

## INTRODUCTION

In order to describe qualitatively a fluid from a production system, petroleum engineers use two main methodologies: black oil and compositional. Each method has its advantages and drawbacks, and depending on the precision required and data available, specialists would select one or the other.

The black oil methodology characterizes three main phases from an oil sample: gas, oil and water phase, and proposes a set of properties to describe the behavior of any sample. These set of properties describe the phases' behavior depending on temperature and pressure. For this methodology, there are two main approaches: correlations with tuning factor, or model development using equations of state (EOS).

The compositional methodology uses EOS to reproduce the behavior of the fluid. One of the major drawbacks is that requires a known composition for the oil sample. If the sample is from light oils, it is possible to use lighter hydrocarbons as main components, but if the samples is more complex, then a previous decomposition in pseudo-components is required. Additional to the components, the following parameters are required:

- Properties such as critical pressure and temperature, acentric factor, and critical compressibility factor must be available.
- Binary interaction parameters (BIP) should also be available for a more accurate fluid characterization.

Specialists in oil production prefer the black oil model, since it is more comprehensive in physical terms and requires less information to predict the behavior of the fluid. One of the downsides is that could be less accurate. On the other hand, process-engineering specialists prefer the compositional method, since it can be easily used to calculate thermodynamic properties for process design, and provide a large variety of EOS depending on the conditions of the fluid.

Considering that the model is more related to oil production, the black oil methodology was preferred in the class' development. Since our focus is not oil characterization and we did not have data related to oil samples, we took the methodology traditional approach including correlations to calculate properties and tuning factors. In a further stage, it is possible to develop a black oil model based on sampling adjustment using EOS, or compositional methods, including additional modules to the class BOObj.

This report includes the details about the correlations used for calculating both thermodynamic and transport properties in the BOObj. In addition, it will cover other correlations that are not

related to the black oil model per se, but are used in property calculations. Most equations were taken from (Bánzer, 1996).

## DOCUMENT OBJECTIVE

Describing the black oil property and other transport property correlations implemented in the BOObj class.

## DOCUMENT SCOPE

The report includes the following:

- Correlation expressions for all properties calculated within the class
- Validity range
- Main assumptions and restrictions from every expression

## PROPERTY CORRELATIONS

### COMPRESSIBILITY

#### Compressibility factor (Z)

Correlation proposed by Hall and Yarborough (Hall & Yarborough, 1973) (Yarborough & Hall, 1974).

$$Z = \frac{-0,06125 \cdot P_{sc,r} \cdot \frac{1}{T_{sc,r}} \cdot \exp(-1,2 \cdot (1 - \frac{1}{T_{sc,r}})^2)}{y} \quad (\text{eq. 01a})$$

$$A \cdot P_{sc,r} + \frac{y + y^2 + y^3 - y^4}{(1 - y)^3} - B \cdot y^2 + C \cdot y^D = 0 \quad (\text{eq. 01b})$$

$$A = 0,06125 \cdot \frac{1}{T_{sc,r}} \cdot \exp(-1,2 \cdot (1 - \frac{1}{T_{sc,r}})^2) \quad (\text{eq. 01c})$$

$$B = 14,76 \cdot \frac{1}{T_{sc,r}} - 9,76 \cdot \left(\frac{1}{T_{sc,r}}\right)^2 + 4,58 \cdot \left(\frac{1}{T_{sc,r}}\right)^3 \quad (\text{eq. 01d})$$

$$C = 90,7 \cdot \frac{1}{T_{sc,r}} - 242,2 \cdot \left(\frac{1}{T_{sc,r}}\right)^2 + 42,4 \cdot \left(\frac{1}{T_{sc,r}}\right)^3 \quad (\text{eq. 01e})$$

$$D = 2,18 + 2,82 \cdot \frac{1}{T_{sc,r}} \quad (\text{eq. 01f})$$

where:

$P_{sc,r}$	Reduced pseudo-critical pressure (recommended range [0,1; 24,0])
$T_{sc,r}$	Reduced pseudo-critical temperature (recommended range [1,2; 3,0])
$\gamma$	Reduced density

### Oil compressibility factor ( $C_o$ )

Correlation proposed by Vazquez and Beggs (Vazquez & Beggs, 1980).

