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AN ADAPTIVE MESH REDISTRIBUTION METHOD FOR THE THREE-PHASE NON-ISOTHERMAL FLOW PROBLEM IN THE GLOBAL FORMULATION

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The work focuses on using the adaptive mesh redistribution method to improve the accuracy of the numerical solution of the three-phase non-isothermal flow problem. For adaptation of the mesh to the solution, the equidistribution method is used. We use the global formulation of the problem based on the concept of global pressure to describe three-phase non-isothermal flow. The paper presents the equations of this model in generalized curvilinear coordinates, a numerical algorithm and the results of computational experiments carried out for a model problem of oil displacement by steam.

Keywords: adaptive mesh, equidistribution method, global pressure, numerical solution

One of the important issues arising in the modeling of multiphase flows is the correct determination of the position of thermal and filtration fronts, because there are relatively small subregions in which the gradient of the solution reaches high values. Obviously, the most detailed research of the flow is required near the injection well and at the phase interfaces. One of the most efficient approaches to increase the accuracy of the solution is the adaptive mesh redistribution method, the idea of which is to reduce the size of the mesh cells in areas with large values of gradients of the solution.

In this paper, the equidistribution method is used for constructing the adaptive mesh. We use the global formulation of the three-phase non-isothermal flow problem which is based on the introduction of a change of variables by which gradients of capillary pressures are excluded from the equations for pressure and temperature. We derive the equations of the model in generalized curvilinear coordinates for the two-dimensional case. We present equations for the determination of mesh points and a computational algorithm for the numerical implementation of the model on an adaptive mesh.

Formulation of the problem. Let us make the following assumptions about the physical data. We assume that the phases are in local thermal equilibrium that in any elemen-

tary volume, fluids saturating the porous medium and the rock have the same temperature. We assume that oil is a homogeneous non-evaporable fluid, the medium is homogeneous, isotropic and there are no gravitational forces. In this case, three-phase non-isothermal flow in a domain $\Omega = [0, L] \times [0, L] \subset R^2$ with the allowance of phase transitions in a water-steam system is described by the following equations [1-4]:

$$\phi \frac{\partial}{\partial t} (\rho_\alpha s_\alpha) + \nabla \cdot (\rho_\alpha \bar{u}_\alpha) + I_\alpha = q_\alpha, \quad (1)$$

$$\bar{u}_\alpha = -\frac{kk_\alpha}{\mu_\alpha} \nabla p_\alpha, \quad \alpha = w, o, g, \quad (2)$$

$$\frac{\partial}{\partial t} \left(\phi \sum_\alpha \rho_\alpha s_\alpha i_\alpha + (1-\phi) \rho_r i_r \right) + \nabla \cdot \sum_\alpha \rho_\alpha \bar{u}_\alpha i_\alpha - \nabla \cdot (k_T \nabla T) = q_T, \quad (3)$$

$$s_w + s_o + s_g = 1,$$

$$p_{ow} = p_o - p_w, \quad p_{go} = p_g - p_o, \quad (4)$$

$$\rho_\alpha = \rho_\alpha(p_\alpha, T), \quad \alpha = w, o, g, \quad (5)$$

where w, o, g, r are the phases of water, oil,

steam and rock; ϕ and k are the porosity and conductivity of the media; p_α , s_α , ρ_α , k_α , μ_α , i_α , $\vec{u}_\alpha$ are pressure, saturation, density, relative permeability, viscosity, enthalpy, velocity of the phase α ; k_T is the thermal conductivity; q_α and q_T are source/sink terms; I_α is the intensity of the phase transitions. We assume that $I_w = -I_g = I$, $I_o = 0$. The set of equations (1)-(5) is complemented with the following initial and boundary conditions:

$$T = T_0, p_\alpha = p_0, s_\alpha = s_{\alpha 0}, x \in \Omega, t = 0 \quad (6)$$

$$p_\alpha \cdot \mathbf{n} = 0, T \cdot \mathbf{n} = 0, s_\alpha \cdot \mathbf{n} = 0, x \in \partial\Omega, t > 0. \quad (7)$$

