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A new approach to the study of a representative anisotropic core sample and two-phase flow in anisotropic filtering porous environments

Theoretical analysis

The modern state of oil production is characterized by the increase in heavily recoverable reserves of hydrocarbons. Therefore new technological processes are used for hydrocarbon recovery and their efficiency is related to a more adequate description of the formation, including allowing for anisotropy of filtration-volumetric properties of the formation. Let's consider the generalization of classical models of the theory of one- and two-phased flow of immiscible fluids, based on the tensor representation of the absolute and phase permeability coefficients in anisotropic porous media which is typical for real hydrocarbon reservoirs.

Measuring the elastic properties of core material seems to be the most efficient method of establishing the fact of anisotropy of filtration-volumetric properties (FVP) and determination of the anisotropy type (symmetry of FVP of real hydrocarbon reservoirs).

In the simultaneous flow of two immiscible fluids (e.g., oil and water) it's accepted, that the Darcy law is kept for each phase and has a form:

$$W_i^\alpha = \frac{K_{ij}^\alpha}{\mu_\alpha} \Delta_j p^\alpha, \alpha = 1, 2 \quad (1)$$

where:

K_{ij}^α – components of symmetric tensors of 2nd rank-phase permeability,

W_i^α – components of phase filtration velocity vector,

μ_α – dynamic viscosity coefficient,

p^α – pressure in phases.

In equ. (1) and in the following the greek letters (sub-indices) denote a phase number and the latin letters (sub-indices) denote the components of vectors and tensors. The recurrent latin letters imply summation, summation is not taken with respect to the greek (indices). For convenience the tensors and the vectors are written in cartesian coordinates. Equation (1) introduces new material characteristics K_{ij}^α , called phase permeability.

Since phase permeability depends on porous space and phase distribution in pores (i.e., on saturation), then initially the separation of these properties is expressed as the linear relationship between K_{ij}^α and the absolute permeability tensor K_{ij} [1]:

$$K_{ij}^\alpha = f^\alpha(S) K_{ij} \quad (2)$$

where relative phase permeability $f^\alpha(S)$ are assumed as saturation universal functions and the tensor symmetry is put as identical.

Later it was shown theoretically [5, 4, 7] and confirmed experimentally [8], that relative phase permeability is dependent not only on saturation, but on flow direction, and the most general relationship between phase and absolute permeability is given by the tensor of 4th rank:

$$K_{ij}^\alpha = F_{ijkl}^\alpha K_{ki} \quad (3)$$

where F_{ijkl}^α is the tensor of relative phase permeability

coefficients with the first and second pair of indices symmetric even when rearranged.

Alongside it, the elastic properties of media are described by Hook's law

$$p_{ij} = C_{ijkl} \varepsilon_{kl} \text{ or } \varepsilon_{ij} = S_{ijkl} p_{ij}$$

where

p_{ij} – components of stress tensor;

ε_{kl} – components of deformation tensor;

C_{ijkl} and ε_{kl} are components of the tensors of 4th rank.

The 4th rank tensors F_{ijkl}^α , prescribing relative phase permeability, are the same rank and the same internal symmetry as the tensors of the elasticity coefficients C_{ijkl} or elastic pliability S_{ijkl} in Hook's law.

Explicit form of the tensors C_{ijkl} , S_{ijkl} is determined by the symmetry group of elastic properties, in which case the symmetry group of tensors C_{ijkl} , S_{ijkl} and F_{ijkl}^α coincide. The symmetry of elastic properties can be determined by the form of tensor surfaces. In particular, the values reciprocal to Young's modulus, $E(n_i)$, in the direction n_i are determined by formula

$$E^{-1}(n_i) = S_{ijkl} n_j n_k n_l$$

Therefore using conventional methods for the determination of elastic characteristics one can measure elastic properties

