Simulation of the filtration process of hydrocarbon binary fluid with retrograde properties

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Abstract. This paper presents the results of the experimental studies of filtration modes of gas-condensate fluid using a binary mixture of methane–n-butane. It is shown that there is a possibility to obtain both the normal two-phase filtration mode and the self-oscillatory mode depending on the filtration conditions and the composition of the model mixture.

1. Introduction
Gas condensate deposits are of particular interest among various types of hydrocarbon deposits. One has to deal with products that constantly change its composition in the process of developing such fields. Such behavior of reservoir fluid can be explained by the phenomenon of retrograde condensation of a hydrocarbon mixture that occurs when reservoir pressure decreases. As soon as the pressure in the reservoir drops below the dewpoint pressure, the high-molecular-weight hydrocarbon components of the mixture begin to pass into the liquid phase, which remains stationary throughout the field development due to the low phase saturation. A further decrease in pressure leads to an increase in the proportion of the liquid phase until the pressure reaches the maximum condensation pressure. In this case, there is a decrease in well production up to the cessation and its preservation, as it was, for example, at the Vuktyl gas-condensate field [1].

The goal of this work was a physical simulation of the process of filtering a model hydrocarbon mixture through a porous medium in a one-dimensional approximation, while this mixture qualitatively repeated the properties of real gas-condensate mixtures. The previously developed mathematical model predicted the possibility of various filtering modes for these mixtures, including the self-oscillatory mode, which cannot be obtained using fluids that do not contain the retrograde region on the phase diagram [2].

2. Experimental setup
Experimental studies of a one-dimensional two-phase isothermal filtration process of a model gas-condensate mixture took place at an experimental stand, the schematic of which is shown in figure 1. The model mixture consisted of two components: methane and n-butane. This mixture was chosen for several reasons: the availability of components, ease of mixing, low supercritical parameters, the presence of retrograde properties in a certain range of pressures and compositions. Molar fractions of methane and n-butane were 0.8 and 0.2 respectively. The model mixture was formed directly in the high-pressure cylinders. The composition of the model mixture was monitored using an Agilent 490 MicroGC gas chromatograph after complete mixing.
Figure 1. The experimental setup lay-out: ES—experimental section; H$_2$O—water tank; CH$_4$—methane tank; C$_4$H$_{10}$—cylinder with n-butane; N$_2$—nitrogen tank; WP—water pump; V—valves; PR—pressure regulator; BPR—back pressure regulator; FM—flowrate meter; M—manometer; F$_2$—2 µm filter; F$_{50}$—50 µm filter; F$_{200}$—200 µm filter; P$_1$–P$_8$—pressure transducers installed on the experimental section; P$_1'$–P$_6'$—pressure transducers; T$_1$–T$_5$, T$_7$, T$_8$—thermocouples installed in the stream; T$_6'$—thermocouple installed on the pipe surface.

The experimental section consists of 9 pipes with an inner diameter of 6 mm and a wall thickness of 1 mm, made of AISI 321 stainless steel. The schematic of the experimental section is shown in figure 2. The lengths of the first and last sections are 100 mm, the lengths of the remaining 7 sections are 400 mm. Tees with connected LEFOO T1030 pressure transducers are installed between the pipes. Thus, the experimental section is 3000 mm long and was filled with quartz sand with a fractional composition of 51–70 µm using a vibrating screen and a special sealing sleeve to increase the backfill density. The permeability coefficient of the obtained porous backfill was $10^{-13}$ m$^2$. It was calculated using the Darcy law [3] on the basis of data obtained after conducting preliminary experiments on pure nitrogen, during which pressure distribution along the length of the experimental section, temperature and mass flow rate of gas were measured.
Meshes made of AISI 321 stainless steel with a mesh size of 50 µm are welded on the ends of experimental section to prevent the outside backfill removal. A Bronkhorst mini CORI-FLOW Coriolis flow meter is installed after the back pressure regulator.

The experimental section was filled with pure methane to a pressure of 140–150 bar before the start of experimental studies. The pressure of the model mixture in the high-pressure cylinder was increased up to 160 bar, then the mixture was supplied to the experimental section. A pressure drop was set at the experimental section to obtain various filtration modes after the methane was displaced by the model mixture using forward and back pressure regulators. The temperature was kept constant during the experiments and its value was 292 K, which was monitored with thermocouples $T_1–T_4$.

Figure 3 shows the phase diagram of the binary mixture methane–n-butane at a temperature of 292 K with the emphasized retrograde region. It was calculated on the basis of the van der Waals type equation of state, developed specifically for natural hydrocarbon systems [4]. There is an occurrence of reverse processes in this region under the condition of a constant mixture composition: condensation with a pressure decrease and evaporation with its increase. The presence of retrograde properties of the model mixture, as well as the difference in the relative phase permeabilities of the gas and liquid phases, create conditions for the occurrence of non-stationary oscillatory filtration modes with a constant pressure drop maintained in the experimental section.

3. Results
Figures 4 and 5 show the results of physical simulation of the process of isothermal two-phase filtration of a model mixture. The horizontal axis shows the experiment time in seconds, the
Figure 4. Dependencies of pressure and flowrate measurements for the filtration of the model mixture: $P_c$—pressure in the high-pressure cylinder; $P_1$–$P_8$—pressure in the experimental section; $G$—flowrate.

Figure 5. Dependencies of pressure and flowrate measurements for the filtration of the model mixture: $P_c$—pressure in the high-pressure cylinder; $P_1$–$P_8$—pressure in the experimental section; $G$—flowrate.

left vertical axis shows pressure in bar, the right vertical axis shows the flow rate at the outlet of the experimental section in mg/s. The brown line shows the pressure in the high-pressure cylinder, the black line shows the mass flow rate at the outlet of the experimental section, the other lines indicate the readings of 8 pressure transducers installed in the experimental section.

Figure 4 shows the results of the model mixture filtration with the inlet pressure $P'_3 = 128$ bar and with outlet pressure $P'_4 = 105$ bar, which were maintained by PR and BPR respectively (see figure 1), thus the pressure drop on the experimental section equals $\Delta P_1 = 23$ bar. Both pressure and flow oscillations are observed without any external energy supply to the system. The cause of these self-oscillations may be the retrograde properties of the model mixture, as
well as the difference between filtration velocities of liquid and gas phases which leads to periodic accumulation of the liquid phase in the porous medium of experimental section.

Figure 5 shows the results of the model mixture filtration with the inlet pressure $P_3' = 135 \text{ bar}$ and with outlet pressure $P_4' = 85 \text{ bar}$, which were maintained by PR and BPR respectively, thus the pressure drop on the experimental section equals $\Delta P_2 = 50 \text{ bar}$. Small flow rate fluctuations are traced, while the pattern of pressure distribution is almost constant. This may be due to the fact that the mixture flow rate is too large for the accumulation of retrograde condensate in the porous medium of the experimental section, therefore, the additional liquid phase formed due to the retrograde properties of the model mixture is removed from the section by the gas stream.

4. Conclusion
Experimental studies on the physical simulation of a one-dimensional two-phase isothermal filtration process of model gas-condensate mixture were carried out. Various filtration modes for model mixture were obtained and the conditions for the occurrence of a self-oscillatory regime were revealed.

References
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