Light oil measurement: density, velocity and modulus from 23 to 200°C and at pressures up to 150 MPa

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Summary

A new density vessel has been made and calibrated. And measurement procedures have been improved for measuring density and velocity of hydrocarbon fluids at temperature up to 200 ℃ and pressure to 150 MPa. Measured data of light oil samples reveal systematic correlations of density, velocity and modulus with extended range of temperature, pressure and Gas-Oil Ratio (GOR).

Introduction

To investigate property of fluid (oil/gas) in high temperature and high pressure condition (HTHP) is increasingly important with increasing efforts of exploring ultra-deep, ultra-hot reservoirs. But there are limited laboratory measurements of density and velocity of hydrocarbon fluids, especially at HTHP condition (Rao, K. and Rao, B., 1959, Batzle and Wang, 1992, Han & Batzle, 2000, McCain, 1990). We have performed laboratory measurements to investigate properties of fluid in situ condition successfully in recent years. But when approaching to HTHP condition, the biggest challenge is seal of the test vessel and transducers. We have tried different O-ring and back-up for vessel and piston sealing. They have worked well if temperature and pressure are not too high. But over to 150 ℃ and 100 MPa, they only worked by chance. We have tried various epoxies for sealing transducers at HTHP condition for repeating measurement, but they can not hold transducers and keep the same condition (sample volume and distance between two transducers) either. Any leakage of test sample affected quality of measured data and disrupted experiment, especially for density measurement. The vessel we used has two chambers: one is used for measurement; and the other for pressure control. They are separately sealed by three groups of O-rings. Unexpected O-ring deformation in HTHP condition will cause uncontrollable volume increase of the measured chamber. In addition, internal leak, even just minimal, can cause under-estimated oil volume. Both of cases will cause systematically low estimate of oil density data. We can calculate modulus of liquid via density, velocity and pressure. Dynamic or adiabatic modulus is the product of density and the square of velocity,

$$K_d = V^2 \rho . \quad (1)$$

Static or isothermal modulus can be calculated with density data,

$$K_s = -\frac{1}{\rho}\frac{\Delta P}{\Delta\left(\frac{1}{\rho}\right)} \quad (2)$$

where K_s is static modulus, P is pressure and ρ is density. Accuracy of calculation mainly depends on quality of density measurement. We can measure density with relative error around 0.5%, which can produce much large errors in density variance, because variance of density is very small (in order of 0.005 gm/cc) for pressure variance, such as 10 MPa. If variance of density drops to 0.004 with error of 0.001 gm/cc, static modulus will shot up 25%. In thermal dynamics, the dynamic modulus of liquid should be higher than the static modulus. However, a tiny error in $\Delta\rho$ can bring significant difference of static modulus, even a reversed result that static modulus is higher than dynamic one at HTHP condition.

In order to keep step with the developing trend of HTHP technology and requirement, we have designed and made a new density vessel that can also be used to measure velocity of liquid. By using the vessel and improved measuring methods, we measured several oil samples provided by our industrial sponsors.

New Equipment and its Calibration

Experimental Setup

To investigate property of fluid up to HTHP condition, our measurement system mainly consists of a density vessel (DV vessel), temperature and pressure transducer, acoustic transducers, and temperature and pressure control equipments (Figure 1).

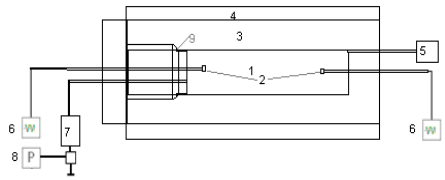

Figure1. Schematic experimental setup. 1. fluid sample; 2. transducers; 3. density and velocity vessel (DV vessel); 4. temperature controller; 5.CSD transducer; 6.scope; 7. Sample-storage vessel; 8. digital pump; 9. tiny O-ring.