Let us introduce a new variable called global pressure according to the formula

$$\begin{aligned} p = p_o + \int_1^{s_w} & \left\{ -\theta_w(\eta, 0, p, T) \frac{\partial p_{ow}}{\partial s_w}(\eta, 0) + \right. \\ & + \theta_g(\eta, 0, p, T) \frac{\partial p_{go}}{\partial s_w}(\eta, 0) d\eta + \\ & + \int_0^s (-\theta_w(s_w, \eta, p, T) \frac{\partial p_{ow}}{\partial s_g}(s_w, \eta) + \\ & \left. + \theta_g(s_w, \eta, p, T) \frac{\partial p_{go}}{\partial s_g}(s_w, \eta) \right\} d\eta \end{aligned} \quad (8)$$

where $\theta_\alpha = \lambda_\alpha / \lambda$, $\lambda_\alpha = \rho_\alpha c_\alpha k_\alpha / \mu_\alpha$, $\lambda = \lambda_w + \lambda_o + \lambda_g$. In this case, it is easy to show that the set of equations (1) - (5) reduces to the following system of equations with respect to the temperature T , global pressure p and saturations s_w, s_o [1, 5-7]:

$$a_1 \frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T - \nabla \cdot (k_T \nabla T) = f_1, \quad (9)$$

$$a_2 \frac{\partial p}{\partial t} - \nabla \cdot (a_3 \nabla p) = c_0 \nabla^2 T + \vec{v} \cdot \nabla T + f_2, \quad (10)$$

$$\phi \rho_w \frac{\partial s_w}{\partial t} + \phi \rho_w s_w \left(\beta_{p_w} \frac{\partial p}{\partial t} + \beta_{T_w} \frac{\partial T}{\partial t} \right) -$$

$$- \nabla \cdot (\omega \nabla s_w) = \nabla \cdot (k \lambda_w \nabla (p - p_c)) + q_w - I, \quad (11)$$

$$\begin{aligned} \phi \rho_o \frac{\partial s_o}{\partial t} + \phi \rho_o s_o \left(\beta_{p_o} \frac{\partial p}{\partial t} + \beta_{T_o} \frac{\partial T}{\partial t} \right) = \\ = \nabla \cdot (k \lambda_o \nabla (p - p_c)) + q_o \end{aligned} \quad (12)$$

where

$$a_1 = \phi \sum_\alpha \rho_\alpha s_\alpha c_\alpha + (1 - \phi) \rho_r c_r,$$

$$a_2 = \sum_\alpha \phi c_\alpha s_\alpha \rho_\alpha \beta_{p_\alpha}, a_3 = k \lambda \gamma, c_0 = b_2 - \frac{b_1 k_T}{a_3},$$

$$b_1 = \sum_\alpha \phi c_\alpha s_\alpha \rho_\alpha \beta_{T_\alpha}, b_2 = k \lambda \xi, \vec{v} = \nabla b_2 + \frac{b_1}{a_3} \vec{u},$$

$$f_1 = q_T - \sum_\alpha q_\alpha i_\alpha, f_2 = \sum_\alpha c_\alpha (q_\alpha - I_\alpha) - \frac{b_1 f_1}{a_3},$$

$$\beta_{p_\alpha} = \frac{1}{\rho_\alpha} \frac{\partial \rho_\alpha}{\partial p}, \beta_{T_\alpha} = \frac{1}{\rho_\alpha} \frac{\partial \rho_\alpha}{\partial T}, \omega = \frac{\partial p_{ow}}{\partial s_w}.$$

Here, the equation (9) is obtained by subtracting from the equation (3) the equations (1) multiplied by the enthalpy i_α . To derive the equation (10), chain rule was applied for the first term in the equations (1) in view of (5). Further, the resulting equations are multiplied by c_α and summed. To determine the initial and boundary values of global pressure, (8) is used. The initial and boundary conditions for s_w, s_o and T remain unchanged.

