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GENERALIZED VISCOUS-ELASTICITY MODEL OF DEFORMED FILTRATOPN, SIMULATION OF MASS TRANSFER AND DIFFUSION

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Abstract

The paper presents the evolutionary topological solution of Navier-Stokes equation with filtration phenomena for natural and man-made super-conductivity and compaction of plastic deformation to de-compact fractured-porous media. Reservoir deformations jointly with dynamic phase moments of micro-scaled porous fluid gives a strong effect upon the structure and anisotropy for block-type conductivity in oil saturated matrix.
The deformation defines the nature of filtration in compact/de-compact dissipative fracturing of the porous micro-structure. The authors present the analytical solution and analysis of a new "second" Darcy (Fick's) Law in view of energy with second energy moments for compacted filtration.
Key words: deformation, diffusion, permeability, mass transfer, de-compaction, geo-sphere

Development and evolution of continuous medium is a rather well-known problem in mechanics faced by the science while modeling the oil and gas field development processes. [1]. The item has become extremely actual of late when the traditional porous reservoirs have been added by complexly structured compact/de-compact reservoirs with various structure of diagenesis [2]. The intensification of these models is an actual item for the present-day science, geology, development, ecology and economics. Representativeness in selecting the specific mathematical model affects the quality of the design solutions and the hydro-dynamic simulation.

Space of State, Standing Waves

Let's consider the space of states having the coordinates in a form of parameters μ^i for the status of phase space. The analogue model for the continuous media is the porous media [3, 4], for example, related to well bottom-hole or subduction of the ocean [5]. Such a complex state of the system is related to the multi-phase fluid inflow to the bottom-hole that includes plastic and solid products.
Defining the parameters of the state is related to the solution of non-linear problems in mathematically complicated theory of wave distribution with final amplitude in heavy fluids. The specific type of a solution for the equations are the solution of progressive type for the steady wave $F(\mathbf{x},\mathbf{k},\omega,t)=Real\ A(\mathbf{x},\mu)e^{i(\mathbf{kr}-\omega t)}$, where $\mathbf{k}=k_j\mathbf{x}_j$ $(j=1\text{-}3)$, ω - frequency, $\mathbf{r}$ – radius-vector, $A(\mathbf{x},\mu)$ – target functions of the state [5].

Sub-Microscopic Equilibrium

In sub-microscopic dynamics for the individual particles that is described in classical mechanics, the time symmetry has definitely its specific place. But in practice we have very limited knowledge on the behavior of the individual components of the system. An important issue of this is whether we have enough basic knowledge on mean "general" parameters for further practical determination of system dynamic behavior with an adequate level of accuracy.

Basing upon the results of the studies in defining the size of pores, their distribution and role in filtration as obtained through testing numerous samples and field test models with dynamic phase permeability, we substantiate a new more adequate model showing the structure of reservoirs and rheology in view of deformation [7 - 10]. This gives the way to calculate the HC recoverable reserves through volumetric methods with an accuracy that in principle may not be achievable while using the present-day accepted model at the basis of Darcy's Law and equations of Euler-type equations for gas dynamics.

Porous Sedimentation, Discontinuity Surfaces

While studying the fluid movement and the elastic media the boundary between them may be considered as the surface of discontinuity, for which it's necessary to put some specific boundary conditions. The surfaces of discontinuity between characteristics of movement and the state should follow some universal correlations in energy. In order to get continuous solution it's necessary to look for another more complicated model. For example this may be the Navier-Stokes equation for the movement and one should introduce additional correlation that account for dissipative effects which arise as related to extremely sharp gradients showing the distribution of speed, density, pressure, etc.

