Calculation of Live Crude Oil Viscosities Using Equations of State

*By W. LITTMANN**

Abstract

For reservoir engineering and numerical simulations it is essential to calculate crude oil properties especially in compositional simulations where these properties are not given explicitly. Such calculations can be carried out using equations of state (EOS). Depending on the accuracy of the description of the crude oil composition the results of such calculations can describe the PVT-behavior of a crude oil system. However the viscosity of the live crude oil cannot be calculated from these data. This is usually achieved using other empirical correlations, having the disadvantage that a different description of the oil is used. Furthermore these correlations need extensive tuning of the parameters. In this paper a method is described to calculate the viscosity of live crude oil as a function of temperature and pressure using the results from EOS calculations. Examples are given to illustrate the validity of the method.

1 Introduction

Equations of state are being used in reservoir engineering and numerical reservoir simulation to calculate the properties of a petroleum fluid from its composition. The composition of a fluid is given by the amount in mole fractions of the pure substances. Equations of state then allow for the calculation of the phase distribution of the components. Parameters like formation volume factor, gas solubility, and densities can then be calculated. Besides these parameters the viscosity of the mixture is needed for the calculation of the flow of oil and gas.

The viscosity of a petroleum gas can be reliably calculated for different pressures and temperatures e. g. by the method of Carr-Kobayashi and Burrows [1]. For the calculation of dead crude oil also many reliable correlations exist, e. g. the one developed by Beggs and Robinson [2]. However for the calculation of the viscosity of live crude oils no correlation exists that can calculate the viscosity of a live crude oil accurately. The widely used correlation by Lohrenz, Bray, and Clark [3] needs intensive tuning of the input parameters. Other improved methods have been proposed e. g. by Quinones-Cisneros et al [7] and Pedersen [4]. These models are improvements of the LBC-calculation and consider the fraction of the oil in the dilute gas phase.

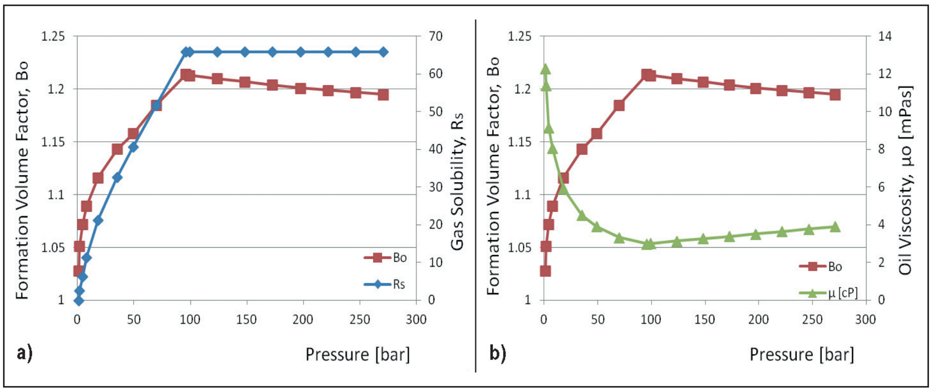

Fig. 1 Typical PVT-data of a live crude oil. (a) Formation Volume Factor Bo, gas solubility Rs (b) viscosity μ and Formation Volume Factor Bo

2 Crude Oil Characterization

2.1 Laboratory/PVT-data

Most live crude oils are composed of hydrocarbons that form a gaseous and a liquid phase at surface conditions. They are characterized by their PVT-behavior. This is the relationship between phase volumes, pressure and temperature. In Figure 1 (a, b) graphs are shown, that describe the behavior of a typical light crude oil at reservoir temperature. The graph shows the formation volume factor B_o and the solubility of gas (a). The formation volume factor B_o represents the increase of volume of the oil when it is transferred from surface condition to reservoir condition. The increase in temperature and the dissolution of gas leads to an increase in volume. *Rs* is the solution gas ratio in $m^3(V_n)$ of gas dissolved in one m^3 of oil at reservoir conditions and equilibrium. Figure 1 (b) shows the viscosity of the oil together with the formation volume factor.