The equidistribution method for generating adaptive mesh. We consider the following one-to-one mapping

$$x_k = x_k(q_1, q_2), k = 1, 2 \quad (13)$$

of the physical domain Ω into the unit square Q . To construct the adaptive mesh, we use the equidistribution method, the essence of which is to achieve permanence of the product of the

area S of a mesh cell with the vertices $x_{i,j}$, $x_{i+1,j}$, $x_{i+1,j+1}$, $x_{i,j+1}$ and the value of a pre-determined control function w in the center of this cell [8]:

$$w\left(x_{i+\frac{1}{2},j+\frac{1}{2}}\right)S_{i+\frac{1}{2},j+\frac{1}{2}} = \text{const.}$$

In this case, the position of the internal mesh nodes is determined by solving the following equation for the unknown functions x_1, x_2 :

$$\frac{\partial}{\partial q_1}\left(wH_2^2 \frac{\partial x_k}{\partial q_1}\right) + \frac{\partial}{\partial q_2}\left(wH_1^2 \frac{\partial x_k}{\partial q_2}\right) = 0, \quad (14)$$

$k=1,2$, where H_1, H_2 are Lamé coefficients. Then, we rewrite the equations of the model (9)-(12) in the generalized curvilinear coordinates (q_1, q_2) as follows:

$$a_1 J \frac{\partial T}{\partial t} + u_1 H_2 \frac{\partial T}{\partial q_1} + u_2 H_1 \frac{\partial T}{\partial q_2} - \frac{\partial}{\partial q_1}\left(\frac{k_r H_2}{H_1} \frac{\partial T}{\partial q_1}\right) - \frac{\partial}{\partial q_2}\left(\frac{k_r H_1}{H_2} \frac{\partial T}{\partial q_2}\right) = f_1 J, \quad (15)$$

$$a_2 J \frac{\partial p}{\partial t} - \frac{\partial}{\partial q_1}\left(\frac{a_3 H_2}{H_1} \frac{\partial p}{\partial q_1}\right) - \frac{\partial}{\partial q_2}\left(\frac{a_3 H_1}{H_2} \frac{\partial p}{\partial q_2}\right) = \tilde{f}_2, \quad (16)$$

$$\phi \rho_w J \frac{\partial s_w}{\partial t} + \phi \rho_w s_w J \left(\beta_{p_w} \frac{\partial p}{\partial t} + \beta_{T_w} \frac{\partial T}{\partial t} \right) - \frac{\partial}{\partial q_1}\left(\frac{\omega H_2}{H_1} \frac{\partial s_w}{\partial q_1}\right) - \frac{\partial}{\partial q_2}\left(\frac{\omega H_1}{H_2} \frac{\partial s_w}{\partial q_2}\right) = \tilde{f}_3, \quad (17)$$

$$\phi \rho_o \frac{\partial s_o}{\partial t} + \phi \rho_o s_o \left(\beta_{p_o} \frac{\partial p}{\partial t} + \beta_{T_o} \frac{\partial T}{\partial t} \right) = \tilde{f}_4 \quad (18)$$

where

$$u_m = -\frac{k\lambda}{H_m} \left(\gamma \frac{\partial p}{\partial q_m} - \xi \frac{\partial T}{\partial q_m} \right), \quad m=1,2, \quad J = H_1 H_2$$

$$\begin{aligned} \tilde{f}_2 = & c_0 \left(\frac{\partial}{\partial q_1} \left(\frac{H_2}{H_1} \frac{\partial T}{\partial q_1} \right) + \frac{\partial}{\partial q_2} \left(\frac{H_1}{H_2} \frac{\partial T}{\partial q_2} \right) \right) + \\ & + \frac{H_2}{H_1} \left(v_1 H_1 + \frac{\partial b_2}{\partial q_1} \right) \frac{\partial T}{\partial q_1} + \\ & + \frac{H_1}{H_2} \left(v_2 H_2 + \frac{\partial b_2}{\partial q_2} \right) \frac{\partial T}{\partial q_2} + f_2 J, \end{aligned}$$

$$\begin{aligned} \tilde{f}_3 = & J(q_w - I) + \frac{\partial}{\partial q_1} \left(\frac{k\lambda_w H_2}{H_1} \frac{\partial(p-p_c)}{\partial q_1} \right) + \\ & + \frac{\partial}{\partial q_2} \left(\frac{k\lambda_w H_1}{H_2} \frac{\partial(p-p_c)}{\partial q_2} \right), \end{aligned}$$

$$\begin{aligned} \tilde{f}_4 = & J q_o + \frac{\partial}{\partial q_1} \left(\frac{k\lambda_o H_2}{H_1} \frac{\partial(p-p_c)}{\partial q_1} \right) + \\ & + \frac{\partial}{\partial q_2} \left(\frac{k\lambda_o H_1}{H_2} \frac{\partial(p-p_c)}{\partial q_2} \right). \end{aligned}$$

The set of equations (15)-(18) describes the distribution of global pressure, temperature and saturations in the coordinates q_1, q_2 and is solved on a uniform mesh in the computational domain Q .

