

# Experimental study on foamy viscosity by analysing CO<sub>2</sub> micro-bubbles in hexadecane

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## To cite this article:

Chanmoly Or, Kyuro Sasaki, Yuichi Sugai, Masanori Nakano, Motonao Imai. Experimental Study on Foamy Viscosity by Analysing CO<sub>2</sub> Micro-Bubbles in Hexadecane. *International Journal of Oil, Gas and Coal Engineering*. Vol. 2, No. 2, 2014, pp. 11-18  
doi: 10.11648/j.ogce.20140202.11

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**Abstract:** Continuous desorbing gas in the heavy oil generates lower viscosity with dispersing gas micro-bubbles. In this study, laboratory experiments were carried out to measure the viscosity of foamy hexadecane, typical component of heavy oil, and to investigate the CO<sub>2</sub> gas micro-bubbles at ranged temperature of 20 – 50 °C and depressurization pressure of 1.0 – 6.0 MPa. Apparently, hexadecane mobility increases with increasing foam swelling. The viscosity ratio of foam vs. original hexadecane showed 0.90 – 0.70 with increasing foam swelling in the swelling range of 3.0 – 4.8%. The foam swelling is caused by dispersed gas micro-bubbles, and its viscosity was more reducible at either low temperature or high foam swelling based on present measurement results. The bubble distribution showed the large bubbles (approximately 50 μm in diameter) were coalesced but the micro-bubbles (approximately 5 μm in diameter) were stable under the shear of 1575 s<sup>-1</sup>, within 3 minutes of measuring. It shows that the micro-bubbles in smaller diameter have higher stability against the high shear rate. Therefore, generating foam by creating CO<sub>2</sub> micro-bubbles is capable to make flow through the pore throats with viscosity reduction and improves oil recovery from non-mobile domain, such as aggregate and fine pores, by its swelling.

**Keywords:** Viscosity Ratio, Foamy Hexadecane, Temperature, Foam Swelling, and CO<sub>2</sub> Micro-Bubble Distribution

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## 1. Introduction

Reducing oil viscosity or improving oil mobility is a common procedure for enhanced oil recovery (EOR) from reservoirs. There are several methods have been implemented to generate this based on the reservoir conditions. One of those methods is foam which takes interested to study due to its significant physical properties.

Foam was first introduced by Bond and Holbrook (1958) [1] to obtain a favorable oil mobility. In gas-drive process, they generated foam to reduce the mobility of gas phase and increase the displacing ability of the injected gas. The term foamy oil describes as the dispersed gas-liquid two-phase fluid that occurs in heavy oil reservoirs during primary production (Sheng *et al.*, 1999)[2]. In 2001, Maini [3] reviewed foam oil flow as a dispersion of gas in oil with a surface-active agent.

As an EOR application, foamy oil has been applied successfully in both of laboratory test (Maini, 1996; Bernard *et al.*, 1980; Yin *et al.*, 2009, Yan *et al.*, 2006; Kovscek *et al.*, 1995)[4–8] and field studies (Blaker *et al.*, 2002; Stevens

and Martin, 1995)[9–10]. It was reported that the primary production of heavy oil from several reservoirs in western Canada is in the form of foamy oil. Those reservoirs exhibit anomalously high production, in terms of both the production rate and the primary recovery factor (Maini, 1996 and 1999)[4, 11]. Especially, in 1999, Maini [11] reported the oil production rate is more than ten times of the flow rate predicted by Darcy's law.

The successful foamy oil operation has been mainly concentrated on fundamental study of bubble generation and stability. The gas bubbles generated from the oil phase due to the pressure decline keeps dispersing in the oil to form foamy oil (Maini *et al.*, 1993)[12]. Some researches found some parameters which affect on the foam stability such as surface tension (Wilkinson *et al.*, 1993; Bennion *et al.*, 2003; Wang *et al.*, 2009) [13–15], asphaltene content (Albartamani *et al.*, 1999) [16], and temperature (Liu *et al.*, 2013) [17]. Those parameters belong to fluid properties; however there is no study about bubble stability under shear rate which is given in porous flows.

Furthermore, Abivin *et al.* (2009) [18] have studied on foam viscosity and they have concluded the effect of gas bubbles is reducing the apparent viscosity. They have correlated the deformation of bubble under low shear rate with the apparent viscosity, but they have not studied the bubble distribution which correlated to the apparent viscosity. So, the physical properties and characteristics of dispersed gas bubble (gas-in-oil) such as the resistance of gas bubbles under high shear rate still are not well understood.

