ANALYSIS OF VISCOSITY OF LIGHT OIL AND ITS EMULSION FROM AN OILFIELD IN THAILAND

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การวิเคราะห์ความหนืดของน้ำมันเบาและอิมัลชันจากแหล่งน้ำมันในประเทศไทย

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อิมัลชันที่เกิดจากน้ำมันและน้ำจากหลุมผลิตจะพบเจอได้เป็นปกติในการผลิตน้ำมัน อิมัลชันเกิดได้ในหลายช่วงเวลาทั้งกระบวนการทางภาคสนาม และกระบวนการในภาคอุตสาหกรรม เช่น กระบวนการขุดเจาะ กระบวนการผลิตน้ำมัน และ การขนส่ง ประเภทส่วนใหญ่ของอิมัลชันที่เกิดขึ้น คือ อิมัลชันประเภทน้ำในน้ำมันอิมัลชัน และปริมาณน้ำในน้ำมันมีมากถึง 60% จึงนำมาซึ่งผลกระทบของการเกิดอิมัลชันในการผลิตน้ำมันคือตวามดันตกในท่อ และความหนืดสูงสำหรับการผลิตน้ำมัน ดังนั้นจุดประสงค์หลักของงานนี้คือ ทำการวัดความหนืดและศึกษาตัวแปรที่มีผลกระทบต่อความหนืดของน้ำมันและอิมัลชันของมัน โดยน้ำมันที่ใช้ในการศึกษานำมาจากแหล่งน้ำมันของประเทศไทย ตัวแปรที่ส่งผลต่อความหนืดของอิมัลชัน ได้แก่ อุณหภูมิ แรงเฉือน และ ปริมาณน้ำในน้ำมัน โดยค่าอุณหภูมิ แรงเฉือน และปริมาณน้ำ ที่ใช้ในการศึกษาอยู่ในช่วง 30 ถึง 90 องศาเซลเซียส, 1 ถึง 74 หนึ่งส่วนวินาที และ ร้อยละ 10 ถึง 60 ตามลำดับ จากการศึกษาได้ว่า อุณหภูมิเป็นตัวแปรสำคัญในการลดความหนืดของอิมัลชัน โดยการเพิ่มอุณภูมิ ในส่วนของแรงเฉือนนั้น ความหนืดของอิมัลชันลดลงเล็กน้อยเมื่อแรงเฉือนเพิ่มขึ้น และความหนืดของอิมัลชันจะลดลงอย่างมากเมื่อปริมาณร้อยละของน้ำในน้ำมันมีค่ามาก นอกจากนี้แล้ว สมการสำหรับทำนายค่าความหนืดของอิมัลชัน ในรูปของอุณหภูมิ แรงเฉือน และปริมาณของน้ำในน้ำมันที่ร้อยละ 10 ถึงร้อยละ 50 ได้ถูกพัฒนาขึ้นด้วย เพื่อใช้สำหรับงานในอนาคตต่อไป

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Emulsion from oil and produced water is normally found during oil production. It forms at many stages in the petroleum recovery and process industry such as drilling, oil production, and transportation. The majority type of emulsion is water-in-oil emulsion and the water volume fraction of emulsion can be up to 60%. This emulsion results in the operating problems for oil production like higher pressure drop in the pipeline and higher viscosity for oil production. Consequently, the objective of this work is to measure the viscosity and evaluates the effects of parameters on viscosity of oil and its emulsion from an oilfield in Thailand. The parameters that influences in emulsion viscosity are temperature, shear rate and water cut. The temperature, shear rate and percentage of water cut for this study are ranging from 30 to 90 °C, from 1 to 74 s-1 and from 10-60%, respectively. The results are shown that temperature plays the significant role in viscosity reduction with increasing temperature. Furthermore, the viscosity of emulsions slightly decreases as the shear rate increases and its viscosity extremely decrease at high percentage of water cut. Moreover, the correlation for predicting viscosity with shear rate, temperature and 10%-50% of water cut is developed for future work.

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Nomenclatures

μ	Oil viscosity
μ_r	Relative viscosity
K	Viscosity ratio of dispersed phase to continuous phase
K_c	System dependent factor
η	Oil viscosity
η_r	relative viscosity
η_c	Viscosity of continuous phase
T	Temperature
Φ	Water content
γ	Shear rate

CHAPTER I
INTRODUCTION

1.1 Introduction

In the petroleum industry, emulsion is normally found. They may form in system containing mixtures of oil and formation water or on account of turbulent mixing in wellbore as well as in a transport pipeline. The emulsion causes many problems during oil production such as declining productivity in wells, higher demulsifier, treatment cost and oil production cost. Furthermore, emulsion can be formed by drilling mud during drilling operations and it may cause formation damage and incorrect in estimation of reserves. For production aspects of emulsion, it is concerned about flow rate of high viscosities of emulsions, productivity declined, oil-water separation and facilities operational. The majority type of emulsions is water-in-oil-emulsions and the water volume fraction can be as high as 60% [1] that effects on emulsion viscosity.

The viscosity of emulsion effects on many process in petroleum industry such as the pumping process, the flow rate, and pressure. Furthermore, the viscosity of oil is important for oil field development and petroleum transportation, so prediction of viscosity is needed and the good estimates of emulsion viscosity are very important. There are many parameters that effect on viscosity of emulsion such as temperature, shear rate and water content. Normally, the viscosity of emulsion can be calculated as a function of temperature and dispersed phase volume fraction. Therefore, the objective of this work is to evaluate the effect of parameters on oil and emulsion viscosity such as shear rate, temperature and water content. Furthermore, the correlation for predicting viscosity of emulsion will be developed.

1.2 Objectives

1. To evaluate the effect of parameters such as temperature, shear rate, and water content on viscosity of light oil and its emulsion.

2. To develop the correlation for viscosity prediction.

1.3 Outline of methodology

1. Study literature reviews and basic theories.
2. Set up equipment and test sample.
3. Run experimental with various operating condition:

- Water cut at 10, 20, 30, 40, 50, 60 %
- Temperature is 30, 40, 50, 60, 70, 90 ℃
- Range of shear rate is 1 – 74 s^{-1}

4. Discuss the result and evaluates the effect of each parameter.
5. Develop the correlation between viscosity and parameters.
6. Compare the value from experiment and viscosity model.

1.4 Outline of thesis

This thesis is divided into six chapters as shown below:

Chapter I introduces the importance of emulsion viscosity investigation and correlation for predicting viscosity of emulsion. Moreover, the objective and methodology are indicated in this chapter.

Chapter II introduces the various literatures related to the study of parameters which are effect on viscosity of emulsion and correlation used for estimate viscosity of emulsion.

Chapter III introduces the relevant theory in this thesis.

Chapter IV describes the conditions of this thesis and methodology.

Chapter V presents the experimental results and discussion on the study of viscosity. Furthermore, the correlations for predicting viscosity are developed and demonstrated in this chapter.

Chapter VI concludes this study.

CHAPTER II

LITERATURE REVIEW

Ronningsen [2] studied the effect of parameters on viscosity of water-in-oil emulsions by using eight different crude oils from North Sea fields and water-in-oil emulsions were prepared at 35°C without adding any emulsifying agent. The viscosity was measured as a function of shear rate at different temperatures and water cuts. For the result of this experiment, the parameters that effect on viscosity are 1) crude oil type, if crude oil has high molecular weight, the viscosity will be high. 2) Water cut, at water cut less than 30% volume, the viscosity slightly increases linearly with water cut but the viscosity rapidly increases at higher water because of higher droplet-droplet interaction. 3) Shear rate, viscosity decreases with increasing shear rate. 4) Temperature, it can influence on viscosity same as shear rate, higher temperature give lower viscosity. Moreover, this work developed correlations for predicting viscosity of water-in-oil emulsions. The correlation developed from Richardson equation:

$$\ln \eta_r = k_1 + k_2.t + k_3\cdot\phi + k_4.t\cdot\phi \tag{2.1}$$

where t is temperature, ϕ is water cut, k_1, k_2, k_3, and k_4 are the constant.

The constants and coefficients from correlation were calculated at different shear rate because the shear rate wasn’t included in the correlation and the calculated constants are shown in Table 2.1.

Table 2.1 Constant of equation at different shear rate.

	Shear rate		
	$30\ s^{-1}$	$100\ s^{-1}$	$500\ s^{-1}$
k_1	0.01334	0.04120	-0.06671
k_2	-0.003801	-0.002605	-0.000775
k_3	0.04338	0.03841	0.03484
k_4	0.0002628	0.0002497	0.00005

Maneeintr et al. [3] study the steam injection to produce emulsion and measured in mass percent to calculate water-oil ratio for studying the effect of it on viscosity of emulsion. Moreover, the parameters that effect on viscosity such as shear rate and temperature were studied. Another objective of this work is to develop the correlation on viscosity and to calculate the average absolute deviations (AADs) between experimental and calculated values. The used oil in this work obtained from Oman and Japan. From the experiment, it was found that the viscosity can be reduced up to 85.92% and 62.6% by increasing temperature and shear rate respectively. On the contrary, the viscosity is higher as the water content increases. Furthermore, this work studied stability of emulsion and it was shown that the droplet sizes become smaller when shear rate is higher because of its breaking up. So, the stability of emulsion becomes lower. The correlation was developed from $\mu = AT^{-B}$ where μ is viscosity, A and B are coefficient and calculated A and B are shown in Table 2.2. From this study, %AADs for this correlation is 13.62% and this value can be acceptable. So this correlation can use for predict the viscosity of this heavy oil.

Table 2.2 Coefficients of each oil type.

Sample	A	B
Original Japanese	3.8187E+07	3.1476
Japanese Emulsion with 15.19 W/O Ratio	7.1618E+07	3.1840
Japanese Emulsion with 31.28 W/O Ratio	1.6485E+08	3.3776
Original Omani	6.4094E+06	2.5148
Omani Emulsion with 13.59 W/O Ratio	2.2599E+07	2.8021

Farah et al. [1] studied viscosity of water-in-oil emulsions depending mainly on the volume fraction of dispersed phase and temperature. The main objective of this study is to present the method to show correctly the difference of kinematic viscosity of water-in-oil emulsions with temperature and water fraction. The different water-in-oil emulsions were prepared with 10%, 20%, 30%, 40% and 60% of water content. The measured viscosity at different dispersed phase volume fractions, temperatures, and shear rates were compared and it showed that the shear rate does not affect much on viscosity because this fluids show Newtonian behavior. Moreover, they developed the correlation between viscosity, temperature, and water fraction by using equation:

$$\ln(\ln(\mu+0.7)) = A - B\ln(T) \qquad (2.2)$$

Where A is $k_1 + k_2\phi$ and B is $k_3 + k_4\phi$. For k_1, k_2, k_3, and k_4, can obtain from the plot between A or B and dispersed phase volume fraction.

Kumar et al. [4] investigated the mechanisms of stabilization of water-in-crude oil emulsions by studying the interaction between the water droplets. The purposes of this work are to study the solvent-solute interactions in relation with dispersion stability and to understand the various mechanisms in stabilizing the emulsion. The used crude oil was a Venezuelan crude oil with 54.5% aliphatic concentration and has no water and solid content. For the result of this work, they found that the stability of the emulsion decreases as the aliphatic concentration is increased by adding heptanes to original crude oil. At an aliphatic concentration of 54.5 wt%, the water separation was not found, showing that the emulsion is greatly stable. While an aliphatic concentration that is higher than 54.5 wt%, the emulsion stability starts to decrease. Furthermore, the interactions between the water droplets are investigated for understanding the stability of the emulsion, determined by calculating radial distribution function from inter-droplet distance. The fluctuating nature of both the radial distribution function and the effective pair potential of interaction between droplets show that the crude oil colloids form a layered structure in the emulsion film, which cause of an increased stability of the emulsion.

Mao and Marsden [5] prepared emulsions from California crude oil and tap water to study the stability of emulsions as a function of shear rate, temperature, and oil concentration. For oil-in-water emulsions, the average droplet size increased with oil concentration and the average droplet size of water-in-oil emulsion also increased with water concentration but continued shear stress decreased the droplet size of both types of emulsion. For the viscosity, it decreases as the temperature increases. Moreover, they found that the oil-in-water emulsions at high temperature are not stable so the effect of shear stress on emulsions is not important.

Alboudwarej and Muhammad [6] prepared emulsions from different oil, oil A and oil B, to study the viscosity correlations. Four viscosity correlations were chosen, such as Taylor correlation, Vand correlation, Ronninsen correlation, and Yaron and Gal-Or correlation, to use for predicting the viscosity of emulsion. All correlations are shown below.

Taylor correlation:

$$\mu_r = 1 + \left(\frac{5K+2}{2K+2}\right)\phi \tag{2.3}$$

where μ_r is relative viscosity, K is the viscosity ratio of dispersed-phase to continuous-phase, and ϕ is the dispersed phase volume fraction.

Vand correlation:

$$\mu_r = exp(\frac{2.5\phi}{1-0.609\phi}) \tag{2.4}$$

where μ_r is relative viscosity, ϕ is the volumetric concentration of dispersed phase.

Ronningsen correlation:

$$\ln \mu_r = k_1 + k_2.t + k_3 \cdot \phi + k_4.t \cdot \phi \tag{2.5}$$

where μ_r is relative viscosity, k_1 to k_4 are constants, T is temperature, and ϕ is the volume percent water cut.

Yaron and Gal-Or correlation:

$$\mu_r = 1 + (\frac{5.5[4\phi^{\frac{7}{3}} + 10 - \left(\frac{84}{11}\right)\phi^{\frac{2}{3}} + (\frac{4}{K})(1-\phi^{\frac{7}{3}})}{10\left(1-\phi^{\frac{10}{3}}\right) - 25\phi\left(1-\phi^{\frac{4}{3}}\right) + \left(\frac{10}{K}\right)(1-\phi)\left(1-\phi^{\frac{7}{3}}\right)})\phi \tag{2.6}$$

where μ_r is relative viscosity, K is the viscosity ratio of dispersed-phase to continuous-phase, and ϕ is the dispersed phase volume fraction.

For oil A, Taylor’s correlation is the best predict of emulsion viscosity because the average error of this correlation is 13%, while the another correlations give the higher value. For oil B, the correlation of Yaron and Gal-Or is the best predict of emulsion viscosity with an average absolute error of 21%.

Dou Dan and Gong Jing [7] developed a new viscosity prediction model based on Pal and Rhodes for non-Newtonian emulsions. Non-Newtonian behavior can be exhibited in emulsion which is in low water cut. The viscosity equation of non-Newtonian emulsion used for this study is:

$$\eta_r = (1-K_e\phi)^{-25} \tag{2.7}$$

Where η_r is relative viscosity, ϕ is volume fraction of dispersed phase and K_e is a system-dependent factor that can be calculated by:

$$K_e(\gamma,\phi) = K_e(\gamma)K_e(\phi) \tag{2.8}$$

Where $K_e(\gamma)$ is the effect of floc and hydration which is in the function of shear rate.

The samples were prepared by mixing crude oil and water at different temperature and stirred by IKA RW20DZM.N for 10 minutes. All of emulsions are water-in-oil emulsion and measured viscosity by HAKKE RV20 viscometer.

The experimental data and predicted data from emulsion viscosity model were compared and calculated by the deviation by:

$$\text{Deviation} = 100 \times \frac{\textbf{(prediction value – experimental value)}}{\textbf{experimental value}} \qquad (2.9)$$

The average deviation is up to 30% compared with viscosity model and experimental data. For non-Newtonian emulsions which are in moderate and high volume fraction of dispersed phase, the predicted viscosity and experimental value are very close. Moreover, they found that at low water cut, water-in-oil emulsions are Newtonian fluids but water-in-heavy oil or waxy oil emulsions show strong non-Newtonian behavior.

Masood and Naza [8] study on factors affecting the heavy crude oil emulsions viscosity by using two heavy crude oil types. From the experiment, the viscosity increases with increasing oil concentration because of more droplets. Conversely, the rising of temperature and shear rate leads to decrease in emulsion viscosity. Furthermore, the correlation to predict the viscosity was developed using Al-Roomi's correlation:

$$\eta = a\gamma^{b}\exp(c\phi + d/T) \qquad (2.10)$$

Where η is viscosity, T is temperature (°C), ϕ is water cut (%), γ is shear rate, a, b, c and d are constant.

The modified correlation compared with two existing rheological models, Ronningsen's correlation and Al-Roomi's correlation, can be fit well with viscosity of emulsions of both oil type's data.

CHAPTER III

THEORY AND CONCEPT

This chapter summarizes relevant theory on characteristic of petroleum emulsion such as stability of emulsion, emulsion preparation, emulsifying agent and rheology of emulsion.

3.1 Petroleum Emulsions

When two immiscible liquids are mixed together, the one of two phases disperses into another phase and then emulsion has been formed. Emulsion may be found at all stages in the petroleum recovery and process industry such as drilling, production process, and transportation of emulsions.

The types of emulsions are distinguished into two types, classified by the liquid type of dispersed phase and continuous phase.

Oil-in-water emulsion, oil is dispersed phase and water is continuous phase.

Water-in-oil emulsion, water is dispersed phase and oil is continuous phase.

Apart from these two types, there is a multiple emulsion such as water-in-oil-in-water emulsions that is the water dispersed in to oil droplet in continuous water phase or vice versa, called oil-in-water-in-oil emulsions. The simple of examples of petroleum emulsion types are shown in Table 3.1.[9]

Table 3.1The examples of petroleum emulsion types

Occurrence	Usual Type
Undesirable Emulsions	
Well-head emulsions	Water-in-oil emulsion
Fuel oil emulsions (marine)	Water-in-oil emulsion
Oil sand flotation process, froth	Water-in-oil emulsion or vice versa
Oil sand flotation process, diluted froth	Oil-in-water-in-oil emulsion
Oil spill mousse emulsions	Water-in-oil emulsion
Tanker bilge emulsions	Oil-in-water emulsion
Desirable Emulsions	
Heavy oil pipeline emulsion	Oil-in-water emulsion
Oil sand flotation process slurry	Oil-in-water emulsion
Emulsion drilling fluid, oil-emulsion mud	Oil-in-water emulsion
Emulsion drilling fluid, oil-base mud	Water-in-oil emulsion
Asphalt emulsion	Oil-in-water emulsion
Enhanced oil recovery in situ emulsions	Oil-in-water emulsion

Physical characteristics of emulsions can classify the type of emulsion by method such as

Texture. Water-in-oil emulsions feel oily or greasy and oil-in-water emulsions feel watery or creamy because the external phase is reflected in texture of an emulsion.

Mixing. A liquid that is miscible with the continuous phase can dilute an emulsion. For example, oil-in-water emulsions can be diluted with water.

Conductance. The conductance of emulsion depends on the continuous phase, so oil-in-water emulsion have high conductance because of the aqueous phase.

3.2 Stability of Emulsions

Most emulsions exhibit kinetic stability that is the stability over a period of time. Produced oilfield emulsions are classified on the basis of their degree of kinetic stability such as loose emulsions that will separate in a few minutes, medium emulsions that will separate in tens of minutes, and tight emulsions that will separate in hours or even days.[10]

Stability is investigated against three processes, creaming, aggregation, and coalescence. Creaming is the internal phase formed downward or upward layer in accordance with the internal phase density. In aggregation, two or more droplets cluster but the total surface area does not change. In coalescence, two or more droplets combine together and result in the larger total surface area. These three different processes are shown in Figure 3.1. Kinetic stability is important to differentiate the degree of change and time scale.

