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Numerical simulation of thermoreversible polymer gel filtration

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Abstract**—**This paper presents results of numerical simulation of filtration of abnormal thermoviscous fluid on an example of thermoreversible polymer gel.

Keywords**—**abnormal thermoviscous fluid, filtration, numerical simulation.

I. Introduction

High-viscosity oil reservoirs are widespread all over the world. Many such reservoirs are located to Russia, the USA, Canada, Venezuela, and China. Various chemical reagents and methods are used for increasing of high-viscosity oil reservoirs recovery.

One of methods is to control filtration flows of reservoir fluids (oil, gas and water) by the solutions of polymers capable to generate gels and foamed gels in situ. For this purpose thermoreversible polymer gels, named METKA, have been developed at the Institute of petroleum chemistry, Siberian Branch of the Russian Academy of Sciences [1]. METKA is used for enhanced oil recovery intended to reduce water cut and to prevent gas breakthrough. At low temperatures METKA is solution with low viscosity, whereas at high temperatures it's converted into gel. It is a reversible process: at cooling the gel again becomes a low-viscous solution. At reheating it transforms into gel etc.

Dependence of METKA's viscosity on temperature is nonmonotonic or abnormal (Fig. 1). At temperature of 47,5 °C viscosity has the minimum value and then it sharply increases.

Earlier authors of work had been considered the structures arising in a stream of the various abnormal thermoviscous fluids, at a current in the flat channel [2], a cylindrical pipe [3], [4] and at natural convection [5].

During numerical simulation in all considered cases, the origin of "a viscous barrier" – a localized area of the curvilinear shape with high viscosity is determined. The passage of a stream through "the viscous barrier" results in occurrence of cross components of velocity field. In internal part of a viscous barrier there is a stream cumulation with the corresponding increase of the longitudinal component of velocity on an axis of the channel.

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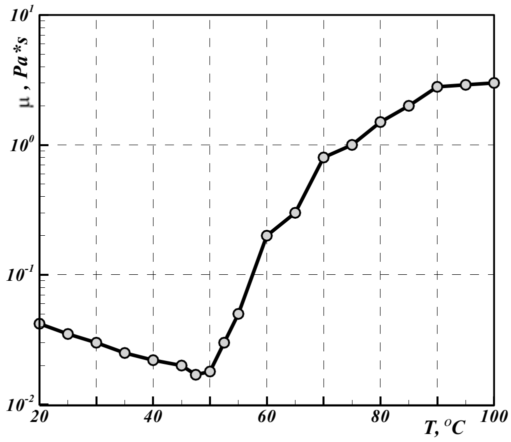


Fig 1. Dependence of METKA's viscosity on temperature

II. Statement of the problem

Let us consider a horizontal cylindrical porous reservoir saturated with thermoreversible polymer gel (Fig. 2). Reservoir thickness and its radius are equal H and R_k, respectively. The top and the bottom of the reservoir are impermeable. At the initial moment of time the gel in the reservoir is at rest, reservoir temperature T_0 and reservoir pressure p_k are constant.

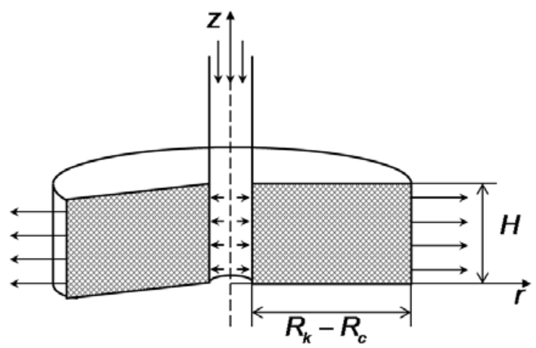


Fig 2. The scheme of thermoreversible polymer gel pumping in the reservoir

There is a input well of radius R_c in the reservoir centre, through which the gel with constant temperature T_{in} injects in the reservoir. Bottom well pressure p_c and pressure at external boundary p_k of reservoir are constant.

The governing equations for filtration process of thermoreversible polymer gel are the conservation of mass (in the form of piezoconductivity equation)

$$\beta^* \frac{\partial p}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{k}{\mu(T)}\frac{\partial p}{\partial r}\right) + \frac{\partial}{\partial z}\left(\frac{k}{\mu(T)}\frac{\partial p}{\partial z}\right),$$

the momentum balance law (Darcy's law)

$$u = -\frac{k}{\mu(T)}\frac{\partial p}{\partial r}, \qquad w = -\frac{k}{\mu(T)}\frac{\partial p}{\partial z},$$

the energy conservation law (in the form of heat inflow equation)

