Viscosity model of Heavy Oil with calibration of shear velocity data

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Summary

New data of the shear wave velocity of heavy oils using the transmission wave at low temperature combined with the data using reflection wave at high temperature provides the probability to build a complete model of shear velocity from liquid phase to solid phase. To get the more reasonable viscosity of heavy oils at low temperature, we modified the existing viscosity models with calibration by glass and liquid points from the shear velocity model. The HN frequency model with new optimal parameters can be used to fit the data with updated viscosity from the modified model. The HN model gives the estimation of shear properties of heavy oils including attenuation in frequency domain.

Introduction

As one of the important energy resource, heavy oil has been one of our research targets for last few years. We measured the shear wave velocity of heavy oils using the reflection wave (Liu and Han, 2004, Han, et al., 2005). The measuring error limits us to get the shear velocity at low temperature at or near the glass point temperature. Based on the data and the existing viscosity model for heavy oil, we developed and improved the frequency model of the shear wave in heavy oils (Han and Liu, 2005, Han, et al., 2006, 2008). The Havriliak-Negami (HN) model gives a good fitting to data and was used to estimate the shear velocity in frequency domain. However. we did not have shear velocity data at the glass point to calibrate the viscosity and the velocity models. The transmission wave was used to measure the shear velocity in low temperature to reach and cross the glass point (Liu et al., 2007, Han, et al., 2008). The transmission wave data with reflection wave data let us build a complete shear velocity model. On the other hand, the data with complete velocity modeling can be used to calibrate the viscosity model since the existing viscosity models cannot give a good estimation at low temperature. A new modified viscosity model with its calibration has been developed based on the shear velocity data and is to be used to check the frequency model. The HN model with updated optimal parameters gives the shear wave properties including velocity and attenuation.

Model of shear wave velocity in heavy oils

We have measured shear wave velocities of heavy oil: first with reflection methods (Han et al., 2005), and recently with a transmission method to cover a wide range of temperatures as shown in Figure 1. The S-wave velocity increases gradually with decreasing temperature. It is interesting that velocity did not tend to be a constant at the temperature below the glass point, instead it continued to increase. It shows that the glass point may not be a correct threshold for phase transition, but just an assumed point for a solid phase. Heavy oil can continue consolidating, viscosity can continue to increase, and shear velocity (dynamic rigidity) can continue increase with decreasing temperature below the glass point.

We have designed a model with a symmetric (non-linear) term and a linear term:

$$Vs = a\left[1+\frac{e^{-c(T-T_0)}-e^{c(T-T_0)}}{e^{-c(T-T_0)}+e^{c(T-T_0)}}\right]+s\left[(T-T_0)-ABS(T-T_0)\right] \tag{1}$$

to describe the S-wave velocity behavior in quasi-solid and liquid phases. It is featured with a linear term to describe the velocity change in solid phase. In this equation, T is an independent variable and there are four

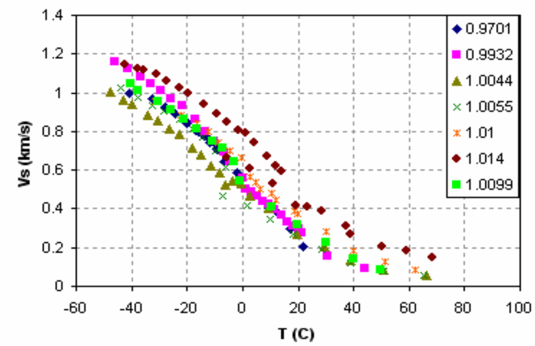

Fig. 1. Measured Vs of heavy oils with different densities as function of temperature.

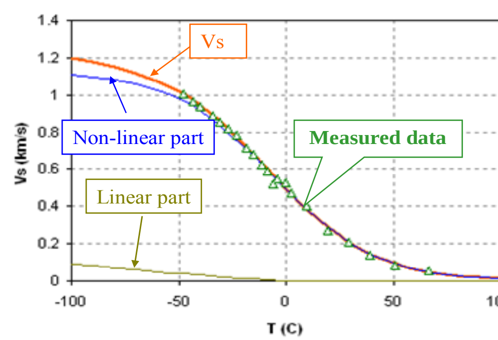

Fig. 2. Vs model vs. temperature (API = 9.38)

parameters to describe shear velocity behavior as a function of temperature T: T_0 is the center temperature for the center of symmetry term; c is a parameter to describe the slop of the curve; a is the maximum of the symmetric part which equals 2 times of the Vs value at the center temperature T_0; and s is the slop of the linear part of the model. ABS is the function of taking absolute value. Figure 2 shows the model and data (green triangles), the blue curve is the first term, the gray line is the linear part and the orange curve is total curve for Vs. It can be seen that the linear part equals to zero when the temperature is higher than T_0. The parameters a, c, s and T_0 are obtained with least square regression for all the data point.

