Introduction

Viscosity can play an important role in the study on elastic properties of heavy oil (e.g. Han et al., 2008a). At lower temperatures than the glass point, heavy oil acts as a solid material due to its high viscosity (> 10^{15} cp). At higher temperatures than the liquid point, viscosity is low enough (< nearly 10^3 cp) so that its effect on velocity can be neglected; it acts as an elastic material like standard liquid. In between these two regions, it acts as a viscoelastic material (so-called quasi-solid state), where wave propagation is strongly dispersive with high attenuation.

Heavy oil in the quasi-solid state has a finite shear modulus induced by shear viscosity. On the other hand the corresponding bulk modulus also significantly increases as compared to conventional oil, which results from additionally induced bulk modulus by the volume viscosity (also called bulk viscosity or second viscosity). The volume viscosity has been considered to have mechanisms such as the molecular rearrangement or the internal mobility (e.g. Litovitz and Davis 1964). However, because accurate measurement is difficult, there is very limited literature concerning the volume viscosity of heavy oil (e.g. Taskoprulu et al. 1961). Thus, we focus on the volume viscosity of heavy oil to investigate the relationship between the shear viscosity and volume viscosity and its-induced bulk modulus.

Background theory

Since a viscoelastic material like heavy oil has frequency and temperature dependencies on its elastic properties, a complex modulus has been introduced. Although the Maxwell model is one of the most common models, our previous studies (Han et al., 2008b) showed that the Havriliak-Negami (HN) model (1967) has better agreement with our ultrasonic measurement data. The complex shear modulus of the HN model is expressed:

\[
G_s^\ast = G_s \left(1 - \frac{1}{1 + (i\omega \tau_s)^{1-\alpha}}\right)
\]

(1)

\[
\tau_s = \frac{\eta_s}{G_s}
\]

(2)

where \(G_s\) and \(\omega\) are the high frequency limiting value of the shear modulus and angular frequency, respectively. \(\alpha\) and \(\gamma\) are adjusting parameters (0 \(\leq\) \(\alpha\) \(\leq\) 1 and 0 \(\leq\) \(\gamma\) \(\leq\) 1). \(\tau_s\) and \(\eta_s\) are relaxation time associated with shear process and shear viscosity, respectively. In a similar way, the bulk modulus of viscoelastic material can be formulated:

\[
K^\ast = K_1 + K_{V1}^\ast = K_1 + K_r \left(1 - \frac{1}{1 + (i\omega \tau_v)^{1-\alpha}}\right)
\]

(3)

\[
\tau_v = \frac{\eta_v}{K_r}
\]

(4)

where \(K_1\) is static bulk modulus and corresponds to bulk modulus of a standard liquid, which is independent on the wave frequency. \(\tau_v\) and \(\eta_v\) are relaxation time associated with compressional process and volume viscosity, respectively. \(K_r\) is the high frequency limiting value of the bulk modulus induced by the volume viscosity. The volume viscosity has been often neglected in theoretical calculations. However, ultrasonic measurement data show the most striking demonstration of its existence in heavy oil.

Analysis of ultrasonic velocity measurement data

We use the ultrasonic measurement data which have been collected over a wide temperature range to investigate the relationship between the bulk and shear moduli. Figure 1 shows the
measured P- and S-wave velocities and the corresponding bulk and shear moduli of bitumen with 9.4 °API. The shear modulus begins to have a finite value at around the liquid point (nearly $10^3$ cp in shear viscosity). The bulk modulus starts to deviate from the static bulk modulus ($K_1$) at around the liquid point, implying that $K_{VIS}'$ (real part of $K_{VIS}*$) also has a finite value. From the deviation from $K_1$, $K_{VIS}'$ is calculated.

Figure 1: P- and S-wave velocities and bulk and shear moduli of bitumen with 9.4 °API as a function of temperature.

Figure 2 shows relationship between the shear modulus ($G_{VIS}'$ : real part of $G_{VIS}*$) and bulk modulus ($K_{VIS}'$) for the whole samples. With increasing shear viscosity from the liquid point, $K_{VIS}'$ increases more rapidly than $G_{VIS}'$. Then, at around $10^8$ cp in shear viscosity, $K_{VIS}'$ increases at a reduced rate and $G_{VIS}'$ starts to increase significantly. When the shear viscosity comes closer to the glass point, $K_{VIS}'$ and $G_{VIS}'$ have similar magnitudes. We assume a single fitting curve, which is cubic below the glass point and linear above the glass point.

(i) Quasi-solid state ($\eta_S < 10^{15}$ cp)

$$K_{VIS}' = 2.81G_{VIS}'^{1.3} -5.34G_{VIS}'^{1.2} +3.67G_{VIS}'$$

(ii) Elastic-solid state ($\eta_S > 10^{15}$ cp)

$$K_{VIS}' = 1.17G_{VIS}'$$

Next, we derive the relationship between the shear viscosity and volume viscosity. The procedures are as follows;

(1) $G_{VIS}*$ at ultrasonic frequency (1 MHz) is calculated each temperature by equation (1).
(2) By using the equation (5), $K_{VIS}'$ is calculated from real part of the $G_{VIS}*$.
(3) The calculated $K_{VIS}'$ is fitted by the HN model to obtain optimum $\tau_v$ at each temperature.
(4) By comparing $\tau_v$ with the corresponding $\tau_s$ at each temperature, the relationship between volume viscosity and shear viscosity can be derived.

Using a given temperature dependent model for the shear viscosity, we can obtain the temperature dependence of the volume viscosity. Figure 3 shows the shear and volume viscosities with respect to temperature.
We predict the shear modulus ($G_{VIS}$) with respect to both temperature and frequency by using the HN model. Figure 4 shows the shear modulus and its quality factor of bitumen with 9.4 °API as a function of temperature at 10 Hz, 10 kHz, and 1 MHz, respectively. As similar as the shear modulus, we predict the bulk modulus ($K_{VIS}$) by using the obtained relationship between the shear and volume viscosities. Adding to them $K_1$, we also obtain the quantity $K_1+K_{VIS}$ (Figure 5). It is obvious that the total bulk modulus has significant frequency dependence with seismic attenuation. Furthermore, the moduli are converted to S- and P-wave velocities. The P-wave velocity shows significant velocity dispersion with seismic attenuation, which results from the contribution from $K_{VIS}$ as well as $G_{VIS}$. The predicted moduli and its velocities are virtually consistent with the measurement data.

Conclusions

We have focused on the volume viscosity of heavy oils. The ultrasonic measurement data show that heavy oil in the quasi-solid state has additional bulk modulus induced by the volume viscosity as well as shear modulus induced by shear viscosity. Thus, it is obvious that we have to take account of influences of not only shear viscosity but also volume viscosity for the rock physics modelling of heavy oil and its saturated-rock. We obtain a relationship between the shear viscosity and volume viscosity from the ultrasonic measurement data. By using the relationship with the HN model, we successfully predict frequency and temperature dependences of the shear and bulk moduli of heavy oil. The predicted moduli and its velocities are virtually consistent with the measurement data.
Figure 4: The shear modulus ($G_{VIS}$) and its quality factor of heavy oil with 9.4 °API at 10 Hz, 10 kHz, and 1 MHz.

Figure 5: The bulk modulus ($K_1 + K_{VIS}$) and its quality factor of heavy oil with 9.4 °API at 10 Hz, 10 kHz, and 1 MHz.

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References

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