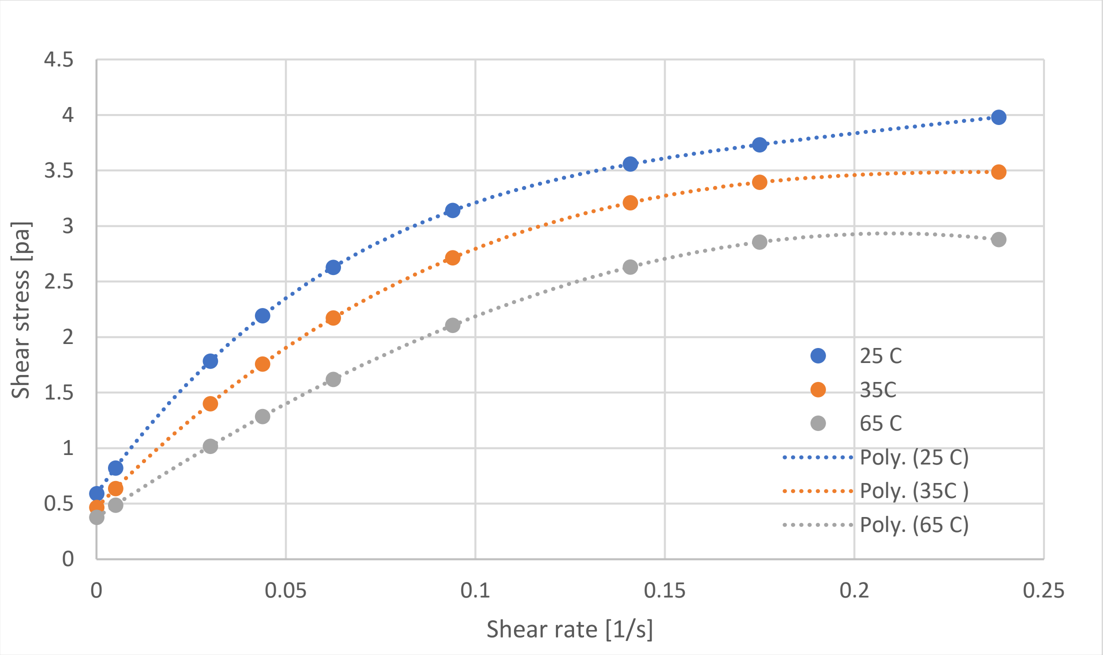


Fig.31. Heavy crude oil yield stress at different temperature.

Heavy crude oil sample	Yield stress $\tau_{0,}$[Pa]
25 °C	0.6
35 °C	0.4
65 °C	0.3

Table 3. Yield stress result at different temperature.

3.6. Thixotropy Measurements:

Throughout this experiment, the heavy crude oil undergoes a shear rate constant in the CR-mode to conduct the loop test. The measurements vary from 2.6 to 630 1/s within 300 seconds for a certain amount of time. The system has been designed to raise the allocated shear rate from a certain initial amount of 2,6 1/s to a final value of 628 1/s slowly and then flow recorded. The corresponding up graph was acquired in order to increase the shear rate slowly. When the full allocated limit has been achieved, the down curve is gradually reduced, Which the time-independent rheological activity should also be similar to the up-curve. Figure (32). illustrates the thixotropic behavior of heavy crude oil by which the concept of hysteresis is evident at 25 ° C. Thixotropy measurement is the area between the curve up and down (hysteresis area).

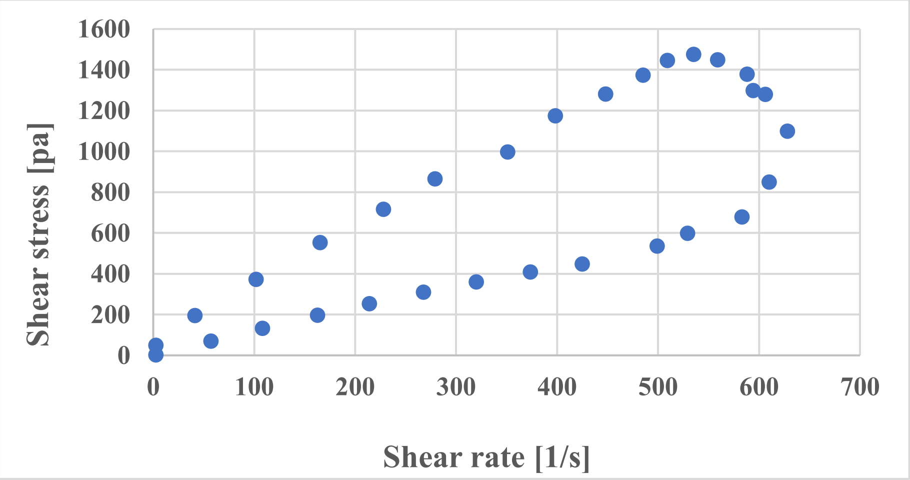


Fig. 32. Heavy crude oil Thixotropic behavior at 25 °C

Figure (33) indicates that if the temperature is increasing, the resultant hysteresis declines. Moreover, the energy needed for the disintegration of thixotropy is thus less at 65 °C than the energy needed at 25 °C.