$$C_o = \frac{-1433 + 5 \cdot R_s + 17,2 \cdot T - 1180 \cdot \gamma_{gc} + 12,61 \cdot \gamma_{API}}{P \cdot 10^5} \quad (\text{eq. 02})$$

where:

$C_o$	Isothermal compressibility [1/psi]
$R_s$	Gas in oil ratio [Sft3/STB]
$T$	Temperature [°F]
$P$	Pressure [psia]
$\gamma_{gc}$	Gas specific gravity at 100 psi
$\gamma_{API}$	Crude oil API gravity

## DENSITY

### Oil density ( $\rho_o$ )

Given by its definition.

$$\rho_o = \frac{\gamma_o \cdot 10^3 + 1,223 \cdot R_s \cdot \gamma_g}{B_o} \quad (\text{eq. 03})$$

where:

$B_o$	Oil phase volume factor [Sft <sup>3</sup> /STB]
$R_s$	Gas in oil ratio [Sft <sup>3</sup> /STB]
$\gamma_o$	Oil phase specific gravity
$\gamma_g$	Gas phase specific gravity

### Gas density ( $\rho_g$ )

Given by its definition.

$$\rho_g = \frac{1,223 \cdot \gamma_g}{B_g} \quad (\text{eq. 04})$$

where:

$B_g$	Gas phase volume factor [Sft <sup>3</sup> /STB]
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$\gamma_g$  Gas phase specific gravity

Water density ( $\rho_w$ )

Given by its definition.

$$\rho_w = \frac{\gamma_w}{B_w} \quad (\text{eq. 05})$$

where:

$\gamma_w$  Water specific gravity

$B_w$  Water volume factor [Sft<sup>3</sup>/STB]

### PSEUDO-CRITICAL PROPERTIES ( $P_{sc}$ , $T_{sc}$ )

Although natural gas is a complex mixture of different hydrocarbon compounds, all of them behave in a similar way in terms of thermodynamic and transport properties. Therefore, it is possible to make a macroscopic approximation to its behavior and model this mixture as a single-phase mono component fluid. This approximation yields to a pseudo one-component fluid.

Pseudo-critical pressure ( $P_{sc}$ )

Standing's adjustment (Standing, Volumetric and Phase behavior of Oil Field Hydrocarbon Systems, 1977) to Brown's plots (Brown, Katz, Oberfell, & Alden, 1948), for natural gas.

$$P_{sc} = 677 + 15 \cdot \gamma_{gHC} - 37,5 \cdot \gamma_{gHC}^2 \quad (\text{eq. 06})$$

where:

$P_{sc}$  Pseudo-critical pressure [psia]

$\gamma_{gHC}$  Specific gravity of hydrocarbons in gas phase

Pseudo-critical temperature ( $T_{sc}$ )

Standing's adjustment (Standing, Volumetric and Phase behavior of Oil Field Hydrocarbon Systems, 1977) to Brown's plots (Brown, Katz, Oberfell, & Alden, 1948), for natural gas.

$$T_{sc} = 168 + 325 \cdot \gamma_{gHC} - 12,5 \cdot \gamma_{gHC}^2 \quad (\text{eq. 07})$$

where:

$P_{sc}$  Pseudo-critical pressure [psia]

$\gamma_{gHC}$  Specific gravity of hydrocarbons in gas phase

## RATIOS

### Gas in oil ratio ( $R_s$ )

Correlation by Standing (Standing, Volumetric and Phase behavior of Oil Field Hydrocarbon Systems, 1977).

$$R_s = \gamma_g \cdot \left[ \left( \frac{P}{18,2} + 1,4 \right) \cdot 10^{(0,0125 \cdot \gamma_{API} - 0,000917 \cdot T)} \right]^{1/0,83} \quad (\text{eq. 08})$$

where:

$R_s$	Gas in oil ratio [Sft <sup>3</sup> /STB]
$\gamma_g$	Gas phase specific gravity
$\gamma_{API}$	Oil phase specific gravity
$T$	Temperature [°F]
$P$	Pressure [psia]

## SATURATION PROPERTIES

### Bubble pressure ( $P_b$ )

Correlation by Standing (Standing, Volumetric and Phase behavior of Oil Field Hydrocarbon Systems, 1977).