$$\frac{\partial (CT)}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\rho_f c_f uT - r\lambda\frac{\partial T}{\partial r}\right) + \\ + \frac{\partial}{\partial z}\left(\rho_f c_f wT - \lambda\frac{\partial T}{\partial z}\right) = 0,$$

where u and w are the radial and axial velocity components, p is the pressure, T is the temperature, $\mu = \mu(T)$ is dynamic viscosity of the gel, t is the time, ρ is the density, λ is the heat capacity per unit volume, c is the heat conductivity coefficient, β^* is the elastic capacity coefficient of the reservoir, $C = m\rho_f c_f + (1-m)\rho_r c_r$ and $\lambda = m\lambda_f + (1-m)\lambda_r$ are the heat capacity per unit volume and the heat conductivity coefficient of the saturated porous medium. Index "f" (fluid) concerns the gel, index "r" (rock) concerns the solid framework of the porous medium.

Initial conditions look like:

$$u|_{t=0} = w|_{t=0} = 0, \quad p|_{t=0} = p_k, \quad T|_{t=0} = T_0.$$

Boundary conditions look like:

- on the external boundary

$$p|_{r=R_k} = p_k, \qquad \left.\frac{\partial T}{\partial r}\right|_{r=R_k} = 0$$

- on the bottom well

$$p|_{r=R_c} = p_c, \qquad T|_{r=R_c} = T_{in};$$

- on the top and the bottom of the reservoir

$$u|_{z=0} = u|_{z=H} = w|_{z=0} = w|_{z=H} = 0,$$
$$\left.\frac{\partial p}{\partial z}\right|_{z=0} = \left.\frac{\partial p}{\partial z}\right|_{z=H} = 0.$$

We use two kinds of boundary conditions for temperature on the top and the bottom of the reservoir:

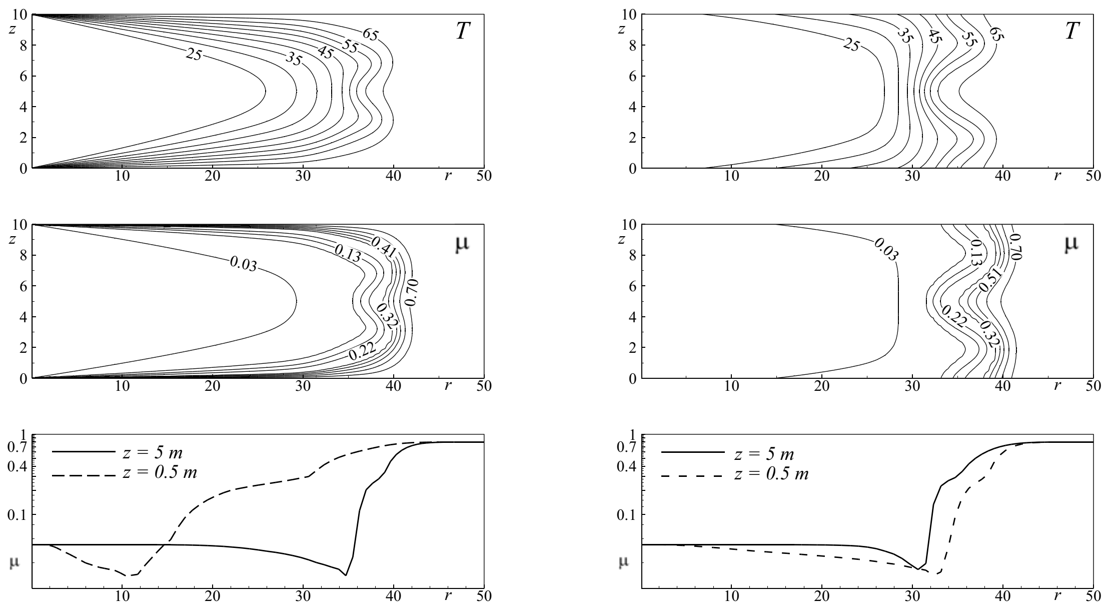
- temperature is constant (first-type boundary conditions)

$$T|_{z=0} = T|_{z=H} = T_0,$$

- Lauwerier's heat exchange conditions are set for temperature (third-type boundary conditions)

$$q_z|_{z=0} = -\frac{\lambda_{mk}(T-T_0)}{\sqrt{\pi t \chi_{mk}}}, \qquad q_z|_{z=H} = \frac{\lambda_{mk}(T-T_0)}{\sqrt{\pi t \chi_{mk}}},$$

where λ_{mk} and χ_{mk} are coefficient of heat conductivity and thermal diffusivity of the rocks surrounding the reservoir, t is the time.