On the other hand, carbon dioxide gas has been pretended to eliminate from the overall environment since it is currently a major gas contributing to global warming. Commonly, CO<sub>2</sub> has been captured and injected into the geological storages. Beside environmental benefit, CO<sub>2</sub> has also been injected into petroleum reservoirs for enhanced oil recovery (EOR). Due to high dissolution into the oil when injecting and slow desorbing from the oil phase when depressurizing, CO<sub>2</sub> is expected to generate high quality of foamy oil and the dispersed gas bubbles are stabilized.

The objective of this study is to measure the apparent foam viscosity under high shear rate and to analyze distribution of CO<sub>2</sub> gas micro-bubble. In this study, the measurement and analysis have been carried out to present a relationship of apparent foam viscosity and micro-bubble distribution. The discussion involves with the effect on physical properties such as foam swelling and apparent viscosity, but excludes the chemical properties change.

## 2. Experimental Apparatus and Procedure

### 2.1. Samples Used for Measurements

Some petroleums, such as Brazilian, are characterized as heavy oil with average properties similar to those of hexadecane (Campos *et al.*, 2009)[19]. Moreover, hexadecane is a pure chemical compound, called alkane hydrocarbon. The pure component liquid has a good reproducibility in measurements since the crude oil has various multi-components. Therefore, the characteristics of hexadecane at low temperature are considered to be quite similar with those of heavy oil in reservoir with high temperature. In addition, hexadecane is colorless that the high transparency allows observing the micro-bubbles clearly. Hexadecane was used as a liquid sample for this study.

Hexadecane (C<sub>16</sub>H<sub>34</sub>), molecular weight 226.44, has density of 0.774 g/ml at 20 °C and freezing point of 16 – 19 °C. This substance is supplied by Wako Pure Chemical Industries, Ltd.

Carbon dioxide (CO<sub>2</sub>) in 99.9% purity was used for solution gas, since CO<sub>2</sub> has relatively high solubility in oils.

### 2.2. Gas Solubility Measurements

A PVT apparatus (RUSKA, Model 2370) has been used to conduct the experiment of CO<sub>2</sub> gas solubility into hexadecane. The apparatus (Fig. 2.1) mainly consists of (1) a

gas pump, (2) a stainless steel cylinder, (3) a piston, (4) a magnet, and (5) a controlling system. The functions and specifications of these elements are briefly described as the following. (1) The gas pump was settled inside the PVT room to ensure the gas temperature and experiment temperature are the same. (2) The stainless steel cylinder is 44.2 mm diameter and 360 ml volume. (3) The piston may be controlled either by automatic system or manual to vary the gas volume. (4) The function of magnet is to shake the liquid surface in order to obtain the gas saturation shortly. (5) The controlling system installed in a computer can be used to record and manage the Pressure, Volume, and Temperature (PVT) of the experiment. The pressure and temperature of this apparatus are limited by 70 MPa and 200 °C, respectively.

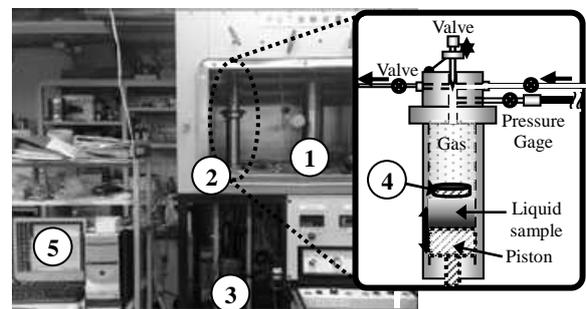


Figure 2.1. PVT equipment (RUSKA Model 2370).

### 2.2. Foamy Oil Preparation and Procedure

The apparatus for generating foamy oil was installed as shown in Fig. 2.2. Hexadecane about 45 ml in the high pressure-mixer cell was heated in desired temperature and CO<sub>2</sub> gas was injected as designed pressure.

After injection, the rotor started stirring the mixer in order to obtain equilibrium condition shortly. The pressure starts reducing after injection and rotation of mixer. Once the equilibrium pressure was obtained, the rotation was stopped and started depressurizing to make foamy hexadecane.

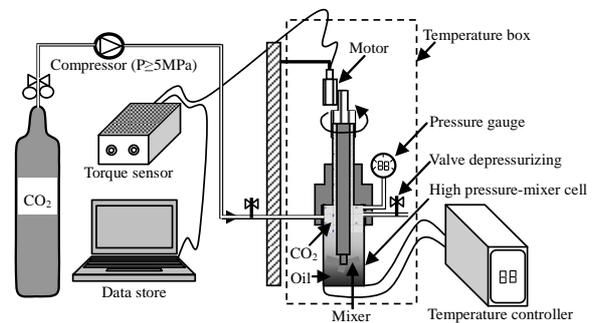


Figure 2.2. Apparatus of foamy oil generation.