2.2 Equations of state

Depending on the problem crude oils can be characterized in different degrees of detail. The gas fraction consists of hydrocarbon components from C_1 to C_6 and the liquid fraction is composed of hydrocarbons from C_7 up to C_{40}. If the composition of a crude oil is known, e. g. from gas chromatography, the PVT-behavior can be calculated using an Equation Of State (EOS) as shown in Figure 2b. However the crude oil viscosity is not obtained. The composition of the gas and oil phase and the phase volumes and densities are results of these calculations.

In Figure 2 a typical chromatograph of a light crude oil (a) and its phase behavior (b) are shown.

The principle equation of state is given in Equation (1). This is a cubic equation for the z-factor, where the parameters *E* are ob-

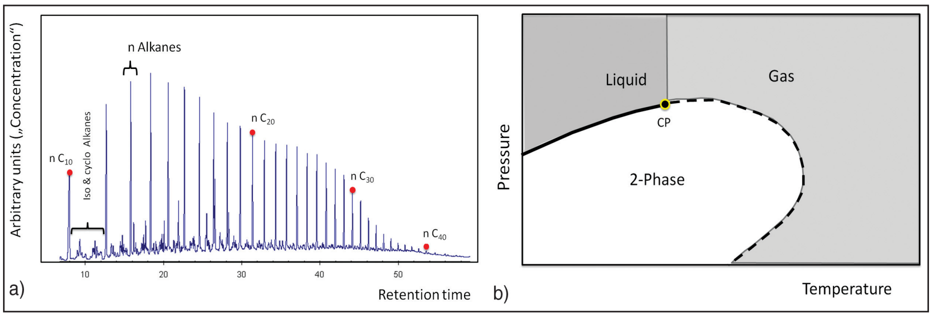

Fig. 2 Chromatograph (a) of a light oil and typical phase behaviour and critical point (b)

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* Wolfgang Littmann, Consulting Reservoir Engineering, Wunstorf, Germany (E-mail: W.Littmann@cre-geo.de). Lecture, presented at the Spring Meeting 2014 of DGMK/ÖGEW, 24./25. April 2014, Celle, Germany.

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tained from the critical data of the components and other parameters, which describe the molecular interaction of the components in a mixture. Using these parameters also fugacity coefficients for each component in the mixture can be calculated, which then allow for the calculation of the phase behavior at equilibrium.

$$z^3 + E_2 z^2 + E_1 z + E_0 = 0 \tag{1}$$

$$z = \frac{pV}{nRT} \tag{2}$$

A cubic equation yields up to three roots or solutions, where the smallest is used for the liquid and the highest for the gaseous phase. From this information the distribution of the components in liquid and gaseous phases and the density of the phases can be calculated for different pressures and temperatures. The calculation of the phase densities can be "tuned" by so-called volume shift factors. For the calculations groups of components can be lumped together to represent pseudo components. This is often done for the higher hydrocarbons, which are often represented by the C_{7+} fraction.

Having a representative composition of a crude oil, the PVT-behaviour from the reservoir to the surface facilities can be obtained. However the viscosities of the oil and gas phases cannot be calculated.

The viscosity of gases can be calculated reliably by correlations such as that from Carr-Kobayashi and Burrows [1]. These algorithms require the gas composition as an equation of state. For the calculation of the liquid phase viscosity the procedure by Lohrenz-Bray-Clark is widely used.

3 Lohrenz-Bray-Clark (LBC) Method for Viscosity Calculation

The Lohrenz-Bay-Clark (LBC) correlation [3] is widely used to calculate live crude oil viscosities.

The basic eq. (3) is shown below, where $\rho_r = \rho/\rho_c$ is the reduced density and ξ is a function of the composition, the components critical temperature, critical pressure and molar mass. μ* is the low pressure gas viscosity.

$$\left[(\mu - \mu^*)\xi + 10^{-4}\right]^{1/4} =$$

$$a_1 + a_2\rho_r + a_3\rho_r^2 + a_4\rho_r^3 + a_5\rho_r^4 \tag{3}$$

$$\xi = \frac{\left[\sum_{i=1}^{N} z_i T_{ci}\right]^{1/6}}{\left[\sum_{i=1}^{N} z_i M_i\right]^{1/2} + \left[\sum_{i=1}^{N} z_i p_{ci}\right]^{2/3}} \tag{4}$$

In Figure 3 an example of a viscosity calculation according to Lohrenz-Bray-Clark is shown. The calculation is according to Pedersen et al. [4] using the oil composition shown in Table 1. The LBC calculation is extremely sensitive to critical molar volume and the density of the C_{7+} fraction. To obtain results as in Figure 3 extensive tuning of the parameters is necessary to match the measured data.