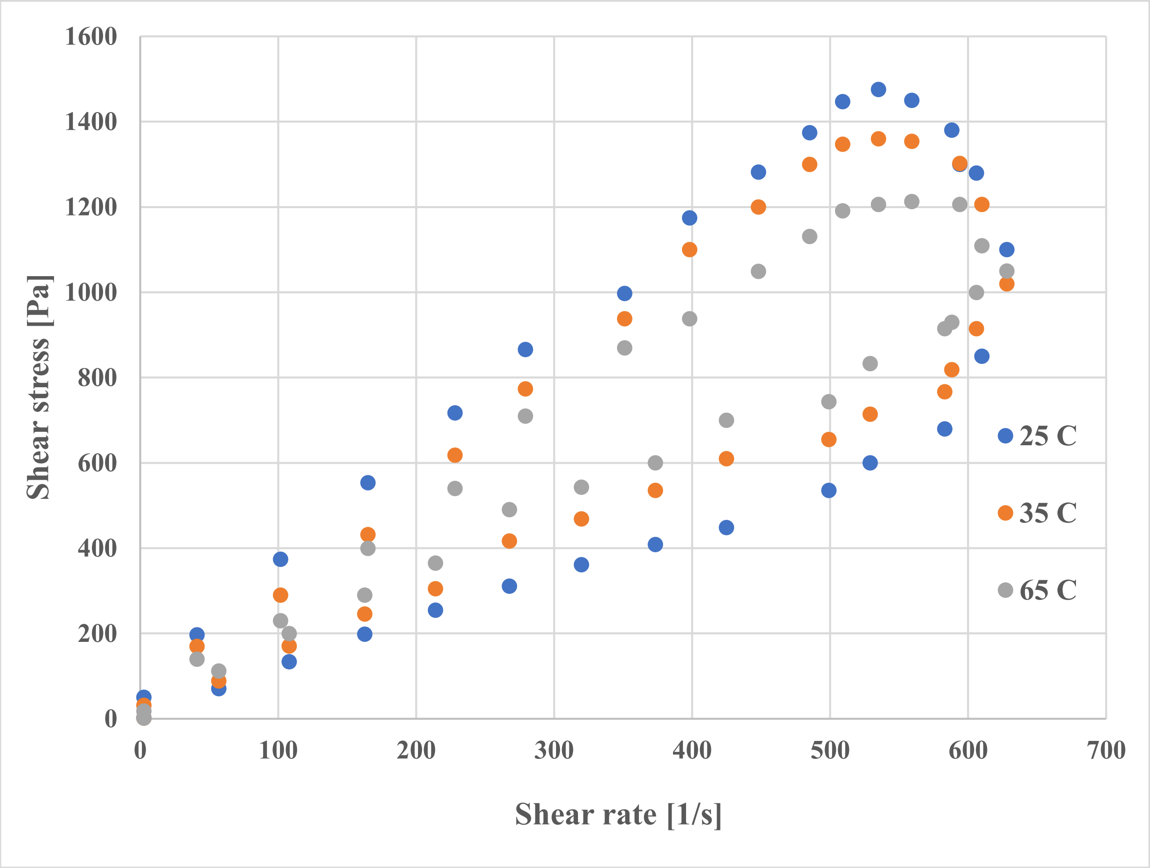


Fig.33. Heavy crude oil Thixotropic behavior at different temperature.

CHAPTER IV

4. Summary and Conclusions.

The major purpose of this thesis is analyzing heavy crude oil viscosity at lower temperature which is below 25 ◦C. The study did base on the theoretical and physical principles governing the flow system combined with experimental data. The kinematic viscosity of heavy crude oil below 25◦C increases significantly and the values predicted can be erroneous. In this study five fractions of crude oil with different boiling point ranges from 100 to 225 °C have been taken also olive oil and water at lower temperature in order to predict best model. Various kinematic viscosity models have been discussed and most suitable model for viscosity analysis at low temperature is “Clarck model”. Table 4 to 8 is illustrating experimental result between real and predicted data for light crude oil and model. Predicted viscosity based on Clarck model and error value is very small all five table. Moreover, very light liquid as an olive oil and water from table 9 and 10 illustrate experimental and predicted viscosity value and it is clearly observing that difference is very small. Due to the “Clarck model” heavy crude oil kinematic viscosity at solidification temperature which is 4◦C is 13706.3*$10^{-6}\,\frac{m^2}{s}$. The kinematic viscosity model has been validated through experimental data as well. All the low viscosity liquid from tables and graph showed us with the help of Clarck model we can predict heavy crude oil viscosity.