### 2.3. Viscosity Measurements

The viscosity measurements under atmospheric pressure were carried out by using a programmable rheometer (Brookfield, Model DV-III). Several functional operations

are available in this rheometer such as viscometer torque (%), viscosity (mPa.s), shear stress (N/m<sup>2</sup>), and shear rate (1/s). These functional operations are controlled by rotational speed (*rpm*) which is in range of 0 – 250 *rpm* with 0.1 *rpm* increments.

The relationship of viscosity and *rpm* may be various depending on cone-and-plate spindle and specification of rheometer itself.

$$\eta = \frac{100}{rpm} \times TK \times SMC \times Torque \quad (1)$$

$$\text{where } Torque = \frac{\tau}{TK \times SMC \times SRC} \quad (2)$$

The viscometer was equipped with a cone-plate (Model CP40) which was made with cone angle of 0.8°, diameter of 48 mm, and spacing of 0.091 mm (gap between spindle and cup). The parameters: *SRC* = 7.5, *SMC* = 0.327, *TK* = 0.09373 were set for the cone plate based on the viscometer manual.

The viscosity accuracy is ± 1.0% of full scale range for a specific spindle running at a specific speed. The temperature sensing is in range of 0 – 100 °C with accuracy of ± 1.0 °C.

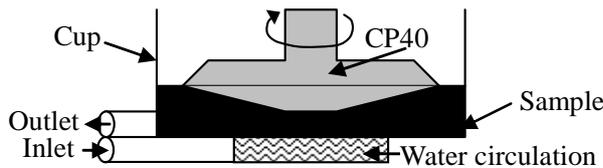


Figure 2.3. Representation of cone-plate apparatus of rheometer.

The foamy hexadecane in the high pressure-mixer cell has been drawn about 0.5 ml into the viscometer by maintaining temperature. The viscosity of foamy hexadecane has been measured with different *rpm*, ranged of 150 – 250.

The micro-bubbles of foamy hexadecane were examined under specific microscope either before or after rheometer measurement. Photo snap was taken for counting the bubbles and measuring the diameters.

### 3. Result and Discussion

#### 3.1. Gas Solubility

Molecular gas of CO<sub>2</sub> starts dissolving in hexadecane after gas injection into PVT cylinder. The gas dissolving makes the pressure drop, and it gradually decreases by the time. Finally, the gas stops dissolving into hexadecane due to saturation and the pressure keeps constant, so-called equilibrium pressure or steady state. On this equilibrium pressure, the molar number of CO<sub>2</sub> gas dissolution in hexadecane,  $n_{dis}$ , can be defined as the equation below:

$$n_{dis} = \frac{1}{M} \left[ \frac{V_i}{v(P_i, T_i)} - \frac{V_e}{v(P_e, T_e)} \right] \quad (3)$$

where

$M$ : Molar mass of CO<sub>2</sub> (g.mol<sup>-1</sup>)

$v$ : CO<sub>2</sub> specific-volume function of ( $P, T$ )

( $P_i, V_i, T_i$ ): CO<sub>2</sub> injected condition

( $P_e, V_e, T_e$ ): CO<sub>2</sub> equilibrium condition

For gas study, the relationship between pressure and temperature is well known, especially for general gas as CO<sub>2</sub>. This relationship can provide the information of gas specific volume by using E-Propath.

The solubility gas-in-oil is generally known by comparing the mole of dissolved gas with mass of oil. Therefore, the gas solubility can be defined by:

$$\text{solubility} = \frac{\text{dissolved gas moles}}{\text{mass oil}} \quad (4)$$

The unit of solubility in Eq. (4) is defined by millimole of dissolve gas per a gram of oil (mmol.g<sup>-1</sup>).

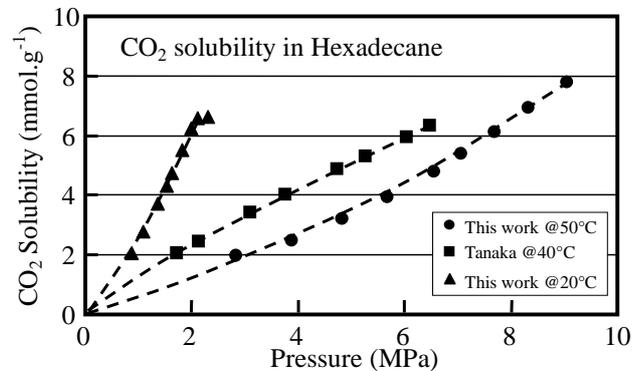


Figure 3.1. CO<sub>2</sub> solubility in hexadecane at different temperatures.