We have designed and made the DV vessel mainly based on two principles. First is a better stiffness and sealing for HTHP condition. Second is to improve accuracy of measured density and velocity data. Because we measure

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the density by weighting the DV vessel and its associations, minimizing their weight change with temperature and pressure variance is crucial for density measurement. The DV vessel is made with Titanium, which is thick enough to resist cracking in many HTHP conditions, but still keeps less weight for density measurement. To minimize measured error of density, we reduced many parts which can cause the volume change. Comparing to the old pressure vessel, the new DV vessel doesn't include piston and its O-rings, and water chamber behind the piston.

Metal-to-metal seal with threaded cover was the best selection which was our first choice. But the DV vessel still leaked in HTHP conditions. Finally we got a satisfied result by using metal-to-metal seal with a tiny O-ring. The tiny O-ring seals well and doesn't give a big error for density measurement, because it is tightly squeezed in a small space which limits its volume change with temperature and pressure variation.

We selected a CSD transducer (manufactured by Custom Sensor Design, Inc.) to measure temperature and pressure of fluid inside the vessel simultaneously. It gives high precision with 0.02% accuracy for pressure measurement and its RTD (resistance temperature detector) sensor gives more accurate than thermocouple for temperature measurement. An additional advantage is that it uses only one hole to connect the fluid sample inside the vessel. Traditionally two holes are needed for connecting pressure transducer and thermocouple separately.

To heat the vessel, we still use a silicon hot pad since its weight is less affected by environmental humidity with different temperature. Additionally for density measurement, two acoustic transducers are placed on both sides of fluid sample for velocity measurement. We use solder method to prepare the transducers in stead of gluing them by epoxy.

System Calibration

Accuracy and correction of laboratory measurement is based on calibration of the measurement system. Because several factors such as property of materials of the vessel components, inside shape of the vessel and O-ring are affected by temperature and pressure, the volume and the distance between the acoustic transducers vary slightly with variation of temperature and pressure, especially at HTHP condition.

Basically, the volume of material decreases with increasing pressure and decreasing temperature. But the sample volume is the interior volume of the chamber of the DV vessel. The sample volume is affected not only by their different compressibility and volumetric thermal expansion of titanium and O-ring, but also by the shape of the vessel chamber. Pressure effect is dominated if temperature isn't too high. But at HTHP condition, the sample volume is determined by complicatedly combined effects of temperature and pressure.

The combined effects on the distance between the acoustic transducers are even more complicated because the distance is related to the directions of their compressibility and volumetric thermal expansion. The threaded connection between the body and cover adds more uncertainty of the distance. At a given pressure, increasing temperature causes its volume decreasing, but the distance increasing, because the cylindrical shape is changed by decreasing its diameter and increasing its length.

Therefore we have carefully calibrated the new system as a function of pressure and temperature. Vacuumed-distilled water is used as a standard sample. "FLAG" program (Fluid Application Geophysics – a computer program developed by the "Fluids/DHI" consortium) and IAPWS-IF97 (the International Association for the Properties of Water and Steam - Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam) (Wagner and Kruse, 1998) are applied as a calibration standard for density and velocity of vacuumed-distilled water. By this way, the calibrated volume and calibrated distance between the transducers are known at the given condition. Following measurements for other fluids only depend on scaled weight for density and measured travel time for velocity. However, we need check the calibration regularly and each time change or resolder a PZT crystal.

Figure 2 shows the calibrated result. The lines are the result of the standard calculation as mentioned above. The symbols are measured result of the vacuumed-distilled water by the calibrated equipment. We also tested repeatability of measurement by giving a constant temperature, and then changing pressure from low to high and back to low; or giving a constant pressure, and then changing temperature form low to high and back to low. The lines at temperature 24 ℃ show the result of repeated measurements as pressure increases from 7 MPa to 138 MPa and then backward to 7 MPa. The calibrated DV vessel system increases accuracy of density measurement to 0.1%.

