Measurement of shear wave velocity of heavy oil

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Introduction

It is well known that the fluids have no shear modulus and therefore no shear wave can propagate through fluids. But heavy oils have properties that are much complex than lighter oils. At low temperatures, heavy oils are extremely viscous and begin to act like solids. An effective shear modulus appears allowing propagation of shear waves. The bulk moduli of heavy oils increase since the bulk and shear moduli are related with each other. Therefore, it is observed that the compressional wave velocity of heavy oils increases faster than that of light oils at low temperatures.

On the other hand, we know from the viscoelastic model of Maxwell that, the shear impedance of the viscous fluid is related with its viscosity which is one of the important control factors for wave attenuation.

$$|Z^*| = \left[\frac{\eta\omega\rho}{(1+\omega^2\tau^2)^{1/2}}\right]^{1/2} = V_S \cdot \rho$$

$$\tau = \frac{\eta}{G_\infty}$$

where, |Z*| is the magnitude of the complex shear impedance, η is viscosity, ρ is density, ω is angle frequency and G_∞ is effective high frequency shear modulus and τ is called relaxation time.

It is apparent that the shear wave velocity information is useful along with P-wave velocity and density to predict the viscosity and attenuation of the heavy oil. This paper describes the method, facilities and accuracy of S-wave velocity measurements for heavy oil.

Measuring Method

The traditional method for measurement of fluid velocity is to measure the travel time of the transmission wave and then the velocity can be derived with the known travel distance. A specially designed chamber with two transducers located at its both ends, the distance of which were calibrated at different temperature and pressure by distilled water, has been used and is good for P-wave measurement for a lot of fluid samples. But the transmission signal is very hard to be recognized due to presence of strong noise if using the S-wave transducers instead of P-wave transducers. It is true even for very heavy oil at low temperatures at which the oil acts like a solid. It means it may not be feasible for direct measurement of shear velocity in heavy oil.

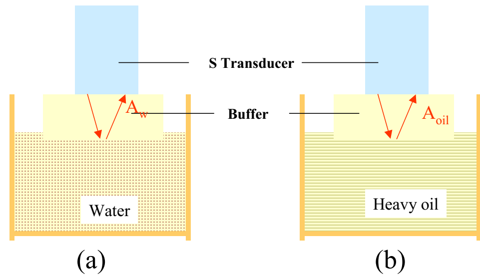


Fig. 1

A method is designed for indirect measurement of shear wave velocity. Figure 1 shows the principle of this method. The shear wave transducer is coupled with a buffer made of some kind of plastic and the transducer is in the mode of self emission and receiving. The measurement is done in two steps. The first is to record the shear reflection from the bottom of the buffer A_w that is in contact with the reference sample (water) and the second is to record the same reflection wave A_h when the buffer is in contact with the real sample (heavy oil). The difference between A_w and A_h is caused by the different reflection coefficient R_w (between buffer and water) and R_h (between buffer and heavy oil) if all measurement conditions can be controlled. It is obvious that the ratio of amplitude of reflected wave equals to the ratio of the reflection coefficient.

$$\frac{R_h}{R_w} = \frac{A_h(f)}{A_w(f)}$$

where, $A_w(f)$ and $A_h(f)$ are the magnitude spectra (function of frequency) of waves A_w and A_h. The reflection coefficient R_w is -1 because the shear impedance of water is 0.

$$R_w = \frac{Z_w - Z_b}{Z_w + Z_b} = \frac{0 - Z_b}{0 + Z_b} = -1$$

where, Z_w and Z_b are shear impedances of water and buffer respectively. If the impedance of the buffer Z_b and the density of the heavy oil ρ_h are known, then the shear velocity V_s of the heavy oil can be derived.

$$R_h = -\frac{R_h}{R_w} = -\frac{A_h(f)}{A_w(f)} = \frac{Z_h - Z_b}{Z_h + Z_b}$$

$$Z_h = \frac{1 - A_h(f)/A_w(f)}{1 + A_h(f)/A_w(f)} Z_b$$

$$V_s = \frac{Z_h}{\rho_h}$$

where, Z_h is the impedance of the heavy oil sample.

Water is used as the reference material, since water can be easily kept in the desired temperature and pressure. In practice, the peak-to-peak amplitude can be taken to replace the spectrum analysis in order to simplify the calculation.

Experimental Facility

The schematic of experimental facility is shown in figure 2. A pressure vessel is used for measuring water or heavy oil sample. The sample pressure can be controlled by a pump through the pipe. The pressure vessel is put into a bath tank filled with anti-freezing liquid which can be adjusted to the desired temperature. The S-wave transducer is used to record the reflection waves from the buffer. Meanwhile, a P-wave transducer is used to receive the transmitted P-wave that is converted from shear wave. Therefore, the compressional velocity can be measured simultaneously during shear velocity measurement.