One of the examples showing these extremely heterogeneous surfaces is presented by structural surfaces of fracturing, facial and phase boundaries of porous media. Migration and diffusion of porous micro-structure are severely governed by the non-linear interaction processes between physical/chemical and hydro-dynamical fluctuations, by processes of re-emergence, convective transfer, adsorption, desorption and dissipation with further sedimentation, compaction and mass transfer of crushed particles along the flow. Within the close limits to the surface of viscous sub-layer one can for sure describe the pulse-type and mean characteristics by Navier - Stokes equations [6].

Structural Model

While modeling the porosity with challenging petro-physical properties they wide use structural mathematical models. Applying these one may describe the non-linear effects of filtration, non-elastic deformation and destruction. Polycrystalline skeleton and viscous-elastic properties of porous fluids are simulated by a system of layers that work with stretching – compaction and viscous flow. Deformations of a local element are presented in a form of $\varepsilon_i = e_i + e_i^{\,p} + p_i$, where e_i – elastic deformation, e_i^p – plastic, p_i – creep process. Orientation of the element is forced by the angles θ and φ $(0 \le \theta \le \pi/2,\ 0 \le \varphi \le 2\pi)$, Fig. 1. We have used the equations of the balance as [11]: $\langle\sigma_x\rangle = 1/\pi \, {}_0\!\int^{\pi/2} \cos^2\theta \sin\theta d\theta \, {}_0\!\int^{2\pi} \sigma(\theta,\varphi) d\varphi$, $\langle\sigma_y\rangle = 1/\pi \, {}_0\!\int^{\pi/2} \sin^3\theta \, d\theta \, {}_0\!\int^{2\pi} \sigma(\theta,\varphi)\cos^2\varphi d\varphi$,

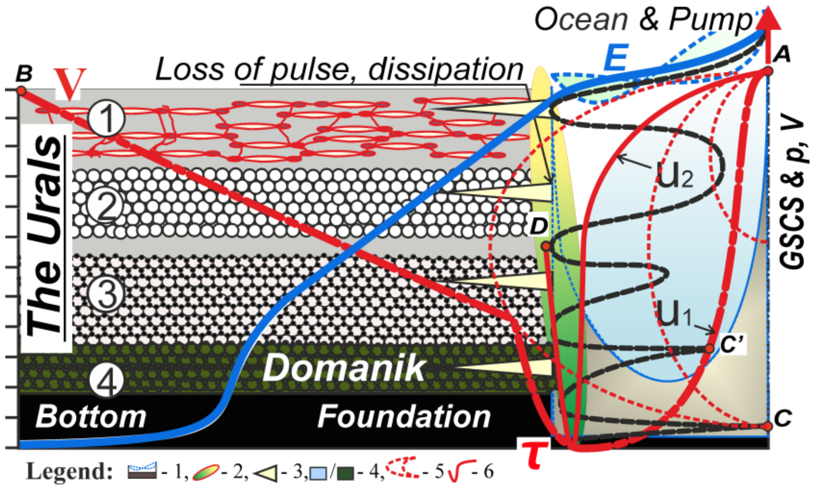

Figure 1. Dynamic skin-factor of phase pulse -/+ τ of the system: pump (A) - reservoir (1 - 3, B) – porous bottom-hole (C): Geo-Statistical Cross-Section (GSCS) of energy ***E*** for filtration velocities in complexly-organized

reservoir for ocean bottom spreading or well 1, deformation 2, perforations 3, de-compaction / compaction 4 for "strong" 5 and "weak" 6 solutions, where A - D – critical points for the models of S.A. Christianovich (1), V.N. Schelkachev (2), Yu.M. Molokovich (3) and dynamic scaling for the model of V.I. Popkov (4).

