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ABSTRACT

of the dissertation for the degree of Doctor of Sciences

METHODS FOR WELL TESTING INTERPRETATION AND FORECASTING OF DEVELOPMENT INDICATORS OF COMPLEX-DEFORMABLE GAS CONDENSATE AND LIGHT OIL RESERVOIRS

Specialty: 2525.01– “Oil and gas field development and operation”
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MAIN CHARACTERISTIC OF THE WORK

The urgency of the problem. The development of gas condensate deposits and volatile oil deposits, represented by deep-seated reservoirs, is accompanied by complex thermodynamic transformations. In addition, as a result of the deformation of reservoir rocks, changes in the filtration-capacity characteristics of the porous medium also affect filtration processes. When developing gas condensate deposits and volatile oil deposits, solving development problems, choosing the correct development strategy without taking into account the thermodynamic properties of hydrocarbon systems and the rheology of the porous medium is impossible. For this reason, the deepening of our knowledge about the peculiarities of the influence of the rheological properties of reservoir rocks on reservoir processes and, therefore, the improvement of the development theory can be considered as one of the main directions of the development of the scientific foundations of development.

At the moment, the development theory is quite highly developed. Fundamental principles of mathematical modeling of filtration of hydrocarbon systems with complex thermodynamic properties in natural reservoirs have been created; Hydrodynamic methods have been created to predict the main indicators of the development of gas condensate deposits and volatile oil deposits; Important research work has been carried out to determine the main regularities of reservoir processes during the development of gas condensate deposits and partially deposits of volatile oils.

Despite this, a sharp manifestation of the rheological properties of reservoirs in new hydrocarbon fields involved in exploitation requires further improvement of the development theory in terms of taking into account complex rock deformations. It also requires the creation of new, more efficient methods for interpreting the results of studies of the well-reservoir system and field data.

Thus, relaxation-elastic and sometimes relaxation-creeping deformations of the rock skeleton accompanying the development of gas condensate deposits and volatile oil deposits in deep-lying reservoirs require a deep study of the effect of deformation on the development process; issues such as the creation of a hydrodynamic model of filtration taking into account relaxation, algorithms for predicting the main indicators of development and methods for interpreting field data in order to solve various problems are becoming relevant. In addition, the discovery of gas condensate and light oil fields with deeper reservoirs with higher initial reservoir pressures requires a study of the influence of inertial forces on the development process.

There are numerous research works in this direction, but they mainly cover oil and gas fields. There is a need for a comprehensive study of the study of the characteristic features of the influence of relaxation changes in the reservoir-capacitive properties of gas condensate and oil reservoirs on the filtration process. Also, such tasks as mathematical modeling of the filtration of gas-condensate mixtures and volatile oils in reservoirs of the indicated type, the creation of algorithms for predicting the main indicators of development, new methods for interpreting the results of hydrodynamic studies of a well and field data on development.

The above mentioned confirm the relevance of the topic of the dissertation work.

The purpose of the work and objectives of the study. The purpose of the work is to create algorithms for predicting the main parameters of the development of gas condensate deposits and volatile oil deposits in nonlinear elastic, relaxation elastic and creeping reservoirs under various geo-technological regimes, taking into account inertial forces; development of effective methods for interpreting the results of well testing and production data; creation of computer simulation models of the well-reservoir system.

The main tasks of research:

1. Creation of hydrodynamic models of filtration of a gas condensate system and volatile oils in nonlinear elastic, relaxation elastic and relaxation creeping porous media and study of the problem of inflow to the well under linear and nonlinear laws of filtration.

2. Creation of algorithms for predicting the main indicators of

the development of gas condensate deposits and volatile oil deposits in nonlinear elastic, relaxation elastic and relaxation creeping reservoirs for depletion and studying the features of the depletion process in the conditions under consideration.

3. Creation of algorithms for calculating the main indicators of the processes of displacement of gas-condensate mixtures and volatile oils to the well in nonlinear elastic, relaxation elastic and relaxation creeping formations and study of the process features in the conditions under consideration.

4. Solution of the problem of filtration of gas-condensate mixtures and volatile oils to the well, taking into account the difference in permeability and deformation characteristics of the bottomhole zone and the remote part of the drainage area; study of the peculiarities of the influence of the rheological heterogeneity of the formation and the skin effect on the filtration process.

5. Creation of computer simulation models of the well-reservoir system during well operation with gas lift and deep pumps of volatile and carbonated oil deposits, represented by difficultly deformable reservoirs.

6. Development of special criteria for assessing the degree of energy activity of the reservoir system and a method for unambiguous determination of the reservoir regime.

7. Creation of more efficient methods for the interpretation of field data in order to solve various problems of the development of gas condensate deposits and volatile oil deposits, represented by difficultly deformable reservoirs, including methods for determining:

- rheological characteristics of reservoirs;
- reservoir characteristics of reservoirs;
- initial balance reserves of hydrocarbons of the deposit;
- reservoir regimes;
- the supply circuit of the well and stagnant zones.

Research methods. The problems are solved using the methods of the theory of hydro-gas dynamics, mathematical physics and computational mathematics. The developed methods and algorithms are realized in computer programs, tested on model and practical examples.

Scientific novelty:

1. A binary model of filtration of gas-condensate mixtures and volatile oils has been modified, on the basis of which algorithms have been developed for calculating the inflow to a well in nonlinear elastic, relaxation elastic and creeping reservoirs with a nonlinear filtration law.

2. Algorithms have been developed to predict the main indicators of development for the depletion of gas condensate deposits and volatile oil deposits in nonlinear elastic, relaxation elastic and creeping reservoirs.

3. Algorithms for predicting the indicators of the process of displacement of gas-condensate mixtures and volatile oils by water to the well in nonlinear elastic, relaxation elastic and creeping reservoirs are proposed.

4. Algorithms have been developed for calculating the flow of gas-condensate mixture and volatile oils to the well, taking into account the difference in permeability and deformation characteristics of the rocks of the bottomhole zone (or near the well) and the remote part of the drainage zone.

5. Computer simulation models of the well-reservoir system have been created for the operation of the well with gas lift and deep pumps in the development of deposits of volatile and carbonated oils, represented by difficultly deformable reservoirs.

6. For the first time, special parameters have been found that characterize the energy of the reservoir of gas condensate and oil deposits. These indicators have been named as “Reservoir Energy Activity Criteria” (CAPE) or simply “Activity Criteria”.

7. Based on the activity criteria, a method has been developed for unambiguous determination of the reservoir regime of gas condensate and oil deposits based on field data at any stage of development. The method has been patented.

8. More effective methods for the interpretation of field data have been created in order to solve various problems of developing gas condensate deposits and volatile oil deposits, represented by difficultly deformable reservoirs, including:

- methods for determining the rheological characteristics of reservoirs;

- method for determining the effective permeability of the formation;
- method for determining the coefficient of porosity;
- methodology for determining the initial balance reserves of hydrocarbons at the initial stage of development;
- methodology for calculating the numerical values of KAPE to determine the reservoir regimes;
- methodology for determining the supply contour of wells and stagnant zones.

Points to be defended:

1. A binary model of filtration of gas-condensate mixtures and volatile oils has been modified, on the basis of which algorithms have been developed for calculating the inflow to a well in nonlinear elastic, relaxation elastic and creeping reservoirs with a nonlinear filtration law.
2. Algorithms have been developed to predict the main indicators of development for the depletion of gas condensate deposits and volatile oil deposits in nonlinear elastic, relaxation elastic and creeping reservoirs.
3. Algorithms for predicting the indicators of the process of displacement of gas-condensate mixtures and volatile oils by water to the well in nonlinear elastic, relaxation elastic and creeping reservoirs are proposed.
4. Algorithms have been developed for calculating the flow of gas-condensate mixture and volatile oils to the well, taking into account the difference in permeability and deformation characteristics of the rocks of the bottomhole zone (or near the well) and the remote part of the drainage zone.
5. Computer simulation models of the well-reservoir system have been created for the operation of the well with gas lift and deep pumps in the development of deposits of volatile and carbonated oils, represented by difficultly deformable reservoirs.
6. For the first time, special parameters have been found that characterize the performance of the reservoir of gas condensate and oil deposits. These indicators have been named as “Reservoir

Performance Index” (RPI) or simply “Performance Index”.

7. Based on the activity criteria, a method has been developed for the unambiguous determination of the reservoir regime of gas condensate and oil deposits based on field data at any stage of development. The method has been patented.

8. More effective methods for the interpretation of field data have been created in order to solve various problems of developing gas condensate deposits and volatile oil deposits, represented by difficultly deformable reservoirs, including:

- methods for determining the rheological characteristics of reservoirs;
- method for determining the effective permeability of the formation;
- method for determining the coefficient of porosity;
- methodology for determining the initial balance reserves of hydrocarbons at the initial stage of development;
- methodology for calculating the numerical values of KAPE to determine the reservoir regimes;
- methodology for determining the supply contour of wells and stagnant zones.

Theoretical and practical significance of the research. The proposed computational algorithms make it possible to predict the main indicators of the development of gas condensate deposits and volatile oil deposits, represented by nonlinear elastic, relaxation elastic and creeping reservoirs. The general patterns established in the work can be used to analyze the development of deposits represented by reservoirs of this type.

For the first time, found "activity criteria" characterizing reservoir energy allow us to assess the degree of activity of the water basin of gas condensate and oil deposits. The new RPI-based approach provides an unambiguous determination of the reservoir regime based on production data at any stage of development.

Other methods of production data interpretation developed in this work allow to determine:

- numerical values of RPI;
- the rheological characteristics of the formation;

- effective formation permeability;
- coefficient of porosity of the formation;
- initial balance reserves of hydrocarbons at the initial stage of development;
- radius of the well feed loop and stagnant zones.

Application of researches.

The developed algorithms and created methods are tested on hypothetical models and in real examples. Some results are implemented in the computer program “X-Oil ver.1.0.0” registered with the Copyright Agency of the Republic of Azerbaijan (Certificate No. 01 / C-5817-11).

The created computer simulator of the well-reservoir system is used by SOCAR during the operation of the well with deep pumps.

The simulator of sucker rod pumps operation in the well-reservoir system, developed on the basis of the results obtained in the dissertation, is used in the educational process in the gas-oil-field faculty of the Azerbaijan State University of Oil and Industry. Some of the solutions proposed in the dissertation work were applied in PA "Azneft", the acts of which are attached to the dissertation.

Approbation of work and publication. The main results of the dissertation work were reported on:

- II International Conference on Control and Optimization with Industrial Applications (COIA-2008), Baku, June 2-4, 2008;
- III Congress of the World Mathematical Society of Turkic-speaking countries, Almaty, June 30-July 4, 2009;
- IV Congress of the World Mathematical Society of Turkic-speaking countries, Baku, July 1-3, 2011;
- III International Conference on Control and Optimization with Industrial Applications (COIA 2011), Bilkent University, Ankara, August 22-24, 2011;
- X international Chetaev’s conference "Analytical mechanics, stability and control", Kazan, June 12-16, 2012;
- International Scientific and Technical Conference “Computer Modeling in Science-Intensive Technologies. KMNT-2012", Kharkov, April 24-27, 2012;
- II International Scientific and Practical Conference "New

Technologies in Oil Production", Baku, NIPI "Neftegaz", September 06-07, 2012;

- I International Scientific and Innovative Conference of the Nobel Brothers, Baku, October 22-23, 2012;
- IV International Conference On Control and Optimization with Industrial Applications, Barovets, Bulgaria, July 10-12, 2013;
- XXI Gubkin Readings "Fundamental basis and innovative technologies for prospecting, exploration and development of oil and gas fields." Gubkin Russian State University of Oil and Gas, Moscow, March 24-25, 2016.