(a) (b)

Fig. 3. Isotherms, viscosity isolines and viscosity profiles on length of the reservoir for the composition METKA for first- (a) and third-type (b) temperature boundary condition

III. Results of Numerical Simulation

We use following values of parametres for numerical simulation of the thermoreversible polymer gel filtration:

$$T_0 = 70\ ℃,\quad T_{in} = 20\ ℃,\quad H = 10\ m,\quad R_c = 0{,}073\ m,$$
$$R_k = 50\ m,\quad p_c = 20\ MPa,\quad p_k = 5\ MPa.$$

Porosity m and permeability k of the reservoir are equal 0,2 and $10^{-12}\ m^2$ respectively.

In Fig. 3 are shown typical isotherms, viscosity isolines and viscosity profiles on length of the reservoir for the composition METKA for first- (Fig. 3,a) and third-type (Fig. 3,b) temperature boundary conditions.

The temperature field of major reservoir part (approximately to $r = 30\ m$) is characteristic for a filtration of a fluid with constant viscosity. At temperature $47{,}5\ ℃$ viscosity of the composition METKA take on the minimum value, and then the composition viscosity increases sharply (Fig. 1). Therefore character of temperature distribution is change. Values of gel viscosity, following character of distribution of temperature, form in a direction of a filtration a zone of nonmonotonic viscosity change.

On Fig. 4 are shown distribution of radial velocity of the composition METKA filtration on different distances from the well axis for two types of temperature boundary conditions.

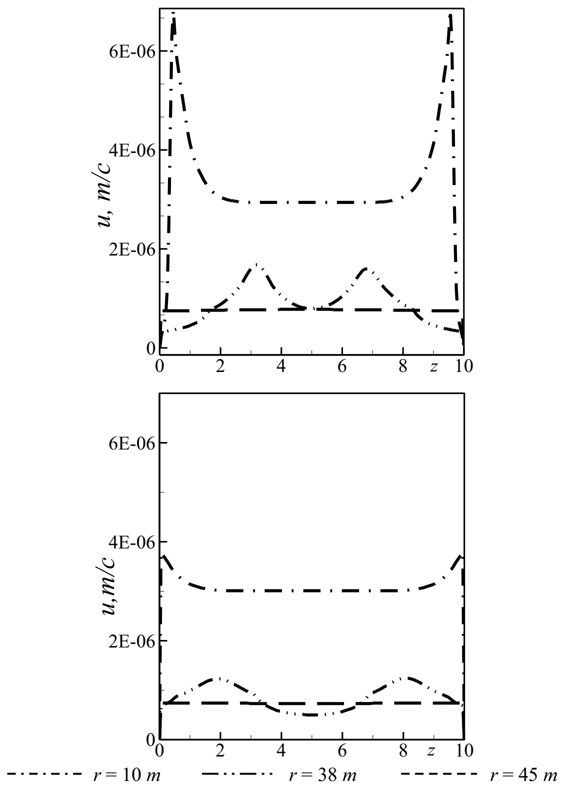


Fig 4. Distribution of radial velocity of the composition METKA filtration on different distances from the well axis for first- (above) and third-type (below) temperature boundary conditions

On distance $r = 10\ m$ from the well axis the major part of the reservoir cross-section the fluid have pumping temperature (Fig. 2). Therefore radial velocity of a filtration in this area is constant (dash-dot lines in Fig. 4). The velocity increase (more than twice for the first-type boundary condition) occurs near to the top and the bottom of the reservoir. It is possible to explain that in this part of the reservoir the fluid has smaller viscosity, than in an average part of the reservoir.

In an average part of the zone of nonmonotonic viscosity change ($r = 38\ m$) the maximum values of radial filtration velocity are displaced to the reservoir middle (dash-dot-dot lines in Fig. 4). It occurs because near to boundaries of the reservoir fluid temperature more than in other part of the reservoir so also viscosity is more.

On sufficient removal from the well ($r = 45\ m$) the fluid has constant reservoir temperature, viscosity and radial velocity are constant that is characteristic for an isothermal filtration (dashed lines in Fig. 4). The difference between minimum and maximum values of radial filtration velocity on the same distance from the well axis decreases with increase in distance from the well axis.

It has appeared that unlike a filtration of a fluid with constant viscosity at a filtration of an abnormal thermoviscous fluid there is an axial filtration velocity. Values of axial filtration velocity at the assignment of first-type boundary conditions appear less, than in case of third-type boundary conditions.

Thus, it is shown that the variety of the hydrodynamic effects which have been found out at a flows of an abnormal thermoviscous fluids in a flat channel [2] and in a cylindrical pipe [3], take place at a filtration too. Filtration process also is defined by character of overcoming by a fluid of a zone of nonmonotonic viscosity change. Formation of a heterogeneity profile of radial filtration velocity which is most expressed under first-type temperature boundary conditions is established.

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