Velocity and Dispersion of Heavy Oils

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Summary

Acoustic properties of heavy oils have been investigated based on laboratory measurement and modeling studies. Based on newly measured shear velocity data in extended low temperature, we have revealed a full spectrum of shear velocity of heavy oils as function of temperature, which we have applied to calibrate viscosity of heavy oils. A series of models has been developed to describe both S- and P-wave velocities of heavy oils as function of temperature and frequencies

Introduction

Acoustic properties of heavy oil is vital to understand seismic characterization and monitoring in heavy oil reservoirs. However, heavy oil properties have showed complicity deviated from conventional black oils because high viscosity at reservoirs. As viscous fluids, heavy oils have no sharp phase transition from a liquid to solid as that of crystal solid, such as the freeze (or melt) point between water and ice. As shown in Figure 1 (Han et. Al., 2006), heavy oils have three phases: liquid, quasi-solid and glass solid and characterized by the liquid point and the glass point in temperature.

Acoustic velocities have shown different features at different phases. At high temeprature (> the liquid point), velocities of heavy oil in the liquid phase are similar as conventional oil: there is ignorable shear velocity; there is ignorable velocity dispersion; there are near contant velocity gradient with respect to temeprature. At very low temeprature, heavy oils are in the galss solid phase, in which both Vp and Vs should behave elastically: there is no more dispersion. In the between the liquid and glass point, heavy oils in the quasi-solid phase are very different in velocities: there is shear velocity; there is velocity dispersion; velocities show transition from the liquid to solid phase. The liquid point, derived from ultrasonic velocities will change with frequency and viscosity. We have found (Han, et. al., 2006) that measured ultrasonic P-wave velocities have offered a resonable definition of the liquid point in oil viscousity: around 800 cp, which provide a low threshold of the liquid phase. With lower frequencies, viscosity of the liquid point can be high.

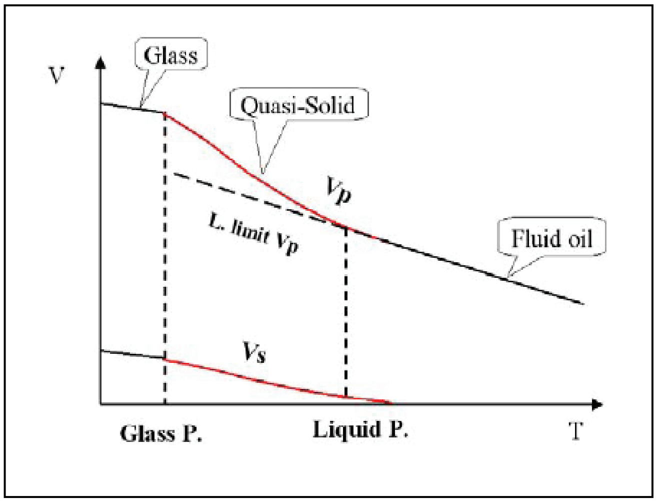


Figure 1: Velocities of heavy oil in phase transition

Velocity Dispersion

To understand acoustic properties in heavy oils in quasi-solid phase, we can write shear velocity as

$$Vs = Vs(\omega, \tau(\eta)) \quad (1)$$

$$\eta = \eta(API, T) \quad (2)$$

where ω is angle frequency, τ is relexation time, which is a fuction of viscousity. Viscosity depends on oil gravity (API) and tmeprature (T). There are two problems. First, direct velocity measurement with wide band frequency at laboratory conditions is very difficult if it is not impossible. We have found that ω and $\tau(\eta)$ are symmetric distributed in equation 1. Ideally, we can measure velocity as function of viscosity to calibrate the frequecy effect. However, there are no proper viscosity model for heavy oils because complicated composition. Direct measurement of viscousity on heavy oils as function of temperature (equation 2) is equaly difficult. Therefore, we decided to measure ultrasonic shear velocity as function of temeprature and use Vs charaterization at the liquid point (~800 cp) and the glass point (10^{15} cp) to calibrate viscosity model (equation 4).

$$Vs = Vs(T) \quad (3)$$

$$\eta = \eta(Vs(T)) \quad (4)$$

Based on measured shear velocity and derived viscosity model, we have developed velocity model as function of frequency (equation 1). In this abstract, we show measured data and model results.

Shear Velocity of Heavy Oils

We have measured shear wave velocities of heavy oil: first with reflection methods (Han et al., 2005), and recently with transmission method to cover wide range of temperatures as shown in figure 2. 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 to continue increase. It shows, a glass point may not be a correct threshold for phase transition, but just an assumed point for a solid phase. Heavy oil can continue consolidation, viscosity can continue to increase, and shear velocity (dynamic rigidity) can continue increase with decreasing temperature below the glass point.

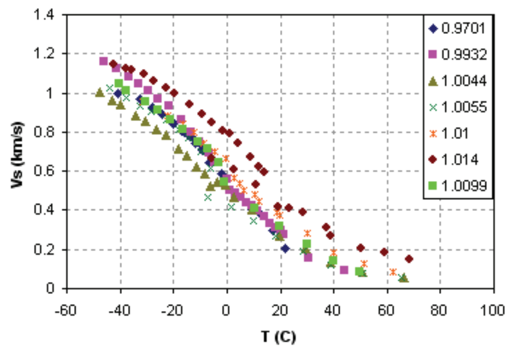


Figure 2: Measured Vs as function of temperature.

