Computational analysis to evaluate one-dimensional rectilinear steady filtration flow of incompressible fluid through homogeneous reservoirs as exemplified by the Yarega field

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Abstract. The paper is concerned with a computational analysis of one-dimensional rectilinear steady filtration flows of incompressible fluids through homogeneous strata as exemplified by the Yarega field. It provides dependence diagrams of key parameters required to characterize the field. Based on the resultant data, it highlights the importance of further studies to evaluate filtration incompressible flows with an aim of enhancing productive oil recovery.

1. Introduction
Oil and gas productive formations have a heterogeneous structure in terms of filtration parameters. A rectilinear-parallel one-dimensional fluid flow is the one in which the value of basic hydromechanical parameters (velocity, head) is assigned one coordinate alone, the origin of which is observed along the flow path. Studying filtration features in a layered inhomogeneous stratum, consisting of two interlayers of different permeability, and a zonally heterogeneous stratum, consisting of two isolated zones with different permeability, is driven by the characteristics of a rectilinear-parallel incompressible flow in heterogeneous strata.

A rectilinear steady filtration flow is characterized by a constant velocity at any point of the reservoir cross section and the laws of motion in each path are equal, which is quite convenient for computational analysis of one-dimensional rectilinear steady filtration flow both in laboratory settings (when a gas-liquid mixture moves through a cylindrical core), and in some sections of a productive stratum with a constant inflow of fluid.

2. Materials and methods
Let us consider filtration features in layered and zonally heterogeneous strip-like formations. When filtering one-dimensional rectilinear-parallel incompressible fluid according to Darcy’s law in a layered heterogeneous reservoir, consisting of 2 interlayers with different permeability $k_1$ and $k_2$ (Fig. 1, a), the pressure in each of the porosity zones is distributed according to a linear law [4-6]. It is necessary to regulate a frontal zone to maintain the same velocity in the interlayers.
Fig. 1. Rectilinear flow in layered heterogeneous (a) and zonally heterogeneous (b) strata

In case of stationary one-dimensional rectilinear-parallel filtration of incompressible fluid according to Darcy’s law in a zonally heterogeneous reservoir, consisting of 2 zones with different permeability. (Fig. 1, b), the pressure distribution in each of the interlayers is linear.

Analyzing the filtration features in layered and zonally heterogeneous strip-like formations, the following can be noticed: a) at constant \( x \)-coordinate value, the pressures in each interlayer are equal and their distribution is linear in the flow path; b) the value of pressure gradient in different layers is the same; c) the filtration rate in an \( i \)-th interlayer is individual and proportional to permeability in the interlayer \( k \); d) the flow rate is the sum of flow rates through each interlayer [7-9].

In a zonally heterogeneous formation, the following features were identified: a) unlike a layered heterogeneous formation, the pressure distribution in each area (zone) obeys a linear law; b) the pressure gradient within each zone is constant, but different in other zones; c) based on the continuity of flow, the flow rate of incompressible fluid is constant in each cross section of the flow; d) filtration rate is constant in any cross section of the flow.

The analysis of these ratios is similar to that performed earlier. They differ in parameter variability along the specified coordinate. Thus, in the case of a layered heterogeneous reservoir for absolutely all interlayers, the logarithmic pressure distribution curve will be common. In the case of a zonally heterogeneous reservoir, the logarithmic curve of pressure distribution will be common for all layers. In the case of zonally heterogeneous formation, each \( i \)-th zone pressure distribution also obeys the logarithmic law [10-12].

3. Computational analysis
To identify the patterns and features of a one-dimensional rectilinear filtration flow of an incompressible fluid in layered heterogeneous and zonally heterogeneous formations, the authors carry out a computational analysis to define the basic filtration parameters of an incompressible fluid for the Yarega field.

Inputs: \( P_c = 9 \) MPa, \( P_g = 6.5 \) MPa, \( L_s = 7.5 \) km, \( B = 200 \) m, \( \mu = 3.5 \) mPa s, \( k_1 = 0.5 \) \( \mu \)m2, \( k_2 = 0.6 \) \( \mu \)m2, \( h_1 = 3 \) m, \( h_2 = 4 \) m, \( l_1 = 4 \) km, \( l_2 = 3.5 \) km.

3.1. Layered heterogeneous stratum
1. With stationary one-dimensional rectilinear-parallel filtration of an incompressible fluid according to Darcy’s law in a layered heterogeneous stratum consisting of 2 interlayers with different permeability \( k_1 \) and \( k_2 \) (Fig. 1, a), the pressure distribution in each of the interlayers is linear and determined by the expression:

\[
P(x) = P_c - \frac{P_c - P_g}{L_s} \cdot x = 9 \cdot 10^6 - \frac{9 \cdot 10^6 - 6.5 \cdot 10^6}{7500} \cdot x = 10^6 \cdot (9 - 0.000333x);
\]

where \( P_c \) is the contour pressure, Pa; \( P_g \) is the gallery pressure, Pa; \( L_s \) is the stratum length, m.
Fig. 2. Pressure distribution function