The rheological properties of the heavy crude oil were studied. The results showed a shear thinning behavior that follows the power law model over a wide range of shear rates of 0.6 to 740 1/s. It was observed that the viscosity decreased with temperature at different values of shear rates. The viscosity of the heavy crude oil decreased from 10 pa*s to 2.5 pa*s when the temperature increased from 25 ◦C to 348 ◦C. Moreover, the heavy crude oil showed a significant thixotropic behavior with 321.65 KPa.s^{-1} hysteresis area which decreases with temperature.

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Table 4. Fraction boiling range:100-125

No.	Temperature °C	Experimental Viscosity [cst[]	Predicted viscosity [cst]	Error % (Clarck model)
1	10	0.787	0.789	-0.21%
2	20	0.706	0.704	0.33%
3	30	0.643	0.636	1.09%
4	40	0.59	0.581	1.46%
5	50	0.536	0.537	-0.14%
6	60	0.499	0.500	-0.18%
7	80	0.443	0.443	-0.11%

Table 5. Fraction boiling range:125-150°C

No.	Temperature °C	Experimental Viscosity [cst[]	Predicted viscosity [cst]	Error % (Clarck model)
1	10	0.973	0.975	-0.18%
2	20	0.871	0.864	0.78%
3	30	0.778	0.775	0.40%
4	40	0.702	0.702	0.06%
5	50	0.64	0.641	-0.12%
6	60	0.591	0.590	0.22%
7	80	0.509	0.509	-0.09%

Table 6. Fraction boiling range :150-175 ◦C.

No.	Temperature °C	Experimental Viscosity [cst[]	Predicted viscosity [cst]	Error % (Clarck model)
1	10	1.22	1.213	0.57%
2	20	1.06	1.061	-0.05%
3	30	0.954	0.940	1.46%
4	40	0.842	0.843	-0.16%
5	50	0.768	0.765	0.43%
6	60	0.699	0.700	-0.14%
7	80	0.6	0.601	-0.11%

Table 7. Fraction boiling range: 175-200°C

No.	Temperature °C	Experimental Viscosity [cst[]	Predicted viscosity [cst]	Error % (Clarck model)
1	10	1.68	1.685	-0.27%
2	20	1.42	1.429	-0.63%
3	30	1.23	1.233	-0.22%
4	40	1.09	1.079	1.00%
5	50	0.953	0.957	-0.42%
6	60	0.857	0.858	-0.17%
7	80	0.717	0.711	0.81%

Table 8. Fraction boiling range: 200-225 ◦C

No.	Temperature °C	Experimental Viscosity [cst[]	Predicted viscosity [cst]	Error % (Clarck model)
1	10	2.41	2.410	-0.01%
2	20	1.99	1.995	-0.26%
3	30	1.69	1.682	0.46%
4	40	1.45	1.441	0.60%
5	50	1.25	1.252	-0.20%
6	60	1.1	1.102	-0.18%
7	80	0.899	0.881	2.03%

Table 9. Water viscosity calculation

No.	**Temperature °C**	**Experimental Viscosity $*10^{-6}[\frac{dm^2}{s}]$**	**Predicted viscosity $*10^{-6}[\frac{dm^2}{s}]$**	**Error % (Clarck model)**
1	7	142.88	143.704	-0.57%
2	10	131.0	131.729	-0.55%
3	15	114.16	114.826	-0.58%
4	25	89.16	89.592	-0.47%
5	40	65.84	65.425	0.64%
6	50	55.30	54.839	0.85%

Table 10. Olive oil viscosity calculation

No.	**Temperature °C**	**Experimental Viscosity $*10^{-6}[\frac{m^2}{s}]$**	**Predicted Viscosity $*10^{-6}[\frac{m^2}{s}]$**	**Error % (Clarck model)**
1	7	162.19	161.791	0.25%
2	10	142.33	141.459	0.62%
3	15	113.08	112.825	0.23%
4	25	72.63	73.840	-1.67%
5	40	42.077	42.036	0.10%
6	50	32.801	32.184	1.88%

Table 11. Yield measurements of heavy crude oil at different temperatures.

