Pressure effect on density and acoustic velocity of heavy oil

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Summary

P-wave velocity of heavy oil was investigated at temperature ranged from 8°C to 90°C, and pressure ranged from 0.1MPa to 48MPa. Pressure effect on velocity remains linear if oil is in its liquid phase, but transfers as nonlinear if oil is in its quasi-solid phase. The liquid-point temperature tends to move higher with increasing pressure. We have developed the model for the pressure effect on heavy oil velocity and integrated into the existing velocity models.

Introduction

With reserves comparable to those of conventional oil, heavy oil is an important energy resource. However, producing heavy oil is quite challenge. Usually a thermal processing is used to reduce heavy oil viscosity and 4-D seismic technique is applied to monitor reservoir performance. Therefore, we have investigated mainly temperature effect on seismic properties of heavy oil. Measured P and S-wave data suggest that with decreasing temperature, heavy oil has three distinguished phases, liquid, quasi-solid, and glass-solid. We utilize measured velocity variation with temperature to define the liquid-point and the glass-point temperature and to separate the three phases (Han et al., 2008).

Based on measured data, we have developed models to predict heavy oil velocity as function of temperature. Intentionally, we have ignore the pressure effects on velocity of heavy oil, mainly because we have focused on heavy oil reservoirs in shallow depths (<1000 m). In addition, the pressure effect is small and systematic, which can be estimated using the conventional oil model with local calibration (Liu et al., 2011).

However, heavy oil reservoirs have also found at deep depths in many basins of world. We need to further investigate pressure effect on properties of heavy oil. With newly measured velocity and density data with pressure from room pressure to 48MPa (7,000 psi), temperature from 8°C to 90°C, we up-date the existing models to include the pressure effect. In this abstract, we present measured data, and updated velocity models.

Experimental procedure and equipment calibration

Our measurement system mainly consists of a pressure vessel for density and velocity measurements with temperature and pressure control. We used the silicon heat pad and a thermal controller to control temperature higher than room condition, and adopt a wine cooler to host the measurement vessel to control temperature lower than room condition from ~4°C to 15.6°C.

We calibrated the system with velocity and density measurement on de-aired, distill water with pressure and temperature conditions. Measured data (shown as symbols) have compared with calculated values (as lines) using "FLAG" program as shown in Figure 1.The accuracy for both of velocity and density is less than 1 %.

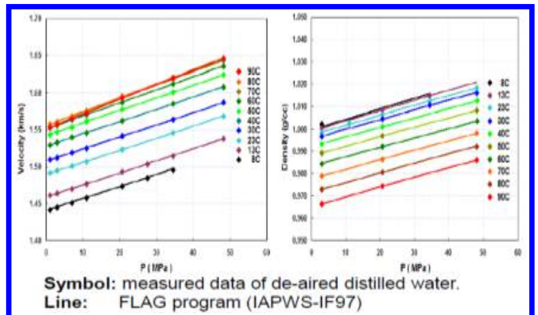

Figure 1. Calibrated measurement system.

During velocity and density measurement, we need to vary pressure and maintain temperature as a constant. However, we have difficult to stabilize temperature, especially at sub-room temperature range. When up-loading pressure, the temperature of the oil sample increases. This will take a long time to cooling down. In comparison, temperature disturbance with down-loading pressure is easier to recover. Therefore, the measurements were made with downloading pressure. We have measured P-wave velocity and density of heavy oil with temperature from 8°C to 90°C, and pressure from 0.1 MPa to 48MPa.

Sample

New data are measured on a heavy oil sample with API gravity of 9.88.

Measured data and analysis

Velocity

Measured data show that the P-wave velocity of heavy oil increases with decreasing temperature and increasing pressure.

Temperature effect

Figure 2 shows measured velocity data as a function of temperature and pressure. The symbols are measured data, and the lines are calculated values using the FLAG program when treated it as conventional oil. The temperature of the liquid point is estimated as 39°C using the viscosity model Vis_2011 (Liu et al., 2011) (Figure 3). In the range of temperature higher than the liquid point, the viscosity of heavy oil is low and its effect on the velocity is ignorable. Therefore, the velocity of heavy oil is similar to that of conventional oil, and the velocities increase linearly with decreasing temperature. With temperature decreasing over the liquid point, the phase of heavy oil transfers from liquid to quasi-solid, and viscosity increases rapidly with decreasing temperature. Correspondently, velocity deviates up from a linear trend in the liquid phase and velocity gradient increases (in absolute value).

