Journal of Engineering Physics and Thermophysics, Vol. 80, No. 1, 2007

ASYMMETRY OF FLUID EXCHANGE IN A DEFORMABLE FRACTURED-POROUS MEDIUM

A. A. Shchipanov UDC 532.546

The mechanism of fluid exchange between fractures and a pore matrix that occurs in the case of flow in a fractured-porous medium has been investigated with the use of an analytical apparatus and numerical modeling. It has been established that the decrease in the permeability of fractures in their deformation causes a symmetry loss by the matrix-fracture exchange. In single-phase flow, the asymmetry of the exchange is in the presence of a crossflow from the fractures to the matrix with increase and decrease in the fluid pressure in the medium. In two-phase oil–water flow, the symmetry of exchange (oil to fractures and water to the matrix) can be broken with decrease in the fracture permeability: the matrix–fractures oil flow is replaced by a fractures–matrix water flow. The asymmetry of the exchange can be the reason for the substantial reduction in the efficiency of cyclic action on the fractured-porous oil bed.

Introduction. The work seeks to investigate flows in a fractured-porous medium by the methods of mathematical modeling. Its main objective is to study the distinctive features of fluid exchange between the pore matrix and the system of fractures caused by the deformability of the latter.

To describe the flows in question one most widely uses a classical model of filtration in a medium with one porosity, double-porosity models, and models of double porosity and permeability (the latter will subsequently be called the double-permeability model for the sake of brevity). In the classical model [1], the fractured-porous medium has one porosity and permeability characterizing the medium as a unit. In the double-porosity model [2], the fractures and the pore matrix are characterized by different porosity and permeability. Figure 1 is an idealized representation of a fractured-porous medium in the form of a pore matrix divided by a system of fractures into blocks. The difference between the double-porosity and double-permeability models is the presence of macroflow in the pore matrix in the latter.

The theory of modeling of flows in a fractured-porous medium has been developed in [3–12]. We consider the aspects of modeling of fluid exchange. G. I. Barenblatt and coauthors [2] proposed that liquid flow in a fractured-porous medium be described as that in a system with two interacting embedded media by introducing a source term for description of crossflows between the embedded media into the equations based on the law of conservation of mass and on Darcy's law. The crossflows in this case are caused by the difference of the pressures in the fractures and the matrix. In [8, 9], it is proposed that in the two-phase oil–water case the oil inflow from the matrix blocks be described by the source term in the filtration equations for fractures (by the function of capillary impregnation (soaking) characterizing hydrophilic rocks); this term is dependent on the time of residence of an oil-saturated block in the flooded zone. Konyukhov et al. [10] propose that two-phase matrix-fractures crossflows be modeled on condition of local pressure equilibrium; in this case the intensity of the crossflows is determined by the compressibility of the system fluids–bed. Models of fluid exchange between the matrix and the fractures occurring under the action of elastic, capillary, and gravity forces, diffusion, and other factors in a multiphase case have been proposed and realized based on the double-medium model at present [5, 6, 11, 12]. In this work, the exchange is investigated based on the Barenblatt model [2], which has enjoyed the widest use.

The present investigations have practical application to description of the processes of filtration in fractured-porous oil beds (a sample of the core of fractured-porous oil-saturated rock is presented in Fig. 2), that occur in their development. The exchange mechanism provides a basis for the method of cyclic (periodic hydrodynamic) action on

PermNIPIneft', 29 Sovetskaya Armiya Str., Perm', 614066, Russia; email: aschipanov@permnipineft.com.
Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 80, No. 1, pp. 35–45, January–February, 2007. Original article submitted November 26, 2004; revision submitted July 18, 2006.

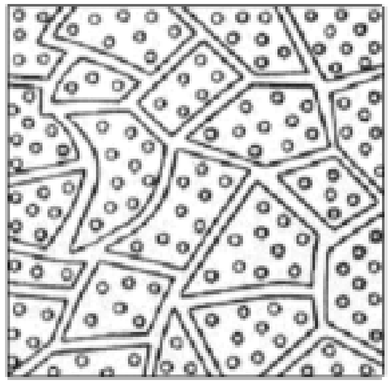

Fig. 1. Scheme of a fractured-porous bed.

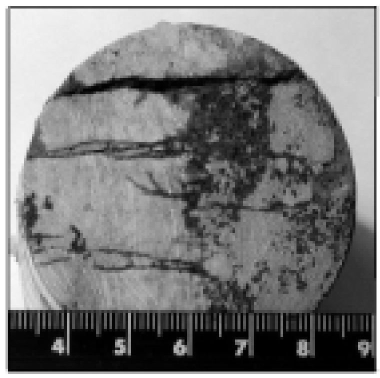

Fig. 2. Sample of the core of fractured-porous oil-saturated rock.

the bed, which is widely used in the practice of oil production. The operation of this mechanism determines the efficiency of action, enabling one to improve the extraction of oil from the matrix.

The cyclic action on the bed is carried out by creating periodic (cyclic) variations of the flow rate (acceleration, yield) or the pressure at the well-bores. The extraction of oil from a fracture-pore reservoir is increased due to the intensification of fluid flows from the matrix to the fractures and conversely [10, 13]. It is assumed that, with reduction in the pressure in a double-porosity and double-permeability bed due to the operation of producing wells, the fluid moves from the matrix to the fractures because of the retardation of the propagation of a zone of low pressure in the matrix (it is caused by the lower hydraulic conductivity of the matrix compared to the fractures). In a double-porosity system, the fluid will move in the same direction and with a higher intensity because of the equalization of the pressures in the matrix and the fractures (the equalization is caused just by the crossflows between two embedded media). With increase in the pressure (e.g., due to the operation of injection wells), the velocity of propagation of a high-pressure zone in the matrix will be lower than that in the fractures for the same reason, and the fluid will move from the fractures to the matrix. Taking into account that the matrix contains predominantly oil, whereas the fractures contain water (the action is carried out after the flooding of the wells as a rule), additional production of oil from the matrix is ensured.