It is therefore desirable to calculate viscosities of the liquid phase more reliably using parameters as obtained from equation of state calculations.

4 Calculating Viscosity from Phase Densities/Volumes

According to Einstein [5] the specific viscosity of a solution of substance, e. g. a polymer, is proportional to the volume it occupies in the solution, eq. (5) [6].

$$\mu_{sp} = \frac{(\mu - \mu_0)}{\mu_0} = k \cdot \varphi \tag{5}$$

Where μ is the viscosity of the solution, μ_0 the viscosity of the solvent, *k* a constant factor and φ stands for the fraction filled with the solvate.

In the case of a live crude oil μ_0 is the dead oil viscosity and the solvate is the gas. Other than in a solution of for example a salt in water, in the case of live oil the solvent viscosity is larger than the viscosity of the solution and the specific viscosity would become negative. If we set $k = 1$ we obtain

$$\mu = \mu_0 \cdot (1 - \varphi)$$

If we apply this to a live crude oil, we can assume that the dead oil is the solvent and the gas is the dissolved substance/solvate. The amount of solvate increases with pressure up to the bubble point as shown in Figure 4. At the bubble point the increase of solvate ceases. The volume fraction of the solvate (gas) decreases because of its higher compressibility.

The live crude oil viscosity can then be calculated from the dead oil viscosity as shown in eq. (6).

$$\mu = \mu_{od} \cdot v_x \tag{6}$$

where μ is the viscosity of the live oil, μ_{do} the viscosity of the dead oil at reservoir/reference conditions and v_x the volume fraction of the dead oil components in the liquid. The composition of the dead oil has to be calculated at standard conditions. The volume of the fraction of the dead oil components in the liquid phase can then be calculated in an additional step.

The volume fraction v_x can be approximated from the formation volume factor and the normalized liquid fraction.

$$v_x = \frac{B_{od} \cdot x_{nd}}{B_o \cdot x_n} \tag{7}$$

where x_n is the normalized liquid fraction and *d* denotes the dead oil.

The dead oil viscosity μ_{od} can be taken from a measurement or calculated. In eq. (8) a correlation by Beggs and Robinson [2] is given to calculate dead oil viscosities.

$$\mu_{od} = 10^x - 1 \tag{8}$$

where

$x = y \cdot T^{-1.163}$

$y = 10^z$

$z = 3.0324\text{-}0.02023 \cdot G$

G is the API gravity and the temperature *T* has to be taken in °R.

The dead oil density can also be calculated using an equation of state. It may be neces-

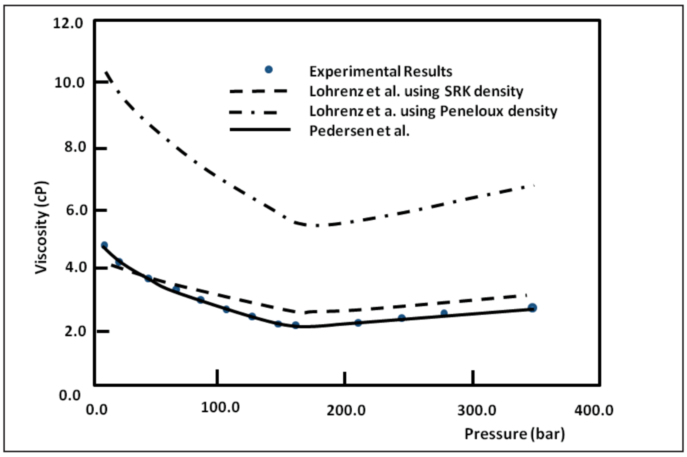

Fig. 3 Examples of viscosity calculations according to LBC [3]. Viscosity calculations according to Pedersen et al. [4]