It is necessary to calibrate the facility first. Distilled water is filled in the vessel and the shear reflection wave and compressional transmission wave are recorded separately at different pressures and temperatures. The reflection waves are used to build the relationship of reflection waves A_w with pressure and temperature. The travel time of the compressional wave is used to calibrate the propagation distance of compressional wave in the sample at various pressure and temperature since the velocity of the distilled water and the buffer along with the thickness of the buffer are known. The calibrated distance is needed to calculate P-wave velocity when the heavy oil is filled in the vessel.

A Virtual Instrument (software) written in LABVIEW for signal spectral analysis was developed in our lab. The S-wave velocity with frequency can be derived by this software.

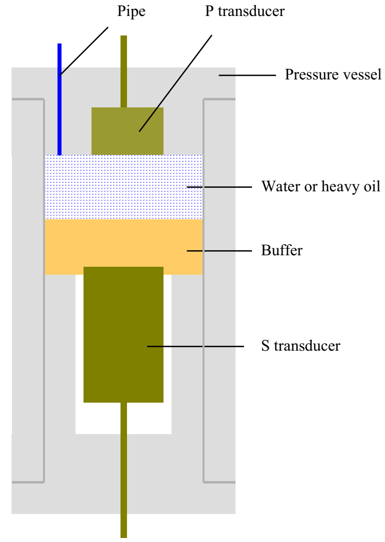


Fig. 2

Examples

Several heavy oil samples with different API gravity have been measured in the lab. Figure 3 shows the P-wave and S-wave velocities versus temperature at pressure of about 0.7 MPa for a sample of heavy oil of API gravity of 8.0. It is clear both velocities decreases with increasing temperature but its a near linear relation for S-wave and non-linear for P-wave. Other samples that we measured support same rule.

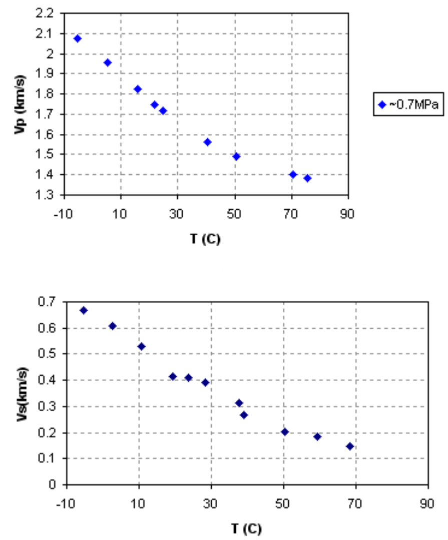


Fig. 3

The spectral analysis can give changes in the shear velocity with frequency, while the peak-to-peak value of the signal can only show the shear velocity near the main frequency of the transducer. Figure 4 shows the shear velocity versus frequency that indicates shear velocity increases slightly with increasing frequency for a sample with API of 10.97. For comparison, the velocity calculated from peak-to-peak is pointed in the figure. We can find from figure 4 that the shear velocity increases gradually with increasing frequency at various temperatures and pressures. Meanwhile, the value of shear velocity about 900 kHz from spectral analysis is consistent with that using peak-to-peak ratio. The dominant frequency of the reflection wave from spectral analysis for various temperatures is in the range of 800 to 1000 kHz with 1MHz transducer.

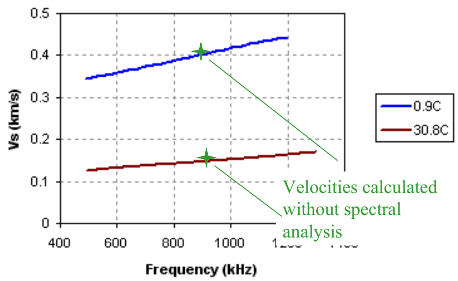


Fig. 4

The modulus of the sample can be derived if its P-and S-wave velocities and density are known. Figure 5 shows the bulk and shear moduli of the first sample (API=8.0) at pressure of about 0.7MPa. It can be seen that the change of the bulk modulus with temperature is very similar to that of shear modulus. It means both moduli are dependent on each other. We think it is possible to estimate S-wave velocity from P-wave velocity. Such relationship will be developed in future.

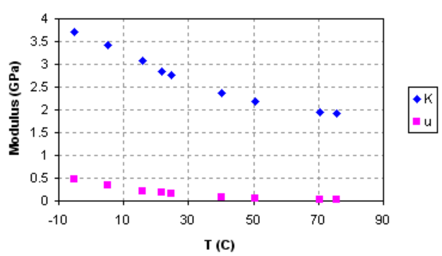


Fig. 5

An interesting sample is wax-rich oil with API of 26.25. It seems solid at room temperature since it contains much wax even though the oil is not very heavy. The shear velocity is rather low compared with the real heavy oil.