The solubility of CO<sub>2</sub> gas into hexadecane at different temperatures with pressure less than 10 MPa is shown in Fig. 3.1. The solubility increases with increasing pressure but it decreases with increasing temperature (Tanaka *et al.*, 1993; Kono *et al.*, 2011)[20, 21]. The type of gas is also another parameter of solubility. CO<sub>2</sub> gas is a gas that much dissolved in the oil, especially heavy oil.

High gas dissolution in the oil, as CO<sub>2</sub> gas, is expected to produce high quality of foamy oil with low viscosity since the bubbles of foamy oil were generated by dissolved gas once the pressure drops.

#### 3.1. Viscosity of Hexadecane

Hexadecane, a lubricant (oil), is considered as non-Newtonian fluid. Zhao *et al.* (2013)[22] stated that the non-Newtonian oil was indicated the viscosity or shear stress of oil increasing with shear rate. To study the hexadecane behavior of non-Newtonian fluid, the relationship between shear stress and shear rate (strain rate) needs to be measured (Fig. 3.2).

It was observed that shear stress and shear rate of hexadecane measurements follow a form of power law (Ostwald-de Waele equation):

$$\tau = K \left( \frac{dv}{dy} \right)^n \quad (5)$$

where fluid behavior depends on  $n$ :

- $n < 1$ : Pseudoplastic or shear-thinning fluid
- $n = 1$ : Newtonian fluid
- $n > 1$ : Dilatant or shear-thickening fluid

Fig. 3.2 shows the increasing of shear stress with shear rate of hexadecane at ranged temperature of 20 – 50 °C. This increasing leads to apply power law expressed by Eq. (5). Regarding the result, the relationships of shear stress and shear rate show the fluid behavior of hexadecane is various once the temperature changes. Basically, the flow behavior index ( $n$ ) of hexadecane increases with increasing temperature. At the ranged temperature of 20 – 50 °C,  $n$  increases in range of 1.0147 – 2.2468. Therefore hexadecane becomes dilatant or shear-thickening fluid which increases resistance with increasing applied stress. This result shows a good agreement with the finding of Cancela *et al.* (2005)[23] by using solutions of sodium carboxymethylcellulose and carboxymethylcellulose.

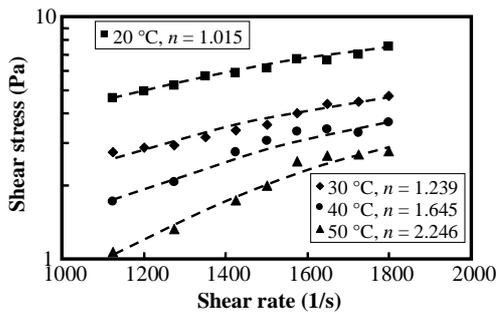


Figure 3.2. Relationship of shear stress and shear rate of hexadecane.

Thermal effect is generally the primary study for reducing oil viscosity as well as hexadecane. The measurements of hexadecane viscosity were carried out at ranged temperature of 20 – 50 °C and atmospheric pressure (Fig. 3.3). The shear rate of measuring viscosity was decided ( $dv/dy = 1575 \text{ s}^{-1}$ ) accordingly to the calibration of standard viscosity (4.73 cP at 25 °C).

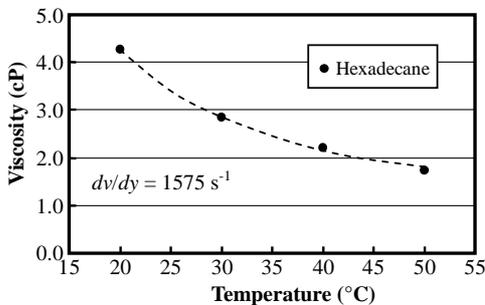


Figure 3.3. Viscosity of hexadecane against temperature (atmospheric pressure).

### 3.2. Foamy Hexadecane

The study of foamy hexadecane, generated at ranged temperature of 20 – 50 °C and ranged pressure of 1.0 – 6.0

MPa, involves with discussion on apparent viscosity, fluid behavior, and CO<sub>2</sub> gas micro-bubble distribution.

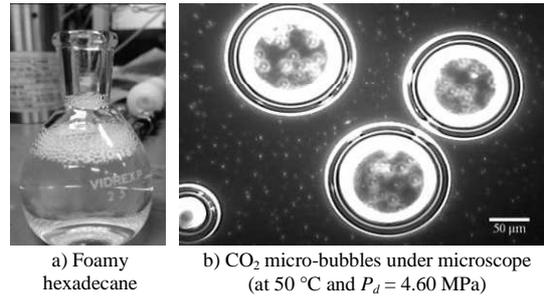


Figure 3.4. Typical foam and CO<sub>2</sub> gas bubble of foamy hexadecane.

