Phase behavior simulation of light oil in the process of gas injection by using PVT simulation

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Abstract. For studying the phase behavior of light oil in the process of gas injection, a series of phase models was built by PVTsim software for understanding the evolution of phase states and physical properties including the gas-oil ratio (GOR), density and viscosity. In this study, a light oil as an initial composition was mixed with methane gas in different degrees of gas injection from 0 to 400 mol%CH₄ for phase modeling, and the temperature-pressure condition at a deep reservoir as well as on the ground was used to calculate their physical properties. Our results show that the process of gas injection can not only impact on the physical properties of pre-oil reservoirs but also change phase states of them overwhelmingly. Especially, a light oil reservoir with a good trap can become either a condensate gas reservoir in a middle degree of gas injection or a saturated reservoir (gas-liquid phases) in a high degree of gas injection. In addition, wet gas and waxy oil can be separated from a light oil reservoir with a poor trap under a high degree of gas injection. This study proved gas injection or gas washing altering the phase state and composition of pre-oil reservoirs is one important mechanism to form the condensate gas, waxy oil, and wet gas in some petroliferous basins, and also provided a new solution to study the gas injection of pre-oil reservoir in some more complex cases.

1. Introduction

Natural gas has a much greater migration ability than oil so that gases are easier to be injected into a pre-oil reservoir underground. This process so-called gas injection causes reservoir compositions as well as their phase states changed, which is one important mechanism to form condensate gas, waxy oil, and wet gas [1-2]. Normally, when gas injection occurs at a good trap, all injected gases can be trapped there to change its composition and phase state. While gas injection at a poor trap that also can be called gas washing or evaporative fractionation can separate pre-oil reservoirs into different parts as the light components can be brought away by the gases but then the heavy components remained [3-5]. In previous works, researchers studying the effect of gas injection regularly focused on the composition and phase changes in a specifically mixing degree under a specific temperature-pressure condition by using the phase simulation experiment corresponding to PVT-based methods [1-2, 6-8]. However, these studies exist some shortcomings like that they are quite time-consuming to conduct the phase simulation experiments and have not considered the effect of diverse degrees of gas injection. It meant that using a finite number of experiments is quite hard to reconstruct the phase behavior of an oil reservoir in the process of gas injection. So, for overcoming these shortcomings, we tried to use PVT simulation technology to construct a series of phase models, and then the relevant changes of phase states and physical properties (GOR, density, and viscosity) were discussed on the
ground and at a deep reservoir condition. This study aims to provide comprehensive knowledge of such gas injections of light oil.

2. Method and data

Fluid phase simulation was conducted by PVTsim software developed by Calsep A/S to build phase diagrams and output fluid characteristics after inputting the detailed fluid compositions. For these purposes, the initial fluid from the software has been chosen at first, which has properties with a GOR$^\text{vol}$ (383) higher than 312, molar percentage of C$_7^+$ (19.37 mol%) less than 20 mol%, and 48°API better than 45° API (Table 1). According to a classification of hydrocarbon by Ahmed et al. (2016), this initial fluid is sorted into light oil and the composition data have shown in Table 1 as the initial data for mixing with gas [9]. Then, the initial data of light oil and methane gas were respectively mixed by different proportions (from 0 to 400 mol% CH$_4$) to calculate the data of mixed composition for representing the final fluid compositions of gas injections with different degrees in a light oil reservoir. After that, the fluid composition data of each degree of gas injection inputted into the PVTsim software for building the phase models respectively. Finally, phase characteristics covering state, GOR, density and viscosity were calculated for further analysis under two certain conditions that are either on the ground (16°C, 0.101MPa) or at a deep reservoir (160°C, 70MPa).

