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The effect of gas-condensate reservoir depletion stages on gas injection and the importance of the aerosol state of fluids in this process

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ABSTRACT

As one of the primary techniques for enhanced oil recovery, the gas injection method has been investigated widely. However, introducing “dry gas” into a gas-condensate reservoir is more than miscible flooding that maintains reservoir pressure and improves oil displacement. This method is associated with complex thermodynamic processes or phase transitions, such as the re-vaporization of heavy hydrocarbon ends and connate water, the reduction of the condensate/gas ratio and retrograde dew point (RDP) pressure, etc. In this paper, a laboratory study was conducted to estimate the effectiveness of the gas injection process during gas-condensate reservoir development. Specific laboratory equipment was constructed to conduct an experimental investigation by modelling the gas injection and reservoir depletion process.

Detailed analysis of experimental investigations suggests the gas injection process might be more effective when the “reservoir” pressure is below the initial RDP pressure of the fluid. Thermodynamically, this pressure stage could be conducive for gas injection, by decreasing the condensate/gas ratio, re-vaporizing the liquid phase that dropped out and maintaining the system in a single gas phase.

To further examine the process of the liquid or fog formation phase in the gas-condensate mixture, the fluid was investigated as a colloidal structure. Theoretical findings confirm that the fog condition is a well-matched feature of gas-condensate fluids with the properties of aerosol-colloidal systems. The correlation between fog up (FU), RDP pressures and temperature was investigated experimentally. The rationale for increasing the difference between the FU and RDP pressures with the increase of temperature and other physical and thermodynamic properties of gas-condensate systems is explained according to the fundamentals of colloidal systems.

Based on these obtained results, conclusions were reached about the physical nature of the condensation under reservoir conditions. The results show that condensation in the reservoir condition can occur when the pressure in the interval creates the formation of liquid phase micro-embryos or aerosols. Thus, the fluid condenses due to surface forces between the sub-micron-sized condensate particles and the rock granules. This phenomenon can cause condensate blockage or condensate banking in the early stage of reservoir development when even the reservoir pressure is greater than the RDP pressure identified in the PVT cell. These results were used to explain the dynamic processes occurring within and influencing the operating characteristics of the gas-condensate wells. Because these colloidal features of fluid can play a significant role in reservoir development, we recommended considering these aspects when planning gas injection methods.

1. Introduction

During the exploitation of gas-condensate reservoirs, downhole and reservoir pressures decrease gradually. When the pressure drops below the retrograde dew point (RDP) pressure, retrograde

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condensation occurs, leading to the segregation of the liquid phase in the near bottom-hole and reservoir regions (Abasov et al., 2011; Gozalpour et al., 2003; Katz and Kurata, 1940; Fan et al., 2005; Raghavan and Jones, 1996). Condensate can accumulate near a downhole zone first because the bottom-hole pressure is the lowest. This process reduces the relative permeability of the formation and ultimately restricts the flow rate, thereby increasing the accumulation of condensate and weakening the forces of contact or link with the surface of the formation rock. After some point, the mass of condensate that accumulated in the reservoir begins to move into the wellbore under drawdown pressure (Li et al., 2008; Mirzadzhanzade et al., 2003), causing the downhole zone to wash up. These factors create a cyclic chain of events resulting in instability in the well operation and the loss of valuable condensate fluid in the reservoir. Furthermore, continuation of this process would result in the appearance of condensate banking in the well region. This liquid phase accumulating in the reservoir forms a ring that can be considered unmovable. This ring progressively impairs condensate deliverability and, consequently, the produced gas becomes lighter and less marketable (Abasov et al., 2005; Korotaev and Zakirov, 1981; Fan et al., 2005; Li et al., 2008; Mirzadzhanzade et al., 2003).

These negative aspects of a depletion regime impact on gas-condensate reservoirs performance. Most of the Azerbaijan gas-condensate field condensate recovery coefficients do not reach 30%. Consequently, a million tons of valuable hydrocarbon condensate in the Russian gas-condensate reservoirs remains underground, and will require special and expensive recovery methods (Abasov et al., 2011; Fan et al., 2005; Mirzadzhanzade et al., 2003).

