Complex properties of heavy oil sand

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Summary

With more core samples measured in laboratory, we observed wide scattering of velocity on heavy oil sand samples from different fields. A simple universal modeling for heavy oil sand velocity is unrealistic at this stage. However, with improvements on measurement techniques, plus additional information from heavy oil study and other sources, we have better understanding on each factor controlling velocities of heavy oil sands, which include: rock texture, pore fluid properties, and interaction between pore fluids and rock frame at different temperatures.

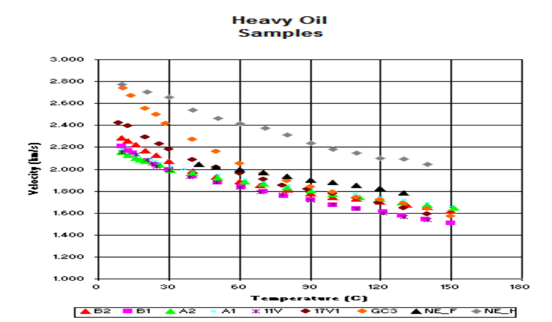

Fig. 1 Vp vs. temperature from different samples.

Introduction

Figure 1 shows observed thermal effect on velocities on different samples. Although a common trend exists, the data still show wide scatter. For example, P-wave velocities can range from 2.2 km/s to over 2.8 km/s and temperature gradients vary over a wide range. Clearly, velocities of heavy oil sands will be affected by many interactive parameters with increasing temperature. We attempt to understand this puzzle with helps from 3 aspects:

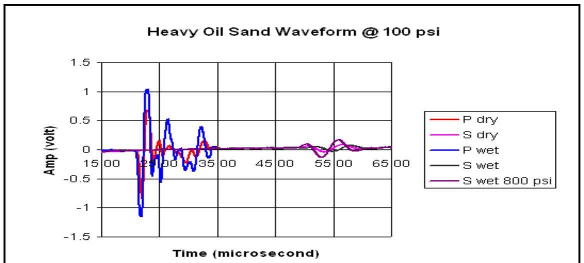

Fig. 2 P and S wave signal in heavy oil sand measurements.

1. Improved measurement equipments and techniques:
   a. Better P and S Signal (Figure 2).
   b. Better temperature and pore pressure control.
   c. Higher quality on core making to preserve integrity of heavy oil sample.
2. Intensive study on heavy oil properties (Han et al, 2006). Heavy oils can have three phases: liquid, glass, and a quasi-solid phase in between (Figure 3). This quasi-solid phase is characterized by a rapid increase of viscosity with decreasing temperature. Heavy oil in the quasi-solid phase possesses shear velocity and frequency dependence. This special heavy oil property may dominant the properties of heavy oil sands, which, in turn, causes complexity compared with properties of simple, conventional unconsolidated sands.
3. Incorporating observations of rock texture as well as employing different measurements to examine different parameter effects on velocities.

We have made significant progress in understanding the properties of heavy oil sands and how these properties change with increasing temperature. However, we are still in an early stage, and continue to collect more data, and attempt to understand what we have observed.

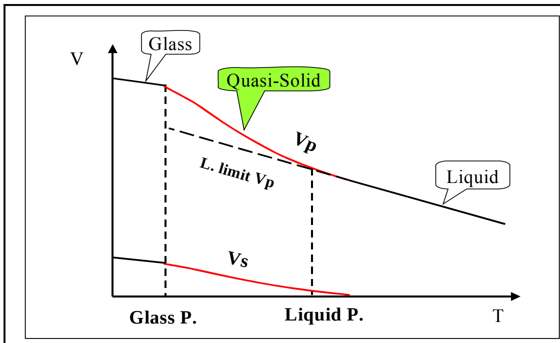

Fig. 3 Schematic of phase change of heavy oil with temperature.

Basic Understanding of Heavy Oil Sands

There are several aspects of basic structure of unconsolidated heavy oil sands:

1. Sand package: Athabasca heavy oil sands are mainly unconsolidated with high porosity, high permeability and poor compaction. Main parameters

of heavy oil sand texture include grain size, grain sorting, porosity and degree of sand compaction.