Based on the materials of the thesis, 63 scientific works were published, of which 49 articles, 1 monograph, 2 patents for invention, 1 copyright certificate, 10 reports and abstracts of conferences. Some research works were carried out within the framework of the thematic plan of scientific research works of SOCAR. The dissertation summarizes the experience the author, aimed at the development of theoretical and scientific and applied works in the field of increasing the efficiency of the development of gas condensate and oil fields.

The author's personal contribution.

The formulation and solution of all problems in the dissertation work belongs to the author. Computer implementation of the results obtained, computer simulation of the processes was made by the author independently. Carrying out computer research based on the created simulator, analysis of the results and their interpretation also belong to the author. In the dissertation, the gas lift process was considered together with scientific consultant F.A.Aliyev and co-authors M.Kh.Ilyasov and N.B.Agaev. Computer calculations related to this task were carried out by employees of the Institute of Applied Mathematics of Baku State University. The idea of taking into account the difference in rheology near the well belongs to the scientific consultant A.M.Guliyev. Methods for interpretation of well test data developed in the dissertation, their computer applications and numerical studies also belong to the author.

The volume and structure of the work. The dissertation work consists of an introduction, 6 chapters, main conclusions with a total volume of 300 pages of typewritten text, 14 tables, 139 figures and a list of used literature, including 220 titles and applications.

The author honors the memory of Corresponding Member of ANAS, Doctor of Technical Sciences, Professor A.M.Guliyev for valuable recommendations and attention during the work on the dissertation.

The author expresses deep gratitude to Academician F.A. Aliev for his attention and support during the work on the dissertation.

MAIN CONTENT OF THE WORK

The introduction. In the introduction, the main provisions of the dissertation are given, the relevance of the research on the topic of the dissertation is substantiated, the scientific novelty of the work, the defended provisions, posed problems and methods for their solution are shown.

The first chapter. The first chapter presents the results of the analysis of existing research work in the field of gas hydrodynamics of the development of gas condensate deposits and volatile oil deposits in nonlinear elastic, relaxation elastic and creeping reservoirs, studying the influence of rheological features of rocks on filtration processes and interpreting the results of hydrodynamic studies of wells and field data. new oil and gas condensate fields with increasing depth requires the development of new methods for interpreting field data and results of hydrodynamic studies of wells taking into account deformations of reservoir rocks.

Experimental studies of N.S. Gudok (1958), V.M.Dobrynin (1963), V.N.Schelkachev (1965), A.T.Gorbunov (1967), I.A. Burlakov and N.P.Fursova (1963), N.N.Pavlova (1975), N.V. Shestakova et al. (1977) found that even a small increase in effective pressure (the difference between rock and pore pressures) can lead to significant deformation of reservoir rocks and, consequently, changes in porosity and reservoir permeability. The results of studies carried out by TK Ramazanov (2005) on the examples of the Bulla-Deniz and Bahar fields demonstrate exactly this.

Assuming that the compressibility of the medium occurs according to a linearly elastic law, the equations of filtration of an elastic fluid in a porous medium were given by V.N.Shelkachev (1959). At the same time, it was assumed that due to deformation, only the porosity of the medium changes.

Important studies on the problems of developing oil and gas fields in conditions of nonlinear elastic deformability of rocks were also carried out by M.T.Abasov, G.I.Dzhalalov, K.N.Dzhalilov, E.Kh.Azimov, A.M.Guliyev (1993).

G.I.Barenblatt, A.P.Krylov (1955), V.N.Nikolaevsky (1964), G.V.Isakov (1964) drew attention to the fact that with a drop in reservoir pressure, deformation of oil-bearing reservoirs sometimes becomes irreversible. Filtration of formation fluids under such conditions was called the elastic-plastic regime.

The works of G.A.Shcherbakov (1977), A.T.Gorbunov (1976), Yu.P.Korotaev, L.G.Gerov, S.N.Zakirov, G.A.Shcherbakov (1979), A.Settari (2002), A.A.Imanov, T.Kh.Suleimanov, F.A. Nurmamedov (2005), R.S.Gurbanova, A.F.Kasimov, A.Kh. Mirzadzhanzade (1967), V.G.Yasov (1980) were devoted to the study of oil and gas filtration processes in elastic plastic mode.

The process of gas filtration in deformable rocks has been extensively studied. Such works include the research of M.T.Abasov, E.Kh.Azimov, A.M.Guliev (1976), A.Ban, K.S.Basniev, V.N. Nikolaevsky (1961), K.S.Basniev (1964), N.V.Shestakov, D.N. Kuzmichev, M.S.Batov, N.A.Golovchenko (1977), A.K.Galimov (1982), A.V.Dinkov, I.N.Fedyukhin (1981), S.N.Zakirov, O.P. Shmygli (1971), L.G.Nakaznoy (1972), K.N.Dzhalilov, G.I.Dzhalalov, A.M.Mamedov and others. (1982), N.S. Ratushnyak, V.A.Tsarev (1979), G.A.Shcherbakov (1977). In the works of Yu.P.Korotaev, L.G.Gerov, S.N.Zakirov, G.A. Shcherbakov (1979), also in S.N.Zakirov, E.F.Morozov (1972) for the first time it was shown that it was not applicable earlier. proposed methods for calculating gas reserves in fields represented by deformable reservoirs.

The basic concepts of filtration of gas-condensate mixtures in non-deformed media were developed by V.N.Nikolaevsky (1963), M.T.Abasov, F.G.Hasanov, F.G.Orudzhaliev (1966). The problems of numerical modeling of the filtration process of gas condensate systems in incompressible reservoirs have been widely studied in the works of M.T.Abasov, G.I.Dzhalalov, T.M.Ibragimov, A.M. Mamedov, Kh.A.Feyzullaev (2002). M.T.Abasov, M.A.Dzhamalbekov, F.G.Orudzhaliev (1985) proposed design schemes for predicting the development indicators of gas condensate deposits in purely fractured reservoirs. In the noted work, it was assumed that the porosity and permeability of rocks is only a function of reservoir pressure. Therefore, changes in the reservoir characteristics of the reservoir with a drop in intrathreshold pressure occurs instantly. However, a number of studies, including in the works of Yu.M.Molokovich (1980), M.T.Abasov, M.A.Dunyamalyev, A.M.Guliyev (1995), M.T.Abasov, K.N.Dzhalilov Z.A.Kerimov, D.R.Mirzoev (2000), A.M. Guliyev, B.Z. Kazymov (2009), A.M.Svalov (2012) found that the reaction of the skeleton of rocks to a drop in pressure does not occur instantly, but in a certain period of time. Experimental studies by P.T.Shmygli, V.A.Chernykh, G.S.Kupin (1984) confirmed that the change in the reservoir characteristics of the reservoir is complex.

Against the background of an increase in recent times in the number of volatile oil deposits open for development, therefore, an increase in the share of volatile oils in total production, taking into account the thermodynamic properties of volatile oils in modeling filtration processes has become relevant. The works of M.T. Abasov, Kh.I. Dadashzade, M.A. Dzhamalbekov (1990), N. Sanchez, SAMaraven (1992), AHEl-Banbi, (2001), MOSanni, ACGringarten (2008) also devoted to the development of volatile oil deposits.

There are a number of works devoted to the study of oil and gas filtration in relaxation elastic and relaxation creeping reservoirs. Of these, one can show the works of Yu.M.Molokovich, P.P.Osipov (1987), M.T.Abasov, K.N.Dzhalilov. Z.A.Kerimov, D.R.Mirzoeva (2000), M.A.Dunyamalyev (2002), S.E.Tagieva (2007), A.M.Guliyev, B.Z.Kazymov (2009) and others. The results of such studies have shown that when predicting development indicators, taking into account the relaxation of the skeleton of reservoir rocks significantly increases the accuracy of calculations.

Analysis of the work performed in the field of hydrodynamics and computer simulation of well-reservoir systems showed that conducting extensive research in this area is relevant. The works of F.A.Aliyev, V.B.Larin (2009), F.A.Aliyev, N.A. Ismailov (2013) and M.M. Mutallimov, R.T.Zulfigarov, L.I.Amirov (2015) are among the few works in the field of optimization of gas-lift process control in the well-reservoir system. The results obtained in the noted works can serve as a basis for a comprehensive solution of the noted problem in the future.

There are numerous works in the field of field data interpretation - for example, the works of M.T.Abasov, A.T.Gorbunov, A.Kh.Shakhverdiev (1981), R.G.Shagiev (1998), D.R.Mirzoeva (2002) , Yu.M.Molokovich (2006), T.Sh.Kazymova (2008), F.Civan, D.Devegowda, R.Sigal (2013), etc. - however, these works are mainly devoted to the problems of oil and gas deposits.

The study of published scientific works in the field of gas hydrodynamics of the development of oil, gas, gas condensate deposits and volatile oil deposits, represented by deformable, including relaxation and creeping reservoirs and the development of methods for interpreting the results of hydrodynamic studies of wells and field data showed the relevance of research in the field of mathematical modeling of development and creation of methods interpretation of production data of gas condensate deposits and volatile oil deposits, taking into account complex deformations of reservoirs and problems of computer simulation of well-reservoir systems.

The second chapter is devoted to modeling the process of filtration of gas-condensate mixture and volatile oils in nonlinear elastic and relaxation reservoirs. The existing approaches are discussed and the solution method used in the dissertation work is determined.

As you know, theoretically, the accuracy of the reservoir simulation model mainly depends on how accurately the mathematical model of reservoir fluid filtration reflects the process. The latter is due to the completeness of accounting for the factors characterizing the process. The factors characterizing the change in the reservoir properties of the reservoir with a drop in pore pressure, the change in the thermodynamic properties of fluids, mass transfer between phases and many other factors are complementary to the mathematical model of the reservoir system. However, increasing the number of parameters in the model does not uniquely improve its accuracy. Because each of the parameters included in the model has its own determination error. In this case, we are talking about the concept of the reliability of determining the numerical value of a particular parameter. Thus, the maximum increase in the number of parameters in order to increase the "accuracy" leads to an over-complication of the model and can reduce its reliability. For example, it is known that porosity and permeability, its rheological properties, and a number of other parameters of a real formation vary depending on the coordinate. However, to create a reliable model of the physical process, such values of these parameters are used, which represent the reservoir as a whole. The same can be said about reservoir fluids, such as the number of components in the hydrocarbon system.

In this regard, there are basically two approaches to modeling the filtration of gas condensate mixture and volatile oils. According to both approaches, two-phase flow and mass transfer between phases are taken into account. According to the first approach, the gas condensate system is considered as a multicomponent system. And according to the second representation, a mono-component system, which is a gas-condensate mixture, is taken as a binary system, i.e. consisted of two pseudo-components and two phases.