$\langle\sigma_z\rangle=1/\pi\ {}_0\int^{\pi/2} \sin^3\theta\, d\theta\ {}_0\int^{2\pi} \sigma(\theta,\varphi) \sin^2\varphi d\varphi$, for consistency $\varepsilon(\theta,\varphi) = \langle\varepsilon_x\rangle\cos^2\theta + \langle\varepsilon_y\rangle\sin^2\theta\cdot\cos^2\varphi + \langle\varepsilon_z\rangle\sin^2\theta\cdot\sin^2\varphi$ and deformation homogeneity $\langle\varepsilon_x\rangle = \varepsilon(0,\varphi)$, $\langle\varepsilon_y\rangle = \varepsilon(\pi/2,0)$, $\langle\varepsilon_z\rangle = \varepsilon(\pi/2,\pi/2)$. In this case $\langle\sigma_j\rangle$, $\langle\varepsilon_j\rangle$ - are macro-mean (basic) values of stresses $\sigma(\theta,\varphi)$ and deformations $\varepsilon(\theta,\varphi)$.

In this paper we make the bench-marking of the effects for longitudinal and transversal fluctuations of the surface for Reynolgs stresses in view of mixed loadings.

Basing upon the equation on mass transfer and persistence of Navier-Stokes quantity of movements we have obtained the energy stable synthesis of Darcy's Law up to the second moments and law on quadratic compaction of reservoirs [12 - 21].

Deformation and Porous Space Energy Equilibrium

The movement of incompressible fluid with dynamic viscosity v is described by a system of Navier-Stokes equations [1, 11-16] for mean values of U and pulsing v velocities and continuity

$$\partial v_i/\partial t+v_j v_{i,j}-\langle v_j v_{i,j}\rangle+v_j U_{i,j}+U_j v_{i,j}=-1/\rho\partial p/\partial x_i+v\Delta v_i,\ v_{i,i}=0,$$

Here $vU'=u_*^2+\langle v_i v_j\rangle$, $v=\mu/\rho$, $\langle v_i v_{i,j}\rangle=(v_i v^*_{i,j}+v_i^* v_{i,j})/4$, *- a complex conjugation. Initial conditions are $U(x,0)=U_o(x)$. The state of phase equilibrium is described by differential type equation on movement and generalized Hooke's law

$$\sigma_{ij}=\mu(\xi_{i,j}+\xi_{j,i})+\lambda\delta_{ij}\,\xi_{i,i}\,,\ \sigma_{ij,j}=\rho\partial^2\xi_i/\partial t^2,$$

where λ, μ - generalized parameters of viscous-elasticity, σ, ξ - stresses and re-positioning. The state of the media is defined by the shear μ and elasticity λ modulus:

$$\mu(\omega)=\mu_o+\Sigma^n{}_{j=1}\mu_j(\omega\tau_j)^2/(1+(\omega\tau_j)^2)-i\Sigma^n{}_{j=1}\mu_j\omega\tau_j/(1+(\omega\tau_j)^2),\ \lambda(\omega)=\lambda_o-2/3(\mu(\omega)+\mu_o),$$

by relaxation function $\mu(t)=\mu_o+\Sigma^n{}_{j=1}\mu_j e^{-t/\tau j}$, where μ_o, λ_o – are static modulus and τ_j - relaxation spectrum. Solution of linear system of non-standard Navier-Stokes equations

$$\partial\mathbf{v}/\partial t+1/\rho\cdot\partial p/\partial x= v\partial^2\mathbf{v}/\partial y^2$$

Is considered as a type of a progressing wave:

$$u=h(y)\exp i[\mathbf{kx}-\omega t],\ v=g(y)\exp i[\mathbf{kx}-\omega t],\ w=f(y)\exp i[\mathbf{kx}-\omega t].$$

Suppose that in sub-layer $\partial p/\partial y=0$ a pulsing pressure at the boundary is as $p = p_o\exp i[\mathbf{kx}-\omega t]$. The boundary conditions for non-flow and sticking are recorded in a form of:

$$u(x,z,0,t)=-\xi_2\partial U/\partial y\big|_{y=0}+\partial\xi_1/\partial t\cdot\cos\theta,\ v(x,z,0,t)=\partial\xi_2/\partial t,\ \ w(x,z,0,t)=\partial\xi_1/\partial t\cdot\sin\theta.$$

