Compressional velocity of heavy oil at high temperature condition

Min Sun and De-hua Han, RPL, University of Houston

Summary

Thermal recovery is the most common technology used to develop heavy oil reservoirs. In order to better understand acoustic properties of heavy oil in-situ condition during reservoir development and production, we measured ultrasonic compressional velocity of heavy oil in high temperature range from 130°C to 320°C. Based on the measured data, the velocity model of heavy oil as a function of temperature has been updated, and its application range of temperature is extended from below 100°C up to 320°C.

Introduction

With conventional oil resources decrease, we have focused our research on heavy oil resources for years. Based on our measurement of the ultrasonic compressional velocity of heavy oils as a function of temperature, we defined the liquid point in temperature as the phase transition threshold between the fluid and the quasi-solid phase. We recognized the compressional velocity and liquid point obtained based on ultrasonic data are frequency dependent when temperature below its liquid point. We developed models to predict compressional velocity and shear velocity of heavy oil as functions of temperature and frequency (Liu, et al., 2007, Han, et al., 2014). Although the models' application is limited to dead heavy oil with room pressure and lower temperature, they can be used by local calibration for shallow heavy-oil reservoir with low GOR and low pressure.

However, in-situ heavy oil isn't easy to produce due to its high viscosity. The most common technology used to develop heavy oil reservoirs is thermal recovery – to reduce viscosity by injecting high temperature steam. As we know, acoustic properties of heavy oil are a fundamental issue, and shear velocity of heavy oil is ignorable when temperature is above its liquid point (Han, et al., 2007), its property of compressional velocity is crucial. In order to better understand acoustic properties of heavy oil in-situ condition during reservoir development and production, we measured compressional velocity in high temperature, and extended the application range of our velocity model as a function of temperature from original below 100°C up to 320°C.

Experimental design and methodology

Measurement system setup and calibration

In order to measure compressional velocity of heavy oil at the atmosphere pressure, 0.1 MPa, and temperature up to 320°C, a measurement system is assembled as shown in Figure 1. A glass container is used as heavy oil bank, and a thermocouple is connected with heavy oil for temperature control. The whole system is merged into a temperature control system, which is combined by heat wrap and heater. A peek (polyether ether ketone) buffer is used between the sample of heavy oil and the P-wave transducer, because peek can transfer P-wave signal but not too much heat.

The reflection method is used for data measurement. Basically, the p-wave signal goes through the buffer first and then the oil sample. Thereby, the first arrived signal is reflected from the bottom of the buffer, and then the second is reflected from the bottom of the sample. Figure 1 also shows an example of the reflected signals.

The sample length is the distance from the bottom of the buffer to the bottom of the inside glass container. At the room temperature and pressure condition, the distance is calibrated carefully using water as the standard sample and the FLAG/Pbrine program (the brine calculator of the Fluid Application Geophysics program developed by the Fluids/DHI consortium) as the calibration standard for water velocity (Figure 2).

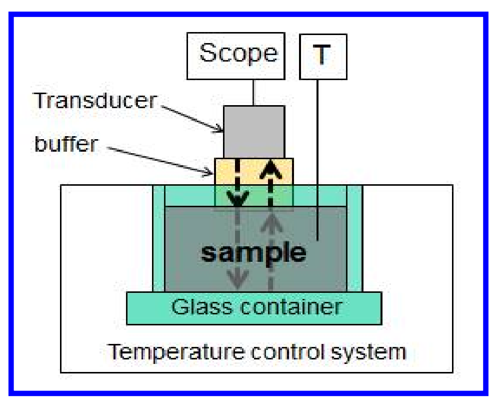
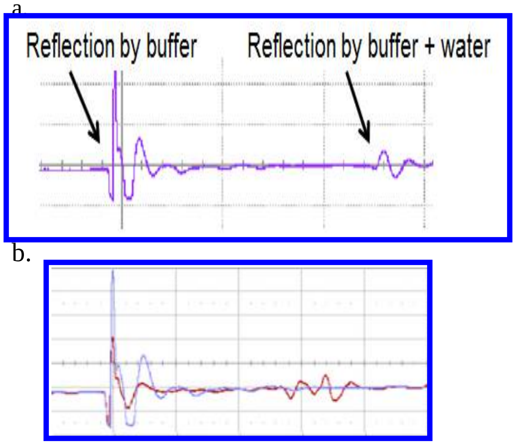


Figure 1. Measurement system setup and a sample of the reflection signal.

a



b.