The complexity of the multicomponent filtration model, the difficulty of determining the thermodynamic properties of each component of the system reduces its reliability and impedes its use. Therefore, in the case of hydrodynamic modeling of development, the use of a binary model is considered more expedient. However, by solving the problems of filtration of hydrocarbon systems based on a binary model, it is possible to obtain an analytical or semi-analytical solution, which makes it possible to create a number of algorithms, including algorithms for interpreting well-test data. In view of the above, within the framework of the dissertation work, a binary model is used when solving the assigned tasks.

The equations of motion of a gas-condensate mixture in a porous medium, the porosity and permeability of which change depending on pressure and time, for a radial flow are written as follows:

$$\begin{gathered}\frac{1}{r}\frac{\partial}{\partial r}\left\{r\left[\frac{f_g(\rho_k)p\beta[1-c(p)\bar{\gamma}(p)]}{\mu_g(p)Z(p)p_{at}}+\frac{f_k(\rho_k)S(p)}{\mu_k(p)a(p)}\right]k(p,t)\frac{\partial p}{\partial r}\right\}= \\ -\frac{\partial}{\partial t}\left\{\left[\frac{(1-\rho_k)p\beta[1-c(p)\bar{\gamma}(p)]}{z(p)p_{at}}+\rho_k\frac{S(p)}{a(p)}\right]m(p,t)\right\}\end{gathered} \tag{2.1}$$

$$\begin{gathered}\frac{1}{r}\frac{\partial}{\partial r}\left\{r\left[\frac{f_g(\rho_k)p\beta c(p)}{\mu_g(p)Z(p)p_{at}}+\frac{f_k(\rho_k)}{\mu_k(p)a(p)}\right]k(p,t)\frac{\partial p}{\partial r}\right\}= \\ -\frac{\partial}{\partial t}\left\{\left[\frac{\rho_k}{a(p)}+(1-\rho_k)\frac{p\beta c(p)}{Z(p)p_{at}}\right]m(p,t)\right\}\end{gathered} \tag{2.2}$$

By analogy with a gas-condensate mixture, according to the concept of a binary model, the equations of motion of volatile oils in a compressible porous medium are also written:

$$\begin{gathered}\frac{1}{r}\frac{\partial}{\partial r}\left\{r\left[\frac{f_g(\rho_n)p\beta c_n(p)}{\mu_g(p)z(p)p_{at}}+\frac{f_n(\rho_n)}{\mu_n(p)a(p)}\right]k(p,t)\frac{\partial p}{\partial r}\right\}= \\ -\frac{\partial}{\partial t}\left\{\left[\frac{\rho_n}{a(p)}+(1-\rho_n)\frac{p\beta c_n(p)}{z(p)p_{at}}\right]m(p,t)\right\}\end{gathered} \tag{2.3}$$

$$\begin{gathered}\frac{1}{r}\frac{\partial}{\partial r}\left\{r\left[\frac{f_g(\rho_n)p\beta[1-c_n(p)\bar{\gamma}(p)]}{\mu_g(p)z(p)p_{at}}+\frac{f_n(\rho_n)S(p)}{\mu_n(p)a_n(p)}\right]k(p,t)\frac{\partial p}{\partial r}\right\}= . \\ -\frac{\partial}{\partial t}\left\{\left[\frac{(1-\rho_n)p\beta[1-c_n(p)\bar{\gamma}(p)]}{z(p)p_{at}}+\rho_n\frac{S(p)}{a_n(p)}\right]m(p,t)\right\}\end{gathered} \tag{2.4}$$

Here ρ_k, ρ - pore saturation coefficients with liquid condensate and oil, respectively; m - coefficient of porosity of the formation; k - formation effective permeability; f_k, f_n, f_g - coefficients of phase permeability of liquid condensate, oil and gas, respectively; μ_k, μ_n, μ_g - coefficients of dynamic viscosity of condensate, oil and gas, respectively; $S(p)$ - the amount of dissolved gas in liquid condensate (or in oil); $a(p)$ - volumetric coefficient of condensate (or oil); $c(p), c_n(p)$ - the content of potentially liquid hydrocarbons and volatile oil components in the gas phase, respectively; $c\gamma(p)$ - fractional content of potentially liquid hydrocarbons in the gas phase in reservoir conditions; β - coefficient of temperature correction for the gas phase; $z(p)$ - coefficient of supercompressibility of the gas phase; p_{at} - Atmosphere pressure; t – time;

In the chapter, studies carried out in the field of rheological models of deep-seated formations are studied, equations are written out describing the dependences of the reservoir properties of nonlinear elastic, relaxation elastic and relaxation creeping reservoirs on time and pressure.

To describe the change in porosity and permeability of nonlinearly elastic formations from pressure, an exponential law was adopted:

$$k = k_0 \exp[\beta_k (p - p_0)] \text{ and} \tag{2.5}$$

$$m = m_0 \exp[a_m (p - p_0)], \tag{2.6}$$

where k_0, m_0 - values of permeability and porosity at initial reservoir pressure (p_0), respectively;

β_k , a_m - elastic coefficients for permeability and porosity, respectively.

It is known that sometimes rocks are deformed not according to elastic, but relaxation-elastic or relaxation-creeping law, in which, with a drop in pore pressure, the deformation of the rock skeleton does not occur instantaneously, but after a certain time, called the relaxation time. In the dissertation work, expressions describing changes in the porosity and permeability of the relaxation formation are used the following equations:

$$m + \tau_m \frac{\partial m}{\partial t} = m_0 \exp[\beta_{sp}(p - p_0)] \tag{2.7}$$

and

$$k + \tau_k \frac{\partial k}{\partial t} = k_0 \exp[\beta_k (p - p_0)] \tag{2.8}$$

In view of the results of work in the field of rock creep, the following equations were used to determine the porosity and permeability of this type of formations:

$$m(r,t) = m_0 \left[1 + a_m (p - p_0) + m_1 \int_0^t e^{\frac{t-\tau}{\tau_m}} (p - p_0) d\tau \right], \tag{2.9}$$

$$k(r,t) = k_0 \left[1 + \beta_k (p - p_0) + k_1 \int_0^t e^{\frac{t-\tau}{\tau_k}} (p - p_0) d\tau \right], \tag{2.10}$$

where k_1, m_1 - creep parameters for permeability and porosity, respectively; τ_m, τ_k - the relaxation time of the porosity and permeability of the creeping medium.

Within the framework of the binary model, the equations of motion of the gas-condensate mixture and volatile oils in difficultly deformed reservoirs are written out. They are complemented by the above rheological models.

Considering the results of works by M.T.Abasov, M.A.Rasulov, Kh.A.Feyzullaev (1991) and M.S.Aslanov, B.Z.Kazymov, S.E.Tagieva (2008), confirming the expediency of using the averaging method for solving problems filtration of gas-condensate mixture and oil by comparing the results obtained by numerical and approximate methods, in the dissertation the application of the averaging method is accepted. Further, by introducing a pseudo pressure function, a method is given for solving the problems of the flow of a gas-condensate mixture and volatile oils to a well in nonlinearly elastic, relaxation-elastic and creeping formations, taking into account inertial forces. According to this technique, semi-analytical solutions for the motion of gas-condensate mixtures and volatile oils were obtained, written out within the framework of the binary model representations (2.1) - (2.2) (or (2.3) - (2.4) - for volatile oils) taking into account the above rheological models (2.5), (2.6), (2.7), (2.8), (2.9), (2.10) and an expression for determining the flow rate of the well is presented. This became possible due to the introduction of the pseudo pressure function $H = \int \varphi(p, \rho_k) dp + C$ and the application of the coordinate averaging method to the right-hand side of equation (2.1) (or (2.3) for oil). After that, the obtained equation was solved under the appropriate boundary conditions with respect to the pseudo pressure H and an expression was obtained for determining the instantaneous flow rate according to Darcy's law:

$$q_g = \frac{2\pi h(H_k - H_s)}{\ln \frac{R_k}{r_s} - \frac{1}{2}}. \qquad (2.11)$$

Here h is the thickness of the formation; The integrand φ for the gas condensate system has the following form: $\varphi = \left[\frac{f_g(\rho_k) p\beta[1 - c(p)\bar{\gamma}(p)]}{\mu_g(p) Z(p) p_{at}} + \frac{f_k(\rho_k) S(p)}{\mu_k(p) a(p)} \right] k(p,t)$, and for volatile oils, it has the form: $\varphi = \left[\frac{f_n(\rho)}{\mu_n(p) a(p)} + \frac{f_g(\rho) p\beta c_n(p)}{\mu_g(p) z(p) p_{at}} \right] k(p,t)$; $k(p,t)$ is determined by law (2.6) or (2.8) or (2.10).

To determine the well flow rate according to (2.11), a transition from the pseudo pressure difference $(H_k - H_s)$ to the actual pressure difference $(p_k - p_s)$ is required. For this purpose, it is proposed to use the approximating logarithmic function

$$\varphi = a \ln \bar{p} - b \qquad (2.12)$$

Here, the unknown coefficients a and b are determined using the values of the integrand function φ on the supply circuit φ_k and at the bottomhole φ_s as follows:

$$a = \frac{\varphi_k - \varphi_s}{\ln \frac{\bar{p}_k}{\bar{p}_s}}, \quad b = \frac{\varphi_k - \varphi_s}{\ln \frac{\bar{p}_k}{\bar{p}_s}} \ln \bar{p}_k - \varphi_k \qquad (2.13)$$

Here $\bar{p}_k$ and $\bar{p}_s$ are the values of dimensionless pressures on the supply circuit and at the bottom of the well, respectively.

It is shown that the accuracy of the adopted approximation is high enough (Fig. 2.1). Taking into account (2.12) and (2.13), the expression for determining the production rate (2.11) will take the following form:

$$q = \frac{2\pi h \left\{ \frac{\varphi_k - \varphi_s}{\ln \frac{p_k}{p_s}} \left[\frac{\ln p_k^{p_k}}{\ln p_s^{p_s}} - p_k + p_s \right] - \left(\frac{\varphi_k - \varphi_s}{\ln \frac{p_k}{p_s}} \ln p_k - \varphi_k \right)(p_k - p_s) \right\}}{\ln \frac{R_к}{r_s} - \frac{1}{2}} \qquad (2.14)$$

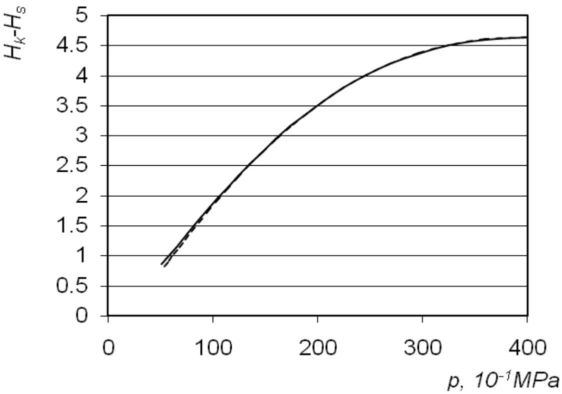

Figure 2.1. Curves of the dependence of $H_k - H_s$ *on reservoir pressure with the numerical integration of the function* φ *(curve -------) and using the logarithmic approximation (curve ______)*

On the basis of the aforementioned hostilities, a computer program was developed, with the help of which a number of numerical experiments were carried out. The calculations were performed for a hypothetical circular gas condensate reservoir with a radius of 1000 m, initial reservoir pressure of 40.0 MPa, drained by one central well. In this case, the thermodynamic data of the gas-condensate mixture of the V block of the VII horizon of the Bulla-Deniz field were used.

