Heavy Oils – Seismic Properties

Michael Batzle*, Brian Zadler, Ronny Hofmann, Colorado School of Mines
De-hua Han, University of Houston

Summary

Heavy oil properties are strongly dependent on composition and temperature. Because of biodegradation, alkanes are destroyed and complex heavy compounds dominate. As a result, the trends for velocities, gas-oil ratios, well as for viscosities developed for light oils often do not apply to heavy oils.

For heavy oils at low temperatures, the viscosity increases and the material can act like a solid. This glass-like behavior results in the ability of the material to have an effective shear modulus and propagate a shear wave. Velocities and moduli are both strongly temperature and frequency dependent. As a result, for heavy oils, properties measured in the ultrasonic ($10^5 - 10^6$ Hz), sonic logging (10^4 Hz), and seismic (10-100 Hz) frequency bands can have completely different values.

Introduction

Heavy oils are defined as having high densities and extremely high viscosities. Our definition here is for oils with an API less than 10 (density greater than 1 g/cc). These are an abundant resource, particularly in Canada, Venezuela, and Alaska. It is estimated that heavy oils represent as much as 6.3 trillion barrels of oil in place. This matches both conventional oil as well as gas in resource magnitude. Seismic monitoring of heavy oil production can improve the effectiveness of the recovery program. However, seismic monitoring still remains only qualitative due to incomplete calibration and poorly understood aspects of the oil and the influence of the recovery process. The situation is complicated since many heavy oils act like solids and their properties have strong frequency dependence.

Heavy oils themselves are often fundamentally different chemical mixtures from more typical crude oils due to biodegradation. Straight alkane chains tend to be consumed by bacteria, leaving a mixture of complex organic compounds (Figure 1). This process requires both relatively low temperatures and contact with circulating fresh water. This results in heavier compounds including asphaltines, bitumens, pyrobitumens, resins, etc. These complex compounds are often rather operationally defined. For example, asphaltines are usually defined as the component of crude oils not soluble in heated heptane. Although this is useful in assessing if solids will form in production pipes, it gives little insight into their physical properties.
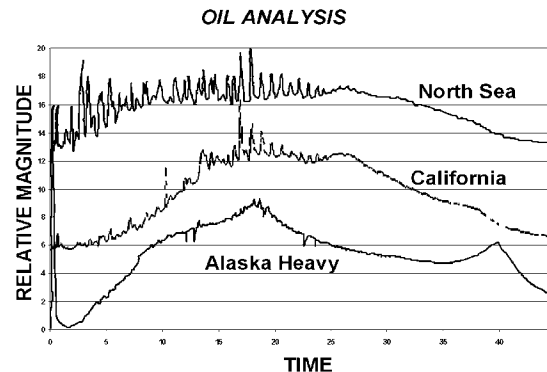

Figure 1. Oil compositions from HPLC analyses. The straight alkanes (pentane, hexane, etc.) are represented by spikes in the North Sea crude. As biodegredation occurs, the alkanes are consumed leaving a background of complex organic compounds, as with the Alaska heavy Oil sample.

Even with very low gas-oil ratios (GOR), The phase boundary can be crossed by changing either pressure or temperatures in the reservoir. In Figure 2, the calculated modulus is plotted as a function of temperature. Crossing the bubble point occurs at about 120 C and the drop in modulus is substantial. Such dramatic modulus fluctuations will have a strong influence on the seismic properties so we need a good understanding of the properties and phase behaviors of these heavy oils.

Heavy Oil Properties

Heavy oils are typically composed of long, very high molecular weight compounds. They not only have 'liquid-like' behavior, but can begin to act like solids. As temperature is lowered, the "glass point" is reached. This is similar to the freezing point for pure compounds.
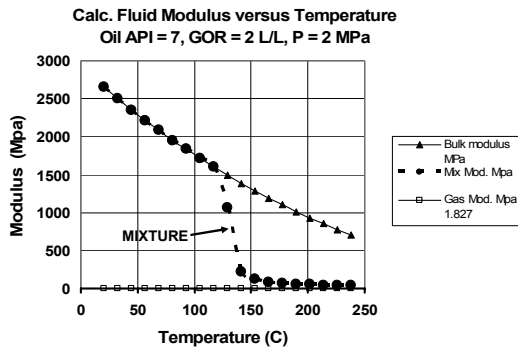
Figure 2. Heavy oil velocity as a function of temperature. Increasing the temperature will also cause the oil to cross the bubble point.

