Acoustic property of heavy oil – measured data

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Summary

Heavy oils are viscous fluid having three phases: fluid, quasi-solid and glass solid depended on temperature. We have measured ultrasonic velocities on 10 heavy oil samples at different phases. Measured data suggest that heavy oil properties are similar to the light oil properties if temperatures are higher than the **liquid** point. With temperature decreases below the **liquid** point, heavy oil transfers from liquid phase to a quasi-solid phase with drastic increase of viscosity, S-wave velocity appears measurable and P-wave velocity deviated up from the light oil trend. P- and S-wave velocities of heavy oils show a systematic relation to API gravity, temperature, pressure, GOR, and appear dispersive as heavy oil in the quasi-solid state.

Introduction

With a high demand of hydrocarbon world wide, heavy oil and bitumen (ultra-heavy oil) emerged as “new” (called unconventional) hydrocarbon resources because of their tremendous potential. We do not have rigorous definition of heavy oil. Based on USGS definition: heavy oil is an asphaltic, dense and viscous oil that is chemically characterized by its content of asphaltenes with API gravity from 22 to less than 10 (ultra heavy oil or bitumen). In terms of thermal dynamics, viscous fluid such as heavy oil is amorphous material. In general, oil viscosity increases with decreasing temperature and API gravity (for example, Beggs and Robinson, 1975) With decreasing temperature, heavy oil can change its phase, from liquid phase with low viscosity to quasi-solid phase as viscosity increases drastically, then eventually to the glass phase as viscosity is over the glass point as shown in Figure 1. The **glass** point has defined as viscosity equals to 10^{13} Poise. The corresponding temperature to the viscosity glass point is also called as glass point. We have not yet defined the “**liquid**” point, which is the transition point between the fluid and the quasi-solid phases.

Thermal method is the main one to reduce viscosity and produce heavy oil (Gupta, 2005). Time lapse seismic is major technique to monitoring where the steam goes (Schmitt, 1999). However, all the techniques are in an early development stage. Producing heavy oil remains as a challenge both economically and environmentally. As we mentioned (Batzle et al, 2004), due to complex heavy compounds, the simple empirical trends developed for light oil to estimate fluid properties such as viscosities, densities, gas-oil ratios and bubble points may not apply well to heavy oils. Heavy oil at high temperatures can be characterized similar as light oil. However, at low temperatures, viscosity of heavy oils increases drastically and properties of heavy oils are significantly different. We need study properties of heavy oil thoroughly in order to build a proper rock physics model for heavy oil reservoirs.

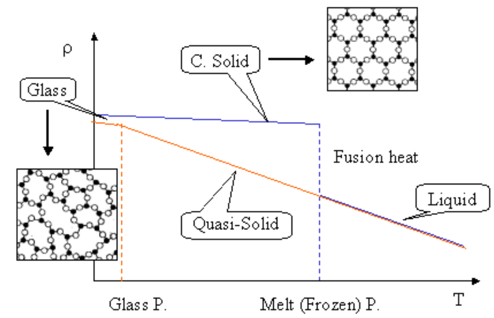

Figure 1 Schematic of phases for crystallized and amorphous materials.

Majority of heavy oils are biodegraded placed at shallow depth (~< 1000 m). Fluid pressure does affect velocities, viscosity, and GOR of heavy oils. But the shallow depth limits pressure, GOR value, and their variation. Therefore, the pressure and GOR effect on heavy oil properties is limited. For under-saturated heavy oil, we mainly concern the API gravity and temperature effect on velocity. In this abstract, we present measured P and S-wave velocities on more than 10 heavy oil samples collected from different fields in worldwide.

Heavy Oil Samples and Measurements

We have collected 10 heavy oil samples worldwide. API gravity of samples ranged from 19 to 6.43, with those of 7 samples in range of 8-11. Unfortunately, we did not have chemical analysis on most of these samples. We also measured a solid oil sample with API of –5 and a wax oil sample with API 26.3.

Increasing temperature (steam flooding) to reduce viscosity is a major method to produce heavy oil. In order to simulate in situ condition, we have studied velocities of heavy oils with temperature from 0 ºC to as high as 170 ºC. We have applied the transmission and reflection method to measure P- and S-wave velocity respectively (Han et al., 2005). We used ultrasonic transducers with central frequency of 1 MHz.