$$P_b = 18,2 \cdot \left[ \left( \frac{R_{sb}}{\gamma_g} \right)^{0,83} \cdot 10^{(0,00091 \cdot T - 0,0125 \cdot \gamma_{API})} - 1,4 \right] \quad (\text{eq. 09})$$

where:

$P_b$	Bubble point pressure [psia]
$R_{sb}$	Gas in oil ratio at $P \geq P_b$ [Sft <sup>3</sup> /STB]
$T$	Temperature [°F]
$P$	Pressure [psia]

## SPECIFIC HEAT CAPACITY

### Oil heat capacity ( $C_{p_o}$ )

Correlation by Watson and Nelson (Watson & Nelson, 1933).

$$C_{p_o} = A1 \cdot (A2 + A3 \cdot T) \quad (\text{eq.10a})$$

$$K = \frac{T_b^{1/3}}{\gamma_o} \quad (\text{eq.10b})$$

$$A1 = 0,055 \cdot K + 0,35 \quad (\text{eq.10c})$$

$$A2 = 0,6811 - 0,308 \cdot \gamma_o \quad (\text{eq.10d})$$

$$A3 = 8,15 \cdot 10^{-4} - 3,06 \cdot 10^{-4} \cdot \gamma_o \quad (\text{eq.10e})$$

where:

$Cp_o$	Specific heat capacity, oil phase [BTU/lb.F]
$K$	Characterization factor
$\gamma_o$	Oil phase specific gravity
$T_b$	Normal boiling point temperature [°F]
$T$	Target temperature [°F]

### Gas heat capacity ( $Cp_g$ )

$$Cp_g = \frac{4,0 - \gamma_o}{6450} \cdot (T + 670) \cdot (0,12 \cdot K - 0,41) \quad (\text{eq. 11a})$$

$$K = \frac{T_b^{1/3}}{\gamma_o} \quad (\text{eq. 11b})$$

where:

$Cp_g$	Specific heat capacity, gas phase [BTU/lb.F]
$K$	Characterization factor
$\gamma_o$	Oil phase specific gravity
$T_b$	Normal boiling point temperature [R]
$T$	Target temperature [°F]

### Water heat capacity ( $Cp_w$ )

$$Cp_w = R \cdot (8,712 + 1,25 \cdot 10^{-3} \cdot \frac{T + 460}{1,8} - 0,18 \cdot 10^{-6} \cdot \left(\frac{T + 460}{1,8}\right)^2) \quad (\text{eq. 12})$$

where:

$Cp_w$	Specific heat capacity, water phase [BTU/lb.F]
$R$	Specific gas constant (= 1,986/18,0153)
$T$	Target temperature [°F]
$P$	Pressure [psia]

## Viscosity

### Oil viscosity ( $\mu_o$ )

Correlation proposed by Beggs and Robinson (Beggs & Robinson, J.R., 1975).

$$\mu_{od} = 10^x - 1 \quad (\text{eq. 13a})$$

$$x = y \cdot T^{-1,163} \quad (\text{eq. 13b})$$

$$y = 10^z \quad (\text{eq. 13c})$$

$$z = 3,3024 - 0,02023 \cdot \gamma_{API} \quad (\text{eq. 13d})$$

where:

$\mu_{od}$	dead oil viscosity, for a given T at atmospheric pressure [cP]
$\gamma_{API}$	oil API gravity [°API]
$T$	temperature [°F]

For saturated oil, they proposed an exponential adjustment using the gas in oil ratio coefficient.

$$\mu_{ob} = A(R_s) \cdot \mu_{od}^{B(R_s)} \quad (\text{eq. 13e})$$

$$A(R_s) = 10,715 \cdot (R_s + 100)^{-0,515} \quad (\text{eq. 13f})$$

$$B(R_s) = 5,44 \cdot (R_s + 150)^{-0,338} \quad (\text{eq. 13g})$$

where:

$R_s$	Gas in oil ratio [Sft <sup>3</sup> /STB]
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### Gas viscosity ( $\mu_g$ )

Correlation by Lee, Gonzalez, and Eakin (Lee, Gonzalez, & Eakin, 1996).

