20.3: Compositional Modeling of Gas-Condensate Reservoirs-The Zero-dimensional Approach

Phase behavior is relevant to every aspect of petroleum and natural gas engineering. According to the complexity of the reservoir fluid phase behavior, reservoir modeling is classified under two distinct groups: black-oil simulation and compositional simulation. Often times, it is safe to assume that reservoir fluid behavior is only a function of pressure and independent of composition. This simplified behavior is typical of “black-oil” systems. In this case, reservoir hydrocarbon fluids are assumed to be comprised of two components, namely oil and gas. The model allows for certain amount of gas to be in solution with the oil at reservoir conditions. The amount of dissolved gas increases with, and is a sole function of, pressure for conditions below the bubble point. Above the bubble point pressure, the oil-component carries all the available gas in the reservoir, and a “variable bubble point” algorithm is usually implemented to predict conditions for the release of the dissolved gas. For this “black-oil” simplified model to be valid, actual oil and gas phases should maintain a fixed-composition throughout the process simulated in the reservoir. In certain cases, the assumption of fixed oil and gas composition is no longer valid: for instance, depletion of gas-condensate reservoirs and volatile-oil reservoirs, and processes that aim at the vaporization or miscible flooding of the in-situ fluids by fluid injection. More complex fluid behavior requires treating all hydrocarbon phases as nC-component mixtures and thus performing a “compositional simulation.”

Although the need for taking compositional dependence of thermodynamic and hydrodynamic parameters into account in reservoir description has been recognized for a long time, the actual implementation has not been realized until relatively recently. One of the main reasons is due to the lack of simple and reliable methods of predicting phase behavior under the conditions of interest. Two things have happened within the last three decades that have changed the situation: They are (1) the availability of fast and relatively inexpensive computational power to carry out the great number of calculations involved and (2) the development of samples and fairly good equations of state.

Simply put, a compositional reservoir simulator is a dynamic integration of the fluid dynamic porous media model and
the phase behavior model, neither of which is subordinated to the other. In fact, in the early days of compositional reservoir simulation, a non-dynamic integration of these two was the norm. The more recent models actually attempt a full dynamic integration. The need for integration had been recognized earlier particularly for gas condensate reservoir, gas cycling processes, and volatile oil systems.

Early developments in reservoir engineering analysis relied on zero-dimensional or tank material balances for the evaluation and forecasting of reservoir performance. In 1936, Schilthuis devised what we now regard as the classical material balance equation. Schilthuis-type material balances are only valid for black-oil systems and are not applicable for reservoir fluids with complex behavior such as gas condensates and volatile oils. Compositional considerations were incorporated into zero-dimensional modeling in the decade of 1950’s with the works of Allen and Row (1950), Brinkman and Weinaug (1957), Reudelhuber and Hinds (1957), Jacoby and Berry (1957), and Jacoby et al. (1959). These can be regarded as the first generation of compositional simulators. Even though zero-dimensional simulations have been largely overthrown by more sophisticated numerical simulation techniques, they are still considered the most simple and fundamental tool available for the analysis of reservoir performance.

The zero-dimensional models make two principal assumptions. The first is to basically ignore the two-way coupling between fluid’s thermophysical properties and the hydrodynamic characteristics. The reservoir is treated as a perfectly mixed tank reactor with uniform properties. We assume no dimensions, and that one single value of pressure and temperature describes the average behavior of the entire reservoir. The second assumption is to neglect the hydrodynamic interactions between the flowing gas and liquid phases. In other words, the zero-dimensional compositional model relies on phase behavior as the most crucial effect controlling the description of recovery performance.

There is no doubt that significant insights, albeit qualitative, are provided by these studies. Zero-dimensional modeling provides a less expensive tool for the engineer to gain some insight into the expected performance of a gas condensate reservoir under depletion. Sometimes we spend a great deal of time dealing with the numerics of the dimensional compositional simulators, and we may forget that phase behavior is the single most important constituent of the depletion performance of, for instance, gas-condensate systems. Nevertheless, the reservoir engineer must keep in mind that this type of analysis does not provide the most accurate reservoir description. For instance, the effect of heterogeneities on reservoir performance cannot be studied with a zero-dimensional model. Again, the goal is to take a look at the qualitative insights that fluid PVT behavior can provide us.