γ, $[s^{-1}]$	**τ (25 °C) [pa]**	**τ (35°C) [pa]**	**τ (65 °C) [pa]**
0.00006459	0.514	0.39	0.29
0.005006	0.945	0.74	0.61
0.03003	1.67	1.37	1.03
0.09398	3.12	2.79	2.15
0.04384	2.24	1.79	1.22
0.06246	2.67	2.09	1.59
0.14088	3.55	3.19	2.69
0.17498	3.74	3.39	2.79
0.23808	3.98	3.49	2.89

Table 12. Viscosity measurement of heavy crude oil at different temperatures

25 ◦C	**25 ◦C**	**35 ◦C**	**35 ◦C**	**45 ◦C**	**45 ◦C**
μ [pa*s]	γ,s^{-1}	μ [pa*s]	γ,s^{-1}	μ [pa*s]	γ,s^{-1}
9.77	50.6	7.8	50.6	7.45	50.6
9.67	101.9	7.7	101.9	7.37	101.9
9.6	153.9	7.69	153.9	7.35	153.9
9.53	204.9	7.67	204.9	7.33	204.9
9.46	255.9	7.56	255.9	7.29	255.9
9.34	307.9	7.52	307.9	7.23	307.9
9.22	358.9	7.45	358.9	7.14	358.9
9.08	410.9	7.3	410.9	7.11	410.9
8.93	461.9	7.2	461.9	7.01	461.9
8.78	513.9	7.1	513.9	6.9	513.9
8.6	564.9	7	564.9	6.77	564.9
8.4	616.9	6.78	616.9	6.54	616.9
8.2	668.9	6.5	668.9	6.37	668.9
7.9	719.9	6.3	719.9	6.1	719.9

55 ◦C	**55 ◦C**	**65◦ C**	**65◦ C**	**75 ◦C**	**75 ◦C**
μ [pa*s]	γ,s^{-1}	μ [pa*s]	γ,s^{-1}	μ [pa*s]	γ,s^{-1}
6.81	51.7	6.55	51.7	6.13	51.7
6.74	103	6.46	103	6.08	103
6.7	155	6.43	155	6.05	155
6.67	206	6.42	206	6.04	206
6.65	257	6.4	257	6.02	257
6.63	309	6.38	309	5.99	309
6.59	360	6.33	360	5.94	360
6.53	412	6.29	412	5.9	412
6.48	463	6.23	463	5.84	463
6.41	515	6.17	515	5.75	515
6.33	566	6.1	566	5.69	566
6.23	618	6.01	618	5.58	618
6.08	670	5.89	670	5.47	670
5.73	721	5.56	721	5.25	721

Table 13. Thixotropic behavior of heavy crude oil at different temperatures.

γ, s^{-1}	**(τ), Pa (25 °C)**	**(τ), Pa (35°C)**	**(τ), Pa (65°C)**
2.6	50.5	31.5	17.5
41	196.5	169.5	139.5
102	373.5	289.5	229.5
165	553.5	431.5	399.5
228	716.9	617.5	539.5
279	865.5	773.5	709.5
351	997	937.5	869.5
398	1174.5	1099.5	937.5
448	1281.5	1199.5	1048.5
485	1373.5	1299.5	1130.5
509	1446.5	1346.5	1190.5
535	1475.5	1359.5	1205.5
559	1449.5	1353.5	1212.5
588	1379.5	818.5	929.5
594	1299.5	1301.5	1205.5
606	1279.5	914.5	999.5
628	1099.5	1019.5	1049.5
610	849.5	1205.5	1108.5
583	679.5	766.5	914.5
529	599.5	713.5	832.5
499	535.5	654.5	743.5
425	448.3	609.5	699.5
373	408.6	535.5	599.5
320	361.3	468.5	542.5
268	310.9	416.5	490.5
214	254.6	304.5	364.5
163	197.8	245.5	289.5
108	133.5	170.5	199.5
57	70.7	88.5	111.5
3	2.166	1.2	1.2

Table 14. Power low model calculation.

Ln(τ)	**ln(γ)**
5.43	3.91
6.13	4.58
6.52	5.00
6.80	5.34
7.00	5.55
7.17	5.73
7.31	5.88
7.44	6.01
7.49	6.13
7.60	6.23
7.65	6.34
7.70	6.43
7.74	6.50
7.78	6.58

Table 15. Bingham model calculation

(τ), Pa	**(γ), s^{-1}**
228.0	50.0
458.0	98.0
678.0	148.0
898.0	208.0
1098.0	258.0
1298.0	308.0
1498.0	358.0
1698.0	408.0
1798.0	458.0
1998.0	508.0
2098.0	568.0
2198.0	618.0
2298.0	668.0
2398.0	718.0

$\tau^{1/2}$	$\gamma^{1/2}$
15.10	7.07
21.40	9.90
26.04	12.17
29.97	14.42
33.14	16.06
36.03	17.55
38.70	18.92
41.21	20.20
42.40	21.40
44.70	22.54
45.80	23.83
46.88	24.86
47.94	25.85
48.97	26.80

Table 16. Casson model calculation