2. Pore fluid: Heavy oil is the main component of the pore fluid. Velocities of heavy oils depend on API gravity, composition, and phase (liquid, quasi-solid and glass-solid phase), these, in turn, depend on viscosity and are largely controlled by temperature.
3. Reservoir condition: Temperature is the most important parameter controlling viscosity, mobility, pore pressure, hydraulic relaxation length and gas generation of heavy oil, as well as change of grain contact and rock frame. Pressure effects are also important under certain conditions.
4. Oil location in pore space: Sands can either be water wet or oil wet. For water-wet sands, oil is simply a detached pore fluid and does not bear overburden pressure. For oil-wet sands, the oil location in sand package can be complicated and depends on in situ conditions. The oil can be part of pore fluid, part of matrix, or work as cement. Sands can be floating suspension, contacted but unconsolidated, or compacted and cemented. The actual status of the heavy oil sand can be combination of any of above scenarios, depending on the temperature.
5. As elastic waves propagate in heavy oil sands, the properties of oil and sands, oil and other pore fluids (water and gas) are frequency dependent. Because hydraulic relaxation length depends on frequency and viscosity, this causes variation of stress in oil and effective modulus of sand frame and pore fluids.

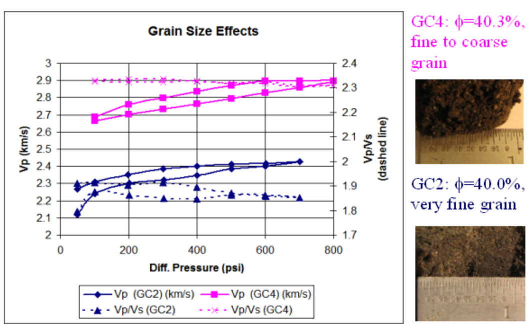

Fig. 4a Grain size effect on velocity and Vp/Vs ratio for heavy oil sand samples.

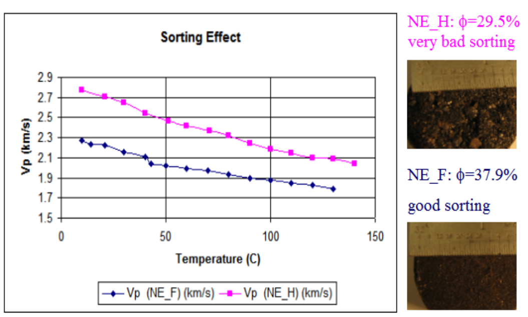

Fig. 4b Grain sorting effect on velocity for heavy oil sand samples.

In the following, we describe effects of individual parameters through measured data.

Observations of Effects on Measured Velocities of Heavy Oil Sands

Effects of rock texture

By incorporating the observation on rock texture, we summary the effect of sand texture on velocity as bellow:
1. Velocities as a function of differential pressure are high in sands with large grain size as (Figure 4a). Large grain sands also show high Vp/Vs ratio.
2. Good sorting (often associated with fine grain size and high porosity) show low P-wave velocities and low Vp/Vs ratios (Figure 4b).

Effect of pore fluid

Acoustic properties of heavy oil sands depend on the quasi-solid phase of heavy oil, which is controlled mainly by API gravity, composition, and viscosity. Oil viscosity is largely a function of temperature. Heavier oil with higher viscosity causes high velocity in oil sands because heavier oil has higher fluid modulus, which determines increment of fluid saturation effect on velocity. Measured velocities on Gulf Canada samples are usually higher than those of Old EnCana samples. We know from measured data that oil density in Gulf Canada sands is higher (~ API gravity 7.4) than oil in Old Encana ones(~ API gravity of 9.4).

Effect of wettability of sands

In general, quartz sands are water wet. A water film will cover sand surface and heavy oil will floating in the pores. However, heavy oils are more chemically active and acidic, and capable of altering the wettability of sand grains, and generates complex scenarios for oil wet sands. Figure 5 shows a schematic of heavy oil distribution in pore space due to variation of wettability.

1. If sands are water wet, heavy oils will be part of pore fluids and will only support the pore pressure but not overburden pressure. Oil effects on velocities will be smaller and similar to those of water saturated sands.
2. If sands are oil wet, oil will directly contact sand

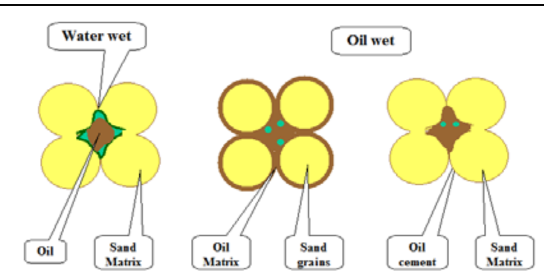

Fig. 5 Various wettablity schemes determine different oil distribution in heavy oil sands.

grains. Oil distribution in sand matrix can be complicated.

