The Yangshuiwu buried hill carbonate gas condensate reservoir has recently become the most promising exploration area in Huabei Oilfield (China). Fractures are commonly seen in this reservoir, which brings about challenges for reservoir engineers to accurately interpret the well test data obtained for this field. We first analyzed the effect of influencing factors such as phase behavior and the height of liquid column in the wellbore on the measured pressure curves. The phase behavior analysis shows that the retrograde condensation occurs in the late stage of the pressure drop. The maximum liquid volume of the retrograde condensate is only 1.62%, which has little influence on the well test curve. When the pressure gauge was placed at the middle depth of formation, the effect of “offset pressure” caused by condensate liquid could be eliminated. Moreover, dense connective fractures could be observed from the micro-resistivity image logging results, implying that a dual-medium reservoir model is more appropriate to characterize the carbonate reservoir. The dual-medium reservoir model was subsequently applied to interpret the pressure build-up data of well AT1X. The double logarithmic curves of pressure differences and pressure difference derivatives were obtained and their characteristics echoed well with the properties of typical gas condensate reservoirs. Finally, the reservoir parameters (including matrix permeability, skin factor, elastic energy storage ratio, and channeling coefficient) were successfully obtained based on the pressure build-up analysis. This study can shed light on improved characterization of gas-condensate carbonate reservoirs with abundant fractures.

**Keywords:** Yangshuiwu Buried Hill; Carbonate; Gas Condensate Reservoir; Well Test Interpretation; Phase Behavior

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1. Introduction

The Yangshuiwu buried carbonate hill reservoir is located in the upthrow block of Hexiwu Fault in the middle-north Hexiwu structural belt of Langgu Sag, North Central Hebei Province of China. It is a buried hill trap with the structural area of 70 km². According to the production data obtained in the interval of 5023.4-5203 m of well AT1X, the gas production rate and oil production rate are 40.89 ×10⁴ m³ and 71.16 m³, respectively. The discovery of this well with high production rate is recognized as a great breakthrough of the exploration of oil and gas in the ultra-deep and ultra-high temperature buried hill of heterogeneous carbonates in the northern part of Jizhong depression (China) [1–4]. The Ordovician trap can be subdivided into four sets of oil and gas bearing strata from the top to the bottom, and they are Fengfeng formation (O₂f), Upper Majiagou formation (O₂s), Lower Majiagou formation (O₂x) and Liangjiashan formation (O₂l). The buried depth of this reservoir is more than 5000 m, the formation pressure of some wells is more than 50 MPa, and the formation temperature is more than 170 °C. The Ordovician carbonate reservoir in Yangshuiwu buried hill mainly contains micrite limestone and micrite dolomite. The micrite limestone is the major composition,
accounting for about 67%. The main types of reservoir space are matrix pores and fractures. Structural fractures and structural dissolution fractures are developed in both dolomite and limestone sections, which is the effective channel to connect the inner formations of buried hill [5]. The reservoir-layer thickness ratio of each Ordovician interval in this area is quite different, ranging from 0.4% to 25.85%. Horizontal stratigraphic correlation shows that the reservoir fracture development has strong heterogeneity, which indicates that the reservoir development between wells has poor correspondence and changes greatly in horizontal. The exploration research demonstrates that the reservoir productivity in this block decreases rapidly, and the productivity difference is obvious.