One of the most important properties of heavy oils for both engineering and geophysical purposes is viscosity. Viscosity is often the limiting factor in heavy oil production. As we shall see, it also has a strong influence on the seismic properties. Viscosity of oils has been studied for many years. Although it is influenced by pressure and gas content, it is primarily a function of oil gravity and temperature. Beggs and Robinson (1975) developed one of the typical relations.

$$Log_{10}(\eta_T + 1) = 0.505y(17.8 + T)^{-1.163} \qquad (1)$$

Where
$$Log_{10}(y) = 0.5693 - 2.863/\rho_0$$

Here, η is viscosity (in centipoise, cp), T is temperature in degrees C, and ρo is the oil density (at STP). The results of this equation are shown in Figure 3. (Note that the figure is plotted in Pascal seconds, 1 Pa s = 1000 cp). The low temperature limit is fixed by the "17.8" in Equation 1. Thus at temperatures below about 0 C, these relations are questionable. The viscosity of bitumen (API = 10.3) from the Cold Lake field reported by Eastwood (1992) is also plotted. For the very heavy oil, a data point is available from Edgeworth et al. (1984) by timing the drops coming out of a funnel filled with 'pitch' or very heavy oil.

Heavy Oil Compressional Velocity

As we expect, the compressional velocity (Vp) of our heavy oils will be a function of composition, pressure, and temperature. An example of the non-linear dependence of velocity of heavy oil on temperature is shown in Figure 4.

This is a gas-free oil with a gravity of API = 7. Note that there is little pressure dependence, but strong temperature dependence. Going from 20 C to 150 C results in a 25% velocity drop. Above about 90 C, the oil velocity drops linearly with increasing temperature, as is common in lighter oils. However, below 70 C, the departure from linearity is obvious. At low temperatures, this oil approaches its glass point and begins to act like a solid. Thus, the change in velocity seen in Figure 4 is not only due to an increase in the bulk modulus, but also the appearance of a shear component.
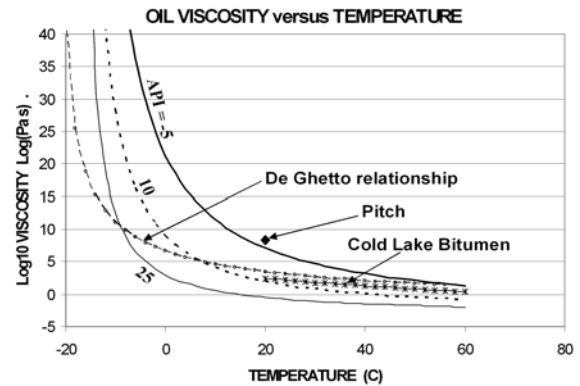

Figure 3. Viscosity versus temperature for oils from Beggs and Robinson (1975). The relation produces a singularity at low temperatures. Also plotted are the data of Eastwood (1992) and Edgeworth et al. (1984) and the heavy oil relation from De Ghetto et al. (1995)
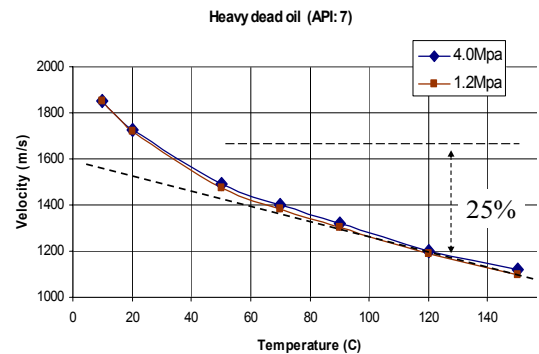

Figure 4. This heavy oil velocity also drops substantially with increasing temperature. At temperatures below about 70 C, the temperature-velocity relation becomes strongly non-linear.

Heavy Oil Shear Properties

As a fluid mixture approaches the glass point, the viscosity becomes so high (Figure 3), that it effectively has a shear modulus. This transition can be tested by propagating a shear wave through the fluid. The shear wave results for the very heavy oil sample (API = -5) are shown in Figure 5. At low temperatures (-12.5 C) a sharp shear arrival is apparent. Thus by many definitions, since this oil has a shear modulus, it is a solid, or glass. Increasing the temperature not only decreases the shear velocity, but dramatically reduces the shear wave amplitude. At this point, this oil is only marginally solid. If we do presume this oil is solid, we can derive the effective bulk and shear moduli for this heavy oil (Figure 6). Both moduli decrease approximately linearly with increasing temperature. However, shear modulus approaches zero at about 80 C.
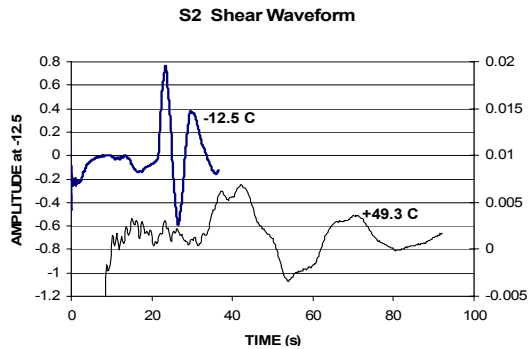
S2 Shear Waveform