The previous investigations [14, 15] sought to evaluate the influence of matrix–fracture exchange occurring under the action of elastic and capillary forces on two-phase flow in a deformable fractured-porous bed with stationary boundary conditions. In the work presented, we investigate fluid exchange occurring under the action of elastic forces with stationary boundary conditions, which is characteristic of the process of displacement of oil from a hydrophobic matrix in the case of pressure pulsations in the bed. In this case the exchange is due to the compression and expansion of the void space of the fractured-porous medium and of the fluids, primarily oil, saturating it.

In the work, the emphasis is on the influence of the deformation of fractures, which is caused by the change in the pressure, on the process under study. The deformation of the fractured-porous medium is allowed for by introducing the dependences of the porosity and the permeability on the pressure [14–18]. It is assumed to use empirical

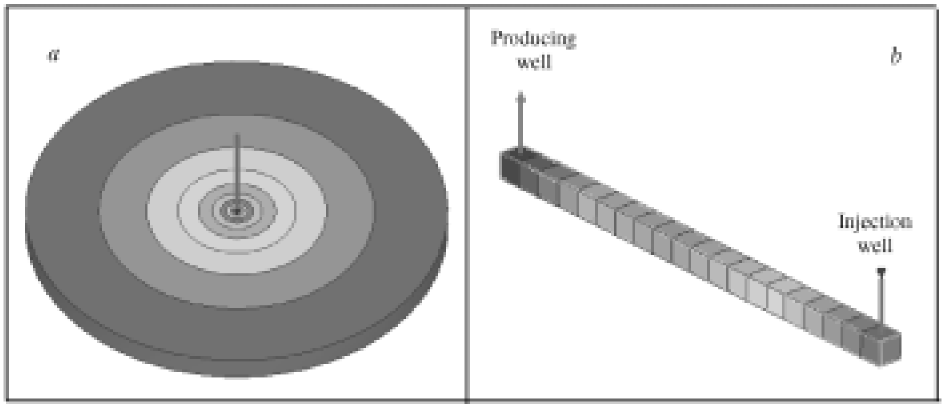

Fig. 3. Visualization of the domain of modeling of one-dimensional radial (a) and linear (b) filtration.

dependences; at the same time, the problem posed can be solved in joint formulation of elasticity and filtration theories [19–21].

The structure of the material presented further is as follows. First a mathematical description of the processes modeled within the framework of the double-permeability model with allowance for the deformation of the medium is given. Next the basic results of investigations carried out on simplified double-permeability models (Fig. 3) — a one-dimensional radial single-phase model and a one-dimensional linear two-phase model — are successively presented. The numerical modeling is carried out with the use of the Eclipse 100 software system developed by Schlumberger GeoQuest. In closing, the basic conclusions of the work are formulated and the lines of further development of investigations are charted.

Models of a Deformable Double Medium for Single- and Two-Phase Flows. We consider the equations of the double-permeability model for the cases of single- and two-phase filtration. In the single-phase case the system consists of two equations each of which is similar to the equation of a classical filtration model but differs by the presence of the exchange term reflecting fluid crossflows (exchange) between the pore matrix and the fractures. The exchange is due to the difference of the pressures in the fractures and the matrix; the pressure difference results from the difference in the velocities of the processes in the embedded media, which is determined by the relation of the parameters of the media. In the present investigations, we disregard the influence of gravity and capillary forces. On this basis, the system of equations describing single-phase flow can be represented in a one-dimensional radial formulation (Fig. 3a) in the form [5]

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{k^1}{B^1\mu^1}\frac{\partial p^1}{\partial r}\right]+q^{1,2}=\frac{\partial}{\partial t}\left(\frac{\phi^1}{B^1}\right), \tag{1}$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{k^2}{B^2\mu^2}\frac{\partial p^2}{\partial r}\right]-q^{1,2}=\frac{\partial}{\partial t}\left(\frac{\phi^2}{B^2}\right), \tag{2}$$

$$q^{1,2}=\sigma k^1\,(1/B\mu)^{1,2}\,(p^2-p^1)\,. \tag{3}$$

For the system of equations (1)–(3), we prescribe the pressure

$$p^i\,(r_\mathrm{w},t)=p_\mathrm{w}\,,\;\;p^i\,(r_\mathrm{e},t)=p_\mathrm{e}\,,\;\;p^i\,(r,0)=p_\mathrm{e} \tag{4}$$

as the boundary and initial conditions.

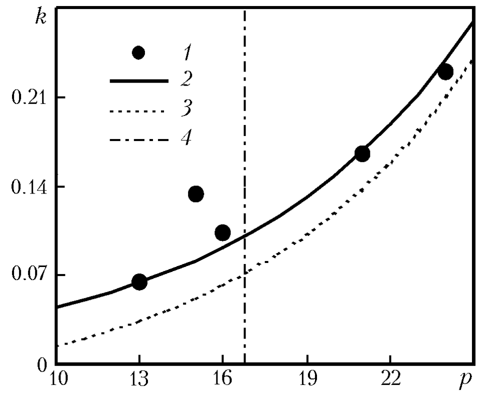

Fig. 4. Pressure dependences of the permeability of the fractured-porous medium (2) and the permeability of fractures (3), obtained in approximation of the results of field investigations (1) with the use of the results of investigations of the core; 4) degassing pressure. p, MPa; k, μm^2.