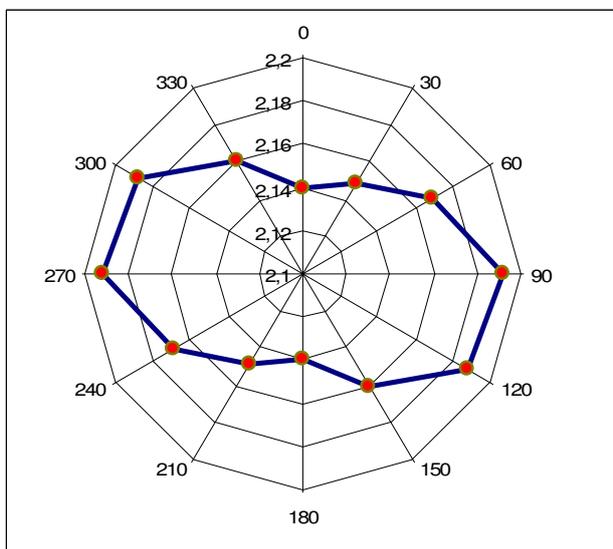


Fig. 2. Section of the surface of elastic properties measured along the lateral surface of the core-sample

The symmetry type principle of filtration properties

A) In the most general case the position of the main axes of the 2nd rank tensors of is unknown and the problem of determination of all six tensor components of the permeability coefficients reduces. Therefore the mini-

for the cross-section of tensor surface; for example, from the normal plane to the core's axis of symmetry, and define their symmetry. In figure 1 there's a photograph of the device, measuring the ultrasound wave velocity through the porous media.

In fig. 2 the measuring results of core elastic properties are shown. The direction of the extreme properties (minimum and maximum) is determined by the measured data, and then the samples of smaller dimensions are cut out from the sample core along the extreme directions for the carrying out of hydrodynamic studies.



Fig. 1. The device «Uzor 2000» for measuring of ultrasound wave velocity through a porous material



num number of measurements equals 6. In principle all six components can be determined by the data of six measurements, obtained along six independent directions.

- B) In the next case with a descending level of complexity is needed to determine four components of tensor permeability. In this case the position of one of the main axes is known and it's necessary to determine the position of two other axes (one rotation angle of the laboratory coordinate system $Oxyz$ around the known main axis), and three main tensor components of permeability. Thus, the minimum number of measurements needed equals 4. In fig. 3c the surface section of elastic properties for cases A and B is shown.
- C) For porous media with orthotropic filtration properties the position of all the main axes is known. Therefore for the specification of filtration properties, three main values of tensor permeability would be enough. The problem is solved by three measurements, obtained along the main directions. In fig. 3b the section of the elastic properties for case C is shown.

- D) For transversal-isotropic material the problem is reduced even more: it's necessary to determine only the two main values of tensor permeability. The minimum number of measurements equals two. Measurements are made in an isotropy plane of filtration properties and in the direction normal to it. In fig. 3a the section surface of elastic properties for case D is shown.

The principle determination schemes of permeability anisotropy in one- and two-phase fluid flow remain the same in the selection of the number of cores and directions of measurements. Thus, the problem of absolute and relative phase permeability determination in anisotropic formations focuses on setting the symmetry of filtration properties and then at carrying out the experiments on the cut samples, core handling and obtaining the permeability matrixes. The determination of the RFP functions can be realized by using the formulae proposed in [4, 5, 7].