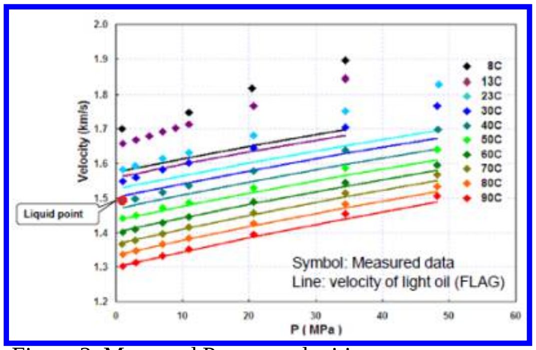

Figure 2. Measured P-wave velocities.

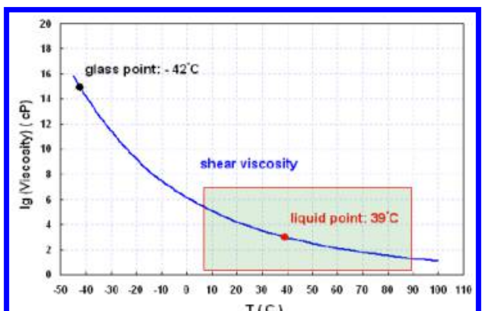

Figure 3. estimated viscosity and liquid point by the viscosity model Vis_2011 (Liu,2011).

Pressure effect

Contrary to the temperature effect on velocity, increasing pressure causes an increase of velocity. However, when studying the pressure effect in detail, there are similar behaviors as that of temperature. In the liquid phase, P-wave velocity increases linearly with increasing pressure at a given temperature. Velocity gradient related to pressure shows slightly increase with decreasing temperature. In the quasi-solid state, we noted that the velocity gradient increases with pressure increasing at a given temperature. In order to emphasize the pressure effect on velocity, we calculate differential velocities based on one at the minimum pressure. Thus we can observe clearly the pressure effects on heavy oil velocity data (as symbols) in comparison with the model trend (as lines) of the conventional oil (Figure 4.A).

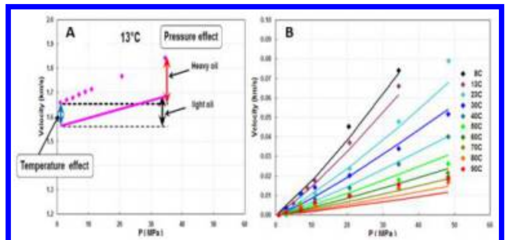

Figure 4. Pressure effect on velocity of heavy oil and modeled correlation.

We also noted pressure effect on liquid point. In general, the liquid point is corresponded to the deviation point of heavy oil velocity from that of conventional oil. At room pressure, the deviation point is the temperature when P-wave velocity is around 1.5km/s. But the deviation point moves upward with pressure increasing. It reveals that the liquid point increases with pressure about 0.5°C/MPa (Figure 5).

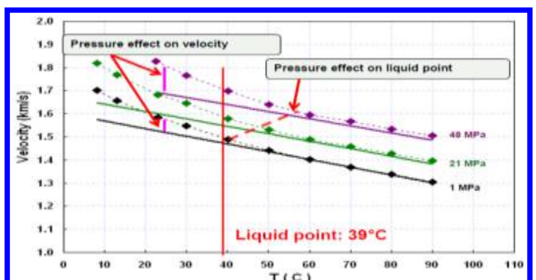

Figure 5. Pressure effect on P-wave velocity and liquid point.

Since viscosity is a main source for the nonlinear behavior of heavy oil velocity, the observed pressure's effect on velocity gradient and the liquid point suggest that viscosity of heavy oil increases with increasing pressure. Furthermore, the frequency dependent of heavy oil velocity may also be affected.

Density

Unlike velocity property affected by temperature, measured data show densities of heavy oil still keep trends of conventional oil when temperature decreases from the liquid phase to quasi-solid phase (Figure 6).