In the case of two-phase filtration the number of equations in the system grows, which is due to the description of flow of each phase. In a one-dimensional formulation (Fig. 3b), the system of equations has the form [5]

$$\frac{\partial}{\partial x}\left[\frac{k^1 k^1_{\mathrm{rel,liq}}}{B^1_{\mathrm{liq}}\mu^1_{\mathrm{liq}}}\frac{\partial p^1}{\partial x}\right]+q^{1,2}_{\mathrm{liq}}=\frac{\partial}{\partial t}\left(\frac{\phi^1 S^1_{\mathrm{liq}}}{B^1_{\mathrm{liq}}}\right)+f^1_{\mathrm{liq}}\,, \tag{5}$$

$$\frac{\partial}{\partial x}\left[\frac{k^2 k^2_{\mathrm{rel,liq}}}{B^2_{\mathrm{liq}}\mu^2_{\mathrm{liq}}}\frac{\partial p^2}{\partial x}\right]-q^{1,2}_{\mathrm{liq}}=\frac{\partial}{\partial t}\left(\frac{\phi^2 S^2_{\mathrm{liq}}}{B^2_{\mathrm{liq}}}\right)+f^2_{\mathrm{liq}}\,, \tag{6}$$

$$q^{1,2}_{\mathrm{liq}}=\sigma k^1\left(k_{\mathrm{rel,liq}}/B_{\mathrm{liq}}\mu_{\mathrm{liq}}\right)^{1,2}(p^2-p^1)\,. \tag{7}$$

$$S^i_{\mathrm{oil}}+S^i_{\mathrm{wat}}=1\,. \tag{8}$$

For the system of equations (5)–(8), we set the impermeability condition at the boundary of the computational domain; the wells are modeled using the inflow model [1] at a prescribed pressure on the wall (point source (sink) in Eqs. (5) and (6)); the initial pressure in the computational domain is assumed to be constant

$$\frac{\partial p^i}{\partial x}(0,t)=\frac{\partial p^i}{\partial x}(L,t)=0\,,\;\; f^i_{\mathrm{liq}}(x_{\mathrm{w}},t)=\frac{2\pi h k^i k^i_{\mathrm{rel,liq}}(p^i_{\mathrm{e}}-p_{\mathrm{w}})}{\mu^i_{\mathrm{liq}}B^i_{\mathrm{liq}}\ln(r_{\mathrm{e}}/r_{\mathrm{w}})}\,,\;\; p^i(x,0)=p^0\,. \tag{9}$$

In the present investigation, in obtaining the analytical solutions and carrying out computational experiments based on the double-porosity model, we allow for the deformability of fractures by introducing the dependence of both the porosity and the permeability on the pressure.

In modeling filtration, one usually allows just for the dependence of the porosity on the pressure, which is necessary for description of the elastic displacement of oil from the reservoir. However, the compressibility of rock is also reflected in the substantial dependence of the permeability on the pressure [17, 18]. For a fractured-porous medium the change in the pressure leads to a substantial change in the permeability [18]. Neglect of this in modeling may bring about substantial errors in the results and even their total inadequacy to the processes modeled [14, 15].

TABLE 1. Parameters of the Fractured-Porous Medium and of the Fluids, Used in the Calculations and Affecting Matrix–Fractures Exchange

Parameter	ϕ^1	ϕ^2	c_r^1	c_r^2	k^1	k^2	α_r^1	α_r^2	c_{oil}	c_{wat}
Value	0.09	0.01	0.001	0.04	0.03	0.24	0.003	0.12	0.002	0.0001

To model the dependence of the porosity, the permeability, and the volume coefficient of the fluid (or the phase) on the pressure we use exponents of the following form:

$$\phi^i = \phi^{i0} \exp\left[c_r^i \left(p^i - p^{i0}\right)\right], \tag{10}$$

$$k^i = k^{i0} \exp\left[\alpha_r^i \left(p^i - p^{i0}\right)\right], \tag{11}$$

$$B^i = B^0 \exp\left[-c \left(p^i - p^0\right)\right]. \tag{12}$$

Fluid exchange in the single-phase case is characterized by the use of expression (3) in Eqs. (1) and (2). An analysis of the equations of the double-medium model and the ideas of fluid crossflows [13, 21, 22] as well as the computational experiments carried out in these investigations enable us to single out the following groups of parameters (appearing in relations (10)–(12)) affecting the intensity of matrix–fractures exchange: the relation of the compressibilities of the matrix and the fractures $\phi^1(c_r^1 + c)/[\phi^2(c_r^2 + c)]$, the permeability of the matrix k^1, the mobility of the fluid $1/B_\mu$, and the exchange coefficient σ (the influence of this parameter is dependent on the values of the above quantities).

To characterize the matrix–fractures crossflows in two-phase flow, we introduce the exchange term of (7) into Eqs. (5) and (6). In the two-phase case the group of parameters affecting the exchange intensity includes the mobilities of phases saturating the matrix and the fractures.

Also, the present investigations are aimed at evaluating the influence of the coefficient of change in the permeability of fractures α_r^2 on the intensity and character of matrix-fractures exchange.