The foamy hexadecane was generated by CO<sub>2</sub> gas depressurizing,  $P_d = 1.0 - 6.0 \text{ MPa}$ . In pynknometer, CO<sub>2</sub> gas bubbles generated from liquid phase and moved quickly upward to accumulate at the surface because hexadecane has low viscosity. Fig. 3.4 a) and Fig. b) show the typical example of foamy hexadecane and CO<sub>2</sub> gas micro-bubbles respectively which generated at temperature of 50 °C and  $P_d$  of 4.60 MPa. The bubble accumulation disappears within approximately 5 minutes, but the bubble generating still remains. The bubbles generated from liquid phase gradually decreases by the time and bubble nucleation is approximately finished after 30 minutes.

### 3.2. Viscosity of Foamy Hexadecane with Temperature Effect

The foamy hexadecane was generated at ranged temperature of 20 – 50 °C with pressure depressurizing,  $P_d = 4.0 \text{ MPa}$ . Several relations shear stress and shear rate were measured for four temperatures to understand the fluid behavior properties of foam. Fig. 3.5 shows the shear stresses increase with increasing of shear rates at each temperature. These increasing analyzed profiles were applied in the power law as Eq. (5). As a result, the fluid behavior indexes ( $n$ ) increase in range of 1.295 – 2.065 with increasing temperature of 20 – 50 °C. Regarding this result, the variation of fluid behavior index (ranged temperature of 20 – 50 °C) of pure hexadecane is larger than that of its foam.

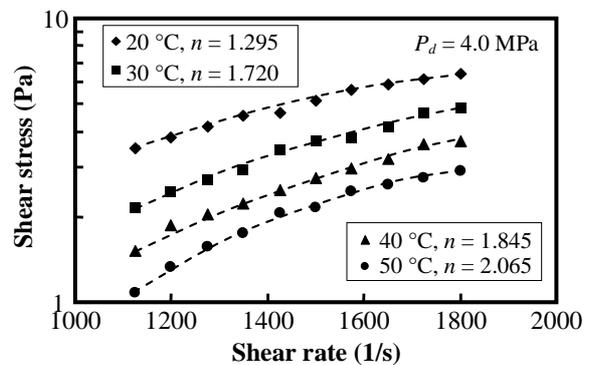


Figure 3.5. Relationship of shear stress and shear rate of foam generated with  $P_d = 4.0 \text{ MPa}$ .

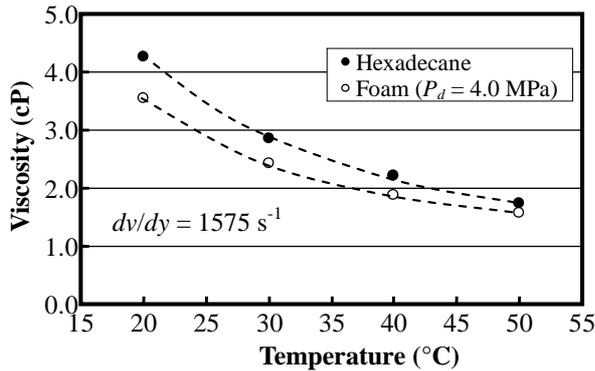


Figure 3.6. Viscosity comparison of foamy hexadecane and hexadecane.

The viscosity–temperature relationships of hexadecane and its foam were shown in Fig. 3.6. The viscosities of either pure hexadecane or its foam were reduced once the temperature increases. It can be said their viscosities both pure hexadecane and its foam are affected by temperature.

Generating foam at low temperature is more capable to reduce viscosity than that at higher temperatures. It may be caused by reducing viscosity and surface tension. High surface tension can maintain gas bubbles better than low one. The surface tension of hexadecane decreases in range of 27.5 – 24.9 mN/m when the temperature increases of 20 – 50 °C (Jasper, 1972)[24].

Viscosity ratio is referred to the comparison of foam viscosity with original viscosity at the same conditions. Foam viscosity ratio is defined by

$$\text{Viscosity ratio term} = \frac{\text{Viscosity of foam}}{\text{Viscosity of hexadecane}} \quad (6)$$

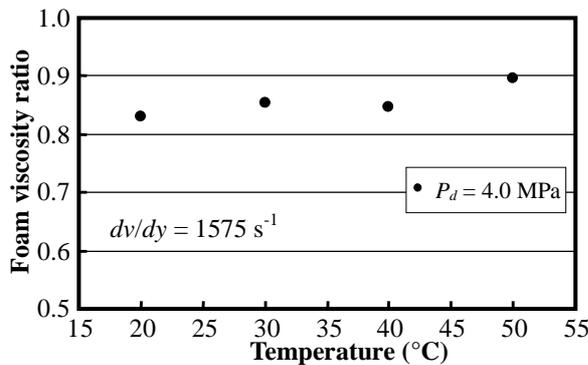


Figure 3.7. Foam viscosity ratio against temperature.

