Velocity model development for heavy oils

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Summary

Based on the existing velocity models of heavy oils and newly measured data, new models for P-wave and S-wave velocities of heavy oil as the function of temperature and frequency effects have been developed.

Introduction

As an important energy resource, heavy oil has been one of our research targets for years. We have measured the ultrasonic compressional velocity of heavy oils as a function of temperature and defined the liquid point in temperature as the phase transition threshold between the fluid and the quasi-solid phase. And we recognized the liquid point obtained based on ultrasonic data is frequency dependent. We have also measured the shear wave velocity in the quasi-solid phase using the reflection method (Liu and Han, 2004, Han, et al., 2005). The S-wave data show consistency with the P-wave data, which validates the liquid point as the phase threshold. We also found that all the viscosity models developed for oil flow are not proper for modeling velocity dispersion and wave attenuation of heavy oil in the quasi-solid phase. Ultrasonic shear velocities of heavy oil from the liquid point to the glass point temperature can help to calibrate viscosity model of heavy oil, as well as proper input for velocity dispersion and attenuation model (Han. et al, 2009). However, because of poor coupling between buffer and oil sample in a quasi-solid phase, shear velocity cannot be measured by the reflection method at near the glass point. We have developed an apparatus to apply transmission wave (Liu et al., 2007, Han, et al., 2008). Based on the data and the existing viscosity model, we developed and improved the frequency model of the shear wave in heavy oils (Han and Liu, 2005, Han, et al., 2006, 2008). We can now build more complete models in this study based on newly measured data. Although all models are built based on ultrasonic measured data, the new models can be applied in dead heavy oil with room pressure. However, for shallow heavy oil with low GOR and low pressure, they can still be used with local calibration.

Velocities of heavy oil

We have measured the P- and S-wave velocities of heavy oil samples for years. Based on the measured data, the first models were developed in 2005 and updated in 2007 named as V_p-2007 and V_s-2007 shown in Equation (1).

$$Vp = \begin{cases} Vp_{\_flag} & T > T_{\_liquid} \\ 0.4698(Vp_{\_flag})^{2.7765} & T \le T_{\_liquid} \end{cases} \quad (1)$$

$$Vs = \begin{cases} 0 & Vp \le V_{K1} \\ 0.5468(Vp^2 - V_{K1}{}^2)^{0.6553} & Vp > V_{K1} \end{cases}$$

where, V_p is P-wave velocity, V_s is S-wave velocity, V_{p_flag} is P-wave velocity estimated by the oil model in FLAG program (the oil calculator of the Fluid Application Geophysics program developed by the Fluids/DHI consortium), T is temperature and $T_{\_liquid}$ is the temperature of liquid point in degree ºC, and V_{k1} is the linear part of the S-wave velocity (The same definitions are applied throughout the paper, and all velocities are in km/s). At the condition with no pressure, V_{k1} equals V_{p_flag}. The V_p-2007 and V_s-2007 models are related to V_{p_flag}, in which API density is the key control factor for oil property.

From theoretical point of view, velocities as a function of temperature can be divided into three sections (Figure 1) depending on oil phases. In liquid phase, V_p changes near linearly with temperature and V_s equals almost 0 at high temperature range. In solid phase, V_p and V_s change linearly again at low temperature range. Both V_p and V_s change non-linearly with temperature between liquid and solid phases and we call it quasi-solid phase. Although phases transit gradually with temperature, we use glass point and liquid point to divide them roughly.

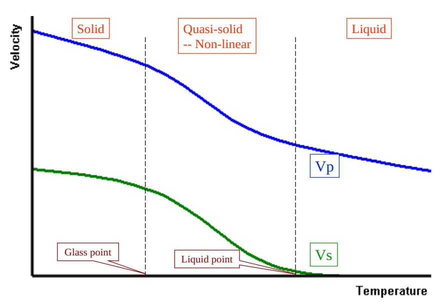

Figure 1. Schematic of velocities of heavy oil with temperature.