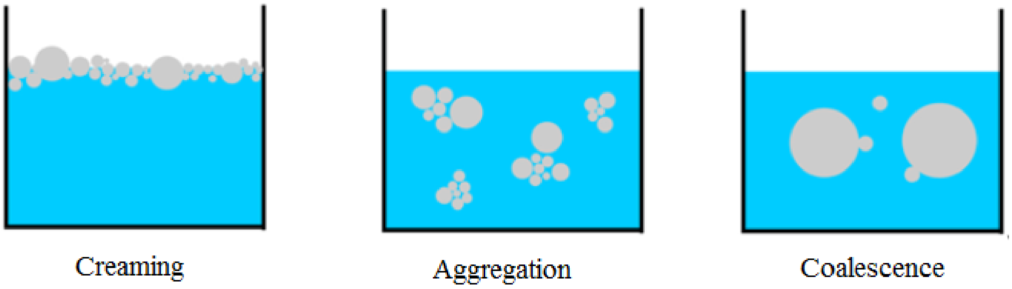

Figure 3.1 The stability of emulsion

The stability of an emulsion depends on various parameters such as the difference in density between oil and water phase, temperature, the size of droplets, viscosity, interfacial tension, and the presence and concentration of emulsifying agents.[11]

Temperature affects the physical properties of oil, water, interfacial films, and surfactant solubility in oil and water phase. Hence, these affect the stability of the emulsion. Temperature increases the thermal energy of the droplets and the frequency of drop collisions. Moreover, it also reduces the interfacial viscosity that effect on faster film-drainage rate and faster drop coalescence.

Emulsions that have smaller droplets size will be more stable because the smaller droplets take the greater time to separate. Furthermore, the droplets size distribution affects emulsion viscosity. Viscosity increases when droplets size is smaller. For increased viscosity, the rate of water particle that move through the oil phase decreases, resulting in less coalescence and the emulsion will be stable.

The interfacial tension between oil and water is too high when no emulsifier is present. So, the water droplets coalesce easily upon contact. The presence of emulsifier decreases the interfacial tension and opposes the coalescence of water particles.

3.3 Emulsions Preparation

The water-in-oil or oil-in-water emulsions can be prepared by mixing oil and water together and then shake it. Another way to making emulsion is to add emulsifying agent, it can lower interfacial tension and then the small droplet can be formed easier. Moreover, the emulsifying agent can stabilize the small droplets so that the coalescence does not occur.

3.4 Emulsifying agents

Emulsifier or surfactant is the molecule which has 2 parts, hydrophilic and hydrophobic. When adding surfactant, it will form monolayer film between oil and water (shown in Figure 3.2). The surfactant is necessary to prevent the coalescence between droplets.

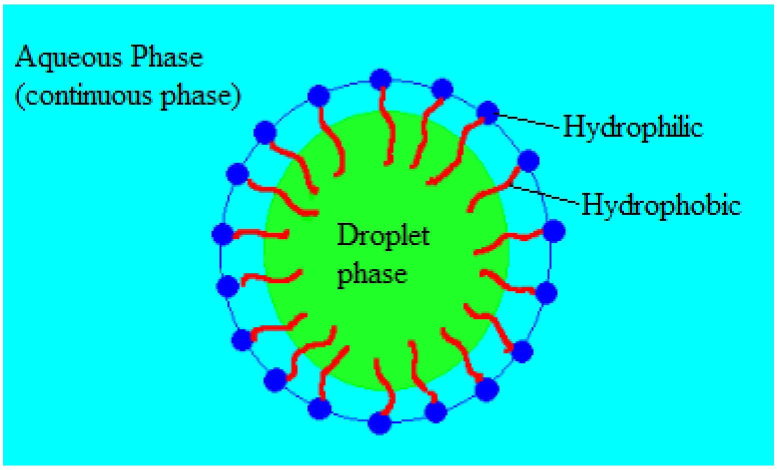

Figure 3.2 Emulsions

The emulsifying agent makes an emulsion stable, some stable emulsions may take long time to separate if left in the tank without treating but unstable emulsion may separate for a short time. Moreover, for transporting highly viscous hydrocarbon is to disperse the heavy crude oil in water as droplets stabilized by surfactants.[12]

Three main processes occur during emulsification.[13]

1. Droplets are deformed and possible broken up.
2. The newly formed droplets adsorbed the surfactant.
3. Droplets encounter each other and possibly coalesce.

3.5 Viscosity of Emulsions

Emulsions show non-Newtonian behavior because its viscosity is a function of shear rate. There are two types of non-Newtonian behavior such as shear-thickening behavior which is increased viscosity with increasing shear rate, for decreasing viscosity with increasing shear rate is called shear-thinning behavior.

The viscosity of emulsion depends on several parameters such as the viscosity of the continuous phase, the volume fraction of the dispersed phase, the viscosity of dispersed phase, the average droplet size and droplets size distribution, shear rate, the nature and the concentration of the emulsifying agent, and temperature. [14]

The most important factor that effects on the viscosity of emulsion is the volume fraction of the dispersed phase. When the droplets disperse more, the rate of energy dissipation is increasing and that is the cause of increasing in the viscosity of emulsions. In general, the viscosity of emulsion is written in terms of the relative viscosity (η_r) that is the proportion of viscosity of emulsion (η) and continuous phase (η_c) or the relative viscosity can be written as η/η_c. Einstein derived the relationship between the relative viscosity and the volume fraction:

$$\eta_r = \frac{\eta}{\eta c} = 1+2.5\phi \qquad (3.1)$$

The effect of particle size distribution on viscosity is significant at high values of dispersed phase concentration but the effect is small at low values of dispersed phase concentration.

Shear rate plays the significant role in viscosity of emulsion which is non-Newtonian fluids. In the high volume fraction range, the emulsions present non-Newtonian behavior. So, at high volume fraction, the apparent viscosity decreases as the shear rate increases. For the low volume fraction range, the shear rate does not effect on viscosity because the emulsions exhibit Newtonian behavior.

For the effect of temperature on viscosity, the increase in temperature causes the decrease in viscosity. Raising the temperature is not only to decrease in the continuous phase viscosity but that also affect the average particle size and particle size distribution. The relationship between apparent viscosity and temperature obeys the Arrhenius relationship:

$$\eta = A \exp (B/T) \qquad (3.2)$$

Where A and B are constant dependent upon the system and shear rate, T is the absolute temperature.

The wax appearance temperature (WAT) is an important characteristic to evaluate the possible wax precipitation of a given fluid. It is defined as the temperature at which a crude oil first precipitates and effect on viscosity of oil. The viscosity extremely decrease when the temperature reach WAT.[15]

CHAPTER IV
METHODOLOGY

Based on the objective of this study, the experiment was operated by Brookfield viscometer model DV2TLV with spindle LV-01(61) and LV-04(64) as shown in Figure 4.1. Temperature was controlled by constant temperature circulating water bath with ± 1.0°C accuracy. Viscosities from this equipment are accurate within ± 1% of the full-scale the spindle/speed combination in use. This chapter describes all steps for the experiment.

Figure 4.1 DV2TLV viscometer and circulating water bath

4.1 Verification of equipment

First step for the experiment is to verify the equipment with standard solution which is known sample. The standard solution supplied by Brookfield with viscosity of 498 cp at 25°C as shown in Figure 4.2. For verification the equipment, the standard solution was tested for 1 hour with speed of 1 and 60 rpm and temperature of 25°C. The viscosities were recorded every 10 second.

Figure 4.2 Standard solution

4.2 Emulsions preparation

The light oil and produced water are obtained from an oilfield in Thailand to prepare the emulsions. The amount of oil and water were measured in volume percent to estimate percent water cut. The emulsions were prepared at 40°C without emulsifying agent and controlled temperature by circulating water bath. The emulsions at any percent of water cut are shown in Figure 4.3 and Figure 4.4

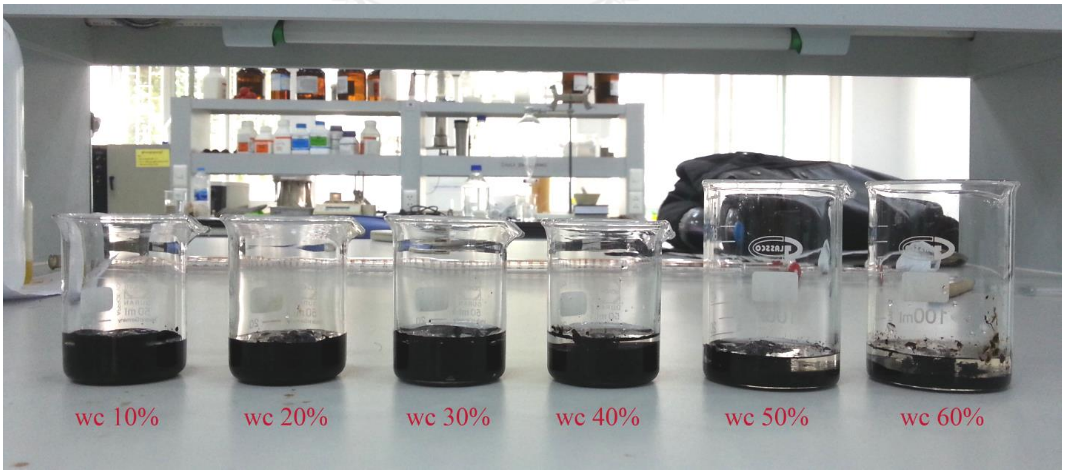

Figure 4.3 Emulsions before mixing

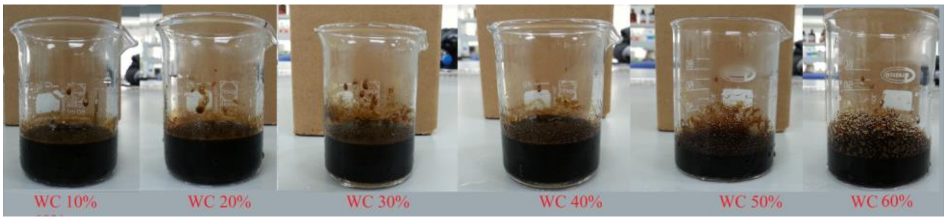

Figure 4.4 Emulsions after mixing

4.3 Experimental conditions

The operation was run at various conditions with the limited of equipment:

The experiment operated at temperature of 30, 40, 50, 60, 70, 90°C. The operation at 30°C used spindle LV-04(64) which is suitable for high viscosity fluid but for the other operation at higher temperature used spindle LV-01(61).

Shear rate of the experiment were operated at 1.223, 6.115, 18.34, 30.58, 42.81, 73.38 s^{-1} which are speed of 1, 5, 15, 25, 35 and 60 rpm respectively for spindle LV-01(61) but for spindle LV-04(64) operated at speed of 1, 5, 15, 25, 35 and 60 rpm. For spindle LV-04(64) cannot calculate speed into shear rate.

The emulsion for this work were prepared and tested at water cut of 0, 10, 20, 30, 40, 50, and 60%.

4.4 Collecting data

Each sample was run for 1 hour at constant speed and shear rate and viscosities were recorded every 10 seconds, so the recorded viscosities are 3600 data per sample. For the first period of experiment the viscosities fluctuated but the viscosities were constant after 30 minutes passed. So the viscosity of each sample is averaged from the recorded viscosity after 30 minutes passed.

4.5 Correlation development

The correlations for predicting viscosity are based on various equations:

4.5.1 Ronningsen's Correlation:

$$\ln \eta_r = k_1 + k_2.t + k_3 \cdot \phi + k_4.t \cdot \phi \qquad (4.1)$$

Where η_r is relative viscosity, t is temperature (°C), ϕ is water cut (%), k_1, k_2, k_3, and k_4 are the constant.

4.5.2 Farah's Correlation:

$$\ln(\ln(\mu_r+0.7)) = A - B \ln(T) \qquad (4.2)$$

Where A is $k_1 + k_2\phi$, B is $k_3 + k_4\phi$, μ_r is relative viscosity, T is temperature(°C), ϕ is water cut (%), k_1, k_2, k_3, and k_4 are constant.

4.5.3 Al-Roomi's Correlation:

$$\eta = a\gamma^{b}\exp(c\phi + d/T) \qquad (4.3)$$

Where η is viscosity, T is temperature (°C), ϕ is water cut (%), γ is shear rate, a, b, c and d are constant.

CHAPTER V

EXPERIMENTAL RESULTS AND DISCUSSIONS

The discussion on the effects of parameters such as temperature, water cut and shear rate on viscosity of light oil and its emulsions is summarized in this chapter. Moreover the correlations for predicting viscosity of emulsion are developed and compared to the experimental viscosity. The best correlation will be chosen for the future work.

5.1 Verification of equipment

The result for verifying equipment is shown in Figure 5.1. The viscosity of standard solution from the experimental is constant at 497.6 cp with speed of 1 and 60 rpm after 1200 second. The viscosity of the standard solution supplied by Brookfield is 498 cp, so the experimental result has a deviation of 0.08%.

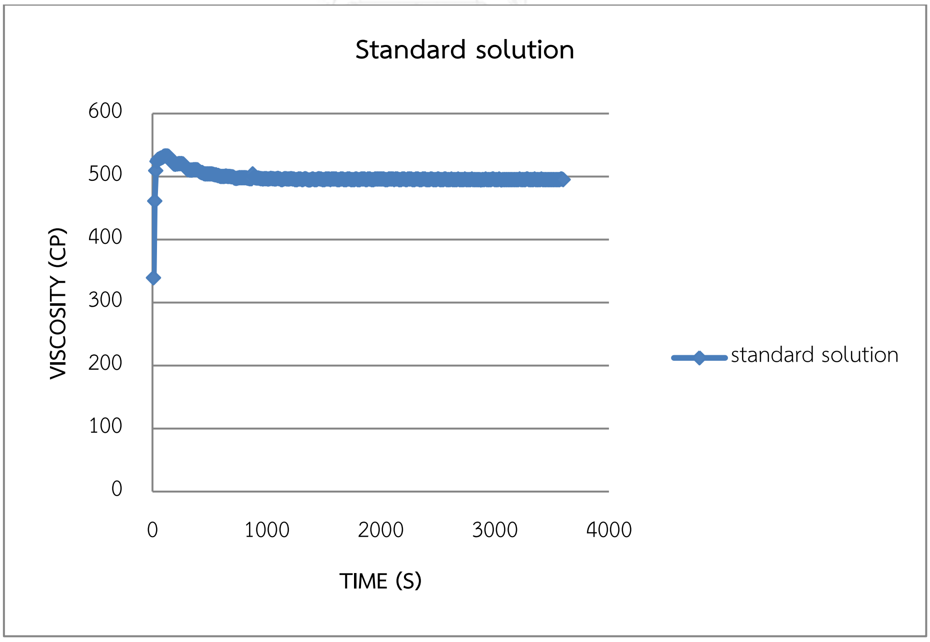

Figure 5.1 Verification of equipment

5.2 Effect of temperature on viscosity

From the experiment, the results are shown in the Table 5.1-5.7 and Figure 5.2-5.8. By comparing at the same speed and water cut, the viscosities decrease as the temperature increases because temperatures provide energy to the molecule of oil and make it less viscous. Furthermore, it is found that increasing temperature has a greater effect in viscosity reduction compared with water content and shear rate. It is also found that increasing temperature plays significant role in decreasing the viscosity of emulsions.

Tabel 5.1 Viscosity at 0% water cut

WATER CUT 0%	VISCOSITY (cP)					
TEMPERATURE (°C)	SPEED 1 (RPM)	SPEED 5 (RPM)	SPEED 15 (RPM)	SPEED 25 (RPM)	SPEED 35 (RPM)	SPEED 60 (RPM)
30	29192.1	84660	3557.889	1886.586	1371.674	964.3094
40	193.412	57.1048	30.5967	23.8997	N/A	N/A
50	10.996	9.0822	8.6663	8.6756	8.7650	8.7577
60	7.7536	6.9534	6.9240	7.1131	7.2957	7.4564
70	6.5569	6.1604	6.2822	6.3667	6.4716	6.5750
90	4.2696	4.4241	4.4928	4.6012	4.7043	4.8322

N/A = Not available

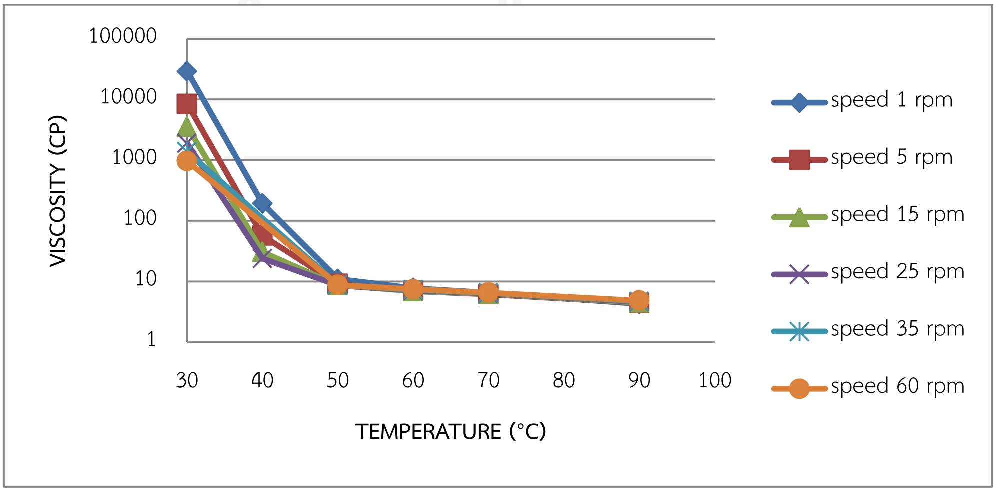

Figure 5.2 Temperature effect on viscosity of original oil

From Table 5.1, the viscosity of original oil which is 0% water cut is decreased by increasing in temperature especially changing temperature from 30°C to 40°C as shown in Figure. 5.2. The viscosity of original oil extremely decreases from 30°C to 40°C and slightly decreases at high temperature. The viscosity at speed of 35 and 60 rpm cannot be measure at 40°C due to the limit of viscometer.

Tabel 5.2 Viscosity at 10% water cut

TEMPERATURE (°C)	VISCOSITY (CP)					
	SPEED 1 (RPM)	SPEED 5 (RPM)	SPEED 15 (RPM)	SPEED 25 (RPM)	SPEED 35 (RPM)	SPEED 60 (RPM)
30	30135	8408	4686.444	3089.267	1823.292	1107.9722
40	168.532	46.3200	23.6501	22.3315	N/A	N/A
50	6.3312	6.1200	6.3600	6.5041	6.6967	6.8469
60	6.5574	6.1837	6.1324	6.1781	6.234	6.3023
70	6.4000	5.3463	5.7200	5.9923	6.1849	6.3341
90	4.9867	4.5167	4.4889	4.5387	4.5898	4.6620

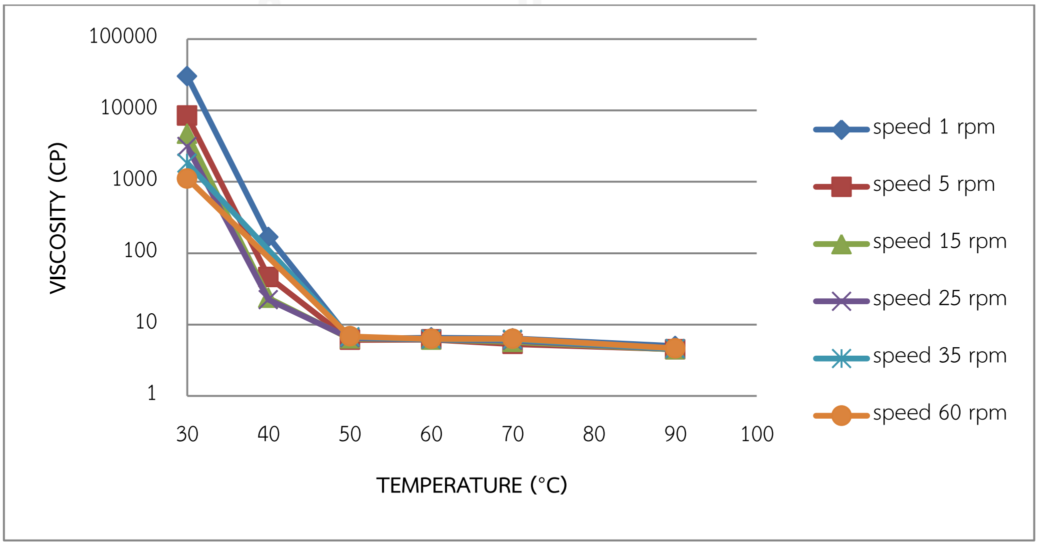

Figure 5.3 Temperature effect on viscosity of emulsion at 10% water cut

The viscosity of emulsion at 10% water cut is greatly decreased by changing temperature from 30°C to 40°C as shown in Figure 5.3. At temperature of 50°C-90°C, the viscosity insignificantly change because temperature reaches the wax appearance temperature (WAT). The wax appearance temperature for this oil is around 40°C because the viscosity of oil at temperature more than 40°C extremely decreases and then slightly decreases as if the viscosity is constant.