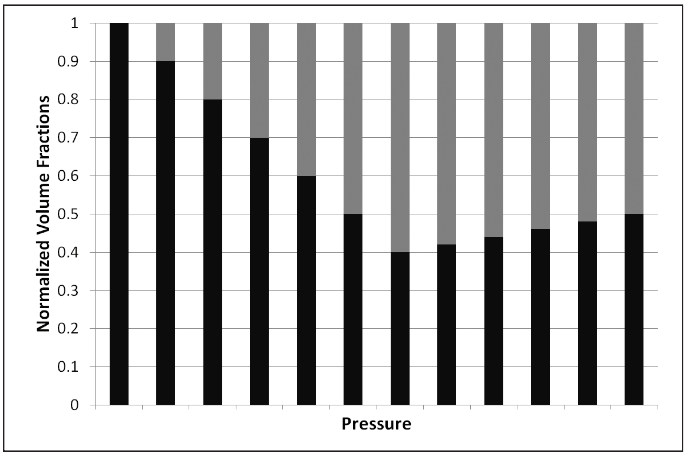

Fig. 4 Normalized volume fractions in a live crude oil as a function of pressure

Table 1 **Molar composition of the North Sea oil mixture (mixture 3, T = 71 °C) according to Pedersen et al. [4]**

Component	Mole %	Vol. Shift Fact.
N_2	0.33	0
CO_2	0.19	0
C_1	35.42	–1.9
C_2	3.36	–2
C_3	0.90	0
i-C_4	0.69	0
n-C_4	0.26	0
i-C_5	0.26	0
n-C_5	0.14	0
C_6	0.72	0
C_{7+}	57.73	0.35
Total	100.00	

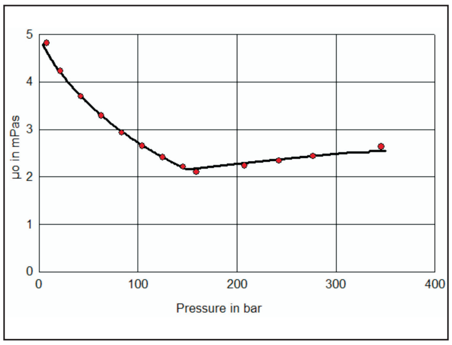

Fig. 5 **Results of viscosity calculations for crude oil mixture (North Sea Mixture 3, Table 1)**

sary to tune the data by volume shift factors to obtain the correct density.

5 Examples

In Table 1 the composition of a crude oil mixture is given as it was used for the calculations given in Figure 3. For this mixture no PVT data were available. The results of the viscosity calculation using the method described here are shown in Figure 5. The dead oil viscosity taken for the calculation was 4.8 mPa·s. The live crude oil viscosities were reasonably matched.

In the following some more examples are given for the viscosity. It is difficult to obtain complete sets of oil data from the literature. If one finds detailed oil compositions and results from EOS calculations viscosity data are missing and vice versa. Therefore some PVT data sets were taken and attempts were made to match these data by an EOS calculation. For this calculation pseudo components were taken since the real compositions were not known. The results therefore cannot be very exact, but nevertheless this demonstrates the method. The oil data used are summarized in Table 2.

The calculation results are shown in Figures 6 to 8.

For crude oil A a good match of the formation volume factor (FVF) and gas solubility (Rs) are obtained. No measured data for the density were available. The viscosity is well matched also without having any knowledge on the dead oil and liquid phase densities. The dead oil viscosity was calculated using the correlation of Beggs and Robinson.