Calculations, in order to study the effect of deformation on the development process, were carried out in two versions - for the case when deformation is neglected and for a compressible formation with a porosity change coefficient a_m = 0.002 1 / MPa. In this case, the ratio of the coefficients of changes in permeability and porosity is taken β_k / a_m = 10. In both cases, the development was carried out at a constant drawdown equal to 1.0 MPa. The obtained results, along with a demonstration of an example of modeling the filtration processes of a gas-condensate mixture and volatile oils in compressible reservoirs within the framework of a binary model, also showed that the influence of changes in porosity and permeability on the development process is significant and sometimes it is of a qualitative nature. The latter is clearly seen from the graphs of the well flow rate versus reservoir pressure for nonlinear elastic and non-deformable reservoirs in Fig. 2.2.

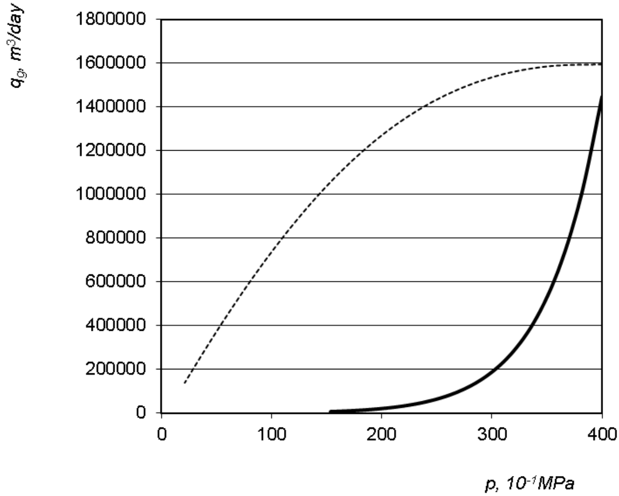

Figure 2.2. Flow rate changes depending on reservoir pressure in compressible (solid line, a_m = 0.002 1 / MPa) and incompressible (dashed line) formations

Using the mathematical induction method, in an unconventional way, the problem of inflow to the well was solved in the case when the flow obeys Forchheimer's law and an expression for the flow rate was obtained in the following form:

$$q = \frac{2\pi h}{2B}\left(- A + \sqrt{A^2 + 4B\left\{ \frac{\varphi_k - \varphi_s}{\ln \frac{p_k}{p_s}} \left[\frac{\ln p_k^{p_k}}{\ln p_s^{p_s}} - p_k + p_s \right] - \left(\frac{\varphi_k - \varphi_s}{\ln \frac{p_k}{p_s}} \ln p_k - \varphi_k \right)(p_k - p_s) \right\}} \right) \quad (2.15)$$

Here
$A = \ln\left(\frac{R_k}{r_s}\right) - \frac{1}{2}\frac{R_k^2 - r_s^2}{R_k^2}$; $B = \frac{k(p)}{\mu(p)} b\left(\frac{1}{r_s} - \frac{1}{R_k} - 2\frac{R_k - r_s}{R_k^2} + \frac{R_k - r_s}{R_k^2} + \frac{R_k^3 - r_s^3}{3R_k^4}\right)$ is a constant characterizing a porous medium.

Based on expression (2.15), to assess the influence of inertial forces on the process, some computer calculations were carried out, the results of which were compared with the case when filtration occurs according to Darcy's law. It was found that the difference between reservoir pressures during the development period reaches 22%. Taking into account the nonlinearity of the flow leads to a decrease in the initial gas production rate by 26% (Fig. 2.3). From a certain moment (in this case, t = 1.35 years), in the variant that takes into account inertial forces, the flow rate becomes higher than in the other.

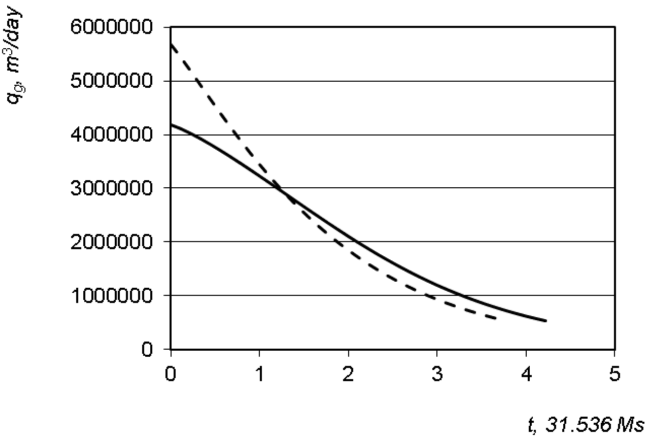

Figure 2.3. Gas flow rate dynamics with taking into account the inertial effects (solid line) and without taking into account (dashed line)

Despite this, inertial forces significantly reduce the current values of the gas recovery coefficient (Fig. 2.4). Thus, at the same time, for the production of 60% of the initial gas reserves, 0.3 years of additional time is required. The final gas recovery coefficient $\eta = 0.875$ is reached in 4.22 years, while the inertial forces are neglected for this it takes 3.78 years.

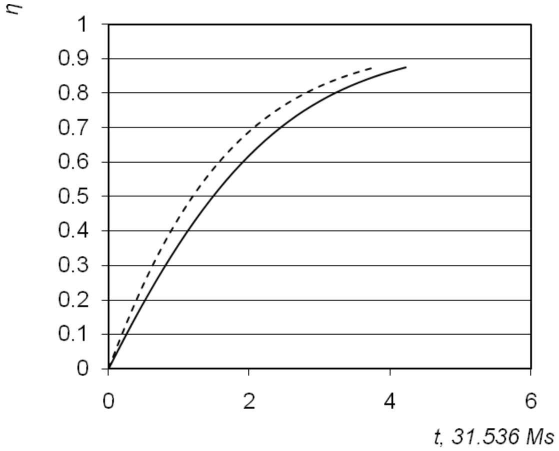

Figure 2.4. Curves of the dynamics of the gas recovery coefficient taking into account the inertial effects (solid line) and without taking into account (dashed line)

In the third chapter The third chapter is devoted to methods for calculating the development indicators of gas condensate and volatile oil deposits, represented by relaxation deformable reservoirs. In the previous chapter, the problem of inflow of gas-condensate mixture to the well in a nonlinear elastic formation was solved an algorithm for calculating the development indicators for the depletion of gas condensate deposits was developed. In a similar way, algorithms are proposed for determining the main indicators of the development of gas condensate deposits and volatile oil deposits, represented by relaxation elastic and creeping reservoirs under various reservoir-drive, including depletion, elastic-pressure and hard-water reservoir-drives, also in the regime of water injection into the reservoir at a given rate.

Using the material balance equations of gas and condensate, the following system of differential equations was obtained, which simulates the process of depletion of a gas condensate reservoir in relaxation formation:

$$\frac{dp}{dt}=-\frac{\dfrac{q_g}{\Omega_0\overline{\Omega}}\left(\alpha_4+\dfrac{\alpha_2}{G}\right)-(\alpha_2\alpha_3+\alpha_1\alpha_4)\dfrac{1}{\overline{\Omega}}\dfrac{\overline{m}(p)-\overline{m}}{\tau_m}}{(\alpha_5+\alpha_6)\alpha_4+(\alpha_7+\alpha_8)\alpha_2},$$

$$\frac{d\rho_k}{dt}=-\frac{\dfrac{q_g}{\Omega_0\overline{\Omega}G}+(\alpha_7+\alpha_8)\dfrac{dp}{dt}+\alpha_3\dfrac{1}{\overline{\Omega}}\dfrac{\overline{m}(p)-\overline{m}}{\tau_m}}{\alpha_4},$$

Here the gas condensate factor (G) is determined by the following formula:

$$G=\frac{\dfrac{\overline{\mu}(p)a(p)p\beta}{z(p)p_{at}}[1-c(p)\overline{\gamma}(p)]+\dfrac{S(p)}{\psi(\rho_k)}}{\dfrac{1}{\psi(\rho_k)}+\dfrac{\overline{\mu}(p)a(p)p\beta c(p)}{z(p)p_{at}}};$$

$$\frac{1}{\psi(\rho_k)}=\frac{f_g}{f_k}\quad;\quad\overline{\mu}(p)=\frac{\mu_k}{\mu_g}\quad;\quad\alpha_1=(1-\rho_k)\frac{p\beta}{z(p)p_{at}}[1-c(p)\overline{\gamma}(p)]-\rho_k\frac{S(p)}{a(p)}\quad,$$

$$\alpha_2=\frac{p\beta}{z(p)p_{at}}[1-c(p)\overline{\gamma}(p)]-\frac{S(p)}{a(p)}\quad,\quad\alpha_3=\rho_k\frac{1}{a(p)}-(1-\rho_k)\frac{p\beta c(p)}{z(p)p_{at}}\quad,$$

$$\alpha_4=\frac{1}{a(p)}-\frac{p\beta c(p)}{z(p)p_{at}}\quad,\quad\alpha_5=(1-\rho_k)\left\{\frac{p\beta}{z(p)p_{at}}[1-c(p)\overline{\gamma}(p)]\right\}'\quad,\quad\alpha_6=\rho_k\left[\frac{S(p)}{a(p)}\right]'\quad,$$

$\alpha_7=\rho_k\left[\dfrac{1}{a(p)}\right]'$, $\alpha_8=(1-\rho_k)\left[\dfrac{p\beta c(p)}{z(p)p_{at}}\right]'$; «$'$» – means the derivative with respect to pressure p. Here the well production rate is determined by expressions (2.14) and (2.15).

Similar expressions based on the corresponding material balance equations were obtained for light oils. On the basis of the calculated relations and algorithms obtained, a computer program was developed, on the basis of which a number of computer experiments were carried out and the influence of relaxation and creep of reservoir rocks on the development process under various reservoir-drive was investigated, including:

1. Influence of rock relaxation on the process of depletion of gas condensate deposits. In order to study the effect of relaxation on the process under consideration, calculations were performed for different values of the relaxation time. The process of depletion is considered at a given flow rate equal to 10% of the initial balance gas reserves and for three different values of $\tau_m = 0$, 1.0, 3.0 and 5.0 years. In addition, for comparison, variants of nonlinear elastic (i.e. $\tau_m = 0$) and incompressible formations are also considered. At the same time, in all "deformable" variants, the coefficient of elastic change in porosity (a_m) was 0.0025 1/MPa. It has been found that in relaxing formations at the beginning of the process, the reservoir behaves like a non-deformable one. Moreover, this is observed in all the considered values of the relaxation time. However, after a certain time, the curves of changes in development indicators both quantitatively and qualitatively approximate the curves of the elastic formation of the same name.

2. On a computer model of **the process of depletion of volatile oil deposits in relaxation deformable reservoirs**, the features of the influence of relaxation elastic deformation of the rock skeleton on the indicators of the development process have been investigated. For this purpose, the process of depletion of nonlinear elastic and relaxation-elastic formations of volatile oil at drawdowns of 1.0 and 4.0 MPa is considered. For comparison, calculations were made for the case when the deformability of the formation is neglected. In calculations for compressible formations, the porosity change coefficient (a_m) was 0.001, 0.005, and 0.01 1/MPa at $\beta_k / a_m = 10$. The relaxation time was 5 years.