A gas cycling method can be employed to maintain reservoir pressure above or near the RDP pressure and prevent condensate losses or condensate banking. There are two methods of gas cycling: full pressure maintenance, where gas is cycled continuously while condensate is withdrawn from the reservoir, and partial pressure maintenance, where gas is injected into the reservoir but depletion is allowed to occur (Al-Abazi et al., 2004). Both methods of gas cycling require gas cycling plants that increase initial capital costs. Some investigations (Al-Abazi et al., 2004; ShiZheng et al., 2001) have shown that full pressure maintenance yielded a higher condensate recovery than partial pressure maintenance. However, partial pressure maintenance is considered more reliable and less expensive, due to factors such as relatively inexpensive equipment, low pressure processes, natural gas savings, better safety aspects and the efficiency of using the reservoir's natural energy (Abasov et al., 2011; Mirzadzhanzade et al., 2003).

Predicting reservoir gas performance and economy requires accurate modelling of the flow behaviour and the thermodynamics of these processes including calculation of minimum miscibility pressure (Jaubert et al., 2002; Jessen and Orr, 2004; Jessen et al., 1998). Thermodynamic or mathematical modelling of the reservoir (mostly based on equations of state) is commonly used for resolving these complex issues. Moreover, experimental determination and empirical correlations can be applied to improve the reliability of modelling (Li et al., 2012; Sun et al., 2012; Gozalpour et al., 2003; Jessen and Orr, 2004; Sadus, 1992; Shen et al., 2001). Using this approach, the authors performed a laboratory study to estimate the effect and mechanisms of gas-condensate reservoir depletion stages on the effectiveness of the gas injection method.

Specific laboratory equipment was built to conduct the experimental investigations by modelling the gas injection and reservoir depletion processes. Also special experimental research was conducted to examine the aerosol state or colloidal features of the reservoir fluids in this process and during gas-condensate reservoir development. A gas mixture containing N_2, CO_2, and H_2S typically is used as an injection agent for economic and environmental safety purposes (Abasov et al., 2011; Jaubert et al., 2002). This paper intends to investigate the effectiveness of the gas injection process depending on reservoir depletion stage; therefore only a “dry” natural hydrocarbon gas mixture was used for simplification of the experimental procedure. The use of this gas allowed us to exclude all other confounding aspects related to the composition of the injection gas. This paper also identifies how improvements can be made to the condensate recovery properties of the gas injection method.

2. Investigation method and procedure

2.1. Laboratory apparatuses

The schematic diagram of the experimental laboratory apparatus and the purposes of laboratory modules are presented in the Appendix. Experiments were conducted on a УГК-3 type of PVT bomb, which is a standard apparatus for determining thermodynamic characteristics and the phase behaviour of gas condensate systems (Zotov and Aliev, 1980). The maximum working pressure is 45 MPa, maximum working temperature is 80 C and cell volume is 3×10^{-3} m^3. The PVT cell is composed of an efficient magnetic fluid mixer mounted on the piston, a dedicated visual head, two sampling valves, an accurate pressure transducer and an electric heater for homogeneous temperature control. An eyeglass permits observation of the fluid behaviour through the cell windows. During Constant Composition Expansion (CCE) or Differential Condensation (DC) tests, the changes of the gas and liquid phases are observed by the full visibility of the gas/condensate interface through the window of the cell. This unit is also linked with nitrogen bottles and vacuum pumps that are used for purging, cleaning and preparing the cell for preservation or the next operation.

This apparatus is also equipped with a separator, which is used to separate gas from the liquid phase during sampling (gas and condensate) from the cell and for modelling the depletion process of the gas-condensate reservoir and the DC test. The Pressure Control Valve on the gas outlet line and the Temperature Controller maintain a stable thermodynamic environment for effective separation. The liquid level in the separator is monitored through the separator window-level gauge. The liquid outlet of the separate is connected to the sampling device, which allows for degassing and further analysis of the thermodynamic properties of the liquid phase. The separator gas outlet is equipped with a gas flow totalizer and is also linked with gas chromatography for composition analysis of the gas phase. ЛХМ-8 gas chromatography is used for all gas analyses.

In addition, the original design has been modified slightly within safe operating limits. To perform or to model gas injection processes, a high pressure (45 MPa) positive displacement compressor was mounted to the PVT cell. An extra heat exchanger was also installed to increase working temperature of the bomb up to 110 °C (see Appendix for more details).

Recent calibrated gauges and devises were used during experiments ensuring their accuracies are in the designed limit. Class 1.0 with ±1% error pressure gauges and temperature gauges with ±0.4 °C were used.

2.2. Gas-condensate sampling

Fluid sampling is a fundamental part of the chemical, thermodynamic and physical analysis of reservoir fluids. The specific requirements for samples and laboratory studies depends on the state of knowledge about a prospect; these types of data are