Velocities of a solid oil sample

We have shown measured velocities on a solid oil sample with ρ_o = 1.12 (API = -5) in Figure 2 (Batzle et al., 2004). For temperature rising from -12.5 ºC up to 40 ºC, this oil has a measurable shear velocity and reasonable rigidity. With increasing temperature, both P- and S-wave velocity decreases near linearly. Then, the sample gradually transfers into quasi-solid phase, loses rigidity, and attenuates acoustic signals.

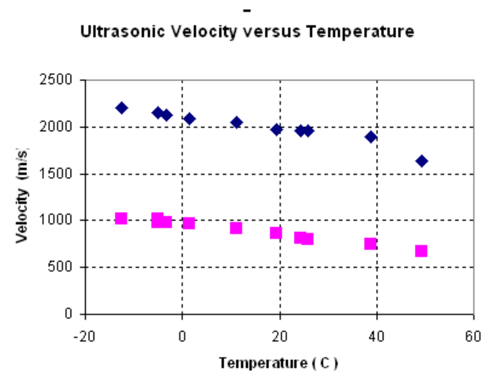

Figure 2 Measured P and S-wave velocities of a solid oil sample.

Pressure effect on velocity of heavy oil

Similar to light oil, P-wave velocity of heavy oil increases

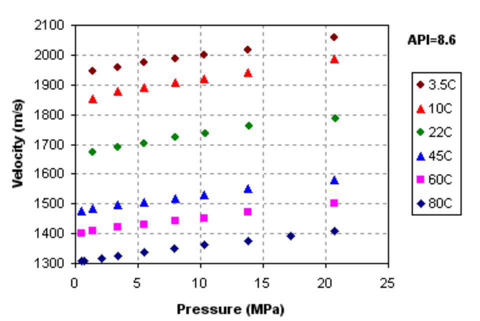

Figure 3 A typical velocity data vs. pressure.

with increasing pressure. Figure 3 shows velocity data measured on a dead oil sample with API gravity of 8.6. P-wave velocity was measured at increasing pressure from 0 to 20.7 MPa (3000 psi) and temperature 3.5 to 80 ºC. For each of temperature, velocity tends to increase linearly with pressure. Velocity gradient with respect to pressure seems to decrease slightly with increasing temperature. We found that increase of the relative velocity with pressure seems to be a constant slightly less than 0.4% per MPa. Overall the pressure effect on heavy oil is small for reservoirs at shallow depths.

Gas effect on velocity of heavy oil

We have measured velocity on a heavy oil sample (API gravity = 11) with Gas-Oil Ratio (GOR) equal to 0 (dead oil), 2 and 37 L/L as shown in Figure 4. The data shows velocity as a function of temperature at pressure of 500 psi (3.45 MPa) for dead and GOR = 2 L/L oil and at pressure of 3500 psi (24.2 MPa) for GOR = 37 L/L oil. Velocity of the dead oil is almost same as that of the live oil with GOR of 2 L/L and few percent higher than the live oil with GOR of 37 L/L. Clearly, Gas dissolved in a heavy oil cause a reduction of oil velocity. Higher the GOR, lower the velocity. However, at shallow, low pressure environment, in addition to low gas solubility, the GOR in heavy oil has negligible effect on velocity. However, if there is free gas phase in heavy oil, gas can reduce velocity drastically as shown in Figure 5. Clearly, evaluate phase condition is the key to estimate modulus of heavy oils.

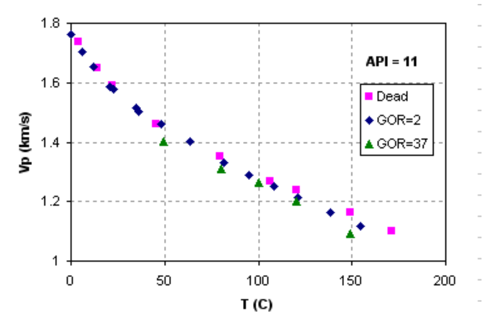

Figure 4 Velocity vs. temperature for oil with different GOR.