For well test interpretation of gas condensate reservoirs, it has been found that when reservoir pressure around a well drops below the dew point pressure, retrograde condensation occurs and three regions appear with different liquid saturations from the wellbore to the area far from the wellbore. To date, considerable researches have been conducted to deal with well test interpretation for gas condensate reservoir. Yousefi et al. [6] examined gas condensate well test analysis using single-phase gas pseudo-pressure and radial composite model assuming capillary number effect and non-Darcy flow and found that estimation of reservoir properties below the dew point is in good agreement with actual input, particularly for lean fluid samples. Jones and Raghavan showed that a “steady-state” two-phase pseudo-pressure can be used to estimate the reservoir flow capacity (kh) and to give a lower bound for the skin [7]. Gringarten et al. proposed a three-zone radial composite model: (1) an outer zone away from the well, with the initial liquid condensate saturation; (2) a zone nearer to the well, with increased condensate saturation and lower gas mobility; and (3) a zone in the immediate vicinity of the well with high capillary number which increases the gas relative permeability [8]. Hashemi et al. [9] found that in horizontal wells of gas condensate reservoirs, condensate deposit near wellbore yields a well-test composite behavior similar to what is found in vertical wells, but superimposed on horizontal-well behavior . In China, Tang et al. [10] applied a multi-zone composite well test model to process actual well test data in a complex gas condensate reservoir, reported that the formation of multiphase action zones caused by retrograde condensation, and analyzed the problem of abnormal curves in the well test process. Based on the characteristics of gas condensate, Liu et al. [11] established a mathematical model after analyzing the flow mechanism of gas condensate, calculated the theoretical curve and applied them in the actual test data of 23 wells in a gas condensate field. Fu et al. [12] established a well test analysis model for gas condensate wells with effusion in order to solve the situation where the wellbore may have effusion and cause abnormal test data, and analyzed the characteristics of the gas condensate reservoir. The researches above mainly focused on the phase behavior changes of gas condensate reservoirs such as condensate and retrograde condensation on the well test interpretation.

The research and analysis of well test theories and methods of conventional gas reservoirs provide a lot of references for well test interpretation of carbonate gas condensate reservoirs. The use of well test analysis for quantifying the characteristic of near well and reservoir is well established for the case of simple single-layer homogenous systems [13]. The behavior, however, is more complex in cases where different rock types or layering effects co-exist. Therefore, it is not easy to select an appropriate reservoir model for the Yangshuiwu buried hill carbonate gas condensate reservoir with strong heterogeneity in reservoir space types. In this paper, we first evaluate the effect of influencing factors including phase behavior and the height of liquid column in the wellbore on the measured pressure curves. Then we analyze the fracture development from the micro-resistivity image logging results. And finally we find that a dual-medium reservoir model is more appropriate to characterize the carbonate gas condensate reservoir and obtain the reservoir parameters based on the pressure build-up analysis.

2. Analysis of influencing factors on well test curves

The Yangshuiwu buried hill carbonate gas condensate reservoir has strong heterogeneity with the deep burial, high temperature and pressure. The complex phase behavior changes of condensate reservoirs under different pressure-temperature conditions will cause condensation and retrograde condensation phenomena. There will be coexistence of gas and liquid in the formation or wellbore and the gas-liquid volume percentage is also constantly changing, which makes it become a composite system of condensate oil phase and gas phase. Thus, when selecting the flow model for well test interpretation of the gas condensate reservoir, the effect of phase behavior change and the height of liquid column in the wellbore on well test curves should be taken into consideration.
2.1. Effect of gas condensate phase behavior on well test curve

During well test in gas condensate reservoirs, formation fluid phase behavior is different under different fluid components and pressure-temperature. To characterize the formation properties, the PVT phase behavior characteristics and physical-chemical properties of formation hydrocarbon systems with pressure change should reasonably be understood.

In the Yangshuivu buried hill condensate gas reservoir, the condensate oil has an average density of 0.742-0.793 g/cm\(^3\), viscosity of 1.24-1.55 mPa·s, average rubber content of 5.56%, high wax content of 13.52-15.96% with little sulfur content, and average freezing point of -6 to 6 °C. Therefore, the condensate oil has the characteristics of low density, low viscosity, low sulfur content, high wax content, and low freezing point. The natural gas is characteristic of C1 content of about 80%, C2+ content of 1.24-1.55%, CO\(_2\) content of less than 0.56-5.59%, N\(_2\) content of 0.10% to 0.79%, and the specific gravity of 0.68 to 0.73. This gas reservoir has typical characteristics of gas condensate reservoirs with low liquid hydrocarbon content. Table 1 and Table 2 show the comparison results of condensate oil and condensate gas from some typical gas condensate reservoir in China. Compared with other gas condensate reservoirs, it is obvious that the oil and gas composition of Yangshuivu buried hill gas condensate reservoir is very different from that of other areas. The gas/oil ratio is higher than that of Yaha field, but lower than that of Dina 2 gas field. The condensate oil has the highest wax content among these three areas. For condensate gas, the relative density of this area is than that of Dina 2 field and Yaha field, and the CO\(_2\) content varies greatly [14, 15].