New viscosity model with shear velocity calibration

The viscosity of heavy oil is a basic parameter used to build frequency models of shear wave in heavy oils. There have been various models to describe the viscosity of heavy oils published (figure 3). In the figure, we can see the various models give similar viscosities at high temperature (higher than 20 ^{o}C), but there are significant differences of viscosities between models in low temperature range. Moreover, all these models are based on API gravity of oil to correlate with oil viscosity. Unfortunately, composition of heavy oil is much more complicated. Viscosity in heavy oil did not correlate well to API gravity (Hinkle, et al., 2007). It means that each heavy oil may have a viscosity specially constituted with its composition. We need a viscosity model, to develop proper velocity dispersion and attenuation models we may have to measure it. Furthermore, all the models cannot be calculated if the temperature is negative. This is because all these models were developed from data in higher temperature range, and they cannot be extended to the low temperature range.

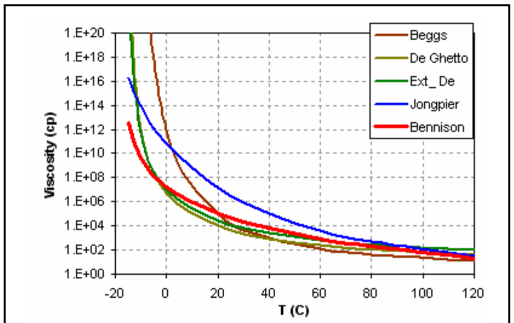

Fig. 3. Viscosities calculated with various models

We need to measure and develop a new viscosity model of heavy oils in the low temperature range. However, direct measurement of viscosity of heavy oils in a wide temperature range is extremely difficult. No proper method or equipment is available. Without proper viscosity data and model, we could not be helped to use the Begges model and De Ghetto model for the velocity dispersion and attenuation models.

As the definitions in our previous study, the viscosities of heavy oil at the glass and the liquid points are 10^{15} and 10^3 cP respectively. We can calibrate the viscosity model if we can find the temperatures of the glass and liquid points. Since we measured the shear wave from both transmission and reflected wave from rather low to high temperature range for heavy oil samples, and obtained the relatively complete shear wave velocity curve through from the glass to the liquid points, it is possible to find the temperature of glass and liquid points from the shear wave velocity data.

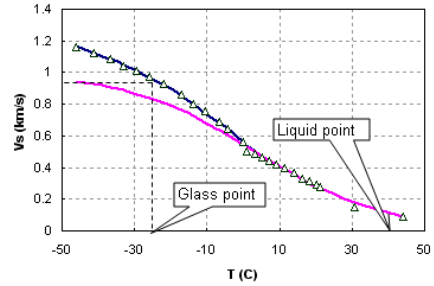

Fig. 4. Definitions of glass and liquid

In practice, we defined the glass point as the temperature at which the shear velocity equals to the maximum value of the non-linear (symmetric) part and the liquid point is the temperature at which the shear velocity equals to 0.1km/s (Figure 4).

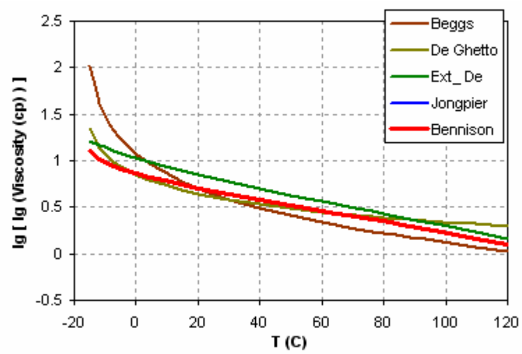

Fig. 5. The double logarithm of viscosity vs. temperature with various models

We have to modify the viscosity model before calibration to solve the calculation problem of negative temperatures. Most existing models show a near linear relationship between the viscosity and temperature with a double logarithm scale used for viscosity (Figure 5). The modified model still uses a double logarithm scale of viscosity but the Kevin's absolute temperature instead of Centigrade or the Fahrenheit system. The modified viscosity is following.

$$\begin{aligned} \eta &= 10^x - 1 \\ x &= 10^y \\ y &= A + C \cdot \lg(T_K) + D \cdot [\lg(T_K)]^2 \end{aligned} \tag{2}$$

Where, η is the viscosity in cP (centi-poise) and T_K is the absolute temperature (^{o}K); A, C and D are constants which are related to the heavy oil properties. To resolve the constants A, C and D, We need three pairs of input parameters for viscosity and T_K. Besides the glass and liquid points, the water point (η = 1 cP) is selected as the third group of input parameters. We have found that the temperature of water point has little effect on the constants A, C and D if the value of water point is high enough. Therefore, we choose a constant temperature 200^{o} C (~473.3ºK) as the water point for all heavy oil samples.