Figure 2. a. The distance of the sample is calibrated by the reflected signal from water; b. an example of the reflected signal form heavy oil.

Experiment procedures

A typical sample of heavy oil is selected with $\rho_0 = 1.0009\ g/cc$ (API = 10). The data are measured at elevated temperature. Before measuring each data point, we give enough time for temperature to achieve stability for each elevation.

Measured data and modeling

The original model for compressional velocity of heavy oil

Based on measured data and the compressional velocity model of conventional oil, we developed the ultrasonic compressional velocity model named Vp-2011 for heavy oil shown in Equation (1) (Han, et al., 2014).

$$Vp_l = Vp_{\_flag}\left[1 + A_P \cdot \frac{e^{C_P \varDelta V_P}}{e^{C_P \varDelta V_P} + 1}\right]$$
$$\varDelta V_P = Vp_{\_flag} - Vp_0, \quad (1)$$
$$A_P = 0.38184, C_P = 18.044, Vp_0 = 1.6820$$

Where V_{p_flag} is compressional velocity of conventional oil estimated by the oil model of the FLAG/Poil program (the oil calculator of the Fluid Application Geophysics program developed by the Fluids/DHI consortium). V_{p_l} is ultrasonic compressional velocity of heavy oil, and the model's application ranges cover temperature from – 80°C to 100°C.

The measured data at high temperature

The measured data shown in Figure 3 cover the temperature range from 130°C to 320°C. The original velocity model of heavy oil matches data well where the temperature is below 150°C. But with temperature increasing continually, the velocities aren't keeping decrease linearly. Obviously the gradient of velocities is decreasing with temperature increasing.

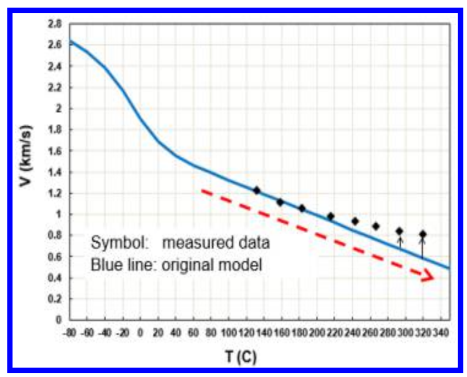


Figure 3. The measured compressional velocities with predicted values by the original model Vp-2011.

The updated compressional velocity model extended temperature rang to 320°C

Based on the measured data, the compressional velocity of heavy oil is apparently underestimated by the original model at high temperature range. An updated model is developed to describe the velocity properties of heavy oil with temperature elevated to 320°C,

$$V_p = V_{p_l} + \Delta V_{p_h} \quad (2)$$

$$\Delta V_{p_h} = a_1 V_{pl}^5 + a_2 V_{pl}^4 + a_3 V_{pl}^3 + a_4 V_{pl}^2 + a_5 V_{pl} + a_6 \quad (3)$$

The values of coefficients in Equation (3) are:

i	a_i	i	a_i
1	0.038647	4	0.19117
2	-0.241712	5	-1.067414
3	0.411407	6	0.712929

Results and discussion

The new model describes the velocity properties of heavy oil more correctly with temperature increasing. Figure 4 shows the measured data with calculated result by the new model. When temperature is higher than the liquid point of heavy oil, the velocity behavior is like conventional oil, and keeps a near lineal relation with temperature. But with temperature increase, the velocity will decrease slowly to reach heavy oil's bubble point. Generally, gas velocity increases as temperature elevates.