Two gas samples and three oil samples are taken from the Ordovician Upper Majiagou Formation (5065.2-5208.8m) in the AT1X well according the sampling specifications. These samples are qualified after examination of water cut and bubble point pressure [16]. We use two kinds of experiments called constant composition expansion (CCE) and constant volume depletion (CVD) respectively, to determine the phase behavior of these samples. The intent of the latter experiment is to mimic the depletion process of a gas condensate reservoir [17].

Figure 1 shows the pressure/temperature phase behavior diagram. In this figure, it can be seen that the dew point pressure of condensate gas is 40.8 MPa. From this pressure, we conduct the CVD experiment and the curve of retrograde condensate fraction with the decrease of pressure in CVD experiment is shown in Figure 2. From Figure 2, the maximum retrograde condensation pressure during constant volume expansion experiment is 14.0 MPa, and the maximum retrograde condensate liquid volume fraction is 1.62%.

In the Yaha gas field, the maximum retrograde condensation pressure is 37 MPa and the maximum retrograde condensate liquid volume fraction is 17%. Thus, there is a “hump phenomenon” in pressure build-up curve shown as Figure 2 [14], which should be paid more attention to when conducting the well test interpretation for this gas condensate reservoir. Compared with the PVT characteristics of Yaha gas condensate reservoir, the PVT data of the Yangshuivu buried hill carbonate gas condensate reservoir show that the maximum retrograde condensate liquid volume fraction is much smaller under the depletion development progress. Therefore, the effect of retrograde
Table 1. Comparison of condensate oil properties of condensate gas reservoirs in China.

<table>
<thead>
<tr>
<th>Region</th>
<th>Density (g/cm³)</th>
<th>Viscosity at 50 °C (mPa·s)</th>
<th>Freezing point (°C)</th>
<th>Sulfur content (%)</th>
<th>Wax content (%)</th>
<th>Gas-oil ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yangshuiwu</td>
<td>0.742-0.793</td>
<td>1.24-1.55</td>
<td>8-13</td>
<td>0.01</td>
<td>13.51-25.96</td>
<td>4700</td>
</tr>
<tr>
<td>Dina 2</td>
<td>0.792-0.812</td>
<td>0.744-1.1</td>
<td>-6</td>
<td>0.022</td>
<td>5.109</td>
<td>8100-12948</td>
</tr>
<tr>
<td>Yaha</td>
<td>0.779-0.825</td>
<td>0.89-3.03</td>
<td>4.5-19</td>
<td>0.12</td>
<td>5.74-13.77</td>
<td>1400-1800</td>
</tr>
</tbody>
</table>

Table 2. Comparison of condensate gas properties in gas condensate reservoirs in China.

<table>
<thead>
<tr>
<th>Region</th>
<th>Relative density</th>
<th>C1 (%)</th>
<th>C2-n (%)</th>
<th>N₂ (%)</th>
<th>CO₂ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yangshuiwu</td>
<td>0.68-0.73</td>
<td>74.44-84.29</td>
<td>10.27-18.01</td>
<td>0.10-0.79</td>
<td>0.56-5.59</td>
</tr>
<tr>
<td>Dina 2</td>
<td>0.63-0.64</td>
<td>86.7-88.85</td>
<td>9.19-12.77</td>
<td>0.8-2.0</td>
<td>0.26-1.02</td>
</tr>
<tr>
<td>Yaha</td>
<td>0.63-0.67</td>
<td>80.34-85.53</td>
<td>9.99-14.25</td>
<td>3.91-6.59</td>
<td>0.23-0.67</td>
</tr>
</tbody>
</table>

Condensate on the well test curve is relatively small and there is no “hump phenomenon” (Figure 3) in the shut-in pressure build-up curve of well test in Yangshui buried hill.

Fig. 3. Pressure build-up curves of well AT1X in Yangshui buried hill and well YH23-2-10 in Yaha Oilfield.