Let us define a uniform mesh in the domain Q as $\{q_{1i}, q_{2j}\}$: $q_{1i} = ih_1$, $q_{2j} = jh_2$, $i = 0, 1, \dots, N_1$, $j = 0, 1, \dots, N_2$ and let the time segment $[0, t_1]$ be divided into discrete steps $t^n = n\tau$, $n = 0, 1, \dots, M$, $t^0 = 0$, $t^M = t_1$. For the numerical implementation of equations (15), (16) and (17), we apply the scheme of alternating directions of the form

$$a^n \cdot \frac{\varphi^{n+\frac{1}{2}} - \varphi^n}{\tau} = \frac{1}{2} \left(\Lambda_1 \varphi^{n+\frac{1}{2}} + \Lambda_2 \varphi^n + f^n \right), \quad (19)$$

$$a^{n+\frac{1}{2}} \cdot \frac{\varphi^{n+1} - \varphi^{n+\frac{1}{2}}}{\tau} = \frac{1}{2} \left(\Lambda_1 \varphi^{n+\frac{1}{2}} + \Lambda_2 \varphi^{n+1} + f^{n+\frac{1}{2}} \right) \quad (20)$$

where difference operators Λ_1 and Λ_2 , coefficient a and right-hand side f of the equation (15) are determined in the form

$$\Lambda_1 T_{i,j}^{n+\frac{1}{2}} = \frac{1}{h_1^2} \left((k_T^n \Phi)_{i+\frac{1}{2},j} T_{q_1,i,j}^{n+\frac{1}{2}} - (k_T^n \Phi)_{i-\frac{1}{2},j} T_{q_1,i,j}^{n+\frac{1}{2}} \right) - \frac{H_{2,i,j}}{2h_1} \left(\tilde{u}_{1,i,j}^n T_{q_1,i,j}^{n+\frac{1}{2}} + \bar{u}_{1,i,j}^n T_{q_1,i,j}^{n+\frac{1}{2}} \right), \quad (21)$$

$$\Lambda_2 T_{i,j}^{n+1} = \frac{1}{h_2^2} \left(\left(\frac{k_T^n}{\Phi} \right)_{i,j+\frac{1}{2}} T_{q_2,i,j}^{n+1} - \left(\frac{k_T^n}{\Phi} \right)_{i,j-\frac{1}{2}} T_{q_2,i,j}^{n+1} \right) - \frac{H_{1,i,j}}{2h_2} \left(\tilde{u}_{2,i,j}^n T_{q_2,i,j}^{n+1} + \bar{u}_{2,i,j}^n T_{q_2,i,j}^{n+1} \right), \quad (22)$$

$$a_{i,j}^n = (a_1^n J)_{i,j}, \quad f_{i,j} = f_1 J, \quad \tilde{r}_{i,j} = \frac{1}{2} (r_{i,j} + |r_{i,j}|),$$

$$\bar{r}_{i,j} = \frac{1}{2} (r_{i,j} - |r_{i,j}|), \quad \Phi_{i,j} = \frac{H_{2,i,j}}{H_{1,i,j}},$$

for the equation (16) in the form of

$$\Lambda_1 p_{i,j}^{n+\frac{1}{2}} = \frac{1}{h_1^2} \left((a_3^n \Phi)_{i+\frac{1}{2},j} p_{q_1,i,j}^{n+\frac{1}{2}} - (a_3^n \Phi)_{i-\frac{1}{2},j} p_{q_1,i,j}^{n+\frac{1}{2}} \right), \quad (23)$$

$$\Lambda_2 p_{i,j}^{n+1} = \frac{1}{h_2^2} \left(\left(\frac{a_3^{n+\frac{1}{2}}}{\Phi} \right)_{i,j+\frac{1}{2}} p_{q_2,i,j}^{n+1} - \left(\frac{a_3^{n+\frac{1}{2}}}{\Phi} \right)_{i,j-\frac{1}{2}} p_{q_2,i,j}^{n+1} \right), \quad (24)$$