We have also measured shear velocity of glycerol that is relatively low although the glycerol has very high density of 1.253 gm/cc.

Factors That Affect Accuracy of Measurement

It is well known that the accuracy of P-wave velocity depends on the accuracies of the travel time and calibrated length of the chamber. The relative error of P wave velocity is less than ±1% as per our experience.

The shear velocity measurement of heavy oil is an indirect measurement and many more factors may affect the accuracy of the measurement.

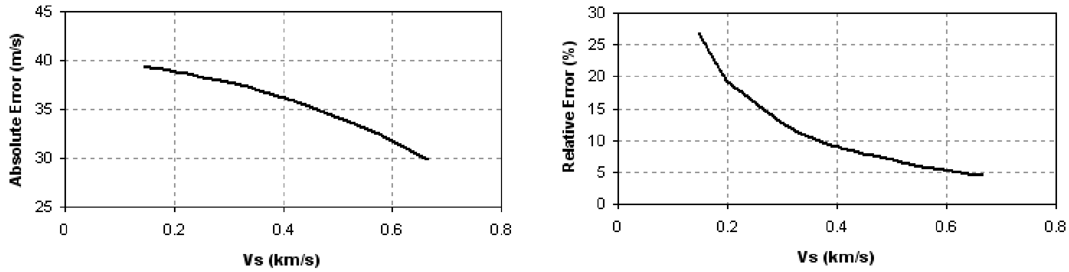
The first problem we met in measurements is the stability of the coupling between the transducer and the buffer. The state of coupling may strongly affect the amplitude of the reflection waves. Because we have to measure water and oil sample separately at different temperatures and pressures, we hope the changes due coupling may reverse while changing the temperature and pressure. We tried several different materials for coupling and finally a fast epoxy is selected and the coupling stability is acceptable.

The main error is probably from the amplitudes for waves A_h and A_w caused by the stabilities of electronic equipment and power. Average difference of the amplitudes of the reflection waves from statistics is in the range of ±3% as per our experience. Therefore, the maximum error may occur when A_h has –3% error and A_w has +3% error or vice versa. As an example, we use the first sample to check the maximum error in the measurement of S-wave velocity. Figure 6 shows the maximum absolute and relative errors in S-wave velocity, respectively. It can be seen that either one of the absolute or relative error is higher if the S-wave velocity is lower. In this figure, the relative error of S-wave velocity may be higher than ±10% (absolute error may be larger then ±36m/s) if the S-wave velocity is less than 0.36km/s. It means the velocity value is reliable when S-wave velocity is higher than 0.4km/s, but may not be accurate enough if the S-wave velocity is relatively small.

On the other hand, the material of buffer may affect the sensitivity of the measurement. The reflection coefficient will be close to ±1 if the impedance of the buffer is very different from water or oil; no matter the buffer is in contact either water or oil. The small difference between A_h and A_w may reduce the accuracy of the velocity calculation. The best buffer should have similar impedance as water and oil. The density and S-wave velocity of the buffer we used are 1.277g/cm^3 and 1.05km/s respectively. In order to reduce the wave attenuation of the buffer, we select a special plastic material as the buffer with small thickness.

Measurement of P-wave Velocity

The P-wave velocity can be obtained simultaneously by our facility (figure 2). The accuracy of the P-wave velocity may be questionable since the transmitted conpressional wave is the convert wave. Our measured data show the differences from the velocities by traditional method are less than ±2% for various temperatures and pressures. The accuracy may raise if



(a) (b)

Fig. 6

the correction of travel time for delay of converted wave is taken.

It is interesting that the amplitude of the conpressional wave changes obviously with the temperature (see figure 7 as an example). The wave amplitude can indicate the attenuation of the P-wave through the heavy oil and the maximum attenuation in this sample is at the temperature about 20°C since the amplitude reaches the minimum at the above temperature. It is known that the maximum attenuation may occur when the wave frequency is at the resonance frequency of the material. The resonance frequency of the heavy oil depends mainly on its viscosity that may vary with temperature.

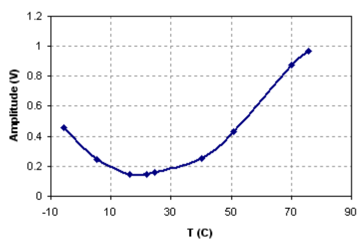


Fig. 7

Conclusion

The measurements of S-wave velocity of heavy oil demonstrate the indirect method for measuring S-wave velocity. In order to obtain certain accuracy, special care should be taken to keep all conditions stable during measurements. The measurement error may be rather large if the value of S-wave velocity is small and therefore, measurements of S-wave velocity of heavy oil with high API gravity at high temperature may not have high accuracy.

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