Improvement of Density Model for Oils

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Summary

Based on newly measured data, a new density model has been developed. There are two aspects in the new model for improvement: new correction for temperature effect and new parameter called effective pseudo-liquid density is used for live oil density estimation.

Introduction

We have developed a density model (Han and Batzle, 2000) to replace the one developed by Batzle and Wang (1992) for under-saturated oil with dissolved gas based on the engineering concept (McCain, 1973, 1990). In 2002, we had made the improvement of the model with new correction to cover pressure higher than 10,000 Psi (69 MPa). In order to apply the density model to "live oil" with high GOR at HTHP conditions, we have to further improve the model.

Current Model

The current model is based on ideal-solution principles, in which there is no exchange in internal energy occurs between mixed fluids. Density is mixture will be as:

$$\rho = \frac{M_1 + M_2}{V_1 + V_2} \qquad (1)$$

We often calculate oil density with equation 1 at 'standard condition' of temperature of 60°F (15.56°C) and atmospheric pressure (0.1013 MPa), which is selected to compare the different properties of hydrocarbon fluids. However, it is problematic when apply the concept to a oil with dissolved gas ("live oil") because gas will bobble out from at in situ condition to the room ("standard") one. Petroleum engineers (McCain, 1973, 1990) had introduced a concept of the pseudo-liquid density, in which composition of under-saturated oil remains no change from at in situ condition to the standard condition assuming gas to remain dissolved in the oil. The density of "live oil" at in situ can be calculated with proper pressure and temperature correction. The pseudo-liquid density is a "standard" one uniquely correlated with the "live oil" with fixed composition. However, in order to apply idea fluid principle, we need to define a density for the gas fraction at the standard condition, which called as apparent liquid density.

Apparent liquid densities were derived through a study of oil-gas system that gas (methane and ethane) dissolved into oils with different API gravity (Standing and Katz, 1942). Experimentally determined density of an oil-gas system at numerous elevated pressures and temperatures was adjusted to standard conditions using proper compressibility and thermal expansion factors. Then, mass and volume contributed by the oil were subtracted. This left the contribution due to methane or ethane as the apparent liquid density. We use the following method to calculate apparent liquid density for natural gas (Katz, 1942). Given specific gravity G for natural gas and API gravity for oil, apparent liquid density ρ_a can be calculated as:

$$\rho_a = 0.61703 \times (10^{-0.00326 API}) + \\ + [1.51775 - 0.54351 \times \lg(API)] \times \lg(G) \qquad (2)$$

$$API = \frac{141.5}{\rho_0} - 131.5$$

Where, ρ_0 is the dead oil density at the standard condition. It is important to notice the apparent liquid density depends on both gas gravity and API gravity of oil, but not Gas-Oil-Ratio (GOR).

Pseudo-liquid density ρ_{p0} of live oil is defined as the density at standard condition, which can be calculated based on the ideal solution principle.

$$\rho_{P0} = \frac{W_{oil} + W_{gas}}{V_{oil} + V_{gas}} = \frac{\rho_0 \times 1 + W_{gas}}{1 + W_{gas}/\rho_a} \qquad (3)$$

where ρ_0 in gm is the weight of 1cc oil. W_{gas} in gm is the weight of gas, which dissolves in 1 cc oil.

$$W_{gas} = 0.001223 * R_s * G \qquad (4)$$

Where R_s is GOR (L/L) and G is gas gravity. With increasing GOR and gas gravity, gas fraction W_{gas} in live oil can be significantly high.

Calculated pseudo-liquid density is the value at the standard conditions. The density of live oil at in situ needs to be corrected with in situ pressure and temperature based on the pseudo-liquid density. The model for pressure correction is

$$\Delta\rho_P = a \cdot P \cdot e^{(-b/a \cdot P)}$$
$$a = 0.00038794 + 0.0375885 \times 10^{(-2.653 \times \rho_{P0})} \qquad (5)$$
$$b = 1.00763 \times 10^{-6} + 0.00088631 \times 10^{(-3.7645 \times \rho_{P0})}$$

where ρ_{p0} is pseudo-liquid density, P is pressure in MPa and $\Delta\rho_p$ is the adjustment for pressure. The density at reservoir pressure and standard temperature (15.56 ºC) is

$$\rho_{bs} = \rho_{p0} + \Delta\rho_p \qquad (6)$$

The model for temperature correction on density is developed by Witte (1987) based on statistic analysis on measured data.