Temperature effect on velocity of heavy oil

Currently, inject steam into heavy oil reservoirs is the main method to reduce viscosity and produce heavy oil. Reservoir temperature can vary in wide range of 0 ºC up to 200 ºC, depended on verging reservoir temperature and temperature increase caused by steam. Temperature of heavy oil reservoirs in Canada can be as low as 0 ºC. Heavy oil at low temperature

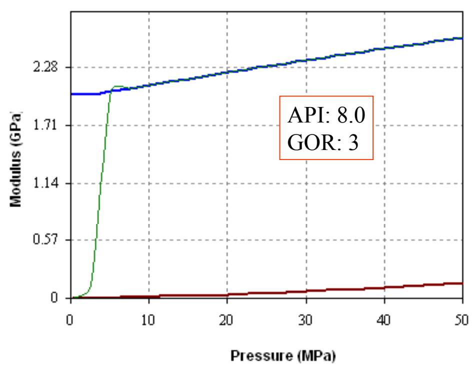

Figure 5 Gas phase effect on modulus of gas-oil mixture.

posses shear rigidity. S-wave can propagate through a solid oil as shown in Figure 2, but attenuated soon as oil soften with increasing temperature. S-wave cannot propagate through a heavy oil in quasi-solid phase. We have developed the reflection method to measure shear velocity of heavy oil (Han et. al, 2005).

We have measured P- and S-wave velocity as function of temperature of heavy oil samples with different API gravity from 8 to 26 at similar low pressures. Measured P-wave velocity (Figure 6) suggests that at high temperature range velocity increases linearly with decreasing temperature at a constant (absolute) gradient of ~ 3.0 m/s/ºC. With decreasing temperature to a threshold point (the liquid point), P-wave velocity deviates up from the linear velocity-temperature trend. Then, velocity approaches to that of glass solid at a low temperature (< the glass point). Velocity gradient reaches the highest value within the transition zone. Measured data (Figure 6) shows that shear velocity appears measurable when temperature decreases lower than a threshold (the liquid point) and increases with decreasing temperature, similar as P-wave velocity. The velocity transition is corresponding to phase transition of the heavy oil from a fluid to a quasi-solid, then to a glass solid. Compiled Vp and Vs data (Figure 7a and b) reveal that heavy oils with low API show higher liquid point temperature, and higher P- and S-wave velocity, and higher P-wave velocity deviation.

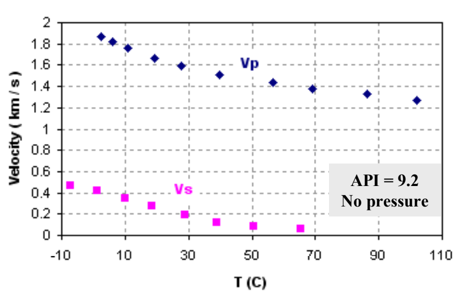

Figure 6 Both measured P- and S-wave velocity vs. temperature.

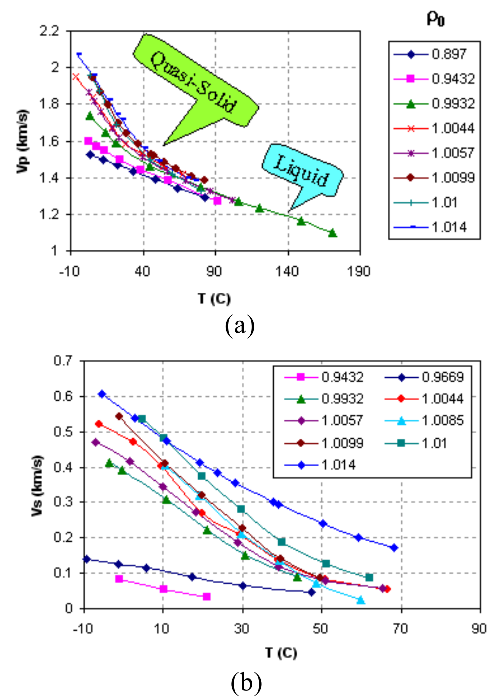

Figure 7 Compiled P- (a) and S-wave (b) velocity data versus temperature.