Tabel 5.3 Viscosity at 20% water cut

TEMPERATURE (°C)	VISCOSITY (CP)					
	SPEED 1 (RPM)	SPEED 5 (RPM)	SPEED 15 (RPM)	SPEED 25 (RPM)	SPEED 35 (RPM)	SPEED 60 (RPM)
30	31405.6	7493.18	3702.83	2609.11	1792.24	1034.04
40	189.806	48.5456	27.3242	22.4192	N/A	N/A
50	14.5923	11.8283	11.1757	11.0656	11.167	11.1573
60	9.2486	8.2966	8.2033	8.2462	8.3524	8.4925
70	5.1481	4.8438	4.8703	4.9969	5.1719	5.4088
90	3.1492	3.8838	4.3211	4.4506	4.5750	4.6948

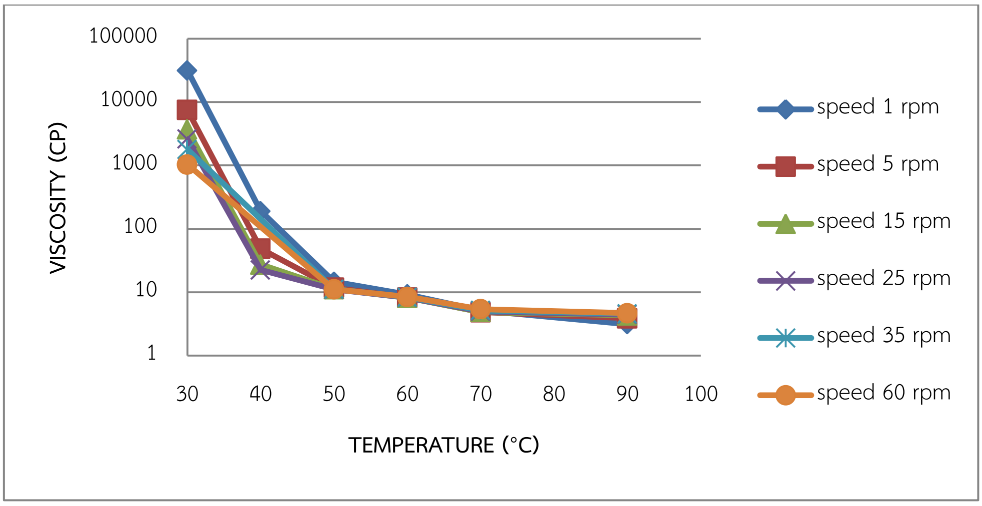

Figure 5.4 Temperature effect on viscosity of emulsion at 20% water cut

The high slope of graph between 30°C-40°C in Figure 5.4 shows that the temperature effect much on viscosity of emulsion at low temperature. The viscosity slightly decreases as the temperature increases from 50°C to 90°C. For water cut of 30-60%, shown in Table 5.4-5.7 and Figure 5.5-5.8, the temperature effect on emulsion's viscosity same as water cut of 0-20%.

Tabel 5.4 Viscosity at 30% water cut

TEMPERATURE (°C)	VISCOSITY (CP)					
	SPEED 1 (RPM)	SPEED 5 (RPM)	SPEED 15 (RPM)	SPEED 25 (RPM)	SPEED 35 (RPM)	SPEED 60 (RPM)
30	30208.3	5884.333	2709.222	1853.467	1296.092	885.5551
40	286.154	62.0745	29.162	22.1885	N/A	N/A
50	9.7292	8.0627	7.7516	7.9093	8.1174	8.2000
60	8.6287	6.6123	6.2192	6.1431	6.0974	6.0928
70	6.6886	6.3457	5.8800	5.907	5.8721	5.7504
90	3.8517	3.4373	3.6311	3.6772	3.7203	3.8061

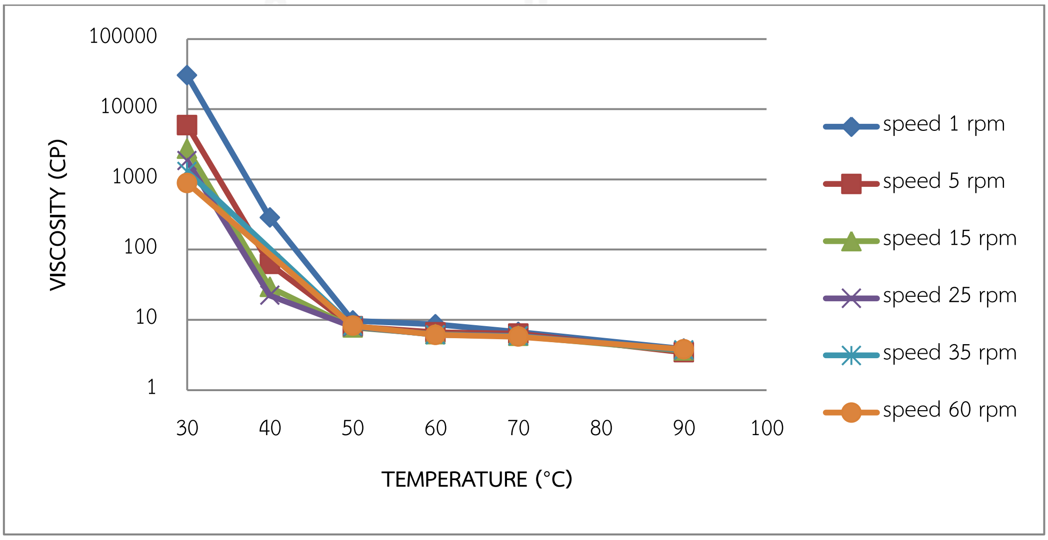

Figure 5.5 Temperature effect on viscosity of emulsion at 30% water cut

Tabel 5.5 Viscosity at 40% water cut

TEMPERATURE (°C)	VISCOSITY (CP)					
	SPEED 1 (RPM)	SPEED 5 (RPM)	SPEED 15 (RPM)	SPEED 25 (RPM)	SPEED 35 (RPM)	SPEED 60 (RPM)
30	26536.7	7917	3944.667	2500.8	1518.547	936.8889
40	267.146	52.0117	23.6385	17.6018	15.174	N/A
50	11.3143	7.7013	6.6398	6.4608	6.5001	6.5282
60	8.1010	6.2514	5.8603	5.7435	5.7965	5.8282
70	5.3700	4.688	4.6774	4.7607	4.8714	5.0722
90	3.3381	3.264	3.3337	3.3472	3.3979	3.4975

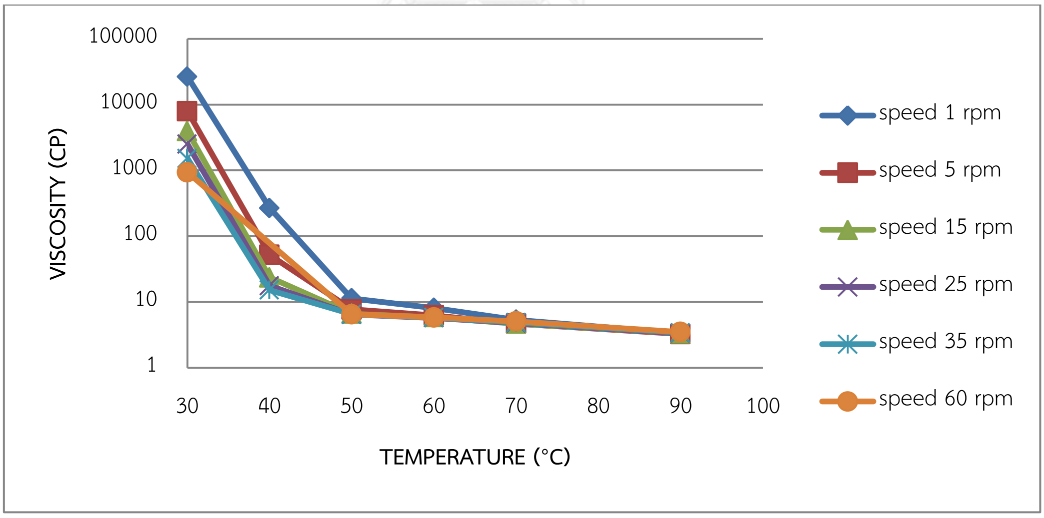

Figure 5.6 Temperature effect on viscosity of emulsion at 40% water cut

Tabel 5.6 Viscosity at 50% water cut

TEMPERATURE (°C)	VISCOSITY (CP)					
	SPEED 1 (RPM)	SPEED 5 (RPM)	SPEED 15 (RPM)	SPEED 25 (RPM)	SPEED 35 (RPM)	SPEED 60 (RPM)
30	43684	12580.11	6334.807	3996.464	2359.354	1415.4696
40	144.547	34.4632	17.8897	13.8311	11.9033	9.7960
50	7.1542	5.9900	5.5626	5.4603	5.5247	5.5970
60	5.891	5.4200	4.7786	4.6481	4.6507	4.8572
70	3.5642	3.3993	3.3799	3.3767	3.396	3.6212
90	1.2365	1.4613	1.7814	1.9078	2.0347	2.1883

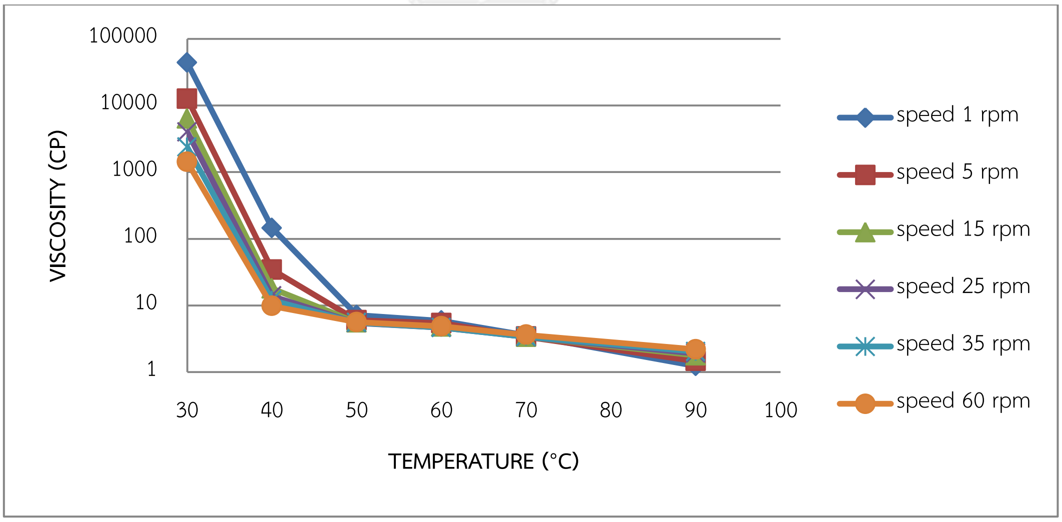

Figure 5.7 Temperature effect on viscosity of emulsion at 50% water cut

Tabel 5.7 Viscosity at 60% water cut

TEMPERATURE (°C)	VISCOSITY (CP)					
	SPEED 1 (RPM)	SPEED 5 (RPM)	SPEED 15 (RPM)	SPEED 25 (RPM)	SPEED 35 (RPM)	SPEED 60 (RPM)
30	48129.3	5340.331	1068.066	560.6188	383.3779	283.4807
40	21.5867	9.8831	6.5929	5.6831	5.2498	4.6848
50	5.4000	3.6683	3.4898	3.4762	3.4636	3.6346
60	3.7400	2.6963	2.8351	2.9378	3.0516	3.2409
70	1.5600	1.7277	1.8407	1.9105	1.9482	2.2000
90	1.2000	1.254	1.5268	1.5794	1.6547	1.8075

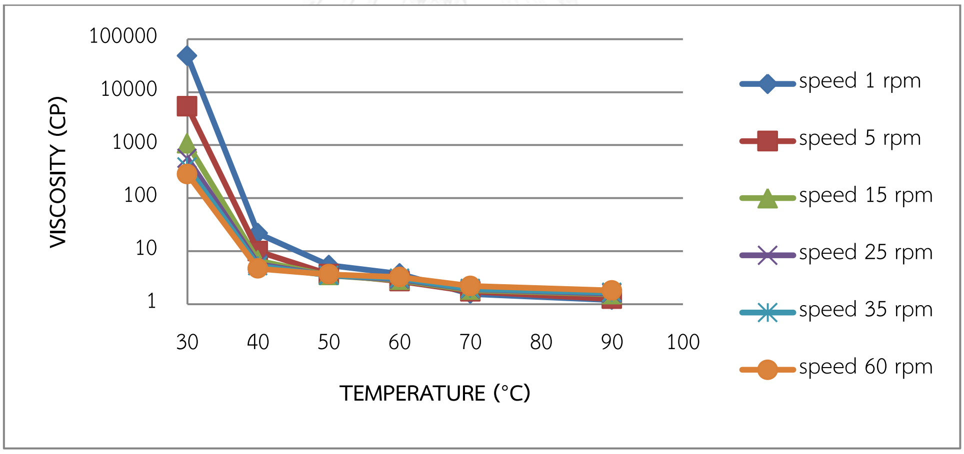

Figure 5.8 Temperature effect on viscosity of emulsion at 60% water cut

5.3 Effect of shear rate on viscosity

The viscosities of emulsions slightly decrease with an increase in shear rate as shown in Table 5.8 and Figure 5.9.

For testing effect of shear rate on emulsion's viscosity at temperature of 30°C, the result from Table 5.8 shows that the viscosity decreases as the speed increases. The speed varies directly with shear rate, so increasing shear rate effect on decreasing viscosity. This oil is Non-Newtonian fluid because its viscosity changes with the shear rate and it shows shear-thinning behavior. The viscosity is decreased by increasing shear rate called shear-thinning behavior as mention in chapter 3.

The viscosity at any water cut of 40°C is decreased by increasing shear rate and displays in Figure 5.10. It shows that the viscosity extremely decreases between shear rate of 1.223 and 6.115 1/s and after that it slightly decreases. From table 5.9-5.10, the viscosities at water cut of 0%-40% cannot be measure because of the limit of equipment.

Tabel 5.8 Effect of shear rate on viscosity at temperature of 30°C

Temperature (°C)	Speed (rpm)	Viscosity (cp) with water cut						
		0%	10%	20%	30%	40%	50%	60%
30	1	29192.1	30135	31405.6	30208.3	26536.7	43684	48129.3
	5	8466	8408	7493.18	5884.33	7917	12580.1	5340.33
	15	3557.89	4686.44	3702.83	2709.22	3944.67	6334.81	1068.07
	25	1886.59	3089.27	2609.11	1853.47	2500.8	3996.46	560.619
	35	1371.67	1823.29	1792.24	1296.09	1518.55	2359.35	383.378
	60	964.309	1107.97	1034.04	885.556	936.889	1415.47	283.481

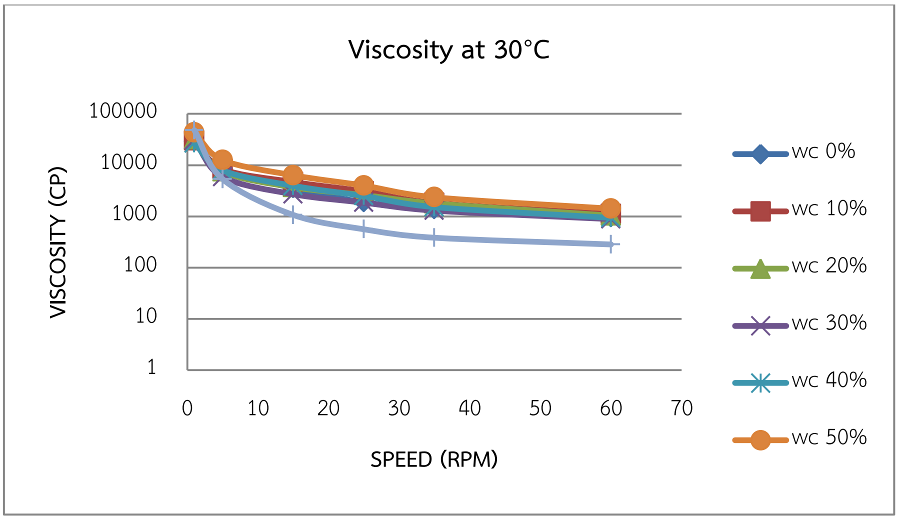

Figure 5.9 Effect of shear rate on viscosity at temperature of 30°

Tabel 5.9 Effect of shear rate on viscosity at temperature of 40°C-60°C

Temperature (°C)	Shear rate (1/s)	Viscosity (cp) with water cut						
		0%	10%	20%	30%	40%	50%	60%
40	1.223	193.412	168.532	189.806	286.154	267.146	144.547	21.5867
	6.115	57.1048	46.3200	48.5456	62.0745	52.0117	34.4632	9.8831
	18.34	30.5967	23.6501	27.3242	29.162	23.6385	17.8897	6.5929
	30.58	23.8997	22.3315	22.4192	22.1885	17.6018	13.8311	5.6831
	42.81	N/A	N/A	N/A	N/A	15.174	11.9033	5.2498
	73.38	N/A	N/A	N/A	N/A	N/A	9.79602	4.6848
50	1.223	10.9956	6.3312	14.5923	9.7292	11.3143	7.1542	5.4000
	6.115	9.0822	6.1200	11.8283	8.0627	7.7013	5.9900	3.6683
	18.34	8.6663	6.3600	11.1757	7.7516	6.6398	5.5626	3.4898
	30.58	8.6756	6.5042	11.0656	7.9093	6.4608	5.4603	3.4762
	42.81	8.7651	6.6967	11.167	8.1174	6.5001	5.5247	3.4636
	73.38	8.7577	6.8469	11.1573	8.200	6.5282	5.5971	3.6346
60	1.223	7.7536	6.5574	9.2486	8.6287	8.101	5.8910	3.7400
	6.115	6.9534	6.1837	8.2966	6.6123	6.2514	5.42	2.6963
	18.34	6.924	6.1324	8.2033	6.2192	5.8603	4.7786	2.8351
	30.58	7.1131	6.1781	8.2462	6.1431	5.7435	4.6481	2.9378
	42.81	7.2957	6.234	8.3524	6.0974	5.7965	4.6507	3.0516
	73.38	7.4564	6.3023	8.4925	6.0928	5.8282	4.8570	3.2410

Tabel 5.10 Effect of shear rate on viscosity at temperature of 70°C-90°C

Temperature (°C)	Shear rate (1/s)	Viscosity (cp) with water cut						
		0%	10%	20%	30%	40%	50%	60%
70	1.223	6.5569	6.4000	5.1481	6.6886	5.3700	3.5642	1.5600
	6.115	6.1604	5.3463	4.8438	6.3457	4.688	3.3993	1.7277
	18.34	6.2822	5.72	4.8701	5.88	4.6774	3.3799	1.8407
	30.58	6.3667	5.9923	4.9969	5.907	4.7607	3.3767	1.9105
	42.81	6.4716	6.1849	5.1719	5.8721	4.8714	3.3960	1.9482
	73.38	6.5750	6.3341	5.4088	5.7504	5.0722	3.6213	2.200
90	1.223	4.2696	4.9867	3.1492	3.8517	3.3381	1.2365	1.2000
	6.115	4.4241	4.5167	3.8838	3.4373	3.264	1.4613	1.2540
	18.34	4.4928	4.4889	4.3211	3.6311	3.3337	1.7814	1.5268
	30.58	4.6012	4.5387	4.4506	3.6772	3.3472	1.9078	1.5794
	42.81	4.7043	4.5898	4.575	3.7203	3.3979	2.0347	1.6547
	73.38	4.8322	4.662	4.6948	3.8061	3.4975	2.1882	1.8075

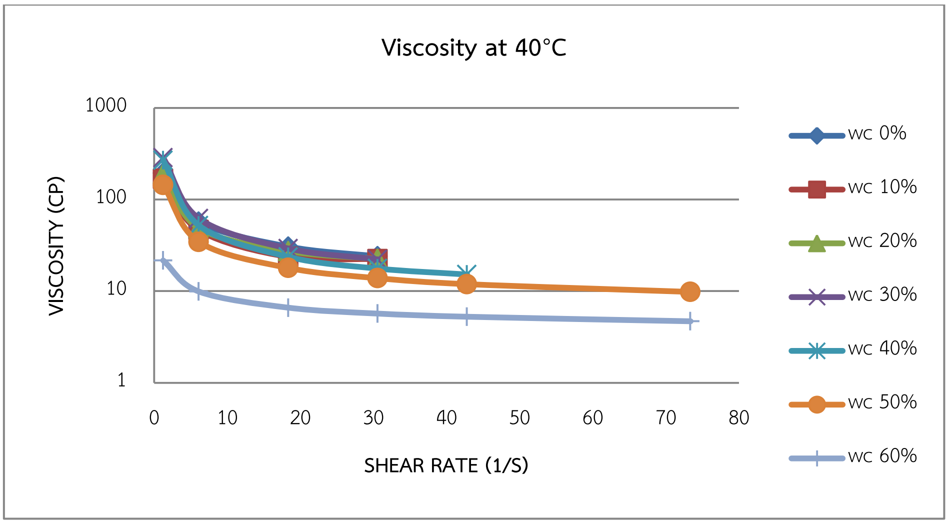

Figure 5.10 Effect of shear rate on viscosity at temperature of 40°C

At temperature of 50°C, the most changing in viscosity of emulsion is between shear rate of 1.223 and 6.115 1/s. From Figure 5.11, the viscosity doesn’t change much at high shear rate. So, it may conclude that high shear rate has less effect on emulsion’s viscosity.