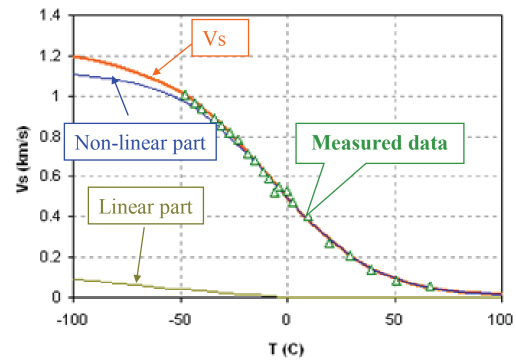


Figure 3: Vs model vs. temperature (API = 9.38)

Shear Velocity Model

We have designed a model with a symmetric term and a linear term:

$$Vs = a\left[1 + \frac{e^{-c(T-T_0)} - e^{c(T-T_0)}}{e^{-c(T-T_0)} + e^{c(T-T_0)}}\right] + s\left[(T-T_0) - ABS(T-T_0)\right] \qquad (5)$$

to describes 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 4 parameters to describe shear velocity behavior as a function of temperature: 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 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. The 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 and shown in figure 3.

Frequency Model for Shear Velocity of Heavy Oils

We have selected non-symmetric Havriliak-Negami (HN) model (1967) to fit measured data.

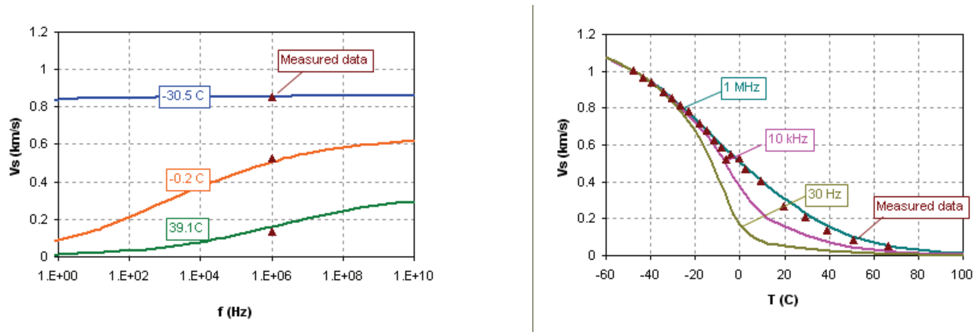
$$G(\omega) = G'(\omega) + iG''(\omega) = 1 - \frac{1}{[1+(i\omega\tau)^{1-\alpha}]^{\gamma}}$$

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

$$R = [1+(\omega\tau)^{1-\alpha}\sin(\pi\alpha/2)]^2 + [(\omega\tau)^{1-\alpha}\cos(\pi\alpha/2)]^2 \qquad (6)$$

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

In the frequency models the normalized shear modulus is a function of ωτ, which is a dimensionless parameter. Therefore, the effect of relaxation time τ and ω on shear modulus is equivalent. We have measured S-wave velocity in temperature domain, which provides two calibration points for viscosity (10^{15} cp at the glass point and near 10^{3} cp at the liquid point). In the figure 4, the S-wave velocity data have been converted into ωτ domain and modeled with the HN model with the optimum parameters α = 0.61 and γ = 0.31 respectively.



(a) (b)

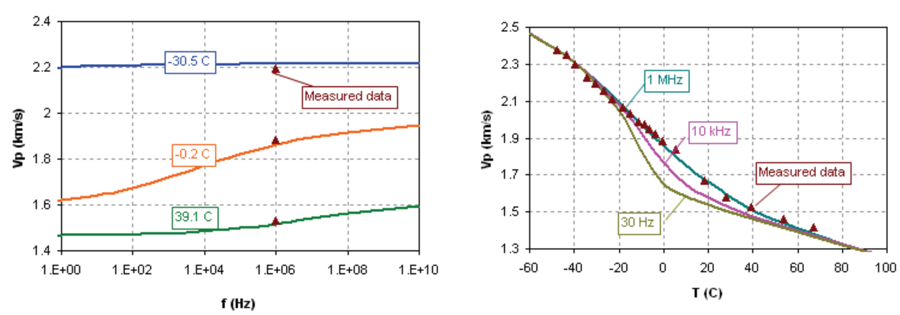
Figure 4: HN model for S-wave velocity applied on a heavy oil with API = 9.38.
(a) S velocities as the function of frequency in different frequencies;
(b) S velocities as the function of temperature in different temperatures.

With the HN model we can estimate dispersion of S-wave velocity. The figure 4 (a) and (b) is an example for a heavy oil sample with API = 9.38. The S-wave velocity of the oil at quazi-solid phase (~0 °C) decreases with decreasing frequency significantly, but much less at near glass solid phase and liquid phase.

We have built a model for estimating P-wave velocity based on S-wave velocity model as shown in the equation (7).

$$Vp = \sqrt{(V_{k1}{}^{2} + \frac{Vs}{0.5468})^{1/0.6553}} \qquad (7)$$

where V_{K1} is a part of P-wave velocity that has linear relation with temperature and has no relation with the viscosity.



(a) (b)

Figure 5: Estimated P velocity vs. frequency for a heavy oil with API = 9.38.
P-wave velocities as the function of frequency in different frequencies;
P-wave velocities as the function of temperature in different temperatures.

The figure 5 shows the P-wave velocities in frequency domain and temperature domain of the same sample of figure 4 (API = 9.38). The P-wave velocity is dispersive (>15%) at quasi-solid phase (around 0 °C) as shown in Figure 5 (a) and (b).

Conclusions

Measured shear velocity as a function of temperature has been used to calibrate viscosity of heavy oil in a quasi-solid phase. We apply calibrated viscosity and measure ultrasonic shear velocity data to model shear velocity as a function of frequency for heavy oil. Currently, the Havriliak-Negami (NH) model (1967) is the best to fit heavy oil data and predict S- and P-wave velocity dispersion.

Acknowledgements

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