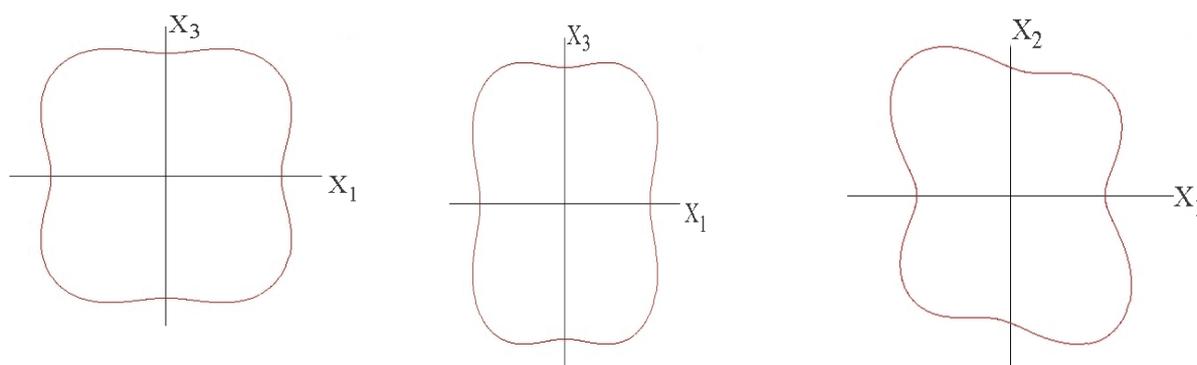


Fig. 3. Section of the surface of elastic properties on plane x_1x_3 in the case when the position of all main the axes is known (isotropic, transversal-isotropic and orthotropic properties)

I – figures 3a, 3b; figure 3c is a section of the surface elastic properties by the plane x_1x_2 when the position of all main axes is unknown

The sequence of performing the complex studies

Finally, to perform the complex studies of filtration-volumetric properties, the following working plan for real core material is suggested:

- the symmetry of elastic core properties is determined by ultrasonic wave velocities and elastic properties measurement,
- the symmetry (anisotropy type or isotropy) of the core filtration properties is determined by the symmetry of elastic properties,
- the number and the directions of core sample cutting out are determined depending on symmetry type (fig. 4),
- for each sample the absolute permeability coefficients are determined using conventional methods,
- for profound check of the test data some check samples can be prepared; test data obtained from the check samples can be recalculated using «base» measurements and allow error estimation,
- after absolute permeability tensor is determined the same samples are used for laboratory measurements of relative e phase permeability functions,
- laboratory test data are processed and empirical constants are determined using the explicit form of relative phase permeability functions.

Below we'll consider an explicit representation of the relation (3) between the phase and absolute permeabilities and the laboratory method for the determination of non-diagonal tensor components of phase permeability for media with monoclinic and triclinic symmetry.

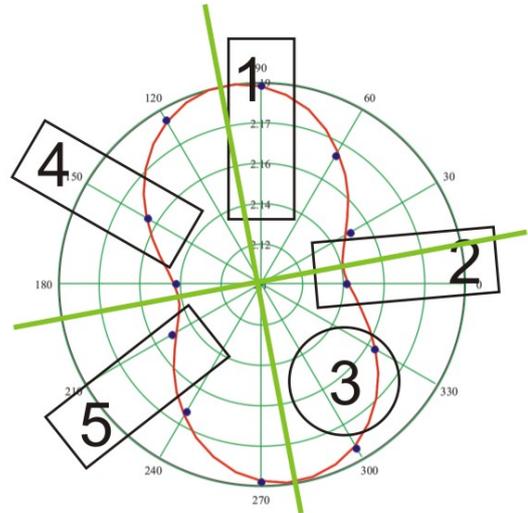


Fig. 4. Scheme of the core-sample cut out

Representation of phase and absolute permeabilities relation to tensor components of phase permeabilities with triclinic symmetry of filtration properties

Explicit form of relationship (3) is determined by anisotropy type (symmetry group) of filtration properties.

In the case of triclinic symmetry of filtration properties the position of the main axes of tensors K_{ij}^α and K_{ij} is unknown, therefore these tensors contain all six components. For transformation of the relationship (3) it's necessary first to define tensor components of absolute permeabilities. After all the tensor K_{ij} components are determined it can be reduced at the main axes. Then relationship (3) can be written in the main axes. The relationship get simplified and take a form:

$$\begin{aligned} K_{11}^\alpha &= \xi_{11}^\alpha K_1 + \xi_{12}^\alpha K_2 + \xi_{13}^\alpha K_3 \\ K_{22}^\alpha &= \xi_{21}^\alpha K_1 + \xi_{22}^\alpha K_2 + \xi_{23}^\alpha K_3 \\ K_{33}^\alpha &= \xi_{31}^\alpha K_1 + \xi_{32}^\alpha K_2 + \xi_{33}^\alpha K_3 \\ K_{23}^\alpha &= \xi_{41}^\alpha K_1 + \xi_{42}^\alpha K_2 + \xi_{43}^\alpha K_3 \\ K_{13}^\alpha &= \xi_{51}^\alpha K_1 + \xi_{52}^\alpha K_2 + \xi_{53}^\alpha K_3 \\ K_{12}^\alpha &= \xi_{61}^\alpha K_1 + \xi_{62}^\alpha K_2 + \xi_{63}^\alpha K_3 \end{aligned} \quad (4)$$

where ξ_{mn}^α are tensor components of relative phase permeabilities in the coordinate system, coinciding with the main axes of the absolute permeability tensor; K_i are main values of the absolute permeability tensor.