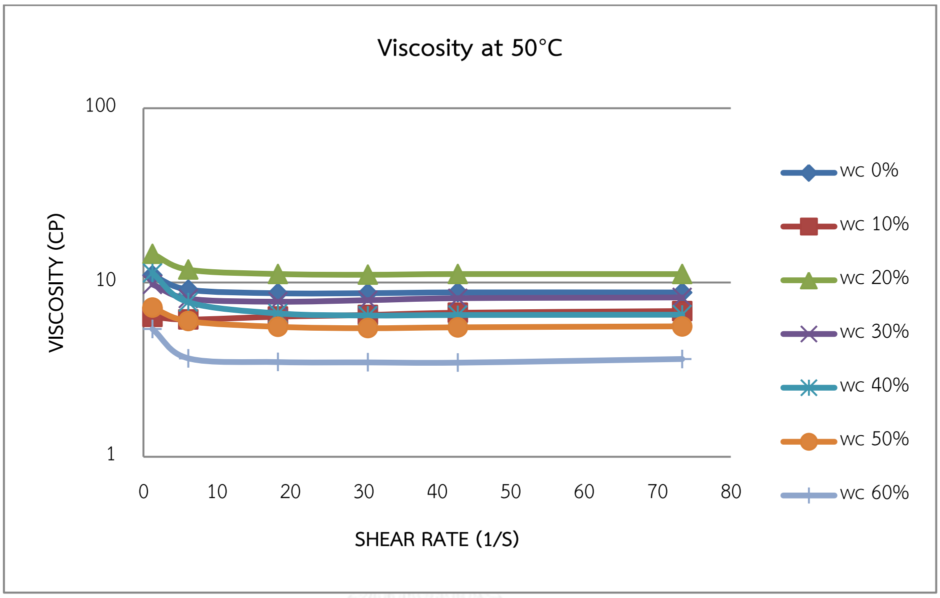

Figure 5.11 Effect of shear rate on viscosity at temperature of 50°C

At high temperature (60°C-90°C), the viscosity decreases as the shear rate increase at low shear rate but higher shear rate has less effect on viscosity of emulsion. From Figure 5.12 and 5.13, the low shear rate has less effect on emulsion’s viscosity but the viscosity at high temperature is seldom changed by increasing shear rate as show in Figure 5.14. Since the water in oil emulsion shows the Newtonian fluid behavior at high temperature.

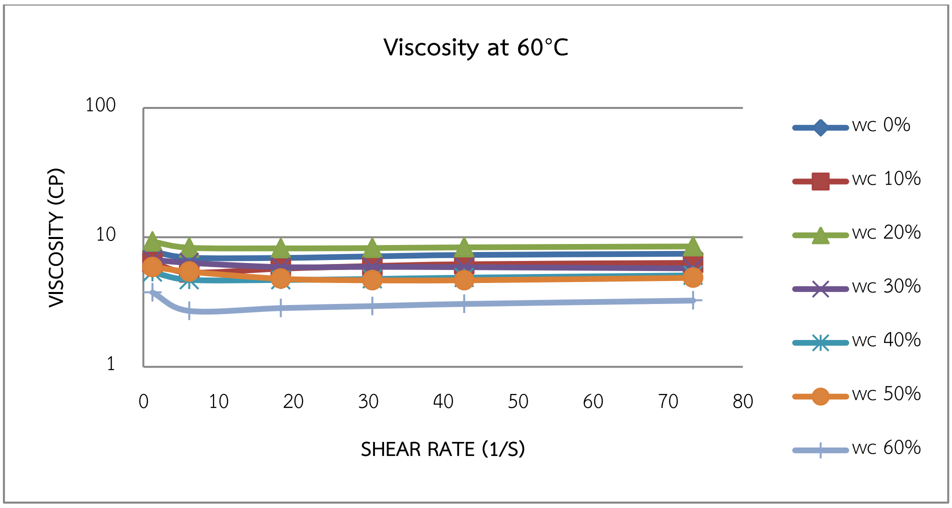

Figure 5.12 Effect of shear rate on viscosity at temperature of 60°C

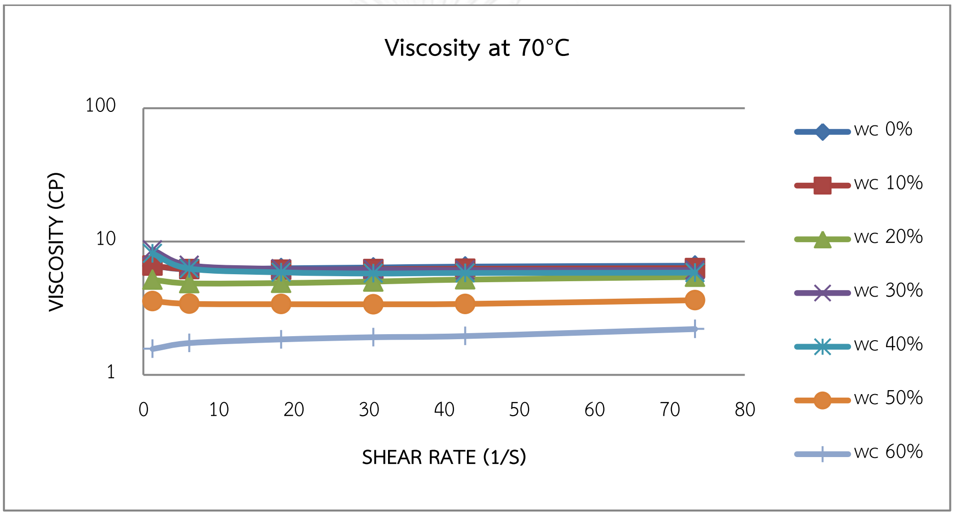

Figure 5.13 Effect of shear rate on viscosity at temperature of 70°C

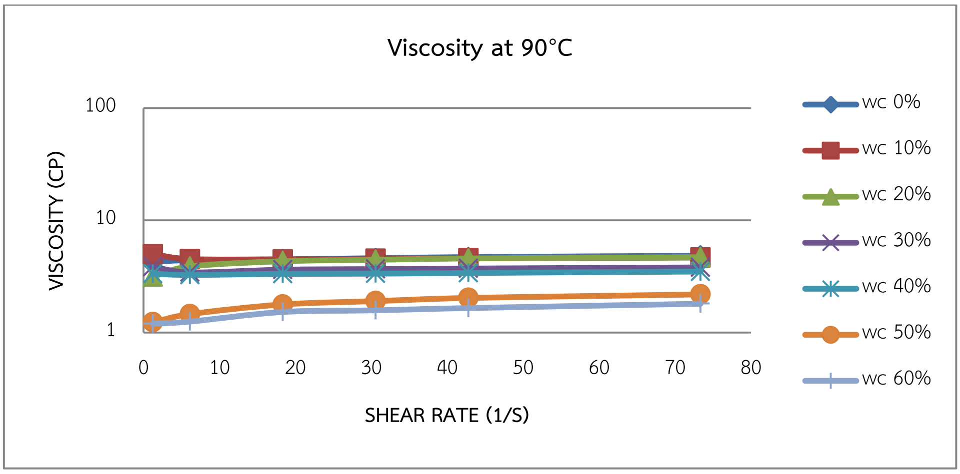

Figure 5.14 Effect of shear rate on viscosity at temperature of 90°C

5.4 Effect of water cut on viscosity

At speed of 1 rpm, the viscosity of 30°C emulsion is relatively constant at water cut of 0-40% but it greatly increases at water cut of 50-60%. Since the amount of water increases, the droplets disperse more and lead to more energy between water and oil. So the viscosity increases as the volume fraction increase. The percent volume fraction doesn’t affect much on emulsion’s viscosity at high temperature because the viscosity of oil at high temperature is less and close to water’s viscosity. So the energy between molecule of water and oil is too small.

At speed of 5 rpm, the viscosity of 30°C emulsion is highest at 50% water cut and drop because the inversion can occur at 60% water cut. So the viscosity of 30°C emulsion greatly decreases at water cut 60%. The higher temperature is the less effect of water cut on emulsion as shown in Table 5.12.

From Figure 5.16-5.21, the effect of water cut at temperature of 30°C is slightly decrease at water cut of 30% and increase as a peak at water cut of 50%, then extremely decrease at water cut of 60% as shown in Figure 5.15. The inversion point occurs at 50% water cut, changing from water-in-oil emulsion to oil-in-water emulsion. The decreasing of viscosity at 30% water cut may happen because of the effect of average droplets size and droplets size distribution. This parameter should be studied in future work.

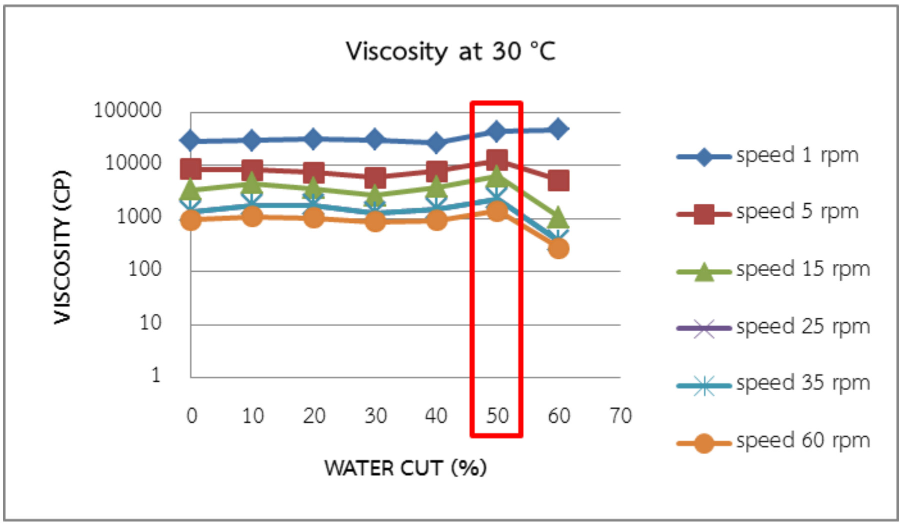

Figure 5.15 Effect of water cut at 30°C

Tabel 5.11 Viscosity at speed 1 rpm

WC (%)	VISCOSITY (CP)					
	30°C	40°C	50°C	60°C	70°C	90°C
0	29192.079	193.4122	10.9956	7.7536	6.5569	4.2696
10	30135	168.5324	6.3312	6.5574	6.4000	4.9867
20	31405.6	189.8055	14.5923	9.2486	5.1481	3.1492
30	30208.333	286.1536	9.7292	8.6287	6.6886	3.8517
40	26536.667	267.1459	11.3143	8.1010	5.3700	3.3381
50	43683.978	144.5470	7.1542	5.8909	3.5642	1.2365
60	48129.282	21.5867	5.4000	3.7400	1.5600	1.2000

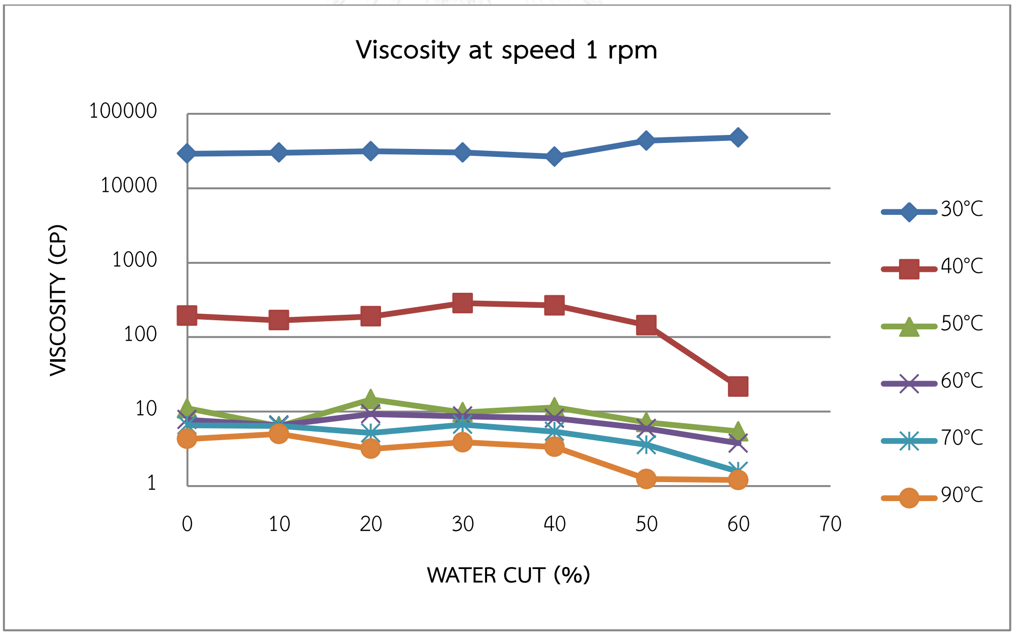

Figure 5.16 Viscosity at speed 1 rpm

Tabel 5.12 Viscosity at speed 5 rpm

WC (%)	VISCOSITY (CP)					
	30°C	40°C	50°C	60°C	70°C	90°C
0	8466	57.1048	9.0822	6.9534	6.1604	4.4241
10	8408	46.3200	6.1200	6.1837	5.3463	4.5167
20	7493.18	48.5456	11.8283	8.2966	4.8438	3.8838
30	5884.3333	62.0745	8.0627	6.6123	6.3457	3.4373
40	7917	52.0117	7.7013	6.2514	4.6880	3.2640
50	12580.11	34.4632	5.9900	5.4200	3.3993	1.4613
60	5340.3315	9.8831	3.6683	2.6963	1.7277	1.2540

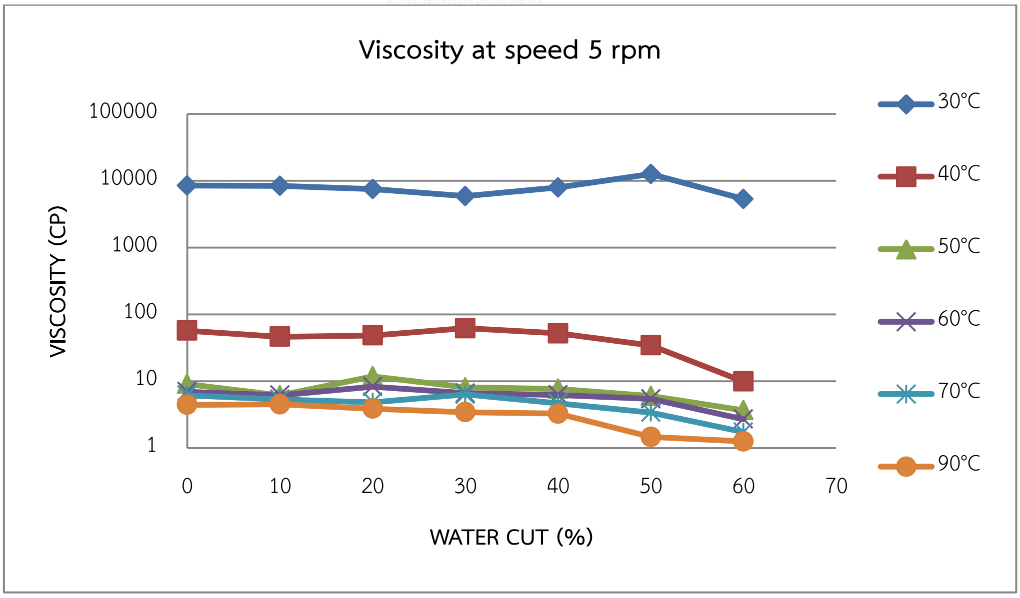

Figure 5.17 Viscosity at speed 5 rpm

Tabel 5.13 Viscosity at speed 15 rpm

WC (%)	VISCOSITY (CP)					
	30°C	40°C	50°C	60°C	70°C	90°C
0	3557.8889	30.5967	8.6663	6.924	6.2822	4.4928
10	4686.4444	23.6501	6.3600	6.1324	5.7200	4.4889
20	3702.83	27.3242	11.1757	8.2033	4.8703	4.3211
30	2709.2222	29.162	7.7516	6.2192	5.8800	3.6311
40	3944.6667	23.6385	6.6398	5.8603	4.6774	3.3337
50	6334.8066	17.8897	5.5626	4.7786	3.3799	1.7814
60	1068.0663	6.5929	3.4898	2.8351	1.8407	1.5268

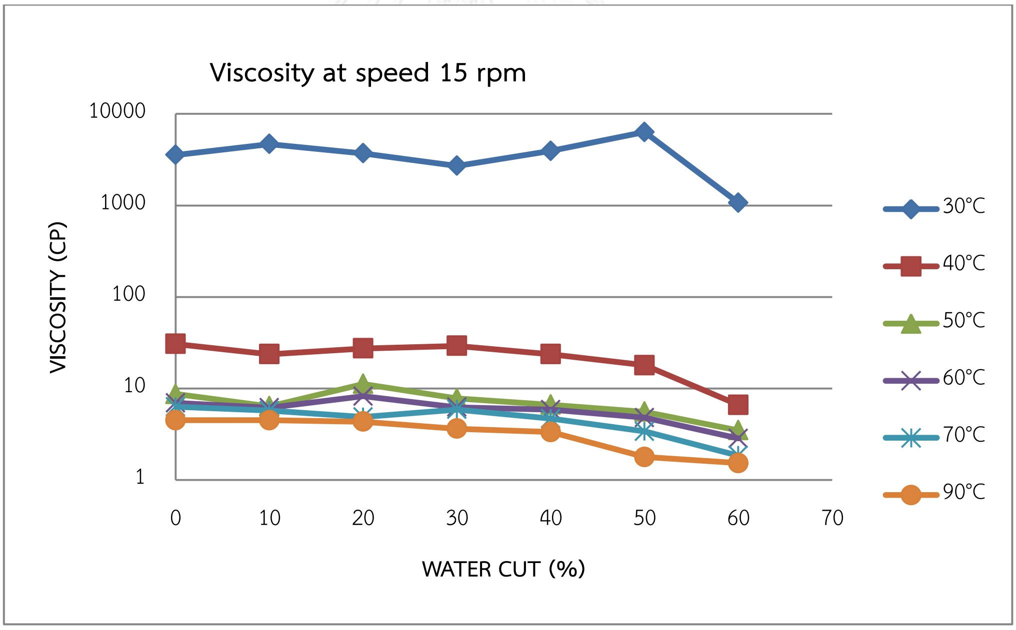

Figure 5.18 Viscosity at speed 15 rpm

Tabel 5.14 Viscosity at speed 25 rpm

WC (%)	VISCOSITY (CP)					
	30°C	40°C	50°C	60°C	70°C	90°C
0	1886.5856	23.8997	8.6756	7.1131	6.3667	4.6012
10	3089.2667	22.3315	6.5042	6.1781	5.9922	4.5387
20	2609.11	22.4192	11.0656	8.2462	4.9969	4.4506
30	1853.4667	22.1884	7.9093	6.1431	5.907	3.6772
40	2500.8	17.6018	6.4608	5.7435	4.7607	3.3472
50	3996.4641	13.8311	5.4603	4.6481	3.3767	1.9078
60	560.6188	5.6831	3.4762	2.9378	1.9105	1.5794