For calculations of fluid flow in a double-permeability medium we use a fully implicit method [1]. A distinctive feature of the computational experiments is its extremely small computational time steps that were found to be necessary in preliminary calculations aimed at evaluating the influence of the time step on the results. The reason is the short duration of the exchange caused by the action of elastic forces.

Next we present results of study of matrix–fractures exchange; the study has been performed on simplified models (Fig. 3, the corresponding systems of equations (1)–(4) and (5)–(9) with account for (10)–(12)) characteristic of problems of identification and modeling of oil beds. The investigations were carried out for a parametric domain characterizing the carbonate oil beds of the deposits of the Perm' Kama Region (Table 1, σ = 1.0 m^{-2}). The series of computational experiments was carried out for two cases whose comparison enables us to evaluate the influence of the change in the permeability on the exchange, when the permeability of the fractures is: a) constant; b) dependent on the pressure. In both cases the fractures are of equal compressibility. To describe the change in the permeability with pressure we used the dependence obtained from the interpretation of the results of field investigations (Fig. 4).

Influence of the Change in the Permeability on the Pressure Distribution. To substantiate the results presented below we investigate the problem on pressure distribution on condition that the permeability is dependent on it. We consider two problems in a simplified formulation: one-dimensional single-phase stationary linear and radial flows of a fluid in a porous medium with a prescribed pressure at the boundaries of the computational domain (the viscosity and the volume coefficient of the fluid are considered to be constant and equal to unity). We give the differential equation describing one-dimensional linear single-phase stationary flow and the boundary conditions:

$$\frac{d}{dx}\left[k \frac{dp}{dx}\right] = 0\,, \tag{13}$$

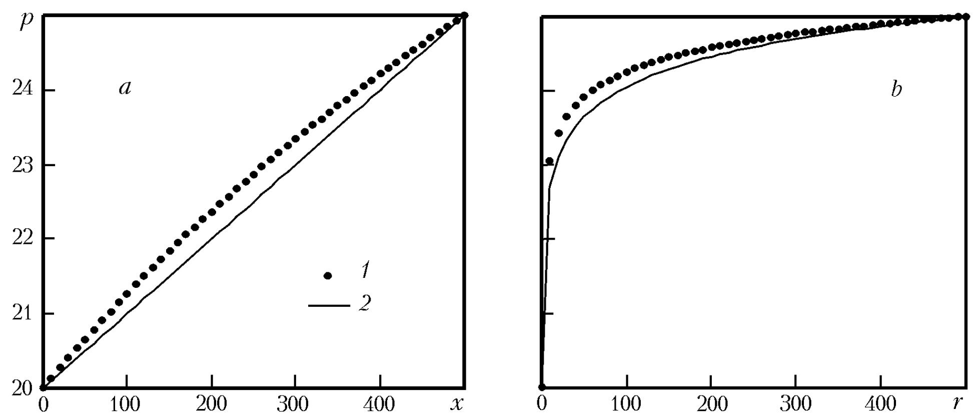

Fig. 5. One-dimensional stationary pressure distribution in a deformable (1) and undeformable (2) porous medium in Cartesian (a) and radial (b) coordinate systems. r, m; p, MPa.

$$p\,(0) = p_0\,, \quad p\,(L) = p_L\,, \tag{14}$$

where the permeability is dependent on the pressure:

$$k\,(p) = k^0 \exp\left[\alpha_r\,(p - p^0)\right]. \tag{15}$$

The analytical solution for system (13)–(15) is as follows:

$$p\,(x) = \frac{1}{\alpha_r} \ln \left\{ \frac{\exp\,[\alpha_r\,(p_L - p^0)] - \exp\,[\alpha_r\,(p_0 - p^0)]}{L}\, x + \exp\,[\alpha_r\,(p_0 - p^0)] \right\} + p^0\,. \tag{16}$$

Under the assumption that the permeability is constant, we obtain the analytical solution for (13) and (14)

$$p\,(x) = \frac{(p_L - p_0)}{L}\, x + p_0\,. \tag{17}$$

The equation describing one-dimensional radial single-phase stationary flow with boundary conditions is

$$\frac{d}{dr}\left[rk\,\frac{dp}{dr} \right] = 0\,, \tag{18}$$

$$p\,(r_w) = p_w\,, \quad p\,(r_e) = p_e\,. \tag{19}$$

The analytical solution for system (18)–(19) and (15) is as follows:

$$p\,(r) = \frac{1}{\alpha_r} \ln \left\{ \frac{\exp\,[\alpha_r\,(p_e - p^0)] - \exp\,[\alpha_r\,(p_w - p^0)]}{\ln\,(r_e/r_w)} \ln\left(\frac{r}{r_w}\right) + \exp\,[\alpha_r (p_w - p^0)] \right\} + p^0\,. \tag{20}$$

Under the assumption that the permeability is constant we obtain the analytical solution for (18) and (19)

$$p\,(r) = \frac{p_e - p_w}{\ln\,(r_e/r_w)} \ln\left(\frac{r}{r_w}\right) + p_w\,. \tag{21}$$

The analytical solutions (16) and (17) for the parameters L = 500 m, $p_0 = p^0$ = 20 MPa, p_L = 25 MPa, and α_r = 0.12 MPa^{-1} are given in Fig. 5a, whereas the solutions (20) and (21) for the parameters r_w = 0.1 m, r_e = 500