At the external boundary u, w are giver and jointed by a angleof skew

$$u=A\cdot\exp i[\mathbf{kx}-\omega t],\ w=B\cdot\exp i[\mathbf{kx}-\omega t],\ w=u\cdot tg\theta,\ \lambda_z=\lambda_x ctg\theta,\ B=A\cdot tg\theta.$$

Vertical component of velocity is defined following the solution of an equation for surface fluctuations in conditions of pulsing load effect [6]:

$$v=-i\omega\xi_2(h,\omega,p_o)\exp i[\mathbf{kx}-\omega t],\ \xi_i=/\xi_i/\exp i[\mathbf{kx}-\omega t-\varphi_i],$$

where ξ_i – amplitude if displacement, φ_i – phase shear in view of load p_o.
Equation for longitudinal pulsing of velocity is resulted through the integration of system's first equation. The longitudinal component is presented in a form of viscous and wave-type constituents u=u_2+u_1, that are in accordance to the equations

$$\partial u_2/\partial t = \nu\partial^2 u_2/\partial y^2, \quad \partial u_1/\partial t = - 1/\rho\cdot\partial p/\partial x.$$

If the influence of viscosity at the external boundary is low, then we get

$$h(\eta)=p_o[1-(1+\xi_2/CU'-1/C\partial\xi_1/\partial t\cdot cos\theta)exp(i-1)\eta]/\rho U_o, \quad f(\eta)=ctg[1-(1-1/C\partial\xi_1/\partial t\cdot cos\ \theta)exp(i-1)\eta].$$

where $U_o=\omega/k_x$, $C=p_o/\rho U_o$, $\eta=y(\omega/2\nu)^{1/2}$, $U'=\partial U/\partial y\big|_{\eta=0}$.
Following the results of equations on continuity and boundary conditions we get

$$g(\eta)=Ck_x(1+tg\ \theta)/(\omega/2\nu)^{1/2}[-i\eta+(1-i)/2(1+i\omega\xi_1/Ccos\ \theta+\xi_2U'/C)\cdot$$
$$\cdot(exp(i-1)\eta-1)-iU_o/C\xi_2(\omega/2\nu)^{1/2}/(1+tg\ \theta)].$$

Reynolds stress having the form of:

$$\rho\langle\text{-uv}\rangle= -1/4\{h(\eta)g^*(\eta)+h^*(\eta)g(\eta)\}=$$
$$= k_xC^2(1+tg^2\theta)/(8\omega/\nu)^{1/2}\{K_1+K_2-2Ssin\ \varphi_2-[(K_1+K_2)cos\ \eta+(K_1-K_2)sin\ \eta+(K_1^2+K_2^2)(cos\ \eta-sin\ \eta)-$$
$$-2S(K_1\cdot sin(\eta+\varphi_2)+K_2cos(\eta+\varphi_2))+2\eta(K_1\cdot sin\ \eta+K_2\cdot cos\ \eta)]exp(-\eta)+(K_1^2+K_2^2)exp(-2\eta)\},$$
где $S=-U_o/C\cdot|\xi_2|(\omega/2\nu)^{1/2}/(1+tg^2\theta)$, $K_1=1+(|\xi_2|U'\cdot cos\ \varphi_2+|\xi_1|\omega\cdot cos\ \theta\cdot sin\ \varphi_1)/C$,
$K_2=(|\xi_1|\omega\cdot cos\ \theta\cdot cos\ \varphi_1-|\xi_2|U'\cdot sin\ \varphi_2)/C.$