2.2. Effect of bottomhole liquid column on well test curve

Generally, when there is liquid phase accumulation at the bottom of the well, the measured bottomhole pressure would shift with time and the test pressure data is not authentic because the liquid column can reduce the productivity of the formation and compensate part of the formation pressure. Figure 4 shows the schematic diagram of the effect of bottomhole liquid column on the measured pressure by the gauge. Given that the pressure gauge locates far from the bottomhole, the liquid is condensate water or condensate oil. Figure 4a shows that at the beginning of shut-in, the wellbore is filled with mixture of gas and liquid, the measured pressure by the gauge should be the difference of bottomhole pressure and the gravity of the mixture of gas and liquid. It can be depicted as:

\[ p_1 = p_{WS} - H \rho_g g \]  \hspace{1cm} (1)

After a short period, some liquid will separate from the gas-liquid mixture produced. There are two sections of fluid in the wellbore: gas in the upper section and liquid in the lower section. Given that the height of the liquid column is \( \Delta H \) (shown as Figure 4b), the measured pressure by the gauge is depicted as:

\[ p_2 = p_{WS} - H \rho_g g - \Delta H (\rho_0 - \rho_g) g \]  \hspace{1cm} (2)

Where

\[ \Delta P_N = \Delta H (\rho_0 - \rho_g) g \]  \hspace{1cm} (3)

Where \( \Delta P_N \) is called “offset pressure”, and it will increase with the increase of \( \Delta H \) value, which will make the measuring point pressure to reduce continually. When the pressure gauge is completely submersed in the liquid (shown as Figure 4c) the offset pressure \( \Delta P_N \) reaches the maximum value. Figure 4d shows that after the liquid surface submerges the pressure gauge, the \( \Delta P_N \) will not rise at all, and the change trend of the pressure at the measuring point is consistent with that of the bottomhole pressure. Therefore, to eliminate the effect of “offset pressure” caused by condensate liquid column, the pressure gauge should be located at the middle depth of formation in well test of Yangshui buried hill gas condensate reservoir. Also, before the consequent production test, it is critical to drainage the liquid accumulation at the bottom of well and to test the pressure gradient firstly to obtain the phase distribution in the wellbore.
3. Well test interpretation for Yangshuiwu buried hill

3.1. Reservoir model selection

There is no essential geologically difference between gas condensate reservoirs and other types of gas fields because gas condensate reservoirs can be found in sandstone formation, carbonate formation and strata with various boundary conditions. Thus, all kinds of current geological models and corresponding typical diagram of pressure difference and its derivative can be applied from the perspective of reservoir structure. We have studied and analyzed that there was no “hump effect” above and the well test curve was not influenced by phase behavior change. Thereby it is not so challenging to select the well test interpretation model. However, when selecting models of the appropriate wellbore, reservoir and boundary the reservoir storage space types should be fully taken into consideration.

For gas condensate reservoir in porous sandstone, there is a condensate oil area called the inner area near the wellbore, while there is still a pure gas area called the outer area far from the wellbore. These two areas show as a composite reservoir model. For example, this composite reservoir model is appropriate to the sandstone condensate gas reservoir in Yaha gas condensate of Tarim Basin. For well test interpretation of gas condensate reservoir in carbonate formation with fractures and pores, according to the scale of the fractures and caves, there are traditionally two treatment methods: first method is to use the radial composite reservoir model approximately because the small-scale fractures and caves group system can be equivalent to one-by-one ‘giant pores’; the second method is to use numerical interpretation method to calculate the flow equation because the large-scale caves can even reach the meter level or above, and the double logarithm curve can be finally obtained. Although Yangshuiwu buried hill is as the same carbonate reservoir type as many other Chinese oilfields, its reservoir space is quite different (Table 3) [15, 18]. Therefore, the two methods above cannot be used for well test interpretation for this gas condensate carbonate reservoir.

We use the micro-resistivity image logging device, a high-resolution wireline tool, to scan the rocks exposed to the wellbore. Figure 5 shows the formation micro-resistivity images of this gas condensate carbonate reservoir. The light color indicates that the reservoir is filled with high resistivity material and can be identified as the matrix, while the dark color indicates that the reservoir can be identified as fractures [19]. From image logging results, it can be observed that high-dip fractures and pores, with strong heterogeneity and less connectivity of the fractures, are dominant in this studied reservoir. This means that the fluid flows in both of two types of storage spaces: fracture and matrix pores. The storage performance and permeability of the fracture system and matrix system are significantly different, which makes the pressure propagation speeds different in these two medium. Therefore, two flow fields are introduced at one point in space during the flow. Addition, there is often a fluid cross-flow between these two fields, which is called “inter-porosity flow” [20, 21]. The flow process that has two types of flow fields of fracture and matrix can be described by the dual-medium flow model. The most obvious feature is that there is a “concave” in the pressure derivative curve, which is the diagnostic feature of the dual-medium flow model.