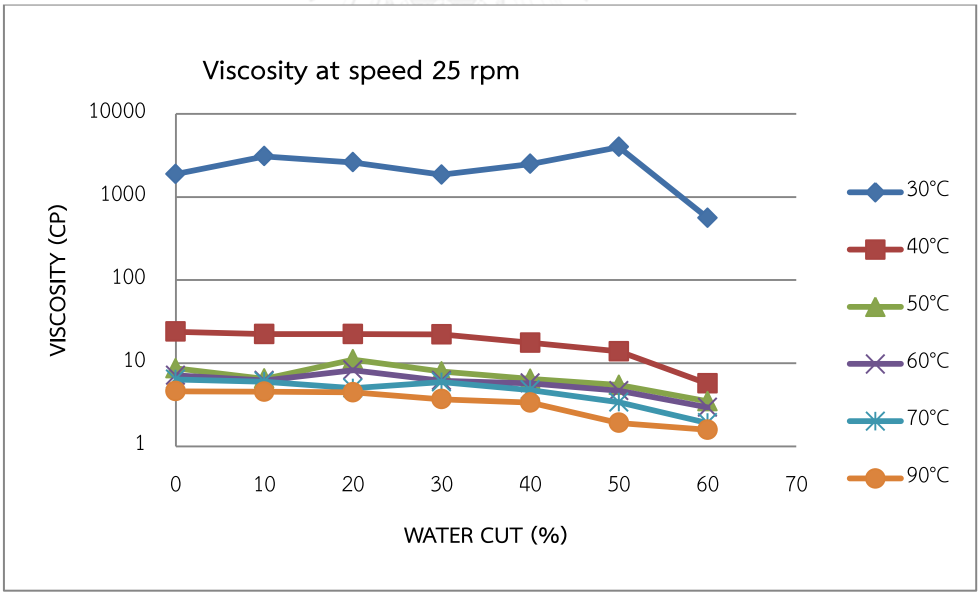

Figure 5.19 Viscosity at speed 25 rpm

Tabel 5.15 Viscosity at speed 35 rpm

WC (%)	VISCOSITY (CP)					
	30°C	40°C	50°C	60°C	70°C	90°C
0	1371.674	N/A	8.7651	7.2957	6.4716	4.7043
10	1823.2917	N/A	6.6967	6.234	6.1849	4.5898
20	1792.24	N/A	11.1670	8.3524	5.1719	4.5750
30	1296.0917	N/A	8.1174	6.0974	5.8721	3.7203
40	1518.5472	15.1740331	6.5001	5.7965	4.8714	3.3979
50	2359.3536	11.9032597	5.5247	4.6507	3.3960	2.0347
60	383.3779	5.24977901	3.4636	3.0516	1.9482	1.6547

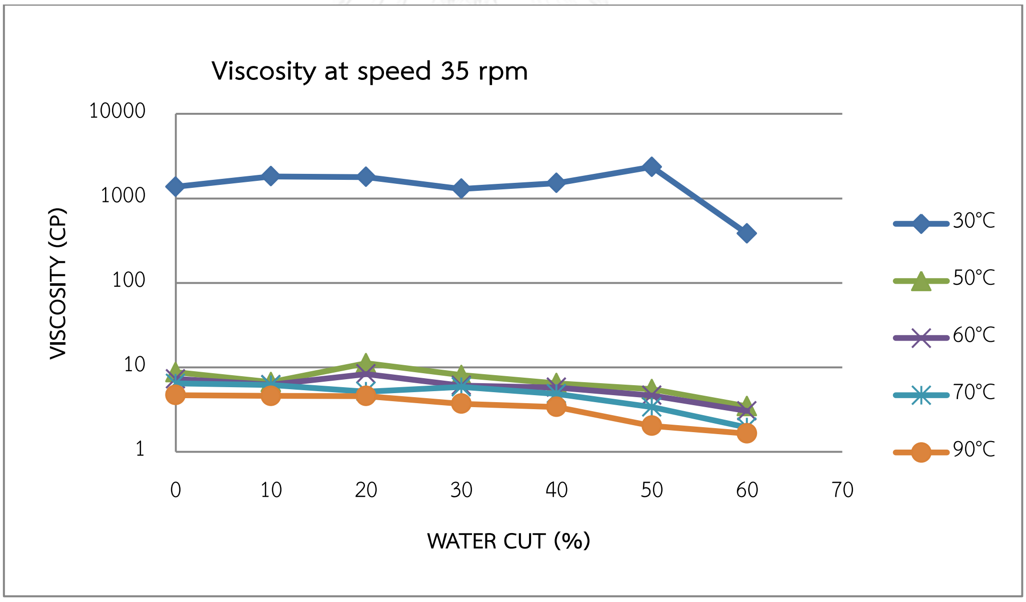

Figure 5.20 Viscosity at speed 35 rpm

Tabel 5.16 Viscosity at speed 60 rpm

WC (%)	VISCOSITY (CP)					
	30°C	40°C	50°C	60°C	70°C	90°C
0	964.3094	N/A	8.7577	7.4564	6.5750	4.8322
10	1107.9722	N/A	6.8469	6.3023	6.3341	4.662
20	1034.04	N/A	11.1573	8.4925	5.4088	4.6948
30	885.5556	N/A	8.2000	6.0928	5.7504	3.8061
40	936.8889	N/A	6.5282	5.8281	5.0722	3.4975
50	1415.4696	9.796	5.5971	4.8572	3.6213	2.1883
60	283.4807	4.6848	3.6346	3.2409	2.2000	1.8075

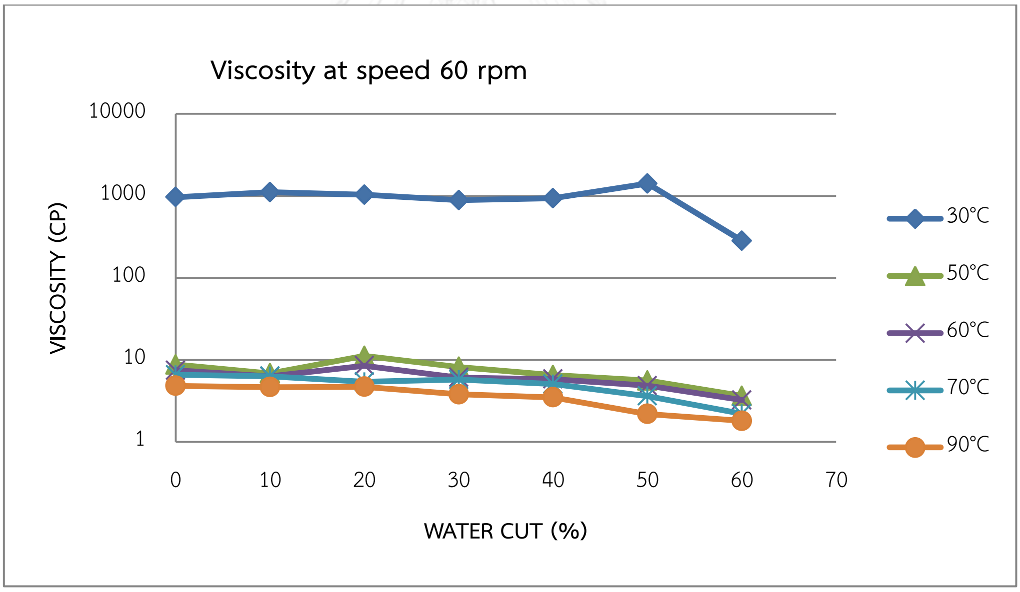

Figure 5.21 Viscosity at speed 60 rpm

5.5 Correlations for predicting viscosity of emulsion

There are three correlations used for this work to predict the viscosity of emulsion.

5.5.1 Ronningsen's Correlation:

$$\ln \eta_r = k_1 + k_2 t + k_3 \cdot \phi + k_4 t \cdot \phi \quad (5.1)$$

Where η_r is relative viscosity, t is temperature (°C), ϕ is water cut (%), k_1, k_2, k_3, and k_4 are the constant.

To develop Ronningsen's correlation of this work, the water cut of 60% is excluded because the emulsion becomes oil-in-water emulsion at 60% of water cut.

From the experiment at shear rate of 1.223 s^{-1}, the constants, k_1-k_4, can be calculated by mathematical method and the correlation should be:

$$\ln \eta_r = -0.591864427 + 0.0106348683 \cdot t - 0.0275436144 \cdot \phi - 0.000560574512 \cdot t \cdot \phi \quad (5.2)$$

The comparison between experimental data and predicted data is demonstrated in Figure 5.22. The point near trend line has less deviation and absolute average deviations (AADs) is calculated by following equation:

$$\%AAD = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{P_{exp} - P_{cal}}{P_{exp}} \right|$$

Where n is the amount of data points.

The absolute average deviationsof equation 5.2 is 24.47%

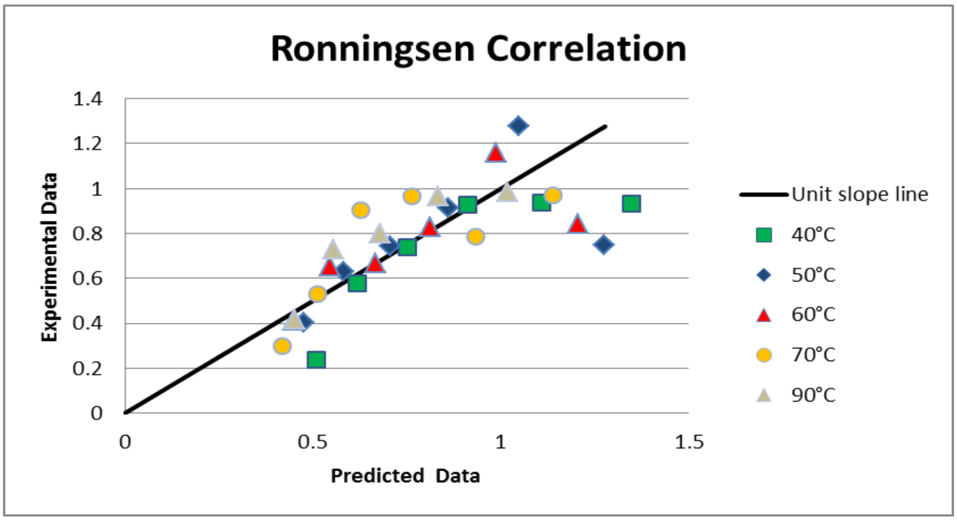

Figure 5.22 Comparison between experiment and correlation of Ronningsen's correlation at shear rate of 1.223 s^{-1}

From the experiment at shear rate of 6.115 s^{-1}, the constants, k_1-k_4, can be calculated by mathematical method and the correlation should be:

$$\ln \eta_r = -0.423224041 + 0.00831392608 \cdot t + 0.014212358 \cdot \phi - 0.00038758453 \cdot t \cdot \phi. \quad (5.3)$$

The comparison between experimental data and predicted data is demonstrated in Figure 5.23 and %AAD of equation 5.3 is 17.43%.

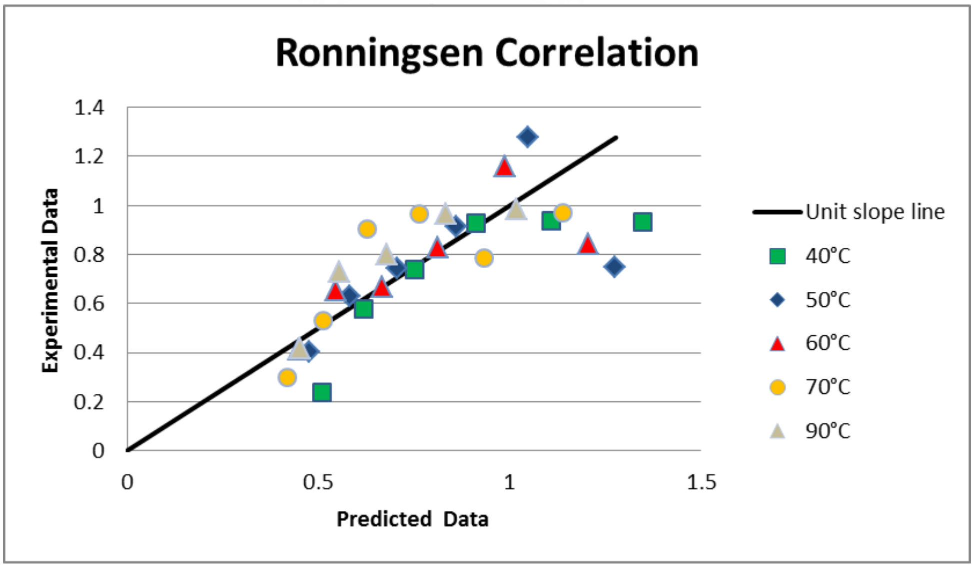

Figure 5.23 Comparison between experiment and correlation of Ronningsen's correlation at shear rate of 6.115 s^{-1}

From the experiment at shear rate of 18.34 s^{-1}, the constants, k_1-k_4, can be calculated by mathematical method and the correlation should be:

$$\ln \eta_r = -0.310200857+0.00680906976 \cdot t +0.00582490757 \cdot \phi -0.000272255805 \cdot t \cdot \phi \quad (5.4)$$

The comparison between experimental data and predicted data is demonstrated in Figure 5.24 and %AAD of equation 5.4 is 14.25%.

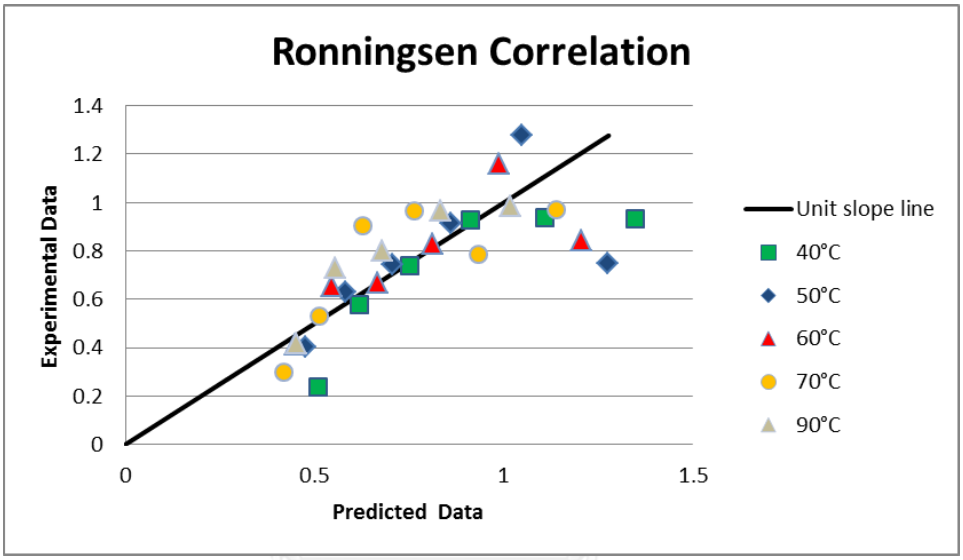

Figure 5.24 Comparison between experiment and correlation of Ronningsen's correlation at shear rate of 18.34 s^{-1}

From the experiment at shear rate of 30.58 s^{-1}, the constants, k_1-k_4, can be calculated by mathematical method and the correlation should be:

$$\ln \eta_r = -0.0593361139+0.0034676822 \cdot t -0.00169893881 \cdot \phi -0.000174940935 \cdot t \cdot \phi \quad (5.4)$$

The comparison between experimental data and predicted data is demonstrated in Figure 5.25 and %AAD of equation 5.5 is 26.03%.

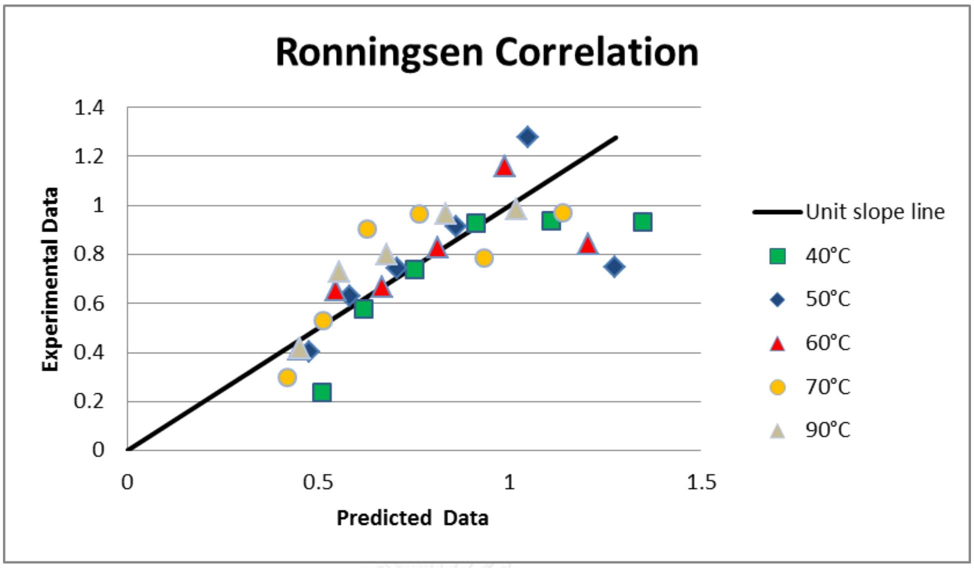

Figure 5.25 Comparison between experiment and correlation of Ronningsen's correlation at shear rate of 30.78 s^{-1}

From the experiment at shear rate of 42.81 s^{-1}, the constants, k_1-k_4, can be calculated by mathematical method and the correlation should be:

$$\ln \eta_r = -0.1589621261+0.00465014085\cdot t+0.00395566961\cdot \phi-0.000246025392\cdot t\cdot \phi \quad (5.6)$$

The comparison between experimental data and predicted data is demonstrated in Figure 5.26 and %AAD of equation 5.6 is 13.51%.