### Table 1. Data of initial composition and properties of light oil

| Component | Mol (%) | Molecular weight (g/mol) | Component | Mol (%) | Molecular weight (g/mol) | Liquid Density g/cm$^3$ |
|-----------|---------|--------------------------|-----------|---------|--------------------------|------------------------|
| N$_2$     | 0.541   | 28.014                   | C$_7$     | 2.527   | 91.5                     | 0.738                  |
| CO$_2$    | 2.798   | 44.010                   | C$_8$     | 2.720   | 101.2                    | 0.765                  |
| H$_2$S    | 0.990   | 34.080                   | C$_9$     | 1.682   | 119.1                    | 0.781                  |
| C$_1$     | 55.015  | 16.043                   | C$_{10}$  | 1.242   | 133.0                    | 0.792                  |
| C$_2$     | 8.509   | 30.070                   | C$_{11}$  | 1.105   | 145.0                    | 0.796                  |
| C$_3$     | 5.688   | 44.097                   | C$_{12}$  | 0.920   | 158.0                    | 0.810                  |
| iC$_4$    | 0.999   | 58.124                   | C$_{13}$  | 1.045   | 171.0                    | 0.825                  |
| nC$_4$    | 2.411   | 58.124                   | C$_{14}$  | 0.884   | 185.0                    | 0.836                  |
| iC$_5$    | 0.886   | 72.151                   | C$_{15}$  | 0.778   | 198.0                    | 0.842                  |
| nC$_5$    | 1.228   | 72.151                   | C$_{16}$  | 0.590   | 209.0                    | 0.849                  |
| C$_6$     | 1.565   | 86.178                   | C$_{17}$  | 0.675   | 226.0                    | 0.845                  |

| Component | Mol (%) | Molecular weight (g/mol) | Component | Mol (%) | Molecular weight (g/mol) | Liquid Density g/cm$^3$ |
|-----------|---------|--------------------------|-----------|---------|--------------------------|------------------------|
| GOR$^\text{vol}$ | 383 | >312 | C$_{18}$ | 0.555 | 242.0 | 0.848 |
| C$_7^+$ (mol%) | 19.37 | <20 mol% | C$_{19}$ | 0.529 | 251.0 | 0.858 |
| API gravity | 48°API | >45°API | C$_{20}$ | 4.118 | 407.0 | 0.905 |

3. Results and discussion

3.1 Phase diagram

Figure 1 displays the results of phase models for the injected light oil, showing a series of envelope curves as a result of different degrees of methane gas injections. The results illustrate that the areas of envelopes are expanding up by the increasing injection degree from 0 to 400 mol% CH$_4$. At the same time, the cricondenbar (P$_m$) is getting bigger from 35 MPa to 80 MPa, while the cricondentherm (T$_m$) is going down from 470°C to 440°C. Moreover, the track of critical points, which is the most important sign of the changes of phase envelope, is fixed by the fitting equation of parabola y=-
0.0005x^2+0.0689x+47.683 (R^2=0.9989), which indicates that the track along with the increasing injection degree first moves toward the high pressure-low temperature area and then turns to the low pressure-high temperature area. Figure 1 also shows that the fluid types of all envelopes can be divided into oil, condensate, and gas reservoirs by the related position between critical point and cricondenbar (P_m) throughout the valid geological conditions (0-200 °C, 0.101-80 MPa). When the injection degrees are lower than 40 mol%CH_4 and critical points are on the right of their cricondenbar (P_m), the fluid type of envelopes still belongs to light oil. When the injection degrees are higher than 40 mol%CH_4 and critical points locate on the left of their cricondenbar (P_m), the fluid type of envelopes becomes belonging to the condensate gas. When the critical points have disappeared, the fluid type of envelopes becomes belonging to the gas reservoir. These suggest that light oil reservoirs can be changed into either condensate gas or gas reservoirs by certain gas injections.

![Figure 1](image.png)

**Figure 1.** Phase diagram of a series of envelope curves as a result of methane gas injections with different degrees from 0 mol% to 400 mol% (solid curves indicate envelope curves; hollow circles on a dotted curve indicate critical points; solid circles on a dotted-straight line are temperature-pressure points)

### 3.2 Phase behavior

Reservoirs’ phase states are not only controlled by their fluid compositions but also by temperature-pressure conditions. So the phase characteristics of light oil related to gas injections have been calculated for discussing when the conditions are either on the ground or at the deep reservoir.