The typical depletion sequence that a zero-dimensional compositional simulator follows is described below. This classical analysis treats gas condensate performance as constant volume depletion (CVD) in a PVT cell. The ultimate output of the model is basically comprised of GOR prediction and the compositions of the gas and condensate surface effluents. We start with a single-phase gas reservoir fluid, of a known composition, at an initial reservoir pressure and temperature. We flash this fluid several times through a series of pressure depletion stages until abandonment conditions are found. Reservoir volume is kept constant throughout the depletion process.

The typical depletion sequence that a zero-dimensional compositional simulator follows are listed below:

1. Calculate the density and molecular weight of the initial reservoir fluid. With this information, and knowing the initial reservoir volume (Vt), calculate the initial amount of gas in place (lbmols). An alternative approach is to start with a fixed amount of lbmols of reservoir fluid, and calculate the corresponding initial reservoir volume (Vt). We assume a volumetric reservoir and thus the initial reservoir volume (Vt) is kept constant throughout the calculations.
2. Using the reservoir fluid composition, distribute the initial moles of reservoir fluids into components, and store such quantities for material balance accounting.

3. **Depletion step:** Lower the reservoir pressure by a given amount (typically, 200 psi). Flash the reservoir fluid at the new pressure, calculate amount of moles in the gas and liquid phases (“GasT” and “LiqT”) and the densities and molecular weights of each of the phases at the new condition.

4. **Expansion:** With molecular weight, density, and total molar amount of each of the phases, calculate the new total volume that the fluids occupy at the new condition ($V_{exp}$).

5. Calculate the excess volume of fluids, taking the difference between the new volume upon expansion ($V_{exp}$) and the reservoir volume ($V_t$). This represents the volume of fluid that must have been withdrawn by the well in order to reach the newly imposed pressure condition, i.e.

   \[ V_{ws} = V_{exp} - V_t(20.3) \]

6. Calculate the percentage of liquid in the well stream using mobility ratio considerations. Trial and error procedure is necessary for the liquid accounting. The total amount of liquid available upon depletion (LiqT) must be distributed between the wellstream (LiqWS) and the liquid remaining in the reservoir (LiqR). Additionally, the moles of reservoir liquid “LiqR” can be expressed in terms of oil/condensate saturation. Oil saturations define the mobility of the gas and liquid phases. These interrelations are shown below:

   \[ \text{LiqWS} = \text{LiqT} \]

   \[ \text{S}_o = \frac{M W_o}{P_o V_t} \text{LiqR} \]

   \[ \lambda_o = \frac{k_{r o}(S_o)}{\mu_o} ; \lambda_g = \frac{k_{r g}(S_g)}{\mu_g} ; \lambda_t = \lambda_o + \lambda_g ; S_g = 1 - S_o \]

   \[ (V_{ws})_{liq} = \frac{\lambda_o}{\lambda_t} V_{ws} = \frac{M W_o}{P_o} \text{LiqWS} S \]

7. $(\text{LiqWS})$ is a function of mobility ratio, which is a function of LiqR (through $S_0$). As a first guess, take LiqR = LiqT and calculate the corresponding LiqWS. Make new guesses (decreasing the value in every new trial) until the liquid balance in Equation (20.4a) is satisfied.

8. Once $(\text{LiqWS})$ and $(V_{ws})_{liq}$ are known, obtain the total volume of gas withdrawn from the reservoir by subtracting the liquid volume $(V_{ws})_{liq}$ from the total wellstream volume $(V_{ws})$. Express this gas volume in moles using reservoir gas density and molecular weight. Calculate the total number of moles of the wellstream.

9. **Material Balance Accounting:** Calculate the number of moles of each component remaining in the reservoir. To do this: subtract the number of moles leaving the well stream from the number in the reservoir before flashing for each of the components. Calculate the new overall composition of the reservoir fluid.

10. Calculate the overall composition of the produced well stream, by mixing the composition of gas and liquid coming along.

11. **Surface Production Facility:** Flash the incoming wellstream composition through the train of separations. Calculate the total amount of gas and liquid leaving the separation facility and GOR. Calculate the percentage of recovery from the reservoir.

12. A depletion loop has been completed. Go back to step 3 until abandonment pressure is reached (typically, 600 psia).

13. Plot liquid production, gas production, GOR, and recovery from the reservoir as a function of pressure depletion, from initial reservoir conditions to abandonment conditions.

The basic VLE calculations required here can be performed using the Peng-Robinson EOS and equilibrium considerations. Liquid viscosities can be calculated through the Lohrenz, Bray, and Clark correlation, and gas viscosities can be calculated using the Lee-Gonzalez correlation. Fluid densities are obtained directly through the Peng-Robinson EOS.
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