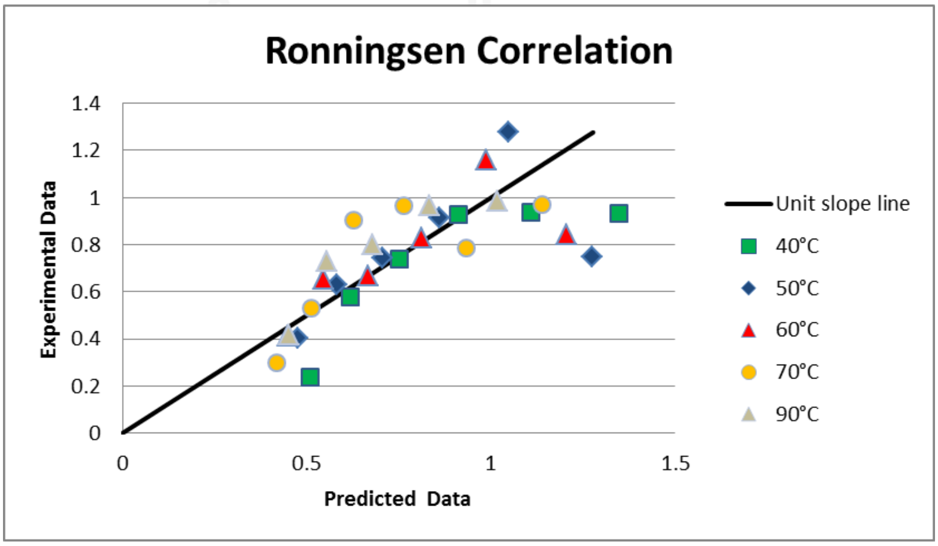

Figure 5.26 Comparison between experiment and correlation of Ronningsen's correlation at shear rate of 42.81 s^{-1}

From the experiment at shear rate of 73.38 s^{-1}, the constants, k_1-k_4, can be calculated by mathematical method and the correlation should be:

$$\ln \eta_r = -0.110051323+0.00375729378\cdot t+0.00256242456\cdot \phi-0.000216702563\cdot t\cdot \phi \quad (5.7)$$

The comparison between experimental data and predicted data is demonstrated in Figure 5.27 and %AAD of equation 5.7 is 12.73%.

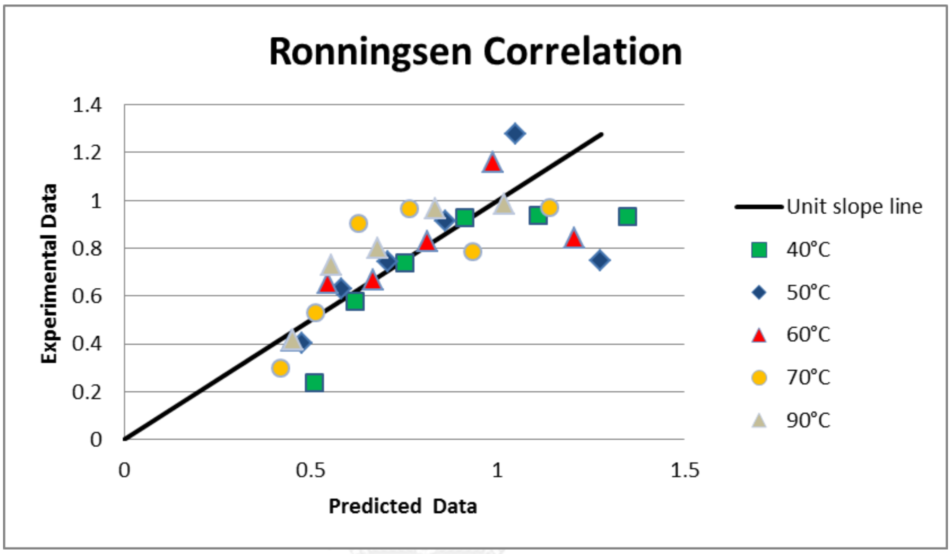

Figure 5.27 Comparison between experiment and correlation of Ronningsen's correlation at shear rate of 73.38 s^{-1}

Tabel 5.17 %AADs of Ronningsen's correlation

Shear rate (1/s)	%AADs (%)
1.223	24.47
6.115	17.43
18.34	14.25
30.58	26.03
42.81	13.51
73.38	12.73

5.5.2 Farah's correlation:

$$\ln(\ln(\mu_r+0.7)) = A - B\ln(T)$$

Where A is $k_1 + k_2\phi$, B is $k_3 + k_4\phi$, μ_r is relative viscosity, T is temperature(°C), ϕ is water cut (%), k_1, k_2, k_3, and k_4 are constant.

To develop Farah's correlation of this work, the water cut of 60% is excluded because the emulsion becomes oil-in-water emulsion at 60% of water cut.

From the experiment at shear rate of 1.223 s^{-1}, the Farah's correlation can be estimated by mathematical method and the correlation should be:

$$\ln(\ln(\mu_r+0.7))=(-2.0587546)+(0.0738605394\cdot\phi)-((-0.343002931+0.01928331\cdot\phi)\cdot T) \quad (5.8)$$

The comparison between experimental data and predicted data is demonstrated in Figure 5.28 and %AAD of equation 5.8 is 26.41%.

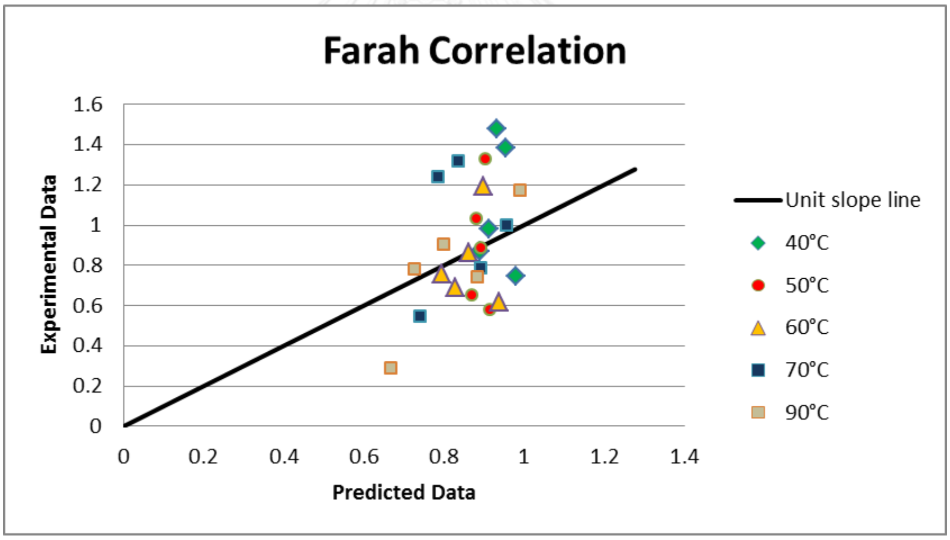

Figure 5.28 Comparison between experiment and correlation of Farah's correlation at shear rate of 1.223 s^{-1}

From the experiment at shear rate of 6.115 s^{-1}, the Farah's correlation can be estimated by mathematical method and the correlation should be:

$$\ln(\ln(\mu_r+0.7))=(-5.49805716)+(0.224415358\cdot\phi)-((-1.24915228+0.0595036755\cdot\phi)\cdot T) \quad (5.9)$$

The comparison between experimental data and predicted data is demonstrated in Figure 5.29 and %AAD of equation 5.9 is 20.66%.

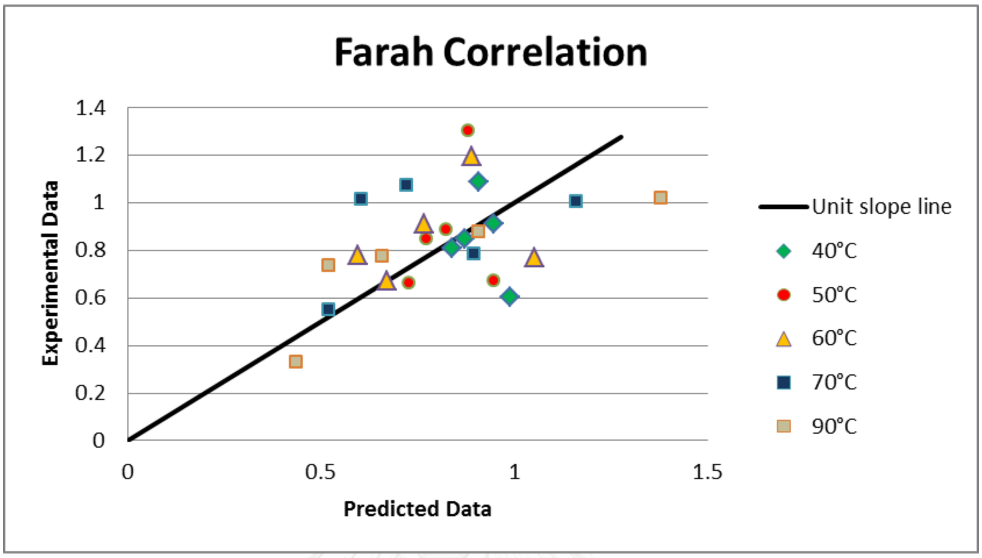

Figure 5. 29 Comparison between experiment and correlation of Farah's correlation at shear rate of 6.115 s^{-1}

From the experiment at shear rate of 18.34 s^{-1}, the Farah's correlation can be estimated by mathematical method and the correlation should be:

$$\ln(\ln(\mu_r+0.7)) =(-3.5184712)+(0.112951281\cdot\phi)-((-0.756105148+0.03183067\cdot\phi)\cdot T) \quad (5.10)$$

The comparison between experimental data and predicted data is demonstrated in Figure 5.30 and %AAD of equation 5.10 is 15.9%.

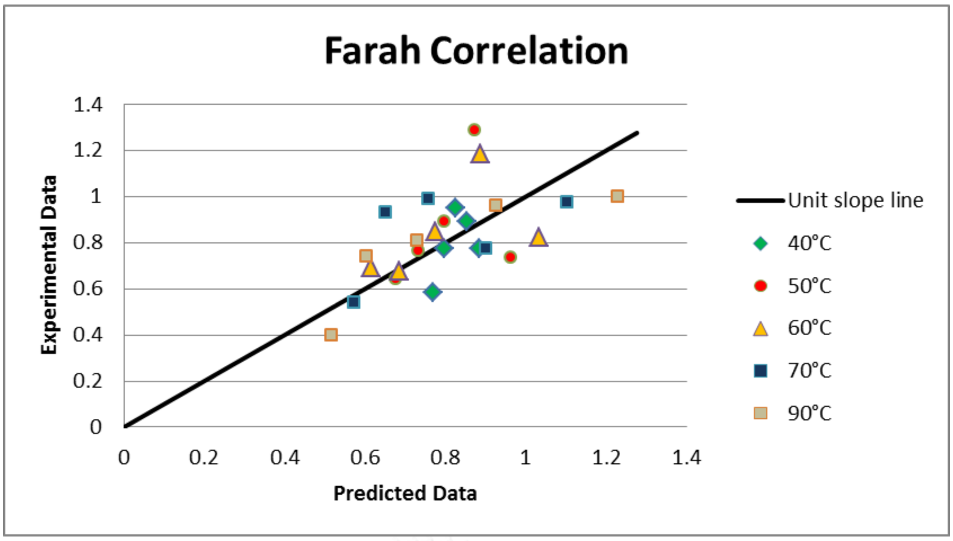

Figure 5.30 Comparison between experiment and correlation of Farah's correlation at shear rate of 18.34 s^{-1}

From the experiment at shear rate of 30.58 s^{-1}, the Farah's correlation can be estimated by mathematical method and the correlation should be:

$$\ln(\ln(\mu_r+0.7))=(-5.13584131)+(0.258009242\cdot\phi)-((-1.35478606+0.075490049\cdot\phi)\cdot T) \quad (5.11)$$

The comparison between experimental data and predicted data is demonstrated in Figure 5.31 and %AAD of equation 5.11 is 37.82%.

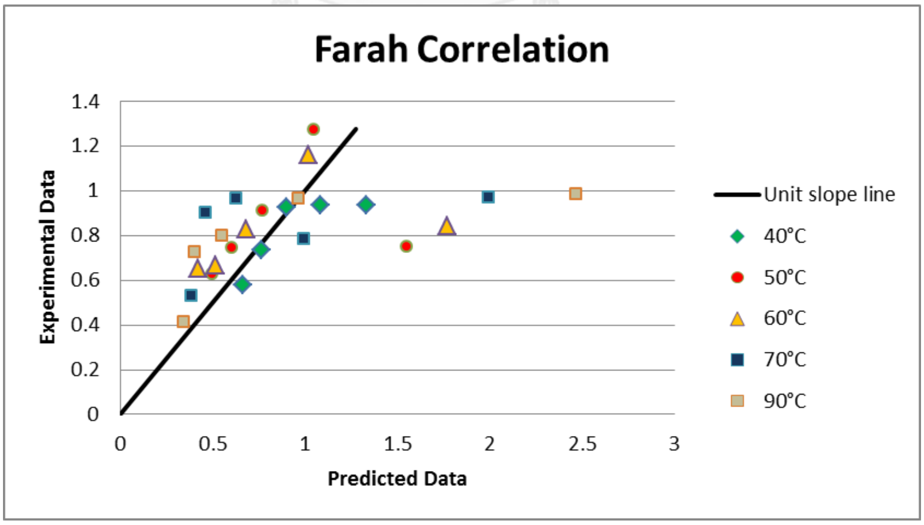

Figure 5.31 Comparison between experiment and correlation of Farah's correlation at shear rate of 30.78 s^{-1}

From the experiment at shear rate of 42.81 s^{-1}, the Farah's correlation can be estimated by mathematical method and the correlation should be:

$$\ln(\ln(\mu_r+0.7))=(-3.2329444)+(0.123637869\cdot\phi)-((-0.68178745+0.0340557222\cdot\phi)\cdot T) \quad (5.12)$$

The comparison between experimental data and predicted data is demonstrated in Figure 5.32 and %AAD of equation 5.12 is 14.61%.

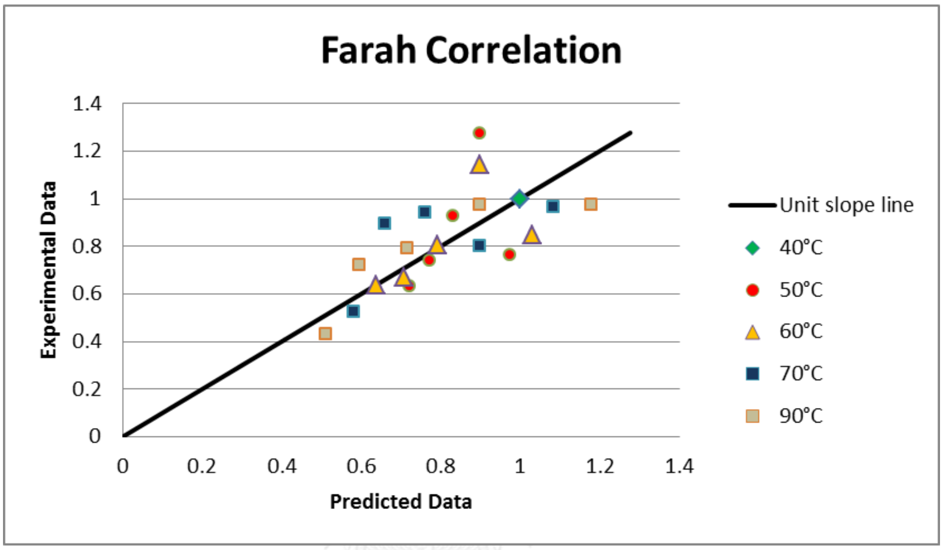

Figure 5.32 Comparison between experiment and correlation of Farah's correlation at shear rate of 42.81 s^{-1}

From the experiment at shear rate of 73.38 s^{-1}, the Farah's correlation can be estimated by mathematical method and the correlation should be:

$$\ln(\ln(\mu_r+0.7))=(-2.71327858)+(0.103566784\cdot\phi)-((-0.551487147+0.028939003\cdot\phi)\cdot T) \quad (5.12)$$

The comparison between experimental data and predicted data is demonstrated in Figure 5.33 and %AAD of equation 5.12 is 13.52%.

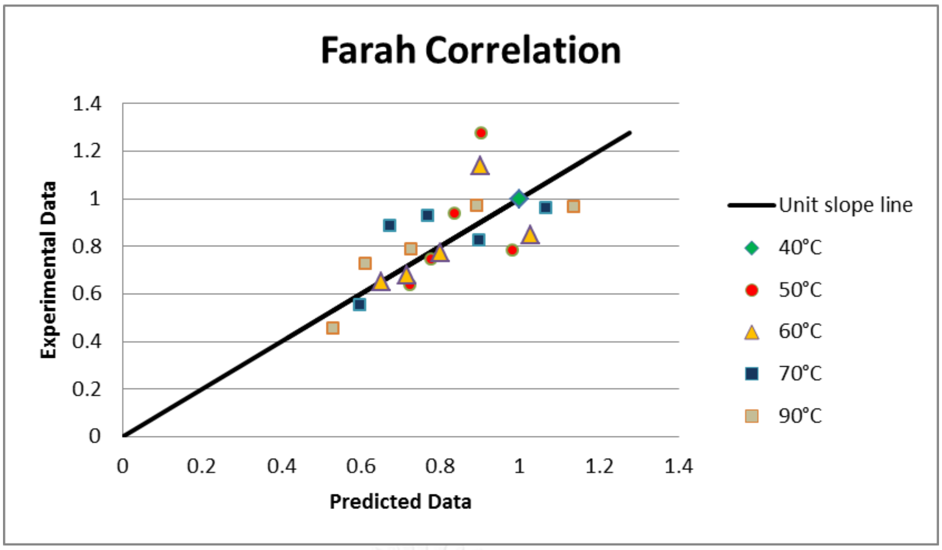

Figure 5.33 Comparison between experiment and correlation of Farah’s correlation at shear rate of 73.38 s^{-1}

Tabel 5.18 %AADs of Farah’s correlation

Shear rate (1/s)	%AADs (%)
1.223	26.41
6.115	20.66
18.34	15.9
30.58	37.82
42.81	14.61
73.38	13.52

5.5.3 Al-Roomi’s Correlation:

$$\eta = a\gamma^{b}\exp(c\phi + d/T) \qquad (5.13)$$

Where η is viscosity, T is temperature (°C), ϕ is water cut (%), γ is shear rate, a, b, c and d are constant.

The equation can be developed by taking natural logarithm (ln) into equation and the equation become:

$$\ln \eta = a + b \cdot \ln \gamma - c \cdot \phi + d/T \tag{5.14}$$

To develop Al-Roomi’s correlation of this work, the water cut of 60% is excluded because the emulsion becomes oil-in-water emulsion at 60% of water cut.

From the experiment at 40°C, The Al-Roomi’s correlation can be calculated by mathematical method and the developed equation should be:

$$\ln \eta = 9.79316347 - 0.725535836 \cdot \ln \gamma - 0.00515277151 \cdot \phi - 171.29178/T \tag{5.15}$$

From the experiment at 50°C, The Al-Roomi’s correlation can be calculated by mathematical method and the developed equation should be:

$$\ln \eta = 6.08217883 - 0.0575482511 \cdot \ln \gamma - 0.0067039375 \cdot \phi - 184.103213/T \tag{5.16}$$

From the experiment at 60°C, The Al-Roomi’s correlation can be calculated by mathematical method and the developed equation should be:

$$\ln \eta = 14.4507482 - 0.0511181403 \cdot \ln \gamma - 0.00751363744 \cdot \phi - 733.602103/T \tag{5.17}$$

From the experiment at 70°C, The Al-Roomi’s correlation can be calculated by mathematical method and the developed equation should be:

$$\ln \eta = 19.0011782 - 0.00836912453 \cdot \ln \gamma - 0.0113273227 \cdot \phi - 1192.07623/T \tag{5.18}$$

From the experiment at 90°C, The Al-Roomi’s correlation can be calculated by mathematical method and the developed equation should be:

$$\ln \eta = 0.574661377 - 0.0910043589 \cdot \ln \gamma - 0.0196768486 \cdot \phi + 125.835134/T \tag{5.19}$$

Viscosity of emulsion in Al-Roomi’s correlation is the function of temperature, water cut and shear rate. The comparison between experimental data and predicted data is demonstrated in Figure 5.34. The absolute average deviations for equation 5.15 - 5.18 are shown in Table 5.17. The correlations are classified by temperature because temperature play significant role in viscosity of emulsion.