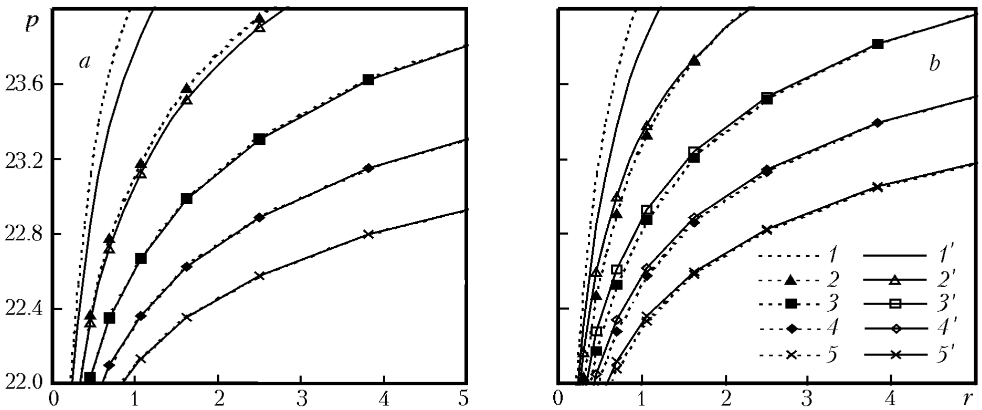

Fig. 6. Evolution of the reduction in the pressure in the near-well zone of the bed for a constant (a) and pressure-dependent (b) fracture permeability at successive instants of time: 1 and 1′) 0.0001; 2 and 2′) 0.001; 3 and 3′) 0.01; 4 and 4′) 0.1; 5 and 5′) 1 day; 1–5) pressure in the matrix; 1′–5′) in the fractures. *r*, m; *p*, MPa.

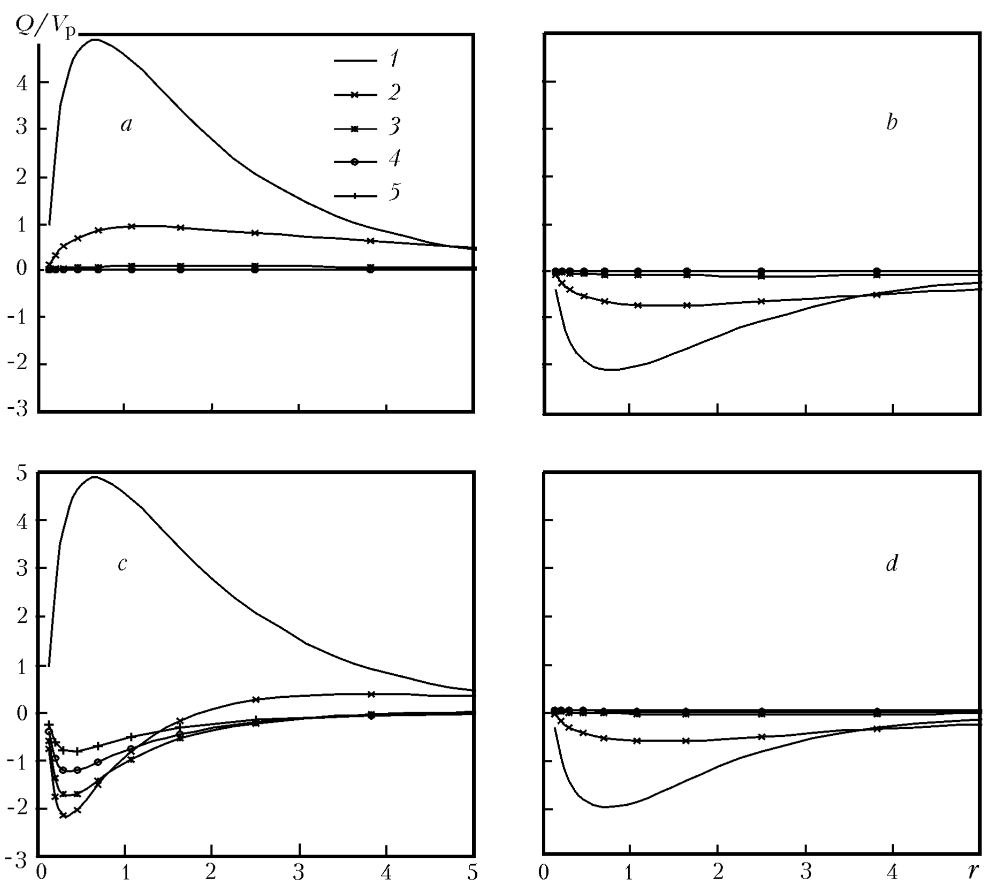

Fig. 7. Density of the fluid crossflows with reduction (a and c) and increase (b and d) in the pressure in the near-well zone of the bed for a constant (a and b) and pressure-dependent (c and d) fracture permeability at successive instants of time after the startup (shutdown) of the well: 1) 0.0001; 2) 0.001; 3) 0.01; 4) 0.1; 5) 1 day. *r*, m.

TABLE 2. Main Direction of Crossflows in Single-Phase Flow for the Cases of a Constant and Pressure-Dependent Permeability of Fractures

Fracture permeability	Character of change in the pressure	Main direction of crossflows
Constant	$p^1, p^2 \downarrow$	Matrix → fractures
	$p^1, p^2 \uparrow$	Fractures → matrix
Pressure-dependent	$p^1, p^2 \downarrow$	Fractures → matrix
	$p^1, p^2 \uparrow$	Fractures → matrix

m, $p_w = p^0 = 20$ MPa, $p_e = 25$ MPa, and $\alpha_r = 0.12$ MPa^{-1} are presented in Fig. 5b. The dependence of the permeability on the pressure (15) causes the pressure within the computational domain to increase, i.e., the pressure curve for the cases of changing permeability lies higher than the pressure curve for the cases of constant permeability. From the viewpoint of the mechanics of the process, the reason is the decrease in the permeability in the region of low pressure and hence the increase in the pressure gradient in this region.