The study of the dependence of the productivity factor of wells on reservoir pressure showed that the effect of deformation to the noted parameter is of a qualitative nature. At the same time, the value of the well productivity index in the elastic formation is always lower relative to the relaxing formation. The change in the productivity factor in an incompressible and weakly compressible reservoir is somewhat different in nature from a relatively highly deformable reservoir. So, at low pressure values, in contrast to a highly deformable reservoir, in an incompressible and weakly compressible reservoir, there is a significant decrease in the rate of decline in the productivity factor and its stabilization during a certain period. It was found that at high drawdowns, the current productivity coefficients in the relaxing formations acquire higher values in comparison with low drawdowns. In addition, the influence of the drawdown on the change in the productivity factor in relaxing formations is stronger than in non-deformable formations.

3. The problems of water displacement of hydrocarbon mixtures in gas condensate and volatile oil reservoirs with various reservoir-drives have been solved. Algorithms for predicting the main indicators of development in water-pressure modes have been developed. On the basis of these algorithms, software has been developed, a number of computer experiments have been performed, and the influence of relaxation on the displacement process has been investigated. The calculation results demonstrated a significant influence of relaxation on the process under consideration. For example, when volatile oils are displaced by water, a comparison of a relaxing formation with an elastic one showed that the oil recovery factor in the first case is slightly higher. It`s naturally. So, higher current flow rates in the relaxing reservoir should have provided a higher oil recovery factor. Comparing the oil recovery factors in the options under consideration, it can be noted that, for example, by the 15th year of development in a relaxing reservoir, the oil recovery factor is 0.72. This is 24% more than in the elastic formation at that time. The oil recovery factor reaches 0.5 in 9.1 years in a relaxed reservoir, while in an elastic reservoir 12.5 years are required for the same level of oil recovery. And finally, in a relaxing reservoir under the conditions under consideration, the final oil recovery factor reaches 0.88 in 20.4 years, and in an elastic reservoir, the same level of oil recovery takes 26 years.

In addition, the results showed that the nature of the influence of relaxation on the process of displacing volatile oil by water is not only quantitative, but sometimes can also be of a qualitative nature. So, in the relaxing reservoir by the 2.5 years of development, a slight short-term increase in pressure was noted. The noted effect is the result of a complex influence on the process of such factors as relaxation time, dynamics of water penetrating into the reservoir, changes in porosity and permeability.

Similar studies were carried out for the gas condensate reservoir. In this case, development is considered in four different depressions - 0.5, 1.0, 1.5 and 4.0 MPa. The calculation results showed that the development process is proceeding against the background of a small decrease in reservoir pressure. For example, with a depression of 0.5 MPa until the end of development, the reservoir pressure decreases only to 34.0 MPa. This is only 15% of the initial reservoir pressure. With a depression of 1.0 MPa, the reservoir pressure decreases by 27.5%. And with drawdowns of 2.0 and 4.0 MPa, the reservoir pressure per weight during the development period drops by 46 and 73 percent relative to its initial value, respectively. By comparing these data, it can be seen that with an increase in drawdown, nonlinearity in the dynamics of a decrease in reservoir pressure also increases. This is due to the fact that with intensive development, the "synchrony" between the production and penetration of water into the reservoir is violated, against the background of ever worsening permeability, the rate of water invasion decreases, as a result of which the drop in reservoir pressure is not compensated. So, while at a depression of 0.5 MPa, the rate of water penetration into the reservoir remains largely constant, then with large depression, after a certain time, a sharp decrease in the flow rate of water penetrating into the productive part of the reservoir occurs.

An algorithm was developed for calculating the main indicators of the development of gas condensate deposits and volatile oil deposits, represented by creeping reservoirs, on the basis of which computer studies were carried out and the effect of creep on the main indicators of the development of gas condensate deposits and volatile oil deposits was studied.

In the fourth chapter, the problem of the flow of gas-condensate mixtures and volatile oils into the well is considered, taking into account the differences in reservoir and rheological properties of rocks in the bottomhole (or near the wellbore) zone and relatively far from the well within the drainage area of the well.

Deterioration of permeability in the bottomhole zone of the well as a result of contamination of this part of the formation (manifestation of the skin effect), changes in the reservoir properties of the bottomhole zone as a result of using various methods of bottomhole zone treatment and similar processes lead to the formation of zonal heterogeneity in the drainage zone of the well. In such cases, the problem under consideration becomes relevant. Taking into account the above, solutions were obtained for the problems of filtration of gas-condensate mixtures and volatile oils to the well. Algorithms have been developed for calculating the flow rate of a well for gas and oil in the case when the drainage zone of the well is zonal heterogeneous in terms of permeability and rheological properties.

In this case, a well with radius r_s is considered, draining a zone with radius R_k . This is shown schematically in Fig. 4.1. The drainage zone of a well with a radius of R_k consists of two rheologically different zones - an inner (near-well) zone with a radius

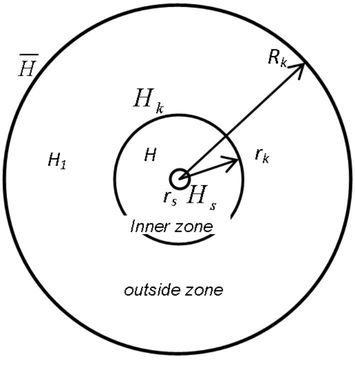

Figure 4.1. Schematic representation of a well and a drainage area consisting of two rheologically different zones

r_k and an outer zone with a radius R_k. Thus, by introducing the integral $H = \int \varphi(p, \rho\,)dp + C$, the flow to the well of gas (in gas condensate formations) or oil (in formations of volatile oils) is expressed by the following equations, linearized by the averaging method:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial H}{\partial r}\right) = -\Phi(t), \tag{4.1}$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial H_1}{\partial r}\right) = -\Phi_1(t) \tag{4.2}$$

Here H is a function similar to that of Khristianovich. The system of equations (4.1) and (4.2) is solved under the following boundary conditions:

$$r = r_s,\ H = H_s;$$
$$r = r_k,\ H = H_k, \tag{4.3}$$

We have the following additional conditions and designations:

$$r = r_k,\ \frac{\partial H}{\partial r} = \frac{\partial H_1}{\partial r}, \tag{4.4}$$

$$r = R_k,\ \frac{\partial H_1}{\partial r} = 0 \tag{4.5}$$

and $r = R_k,\ H_1 = \overline{H}_k;\ r = r_k \quad H_1 = H_k$. (4.6)

By solving the system of equations (4.1) and (4.2) with the above stated boundary conditions, an expression was obtained for calculating the instantaneous value of the production rate in the following form:

$$q_g = 2\pi h \frac{\dfrac{\overline{H}_k - H_k}{R_k^2 \ln\dfrac{R_k}{r_k} - \dfrac{1}{2}\left(R_k^2 - r_k^2\right)}\left(r_k^2 - \dfrac{1}{2}\dfrac{R_k^2 - r_k^2}{\ln\dfrac{R_k}{r_k}}\right) - \dfrac{\overline{H}_k - H_k}{\ln\dfrac{R_k}{r_k}} + \dfrac{H_k - H_s}{\ln\dfrac{r_k}{r_s}}}{r_k^2 - \dfrac{1}{2}\dfrac{r_k^2 - r_s^2}{\ln\dfrac{r_k}{r_s}}} \rightarrow$$

$$\to \left(r_s^2 - \frac{1}{2}\frac{r_k^2 - r_s^2}{\ln\frac{r_k}{r_s}} \right) + \frac{H_k - H_s}{\ln\frac{r_k}{r_s}} \qquad (4.7)$$

Material balance equations were written for each zone of a heterogeneous formation, on the basis of which systems of ordinary differential equations were obtained, which allow predicting the change in time of parameters in both zones of the formation. By using these systems together with expression (4.7), a number of computer calculations were carried out to study the effect of changing the radius of the inner zone on the productivity of gas condensate and oil wells. It has been found that in a heterogeneous oil reservoir the reservoir pressure versus time curve has one breakpoint. This distinguishes the curve from the anological curve of a homogeneous formation, which is smooth. At the beginning of the development of an oil reservoir, an intense drop in reservoir pressure is observed. However, after a certain moment, the nature of the drop in reservoir pressure changes. This effect is not observed on the analogous curve of the gas condensate reservoir. Note that in a zonally heterogeneous volatile oil reservoir, the peculiar character of the curve is associated with the process of pressure distribution in the inner zone. So, at the beginning of development, there is an intense drop in the average pressure in the inner zone until the pressure disturbance reaches the boundary. From the moment the pressure drop perturbation is reached to the boundary, oil flows from the outer zone to the inner zone. From this moment on, the intensity of the pressure drop in the inner zone changes. Since the time required to reach the disturbance to the boundary in the gas-condensate formation is much shorter due to the lower viscosity of the gas-condensate mixture, this effect is not observed.

Fifth chapter. The fifth chapter is devoted to the problems of modeling the well-bed system in the mechanized operation of light oil (and non-evaporating oil) fields, represented by nonlinear elastic, relaxed elastic and relaxed creeping reservoirs. In particular, for the first time, computer-simulation models of wells operation by gas-lift method and deep-well pumps (both sucker rod and rodless) in the well-reservoir system were built using imitational modeling methods. On the basis of these models, a computer simulator was created, with the help of which the influence of various factors on the development of the formation and on the process of well operation (especially when the rods were pumped) were investigated.

For the purpose of mathematical modeling of the process at the bottom of the well, i.e. for the mathematical description of the process of formation of a gas-liquid mixture during the gas-lift operation, a set of field experiments were carried out in gas-lift well No. 2390 of the “Neft Dashlari” field. The purpose of the experiments was to study the regularities of the influence of the immersion depth, the diameter of the lift pipes and the flow rate of gas injected into the well on the process of formation of gas-liquid mixtures.

An empirical formula for determining the flow rate was formulated, which, together with a system of equations describing the distribution of pressure and flow in the lift and with the equations of reservoir fluid inflow, created a complete system of calculation equations for modeling the process.

The isothermal and unsteady movement of the gas-liquid mixture (GLM) in a vertical pipe can be expressed by the following differential equations (Fig. 5.1):

$$-\frac{\partial p}{\partial x}=\frac{\partial(\rho_c w_c)}{\partial t}+\rho_c g+\lambda_c\,\rho_c\frac{w_c^2}{2D}, \tag{5.1}$$

$$-\frac{\partial p}{\partial t}=c^2\frac{\partial(\rho w_c)}{\partial x}\,,\ 0<x<L,\ t>0 \tag{5.2}$$

Here $p=p(x,t),\ w_c=w_c(x,t)$ are the excess over static pressure of the mixture and the average velocity of the liquid across the pipe; c - speed of sound in the mixture; $\rho_c,\ \lambda,\ g$ - mixture density, hydraulic resistance coefficient of the pipe and free fall acceleration, respectively; D is the internal diameter of the lifting pipe.