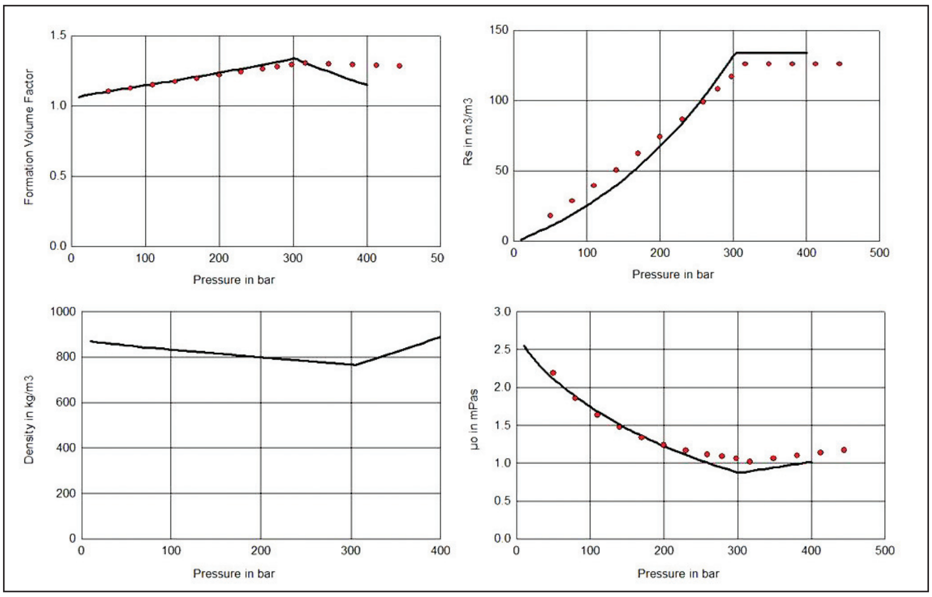

Fig. 6 **Results for crude oil A (EOS: Soave-Redlich-Kwong, lines: calculated, dots: measured)**

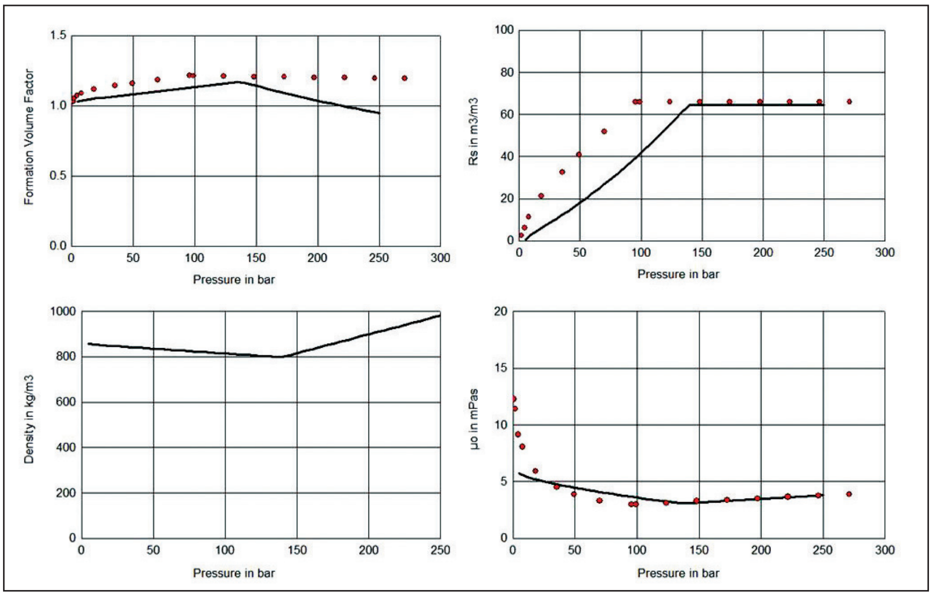

Fig. 7 **Results for crude oil B (EOS: Peng-Robinson, lines: calculated, dots: measured)**

For crude oil B the coarse description of the phase behaviour by three components is not sufficient. FVF and Rs are only matched roughly, but nevertheless the viscosity is still matched satisfactorily for higher pressures. The dead oil viscosity was calculated.

For crude oil C no complete match for Rs was obtained, however it seems that these measurements are incorrect, as the measured data start at very high values, indicating that a lot of gas is dissolved in the dead oil. Again, if the dead oil density and Rs are calculated correctly reasonable results for the viscosity are also obtained. The dead oil viscosity was taken as 2.8 mPa·s.