The figure 6 shows the viscosities as a function of temperature using the new viscosity model for three samples. The constants A, C and D have been calibrated with measured shear velocity data. As a comparison, the viscosities calculated by the Beggs and De Ghetto models are also shown in the figure. The new model gives very similar values as those of the Beggs and De Ghetto models in the higher temperature range, but significantly difference in low temperature. The viscosity increases more gradually with decreasing temperature in the new model than other models and seems more reasonable. The new model is an empirical one with calibration of measured shear velocity data as a function of temperature. Therefore, we provide a new method to estimate viscosity for given heavy oil as a function of temperature (not just one point). The new viscosity model should help to improve velocity dispersion and attenuation model.

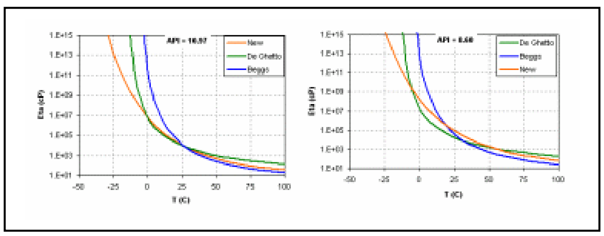

Fig. 6. The viscosities as function of temperature using modified model for three samples compare with Beggs and De Ghetto models calculation

Update of the frequency model

To build the frequency model for shear velocity of heavy oil, we have to transfer the shear velocity data from temperature to the omega-tao (ωτ) domain where ω is angle frequency and τ is the relaxation time. The relaxation time depends on the viscosity and shear modulus. Since the viscosities of the samples are calculated by the modified model, the relaxation times have to be re-calculated and the figure 7 shows the new cross plot of normalized shear moduli versus ωτ.

$$\omega = 2\pi f \qquad \tau = \frac{\eta}{G_\infty} \qquad (3)$$

Where ω is the angle frequency, f is the frequency, τ is the relaxation time, η is the viscosity and G_∞ is the shear modulus at highest frequency.

We have found that the Havriliak-Negami (HN) model (equation 4) that was applied in our previous study is still good for fitting the data with the optimal parameters of $\alpha = 0.51$ and $\gamma = 0.27$ (Figure 7).

$$HN(\alpha,\gamma) = G(\omega) = G'(\omega) + iG''(\omega) = 1 - \frac{1}{[1+(i\omega\tau)^{1-\alpha}]^{\gamma}}$$

$$G'(\omega) = 1 - R^{-\gamma/2}\cos(\theta\gamma)$$

$$G''(\omega) = R^{-\gamma/2}\sin(\theta\gamma)$$

$$R = [1+(\omega\tau)^{1-\alpha}\sin(\pi\alpha/2)]^2 + [(\omega\tau)^{1-\alpha}\cos(\pi\alpha/2)]^2$$

$$\theta = arctg\left[\frac{(\omega\tau)^{1-\alpha}\cos(\pi\alpha/2)}{1+(\omega\tau)^{1-\alpha}\sin(\pi\alpha/2)}\right] \qquad (4)$$

Where, G is the normalized shear modulus, G' and G" are its real and imaginary parts respectively, α and γ are parameters of HN model.

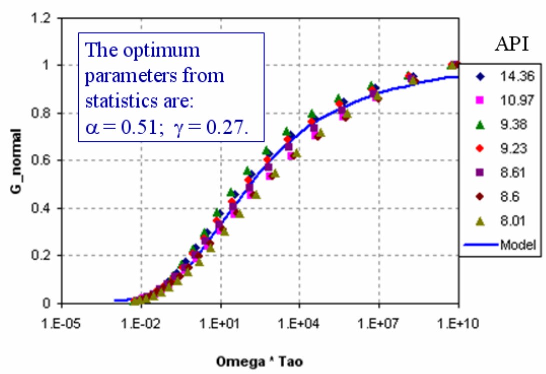

Fig. 7 Normalized shear moduli in ωτ domain with HN model fitting

With the optimal parameters for the HN model, we have updated the dispersion of the shear velocity of heavy oils and figure 8 (a) shows an example. In the left part of the figure, we can see the dispersion is rather small at both temperatures of glass (-28.8 ºC) and liquid (42.4 ºC) points, in which the heavy oil in quasi-elastic phase and viscosity effect can be ignored. But, there is a strong dispersion at the temperature between the glass and liquid points, in which viscosity of the heavy oil in quasi-solid phase generates shear velocity. Figure 8 (b) shows that the shear velocity decreases with increasing temperature more rapidly at a low frequency than that at a high frequency. This is due to shear rigidity at a low frequency requires high viscosity to support. Therefore, the liquid point moves to a lower temperature at a low frequency. Range of quasi-solid phase in temperature narrows with decreasing frequency of shear waves.