Single-Phase Radial One-Dimensional Flow. The first series of computational experiments seeks to study the mechanism of matrix–fractures exchange on a single-phase radial double-porosity model (model of fluid inflow from the external boundary to the well, Fig. 3a). It is assumed that oil (single-phase fluid) saturates a fractured-porous medium and moves in it. We model the process of filtration on condition of a prescribed pressure at the external boundary ($p_e = 25$ MPa) and starting up of the well with a prescribed wall pressure ($p_w = 21$ MPa) followed by its shutdown.

The modeling results demonstrate that the mechanism of crossflows of the fluid with a constant permeability operates as follows. The process of reduction in the pressure in the matrix is retarded compared to that in the fractures (Fig. 6a), which, as Fig. 7a shows, brings about a fluid crossflow from the matrix to the fractures; the crossflow fades with pressure equalization. In Fig. 7, V_p is the pore volume corresponding to the crossflow and including the void volumes of the matrix and the fractures. When the pressure is restored, the process of increase in the matrix pressure is also retarded, bringing about a fluid flow in the opposite direction: from the fractures to the matrix (Fig. 7b). The results obtained are consistent with the well-established ideas [13, 21] of the fluid crossflow between highly and low-permeable zones in the case of pressure pulsations in the bed.

In the case of pressure-dependent permeability the velocity of propagation of the cone of depression in the matrix begins to exceed the velocity of its propagation in fractures (Fig. 6b), which leads to a predominant fractures–matrix crossflow (Fig. 7c). The process of pressure restoration and the fluid flows are similar to the constant-permeability case: the fluid flows from the fractures to the matrix (Fig. 7d). The effect observed is related to the propagation of the cone of depression and the reduction in the permeability of the fractures, which involves the increase in the pressure gradients in the system of fractures in the deformation zone. The increase in the pressure (pressure gradients) in a deformable medium with respect to an undeformable one has been substantiated above on the basis of the analytical solutions obtained (Fig. 5b).

Based on the analytical solutions obtained and on the results of the numerical experiment it may be inferred that, in the above formulation of the problem, the decrease in the permeability of fractures produces the effect of non-symmetric exchange: in the case of both the reduction and increase in the pressure the fluid flows predominantly from the fractures to the matrix (Table 2).

The influence of the decrease in the porosity of fractures on the exchange lies solely in the decrease in the crossflow intensity as demonstrated by the results of the computational experiments carried out and by an analysis of the analytical solutions of equations describing flow in a double-porosity medium [22]: the increase in the compressibility of fractures causes the ratio of the compressibilities of the matrix and the fractures to decrease, which brings about the reduction in the intensity of exchange.

Two-Phase Linear One-Dimensional Flow. The second series of computational experiments is aimed at studying exchange processes in modeling the two-phase displacement of oil from the injection well to the producing well by water (Fig. 3b) in a double-permeability medium (analog of the Buckley–Leverett problem).

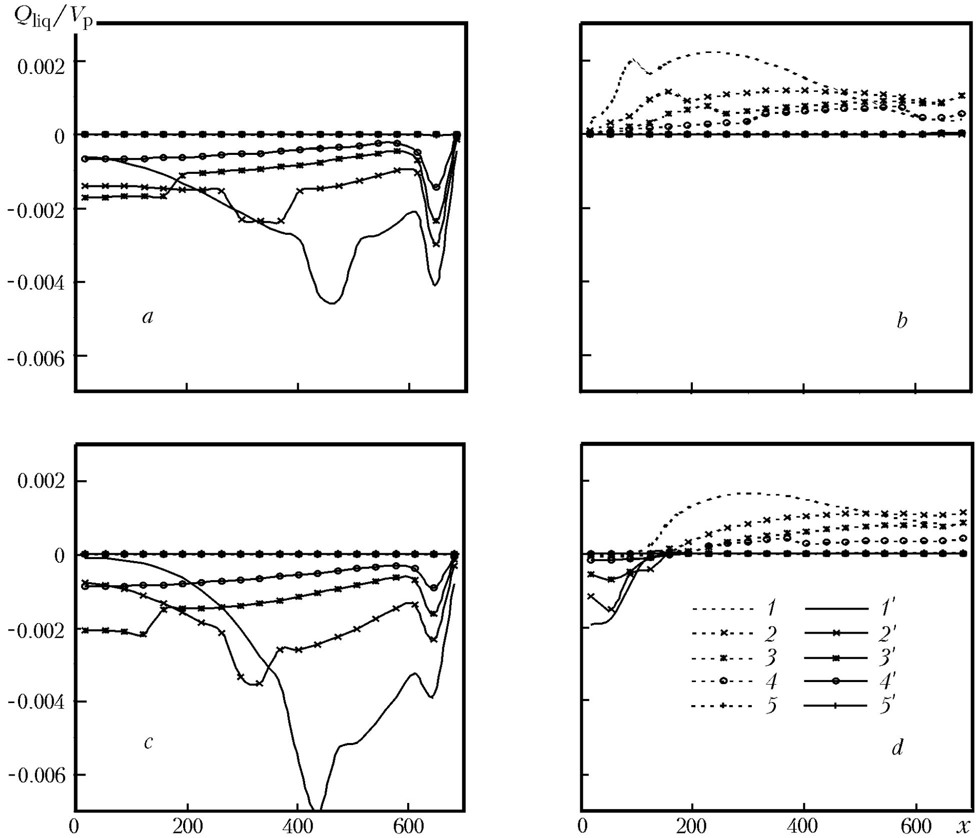

Fig. 8. Density of the crossflows of oil (1–5) and water (1′–5′) with increase (a and c) and reduction in the bed pressure for a constant (a and b) and pressure-dependent (c and d) fracture permeability at successive instants of time after the startup of the injection (producing) well: 1 and 1′) 1; 2 and 2′) 2; 3 and 3′) 4; 4 and 4′) 8; 5 and 5′) 30 days. *x*, m.