$a_{i,j}^n = (a_2^n J)_{i,j}$, $f_{i,j} = \tilde{f}_{2,i,j}$, and similarly for the equation (17) in the form of

$$\Lambda_1 s_{w,i,j}^{n+\frac{1}{2}} = \frac{1}{h_1^2} \left((\omega^n \Phi)_{i+\frac{1}{2},j} s_{w,q_1,i,j}^{n+\frac{1}{2}} - (\omega^n \Phi)_{i-\frac{1}{2},j} s_{w,q_1,i,j}^{n+\frac{1}{2}} \right), \quad (25)$$

$$\Lambda_2 s_{w,i,j}^{n+1} = \frac{1}{h_2^2} \left(\left(\frac{\omega^{n+\frac{1}{2}}}{\Phi} \right)_{i,j+\frac{1}{2}} s_{w,q_2,i,j}^{n+1} - \left(\frac{\omega^{n+\frac{1}{2}}}{\Phi} \right)_{i,j-\frac{1}{2}} s_{w,q_2,i,j}^{n+1} \right), \quad (26)$$

$$a_{i,j}^n = (\phi \rho_w^n J)_{i,j},$$

$$f_{i,j}^n = \tilde{f}_{3,i,j}^n - (\phi \rho_w^n s_w^n J)_{i,j} (\beta_{p_w} p_{t,i,j}^n + \beta_{T_w} T_{t,i,j}^n).$$

To solve the equation (14), we use the scheme of the form

$$\frac{x_{k,i,j}^{n+\frac{1}{2}} - x_{k,i,j}^n}{\tau} = \frac{1}{2} \left(\Psi_1 x_{k,i,j}^{n+\frac{1}{2}} + \Psi_2 x_{k,i,j}^n \right),$$

$$\frac{x_{k,i,j}^{n+1} - x_{k,i,j}^{n+\frac{1}{2}}}{\tau} = \frac{1}{2} \left(\Psi_1 x_{k,i,j}^{n+\frac{1}{2}} + \Psi_2 x_{k,i,j}^{n+1} \right), \quad (27)$$

$k = 1, 2$, where

$$\Psi_1 x_{k,i,j} = \frac{1}{h_1} \left((w H_2^2)_{i+\frac{1}{2},j} x_{k,q_1,i,j} - (w H_2^2)_{i-\frac{1}{2},j} x_{k,q_1,i,j} \right),$$

$$\Psi_2 x_{k,i,j} = \frac{1}{h_2} \left((w H_1^2)_{i,j+\frac{1}{2}} x_{k,q_2,i,j} - (w H_1^2)_{i,j-\frac{1}{2}} x_{k,q_2,i,j} \right).$$

The transition from the n -th time layer to the $(n+1)$ -th one is carried out according to the following algorithm. Using the values p, s_w, s_o, T at the n -th time layer, global pressure p^{n+1} is calculated from the equations (19), (20), (23), (24) which reduces to solving tridiagonal systems of linear equations by the sweep method. Similarly, from (19), (20), (21), (22), (25), (26), we determine the temperature field T^{n+1} and the saturation of water s_w^{n+1} . The obtained values are used to determine the intensity of the phase transitions J^{n+1} . Using the equation (27), the position of the internal mesh nodes are updated. An iterative process is conducted until the condition $|s_g^{n+1} - s_g^n| < \varepsilon$ holds for some $\varepsilon > 0$.