Linearizing equation (5.1), it can be expressed as follows:

$$-\frac{\partial p}{\partial x}=\frac{\partial(\rho_c w_c)}{\partial t}+2a\rho_c w_c,\ 2a=\frac{g}{w_c}+\frac{\lambda_c w_c}{2D}. \tag{5.3}$$

Assuming the pipe section to be constant, we write equations

(5.3) and (5.2) for pressure and mass flow as follows:

$$-\frac{\partial p}{\partial x}=\frac{1}{F}\frac{\partial Q}{\partial t}+\frac{2a}{F}Q \qquad (5.4)$$

$$-\frac{\partial p}{\partial t}=\frac{c^2}{F}\frac{\partial Q}{\partial x}. \qquad (5.5)$$

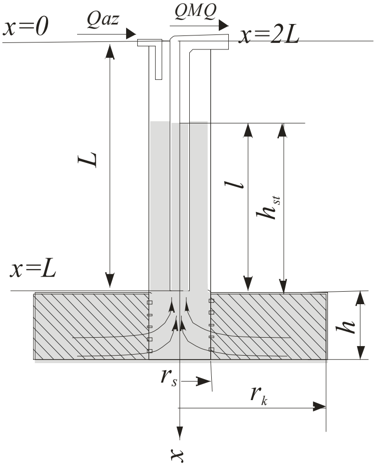

Figure 5.1. Schematic representation of a gas lift well. Qaz- gas, QMQ- gas-liquid mixture

Assuming that the velocity of the gas and the mixture is equal to $w_c=\frac{dx}{dt}$, we can assume that the velocity in a pipe segment of length $dx=w_c dt$ is equal to the average value of this segment and does not depend on time. In this case, the system of equations (5.4) - (5.5) can be reduced to the following system of ordinary differential equations:

$$\frac{dQ}{dx}=\frac{2a\rho FQ^2}{c^2\rho^2F^2-Q^2}, \qquad (5.6)$$

$$\frac{dp}{dx}=\frac{2ac^2\rho^2FQ}{c^2\rho^2F^2-Q^2}. \qquad (5.7)$$

Taking into account that $Q=F\rho_c w_c$ and dividing the numerator and denominator of the fraction in the first equation $F^2\rho^2$, and in the second equation by the product $F\rho^2$, equations (5.6) and (5.7) can be written as follows:

$$\frac{dQ}{dx} = -\frac{2aw_c}{w_c^2 - c^2}Q, \tag{5.8}$$

$$\frac{dp}{dx} = -\frac{2ac^2}{F(w_c^2 - c^2)}Q, \text{ where } c >> w_c \tag{5.9}$$

If the denominator of (5.8) is not equal to zero and the first equation of the system does not depend on the second, then it can be solved separately, by the method of separation of variables. The system of equations (5.8)-(5.9) can be solved under the following initial conditions: $p(x,0) = p_0, Q(x,0) = Q_0$. At the borders of $x = 0$ and $x = L$, different conditions may be accepted, for example, $p(0,t) = p_1(t),\ Q(0,t) = Q_0(t)$ and $p(L,t) = p_2(t),\ Q(L,t) = Q_2(t)$, or $p(0,t) = p_1 = const,\ Q(0,t) = Q_0(t)$ and $p(L,t) = p_2(t),\ Q(L,t) = Q_2(t)$.

At the Bottomhole, i.e. on $x = L$, the condition can be specified as, for example, $Q(L+0) = \gamma Q(L-0) + \gamma_1 \overline{Q}$.

Also, a computer simulation model of the well-reservoir system was developed when operating with deep pumps, on the basis of which a computer simulator of the well-reservoir system was created when operating a well with submersible rodless and sucker-rod pumps. With the help of the noted simulator, a number of machine experiments were carried out and the features of the flow of fluids from the reservoir to the well, the formation of a static liquid column in the well were investigated. It was found that reaching the liquid level in the well to a static level is asymptotic. It was also found that the time required to restore the static fluid column in the well does not depend on the reservoir pressure.

The dependence of the sucker rod pump feed on the number of swings (N) of the rocker head of the rocker is investigated. It was found that an increase in the number of swinging of the balancer head at lower values of it leads to a sharp increase in the pump flow. However, this is observed up to a certain value of the N number. At comparatively large values, the influence of an increase in the N on the pump flow weakens, and with further reduction of swinging, the noted influence almost disappears (Fig. 5.2).

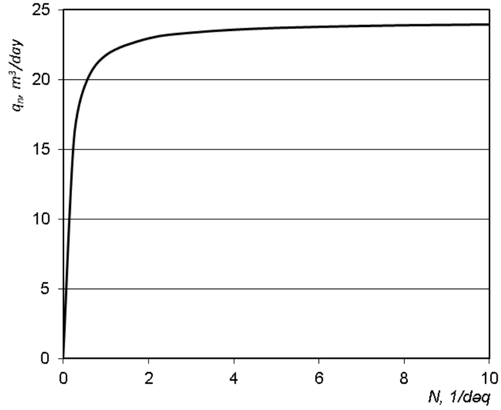

Figure 5.1. The curve of the dependence of the pump flow on the number of swings

In the case when the reservoir productivity is low, the complete filling of the pump cylinder becomes impossible and the efficiency of the pump decreases. At the same time, transferring the pump to intermittent mode becomes relevant. In intermittent mode, the pump operating cycle consists of two stages - recovery of the dynamic fluid level in the well (waiting period) and fluid rising stage (operating period). The problem of determining the rational operation regime of the pump consists of determining the optimal durations of the waiting and operating periods.

On the basis of the minimum cost condition, an algorithm is proposed for calculating the duration of the pump waiting period for a periodic well operation.

In this case, the criterion of the minimum cost of oil produced for the full cycle of the plunger swing is used. That is, the maximum waiting time of the pump is chosen so that the cost of lifting the accumulated oil during this time to the surface is minimal. In this case, the following formula is used to calculate the cost of lifted oil:

$$M = \frac{X_d t_d + \tilde{X}\tilde{t} + X^*}{q_n(t_d + \tilde{t})}. \tag{5.10}$$

Here t_d, X_d is the waiting period and the cost of maintaining the well at this time; $\widetilde{t}, \widetilde{X}$ - the time spent on lifting the accumulated liquid and the cost of lifting the liquid; X^* – well start-up costs; $q_n(t_d + \widetilde{t})$ - the amount of oil produced.

Dependence $q_n(t)$ must be known to determine the time t_d spent on the accumulation of fluid. It is shown that the process of fluid inflow from the reservoir into the well can be approximated by the exponential expression:

$$q_n = q_0 \exp(\alpha t) \qquad (5.11).$$

Here $\alpha = \dfrac{\ln \dfrac{q^*}{q_0}}{t^*}$ is determined by the method of selected points. As the selected point, you can take the value of the flow rate q^* at any time t^*, where t^* is less than the recovery time of the static level; q_0 - the initial flow rate of the inflow at the moment of time $t = 0$.

It should be noted that the $M(t_d)$ dependence is a concave curve. In this case, the minimum cost will correspond to zero of the derivative of the function $M(t_d)$. Then, taking into account (5.11) and the condition $\dfrac{dM}{dt_d} = 0$, from equation (5.10) it is easy to obtain an expression for calculating t_d:

$$t_d = \frac{-\alpha\left(\widetilde{t} + \dfrac{\widetilde{X}\widetilde{t} + X^*}{X_d}\right) - \sqrt{\left[\alpha\left(\widetilde{t} + \dfrac{\widetilde{X}\widetilde{t} + X^*}{X_d}\right)\right]^2 - 4\alpha \dfrac{\widetilde{X}\widetilde{t} + X^*}{X_d}(\alpha\widetilde{t} + 1)}}{2\alpha} \qquad (5.12)$$

The results obtained in this chapter are applied in software. Computer studies conducted on the basis of real field data using this program have shown that, if other conditions are not taken into account, the transition to batching in most wells operated with a rod pump by “Azneft” PA can have a significant economic effect.

The sixth chapter is devoted to solving the problems of interpretation of field data for the development of gas condensate deposits and volatile oil deposits (in particular cases, gas and oil deposits, respectively), including the results of hydrodynamic studies of wells (well-test data):

1. New method for determining the reservoir-drives. For the first time, special parameters are proposed that characterize the degree of activity of reservoir energy. It was found that there is a strict relationship between the nature of the reservoir energy and the values of the parameters $\overline{\Omega}_p = \frac{\overline{\Omega}}{\overline{p}}$ and $\overline{\Omega}_m = \frac{\overline{\Omega}}{\overline{m}}$, where $\overline{\Omega}$ is the ratio of the current volume of voids of the productive area of the formation (Ω) to its initial value Ω_0, $\overline{m} = \frac{m(p)}{m_0}$ is the ratio of the current porosity of the formation to its initial value, $\overline{p} = \frac{p}{p_0}$ is the ratio of the current reservoir pressure to its initial value.

To study the parameters noted, numerous computer calculations were carried out for gas condensate deposits and volatile oil deposits under various geological and technological conditions. The dependence of $\overline{\Omega}_p$ as a function of $\overline{p}$ was investigated for different reservoir-drives at different rates of gas extraction from the reservoir in the case of deformable and non-deformable reservoirs. The results are illustrated in Figure 6.1.

As you can see, the $\overline{\Omega}_p(\overline{p})$ curves are clearly divided into two types: the first - increasing with a drop in reservoir pressure, starting from unity, and the second - vice versa. And this does not qualitatively depend on the degree of deformability of the rock and the rate of production of the deposit. Curves of the first type are typical for the case when a decrease in the volume of voids in the productive part of the formation occurs as a result, mainly, of the compressibility of the rock and the movement of fluids occurs due to the elastic reserve of the formation system.

In this case, a more intense drop in reservoir pressure $\overline{p}$ outstrips the decrease in $\overline{\Omega}$ and leads to a sharp increase in $\overline{\Omega}_p$ in all considered options. As a result, in the “elastic” (gas or elastic-water-driven) regime, with a drop in reservoir pressure, $\overline{\Omega}_p$ increases, and in the hard-water regime, a decrease in $\overline{\Omega}_p$ is observed.

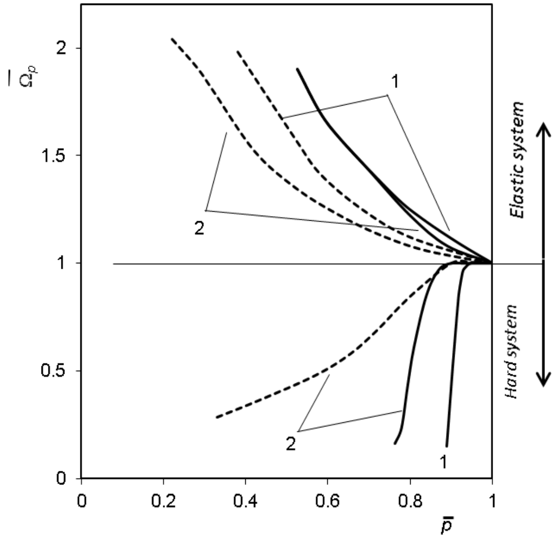

Figure 6.1. Dependence of the $\overline{\Omega}_p$ parameter on dimensionless pressure $\overline{p}$ for various energy systems: 1, 2 - production rate from the initial balance reserves is equal to 10 and 20% per year, respectively; ----- - deformable ($a_m = 0.01\ {}^1\!/_{MPa}$) reservoir, ______ - non-deformable reservoir

The second parameter, $\overline{\Omega}_m$, is also investigated. It turned out that the $\overline{\Omega}_m$ parameter is in fact an indicator of the elasticity of the medium. As seen from the $\overline{\Omega}_m(\overline{p})$ curves in Fig. 6.2 the development of deposits under water-drive is accompanied by a decrease in the value of $\overline{\Omega}_m$.