Since temperature did not reach glass point in our measurement, previous data did not show the three sections clearly. In 2008, we measured P- and S-wave velocities of several samples at very low temperature. The data of S-

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wave velocity reflect liquid, quasi-solid and solid phases of heavy oil respecting to temperature as the theoretical analysis. We developed a mathematic model for S-wave velocity based on data, and called it V_s-2008 model.

$$Vs = a\left[1+\frac{e^{-c\Delta T}-e^{c\Delta T}}{e^{-c\Delta T}+e^{c\Delta T}}\right]+s[\Delta T - ABS(\Delta T)] \quad (2)$$
$$\Delta T = T - t_0$$

It can describe S-wave behavior in the three phases, but the coefficients a, c, t_0 and s, are obtained from the measured data by statistics for each individual heavy oil sample.

With more samples being measured in recent years, it is now possible to improve or develop general models. Comparing measured V_p of heavy oils with estimated V_p by the general oil model in FLAG (Figure 2.A), they are consistent when the velocity is not higher than 1.5 km/s, which is in high temperature range (heavy oil is in liquid phase). But correction must be made when it is out of liquid phase. Considering the three phases of heavy oil, a new model named V_p-2011 Model is designed as

$$\begin{aligned} Vp &= Vp_{\_flag}\left[1+A_P\cdot\frac{e^{C_P \Delta V_P}}{e^{C_P \Delta V_P}+1}\right] \\ \Delta V_P &= Vp_{\_flag} - Vp_0, \\ A_P &= 0.38184, C_P = 18.044, Vp_0 = 1.6820 \end{aligned} \quad (3)$$

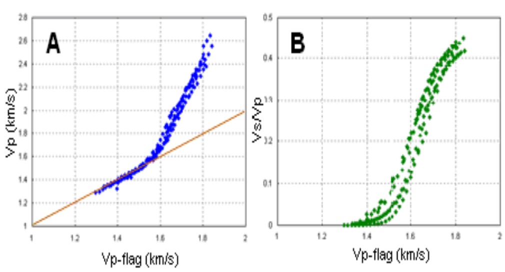

Figure 2. A. Measured P velocity in comparison with estimated V_{p_flag}; B. Measured ratio of V_s over V_p in comparison with estimated V_{p_flag}.

Like oil velocity model of FLAG, API density is also the key control factor of the heavy oil in the V_p-2011 model besides the environmental condition such as temperature and pressure. For example, Figure 3.A. shows measured data and estimated data by models for the sample with API density of 1.0194 g/cc. The orange and blue lines show the estimated by V_p-2011 and V_p-2007 models, respectively. Although the estimated values are not apart too much from the measured data, only the orange line can show that V_p passes gradually through three phases. The relative standard deviation of V_p-2011 model is about 3%.

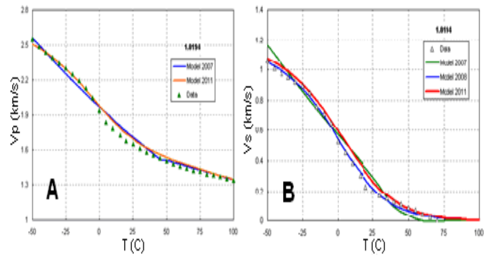

Figure 3. A. Measured and estimated P velocity; B.Measured and estimated S velocity.

As mentioned above, S-wave velocity of heavy oil depends on viscosity, frequency, and oil density. Although viscosity mainly depends on API gravity, it may be altered by different oil compositions such as asphaltenes and resins. We had tried to make simple correlations between the measured Vs data with various parameters, but no satisfied correlation had been found. Because the content of asphaltenes and resins is not easy to come by for most users, we still use the API density as the key control factor for the new model and a systematic calibration for the API based model is recommended. From this point of view, we have found the following correlation between the ratio of S-wave to P-wave velocities and V_{p_flag} (Figure 2.B). And then a new model named V_s-2011 Model is built below.

$$\begin{aligned} Vs &= Vp\cdot A_S\cdot\frac{e^{C_S \Delta V_S}}{e^{C_S \Delta V_S}+1} \\ \Delta V_S &= Vp_{\_flag} - Vs_0 \\ A_S &= 0.44034, C_S = 16.4651, Vs_0 = 1.6281 \end{aligned} \quad (4)$$

An example of the sample with API density of 1.0194 g/cc is shown in Figure 3.B. Comparing with the measured data (dots), the estimated (lines) by V_s-2011(red), V_s-2007 (green) and V_s-2008(blue) models are plotted. It is clear that the V_s-2007 model cannot give smooth transition between liquid and quasi-solid phases, and it does not show the solid phase in low temperature range, either. Although the V_s-2008 model gives the best estimation of S-wave velocity for the sample, its coefficients cannot obtained without the real measured data. The V_s-2011 model shows the smooth transitions among three phases and gives an acceptable estimation. Statistics shows that the relative standard deviation of V_s-2011 model is about 10%.