Tabel 5.19 %AADs of Al-Roomi’s correlation

Temperature (°C)	%AADs
40	17.19
50	19.39
60	11.12
70	11.60
90	17.44

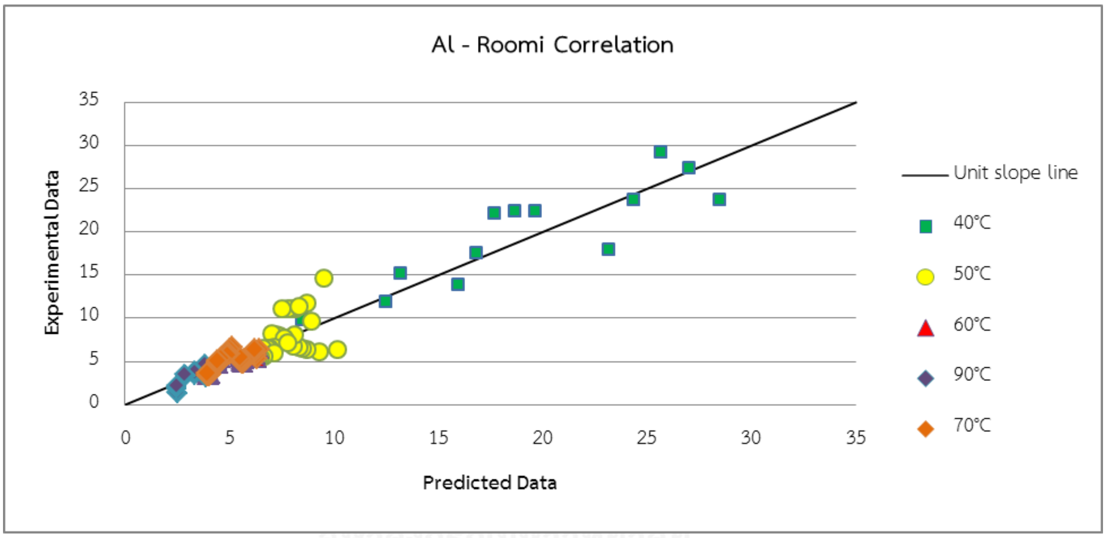

Figure 5.34 Comparison between viscosity from experiment and Al-Roomi’s correlation

5.6 The best correlation for predicting viscosity of emulsion from an oilfield in Thailand

In this work, there are three developed correlations for predicting viscosity of emulsion such as Ronningsen’s correlation, Farah’s correlation and Al-Roomi’s correlation. The comparison of the average absolute deviations between Ronningsen’s correlation, Farah’s correlation and Al-Roomi’s correlation is displayed in Table 5.6.1. Comparing with the average absolute deviations, Al-Roomi’s correlation has 15.35% of AAD which is the lowest %AADs. Moreover, the viscosity of emulsion in Al-Roomi’s correlation is the function of temperature, water cut and shear rate which are the main parameters of viscosity changing. While the viscosity of emulsion in Ronningsen's correlation and Farah's correlation is just the function of temperature and water cut. So Al-Roomi's correlation should be chosen as the effective correlation for predicting emulsion viscosity in the future work.

Tabel 5.20 %AAD of correlations

Correlation	%AADs
Ronningsen	18.07
Farah	21.5
Al-Roomi	15.35

The best correlation for this work is Al-Roomi's correlation at 60% of water cut with 11.12% of AADs. The comparison between viscosity from experiment and correlation is shown in Table 5.21-5.22 and Figure 5.35. The deviation is ranging from -29.4365% to 24.791%.

Tabel 5.21 Comparison of Al-Roomi's data and experimental data at 60°C

Temperature (°C)	Shear rate (1/s)	Water cut (%)	Viscosity (cp)		Deviation (%)
			Experiment	Correlation	
60	1.223	10	6.5574	8.4877	-29.4365
60	6.115	10	6.1837	7.8174	-26.4197
60	18.34	10	6.1324	7.3906	-20.5157
60	30.58	10	6.1781	7.1999	-16.5395
60	42.81	10	6.2340	7.0771	-13.5255
60	73.38	10	6.3023	6.8849	-9.2443
60	1.223	20	9.2486	7.8733	14.8700
60	6.115	20	8.2966	7.2515	12.5962
60	18.34	20	8.2033	6.8556	16.4288
60	30.58	20	8.2462	6.6788	19.0085
60	42.81	20	8.3524	6.5649	21.4015
60	73.38	20	8.4925	6.3865	24.7981

Tabel 5.22 Comparison of Al-Roomi’s data and experimental data at 60°C (continued)

Temperature (°C)	Shear rate (1/s)	Water cut (%)	Viscosity (cp)		Deviation (%)
			Experiment	Correlation	
60	1.223	30	8.6287	7.3035	15.3589
60	6.115	30	6.6123	6.7266	-1.7287
60	18.34	30	6.2192	6.3594	-2.2536
60	30.58	30	6.1431	6.1953	-0.8500
60	42.81	30	6.0974	6.0897	0.1271
60	73.38	30	6.0928	5.9242	2.7660
60	1.223	40	8.1010	6.7748	16.3707
60	6.115	40	6.2514	6.2397	0.1864
60	18.34	40	5.8603	5.8991	-0.6609
60	30.58	40	5.7435	5.7469	-0.0591
60	42.81	40	5.7965	5.6489	2.5463
60	73.38	40	5.8282	5.4954	5.7097
60	1.223	50	5.8910	6.2844	-6.6793
60	6.115	50	5.4200	5.7881	-6.7914
60	18.34	50	4.7786	5.4721	-14.5131
60	30.58	50	4.6481	5.3309	-14.6899
60	42.81	50	4.6507	5.2400	-12.6711
60	73.38	50	4.8572	5.0976	-4.9498

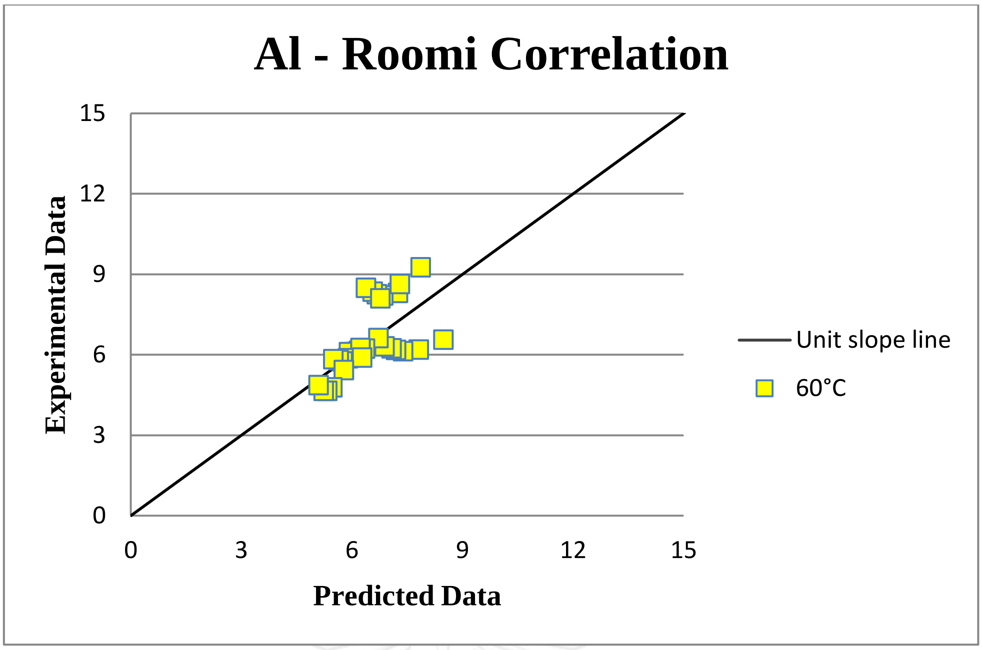

Figure 5. 35 Comparison of viscosity from correlation and experiment at 60°C

CHAPTER VI
CONCLUSIONS

From the study of parameters effect on emulsion's viscosity from an oilfield in Thailand and develop correlation for predicting the viscosity, the following conclusion can be drawn.

1. There are several parameters that effect on viscosity of emulsion such as temperature, shear rate and amount of water dispersing in oil. The most importance parameter for emulsion's viscosity is temperature because the temperature changes viscosity of emulsion in highest value.
2. The viscosity of emulsion is decreased by increasing temperature. At temperature of 30°C - 50°C, the viscosity of emulsion extremely decreases as the temperature increases but the viscosity slightly decreases at high temperature.
3. Shear rate has less effect on viscosity of emulsion at temperature of 50°C - 90°C. For viscosity of emulsion at 40°C, the viscosity decrease as the shear rate increase at low shear rate but after that the viscosity slightly decrease. Conversely, the viscosity of emulsion largely decreases as the shear rate increase at temperature of 30°C. The emulsion shows Non-newtonian fluid behavior at low temperature because its viscosity is a function of shear rate.
4. At any percentage of water cut, the viscosity of emulsion increases as the water cut increase because more dispersed phase needs more energy between water droplet and oil. Whereas, the viscosity of emulsion acutely decrease at high percentage of water cut because of the split of droplet.
5. The correlations for predicting the emulsion's viscosity of this work develop from Ronningsen's correlation, Farah's correlation and Al-Roomi's correlation. For Ronningsen's correlation and Farah's correlation, the viscosity is the

function of %water cut and temperature but the viscosity of Al-Roomi's correlation is the function of %water cut, temperature and shear rate.

6. The water cut of 60% is excluded for developing correlations because the emulsion becomes water-in-oil emulsion at 60% of water cut.
7. The average absolute deviations (AADs) of Ronningsen's correlation, Farah's correlation and Al-Roomi's correlation are 18.07, 21.5 and 15.35 respectively.
8. The best correlation for predicting viscosity of emulsion is Al-Roomi's correlation because the viscosity of Al-Roomi's correlation is the function of all important parameters and Al-Roomi's correlation gives the lowest %AADs.
9. The correlation can be used for future work to predict the viscosity of emulsion from an oilfield in Thailand.

Recommendations

1. Study other parameters that effect on viscosity of emulsion such as the average droplets size and droplets size distribution because the study in average droplets size and droplets size distribution can affect the emulsion viscosity and stability.

2. Study the effect of interfacial tension and emulsifier on viscosity of emulsion because interfacial tension and emulsifier effect on stability of emulsion and it may effects on emulsion's viscosity.

REFERENCES

[1] Farah, M.A., Oliveira, R.C., Caldas, J.N., and Rajagopal, K., Viscosity of water-in-oil emulsions: Variation with Temperature and Water Volume Fraction. **Journal of Petroleum Science and Engineering**, 2005. 48(3–4): p. 169-184.

[2] Ronningsen, H.P. Correlations for predicting Viscosity of W/O-Emulsions based on North Sea Crude Oils. in **SPE International Symposium on Oilfield Chemistry**. San Antonio, Texas: Society of Petroleum Engineers, 1995.

[3] Maneeintr, K., Sasaki, K., and Sugai, Y., Investigation of the Effects of Parameters on Viscosities and Correlation of Heavy Oil and Stability of Its Emulsion. **Journal of the Japan Institute of Energy**, 2013. 92(9): p. 900-904.

[4] Kumar, K., Nikolov, A.D., and Wasan, D.T., Mechanisms of Stabilization of Water-in-Crude Oil Emulsions. **Industrial & Engineering Chemistry Research**, 2001. 40(14): p. 3009-3014.

[5] Marsden, S.S. and Mad, M.L., Stability Of Concentrated Crude Oil-In-Water Emulsions As A Function Of Shear Rate, Temperature And Oil Concentration, in Annual Technical Meeting. Petroleum Society of Canada: Banff.

[6] Alboudwarej, H., et al., Rheology of Heavy-Oil Emulsions. 22(03).

[7] Dan, D. and Jing, G., Apparent Viscosity Prediction of Non-Newtonian Water-in-Crude Oil Emulsions. **Journal of Petroleum Science and Engineering**, 2006. 53(1–2): p. 113-122.

[8] Masood, A. and Nazar, R.S., An Experimental Study on Factors Affecting the Heavy Crude Oil in Water Emulsions Viscosity. **Journal of Petroleum Science and Engineering**, 2013. 106: p. 1-8.

[9] Laurier, L.S., Petroleum Emulsions. in **Emulsions**, pp. 1-49. American Chemical Society, 1992

[10] Kokal, S.L. and Aramco, S., Crude Oil Emulsion. Petroleum Engineering handbook. Vol. 1. 2006, United States of America.: Society of Petroleum Engineers.

[11] Arnold, K. and Stewart, M., Surface Production Operations. Emulsion Treating Theory. Vol. 1. 1998, Houston, TX: Gulf Publishing Company.

[12] Langevin, D., Poteau, S., Henaut, I., and Argillier, J.F. Crude oil Emulsion Properties and their Application to Heavy Oil Transportation. in **Oil & Gas Science and Technology**. France, 2004.

[13] Walstra, P., Principles of Emulsion Formation. **Chemical Engineering Science**, 1993. 48(2): p. 333-349.

[14] Pal, R., Yan, Y., and Masliyah, J., Rheology of Emulsions. in **Emulsions**, pp. 131-170. American Chemical Society, 1992

[15] Karen, S.P. and Ronningsen, H.P., Effect of Precipitated Wax on Viscosity-Amodel for predicting Non-Newtonian Viscosity of Crude Oil, in Energy & Fuels. 2000. p. 43-51.

APPENDIX

APPENDIX

1. Table data of correlations

Comparison between experiment and correlation of Ronningsen’s correlation (shear rate of 1.223 s^{-1})

Temperature (°C)	Water cut (%)	Relative Viscosity		Deviation (%)
		Experiment	Correlation	
40	10	0.87136406	0.891131428	-2.2685547
40	20	0.98135262	0.937951519	4.42257966
40	30	1.47950159	0.98723154	33.2726951
40	40	1.38122579	1.039100736	24.7696689
40	50	0.747352	1.093695141	-46.342705
50	10	0.57579697	0.937093585	-62.747224
50	20	1.3271028	0.932558648	29.7297357
50	30	0.88483106	0.928045657	-4.883938
50	40	1.02898488	0.923554506	10.2460569
50	50	0.65064598	0.919085089	-41.257322
60	10	0.61906798	0.985426347	-59.179021
60	20	1.19281744	0.927196784	22.2683413
60	30	0.86264277	0.872408049	-1.1320184
60	40	0.6925823	0.82085682	-18.521195
60	50	0.75977052	0.772351791	-1.6559302
70	10	1.00008027	1.036251981	-3.6168803
70	20	0.7851365	0.921865749	-17.41471
70	30	1.31597573	0.820105991	37.6807664
70	40	1.23549073	0.729578942	40.9482464
70	50	0.54358107	0.649044681	-19.401635
90	10	1.16794341	1.145902806	1.88712938
90	20	0.73757764	0.911295456	-23.552479
90	30	0.90211137	0.724720634	19.6639508
90	40	0.7818323	0.576344361	26.2828662
90	50	0.28959627	0.458346026	-58.270692

Comparison between experiment and correlation of Ronningsen's correlation (shear rate of 6.115 s^{-1})

Temperature (°C)	Water cut (%)	Relative Viscosity		Deviation (%)
		Experiment	Correlation	
40	10	0.81114091	0.901606489	-11.152881
40	20	0.85011552	0.890041454	-4.6965305
40	30	1.0870282	0.878624765	19.1718518
40	40	0.91081235	0.867354519	4.77132632
40	50	0.60350853	0.856228839	-41.875185
50	10	0.67384481	0.94252175	-39.872229
50	20	1.30235784	0.895059726	31.2739018
50	30	0.88774977	0.84998772	4.25368192
50	40	0.84795808	0.807185379	4.80833952
50	50	0.65993483	0.766538411	-16.153653
60	10	0.76888375	0.985293761	-28.145999
60	20	1.19317315	0.900106293	24.5619722
60	30	0.91260303	0.822284044	9.89685343
60	40	0.67420544	0.751190225	-11.418594
60	50	0.77947813	0.686243104	11.9612117
70	10	1.00376997	1.030006783	-2.6138273
70	20	0.78626776	0.905181313	-15.123799
70	30	1.07335372	0.795483314	25.8880555
70	40	1.01476431	0.699079504	31.1091749
70	50	0.55180023	0.614358773	-11.337171
90	10	1.02092595	1.125612192	-10.254048
90	20	0.87786603	0.915417358	-4.2775696
90	30	0.77695856	0.744473935	4.18099785
90	40	0.73777911	0.605452186	17.9358458
90	50	0.33031287	0.492391113	-49.068098

Comparison between experiment and correlation of Ronningsen's correlation (shear rate of 18.34 s^{-1})

Temperature (°C)	Water cut (%)	Relative Viscosity		Deviation (%)
		Experiment	Correlation	
40	10	0.77296282	0.915311062	-18.415923
40	20	0.89304442	0.870102238	2.56898557
40	30	0.95310943	0.827126357	13.2181117
40	40	0.77258216	0.786273131	-1.7721056
40	50	0.58469484	0.747437718	-27.833816
50	10	0.73387734	0.953490139	-29.925
50	20	1.28955757	0.882051334	31.6004685
50	30	0.89444827	0.815964974	8.77449245
50	40	0.76616077	0.754830034	1.47889752
50	50	0.64186061	0.698275536	-8.7892797
60	10	0.82611471	0.993261726	-20.232906
60	20	1.18476908	0.894164527	24.5283707
60	30	0.84922281	0.804954203	5.21283817
60	40	0.67554295	0.724644347	-7.2684348
60	50	0.69014599	0.652346962	5.47696061
70	10	0.97616038	1.034692249	-5.9961324
70	20	0.77524888	0.90644407	-16.922977
70	30	0.98997364	0.794092014	19.7865493
70	40	0.93284583	0.695665787	25.4254276
70	50	0.53800954	0.609439307	-13.276673
90	10	0.99912554	1.122809776	-12.379249
90	20	0.96178062	0.931511376	3.14720872
90	30	0.80820353	0.772805387	4.37985508
90	40	0.7419991	0.641138887	13.593037
90	50	0.3965094	0.531905029	-34.14689

Comparison between experiment and correlation of Ronningsen's correlation (shear rate of 30.58 s^{-1})

Temperature (°C)	Water cut (%)	Relative Viscosity		Deviation (%)
		Experiment	Correlation	
40	10	0.9343831	0.992434178	-6.212771
40	20	0.9380537	0.909772828	3.01484612
40	30	0.9283978	0.833996468	10.1681985
40	40	0.73648409	0.764531635	-3.808303
40	50	0.57871395	0.700852634	-21.10519
50	10	0.74970971	1.009634254	-34.670025
50	20	1.2754859	0.909489601	20.8431662
50	30	0.91167134	0.8192782	0.23931245
50	40	0.74470524	0.738014781	-10.013755
50	50	0.62938795	0.664811803	-17.259122
60	10	0.84242526	1.027132428	21.0835864
60	20	1.15930468	0.909206462	21.5731227
60	30	0.83043523	0.804819678	-23.686037
60	40	0.66928994	0.712417632	-35.846425
60	50	0.65345842	0.630624344	-23.163105
70	10	0.97037677	1.044933866	26.5834003
70	20	0.78484341	0.908923411	19.6496605
70	30	0.96488377	0.790616318	18.0609787
70	40	0.90211781	0.687708288	-15.831198
70	50	0.53037368	0.598194951	-71.374153
90	10	0.98641206	1.081467651	19.8492853
90	20	0.96725583	0.908357573	28.9010965
90	30	0.79917893	0.762957153	25.1488083
90	40	0.72745875	0.640830919	11.9082806
90	50	0.41463078	0.53825338	-160.82667

Comparison between experiment and correlation of Ronningsen's correlation (shear rate of 42.81 s^{-1})