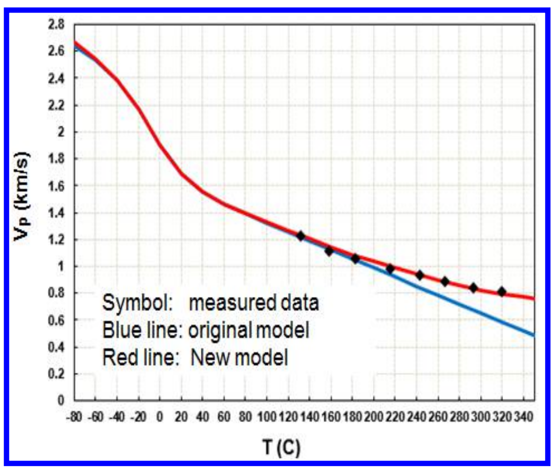


Figure 4. The measured data with the calculated results of the new model.

During the data measurement, the experimental errors may come from three sources - the thermal expansion of the buffer material, the thermal expansion of the glass container, and the light compound evaporation of heavy oil.

The thermal expansion of the buffer material is minimized by the movable buffer, which is inserted into the sample just before a data measurement. Also, the signal's arrival times are read between the two reflection waves. The thermal expansion of the buffer only affects the time before the arrival of the first buffer reflection signal.

The linear thermal expansion of the glass can be ignored. When temperature increases from 22°C to 350°C, it is only 0.065 mm expansion for the height of the glass container 23.4 mm. The error is 0.28%.

Considering effect of light compound evaporation, the density of heavy oil increased from the original ρ_0 = 1.0009 g/cc (API = 10) to 1.0257 g/cc (API = 6.46) after the experiment measurement. Figure 5 shows the comparison of the two velocity trends which may cause 2.45% overestimation. But with temperature increasing, their difference decreases. Similar open system may exist in-situ condition.

Generally, API gravity of heavy oil is ranged from 5 to 22 degrees. Although the model is based on the measured data of heavy oil API = 10, it can be used within whole heavy oil range reasonably as shown in Figure 6.

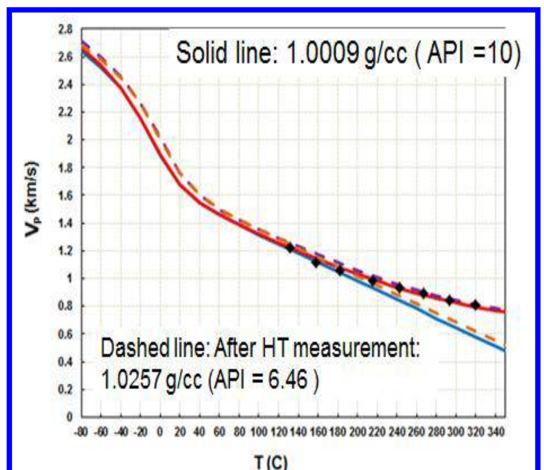


Figure 5. Error caused by the evaporation of light compounds in the heavy oil.

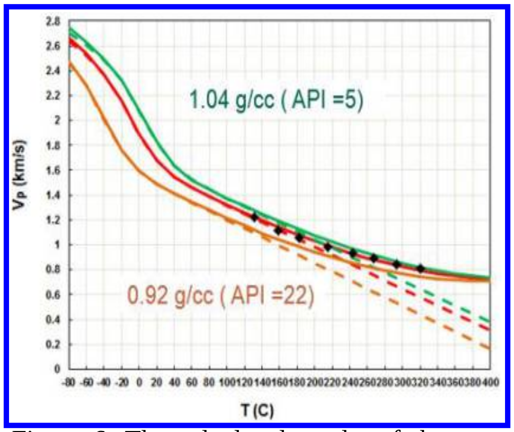


Figure 6. The calculated results of the new model for heavy oil API = 5 (green line) and API = 22 (brown line).

Conclusion

The ultrasonic compressional velocity of heavy oils was measured as a function of temperature from 130°C to 320°C. Above its liquid point, the gradient of the compressional velocity decreases with temperature increasing.

Based on the newly measured data, the original compressional velocity model of heavy oil as a function of temperature has been updated. Its application range of temperature extends from $-80°C < T < 100°C$ to $-80°C < T < 320°C$.

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EDITED REFERENCES

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