$$\Delta\rho_T = 0.01602 \times \{(0.00302 + 0.02952 \times \rho_{bs}^{-0.951}) \times (1.8 \times T - 28)^{0.938} - [0.0216 - 0.0233 \times (10^{-1.0051 \times \rho_{bs}})] \times (1.8 \times T - 28)^{0.475}\} \qquad (7)$$

where ρ_{bs} is liquid density at pressure and 15.56°C, T is temperature in °C and $\Delta\rho_T$ is the adjustment for temperature in gm/cc. The density of live oil at reservoir conditions ρ is equal to

$$\rho = \rho_{P0} + \Delta\rho_P - \Delta\rho_T \qquad (8)$$

Shortcoming of the Current Model

The current model has been used for years and can give good prediction for oil densities if the oil has not very high GOR and at not very high temperature and pressure. But errors on prediction are obvious for the high GOR samples at high temperature and pressure.

We checked measured density data of some dead oil samples in comparison with the model prediction (Figure 1 as an example) at room temperature. The temperature correction can be neglected since the room temperature (~ 20 ºC) is near to the standard temperature (15.56 ºC). We can focus to exam the pressure correction of the model. Clearly, the current model gives good pressure correction for dead oils. However, at high temperature, such as 100ºC and 150ºC, the model shows systematic over-correction from measured data as shown in Figure 2.

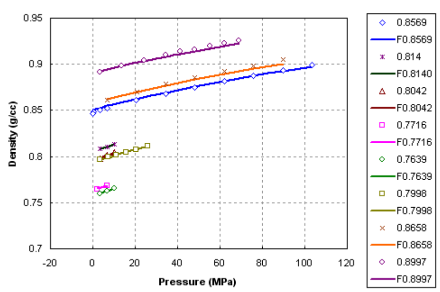

Fig. 1 Densities of dead oils with pressure at room temperature.
Dots – measured data;
Lines – Predicted by the current model

Meanwhile, we have also found the model can not give good prediction of densities if the sample has rather high GOR. An example of a sample with GOR of 400 L/L is shown in Figure 3, the predictions are not match the measured data in all temperatures and pressures. It shows that the current model needs to be improved for oils with high GOR.

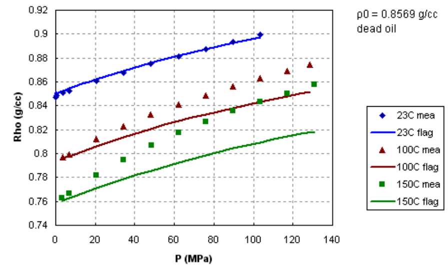

Fig. 2 Densities of dead oils with pressure at different temperatures.
Dots – measured data;
Lines – Predicted bv the current model

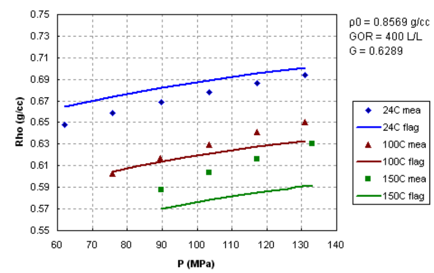

Fig. 3 Densities of live oils with pressure at different temperatures.
Dots – measured data;
Lines – Predicted by the current model.

New Model

We have maintained the pressure adjustment (Equation 5) in the new model, because it worked with "dead oil" well. And we have improved the temperature adjustment for dead oils and GOR adjustment for live oils. Figure 4 shows density correction based on equation 8. Clearly measured density variation $\Delta\rho_T$ due to temperature change correlates to density variation $\Delta\rho_p$ due to pressure change although data have been measured on different samples with different procedures. We should apply the relation for the temperature correction.

$$\Delta\rho_T = c \cdot e^{(-d \cdot \Delta\rho_P)} \qquad (9)$$

where c and d are coefficients which are functions of the temperature.

$$c = c_0 + c_1 \cdot (T - 15.56) + c_2 \cdot (T - 15.56)^2$$
$$d = d_0 + d_1 \cdot (T - 15.56) + d_2 \cdot (T - 15.56)^2 \qquad (10)$$

Where, T is the temperature in ºC and

$c_0 = 0.000169756$
$c_1 = 0.000933538$
$c_2 = -0.00000153832$
$d_0 = 12.9686$
$d_1 = 0.00401368$
$d_2 = -0.00011863$

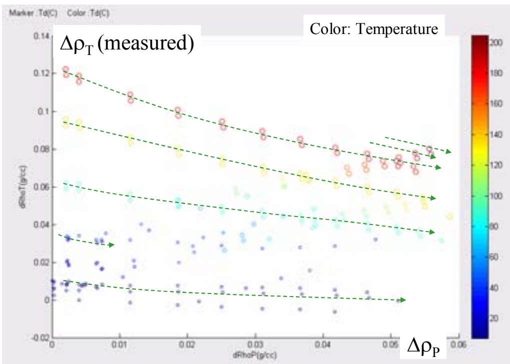

Fig. 4 Temperature adjustment ($\rho\Delta_T$) as the function of pressure adjustment ($\rho\Delta_P$) with temperatures.