In the presented formulation of the problem, the fractures are initially filled with water, and the matrix is filled with oil. We investigate exchange in successive operation of the injection (pumping of water) and producing (drainage) wells. The injection well operates with a wall pressure $p_{w.i}$ = 30 MPa; the producing well operates with a pressure $p_{w.p}$ = 20 MPa (initial pressure in the bed p = 20 MPa). The oil is displaced from the matrix due to the water inflow from the injection well and to the water crossflows from the fractures, which are caused by successive increase and reduction in the pressure.

The computational experiments have shown that the increase in the pressure in the computational domain brings about a water flow from the fractures to the matrix (mainly due to the compression of oil), whereas the reduction of the pressure causes a predominant crossflow of oil from the matrix to the fractures (due to the retention of water in the matrix under the action of capillary forces) in the case of both a constant (Fig. 8a and b) and pressure-dependent (Fig. 8c and d) permeability of the fractures. Substantial crossflows are present throughout the inter-well space.

The presence of the crossflow of oil from the matrix to the system of fractures in the two-phase case (compared to the single-phase one) is attributed to the replacement of oil by water (possessing a lower compressibility) in the fractures and to the higher mobility of the oil $k^1 k^1_{rel,oil}/\mu^1_{oil}$ in the matrix compared to the mobility of water $k^1 k^1_{rel,wat}/\mu^1_{wat}$. We dwell on the relation between the values of the crossflows in different directions for a constant and varying permeability. In the second case a substantial increase/decrease in the crossflow intensity is observed in operation of the injection/producing wells. The reason for the phenomenon is the influence of the change in the permeability of the fractures: the pressure and the permeability increase in operation of the injection well and decrease in operation of the producing well. However, unlike most of the computational domain, a water flow in the fractures–matrix direction is observed in the near-well zone of the producing well with decrease in the permeability. The size of this zone is determined by the region of the largest dynamic drop in the permeability, which causes return crossflows. The effect observed is attributed to the asymmetry of exchange in a deformable medium; the asymmetry has been found in investigating one-dimensional single-phase radial flow and is related to the influence (revealed based on the analytical solutions) of the change in the permeability on the pressure distribution (Fig. 5a).

Also, the computational experiments have shown that, just as in the case of single-phase flow, the decrease in the porosity of fractures in two-phase filtration leads solely to a reduction in the intensity of crossflows.

The results obtained enable us to draw the following conclusion useful from the viewpoint of applications: the deformation of fractures diminishes the efficiency of cyclic action on the bed, leading to a decrease in the intensity of exchange and to a replacement of the oil crossflows by water crossflows of opposite direction.

Conclusions. The results of an analysis of the analytical solutions and of numerical modeling of single-phase filtration in a deformable fractured-porous medium enable us to state that the deformation of the fracture component described in the model by the dependence of the permeability on the pressure, in addition to the compressibility of the void space, brings about the effect of asymmetry of exchange: in the case of both reduction and increase in the pressure the fluid moves predominantly from the fractures to the matrix.

The modeling of two-phase displacement in the case of pressure pulsation has shown that, when the oil in the fractures is replaced by water, we observe fluid exchange: the crossflows of water are directed from the fractures to the matrix, whereas the crossflows of oil move in the opposite direction. However, the deformation can lead to a substantial decrease in the intensity of the oil crossflows, a replacement of the oil in the flow by water, and a change in the flow direction, which is related to the effect of asymmetry of exchange, described above.

From the viewpoint of the development of deformable fractured-porous oil beds, the exchange asymmetry found leads to a substantial reduction in the efficiency of cyclic action on the bed. A reduction in the efficiency with drop in the bed pressure is predicted; it is related to the decrease in the permeability of fractures, leads to a replacement of the oil crossflows by water crossflows of the opposite direction, and to the reduction in the fracture porosity, which decreases the intensity of the oil flow between the matrix and the fractures.

A possible trend in development of investigations is the study of matrix–fractures flows based on a modified exchange model. Representation of the exchange term in the form of (3) or (7) assumes the use of the matrix permeability for calculation of the crossflows between the matrix and the fractures. Under the conditions of considerable deformation of fractures, when their permeability vanishes, representation of the exchange term must allow for the present change in the fracture permeability:

$$q^{1,2} = \sigma k^{1,2} \, (1/B\mu)^{1,2} \, (p^2 - p^1) \,,$$

where $k^{1,2}$ is the permeability obtained by averaging the values for the matrix and the fractures (e.g., by harmonic averaging). Experimental and theoretical investigations are required for a substantiated form of averaging. Modification of the exchange model will enable one to find new effects in interaction of two components in a fractured-porous medium.

The author expresses his thanks to S. V. Rusakov and D. V. Lyubimov for useful consultations and interest in the work.