Fig. 5. Image logging images in 5103.0-5105.0m section for well AT1X.
### Table 3. Comparison for storage space types of gas condensate reservoirs in China.

<table>
<thead>
<tr>
<th>Name of gas reservoirs</th>
<th>Strata location</th>
<th>Property of rock</th>
<th>Storage space types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yangshuiwu</td>
<td>Ordovician</td>
<td>Carbonate rock</td>
<td>Fracture-pore</td>
</tr>
<tr>
<td>Yaha</td>
<td>Tertiary</td>
<td>Chalk</td>
<td>Pore</td>
</tr>
<tr>
<td>Dina 2</td>
<td>Tertiary</td>
<td>Clastic</td>
<td>Pore</td>
</tr>
<tr>
<td>Tazhong No.</td>
<td>Ordovician</td>
<td>Carbonate rock</td>
<td>Fracture-cave</td>
</tr>
<tr>
<td>Lungu</td>
<td>Ordovician</td>
<td>Carbonate rock</td>
<td>Fracture-cave</td>
</tr>
</tbody>
</table>

A well test program involving an open-well for 30.8 hours, followed by a shut-in (pressure build-up) for 67.2 hours, is conducted at the section of 5065.2-5108.0m in well AT1X of this studied reservoir [22]. Figure 6 shows the measured pressure curve with time during well test. According to the blowing off data, the oil production rate is 20.4 m$^3$/day and the gas production rate is 32299 m$^3$/day. Therefore, this reservoir is a condensate gas reservoir according to the gas-oil ratio and condensate oil characteristics. We use the dual-medium model to interpret the pressure build-up data using the interpretation software Ecrin. Figure 7 shows the double logarithmic curves of pseudo-pressure difference and pseudo-pressure difference derivative.

![Fig. 6. Measured pressure curve of well AT1X.](image)

From Figure 7, it can be seen that the double logarithmic curves is divided into four different phases [23]: (1) the variable-well storage and continuous flow sections reflect the characteristics of near-wellbore flow. It can be seen that fractures play a dominated role to the flow, which echoes to the image logging results in Figure 4 where there is indeed plenty of fracture in the near-wellbore zone of well AT1X; (2) the radial flow section of the fracture. At this time, the formation fluid only flows in the fractures, and the fractures play a dominant role to the flow as well. There is no flow from the matrix to fractures. (3) the transition section, where the formation fluid flows from the matrix to fractures. At this time, the derivative curve shows "concave" because of the "inter-porosity flow" effect; (4) the total radial flow section, where the fluid flowing from the fractures to wellbore equals to that from the matrix to fractures and the pressures in the matrix and the fractures decline simultaneously. Both the fracture and the matrix participate in the flow, forming a pseudo-stable state.

The characteristics of the near-well and far-well areas within the detection range echo to the logging results. This demonstrates that the well test interpretation model is appropriate to Yangshuiwu buried hill carbonate gas condensate reservoir with the characteristic of plenty of fractures and pores. Then, various formation parameters are obtained by employing this model. The permeability $K$, the skin factor $S$, the elastic energy storage ratio $\omega$, and the channeling coefficient $\lambda$ are calculated as Table 4.

![Fig. 7. Double logarithmic curve of well AT1X.](image)

### 4. Conclusions

A systematic study has been conducted to select an appropriate reservoir model to interpret well test data for a carbonate gas condensate reservoir. The following conclusions can be drawn:
(1) The phase behavior analyzes for gas and condensate oil show the maximum condensate oil volume fraction is only 1.62%, which will not influence the pressure build-up curve measured.

(2) The effect of pressure migration on well test data can be effectively eliminated when the pressure gauge goes down to the middle of the reservoir during well test. This can guide the consequent production test for this kind of gas condensate reservoir.

(3) The image logging results show that high-dip fractures and pores are dominant to the flow of fluid in Yangshuiku buried hill carbonate gas condensate reservoir, Huabei Oilfield (China). The dual-medium reservoir model is appropriate to the well test interpretation of this reservoir and the reservoir geological parameters are reasonably calculated using this model.

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References