Figure 3.7 shows that viscosity ratio seems linearly increase with temperature. This result illustrates the thermal effect on foamy hexadecane viscosity; the higher temperature foam generated, the less viscosity reduction obtain.

High viscosity reduction of foam at low temperature is affected by CO<sub>2</sub> solubility in hexadecane because the molecular CO<sub>2</sub> gas dissolved in hexadecane increases with increasing pressure or/and reducing temperature (Fig. 3.1). Thus, the high content of dissolved CO<sub>2</sub> in hexadecane can generate the foam which has low viscosity ratio.

### 3.3. Viscosity of Foamy Hexadecane with Depressurization Pressure Effect

At a constant temperature, foamy hexadecane was generated at ranged depressurization pressure of 1.0 – 6.0 MPa. As shown in Fig. 3.8, the typical relationship of shear stress and shear rate of foamy hexadecane were measured at 20 °C. According to the result, the fluid behavior index basically increases with increasing  $P_d$ .

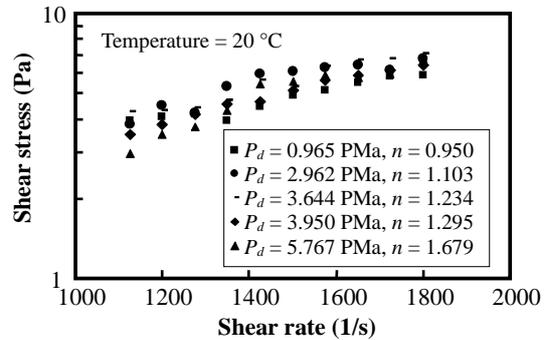


Figure 3.8. Typical relationship of shear stress and shear rate of foamy hexadecane measured at 20 °C.

The non-Newtonian fluid of foamy hexadecane was realized by non-linear increasing of shear stress and shear rate (Fig. 3.5 and Fig. 3.8). In 2001, Maini [3] stated the foam is non-Newtonian fluid because it is two-phase fluid (gas-in-oil) and compressible pseudo fluid.

Figure 3.9 shows the foam viscosity ratio against  $P_d$  at ranged temperature of 20 – 50 °C. There is not clear that the viscosity ratio decrease with increasing  $P_d$ . According to the result, the foam viscosity ratio is mainly various in a range of 0.6 – 0.9, and average value is approximately a value of 0.8.

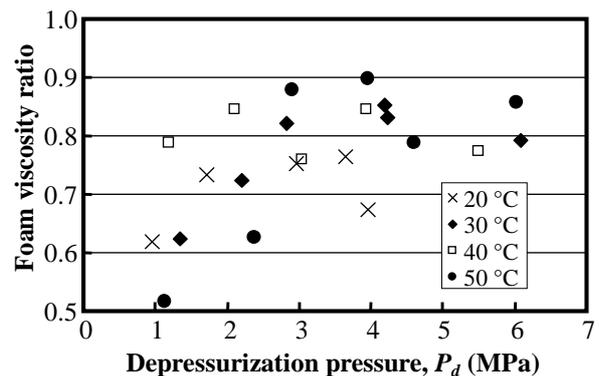


Figure 3.9. Viscosity of foamy hexadecane against depressurization pressure.

### 3.4. Micro-bubble Analysis

Foamy hexadecane consists of many dispersed CO<sub>2</sub> gas bubbles and micro-bubbles. The larger bubbles have the major contribution for oil swelling. To study swelling caused by bubbles of foamy hexadecane, the volume of foam just after generating and the original hexadecane volume were measured. The swelling ratio is defined by:

$$\text{Swelling}(\%) = \left( \frac{V_{\text{foam}}}{V_0} - 1 \right) \times 100 \quad (7)$$

The swelling increases slightly with increasing depressurization pressure ( $P_d = 1.0 - 6.0$  MPa) as shown in Fig. 3.10. The low temperature foam has high swelling because CO<sub>2</sub> gas is more stable mechanically in low temperature rather than that in high temperature. So the foam swelling depends on oil surface tension and viscosity.