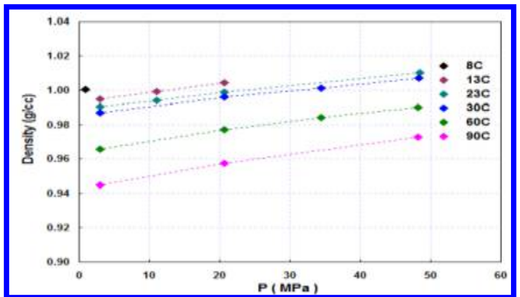

Figure 6. Measured density.

Modulus

We can estimate bulk modulus from the measured velocity and density as shown in Figure 7. Trends of modulus follow the trends of velocity.

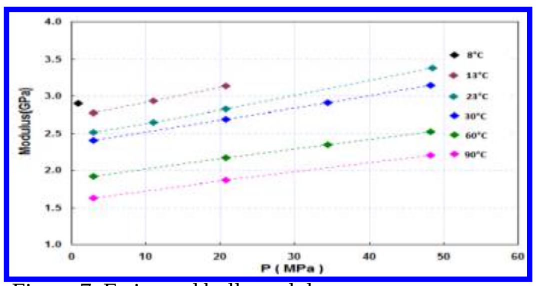

Figure 7. Estimated bulk modulus.

Modeling pressure effect on velocity of heavy oil

Based on the newly measured data, we can include pressure's effect in the existing model to describe velocity of heavy oil more accurately. Basically, we still use the velocity model of conventional oil, and then give correction for pressure effect on heavy oil.

Pressure effect on P-wave velocity

The velocity model for conventional oil

The velocity model for conventional oil is formulized in the FLAG program. The model has been used in the velocity model for heavy oil without pressure effect. When temperature is higher than liquid point, the velocity of heavy oil as a function of temperature and pressure is similar to conventional oil. We can still use it to describe velocity of heavy oil with pressure effect. However, the velocity data in quasi-solid phase are significantly higher than the trend of conventional oil. Additional correlations for temperature and pressure effects on heavy oil velocity are required.

The existing velocity models for heavy oil

The velocity models of heavy oil, Vp_T_2011 and Vs_T_2011, have been used to predict ultrasonic P- and S-wave velocities as function of temperature and API gravity. The models have also been extended to apply to a low-pressure heavy oil reservoir successfully (Liu et al., 2011, Han et al., 2008). Therefore we maintain the existing models but extend them to include pressure effect.

Model modification for pressure effect

Based on the measured data, we need to modify velocity models with pressure effect for the difference as shown in Figure 5,

$$V_{p\_non} = V_T + \Delta V_{p\_non} \tag{1}$$

where

V_{p_non} is the nonlinear part of heavy oil velocity, V_T is velocity of heavy oil with temperature effect in the existing model, and ΔV_{p_non} is the correction for pressure effect which is a function of temperature, pressure , and API (Equation 10). The measured data (symbols) with estimated values of the correction are shown in Figure 4.B.

Since the velocity correction describes pressure's effect on the nonlinear behavior of heavy oil velocity, we included it to the Vp_non_2011 part of the existing model. Therefore, based on the existing model, the updated model with pressure effect can be expressed in two updated terms and keep the other untouched. One term is V_{p_CTP} , which is the P-wave velocity estimated by the velocity model of conventional oil used in FLAG programs. The other term is V_{p_non} included with ΔV_{p_non} as shown in Equation 10.

$$V_p = V_{p\_CTP} + V_{p\_non} + V_{p\_lin} \tag{2}$$

where

$$V_{p\_non} = A_{pT}\frac{e^{C_{pT}\Delta T_p}}{e^{C_{pT}\Delta T_p+1}} + \Delta V_{p\_non} \tag{3}$$