So, the viscous boundary stimulate Reynolds' negative stress that is attenuating exponentially and in asymptotics tends to $\tau/\tau_o = K_1$, where τ_o - is stress at a smooth refractory surface, Fig. 2. With $\omega > \omega_s$, where ω_s – is the proper frequency of the elastic surface, we get $K_1 > 0$, i.e. the stress exceeds the initial one in K_1 folds. At the elastic surface the stress amplitude are at order of magnitudes greater than the neutral ones. The surface is pressed under the effect of normal stress thus killing the velocity but with the same velocity it is pushed out along the flow.
The external flow U_o defines phase velocity $C=0,8U_o$ and energy spectrum of pulsing [17]:

$$p(\omega)=0,75\cdot10^{-5}\alpha^2\rho^2U_o^3\delta^*[3/2(m-1/m)],\ \omega<\omega_o,$$
$$p(\omega)=1,5\cdot10^{-5}\,(\alpha^2\rho^2U_o^6/\omega^3\delta^{*2})\,[3/2(m-1/m)](2\pi U_o/5\omega\delta^*)^{m-3},$$
$$\omega_o=2\pi U_o/\delta=2\pi U_o/5\delta^*,\ \delta=5\delta^*,$$

where δ^* - is the effective thickness of viscous layer, parameters $m=1/C$ and α (dragging and Kraichnan) as considered as given. The value of pulsing pressure was dictated by constant value of $p(\omega)/\rho u_*^2 = 1$, that correspond to an average value of energy-carrying frequency ω_o. In case of transition across its proper frequency ω_s with $C > a_\mu$ phase angles of velocity are changed by 180º, that gives the change in sign K_1. The running and soft layers at phase velocities $C/a_\mu>1$ with $\omega>\omega$ are capable to instigate only negative values that reduce friction resistance and stress in viscous sub-layer completely. The amplitudes arising at these surfaces significantly exceed the viscous layer and in the area of its proper frequency $\omega_k \sim 1$ – by several dozens of times. So, the elastic surface is capable to the friction resistance at $\omega_o > \omega_s$, $C > a_\mu$.
The effect of viscous surface is based in its aperiodicity of fluctuations, in phase shear in respect to pulsing pressure. Viscous-elastic layer is sagged under the effect of pulsing pressure and slowly restores its original shape without instigating any positive stresses to the flow and thus not shaking it if compared to elastic one. Viscous-elastic surface in this case acts as a damper thus forming the stagnant zones with large relaxation time, as in case with geological Domanik formations of the Cis-Ural region or with development of technogenic silt sediments.

Analyzing the calculation results for the interaction between surfaces and viscous layer it is possible to draw the conclusion: maximum effect is seen at the surfaces that create maximum diffusive flow at minimum fluctuation amplitudes. In balanced geological media the ration of elastic and viscous properties is equalized in the optimum way: maximum level of pulsing energy corresponds to in maximum dissipation at minimum fluctuation amplitudes.

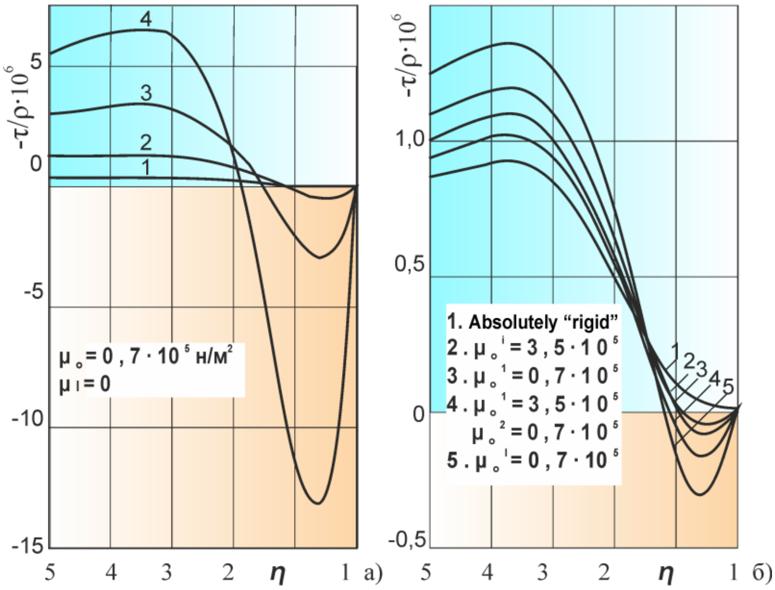

Figure 2. Reynolds' stresses vs frequency at elastic (a) and viscous-elastic surfaces with frequency 2000 Hz (б)