a. If oil is sufficiently heavy and viscous (such as tar sands) and rich (high saturation), it can form a continuous matrix, with sand grains floating inside. Hashin-Shtrikman lower bound (1963) can be used to model it and get low velocities.

b. Sands are grain contacted. Heavy oil is part of sand matrix to cement sand grains, and part of pore fluid, depends on oil viscosity and wave frequencies. Velocities in case b is higher than case a.

c. In general oil location can be a combination of case (a) and (b). Velocities of oil sands will be affected by fraction distribution of heavy oil location.

d. At high temperature with heavy oil in the liquid phase, oil will be moved out of grain contacts. Sands will be a matrix and oil will be the pore fluid. Wettability is less important.

In general, heavy oil sands may have mixed wettability, with resulting effects on velocity varying depending on the fraction of wetted oil.

Effect of temperature

Thermal processing is a major method to produce heavy oil. With increasing temperature velocities of heavy oil reduce significantly. Figures 6 shows measured P- and S-wave velocities and bulk and shear modulus as a function of temperature. Measured data show both P/S velocities and K/G decrease with a large gradient with respect to increasing temperature from 10 to 60 °C. As temperature increases over 60 °C, the Vp and K continue to decrease with a smaller gradient, and the Vs and G mainly remain as a constant. Data suggest that at low temperature (< 60 °C), Gassmass's requirement of a constant shear modulus is no longer valid.

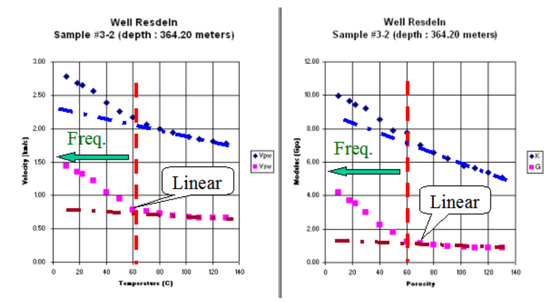

Fig. 6 Vp, Vs (left) and K, G (right) as functions of temperature for heavy oil sand sample.

60 °C appears as the liquid point for the heavy oils in this sample. We have validated this by measuring the density from a heavy oil drop produced from the sample by steam flooding. Using the FLAG program, we calculated viscosity of this extra-heavy oil (De Ghetto, 1995, FLAG, 2006) and results show, as at temperature of 60 °C, oil viscosity is 1164 cp, which approximately matches the definition of the liquid point.

Our measured temperature effects on velocities can be summarized as follows:

1. Moduli and velocities of heavy oil decrease with increasing temperature (Han and Liu, 2005). So are the velocities of heavy oil sands.
2. Oil viscosity decreases with increasing temperature. Phase of heavy oil will transits from quasi-solid phase at a high viscosity (>>800 cp) to liquid phase at a low viscosity (<800 cp).
3. At liquid phase, heavy oil is basically same as conventional oil. Velocities of heavy oil sands have negligible dispersion.
4. At quasi-solid phase, velocities of oil are dispersive and attenuative, so are the velocities of heavy oil sands. Ultrasonic velocities represent a high bound for the seismic data.

In addition, the thermal measurements can cause repacking of unconsolidated samples because of the transition of heavy oil to liquid. Therefore, data in the thermal measurement is difficult to repeat because unrecoverable thermal processes. We have observed velocity increase in the second cycle of measurement.

Effects of wave frequencies

For heavy oil in quasi-solid phase, the modulus is frequency dependent and controlled by oil viscosity. This depends on hydraulic relaxation length L_r in comparison with characterization length L_c of fluid distribution. In the cases of L_c is far larger than L_r (unrelaxed, patchy or iso-strain condition), or L_c far smaller than L_r, (relaxed, iso-stress condition), the rock systems are both under elastic conditions. In between these extreme cases, waves in the rock and fluid system will be dispersive and attenuated. Hydraulic relaxation length is defines as

$$L_r = \sqrt{K * K_f / \eta * f}$$

where K is permeability, K_f is fluid modulus, η is fluid viscosity and f is wave frequency. For high viscosity oil (> 10^7 cp), L_r can be as small as a micron even at seismic frequencies. Characterization length for heavy oil sand can be as large as a millimeter. Properties of heavy oil-rock and heavy oil-water (or gas) system can change significantly with frequencies at different temperatures.