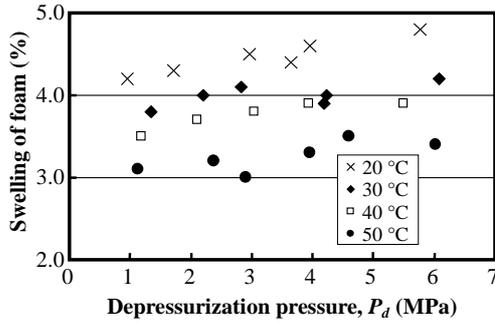


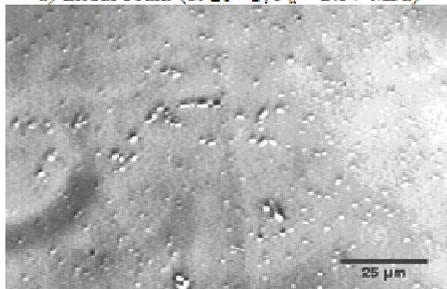
Figure 3.10. Relationship of foam swelling and depressurization pressure.

### 3.5. Micro-bubble Distribution

Foamy hexadecane consists of many gas bubbles which are capable to reduce apparent viscosity. Measurements indicated the viscosity of foamy hexadecane was quickly increased after the rotation starts. This increasing is caused by coalescing bubbles once the cone starts rotating. Engelsen *et al.* (2002)[25] reported that the skewness of number distribution decreases for increasing rotation speeds. The bubble coalescing is also relatively with the fluid properties such as fluid viscosity, surface tension, content of dissolved gas and temperature.



a) Initial foam (at 20 °C,  $P_d = 2.37$  MPa)



b) Foam under the shear (3 minutes under  $1575 \text{ s}^{-1}$ )

Figure 3.11. Microscopic observation of CO<sub>2</sub> gas bubbles in the foam before and after measuring shear stress in atmosphere.

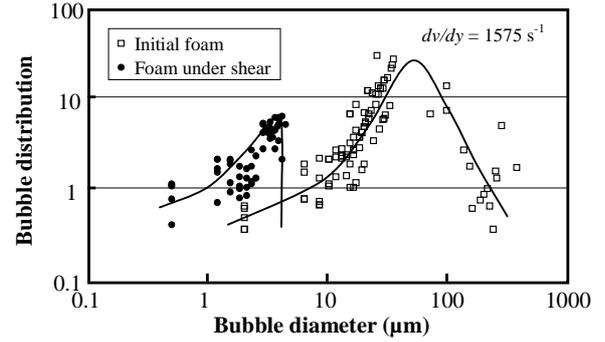


Figure 3.12. Bubble distribution in foamy hexadecane before and after shear measurement.

Both before and after measuring shear stress, the CO<sub>2</sub> gas bubbles were observed under microscope (see Fig. 3.11) including diameter measurement and bubble number. These data were analyzed to determine the distribution of bubble diameters for performing the quality of foamy hexadecane. The distribution can be calculated by:

$$\text{Bubble distribution} = \frac{\sum_{i=1}^n \left( N \times r_i^3 \right)}{\sum_{i=1}^n \left( \log \frac{r_{i+1}}{r_i} \right) \left( N \times r_i^3 \right)} \quad (8)$$

Based on the present measurements, the small bubbles were more interesting to study than large ones, since the large bubbles pretended to disappear and were not rheological resistance. The disappearing of large bubbles is caused by interfacial tension and contact angle effect (Javadpour and Jeje, 2003)[26]. Simply, a bubble disappears once the internal forces (expansion forces) are excess than the external forces (such as capillary and viscous forces) (Albartamani *et al.*, 1999)[16].

Figure 3.12 shows the CO<sub>2</sub> gas bubble distribution of foamy hexadecane generated at 20 °C with  $P_d = 2.37$  MPa. At condition of initial foam, the graph shows high bubble distribution and it is dominant at large diameter, approximately 50 μm. Due to cone rotation, the large bubbles were disappeared. At condition of foam under the shear, the graph shows the distribution was shifting to smaller size and it is dominant at diameter approximately 5 μm. The distribution shifting is caused by disappearing of large bubbles. According to the micro-bubble diameter is finer than pore throat size of typical sandstone, the micro-bubbles can move freely passing through pore throat. This factor leads to improve the mobility of the residual oil.

Regarding the result (Fig. 3.12), it is indicated that the large bubbles (Fig. 3.11.a) are unstable and potential for swelling only, but the micro-bubbles (Fig. 3.11.b) are more stable and highly effective for lowering viscosity. According to the distribution shifting (Fig. 3.12) and bubble disappearing (Fig. 3.11), the micro-bubbles are more resistant than the large one.