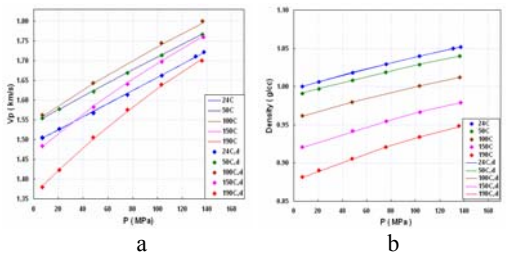

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Figure 2. The result of the density vessel calibration. a. comparison of measured density (symbol points) to calculated density by the calibration standard (lines). b. comparison of measured density (symbol points) to calculated density by the calibration standard (lines).

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Improved Measuring Methods

During HTHP measurement, the biggest challenge is to keep sealing of the system. It is even more difficult for density measurement. For each data point we need weight the measurement system including the DV vessel and heat system which have to be disconnected from and reconnected to the sample-storage vessel and other equipments. In order to measure data at HTHP condition and improve the data quality, we use a combination of the four measurement methods such as constant temperature, constant pressure, matched condition and constant mass expansion (CME).

Constant temperature method is to measure velocity and density of fluid as a function of pressure with a specified temperature. This is a general and effective way to reveal effect of temperature and pressure since usually pressure effect is more than that of temperature on fluid property, and pressure is easier to stable than temperature. Like constant temperature method, constant pressure is to investigate velocity and density of liquid as a function of temperature but with a constant pressure.

Matched condition is to maintain the same investigated temperature and pressure condition with that of calibrated condition. Because the complicated correlations of the vessel volume and distance between the transducers with temperature and pressure, there may be still tiny error caused by the system itself at HTHP condition.

CME method is to keep mass of the sample constant during temperature and pressure variance. The sample is sealed in the DV vessel that is disconnected to the sample-storage vessel, which means there is no mass transfer during measurement. A constant mass is weighted at an initial temperature and pressure point. And then by heating the system to a given temperature, pressure will increases with temperature increasing. The measurement is recorded when the temperature is at equilibrium. This method is suitable for a stable system and HTHP measurement. Because the system is disconnected and pressure increasement is caused by increasing temperature in stead of a pressure pump. HTHP condition can be reached beyond the maximum value provided by the pressure pump. And it is also a better way to cross check quality of data measured by other methods.

Light Oil Measurement

We have measured density and velocity on samples of light oil by using the new measurement system. The dead oil samples were donated by our sponsors. The live oil samples with different Gas-Oil Ratio (GOR) were obtained by adding gases to the dead oil based on reported composition. The invested range covers temperature from 24 up to 190°C, pressure from 7 MPa to 138 MPa (1000 to 20000 psi). The measured results clearly show that density and velocity of light oil are closely correlated to their compositional parameters such as API, GOR and gas gravity, and their in situ temperature and pressure conditions even up to HTHP condition.

Measured Data of Density

Figure 3 shows the measured density of a sample (API gravity 25.77) as a function of temperature and pressure. Figure 3.a is the density of the dead oil and 3.b the density of the live oil with GOR 365 L/L. The two lines of triangle symbols are measured by the CME method and the others by constant temperature. The line of CME of dead oil shows density from 50 °C and 1.294 MPa to the highest temperature and pressure point (190 °C, 135.94 MPa). The density points of the CME line, which fall on the density lines measured by constant temperatures at 50, 100 and 190 °C, reveal the quality of measured data by the constant temperature is consistent. The density of dead and live oils show a typical property of oil density: it increases with increasing pressure and decreases with increasing temperature.

However, at the HTHP condition, effect of temperature becomes smaller. At low pressure condition, for example, 20 MPa, the density difference of the deal oil is about 0.039 g/cc between 100 and 190 °C. The difference decreases to about 0.027 g/cc when pressure increases to its highest point.