$$V_{p\_lin} = S_{pT}[\Delta T_p - ABS(\Delta T_p)] \tag{4}$$

$$\Delta T_p = T - t_{0pT} \tag{5}$$

$$A_{pT} = -0.0576 + 1.211\rho_0 - 0.528\rho_0{}^2 \tag{6}$$

$$C_{pT} = -0.0934 + 0.0361\rho_0 \tag{7}$$

$$t_{0pT} = -375.59 + 366.74\rho_0 \tag{8}$$

$$S_{pT} = -0.008071 + 0.013442\rho_0 - 0.0060654\rho_0{}^2 \tag{9}$$

$$\Delta V_{p\_non} = \frac{a}{API[150+(150+T)^b]}P^c \tag{10}$$

Where

$a = 5669749940.5783;\ b = 5.32334; c = 1.17528$

Pressure effect on S-wave velocity

Based on the relation of the non-linear parts of P- and S-wave velocities (Liu et al., 2011). we can derive the nonlinear part of S-wave velocity including pressure effect from the nonlinear part of P-wave velocity as shown in the equation (3).

$$V_{s\_non} = -0.539948 + \frac{(0.1168288+1.2416V_{p\_non})^{0.5}}{0.6208} \quad (11)$$

Therefore, the effect of pressure on S-wave velocity can still be expressed as,

$$V_s = V_{s\_non} + V_{s\_lin} \quad (12)$$

where

$$V_{s\_lin} = S_{sT}[\Delta T_s - ABS(\Delta T_s)] \quad (13)$$

$$\Delta T_s = T - t_{0sT} \quad (14)$$

$$t_{0sT} = -372.57 + 371.72\rho_0 \quad (15)$$

$$S_{sT} = -0.0116 + 0.0197\rho_0 - 0.0092{\rho_0}^2 \quad (16)$$

where, $Vp_{\_non}$ and $Vs_{\_non}$ are non-linear parts of P and S velocities, respectively.

Updated model evaluation

Figure 8 shows the comparison of the measured data with calculated values by the existing and updated models. The 482 points of our measured data are used for the model evaluation, which cover a wide range of temperature and pressure. The comparison of the measured data with estimated values by the conventional oil model is shown in Figure 8.A. Figure 8.B is the data with results of the existing heavy oil model for temperature correlation only. Predicted values of the updated heavy oil model for temperature and pressure effects match the measured data well as shown in Figure 8.C.

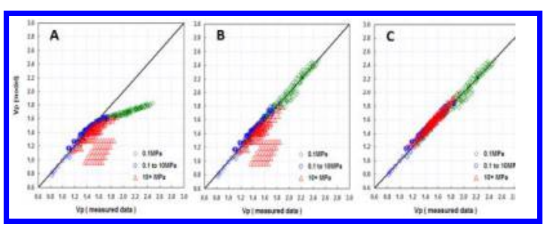

Figure 8. Comparisons of measured data with predicted values of P-wave velocity models. A. data with values of the conventional oil model; B. data with values of the existed heavy oil model for temperature effect; C. data with values of the updated heavy oil model for temperature and pressure effects.

The Average Absolute Relative Error (AARE) analysis is used to test their validity as,

$$AARE = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{(V_{i\_predicted} - V_{i\_measured})}{V_{i\_measured}}\right| \quad (17)$$

where N is the number of measured points, $V_{i\_calculated}$ is the calculated velocity by the updated model, and $V_{i\_measured}$ is the measured value.

The table 1 shows the result. The AARE analysis reveals that the predicted velocities by the both models almost keep the same for oil with room or lower pressure. But with pressure increases to high, the updated model can describe pressure features more correctly.

	Total	0.1 MPa	0.1<P ≤ 10MPa	P>10MPa
Data points	482	224	114	144
Existed model	4.67%	2.04%	2.04%	10.01%
Updated model	2.62%	2.05%	2.18%	2.56%

Table 1. Models evaluation result.

Conclusions

Pressure effects on P-wave velocity of heavy oil are different within the different phases:

1. At the liquid phase, pressure effect is similar on those of conventional oil. The relation of velocity and pressure is linear.
2. At the quasi-solid phase, P-wave velocity and its gradient with pressure increase with pressure. Velocity-pressure relation is nonlinear.

Pressure effect on P-wave velocity and liquid point was observed. Viscosity and the temperature of liquid point increase with pressure.

Pressure effect has been modeled and integrated into the existing models, and the updated models have been evaluated and match well with measured data.

Pressure effect on S-wave velocity was induced from the updated P-wave velocity model.

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EDITED REFERENCES

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