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In order to study the frequency effects on both P- and S-wave velocities, we have developed V_p-2011 model and V_s-2011 model in another format, V_p-T-2011 and V_s-T-2011, respectively, which can separate linear and non-linear parts as we need, because the dispersion concentrates on quasi-solid phase (non-linear part of the velocity).

The V_p-T-2011 model shows the relation between P-wave velocity with temperature and their coefficients are functions of API density of heavy oil.

$$\begin{aligned} &Vp = Vp_{\_flag} + Vp_{\_non} + Vp_{\_lin} \\ &Vp_{\_non} = A_{PT}\cdot\frac{e^{C_{PT}\Delta T_P}}{e^{C_{PT}\Delta T_P}+1}, \quad Vp_{\_lin} = S_{PT}\left[\Delta T_P - ABS(\Delta T_P)\right] \\ &\Delta T_P = T - t_{0PT}, \quad A_{PT} = -0.0576 + 1.211\rho_0 - 0.528\rho_0^{\;2} \\ &C_{PT} = -0.0934 + 0.0316\rho_0, \quad t_{0PT} = -375.59 + 366.74\rho_0 \\ &S_{PT} = -0.008071 + 0.013442\rho_0 - 0.0060654\rho_0^{\;2} \end{aligned} \tag{5}$$

Where, V_{p_non} is the non-linear part of P-wave velocity in quasi-solid phase and $Vp_{\_lin}$ is the linear part in solid phase. ρ_0 is the API density of heavy oil in g/cc. Both V_p-2011 and V_p-T-2011 models give almost the same estimation of P-wave velocity. The V_p-2011 model is suggested for first use if P-wave velocity is in ultrasonic frequency. Because the V_p-T-2011 model is based on V_p-2011 model, additional errors may occur. For frequency effect estimation the V_p-T-2011 model has to be applied.

Similarly, the V_s-T-2011 model is built as,

$$\begin{aligned} &Vs = Vs_{\_non} + Vs_{\_lin} \\ &Vs_{\_non} = A_{ST}\cdot\frac{e^{C_{ST}\Delta T_S}}{e^{C_{ST}\Delta T_S}+1}, \quad Vs_{\_lin} = S_{ST}\left[\Delta T_S - ABS(\Delta T_S)\right] \\ &\Delta T_S = T - t_{0ST}, \quad A_{ST} = -0.2870 + 2.4132\rho_0 - 1.1324\rho_0^{\;2} \\ &C_{ST} = -0.0798 + 0.0254\rho_0, \quad t_{0ST} = -372.57 + 371.72\rho_0 \\ &S_{ST} = -0.0116 + 0.0197\rho_0 - 0.0092\rho_0^{\;2} \end{aligned} \tag{6}$$

Where, V_{s_non} is the non-linear part of S-wave velocity in quasi-solid phase and V_{s_lin} is the linear part in solid phase. V_s-2011 and V_s-T-2011 models give close estimations, and the same suggestion is given as using V_p models above.

Frequency effects

Since there are no different frequency measurements of heavy oil samples, the superposition is applied that transfer the shear velocity data from temperature domain to omega tau ($\omega\tau$) domain.

$$\omega = 2\pi f, \quad \tau = \frac{\eta}{G_\infty} \tag{7}$$

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.

