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Unusual behavior of produced gas oil ratio in low permeability fractured reservoirs

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ABSTRACT

Leading unconventional plays in the US such as Eagle Ford, Bakken and Niobrara have average gas oil ratio (GOR) ranging from 500 SCF/STB to 4000 SCF/STB. The behavior of produced GOR is difficult to characterize for unconventional reservoirs. Initial reservoir pressure (P_i), well operating pressure and fluid properties directly related to Pressure Volume Temperature (PVT) such as bubble point pressure (P_b), initial GOR (R_{si}), GOR at P_b (R_{sb}), GOR at flowing bottom hole pressure (R_{sw}) are the key factors affecting produced GOR from low permeability (10–5000 nD) reservoirs. Gas production may be controlled and kept in the desired production window by maintaining the flowing bottom hole pressure (P_{wf} or BHP). A single characteristic factor affecting the produced GOR is found to be $\left(1-\frac{R_{sw}}{R_{sb}}\right)\frac{\left(1-\frac{P_{wf}}{P_b}\right)}{\left(1-\frac{P_{wf}}{P_i}\right)}$. The first part $\left(1-\frac{R_{sw}}{R_{sb}}\right)$ considers the fluid PVT effect with operating condition, second part $\left(1-\frac{P_{wf}}{P_b}\right)$ accounts for the proximity of operating pressure with bubble point pressure and third part $\left(1-\frac{P_{wf}}{P_i}\right)$ is the drawdown effect. Production behavior in terms of produced GOR can be predicted using this single factor. Produced GOR increases with time when this factor exceeds a certain value, while, little or no deviations from the initial GOR are observed for lower values of the factor. It should be noted that the predictive factor does not depend on reservoir matrix permeability. Initially, a factor $\frac{(P_b-P_{wf})}{(P_i-P_{wf})}$ comprising only pressure terms was developed which failed to capture the behavior of produced GOR. Initial reservoir pressure and flowing bottom hole pressure (P_{wf}) are varied to study a wide range of reservoirs and production conditions. The oil rates, recovery factor and produced GOR are the key production parameters for this study. Suitability of this factor is validated by comparing simulation data with field data. The optimum well operating pressure can also be determined using this factor to maximize recovery. Deviation of GOR from its initial value is higher for low permeability reservoirs. Higher gas and oil are recovered from reservoirs with higher initial gas oil ratios (R_{si}).

1. Introduction

Obtaining higher estimated ultimate recovery (EUR) of oil is the primary concern of an operating company. Dissolved gas helps to improve the mobility of oil by making the oil lighter. Oils classified as Black oils contains certain amount of dissolved gas, which evolves when the reservoir pressure drops below bubble point pressure in the course of production. Gas flows easily through porous medium than oil because of its higher mobility and starts dominating two-phase flow by suppressing the flow of oil. On the other hand, free gas sustains the pressure in the reservoir. Produced GOR gradually increases with time as the reservoir pressure declines in the reservoir.

The reasons behind the increase of GOR and decline of oil rate with time are first explained by Millikan (1926) by compiling field data and he also discussed the drawdown effect on produced GOR. Well placement and proper design of flow column were the two sets of factors to determine GOR (Albertson and Schaeffer, 1931). Different possible ways to control producing GOR to optimize the ultimate recovery without compensating with rate of production were

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Nomenclature

GCI	Gas-Oil-Ratio Characteristic Index (dimensionless)
f_p	Difference in Pressure Ratio Factor (dimensionless)
f_{pn}	Normalized Difference in Pressure Ratio Factor (dimensionless)
GOR	Gas Oil ratio (SCF/STB)
k_{fx}	Fracture Absolute Permeability in X-direction (mD)
k_{fy}	Fracture Absolute Permeability in Y-direction (mD)
k_{fz}	Fracture Absolute Permeability in Z-direction (mD)
k_m	Reservoir Absolute Permeability (nD)
P_b	Bubble Point pressure (psi)
P_i	Initial Reservoir pressure (psi)
PVT	Pressure Volume Temperature (dimensionless)
P_{wf}	Flowing Bottom Hole pressure (psi)
R_{pc}	Cumulative Gas Oil ratio (SCF/STB)
R_{sb}	Gas Oil ratio at Bubble Point Pressure (SCF/STB)
R_{si}	Initial Gas Oil ratio (SCF/STB)
R_{sw}	Gas Oil ratio at Flowing Bottom Hole Pressure (SCF/STB)
X	Reservoir Dimension in X-direction (ft)
Y	Reservoir Dimension in Y-direction (ft)
Z	Reservoir Thickness (ft)