The parameters $\overline{\Omega}_p$ and $\overline{\Omega}_m$, in view of their physical meaning, were called the criteria for the activity of the energetics of the reservoir system, or simply - the “criteria of activity”.

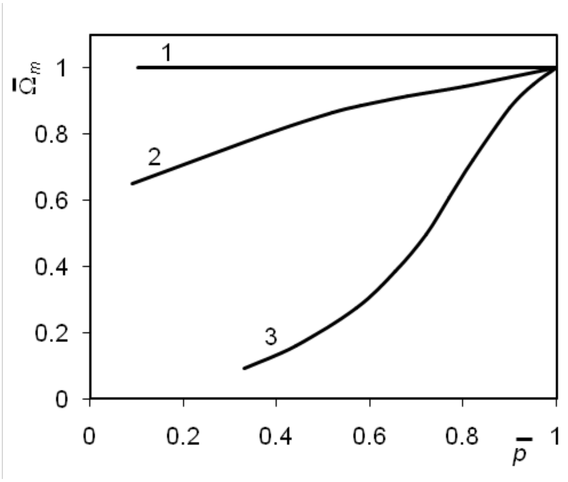

Figure 6.2. Dependence of the $\overline{\Omega}_m$ parameter on dimensionless pressure: 1 - depletion, 2 and 3- elastic and hard water-drive mechanisms

Table 6.1.

Determination of the reservoir regime according to the criteria of $\overline{\Omega}_p$ and $\overline{\Omega}_m$ activity.

$\overline{\Omega}_p$	$\overline{\Omega}_m$	**Reservoir-drive mechanisms**
>1	=1	Depletion
>1	<1	Elastic water-drive
<1	<1	Hard water-drive

Moreover, with an increase in the degree of rigidity of the energy system, the value of $\overline{\Omega}_m$ also decreases. At depletion, $\overline{\Omega}_m$ remains constant at one.

Summarizing the above results, to determine the reservoir-drive according to the activity criteria $\overline{\Omega}_p$ and $\overline{\Omega}_m$, we will draw up the following table (Table 6.1).

Thus, to determine the nature of reservoir energy according to Tab. 6.1 for a specific reservoir, you only need to calculate the numerical values of the parameters $\overline{\Omega}_p$ and $\overline{\Omega}_m$.

To apply the proposed approach to determining the reservoir-drive, the calculated ratios were obtained for calculating the numerical values of the criteria for the activity of gas condensate and volatile oil deposits based on field data. For gas condensate deposits, they are written in the following form:

$$\overline{\Omega}_p = \frac{\dfrac{\overline{Q}_g - \alpha_0}{\alpha_p - \dfrac{S(p)}{a(p)}} - \dfrac{\overline{Q}_k - \alpha_0^*}{\alpha_p^* - \dfrac{1}{a(p)}}}{\dfrac{\alpha_p^*}{\alpha_p^* - \dfrac{1}{a(p)}} - \dfrac{\alpha_p}{\alpha_p - \dfrac{S(p)}{a(p)}}} \cdot \frac{p_0}{p}$$

and

$$\overline{\Omega}_m = \frac{\dfrac{\overline{Q}_g - \alpha_0}{\alpha_p - \dfrac{S(p)}{a(p)}} - \dfrac{\overline{Q}_k - \alpha_0^*}{\alpha_p^* - \dfrac{1}{a(p)}}}{\dfrac{\alpha_p^*}{\alpha_p^* - \dfrac{1}{a(p)}} - \dfrac{\alpha_p}{\alpha_p - \dfrac{S(p)}{a(p)}}} \cdot \frac{1}{e^{a_m(p-p_0)}},$$

Here $\alpha_p = \dfrac{p\beta}{z(p)p_{at}}[1 - c(p)\overline{\gamma}(p)]$; $\alpha_0 = \dfrac{p_0\beta}{z_0 p_{at}}[1 - c_0\overline{\gamma}_0]$; $\alpha_0^* = \dfrac{p_0\beta c_0}{z_0 p_{at}}$;

$\alpha_p^* = \dfrac{p\beta c(p)}{z(p)p_{at}}$; $\overline{Q}_g = \dfrac{Q_g}{\Omega_0}$, $\overline{Q}_k = \dfrac{Q_k}{\Omega_0}$;

Q_g, Q_k is the cumulative production of gas and condensate, to the moment corresponding to the current reservoir pressure p. Parameters with zero indices correspond to the initial reservoir pressure.

Similar expressions were obtained for light oil deposits and carbonated oil deposits, as a special case.

It has been established that at the beginning of development, the energy system behaves like an elastic system, even if there is a water-pressure system with a high degree of activity. This is due to the inertia of activation of the reservoir water basin.

The developed method for determining the reservoir-drive and the methodology for calculating the values of the activity criteria were verified on the examples of real fields "Bahar" and "Janub", fields that are almost depleted and sufficiently studied.

In addition, the following techniques have been developed for the interpretation of production data (well-test data) for gas condensate and volatile oil deposits:

2. Methodology for calculating the initial balance reserves of hydrocarbons. The proposed technique is based on the principle of pressure drop and material balance equations between the phases of the hydrocarbon system. Material balance equations express the relationship between production, balance reserves and reservoir pressure. This approach does not require the drilling of additional exploration wells to define the contours of the reservoir. To apply this technique, it is necessary to have flow rates measured at two different reservoir pressures and PVT data from the hydrocarbon system at the same reservoir pressures.

On the basis of the binary model, the material balance equations for the gas condensate mixture and light oils in the nonlinearly elastic, relaxationally elastic and relaxationally creeping reservoirs are written. From these equations, expressions for the dependence between the change in reservoir pressure over time ($\frac{dp}{dt}$), well flow rate (q - gas or oil flow rate in a gas condensate or light oil reservoir, respectively) and the pore volume of the reservoir in the form $\frac{dp}{dt} = f(q, \Omega_0, m, p, \rho)$. From the approximate integration of these expressions at the boundaries of p_2, p_1 and t_1, t_2, the following expression was obtained for determining the initial volume of gassaturated (or oil-saturated) pores (Ω_0):

$$\Omega_0 \approx \frac{\lfloor K(p,\rho)_{t2}q_{t2} + K(p,\rho)_{t1}q_{t1} \rfloor T}{2(p_1 - p_2)}$$

Here $T = (t_2 - t_1)$ is the time interval, $K(p,\rho)_{t1}$, $K(p,\rho)_{t2}$, q_{t1}, q_{t2} are the value of the K and the well flow rate at t_1 and t_2, respectively. $K(p,\rho)$ is determined by an expression corresponding to the reservoir model under consideration and the type of hydrocarbon system. For example, for a gas condensate system $K(p,\rho)$ has the following form:

$$K = \frac{\frac{1}{\overline{m}(p)}(\alpha_4 + \frac{\alpha_2}{G})}{(\overline{\alpha}_5 \cdot \alpha_4 + \overline{\alpha}_8 \cdot \alpha_2) - (\alpha_2\overline{\alpha}_3 + \overline{\alpha}_1\alpha_4) \cdot a_m}$$, where $\overline{\alpha}_1, \alpha_2, \overline{\alpha}_3, \alpha_4, \overline{\alpha}_5, \overline{\alpha}_8$ are known pressure-dependent parameters characterizing the considered hydrocarbon system (not shown here for compactness).

If accurate measurement of current rates is difficult in practice due to jumps, then the last expression can be expressed in terms of production as follows:

$$\Omega_0 \approx \frac{[K(p,\rho)_{t2} + K(p,\rho)_{t1}] \cdot Q_{t_1t_2}}{2(p_1 - p_2)}, \qquad (6.1)$$

where $Q_{t_1t_2}$ is the production for the time interval $(t_2 - t_1)$.

After determining the Ω_0, one can accordingly calculate the initial balance reserves (resource-in-place) of gas, condensate and oil in gas condensate and oil reservoirs:

$$V_{g0} = \left\{ \frac{p_0\beta}{z(p_0)p_{at}}[1 - c(p_0)\bar{\gamma}(p_0)] \right\} \Omega_0, \; V_{c0} = \frac{p_0\beta c(p_0)}{z(p_0)p_{at}}\Omega_0;$$

$$V_{n0} = \frac{1}{a(p_0)}\Omega_0, \; V_{g0} = \frac{S(p_0)}{a(p_0)}\Omega_0.$$

It should be noted that when the reservoir pressure is less than the pressure of the start of condensation (dew point) or saturation pressure in oil fields, the corresponding expressions are given for determining the saturation of pores with gas or liquid (in oil reservoirs).

The above expressions and algorithms for calculating the initial balance reserves of hydrocarbons have been tested on hypothetical reservoirs, the reserves of which were known in advance. To do this, a number of preliminary computer experiments were carried out to simulate the development of the field and obtain "field data" on development indicators. The results confirmed the high accuracy and reliability of the developed technique;

It should be noted that when the reservoir pressure is lower the dew point pressure or vapor pressure (in oil reservoirs), the corresponding expressions are given for determining the saturation of pores with liquid.

The above expressions and algorithms for calculating the initial balance reserves (resource-in-place) of hydrocarbons have been verified on hypothetical reservoirs, the reserves of which were known in advance. To do this, a number of preliminary computer experiments were carried out to simulate the development of the reservoir and obtain "field-data" on development indicators. The results confirmed the high accuracy and reliability of the developed technique;

3.The method for determining of the porosity change profile and the initial value of the porosity coefficient. Based on the material balance equations, a methodology was developed to determine the initial porosity coefficient of the formation and the nature of its change depending on the reservoir pressure.

It is possible to determine the numerical value of porosity and the nature of its change based on expression (6.1). Considering that $\Omega(p) = \Omega_0 \overline{m}(p)$, then expression (6.1) is written as follows:

$$\Omega(p) \approx \frac{\left[K^*(p,\rho)_{t2} + K^*(p,\rho)_{t1}\right] \cdot Q_{t_1 t_2}}{2(p_1 - p_2)}, \text{ where} \qquad (6.2)$$

$$K^* = \frac{(\alpha_4 + \frac{\alpha_2}{G})}{\left[(\alpha_5 + \alpha_6) \cdot \alpha_4 + (\alpha_7 + \alpha_8) \cdot \alpha_2\right]}$$

Here $K^*(p,\rho)_{t2}, K^*(p,\rho)_{t1}$ are the values of K^* at time points t_2 and t_1, respectively.

In the first approach, using the value of Ω_0, calculated by (6.1) neglecting the change in $\overline{m}$, one can determine the law of dependence of $\overline{m}(p)=\frac{\Omega(p)}{\Omega_0}$ on pressure from expression (6.2). To do this, a $\overline{m}(p)$ dependence graph is constructed, and then the resulting curve is approximated by one of the known methods. It is clear that the extrapolation of the curve to the initial reservoir pressure will give the initial value of the porosity factor.

Knowing the porosity factor and Ω, one can get certain ideas about the geometric parameters of the reservoir from the $\Omega=2\pi R_k hm$ formula.