The new temperature adjustment is applied on the sample in Figure 2 and shows significant improvement of the model on measured data as shown in Figure 5.

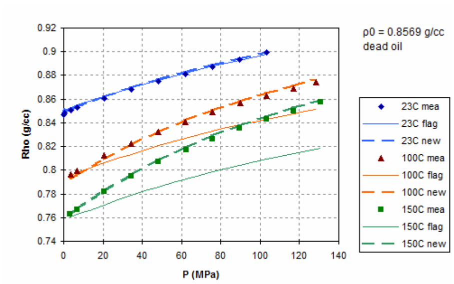

Fig. 5. Densities of dead oils with pressure at different temperatures.
Dots – measured data;
Solid lines – Predicted by the current model;
Dashed lines – Predicted by new model.

Then, we have examined the new model with data measured on live oils and found that predicted density is higher than measured, especially for oils with high GOR. In order to analyze the reason of mismatch for live oils, we have examined densities of live oil at room temperature as shown in Figure 6. The predicted value is calculated from pseudo-liquid density (Equation 3), pressure adjustment (Equation 5) and temperature adjustment (Equation 9 and 10). It can be seen that the predicted densities are systematically higher than measured density. The data suggest that the mismatch is not relevant to the temperature and the pressure correction, but a low estimation of the pseudo-liquid density for the live oil with a high GOR. In the model, the dissolved gas is treated as a liquid with the apparent density. There is assumed: no energy change between the two liquids of live oil according to the ideal-solution principle. The apparent density of dissolved gas depends on both gas gravity and oil API gravity. Equilibrium of dissolved gas and host oil molecules determines the space occupied per gas molecule, which is the apparent density of gas. However, validation of the concept has to be based on an assumption: gas molecule has to be dissolved into oil molecules, which is solution. With more gas dissolved into oil, eventually, oil molecule will become minor component dissolved (trapped) into gas (solution). From gas as a solvent transferring as a solution, the model for the apparent liquid density of gas have to be modified to correlate with increasing GOR.

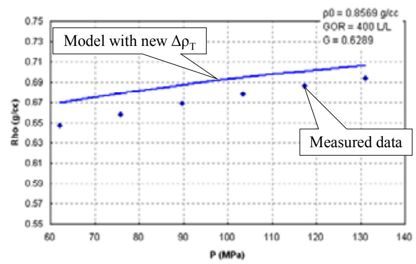

Fig. 6 Model with new temperature adjustment can not fit the live oil data at room temperature.

We have found that the current apparent density model works well with the measured data in the range of 0.95 to 0.75 gm/cc. For samples with the apparent density less than 0.75 gm/cc, the model systematically overestimates. Lower the density, higher deviation of modeled density than measured one. This makes a better physical sense if think about scope of oil-gas mixture from liquid oil (dead) to “live oil” with more and more dissolved gases (volatile), and then transfer to that gas become dominate and oil dissolve in gas (condensate). The space available for dissolved gas in oil matrix is limited. As long as gas molecules are trapped by oil molecules, space occupied by gas per molecule is determined only by gas and oil API gravity, or balanced force between dissolved gas and host oil molecules. The apparent liquid density of gas will maintain as a constant. With continue increase dissolved gas, equilibrium of dissolved gas and oil molecules will be gradually modified. If space in oil molecules (matrix) is fully trapped with gas molecule, additional dissolved gas molecule have to squeeze into contact with other gas molecule and broken the equilibrium of gas-oil system. More gar aggregate together, more distance among gas molecules. And the apparent density of dissolved gas will reduce. We need to modify the current apparent density model to cover broad band GOR data. In the new model, we create a new parameter called effective pseudo-liquid density, which is defined as hypothetical density of the live oil at the standard condition to replace the pseudo-liquid density in the current model for density.