Figure 5. Ultrasonic shear waveforms in very heavy oil at -12.5 C and 49.3 C. The sharp arrival at low temperature is delayed and dramatically decreased in amplitude at higher temperature.
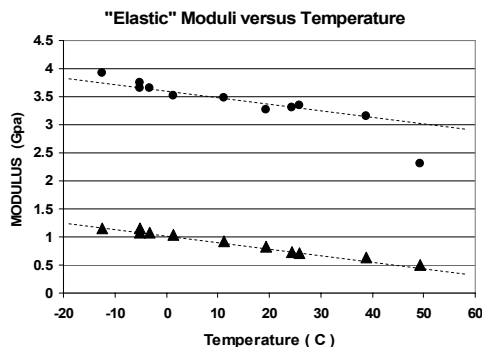
"Elastic" Moduli versus Temperature

Figure 6. Elastic moduli of the heavy oil from ultrasonic data. The effective shear modulus drops toward zero as temperatures approach 80 C.

As we have seen, very viscous fluids can support a shear stress and propagate a shear wave. We can describe this using the viscoelastic model of Maxwell.

$$\sigma = Z^* \frac{\partial u}{\partial t} , \qquad (2)$$

where σ is the stress, u is displacement, and Z^* is the complex acoustic impedance (Blitz, 1967). This impedance can be expressed as a function of viscosity η, fluid density ρ, the effective high frequency shear modulus G, and frequency ω.

$$Z = \left(\frac{i \eta \omega \rho}{1 + i \eta \omega / G} \right)^{1/2} \qquad (3)$$

The shear velocity, Vs, can be derived from the general relation

$$Vs = |Z^*| / \rho \qquad (4)$$

The results of using the high frequency shear modulus shown in Figure 5 and the viscosities from Figure 3 are shown in Figure 7. Notice the strong temperature and frequency dependence of the shear properties. At low temperatures (0 C), this oil acts like a solid. However, by +40 C, the shear properties are in transition. At high frequencies, such as with our laboratory ultrasonics, this material is still effectively a solid. At seismic frequencies, however, the material can go through shear relaxation, and acts like a liquid, with no shear modulus. Thus for this oil at 40 C, ultrasonics are in a completely different viscoelastic regime and will not give results representative of properties at seismic frequencies. Logging frequencies will be in the transition and give some intermeadiate value. In addition, because of this transition, logging frequencies will suffer high attenuation.

We can confim this kind of behavior with heavy oils by resonance techniques. In Figure 8, a rectangular parallel piped is resonated in the 15 to 30 kHz range. At low temperatures, the peaks are sharp (low attenuation) and at relatively high frequency. As temperature increases, the frequencies of the peaks decrease, indicating lower moduli and velocities. Also at higher temperatures, the width of each peak increases indicating a large increase in attenuation. As the peaks broaden and flatten, these modes of propagation eventually approach zero. This is consistent with the ultrasonic waveforms seen in Figure 5.
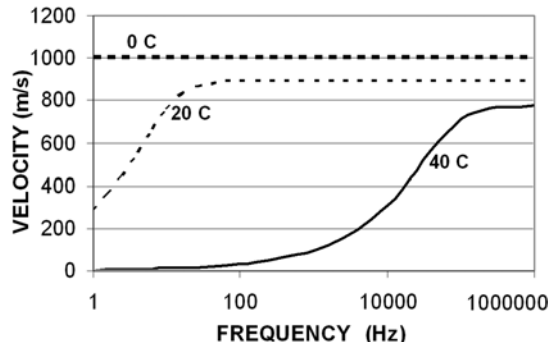
Figure 7. Calculated shear velocity in a heavy oil of API = -5 using a viscoelastic liquid (Maxwell) model.
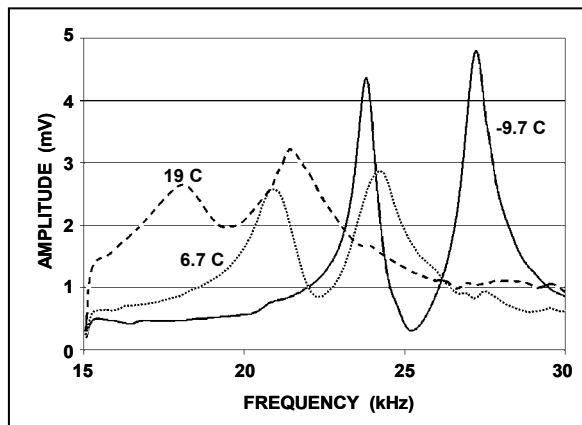

Figure 8. Resonance spectra of a bar of the heavy oil as a function of temperature. Sharp, high frequency (high velocity) peaks are broadened and fattened indicating decreasing velocity and increasing attention as temperature goes up.

Conclusions

Heavy oils are complex mixtures of heavy organic compounds. They can become sufficiently viscous, or glass-like that they can propagate a shear wave. However, this behavior is strongly temperature and frequency dependent. Seismic monitoring of heavy oil reservoirs will require complete understanding of their viscoelastic properties.

References

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