2. Pressure gradients in each interlayer are constant and equal to each other:
\[ \text{grad } P = -\frac{P_c - P_m}{L_x} = -\frac{9 \times 10^6 - 6.5 \times 10^6}{7500} = -333. \]

Fig. 3. Pressure gradient distribution graph

3. Filtration rates by interlayers:
\[ V_1 = -\frac{K_1}{\mu} \text{grad} P_1 = \frac{K_1}{\mu} \cdot \frac{P_c - P_m}{L_x} = \frac{0.5 \times 10^{-12}}{3.5 \times 10^{-3}} \cdot 333 = 47.571 \cdot 10^{-9} \text{ m/s}. \]
\[ V_2 = -\frac{K_2}{\mu} \text{grad} P_2 = \frac{K_2}{\mu} \cdot \frac{P_c - P_m}{L_x} = \frac{0.6 \times 10^{-12}}{3.5 \times 10^{-3}} \cdot 333 = 57.086 \cdot 10^{-9} \text{ m/s}. \]

4. The total volumetric flow rate of a strip-like reservoir \( Q \):
\[ Q = Q_1 + Q_2 = \frac{B(P_c - P_m)}{\mu L_x}(k_1 h_1 + k_2 h_2) = 0.0741 \cdot 10^{-3} \frac{m^3}{s}. \]
Fig. 4. Filtration velocity distribution

5. Mean permeability of a strip-like reservoir $K_{\text{mean}}$

$$K_{\text{mean}} = \frac{K_1 h_1 + K_2 h_2}{h_1 + h_2} = \frac{3.9 \times 10^{-12}}{7} = 0.557142 \times 10^{-12} \text{ m.}$$

3.2. Zonally heterogeneous stratum

1. In case of stationary one-dimensional rectilinear-parallel filtration of incompressible fluid according to Darcy’s law in zonally heterogeneous stratum, consisting of 2 homogeneous zones with different permeability $K_1$ and $K_2$. The pressure distribution in each of the porosity zones is linear, but determined by the following expressions:

$$p' = \frac{K_1 L_2 p_c + K_2 L_1 p_g}{K_1 L_2 + K_2 L_1} = 7.55 \times 10^6 \text{ Pa};$$

$$P_1(x) = p_c - \frac{p'_c - p'}{l_1} \cdot x, \quad 0 \leq x \leq l_1;$$

$$P_2(x) = p_c - \frac{p'_c - p_g}{l_2} \cdot x, \quad 0 \leq x \leq l_2;$$

$$P_1(x) = 9 \cdot 10^6 - \frac{9 \cdot 10^6 - 7.55 \cdot 10^6}{4000} \cdot x = (9 - 0.0003625x) \cdot 10^6;$$

$$P_2(x) = 9 \cdot 10^6 - \frac{7.55 \cdot 10^6 - 6.5 \cdot 10^6}{3500} \cdot x = (9 - 0.0003x) \cdot 10^6.$$
2. The pressure gradients in each zone are constant, but not equal to each other, since:

\[ \text{grad} P_1 = -\frac{p_c - p'}{l_1} = -362.5; \]

\[ \text{grad} P_2 = -\frac{p' - p}{l_2} = -300. \]

![Fig. 6. Distribution of pressure gradients](image)

3. Filtration rates by porosity zones:

\[ V_1 = -\frac{K_1}{\mu} \text{grad} P_1 = \frac{K_1}{\mu} \frac{p_c - p'}{l_1} = \frac{0.5 \cdot 10^{-12}}{3.5 \cdot 10^{-3}} \cdot 362.5 = 51.786 \cdot 10^{-9} \frac{m}{s}; \]

\[ V_2 = -\frac{K_2}{\mu} \text{grad} P_2 = \frac{K_2}{\mu} \frac{p' - p}{l_2} = \frac{0.6 \cdot 10^{-12}}{3.5 \cdot 10^{-3}} \cdot 300 = 51.429 \cdot 10^{-9} \frac{m}{s}. \]

4. Definitions of \( K_{\text{mean}} \):

\[ K_{\text{mean}} = \frac{L}{\frac{l_1}{K_1} + \frac{l_2}{K_2}} = \frac{7500}{13833.3 \cdot 10^{12}} = 0.5421 \cdot 10^{-12} \text{ m}. \]

![Fig. 7. Filtration rate distribution](image)

5. Total volumetric flow rate:

\[ Q = \frac{K_{\text{mean}}}{\mu} \cdot \frac{p_c - p'}{l_1} Bh = 0.0786 \cdot 10^{-3} \frac{m^3}{s}. \]
4. Conclusion

Based on the outputs, the authors obtained the basic parameters for the Yarega field, characterizing a one-dimensional rectilinear-parallel filtration flow of an incompressible fluid. The paths of all liquid particles are parallel straight lines, therefore the filtration rates at all points of any cross-section of the flow are equal to each other. The layered heterogeneous and zonally heterogeneous strata are considered, their structural differences are determined and the pressure variability patterns are found. The obtained dependencies are necessary for further research of the Yarega field in order to enhance productive oil recovery.

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