NOTATION

B, volume coefficient of the fluid (phase); c, compressibility factor, MPa^{-1}; f, source (sink), sec^{-1}; h, bed thickness, m; k, permeability, μm^2; L, length of the computational domain, m; p, pressure, MPa; Q, bulk fluid crossflow between the matrix and the fractures, m^3·days^{-1}; q, fluid crossflow between the matrix and the fractures, sec^{-1}; r, radial coordinate, m; S, phase saturation; t, time, sec; $V_{\rm p}$, pore volume, m^3; x, Cartesian coordinate, m; α, coefficient of change in the permeability, MPa^{-1}; ϕ, porosity of the medium; μ, dynamic viscosity, mPa·sec; σ, parameter of the double-medium model, m^{-2}. Subscripts and superscripts: 0 (superscript), initial (t = 0) or specified conditions; 0 (subscript), boundary of the computational domain (x = 0); e, external boundary of the wall; i, medium: 1, matrix, 2, fractures, 1 and 2, averaging over both media; liq, liquid phase; oil, oil; wat, water; r, void (reactor) medium; rel, relative phase property; w, wall of the well: w.i, injection; w.p, producing.

REFERENCES

1. K. Aziz and A. Settari, *Petroleum Reservoir Simulation* [Russian translation], Nedra, Moscow (1982).
2. G. I. Barenblatt, Yu. P. Zheltov, and I. N. Kochina, Basic notions of the theory of filtration of homogeneous fluids in jointing rocks, *Prikl. Mat. Mekh.*, **24**, Issue 5, 852–864 (1960).
3. J. E. Warren and P. J. Root, The behavior of naturally fractured reservoirs, *SPE J.*, September, 245–255 (1963).
4. H. Kazemi, L. S. Merrill, L. Porterfeld, and P. K. Zeman, Numerical simulation of water-oil flow in naturally fractured reservoirs, *SPE J.* (SPE 5719), December, 317–326 (1976).
5. T. D. Golf-Racht, *Principles of Oil-Field Geology and Development of Jointing Collectors* [Russian translation], Nedra, Moscow (1986).
6. J. C. Sabathier, B. J. Bourbiaux, M. C. Cacas, and S. Sarda, A new approach of fractured reservoirs, in: *Proc. SPE Int. Petroleum Conf. and Exhibition of Mexico* (SPE 39825), Villahermosa, Mexico (1998), pp. 1–12.
7. B. Noetinger, T. Estebenet, and P. Landereau, A direct determination of the transient exchange term of fractured media using a continuous time random walk method, *Transport Porous Media*, **44**, 539–557 (2001).
8. V. M. Ryzhik, Displacement of oil by water in a porous medium with low-permeable inclusions, *Izv. Akad. Nauk SSSR*, *Mekh. Mashinostr.*, No. 1, 121–124 (1964).
9. A. A. Bokserman, V. L. Danilov, Yu. P. Zheltov, and A. A. Kocheshkov, On the theory of filtration of immiscible fluids in cracked-porous media, in: *Theory and Practice of Oil Production* [in Russian], Nedra, Moscow (1966), pp. 12–30.
10. V. M. Konyukhov, A. V. Kosterin, and A. N. Chekalin, Mathematical modeling of displacement of oil by water under a cyclic action on the cracked-porous stratum, *Inzh.-Fiz. Zh.*, **73**, No. 4, 695–703 (2000).
11. P. Quandalle and J. C. Sabathier, Typical features of a multipurpose reservoir simulator, *SPE Reservoir Eng.*, November, 475–480 (1989).
12. R. H. Dean and L. L. Lo, Simulations of naturally fractured reservoirs, *SPE Reservoir Eng.*, May, 638–648 (1988).
13. A. T. Gorbunov, S. A. Mykhtaryants, V. I. Safronov, M. L. Surguchev, O. É. Tsynkova, and I. N. Sharbatova, *Cyclic Flooding of Oil Pools* [in Russian], VNIIOÉNG, Moscow (1977).
14. A. V. Raspopov and A. A. Shchipanov, Influence of the dynamic deformation of a crack-pore reservior on oil production, *Neft. Khoz.*, No. 6, 97–99 (2002).
15. A. A. Shchipanov, Influence of the dynamic deformation of a crack-pore reservoir on the effect produced by an increase in depression, *Geology*, *Geophysics*, *and Mining of Oil and Gas Fields*, No. 2, 33–37 (2003).
16. G. I. Barenblatt, V. M. Entov, and V. M. Ryzhik, *Motion of Liquids and Gases in Natural Strata* [in Russian], Nedra, Moscow (1984).
17. A. T. Gorbunov, *Mining of Anomalous Oil Fields* [in Russian], Nedra, Moscow (1981).
18. V. D. Viktorin, *Influence of the Characteristic Features of Carbonate Collectors on the Efficiency of Development of Oil Pools* [in Russian], Nedra, Moscow (1988).
19. R. K. Wilson and E. C. Aifantis, On the theory of consolidation with double porosity, *Int. J. Eng. Sci.*, **20**, No. 9, 1009–1035 (1982).
20. V. N. Nikolaevskii, *Mechanics of Porous and Jointing Media* [in Russian], Nedra, Moscow (1984).
21. R. N. Diyashev, A. V. Kosterin, and É. V. Skvortsov, *Fluid Filtration in Deformable Oil Pools* [in Russian], Izd. Kazansk. Mat. Ob., Kazan' (1999).
22. Yu. M. Molokovich, A. I. Markov, A. A. Davletshin, and G. G. Kushtanova, *Piezometry of the Neighborhood of Wells. Theoretical Principles* [in Russian], Izd. "DAS," Kazan' (2000).