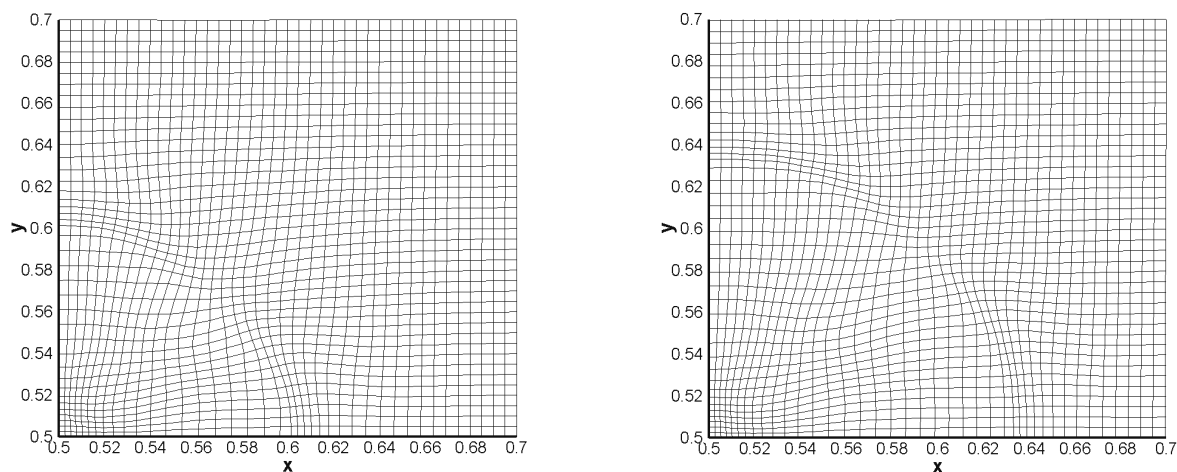


Fig. 1. The constructed adaptive mesh at $t = 20\tau$ and $t = 50\tau$

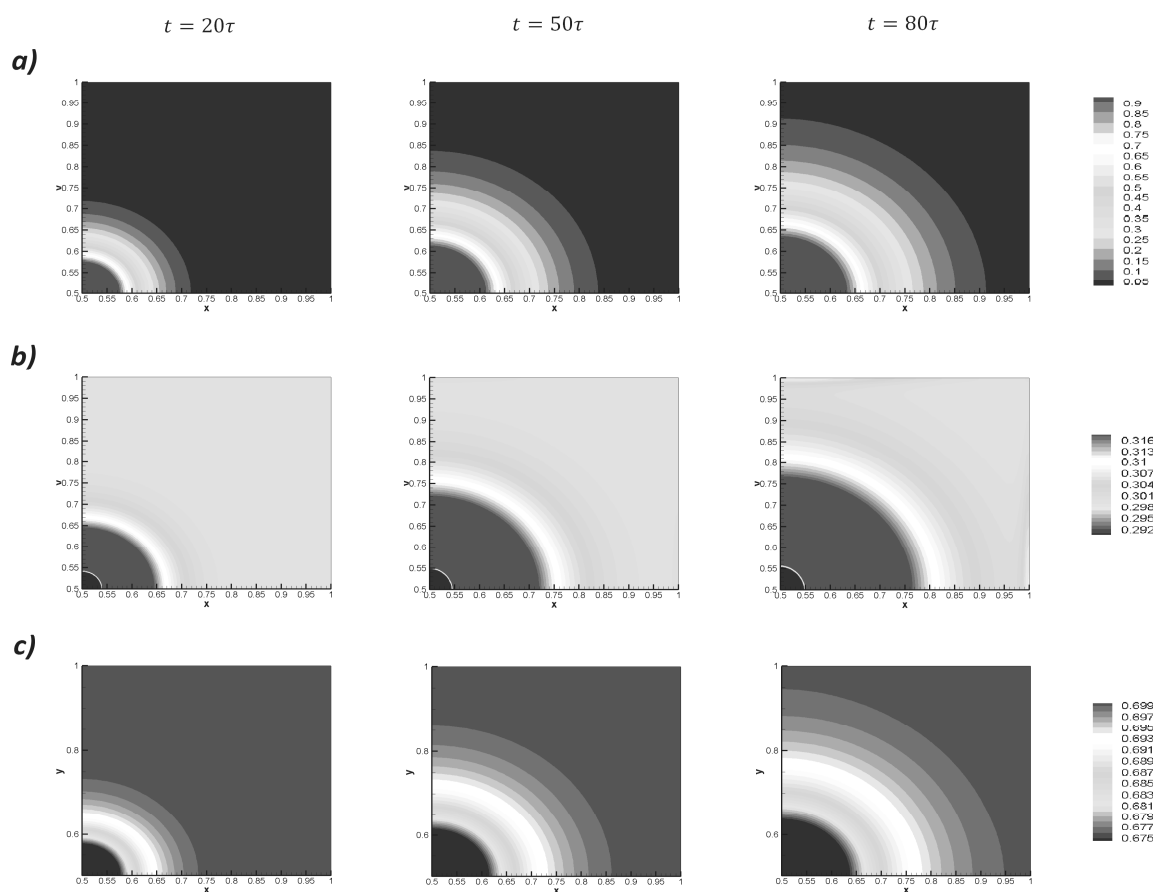


Fig. 2. The simulation results for: a) the temperature field; b) water saturation; c) oil saturation at $t = 20\tau, 50\tau, 80\tau$

The results of computational experiments. Now we present the results of computational experiments carried out for the problem (15)–(18), (6)–(7) on an example of the prob-

lem of displacement of oil by injecting steam into the reservoir. As the computational domain Ω , we consider a square, at the center of which an injection well is placed.