The data shown above were calculated using the Soave-Redlich-Kwong and Peng-Robinson equations of state. The data were calculated using own software so that the calculation procedures especially for the viscosity

Table 2 **Compositions and volume shift factors used for EOS calculations**

	Crude OIL A 90 °C		Crude OIL B 120 °C		Crude OIL C 65 °C	
Comp.	Conc.	Vol. Shift-F.	Conc.	Vol. Shift-F.	Conc.	Vol. Shift-F.
C_1	0.589	0.290	0.296	0.000	0.19	–1.2
C_5	0.031	0.200	0.074	0.000	0.01	0
C_{7+}	0.380	0.322	0.630	0.205	0.80	0.2
Total	1.000		1.000		1.00	

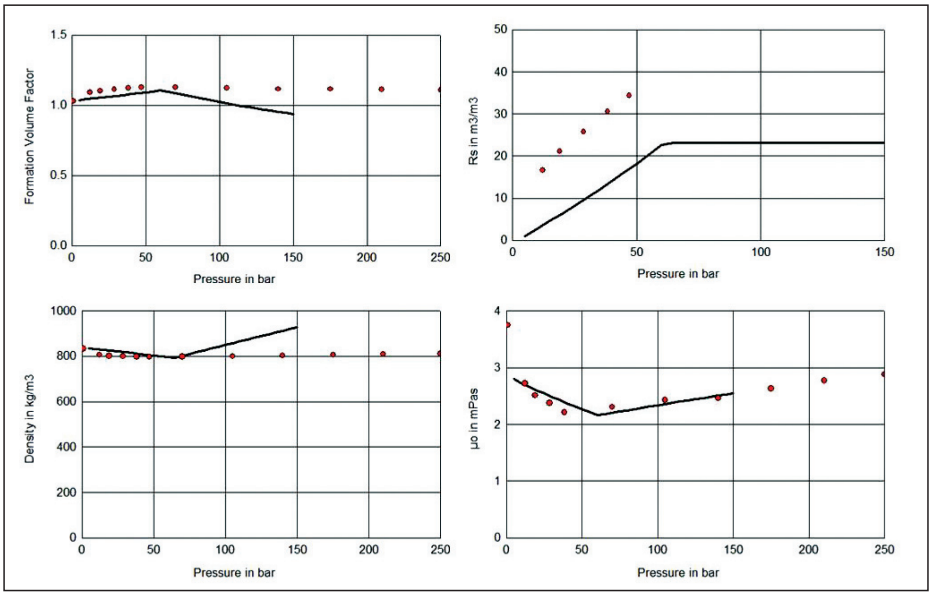

Fig. 8 Results for crude oil C (EOS: Peng-Robinson, lines: calculated, dots: measured)

calculation could be implemented. At high temperatures of 90 and 95 °C the SRK equation of state gave the best results, at lower temperature the PR equation was better.

6 Summary

PVT-data are often incomplete and viscosity data may be missing. In such cases the approach described can help to calculate reliable viscosity data from the dead oil viscosity by matching gas solubility behaviour. The viscosity of a live crude oil can be calculated from the dead oil viscosity and the volume fraction the dead oil captures in the solution. The fraction of the dead oil components in the liquid phase (mixture of dead oil and gas) can be calculated using equations of state. This approach is analogue to the viscosity calculations of for example aqueous solutions of solids or polymers as proposed by Einstein.

The viscosity of the dead oil can either be taken from measurements or it can be calculated from the dead oil density obtained from the equation of state. Examples were given which showed a good match between measured and calculated data, though only a coarse description of the oil properties using three pseudo-components was used.

The calculation method has the advantage that it uses the results from the EOS calculations and no other modelling method has to be applied. Once a good description of the oil properties with an equation of state is obtained also reliable viscosity data are received. The dead oil viscosity is calculated correctly if the density is well matched and can be taken for the viscosity calculations.

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Wolfgang Littmann*, independent oil and gas industry consultant: reservoir engineering and production geology, numerical reservoir simulation, logging and well testing, enhanced oil recovery. He holds an M.Sc. degree and Ph.D. in physics from the University of Hannover. Since 1977 in several positions in research and production in the German oil industry, consultant since 1994.*