Both S-wave velocity and P-wave velocity deviation are correlated to viscosity, which increases drastically with temperature lower than the liquid point. In general, lower the API gravity (higher the density) correlate to higher the viscosity. But API gravity may not have unique relation to viscosity because of different chemical composition. We have examined a wax oil with density of 0.897 g/cc (API gravity of 26). The oil appears solidified and cannot flow at room temperature. However, measured data show that P-wave velocity is linearly related to temperature and S-wave velocity is very low (Figure 7a and b). The wax oil has similar behavior as that of light oil. Apparently, viscosity of the wax oil is not high enough to make it as a heavy oil. The API gravity is the parameter to separate light oil from heavy one.

We can formulize velocity of heavy oil in the liquid phase related to temperature linearly as

$V \sim= V_{liq}\,(API) - B\,(T - T_{liq})$
$V_s \sim= 0 \quad (T > T_{liq}) \qquad (1)$

Where V_{liq} is velocity at liquid point and T_{liq} is the liquid point of temperature. For heavy oil in the liquid phase, viscosity effect on velocity is negligible. For the heavy oil in the quasi-solid phase (as temperature is lower than the liquid point), viscosity η plays a role to affect velocity as:

$V \sim= V_0\,(API) - B\,(T - T_{liq}) + C(\eta(API, T), f)$
$V_s \sim= V(\eta(API, T), f) \qquad (T < T_{liq}) \qquad (2)$

Where C is deviation from the linear velocity-temperature trend, f is frequency of acoustic wave. Measured data suggest that viscosity of heavy oil controls the liquid point temperature T_{liq}, P-wave velocity deviation from the linear trend, and S-wave velocity with decreasing temperature. Viscosity is mainly controlled by API gravity and temperature and velocity is compound function of API as shown in equation 2. For different heavy oils with the same API gravity viscosity can be different due to different chemical composition. However, the measured data suggest that velocity show a systematic relation to API gravity. Viscosity effect on velocity seems to be consistent with API gravity effect and may be not sensitive to the chemical composition.

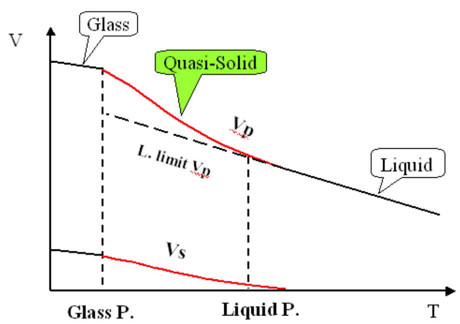

Figure 8 Velocity of heavy oil relates to temperature in three phases.

Summary of measured velocity data

The heavy oils are biodegraded and found in a shallow, low pressure and temperature environment (<1000 m depth). Heavy oil is usually containing low dissolved gas (GOR) with low pressure (<10 MPa). Pressure and GOR effect on velocity is relatively small and manageable. Knowing gas phase in heavy oil reservoir may be more important. Gas phase can reduce modulus of gas-heavy oil (in liquid phase) mixture drastically.

In summary, velocity of heavy oil (or any oil) can be schemed as shown in Figure 8.

1. When temperature higher than the **liquid** point, velocity decreases linearly with increasing temperature same as in case of light oil.
2. When temperature is in between the **liquid** and **glass** point, heavy oil is in quasi-solid phase. Shear velocity of heavy oil is measurable but highly attenuated. Both P- and S-wave velocity increases with decreasing temperature, and transit from fluid to glass phase.
3. When temperature approach to the **glass** point, heavy oil become glass solid. With decreasing temperature both P- and S-wave velocity will continue increasing with a low gradient.

All the velocity data were measured at ultrasonic frequencies (MHz). Acoustic properties on viscous fluid depend on the multiple of viscosity and frequencies. The velocities measured on heavy oil samples in quasi-solid phase are in high bound of those in lower frequencies. Velocities measured on heavy oil samples in the **glass** solid and liquid phase are not sensitive to frequency because either viscosity too high or too low.

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EDITED REFERENCES

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