### 3.5. Viscosity Reduction

Abivin *et al.* (2009)[18] presented that the pressure, dissolved gas content, and presence of bubble control the viscosity of foamy oil. Since the presence of bubbles is a function of swelling (Eq. (7)) and the foam viscosity is a function of foam viscosity ratio (Eq. (6)). The viscosity ratio of foamy hexadecane could be shown as a function of foam swelling. Fig. 3.13 shows the viscosity ratio decreases in range of 0.90 – 0.70 with increasing swelling of 3.0 – 4.8%. Therefore, foamy hexadecane viscosity decreases with increasing apparent swelling.

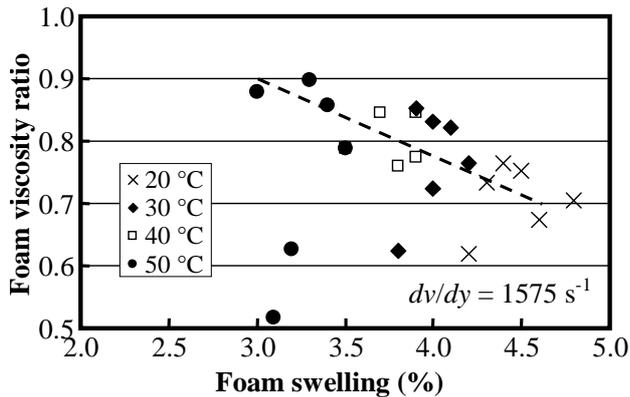


Figure 3.13. Viscosity ratio of foamy hexadecane against foam swelling.

## 4. Conclusions

The foam, generated by CO<sub>2</sub> gas dissolution and dissolving in hexadecane, was studied at ranged temperature of 20 – 50 °C and depressurization of 1.0 – 6.0 MPa. The effects of the distribution of generated micro-bubbles in foamy hexadecane on physical properties as viscosity ratio were discussed based on experimental measurements. The present result is summarized as in the following:

- Viscosity ratio of foam over original hexadecane showed 0.90 – 0.70 with increasing foam swelling of 3.0 – 4.8% for ranged temperature of 20 – 50 °C. The viscosity of foam is more reducible at either low temperature or high foam swelling.
- Regarding the bubble size analysis, the bubble distribution showed the large bubbles (approximately 50 μm in diameter) were coalesced but the micro-bubbles (approximately 5 μm in diameter) were stable under the shear of 1575 s<sup>-1</sup>, after 3 minutes of measuring. The high resistance of micro-bubble reflects to the application of foam flow in the reservoir in which the porous media contribute high shearing.

Foam including micro-bubbles with high stability against high shearing can contribute for smoother flow through pore throats in porous medium by changing physical properties. Due to high viscosity of heavy oil is a force which effectively controls the desorbing process, the CO<sub>2</sub> bubbles will be more stable and trapped in the oil phase for

a longer time. The phenomena lead the significant change of physical properties such as swelling and apparent viscosity. Therefore, CO<sub>2</sub> foamy oil with consideration of micro-bubble is expected to be more productive method for unconventional heavy oil reservoirs.

## Acknowledgements

This research was carried out by supporting from JSPS KAKENHI (Grant # 24360372) and JAPEX Research Center. Sincerest thanks are extended to AUN/SEED-Net Program (JICA) and Global Center of Excellent Program of Kyushu University for their financial supports.

## Nomenclature

- $n_{dis}$  : molar number of dissolved gas (mol)  
 $M$  : molar mass of CO<sub>2</sub> (g·mol<sup>-1</sup>)  
 $V$  : equilibrium gas phase volume (m<sup>3</sup>)  
 $v$  : CO<sub>2</sub> Gas specific-volume, function of ( $P, T$ ) (m<sup>3</sup>·kg<sup>-1</sup>)  
 $P$  : equilibrium pressure (MPa)  
 $T$  : equilibrium temperature (K)  
 $P_d$  : depressurization pressure (MPa)  
 $\tau$  : shear stress (Pa)  
 $K$  : flow consistency index (Pa·s<sup>n</sup>)  
 $dv/dy$  : shear rate or velocity gradient (s<sup>-1</sup>)  
 $n$  : flow behavior index (-)  
 $\eta$  : viscosity (mPa·s or cP)  
 $rpm$  : revolution per minute (min<sup>-1</sup>)  
 $TK$  : model spring constant of viscometer  
 $SMC$  : spindle multiplier constant of viscometer  
 $SRC$  : shear rate constant of viscometer  
 $V_{foam}$  : volume of foam after immediately generating (ml)  
 $V_0$  : original volume of hexadecane (ml)  
 $N$  : number of micro-bubbles [a,b]  
 $r$  : average radius of bubbles in interval diameter [a,b] (μm)

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