Temperature (°C)	Water cut (%)	Relative Viscosity		Deviation (%)
		Experiment	Correlation	
50	10	0.76401635	0.990138726	-29.596535
50	20	1.27403434	0.910859866	28.5058623
50	30	0.92610204	0.83792874	9.52090532
50	40	0.74159152	0.770837095	-3.9436235
50	50	0.63030715	0.709117374	-12.503463
60	10	0.84774316	1.012060803	-19.382951
60	20	1.14484446	0.908400527	20.6529303
60	30	0.80486631	0.81535765	-1.303489
60	40	0.66771533	0.731844685	-9.6042961
60	50	0.63746155	0.656885531	-3.0470832
70	10	0.96328112	1.034468243	-7.3900674
70	20	0.79916507	0.905947829	-13.36179
70	30	0.94218468	0.793394553	15.792034
70	40	0.89568237	0.694824687	22.4251017
70	50	0.52475842	0.608500958	-15.958302
90	10	0.97565389	1.080782438	-10.775188
90	20	0.97250669	0.901062282	7.34641851
90	30	0.79083517	0.751227266	5.00836435
90	40	0.72229872	0.626307878	13.2896324
90	50	0.43252304	0.522160969	-20.724427

Comparison between experiment and correlation of Ronningsen's correlation (shear rate of 73.38 s^{-1})

Temperature (°C)	Water cut (%)	Relative Viscosity		Deviation (%)
		Experiment	Correlation	
50	10	0.78180731	0.995098382	-27.281795
50	20	1.2739961	0.916089963	28.0931894
50	30	0.93631518	0.843354623	9.92833981
50	40	0.7454236	0.776394294	-4.1547775
50	50	0.63909854	0.714750453	-11.837284
60	10	0.84949178	1.011049613	-19.018174
60	20	1.13895969	0.910821554	20.0303961
60	30	0.77120657	0.820529371	-6.3955367
60	40	0.68025505	0.739188094	-8.663374
60	50	0.65142059	0.665910397	-2.2243404
70	10	0.95851404	1.027256538	-7.1717783
70	20	0.82263377	0.905583442	-10.083426
70	30	0.92665199	0.79832188	13.8487923
70	40	0.88641368	0.703764882	20.6053678
70	50	0.55075867	0.62040766	-12.646008
90	10	0.96477021	1.060453934	-9.917773
90	20	0.97156512	0.895197419	7.860276
90	30	0.78764284	0.755693759	4.05629024
90	40	0.72378317	0.63792974	11.8617608
90	50	0.45285139	0.538517552	-18.917059

Comparison between experiment and correlation of Farah’s correlation (shear rate of 1.223 s^{-1})

Temperature (°C)	Water cut (%)	Relative Viscosity		Deviation (%)
		Experiment	Correlation	
40	10	0.87136406	0.89166417	-2.32969402
40	20	0.98135262	0.91224528	7.04204975
40	30	1.47950159	0.93367259	36.8927619
40	40	1.38122579	0.95598894	30.7869179
40	50	0.747352	0.97923981	-31.0279233
50	10	0.57579697	0.91707429	-59.270426
50	20	1.3271028	0.90496562	31.8089289
50	30	0.88483106	0.89313487	-0.93846263
50	40	1.02898488	0.88157431	14.3258252
50	50	0.65064598	0.87027647	-33.7557597
60	10	0.61906798	0.93879181	-51.6459968
60	20	1.19281744	0.89909303	24.6244229
60	30	0.86264277	0.86225672	0.0447528
60	40	0.6925823	0.82803585	-19.5577558
60	50	0.75977052	0.79620885	-4.79596452
70	10	1.00008027	0.95785931	4.22175779
70	20	0.7851365	0.89417994	-13.8884687
70	30	1.31597573	0.83760559	36.3509848
70	40	1.23549073	0.78719663	36.2846998
70	50	0.54358107	0.74216006	-36.5316237
90	10	1.16794341	0.99040864	15.2006314
90	20	0.73757764	0.88627089	-20.1596748
90	30	0.90211137	0.80005664	11.3128752
90	40	0.7818323	0.7281621	6.86466916
90	50	0.28959627	0.66782601	-130.605871

Comparison between experiment and correlation of Farah's correlation (shear rate of 6.115 s^{-1})

Temperature (°C)	Water cut (%)	Relative Viscosity		Deviation (%)
		Experiment	Correlation	
40	10	0.81114091	0.839258	-3.46636306
40	20	0.85011552	0.87305812	-2.69876236
40	30	1.0870282	0.90935998	16.3443984
40	40	0.91081235	0.94839252	-4.12600554
40	50	0.60350853	0.9904106	-64.1088003
50	10	0.67384481	0.94720537	-40.5672885
50	20	1.30235784	0.88254342	32.2349513
50	30	0.88774977	0.8253134	7.03310479
50	40	0.84795808	0.77450456	8.66240043
50	50	0.65993483	0.72926823	-10.5060983
60	10	0.76888375	1.05469433	-37.1721451
60	20	1.19317315	0.89043003	25.372941
60	30	0.91260303	0.76652482	16.0067633
60	40	0.67420544	0.67158174	0.38915436
60	50	0.77947813	0.59788158	23.2971969
70	10	1.00376997	1.16255497	-15.8188636
70	20	0.78626776	0.89719576	-14.1081717
70	30	1.07335372	0.72266644	32.6721075
70	40	1.01476431	0.60396925	40.4818194
70	50	0.55180023	0.52118597	5.54807078
90	10	1.02092595	1.38146985	-35.3153815
90	20	0.87786603	0.908422	-3.48071004
90	30	0.77695856	0.66084777	14.9442702
90	40	0.73777911	0.52109373	29.3699526
90	50	0.33031287	0.43825497	-32.678746

Comparison between experiment and correlation of Farah's correlation (shear rate of 18.34 s^{-1})

Temperature (°C)	Water cut (%)	Relative Viscosity		Deviation (%)
		Experiment	Correlation	
40	10	0.77296282	0.88594003	-14.6161245
40	20	0.89304442	0.85429873	4.33860731
40	30	0.95310943	0.82463079	13.479946
40	40	0.77258216	0.79678916	-3.13325919
40	50	0.58469484	0.77063988	-31.8020678
50	10	0.73387734	0.96280297	-31.1939906
50	20	1.28955757	0.87293301	32.3075576
50	30	0.89444827	0.79698115	10.896898
50	40	0.76616077	0.73242208	4.40360407
50	50	0.64186061	0.67726537	-5.51595802
60	10	0.82611471	1.03456644	-25.2327821
60	20	1.18476908	0.88870318	24.9893339
60	30	0.84922281	0.77563443	8.66537989
60	40	0.67554295	0.68684725	-1.67336504
60	50	0.69014599	0.61636617	10.6904647
70	10	0.97616038	1.10256261	-12.9489206
70	20	0.77524888	0.90243431	-16.4057539
70	30	0.98997364	0.75840641	23.3912522
70	40	0.93284583	0.65252832	30.049715
70	50	0.53800954	0.57336209	-6.57098934
90	10	0.99912554	1.23042066	-23.1497553
90	20	0.96178062	0.92563504	3.75819387
90	30	0.80820353	0.73183033	9.44974861
90	40	0.7419991	0.60365783	18.6443991
90	50	0.3965094	0.51639936	-30.2363462

Comparison between experiment and correlation of Farah’s correlation (shear rate of 30.58 s^{-1})

Temperature (°C)	Water cut (%)	Relative Viscosity		Deviation (%)
		Experiment	Correlation	
40	10	0.9343831	1.33348159	-42.7125127
40	20	0.9380537	1.08318489	-15.4715226
40	30	0.9283978	0.9021723	2.82481312
40	40	0.73648409	0.76833487	-4.3247074
40	50	0.57871395	0.66757752	-15.3553527
50	10	0.74970971	1.55107806	-106.890486
50	20	1.2754859	1.04846084	17.799104
50	30	0.91167134	0.76923986	15.623117
50	40	0.74470524	0.60334661	18.9818229
50	50	0.62938795	0.50013525	20.5362523
60	10	0.84242526	1.77240106	-110.392678
60	20	1.15930468	1.02144772	11.8913483
60	30	0.83043523	0.68531902	17.4747177
60	40	0.66928994	0.51601232	22.9015281
60	50	0.65345842	0.42452119	35.0347052
70	10	0.97037677	1.99901668	-106.004176
70	20	0.78484341	0.99951036	-27.3515641
70	30	0.96488377	0.62747084	34.9692829
70	40	0.90211781	0.46335557	48.6369112
70	50	0.53037368	0.38417556	27.5651174
90	10	0.98641206	2.47227071	-150.632652
90	20	0.96725583	0.96541898	0.18990276
90	30	0.79917893	0.55278661	30.8306831
90	40	0.72745875	0.40470328	44.3675283
90	50	0.41463078	0.34497882	16.7985489

Comparison between experiment and correlation of Farah’s correlation (shear rate of 42.81 s^{-1})

Temperature (°C)	Water cut (%)	Relative Viscosity		Deviation (%)
		Experiment	Correlation	
50	10	0.76401635	0.97529855	-27.6541451
50	20	1.27403434	0.89809396	29.5078688
50	30	0.92610204	0.83103777	10.2649885
50	40	0.74159152	0.77255557	-4.17535171
50	50	0.63030715	0.72135982	-14.4457615
60	10	0.84774316	1.03171578	-21.7014576
60	20	1.14484446	0.8981859	21.545159
60	30	0.80486631	0.79234973	1.55511235
60	40	0.66771533	0.70754525	-5.96510507
60	50	0.63746155	0.63895846	-0.23482396
70	10	0.96328112	1.08384234	-12.5156841
70	20	0.79916507	0.89826364	-12.4002628
70	30	0.94218468	0.76216193	19.1069494
70	40	0.89568237	0.66043859	26.2641963
70	50	0.52475842	0.5832355	-11.1436186
90	10	0.97565389	1.17872434	-20.8137786
90	20	0.97250669	0.89839042	7.62115846
90	30	0.79083517	0.71738249	9.28798946
90	40	0.72229872	0.59618491	17.4600626
90	50	0.43252304	0.51281597	-18.5638496

Comparison between experiment and correlation of Farah’s correlation (shear rate of 73.38 s^{-1})

Temperature	Water cut	Relative Viscosity		Deviation
(°C)	(%)	Experiment	Correlation	(%)
50	10	0.78180731	0.98346886	-25.7942778
50	20	1.2739961	0.90476078	28.9824528
50	30	0.93631518	0.83648087	10.6624675
50	40	0.7454236	0.77699805	-4.2357723
50	50	0.63909854	0.72498079	-13.4380295
60	10	0.84949178	1.0269388	-20.8886089
60	20	1.13895969	0.90099768	20.8929267
60	30	0.77120657	0.79990048	-3.7206512
60	40	0.68025505	0.71794845	-5.54106743
60	50	0.65142059	0.65095387	0.07164512
70	10	0.95851404	1.06628106	-11.2431346
70	20	0.82263377	0.89783743	-9.14181557
70	30	0.92665199	0.77120786	16.7748121
70	40	0.88641368	0.67446306	23.9110273
70	50	0.55075867	0.59956098	-8.86092491
90	10	0.96477021	1.13603631	-17.7520089
90	20	0.97156512	0.89272691	8.11455728
90	30	0.78764284	0.72838929	7.52289615
90	40	0.72378317	0.61406647	15.1587793
90	50	0.45285139	0.53272044	-17.6369225

Comparison between experiment and correlation of Al-Roomi’s correlation

Temperature	Shear rate	Water cut	Relative Viscosity		Deviation
(°C)	(1/s)	(%)	Experiment	Correlation	(%)
40	1.223	10	168.5324	203.01623	-20.461245
40	6.115	10	46.32	63.154306	-36.343493
40	18.34	10	23.6501	28.465597	-20.361422
40	30.58	10	22.3315	19.643716	12.03584
40	42.81	10	N/A	15.389243	N/A
40	73.38	10	N/A	10.409223	N/A
40	1.223	20	189.80552	192.82021	-1.5883031
40	6.115	20	48.545635	59.982529	-23.559056
40	18.34	20	27.324199	27.035979	1.0548172
40	30.58	20	22.419227	18.657157	16.780551
40	42.81	20	N/A	14.616354	N/A
40	73.38	20	N/A	9.8864438	N/A
40	1.223	30	286.15359	183.13626	36.000711
40	6.115	30	62.074475	56.970045	8.223074
40	18.34	30	29.161989	25.678159	11.946475
40	30.58	30	22.188453	17.720144	20.137992
40	42.81	30	N/A	13.882281	N/A
40	73.38	30	N/A	9.3899201	N/A
40	1.223	40	267.14586	173.93867	34.889999
40	6.115	40	52.011713	54.108857	-4.0320618
40	18.34	40	23.638453	24.388533	-3.1731364
40	30.58	40	17.601768	16.830191	4.3835184
40	42.81	40	15.174033	13.185076	13.107635
40	73.38	40	N/A	8.9183332	N/A
40	1.223	50	144.54696	165.20301	-14.290196

Comparison between experiment and correlation of Al-Roomi's correlation (continued)

Temperature (°C)	Shear rate (1/s)	Water cut (%)	Relative Viscosity		Deviation (%)
			Experiment	Correlation	
40	6.115	50	34.463204	51.391366	-49.119522
40	18.34	50	17.889724	23.163676	-29.480345
40	30.58	50	13.831105	15.984934	-15.572357
40	42.81	50	11.90326	12.522886	-5.2055216
40	73.38	50	9.7960221	8.4704306	13.531936
50	1.223	10	6.3312217	10.19085	-60.961827
50	6.115	10	6.12	9.2893626	-51.78697
50	18.34	10	6.36	8.7203765	-37.112837
50	30.58	10	6.5041667	8.4675414	-30.186414
50	42.81	10	6.6966667	8.3051806	-24.019621
50	73.38	10	6.8468611	8.0515765	-17.595148
50	1.223	20	14.592265	9.5300583	34.691028
50	6.115	20	11.828287	8.6870247	26.557206
50	18.34	20	11.175691	8.1549326	27.029721
50	30.58	20	11.06558	7.9184918	28.440338
50	42.81	20	11.167017	7.7666588	30.450011
50	73.38	20	11.15732	7.5294987	32.515167
50	1.223	30	9.7292308	8.9121133	8.3985821
50	6.115	30	8.0627298	8.1237434	-0.7567367
50	18.34	30	7.7515556	7.6261531	1.6177718
50	30.58	30	7.9092778	7.4050435	6.3752259
50	42.81	30	8.1173611	7.2630556	10.524425
50	73.38	30	8.2	7.0412734	14.130812
50	1.223	40	11.314286	8.3342369	26.338815
50	6.115	40	7.7013333	7.5969863	1.354922

Comparison between experiment and correlation of Al-Roomi’s correlation (continued)

Temperature (°C)	Shear rate (1/s)	Water cut (%)	Relative Viscosity		Deviation (%)
			Experiment	Correlation	
50	18.34	40	6.6397778	7.1316605	-7.4081203
50	30.58	40	6.46075	6.924888	-7.1839646
50	42.81	40	6.5001111	6.7921068	-4.492165
50	73.38	40	6.5282222	6.5847054	-0.865215
50	1.223	50	7.15423	7.793831	-8.9401796
50	6.115	50	5.99	7.1043849	-18.531532
50	18.34	50	5.5625556	6.6692317	-19.895102
50	30.58	50	5.4603056	6.4758666	-18.598979
50	42.81	50	5.5246944	6.3516952	-14.969168
50	73.38	50	5.5970556	6.157742	-10.017526
70	1.223	10	6.4	6.401675688	-0.0261826
70	6.115	10	5.346333333	6.316025893	-18.137525
70	18.34	10	5.72	6.25823411	-9.4096872
70	30.58	10	5.99225	6.231513503	-3.9928825
70	42.81	10	6.184871795	6.213992811	-0.4708427
70	73.38	10	6.334111111	6.186031106	2.3378182
70	1.223	20	5.148066298	5.71609886	-11.033901
70	6.115	20	4.843756906	5.639621588	-16.430731
70	18.34	20	4.870276243	5.58801892	-14.737207
70	30.58	20	4.996850829	5.564159912	-11.353332
70	42.81	20	5.171878453	5.54851557	-7.2824046
70	73.38	20	5.408839779	5.523548377	-2.1207616
70	1.223	30	6.688579387	5.103942745	23.691677
70	6.115	30	6.345666667	5.035655679	20.644182
70	18.34	30	5.88	4.989579313	15.143209

Comparison between experiment and correlation of Al-Roomi’s correlation (continued)

Temperature (°C)	Shear rate (1/s)	Water cut (%)	Relative Viscosity		Deviation (%)
			Experiment	Correlation	
70	30.58	30	5.906963788	4.968275446	15.891215
70	42.81	30	5.872055556	4.954306509	15.629093
70	73.38	30	5.750388889	4.932013136	14.231659
70	1.223	40	5.37	4.557344472	15.13325
70	6.115	40	4.688	4.496370496	4.0876601
70	18.34	40	4.677444444	4.455228602	4.750796
70	30.58	40	4.760722222	4.436206237	6.8165285
70	42.81	40	4.871444444	4.42373328	9.1905218
70	73.38	40	5.072222222	4.403827379	13.177554
70	1.223	50	3.56421	4.069283234	-14.170692
70	6.115	50	3.399333333	4.014839165	-18.106663
70	18.34	50	3.379888889	3.978103293	-17.699233
70	30.58	50	3.376722222	3.961118097	-17.306602
70	42.81	50	3.396027778	3.94998091	-16.311796
70	73.38	50	3.621253482	3.932206799	-8.5868973
90	1.223	10	4.9866667	4.4875936	10.00815
90	6.115	10	4.5166667	4.473651	0.9523772
90	18.34	10	4.4888889	4.4641609	0.5508714
90	30.58	10	4.5386944	4.4597503	1.739359
90	42.81	10	4.5897778	4.4568503	2.8961635
90	73.38	10	4.6619722	4.4522092	4.4994491
90	1.223	20	3.1491713	3.877757	-23.135793
90	6.115	20	3.8837569	3.8657091	0.4646991
90	18.34	20	4.321105	3.8575087	10.728651
90	30.58	20	4.4505525	3.8536974	13.410808

Comparison between experiment and correlation of Al-Roomi's correlation (continued)

Temperature (°C)	Shear rate (1/s)	Water cut (%)	Relative Viscosity		Deviation (%)
			Experiment	Correlation	
90	42.81	20	4.5749724	3.8511916	15.820441
90	73.38	20	4.6948066	3.8471811	18.054535
90	1.223	30	3.8516667	3.3507935	13.004063
90	6.115	30	3.4373333	3.3403829	2.8205141
90	18.34	30	3.6311111	3.3332968	8.2017401
90	30.58	30	3.6771944	3.3300035	9.441735
90	42.81	30	3.7203333	3.3278382	10.55
90	73.38	30	3.8060556	3.3243727	12.655697
90	1.223	40	3.3381215	2.8954412	13.261362
90	6.115	40	3.264	2.8864452	11.567242
90	18.34	40	3.3336667	2.8803221	13.598976
90	30.58	40	3.3471944	2.8774764	14.033188
90	42.81	40	3.3979167	2.8756053	15.371519
90	73.38	40	3.4974722	2.8726108	17.866088
90	1.223	50	1.2364641	2.5019684	-102.34865
90	6.115	50	1.4613333	2.494195	-70.679399
90	18.34	50	1.7814444	2.488904	-39.71269
90	30.58	50	1.9078056	2.4864449	-30.3301
90	42.81	50	2.0347222	2.4848281	-22.121244
90	73.38	50	2.188273	2.4822405	-13.433768

2. Oil composition

Light Oil is obtained from an oilfield in Thailand with 39 °API

C_8-C_{13} = 39.83%

C_{12}-C_{17} =41.53%

C_{17}-C_{20} = 13.64%

C_{20}+ = 5.0%

VITA

Miss Sarin Wutthisirisart was born on July 22, 1989 in Bangkok, Thailand. She received her Bachelor degree in Civil Engineering from Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University in 2012. After graduation, she has been a student in the Master's Degree program in Petroleum Engineering at Department of Mining and Petroleum Engineering, Faculty of Engineering, Chulalongkorn University since the academic year 2012.