$$\mu_g = \frac{K \cdot \exp(X \cdot \rho_g^Y)}{10^4} \quad (\text{eq. 14a})$$

$$\rho_g = 1,4935 \cdot 10^{-3} \cdot \frac{P \cdot M}{Z \cdot T} \quad (\text{eq. 14b})$$

$$K = \frac{(9,4 + 0,02 \cdot M) \cdot T^{1,5}}{209 + 19 \cdot M + T} \quad (\text{eq. 14c})$$

$$X = 3,5 + \frac{986}{T} + 0,01 \cdot M \quad (\text{eq. 14d})$$

$$Y = 2,4 - 0,2 \cdot X \quad (\text{eq. 14e})$$

where:

$\mu_g$	Gas viscosity [cP]
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$\rho_g$	Gas density [kg/m <sup>3</sup> ]
$M$	Molecular weight (= 28,96γ <sub>g</sub> )
$Z$	Compressibility factor
$P$	Pressure [psia]
$T$	Temperature [R]

### Water viscosity (μ<sub>w</sub>)

Brill and Beggs approximation to van Wingen correlation (Brill & Beggs, 1991).

$$\mu_w = \exp(1,003 - 1,479 \cdot 10^{-2} \cdot T + 1,982 \cdot 10^{-5} \cdot T^2) \quad (\text{eq. 15})$$

where:

$\mu_w$	Water viscosity [cP]
$T$	Temperature [°F]

### Emulsion viscosity (μ<sub>e</sub>)

Richardson model for W/O and O/W emulsions (Stanko, 2014).

$$\mu_e = \mu_o \cdot \exp\left(\frac{Ro \cdot WC}{100}\right) \quad (WC < WC_e) \quad (\text{eq. 16a})$$

$$\mu_e = \mu_w \cdot \exp\left(\frac{Rw \cdot WC}{100}\right) \quad (WC \geq WC_e) \quad (\text{eq. 16b})$$

where:

$\mu_e$	Emulsion viscosity [cP]
$\mu_o$	Oil phase viscosity [cP]
$\mu_w$	Water phase viscosity [cP]
$Ro$	Richardson's coefficient W/O emulsion [cP]
$Rw$	Richardson's coefficient O/W emulsion [cP]
$WC$	Water cut [%]
$WC_e$	Water cut, emulsion inversion point [%]

## VOLUME FACTOR

### Oil volume factor (B<sub>o</sub>)

Correlation proposed by Standing (Standing, A Pressure-Volume-Temperature Correlation for Mixtures of California Oils and Gases, 1947).

$$B_{od} = 0,972 + 1,47 \cdot 10^{-4} \cdot F^{1,175} \quad (\text{eq. 17a})$$



$$F = R_{sb} \cdot \sqrt{\frac{\gamma_g}{\gamma_o}} + 1,25 \cdot T \quad (\text{eq. 17b})$$

$$B_o = B_{ob} \cdot \exp[C_o \cdot (P_b - P)] \quad (\text{eq. 17c})$$

where:

$B_{od}$	Dead oil volume factor [Sft <sup>3</sup> /STB]
$R_{sb}$	Gas in oil ratio at $P \geq P_b$ [Sft <sup>3</sup> /STB]
$T$	Temperature [°F]
$P$	Pressure [psia]
$P_b$	Bubble point pressure [psia]
$\gamma_g$	Gas phase specific gravity
$\gamma_o$	Oil phase specific gravity

### Gas volume factor ( $B_g$ )

Given by its definition.

$$B_g = \frac{14,7}{520} \cdot \frac{Z \cdot (T + 460)}{P} \quad (\text{eq. 18})$$

where:

$B_g$	Gas volume factor [Sft <sup>3</sup> /STB]
$Z$	Compressibility factor
$T$	Temperature [°F]
$P$	Pressure [psia]

### Water volume factor ( $B_w$ )

Correlation proposed by Frick (Frick, 1962)

$$B_w = (1 + 1,25 \cdot 10^{-4} \cdot DT + 9,88 \cdot 10^{-7} \cdot DT^2) \cdot (1 - 3,00 \cdot 10^{-6} \cdot DP) \quad (\text{eq. 19a})$$

$$DP = P - 14,7 \quad (\text{eq. 19b})$$

$$DT = T - 60 \quad (\text{eq. 19c})$$

where:

$B_w$	Water phase volume factor [Sft <sup>3</sup> /STB]
$Z$	Compressibility factor
$T$	Temperature [°F]
$P$	Pressure [psia]

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