At low temperature, heavy oil viscosity is so high, that the relaxation length be much smaller than sand grain size. When seismic waves pass through the sands, pressure generated in oil cannot be relaxed with other pore fluid. Oil behaves same as solid media. We need to

treat oil as part of matrix, and gas (and/or water) will have minor effect on velocity of heavy oil sands.
With increasing temperature, oil viscosity decreases and oil tends to be relaxed to generate pressure equilibrium with other pore fluid. Oil becomes a part of pore fluid to bear the pore pressure. In this case, other fluids can be important. The data in Figure 7 compares the measured heavy oil sand velocities at "as is" condition without control of pore pressure and at "water saturated" condition with pore pressure control. The much lower "As is" P-wave velocity suggests that there is air or gas in the pores, to reduce velocity to even less than water velocity 1.5km/s at T>70 °C. For the same sample, the "water saturated" velocity shows only a mild decrease with increasing temperature, because the controlled pore pressure prevent the air or gas coming out of fluid. At higher temperature air-oil mixture is in iso-stress relation, and velocity is controlled by properties of air-oil system but much less temperature dependent.

In summary, viscosity is a primary heavy oil property. Temperature controls viscosity, thus any frequency effect depends on viscosity, and temperature conditions. With increasing temperature, frequency effects reduce gradually and vanish as heavy oil transforms to a liquid phase.

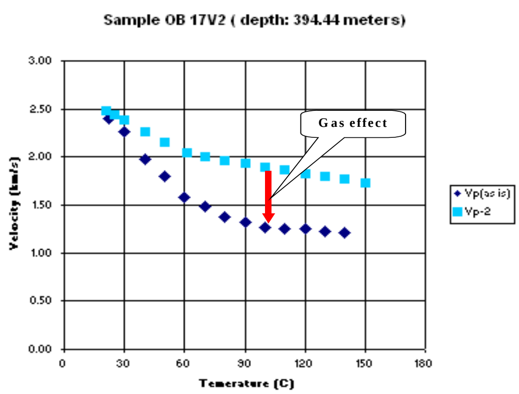

Fig. 7 Measured velocity at "as is" condition and controlled pore pressure condition.

Effect of Pore pressure
Simple PVT calculation shows that heavy oil has a large volume expansion due to temperature increase, if the pressure is constant (Figure 8 left). If we assume that the heavy oil remains a constant volume, then the thermal pressure of oil has to increase over 100 MPa at 80 °C, far greater than overburden pressure as shown in Figure 8. This suggests that the thermal pressure of heated oil can easily generate hydro-fractures even only with a small temperature increase. Sand frame can be damaged by break of grain contacts and repacked. This may suggests that large reduction of velocity with increase temperature at low temperature range may be caused by two additional factors: reduce effective pressure and damaged grain contacts due to the thermal pressure.

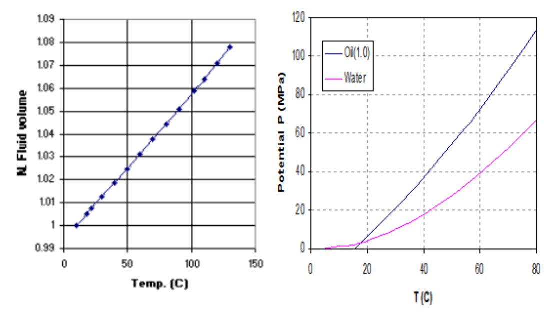

Fig. 8 Volume expansion (left) or pressure increase (right) of heavy oil due to temperature increase.

Effect of Oil saturation
We find that velocities of heavy oil sands correlate with heavy oil saturation differently in different conditions. At low temperatures with oil in quasi-solid phase, velocities of heavy oil sands are not very sensitive to the oil saturation but more to the sand texture and oil properties. It means that small amount of heavy oil ($S_o \sim 30\%$) may play a dominant role to effectively cement sands and increase velocity at high frequencies. Additional amount of heavy oil has much less effect on velocities of sands. However, at high temperatures, P-wave velocity of sands increases significantly with increasing of water fraction due to oil production, because fluid modulus increases with increasing of water fraction.

Conclusion

Measured data suggest that properties of heavy oil sands are controlled by properties of rock frame, pore fluids (mainly heavy oil), oil distribution (wettability) and wave frequencies. For thermal recovery processes, oil viscosity can decrease drastically and transform from quasi-solid phase to liquid phase. Changing viscosity leads to dynamic properties changing with frequencies. In addition to the static change of rock frame and oil distribution, combination effects can be more difficult to quantify. We hope to use the local reservoir depositional environment to help to sort out the numerous complicated parameters into few dominant ones.

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EDITED REFERENCES

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