demonstrated (Marsh and Robinson, 1929; Sullivan, 1937) incorporating field data. Multiphase black oil flow equation (Muskat, 1945) was solved numerically (Arps and Roberts, 1955) for initial GOR up to 2000 SCF/STB to obtain oil recovery and the method was validated by comparing the results with actual field data. It was concluded that a definite relationship could be established between oil recovery and reservoir fluid properties like initial GOR, API gravity and type of reservoir rock. Compositional simulations are used (Brinkman and Weinaug, 1956) to predict the GOR and formation volume factors for dissolved gas drive reservoir at saturated conditions. Jones-Parra and Reytor (1959) developed a material balance method incorporating gravity segregation to show the effect of GOR on production from fractured limestone reservoirs. Their results proved that oil rates declined less at higher initial GOR. Levine and Prats (1961) concluded that the produced GOR is independent of reservoir permeability by numerically solving partial differential equations describing solution gas drive reservoirs. Another study by Prats and Levine (1963) showed that the produced GOR for vertically fractured reservoir is higher than unfractured reservoir. A new method to forecast GOR dependent on oil rate and consistent with reservoir mechanisms was developed (Lawal et al., 2006). Laboratory experiments (Busahmin and Maini, 2010) showed that the performance of foamy heavy oil system is affected negatively with increase in initial GOR which were counter-intuitive. Ultra-low permeable reservoirs like shales behave differently from conventional reservoir with high reservoir permeability. Downhole well sensors (Al-Khelaiwi et al., 2014) were used to calculate produced gas oil ratio to avoid faulty gas meter reading at separator on surface. Impact of nano-pores (Khoshghadam et al., 2015) on gas oil ratio was investigated by compositional simulation of liquid rich shale oil reservoir.

In this study, we characterize the qualitative behavior of produced GOR from ultra-low permeability fractured reservoirs such as shales. For this purpose, various factors combining pressure terms and/or fluid properties terms are examined. Two possible factors are attempted initially, to capture the behavior of produced GOR; one factor is able to predict the behavior of produced GOR correctly. We also investigated the effect of dissolved GOR on production performance for different reservoir permeabilities and flowing bottom hole pressures.

2. Characterization of GOR

A variety of criteria such as constant pressures (initial, bubble point or bottom hole pressures), constant pressure differences and constant ratio of pressure differences are tried initially in this study. Discussing the results of this initial screening study is out of scope of this article. It is observed that none of the them is the valid criteria for characterizing the performance (oil rate, GOR and oil recovery) but combining them in particular manner can exhibit a conclusive relationship which can predict qualitative behavior of production performance. The ratio of pressure differences (f_p) is first examined as shown by Eq. (1).

$$f_p=\frac{(P_b-P_{wf})}{(P_i-P_{wf})} \tag{1}$$

The oil rate and oil recovery can be explained using ratio of pressure difference factor (f_p) (shown in Eq. (1)). However, without incorporation of GOR into the factor, it is ineffective to correctly predict the behavior of the produced GOR. This fact will be established in the later part of the article as we analyze the results. The depletion of long transient state reservoir can be represented by the extent of the difference between the bubble point pressure and flowing bottom hole pressure since the average reservoir pressure for this kind of reservoir is not representative of the behavior. The difference in the GOR at P_{wf} and GOR at P_b is one characteristics parameter to predict the behavior of produced GOR from ultra-low permeable fractured reservoir. All these factors are accommodated with Eq. (1) into a single characteristic factor, GOR characteristic index (GCI) as given by Eq. (2).

$$\text{GCI}=\left(1-\frac{R_{sw}}{R_{sb}}\right)\frac{\left(1-\frac{P_{wf}}{P_b}\right)}{\left(1-\frac{P_{wf}}{P_i}\right)} \tag{2}$$

The factor, GCI, can be used only when flowing bottom hole pressure is less than the bubble point pressure. When flowing bottom hole pressure is above the bubble point pressure, the well produces initial GOR because reservoir is undersaturated. The value of GCI is presented in Table 1 for the different cases in this study. The effect of this factor is clearly observed in the qualitative behavior of produced GOR which is discussed later.

3. Experimental design

The common industry belief is that the drawdown i.e. the difference between the reservoir pressure and flowing bottom hole pressure is the key factor to dictate the production behavior. In this study, the significance of location of bubble point pressure is also considered. To get rid of the established idea of drawdown, the experiments are designed in such a way that drawdown i.e., the difference between initial reservoir pressure and flowing bottom hole pressure are same for all runs. The same drawdown for all experiments ensures that drawdown is not affecting the changes in production performance. The location of bubble point pressure with respect to flowing bottom hole pressure and initial reservoir pressure is a significant factor in the production performance of oil and gas. To create different scenarios of experiment,