In the previous study, we had tested some known models to fit our data in $\omega\tau$ domain, such as Maxwell model, and found the Havriliak-Negami (HN) model is the best one (equation 8) (Havriliak and Negami, 1967; Liu and Han, 2006, 2007, 2008). The references give more details about the frequency model fitting.

$$\begin{aligned} &HN(\alpha,\gamma) = G(\omega) = G'(\omega) + iG''(\omega) = 1 - \frac{1}{[1+(i\omega\tau)^{1-\alpha}]^{\gamma}} \\ &G'(\omega) = 1 - R^{-\gamma/2}\cos(\theta\gamma), \quad G''(\omega) = R^{-\gamma/2}\sin(\theta\gamma) \\ &R = [1+(\omega\tau)^{1-\alpha}\sin(\pi\alpha/2)]^2 + [(\omega\tau)^{1-\alpha}\cos(\pi\alpha/2)]^2 \\ &\theta = arctg\left[\frac{(\omega\tau)^{1-\alpha}\cos(\pi\alpha/2)}{1+(\omega\tau)^{1-\alpha}\sin(\pi\alpha/2)}\right] \end{aligned} \tag{8}$$

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. Since the dispersion concentrates in the quasi-solid phase of heavy oil (visco-elastic material), the non-linear part of shear modulus is used to fit the HN model. In our previous study, α = 0.61 and γ = 0.31 are used to fit data from V_s-2007 model. And then based on V_s-2008 model, the optimal parameters of α = 0.51 and γ = 0.27 are used. Now they are updated to α = 0.5299 and γ = 0.2687 for data by V_s-T-2011 model (Figure 4).

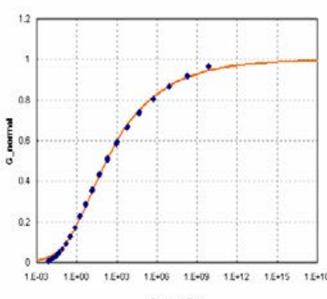

Figure 4. Normalized shear modulus vs. $\omega\tau$. Dots are data based on non-linear part of V_s-T-2011 model, and line is calculated by HN model with α = 0.5299 and γ = 0.2687.

The frequency effect on P-wave velocity can be derived by a relation between the non-linear parts of P- and S-wave

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velocities as shown in equation (9).

$$Vp_{\_non} = -0.0036 + 0.3352\, Vs_{\_non} + 0.3104\, Vs_{\_non}^{\,2} \qquad (9)$$

With the optimal parameters for the HN model, we can estimate the velocity dispersion and Figure 5 shows an example. At the upper part of the figure, the dispersion is rather small at both glass (-36.36 °C) and liquid (46.6 °C) points, but at the temperature between them, strong dispersion appears. It also tells that there is still little dispersion at the glass and liquid points since the phase of heavy oil changes gradually with temperature. On the other hand, the lower part of the figure shows that velocities decrease with increasing temperature more rapidly at lower frequency than that at higher frequency. This is due to shear rigidity at a low frequency that requires high viscosity to support. Therefore, the liquid point moves to low temperature for shear velocity with a low frequency.

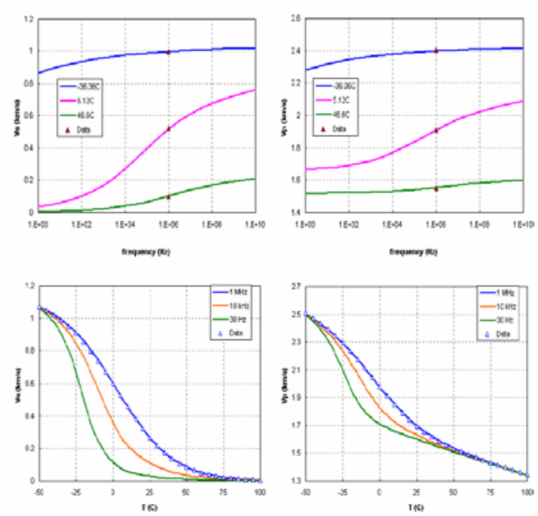

Figure 5. The dispersion of S and P velocities for the sample with ρ_0=1.0194 g/cc.

Summary

We have developed new models V_p-2011 and V_s-2011 for ultrasonic P- and S-wave velocities as a function of a broad band of temperature and API gravity for heavy oils based on measured data and the oil model used in the FLAG program.

In order to describe both P- and S-wave velocities of heavy oil in the quasi-solid phase as a function of frequency, we have developed independent V_p-T-2011 and V_s-T-2011 models based on the V_p-2011 and V_s-2011. Improving HN model with new optimal parameters, we can calculate P- and S-wave velocities dispersion and attenuation with the V_p-T-2011 and V_s-T-2011 models.

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EDITED REFERENCES

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