The figure 8 (b) shows that shear velocities at different frequencies tend to converge at temperature lower than -40 ºC (no dispersion), which indicate that the heavy oil is in an elastic solid phase. As we mentioned at the beginning, the glass point (~ -28.8 C for the oil) is not a physical threshold for phase transition, but can be considered as the point of the solid. For the elastic phase of the oil, the new model gives the more reasonable value of viscosity (10^{22} cp) than the old model (10^{33} cp).

Shear wave attenuation of heavy oils

The attenuation can be described by the parameters of the quality factor Q (or its reciprocal 1/Q). 1/Q can be calculated using equation 5.

$$\frac{1}{Q} = \frac{G''}{G'} \qquad (5)$$

Where, *G'* and *G"* is the real and imaginary part of shear rigidity of heavy oil. Figures 9 display the attenuation (1/Q) as functions of frequency and temperature respectively. We can see that the heavy oil has a higher shear wave attenuation in lower frequencies and at higher temperatures. The attenuation decreases significantly from the frequency of 100Hz to 1MHz at 6.8 C (figure 9a). The attenuation decreases rapidly when the temperature reaches below the glass point (figure 9b). This is because the shear wave will be attenuated strongly in the liquid phase (low viscosity) of heavy oil but only slightly in solid phase (high viscosity).

Conclusion

We have developed a method to calibrate a new viscosity-temperature model for heavy oils in a wide viscosity range from 1 cP to over 10^{15} cP. The model needs calibration from measured shear velocity in the temperature range from the high as over 70 ºC to the low as –50 ºC. With the calibrated viscosity model, we have improved shear modulus model as a function of viscosity and frequency based on the Havriliak-Negami (HN) model. Based on the new model, we can predict velocity dispersion and attenuation trends.

Acknowledgment

This work was supported by the Fluids/DHI consortium sponsored by multi-companies from oil industry worldwide.

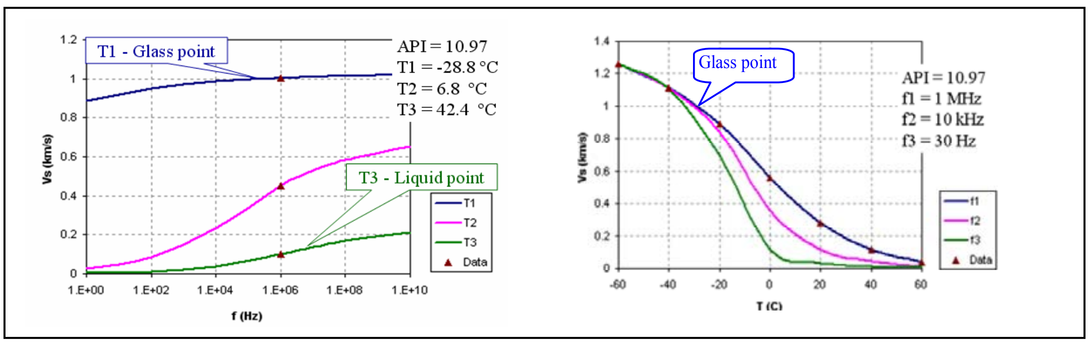

Fig. 8. Shear velocity dispersion of heavy oil with API = 10.97
(a) Vs vs. frequency with temperatures. (b) Vs vs. temperature with frequencies.

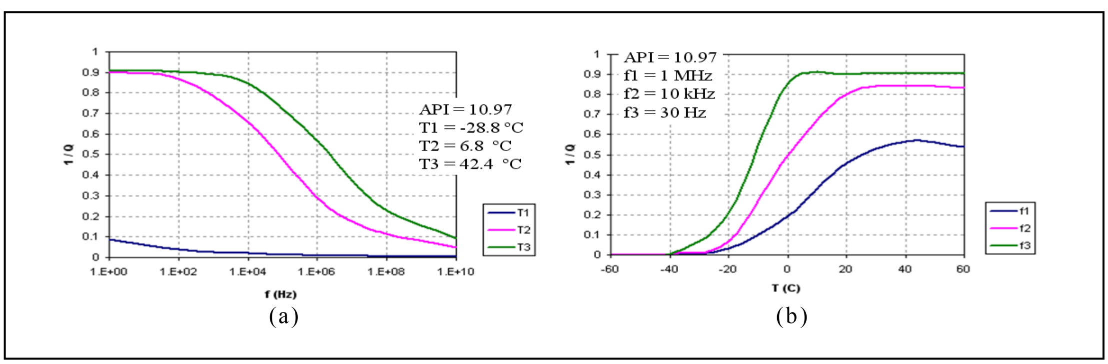

Fig. 9. Attenuation of shear wave in heavy oil with API = 10.97 as function of
(a) frequencies and (b) temperature.

EDITED REFERENCES

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