#### 3.2.1 Phase behavior on the ground (16°C, 0.101MPa)

The results show that light oil reservoirs on the ground keep in the gas-liquid phases in each degree of gas injection (Figure 1), while the GOR is growing up from 383 m³/m³ (0.48 kg/kg) to 2500 m³/m³ (2.33 kg/kg) due to the continuous adding of methane gas. With the increase of gas injection from 0 to 400 mol%CH_4, a growing amount of light components are dissolving into the gas phase, which causes the density and viscosity of the liquid phase heavier and more viscous. The density of liquid phase is increasing from 0.8346 g/cm³ to 0.8476 g/cm³, while the viscosity is from 2.56 cP to 3.43 cP. Differently, the density of gas phase is decreasing from 0.0011 g/cm³ to 0.0007 g/cm³, which the viscosity is increasing from 0.0103 cP to 0.0108 cP.

#### 3.2.2 Phase behavior at a deep reservoir (160°C, 70MPa)
The phase states and their physical properties display more diverse changes when different degrees of gas injection take place at the deep reservoir of light oil. The results are shown in Figure 2. When the degree of gas injection is lower than 35 mol\%CH\_4, the light oil reservoir keeps in single liquid phase without GOR, but its density and viscosity keep decreasing by the increasing degree of gas injection. It is because more CH\_4 dissolved into the unsaturated-liquid phase can cause the density and viscosity reduced, showing that the density decreases from 0.5925 g/cm\^3 to 0.5305 g/cm\^3 while the viscosity decreases from 0.1711 cP to 0.1244 cP. When the degree of gas injection ranges from 35 to 170 mol\%CH\_4, the single liquid phase changes into the condensate gas phase by reverse evaporation, so that the density and viscosity of the changed phase decreases from 0.5305 g/cm\^3 to 0.4083 g/cm\^3 and from 0.1244 cP to 0.0702 cP, respectively. With the further increasing degree of gas injection from 170 to 400 mol\%CH\_4, the condensate phase begins to start the retrograde condensation to form two phases of liquid and vapour, so that its GOR undergoes a rapid decrease (approximately \(1500~\sim~70.43\) m\(^3\)/m\(^3\); approximately \(850~\sim~39.65\) kg/kg) from 170 to 200 mol\%CH\_4, a slow decrease \((70.43~\sim~46.17\) m\(^3\)/m\(^3\); 39.65~\sim~22.20 kg/kg) from 200 to 300 mol\%CH\_4, and a slow increase \((46.17~\sim~80.30\) m\(^3\)/m\(^3\); 22.20~\sim~36.31 kg/kg) from 300 to 400 mol\%CH\_4. Since the condensate gas phase is separated into two phases, the density and viscosity of liquid phase change from 0.6751 g/cm\^3 to 0.3283 g/cm\^3 and from 0.4605 cP to 0.0477 cP, respectively, while the density and viscosity of the vapour phase change from 0.4075 g/cm\^3 to 0.3631 g/cm\^3 and from 0.0699 cP to 0.0477 cP, respectively.

4. Conclusion

In this paper, we studied the phase state and relevant physical properties of light oil reservoir under different degrees of gas injection. Our results testify that a light oil reservoir with a good trap is able to keep single liquid phase in a low degree of gas injection (< 35 mol\%CH\_4), but also can become either a condensate gas reservoir in a middle degree of gas injection (35~170 mol\%CH\_4) or a saturated reservoir (gas-liquid phases) in a high degree of gas injection (170~400 mol\%CH\_4). It is worth noticing that wet gas and waxy oil can be separated from a light oil reservoir with a poor trap under a high degree of gas injection, which has been illustrated in part III, Figure 2. This study furthermore proved that the phase state and composition of pre-oil reservoirs can be converted into the condensate gas, waxy oil, and wet gas by either gas injection or gas washing in some petroliferous basins like the Tarim basin [10-12]. Although this article has only modeled the situation of mixing between light oil and methane gas, it has pointed out a new solution to study the gas injection of pre-oil reservoir in
some other cases. More complex types of either crude oil or gas composition can be taken into account in the modeling studies further.

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