With fluctuations in viscous-elastic layer they generate the negative tangent stresses, that at $\tau_\omega \geq \rho u_*^2$ may arrange the force. Let's imagine that $|\xi_2| \sim \delta_л \cdot 10^{-1}$, $|\xi_1| \sim \beta |\xi_2|$, where $\beta \geq 1$, $\cos\theta \approx 1$ and φ_2-φ_1=0, then at frequencies $\omega \geq 1/2\pi(2/\beta)^{1/2}u_*^2/\nu$ the unit of the fluctuating surface length may give the compensation to friction viscous resistance. In this vase they form resonant - super-conductive pulse outbreak of fine-dispersed fraction and micro-elements of "precious" metals that are commonly found in oil, like vanadium, nickel, etc. If to consider the this process in geological and technogenic time space then the evolutionary enforcement of the deformation is seen at the boundaries of the geological blocks, including drained and developed ones.

The structure of porous space is defined by the criticalpoints of solutions *A* - *G*, Fig.1. Point *A* defines the depth of pumpunit installataion or the exit to the atmosphere, *D* – zero velocity, i.e. "islands" in sediments along the river beds. Point *E* – are the positive values of Reynolds' stresses, i.e. driving force of the layer with possible exit to the surface and formation of "lakes" that are widely spead across the daylight surface of the continents.

Conclusion

The process of dynamic interaction between the flow and porous structure of Terrigenous and cavernously compacted Carbonate formations is severaly complicated in case with deforming surface availability. Reynolds' numbers in case with interaction scale changes may grow to the critical values of flow separation. The flow regime in this case in changing from convergent to divergent flow with the arrangement of fine-dispersed compact fraction "shady tails".

Fluctuating surface generates stresses proportionally to the square of frequency and product of amplitudes, as well as the difference of phases $\tau_\omega = -1/2 \cdot \rho\omega^2 |\xi_2| \, |\xi_1| \cos\theta \cdot \cos(\varphi_2 - \varphi_1)$.

In view of resonant frequencies and dissipative characteristics the deformation amplitudes grow to the critical values of rock destruction with the arrangement of fracturingthat in geological time will be additively expending, with aperiodic fluctuations of downfold amplitudes like the thickness of the viscous layer, but in geoplogical time the evolutionary solution will largerly leave its boundaries. In this case behind the from they form the completely crushed porous space of one or the other fraction.

Following the viscous-elastic properties of the reservoirs and the model of porous space one may come to a conclusion that deformations occur at various velocities and various phase angles in viscous dissipation. This defines the optimum conditions in applying the new methods in searching, exploration, development of high-viscous pools, their multi-stage and stage-by-stage development, water shut-off operations, addition of micro-elements, enhanced oil recovery from high water content reservoirs in view of energy summation at the basis of Darcy's law and deformation moments.

This solution illustrates that subduction structure of river-bed flows forms the regular network at the bottomof the oceans and basement, like uplifts and downthrows that were discovered by NASA in the Atlantic Ocean while processing the satellite images. Mopreover, the number of islands and lakes is defined by the scaleof geological factors and oceanic off-shore.

The method enables the creation and testing of a new type of multi-phase computer programs for numerical evaluation of oil and gas basin models, pressure fields and well production rates [20]. Three-phase hydro-dynamic simulator *FLORA* with dynamic conditions for phase equilibrium was tested both at Carbonate and Terrigenous reservoirs, at low-viscous and high water-cut fields, at high-viscous and bitumen pools of Russia and Peri-Caspian region.

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