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An accurate method to generate composite PVT data for black oil simulation

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ABSTRACT

Lookup Black Oil Tables (BOT) are widely utilized by professional software packages for providing fluid properties during reservoir, wellbore and pipeline flow simulation instead of having to solve repeatedly the highly non-linear phase behavior problem at a very high CPU cost. These Tables, are either generated using an Equation of State (EoS) model already tuned to the available lab data or from the data itself or by applying available correlations of general use. Given the considerable effort and expertise required for achieving a comprehensive EoS tuning, the methods for generating the BOT utilizing the PVT lab data are still very popular. Such methods currently available are based on simplifying assumptions and often fail to match accurately the required composite vaporization B_o and R_s curves along the entire operating pressure range. In addition, these methods do not allow the recalculation of the BOTs when the selected separation train conditions are altered unless such a PVT lab separation test data is already available.

In this work, an accurate method is presented to derive BOTs by combining PVT lab depletion data with properties values which can be generated by running simplified surface flash calculations. Separator gas and tank oil volumes are obtained by flashing the reservoir oil at the selected pressures using k-values generator methods and by taking advantage of the fact that, at surface train conditions, equilibrium coefficients are practically independent of composition. The results obtained can be also matched against available PVT lab report flash data or field measurements. The method was applied to several reservoir oils and the accuracy of these test cases proved to be of the order of 1% and 2% for the prediction of B_o and R_s respectively all along the operating pressure range. Finally, an approach is presented by which the generated BOTs can be accurately adjusted according to any variations of the separator train conditions without the need of additional lab data.

1. Introduction

Fluid properties play a crucial role in petroleum engineering applications as they are involved in all types of calculations such as recoverable reserves estimation, flow within the reservoir, subsurface manifolds and surface facilities. Phase behavior, PVT values, rheology and thermal properties are all involved in the governing differential equations thus affecting production forecasts and optimization processes. Specifying the phase behavior of a hydrocarbon mixture aims at determining the number of phases in equilibrium, their molar and volumetric amounts, compositions and physical properties. The PVT values describe the change of volume and physical properties when the fluids undergo depletion and flash processes such as production through the wellbore and the surface separation system. Rheology is related to the pressure drop occurring during fluid flow in the porous medium or in pipelines. Finally, thermal properties such as phase heat capacities and the Joule-Thompson coefficient are related to calculations of the flowing fluid temperature. Additionally, the derivatives of phase properties with respect to pressure, temperature and composition are also often required for the solution of reservoir and pipeline flow simulation problems.

When dealing with flow simulation, the governing differential equations that impose conservation of mass, momentum and energy cannot be solved analytically due to their severe non-linearity. Complex boundary conditions for modeling aquifers encroaching water, horizontal or multilateral wells as well as the assumption of thermodynamic equilibrium prevailing at any time increase dramatically the complexity of the mathematical problem. For this purpose, space and time are discretized in small blocks and steps respectively and for each block a set of algebraic equations involving PVT properties values describes the physical processes that take place. Utilizing accurate PVT values is of major importance to a flow simulation as the volumetric factors allow recorded fluid volumes and flowrates at surface conditions to be translated to reservoir ones and vice versa.

Current practice is to calculate the required PVT values by means of

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Equations of State (EoS) or to read them from Black Oil Tables. In the former case, cubic EoS models such as the Soave-Redlich and Kwong (SRK) and Peng and Robinson (PR) ones are usually utilized to provide all required properties. Prerequisite for obtaining accurate values is a proper and physically sound tuning of the EoS parameters against a set of lab experiments. Once this is done, the EoS approach can describe accurately complex phase behaviors such as those taking place during miscible gas displacement, dry gas injection during the depletion of rich gas condensates and in reservoirs with strong compositional gradient (Fevang et al., 2000). The price to be paid when running fully compositional simulations is that the dimensionality of the mathematical formulation increases severely as each component introduces an extra degree of freedom. Additionally, the phase stability problem and, if required, the phase split one, both governed by complex non-linear algebraic systems, need to be solved at each cell and at each timestep (Voskov and Tchelepi, 2014).

On the other hand, BOTs are still widely utilized as a significantly simpler, adequately accurate, approach to describe phase behavior phenomena particularly of black oils. According to this approach the fluid encountered at any point within the reservoir, the wellbore or the pipelines is assumed to be a mixture of two fixed composition surface fluids, namely the stock tank oil and the stock tank gas. At any pressure, a given quantity of tank gas, denoted by the solution gas-to-oil ratio R_s, is dissolved in the tank oil thus causing its swelling as indicated by the formation oil volume factor B_o. If mass conservation indicates that additional gas is present, a free gas phase is formed with the formation gas volume factor B_g denoting its compression with respect to the surface conditions. Water's volume change with pressure is defined by its own formation volume factor B_w. The PVT values, according to the black oil approach, are treated as functions of pressure solely thus neglecting the effect of fluid composition. As a result, the liquid and gas phase densities can be obtained by:

$$\rho_o = \frac{1}{B_o}\left(\rho_o^{(SC)} + R_s\rho_g^{(SC)}\right) \tag{1}$$

$$\rho_g = \frac{1}{B_g}\rho_g^{(SC)} \tag{2}$$

$$\rho_w = \frac{1}{B_w}\rho_w^{(SC)} \tag{3}$$

The densities of the stock tank oil and stock tank gas are denoted by $\rho_o^{(SC)}$ and $\rho_g^{(SC)}$ respectively where as B_o, R_s, B_g and B_w are functions of pressure and temperature. The black oil formulation reduces the number of material balance equations to that of the existing phases. In addition, the calculation of the density derivatives with respect to pressure and temperature is of extremely low computational cost as they depend on the derivatives of the formation factors solely since $\rho_o^{(SC)}$ and $\rho_g^{(SC)}$ are treated as constants. Therefore, compressibility values which are needed to account for mass accumulation can be calculated directly. The black oil model formulation also assumes that the free gas is a non-retrograde one thus yielding no condensate when brought at surface conditions whereas the Modified Black Oil (MBO) formulation (Whitson et al., 1988) includes a fourth parameter, the oil-to-gas ratio r_s.

Modern commercial reservoir simulation software utilizes lookup BOTs containing PVT values entries at various pressures at constant temperature. At each timestep, the flow simulator interpolates those entries at the pressure prevailing at each cell. BOTs can be generated by means of correlations, a tuned EoS model or experimental data. Correlations are of limited accuracy as they only utilize surface production data and reservoir temperature to predict PVT values as functions of pressure (Danesh, 1998). Nevertheless, this approach is the only option when a new reservoir discovery is considered for which no PVT report is available and properties can be only approximated by means of simple expressions such as those of Standing, Vazquez and Beggs, Glaso, etc (de Ghetto et al., 1994). When the actual saturation pressure as well as the lab flash values of B_o and R_s at that pressure measured from the separation test become available, the correlations can be "pinned" at those individual points (Petroleum Experts, 2014) without any guarantee that the shapes of the curves will improve. The reliability of this approach depends strongly on the conformance of the reservoir fluid under study with the average properties of the fluids which had been used for the derivation of the correlations. The above requirement often is not satisfied for very volatile and near critical oils, biodegraded oils, etc.

The EoS approach to generate a BOT utilizes a tuned EoS model to simulate the required flash calculations of the Composite Differential Vaporization study (Ahmed, 2016). For very volatile oils, the EoS model can also be used to compute the solution oil-to-gas ratio r_s which corresponds to the liquid that the reservoir gas yields when brought to the surface. The EoS approach, though the most accurate one, requires a comprehensive set of experimental values and considerable tuning expertise so as to maintain physical soundness of the thermodynamic model in a wide range of the compositional space and conditions (Gaganis and Varotsis, 2005). The authors' experience indicates that tuning is not trivial, it cannot be fully automated and requires considerable expertise and in depth knowledge of the EoS modeling techniques. Moreover, operators are often reluctant to allocate resources towards generating an EoS model if a black oil simulation is going to be run.

From the discussion above it is clear that the generation of BOTs from a PVT lab study still remains a popular option in commercial petroleum engineering software packages. In this work, a computational method is proposed to generate reliable and physically sound BOTs by utilizing a PVT lab depletion study report values. The method combines measured data with properties values which can be generated by running simplified surface flash calculations. Separator gas and tank oil volumes are obtained by flashing the reservoir fluid at the selected pressures using k-values generator methods and by taking advantage of the fact that, at surface train conditions, equilibrium coefficients are practically independent of composition. Finally, matching the predicted properties against available PVT measurements ensures the accuracy of the utilized method. The proposed approach provides saturated oil PVT values below the original reservoir fluid's bubble point pressure, hence for pressures above the saturation one, the available extrapolation techniques can be directly applied (Singh et al., 2007; Nojabaei and Johns, 2016).

The paper is organized as follows. Firstly, a discussion is presented about the advantages and limitations of the available BOT generation methods based on lab PVT data. Subsequently, the proposed method is described in detail. A validation procedure is run to demonstrate the accuracy of the proposed method followed by a set of case studies. The paper ends with conclusions and recommendations.

2. Current BOT generation practice

To get PVT values versus pressure and temperature for their black oil models, reservoir engineers need to combine data from reservoir depletion studies such as the Differential Vaporization study (DV) or the Constant Volume Depletion (CVD) one and surface separator processes. A DV study is considered to describe the change of compositions within the reservoir assuming that the liberated gas travels fast and is separated immediately from its equilibrium liquid due to its higher mobility whereas a CVD study is suitable for very volatile oils or gas condensates as it assumes that the produced condensate remains immobile as long as its saturation remains lower than the critical one. Once the produced fluids arrive at the surface, they are considered to attain equilibrium at each separation stage on their way to the tank.

Dodson et al. (1953) was first to note that the composite differential vaporization (Fig. 1) is the best means to truly approximate the entire liberation sequence as it takes into account the fact that the properties of the phases produced from the reservoir vary during reservoir depletion. Moses (1986) further supported this argument by showing that failing to