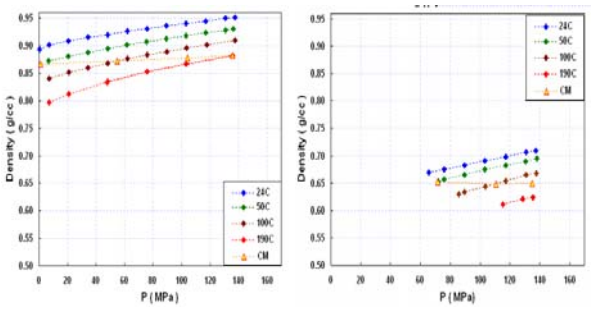

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Figure 3. Measured density as a function of temperature and pressure. a. measured density of dead oil. b. measured density of live oil with GOR 365L/L.

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Since density is decreased by dissolved gas, the density of the live oil is significantly lower than that of the dead oil. At HTHP condition, density of the live oil is about 30% lower than that of the dead oil. This result also can be clearly revealed by GOR effect on density of the live oil (Figure 4).

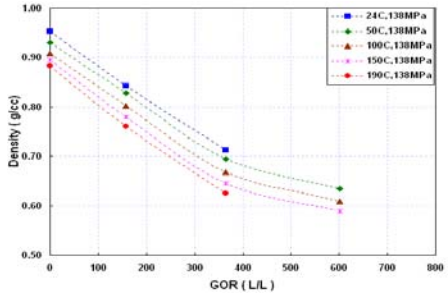

Figure 4. Measured density as a function of GOR.

Measured Data of Velocity

Generally velocity increases with increasing pressure and decreases with increasing temperature. The measured data shows in Figure 5. The almost parallel temperature lines with increasing pressure reveal that effects of temperature and pressure seem to be independent to each other and the paralleling trend is still preserved when temperature and pressure rise up to 190 ℃ and 138 MPa.

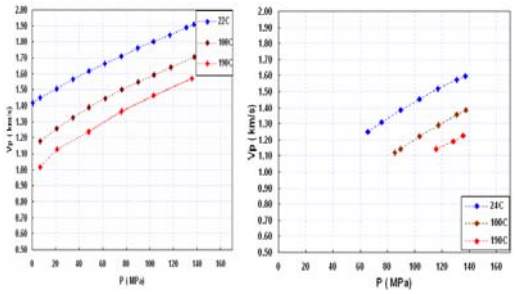

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Figure 5. Measured velocity as a function of pressure and temperature. a. measured velocity of dead oil. b. measured velocity of live oil with GOR 365L/L.

Dissolved gas in oil also decreases velocity significantly. Comparing the measured velocity of dead oil with live oil (GOR 365L/L), the GOR lowers velocity by about 22% at the HTHP condition.

Calculated Modulus from Measured Density and Velocity

Using the measured data of density and velocity, equations (1) and (2), we can calculate modulus of light oil at given temperature and pressure condition (Figure 6). The data show the dynamic modulus is higher than the static modulus.

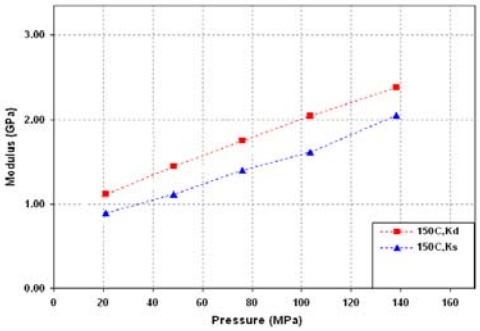

Figure 6. Comparison of calculated modulus of the dead oil as a function of pressure at temperature 150 ℃: dynamic modulus (red symbols) vs. static modulus (blue symbols).

Conclusion

The new DV vessel is suitable for density and velocity measurement at temperature up to 200 °C and pressure up to 150 MPa (HTHP condition). Using the DV vessel and a combination of improved measuring methods, we can obtain measured data of density and velocity with high quality.

Measured data of light oil samples show that their density, velocity and modulus are systematically correlated to their API gravity, GOR and at in situ temperature and pressure conditions. Those correlations are extended to HTHP condition.

Acknowledgments

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EDITED REFERENCES

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