The control function is selected as a linear combination of gradients of global pressure and saturations in the form

$$w = 1 + \alpha_0 |\nabla p|^2 + \beta_0 |\nabla s_o|^2 + \gamma_0 |\nabla s_g|^2.$$

Fig. 1 shows the results of construction of the adaptive mesh at $t = 20\tau$ and $t = 50\tau$. The figure shows that the thickening of the mesh nodes occurs near the injection well and at the interface between the phases of oil and steam. In the course of the process, the mesh nodes are redistributed according to the position of the filtration front.

Fig. 2a shows the distribution of the temperature field for the development time $t = 20\tau, 50\tau, 80\tau$. Simulation results reveal the three temperature zones that are typical for the oil displacement process by steam: in the first zone, i.e. near the injection well, the temperature is equal to the temperature of steam injected, and then slowly decreases due to heat loss to the surrounding formation. In the second zone, the temperature decreases continuously from the condensation temperature to the reservoir temperature, wherein heating is carried out by hot condensate. The third zone is an area not covered with steam. As the amount of injected agent increases, the first and second zones are gradually expanding, and the third one is shortened.

Fig. 2b shows the water saturation profile. Near the injection wells, the steam saturation increases due to the evaporation of the water initially filled the reservoir, so water saturation in this subregion is decreasing. In the transition zone with variable temperature, the injected steam condenses, thus in this area the water

saturation increases dramatically. Fig. 2c shows the movement in the oil phase in the direction of heat transfer flow.

Conclusion

Thus, the described method allows to dynamically change the density of mesh nodes depending on the nature of the flow, thereby improving the accuracy of the solution of the three-phase non-isothermal flow problem in the subregions with large gradients of solutions without increasing the number of nodes.

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**İZOTERMİK OLMAYAN ÜÇFAZALI SÜZÜLMƏ MƏSƏLƏSİ ÜÇÜN QLOBAL QOYULUŞDA
ADAPTİV ŞƏBƏKƏ ÜSULU****N.M.Temirbekov, D.R.Baygerayev**

İşdə adaptiv şəbəkə üsulu ilə qarışmayan mayelərin üçfazlı izotermik olmayan süzülmə məsələsinin həllinin dəqiqliyinin artırılması məsələsinə baxılır. Məsələnin həlli şəbəkənin ekvipaylanma üsulunun tətbiqi ilə əldə edilir. Bu prosesi təsvir etmək üçün global təzyiq konsepsiyasına əsaslanan yeni quruluşda qoyulmuş məsələ təklif edilir. İşdə modelin tənliyi ümumiləşmiş koordinat sistemində verilir və ədədi üsulla həllin alqoritmi buxar və neft məsələsinə uyğun qurulur.

Açar sözlər: adaptiv şəbəkə, ekvipaylanma üsulu, global təzyiq, ədədi həlli

**МЕТОД АДАПТИВНЫХ СЕТОК ДЛЯ ЗАДАЧИ ТРЕХФАЗНОЙ НЕИЗОТЕРМИЧЕСКОЙ
ФИЛЬТРАЦИИ В ГЛОБАЛЬНОЙ ПОСТАНОВКЕ****Н.М.Темирбеков, Д.Р.Байгереев**

Работа посвящена применению метода адаптивных сеток для повышения точности решения задачи трехфазной неизотермической фильтрации несмешивающихся жидкостей. Адаптация сетки к решению задачи осуществляется методом эквираспределения. Для описания трехфазного неизотермического течения в пористой среде в работе используется новая постановка задачи на основе концепции глобального давления. В работе приведены уравнения модели в обобщенных криволинейных координатах, алгоритм численного решения задачи и результаты вычислительных экспериментов, проведенных для рассматриваемой модели на примере модельной задачи вытеснения нефти паром.

Ключевые слова: адаптивные сетки, метод эквираспределения, глобальное давление, численное решение