To test the method described above, a number of calculations were carried out on a sample of a gas condensate reservoir. The error was estimated by comparing the calculated $\overline{m}$ values with its actual value. At lower values of reservoir pressure, the error increased, but with a further decrease in pressure, the error began to slightly decrease. Thus, the value of the maximum deviation did not exceed 2.7% in the entire interval of reservoir pressure drop and for all considered variants. The proposed approach makes it possible to determine the capacitance characteristics of gas condensate and oil (including light oil) reservoirs. This solution can be applied to reservoirs that are in the early stages of development and there is not enough development information available;

4. Method for determining the nature of the change and the initial value of the permeability. A technique has been developed for the interpretation of data from the study of gas condensate and oil reservoirs in a stationary mode in order to determine the initial permeability of the reservoir, the degree and nature of its change depending on the pressure drop. The proposed solution is based on a binary model of a complex hydrocarbon system, which takes into account the real phase properties- phase transformation and mass transfer between the pseudo components of the hydrocarbon system. To apply the technique, flow rates measured at two different bottomhole pressures at steady state and thermodynamic data of the hydrocarbon system at the considered reservoir pressure are required.

Determination of the initial value of permeability. Taking into account the approximation of the integrand (2.12), we write the expression for the debit (2.11) in the following form:

$$q = M\left\{a\left[\overline{p}_k \ln \overline{p}_k - \overline{p}_k - \overline{p}_s \ln \overline{p}_s + \overline{p}_s\right] - b(\overline{p}_k - \overline{p}_s)\right\}, \quad M = \frac{2\pi h}{\ln\frac{R_k}{r_s} - \frac{1}{2}}$$

The a and b coefficients can be determined using the values of the flow rates q_1, q_2, measured at two different bottomhole pressures p_{s1}, p_{s2}, respectively:

$$a = \frac{\frac{q_2}{M} - \frac{q_1}{M}\frac{\overline{p}_k - \overline{p}_{s2}}{\overline{p}_k - \overline{p}_{s1}}}{\ln\frac{\overline{p}_k^{\overline{p}_k}}{\overline{p}_{s2}^{\overline{p}_{s2}}} - \overline{p}_k + \overline{p}_{s2} - \left(\ln\frac{\overline{p}_k^{\overline{p}_k}}{\overline{p}_{s1}^{\overline{p}_{s1}}} - \overline{p}_k + \overline{p}_{s1}\right)\frac{\overline{p}_k - \overline{p}_{s2}}{\overline{p}_k - \overline{p}_{s1}}}$$

$$b = \frac{a\left(\ln\frac{\overline{p}_k^{\overline{p}_k}}{\overline{p}_{s1}^{\overline{p}_{s1}}} - \overline{p}_k + \overline{p}_{s1}\right) - \frac{q_1}{M}}{\overline{p}_k - \overline{p}_{s1}}.$$

Taking into account the (2.12) expression (see page 20), we write:

$$k(p_k)f(\rho) = \frac{a\ln(\overline{p}_k) - b}{\overline{\varphi}}$$

Due to the inaccuracy of the extrapolation of the $k(p_k)f(\rho)$ curve, a direct determination of the permeability from this expression is unreliable. It is established that the dependence of $-\ln(kf)$ on pressure is similar to a straight line. This allows us to approximate the dependence under consideration by the following binomial: $-\ln(kf) = a_1 p_k + b_1$

Here, the a_1 and b_1 coefficients can be determined using the $k(p_k)f(\rho)$ values corresponding to two different reservoir pressures, p_{k1} and p_{k2}, as follows:

$$a_1 = \frac{\ln(\frac{k_2 f_2}{k_1 f_1})}{p_{k1} - p_{k2}}, \quad b_1 = -\left[\ln(k_1 f_1) + \frac{\ln(\frac{k_2 f_2}{k_1 f_1})}{p_{k1} - p_{k2}} p_{k1}\right]$$

Knowing the a_1, b_1 coefficients, one can determine the permeability value at any reservoir pressure as follows:

$$k(p_k) = \frac{e^{-(a_1 p_k + b_1)}}{f} \tag{6.3}$$

With $p_k = p_0$, i.e. at the initial reservoir pressure $f = 1$, hence $kf = k_0$. Therefore, the $k_0 = e^{-(a_1 p_0 + b_1)}$ expression can be used to determine the initial permeability.

Algorithms are proposed to improve the accuracy of proposed methodology using the least squares method under conditions of an abundance of field data and to determine the effective permeability (f), the saturation coefficient of the pores with liquid (condensate in the gas condensate reservoir and oil in the oil reservoir) at an initial reservoir pressure less than one.

Determination of the permeability change factor. If we compare expression (6.3) with one of the laws of conductivity change, for example, with the $k = k_0 \left(\frac{p_k}{p_0} \right)^{\beta_k}$ power law, which will be used in the hydrodynamic model used in the development design: $\frac{e^{-(a_1 p_k + b_1)}}{f} = k_0 \left(\frac{p_k}{p_0} \right)^{\beta_k}$, from which we write the following expression to determine the value of the permeability change factor at the $p_k < p_0$ current reservoir pressure:

$$\beta_k = \frac{\ln\left[\frac{e^{-(a_1 p_k + b_1)}}{k_0 f} \right]}{\ln\left(\frac{p_k}{p_0} \right)} \tag{6.4}$$

If the permeability changes exponentially, then a similar expression for determining the permeability change factor is obtained in the following form:

$$\beta_k = \frac{\ln\left[\frac{e^{-(a_1 p_k + b_1)}}{k_0 f} \right]}{p_k - p_0}, \text{ где } p_k < p_0. \tag{6.5}$$

Contrary to what can be seen from (6.4) and (6.5), β_k is not a function of reservoir pressure, but a constant value for a considered reservoir. It characterizes the response of reservoir permeability to changes in reservoir pressure (more precisely, effective pressure). This means that at different reservoir pressures, all values calculated according to (6.4) or (6.5) must match. Therefore, β_k in the $\beta_k(p_k)$ coordinate system will be expressed by a horizontal line. In other words, the β_k values calculated at different reservoir pressures will be a set of points around a horizontal line. The ordinate of this line must be equal to the true value of β_k. The line should be drawn as close as possible to each of the calculated points. This means minimizing the $\overline{F} = \sum_{i=1}^{n} (\beta_{ki} - \beta_k)^2$ function: $\overline{F} = \sum_{i=1}^{n} (\beta_{ki} - \beta_k)^2 \to min$, where β_{ki} is the i-th value of β_k, obtained from calculations with the total number of n. β_k - the actual value of the permeability change factor.

If the minimization of the $\overline{F}$ function is satisfied under the $\frac{\partial \overline{F}}{\partial \beta_k} = -2\sum_{i=1}^{n} (\beta_{ki} - \beta_k) = 0$ condition, then the $\beta_k = \frac{\sum_{i=1}^{n} \beta_{ki}}{n}$ expression can be written. Therefore, the arithmetic mean of the calculated values can be taken as the true value of β_k.

The developed algorithms were tested in different cases, including for reservoirs with different compacting factor, and it was found that they have high accuracy and reliability;

5. Algorithms for determining the dynamic drainage and non-drained zones. A method for determining the dynamic radius of the well drainage zone an algorithm for determining stagnant (i.e. not drained) zones in the reservoir have been developed. To determine the dynamic radius of the well drainage zone bounder, the following expression was obtained:

$$R_k = r_s \exp\left\{ \frac{2\pi h}{Q} T \left[a\left(\ln \frac{\overline{p}_k^{\overline{p}_k}}{\overline{p}_s^{\overline{p}_s}} - \overline{p}_k + \overline{p}_s \right) - b(\overline{p}_k - \overline{p}_s) \right] + \frac{1}{2} \right\}$$

Here, the values of the coefficients a and b are determined from the well-testing data for bottomhole p_{s1} and p_{s2}, using the following formulas:

$$a=\frac{\dfrac{1}{M}\left(q_2-q_1\dfrac{\overline{p}_k-\overline{p}_{s2}}{\overline{p}_k-\overline{p}_{s1}}\right)}{\ln\dfrac{\overline{p}_k^{\overline{p}_k}}{\overline{p}_{s2}^{\overline{p}_{s2}}}-\overline{p}_k+\overline{p}_{s2}-\left(\ln\dfrac{\overline{p}_k^{\overline{p}_k}}{\overline{p}_{s1}^{\overline{p}_{s1}}}-\overline{p}_k+\overline{p}_{s1}\right)\dfrac{\overline{p}_k-\overline{p}_{s2}}{\overline{p}_k-\overline{p}_{s1}}},$$

$$b=\frac{a\left(\ln\dfrac{\overline{p}_k^{\overline{p}_k}}{\overline{p}_{s1}^{\overline{p}_{s1}}}-\overline{p}_k+\overline{p}_{s1}\right)-\dfrac{q_1}{M}}{\overline{p}_k-\overline{p}_{s1}},$$

Here $M=\dfrac{2\pi h}{\ln\dfrac{R_k}{r_s}-\dfrac{1}{2}}$; $\overline{p}_k$, $\overline{p}_s$ are dimensionless pressures on the well drainage zone bounder and at the bottomhole, respectively; Q is the total volume of extraction in the considered technological regime for the period of T.

On the basis of the obtained expression, an algorithm was developed to determine the reservoir stagnant zones on the development map.

CONCLUSIONS

A complex of studies on hydrodynamic modeling of filtration of a gas-condensate mixture and volatile oils in nonlinear elastic, relaxation elastic and relaxation creeping reservoirs, taking into account the inertial effects; have been studied the features of the influence of complex deformation of the reservoir rocks on the development process; have been created computer simulation models of the well-reservoir system during operation wells using gas-lift and downhole pumping, including sucker rod pumping methods; more effective methods and techniques have been developed for interpreting well-test data:

1. Hydrodynamic models of filtration processes of gas condensate mixtures and volatile oils in nonlinear elastic, relaxation elastic and relaxation creeping reservoirs have been created, taking into account the effects of inertial forces.

2. Algorithms have been developed to predict the depletion indicators of gas condensate and volatile oil deposits, taking into account inertial effects and complex deformations of reservoir rocks.

3. Algorithms for predicting the indicators of the processes of displacement of hydrocarbon mixtures by water into a well in gas condensate and volatile oil reservoirs under various geological and technological conditions have been developed.

4. Algorithms are proposed for calculating the main indicators of the development of gas condensate and light oil deposits, taking into account the difference in permeability and deformation characteristics of the bottomhole zone and the part of the reservoir remote from the well.

5. Algorithms for calculating the main indicators of the development of volatile oil deposits by means of gas lift and deep pumps have been developed, a computer simulation model of the well-reservoir system has been created.

6. For the first time, special criteria have been proposed, called “the reservoir energy activity criteria”, which characterize the degree of reservoir energy activity. Based on the activity criteria, a new approach has been developed for the unambiguous determination of the reservoir drive.

7. Methods have been developed for calculating the numerical values of the reservoir activity criteria for gas condensate and volatile oil deposits based on field data.

8. More efficient methods have been developed for the interpretation of field data for the development of gas condensate deposits and volatile oil deposits, represented by complex deformable reservoirs, namely:

- method for determining the rheological characteristics of the formation;
- a technique for determining the permeability and reservoir properties of a formation;
- methodology for calculating the initial balance reserves of hydrocarbons in gas condensate and volatile oil deposits;
- method for determining the reservoir-drive of gas condensate and oil deposits;

- method for determining the feed loop of a well, draining gas condensate and volatile oil reservoirs.

The main content of the dissertation has been reflected in the following works:

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Work [45] – creation of a mathematical model, writing a program, carrying out computer calculations and processing numerical results.

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Works [6-8, 10-15] – statement of the problem and processing of numerical results.

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