We use the model with new temperature adjustment to find the effective pseudo-liquid density from measured data by optimization method. To normalize, we use the ratio of effective pseudo-liquid density ρ_{e0} over pseudo-liquid density ρ_{p0} (that is calculated by Equation 2) as the function of the ratio of pressure P over the temperature T for various ρ_{p0}/ρ_0 (ratio of the pseudo-liquid density over the API density) shown in Figure 7 and a statistical model for estimation of the effective pseudo-liquid density has been developed.

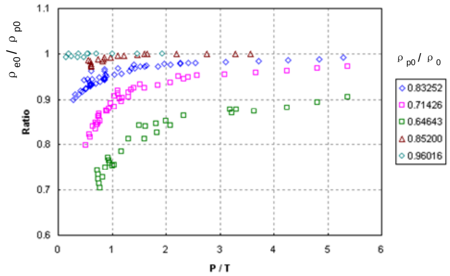

Fig.7 The ratio of effective pseudo-liquid density over pseudo-liquid density vs. pressure P and temperature T.

The effective pseudo-liquid density can be estimated as follows in our new model:

$$\rho_{e0} = \begin{cases} \rho_0 & Rs = 0 \\ \rho_{p0} \cdot [m + n \cdot \ln(P/T)] & Rs > 0 \end{cases}$$

$$m = m_0 + m_1 \cdot (\rho_{p0}/\rho_0) + m_2 \cdot (\rho_{p0}/\rho_0)^2 \qquad (11)$$

$$n = n_0 + n_1 \cdot (\rho_{p0}/\rho_0) + n_2 \cdot (\rho_{p0}/\rho_0)^2$$

Where, ρ_{e0} is the effective pseudo-liquid density, ρ_{p0} is the pseudo-liquid density which is calculated by Equation 3, and ρ_0 is the API density of dead oil. P and T are pressure and temperature respectively. The coefficients are

$m_0 = -1.2818$
$m_1 = 4.8303$
$m_2 = -2.5485$
$n_0 = 0.6827$
$n_1 = -1.3039$
$n_2 = 0.6212$

All Equations use the metric units, i.e. g/cc for ρ_0, ρ_{p0}, and ρ_{e0}; L/L for GOR; ºC for temperature and MPa for pressure.

In brief, we can describe the new density model as follows.

1. Calculate the effective pseudo-liquid density (Equations 3 and 11). It can be seen both the effective pseudo-liquid density and Pseudo-liquid density equal to the API density for all dead oils.
2. Calculate the pressure adjustment (Equation 5 in which ρ_{p0} should be replaced by ρ_{e0}).
3. Calculate the temperature adjustment (Equations 9 and 10).
4. Calculate the density at specified conditions (Equation 8 in which ρ_{p0} should be replaced by ρ_{e0}).

A live oil example in Figure 8 reveals the better fitting of new model.

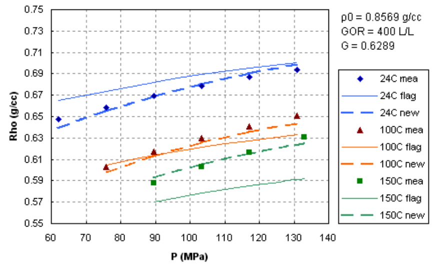

Fig. 8. Densities of live oils with pressure at different temperatures.
Dots – measured data;
Thin solid lines – Predicted by the current model;
Thick dashed lines – Predicted by new model.

Conclusion

We have developed new density model based on the current model and newly measured density data in two aspects. One is temperature adjustment and the other is using the effective pseudo-liquid density instead of the original pseudo-liquid density for live oils. The new density model shows a significant improvement, especially for live oils with high GOR at high temperature condition.

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EDITED REFERENCES

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REFERENCES

Batzle, M., and Z. Wang, 1992, Seismic properties of pore fluids: Geophysics, **57**, 1396–1408, doi:10.1190/1.1443207.

Han, D., and M. Batzle, 2000, Velocity, density and modulus of hydrocarbon fluids — Empirical modeling: 70th Annual International Meeting, SEG, Expanded Abstract, 1867-1870.

McCain, W. D. Jr, 1977, 1990, The Properties of Petroleum Fluids: Pennwell.

Standing, M. B., and D. L. Katz, 1942, Density of Crude Oils Saturated with Natural Gas: Trans: AIME, **I46**, 159–165.

Witte, T. W. Jr., 1987, The Development of Correction for Determining Oil Density in High Temperature Reservoir: M.S. Thesis, Texas A&M University.