Using relationship (4) it can be shown, that tensors K_{ij}^α and K_{ij} can belong to different symmetry groups. Indeed, assuming that all the tensor components ξ_{mn}^α are non-zero, then tensors K_{ij}^α and K_{ij} have different symmetry axes. Moreover, the symmetry of tensor K_{ij} can be increased from triclinic to orthotropic one and then to transversal-

isotropic and isotropic, successively supposing that $K_1 = K_2 \neq K_3$ and $K_1 = K_2 = K_3$. In any case the phase permeability tensors will have triclinic symmetry, i.e. they will be characterized by all six non-zero components. Hence, the symmetry of the filtration properties tensors K_{ij}^α and K_{ij} may not coincide. In which case relative phase permeability tensors symmetry should coincide with phase permeability tensors symmetry.

For solution of the applied problems, a case of great interest, is when limiting values of saturations differ from zero and 1. Therefore let's consider the generalization of explicit form for relative phase permeability functions for this particular case. The general form of the relative phase permeability functions (4) can be written as:

$$\varphi_i^\alpha = \xi_{ij}^\alpha + \xi_{ik}^\alpha \theta_{ki} + \xi_{i,1}^\alpha \theta_{li} \quad (5)$$

where $\varphi_i^\alpha = K_i^\alpha / K_i$, $\theta_{ij} = K_i / K_j$.

Equ. (5) should satisfy the following conditions: when $S = S(i)^*$, $\varphi_i^1 = 0$, and when $S = S^*(i)$, $\varphi_i^2 = 0$. Assuming that all the functions are of the same order, then (5) can be transformed in the following approximate equations:

$$\begin{aligned} \varphi_i^1 &= \frac{I_1(K)}{K_i} \cdot \xi_{ii}^\alpha \cdot (S - S(i)^*) \\ \varphi_i^2 &= \frac{I_1(K)}{K_i} \cdot \xi_{ii}^\alpha \cdot (S(i)^* - S) \end{aligned} \quad (6)$$

where summation with respect to (i) is absent.

The multipliers $(S - S(i)^*)$ and $(S^*(i) - S)$ ensure satisfaction of the above mentioned conditions and correspond to the common approximation of relative phase permeability for isotropic porous media. The multiplier $I_1(K)/K_i$, where $I_1(K)$ is a first invariant of absolute permeability tensor, is due to anisotropy. Then, for approximation of the functions, it's needed to take into account the condition at another range of the interval saturation change. Initially the phase permeability functions were constructed in the interval $S^* \leq S \leq 1$ (for water) and $0 \leq S \leq S^*$ (for oil or gas). In this case φ^α values at the interval boundaries were fixed: $\varphi_1^1(1)=1$ (for water) and $\varphi_1^2(0)=1$ (for oil or gas). Recently the measurements have been performed in the mobility interval for both phases $S^* \leq S \leq S^*$. Therefore the $\varphi_1^1(S=S^*)$ values (for water) and $\varphi_1^2(S=S^*)$ values (for oil and gas) transform in the values «at free range» and are determined experimentally. Thus, it's needed that the initial relative phase permeability representation $\varphi = [(S - S^*)^\varepsilon / (1 - S^*)]$ for isotropic media to be replaced by $\varphi_1^1 = \alpha_i^1 (S - S(i)^*)^{\varepsilon_i} / (S_{(i)}^* - S(i)^*)$. Therefore, assuming that multiplier $I_1(k)F_\nu/k_\alpha$ in (6) is due to anisotropy and equals 1 for isotropic media, then in the case of anisotropy the relative phase permeability functions representation, satisfying the above mentioned conditions, can be presented as:

$$\varphi_1^1 = \left[\alpha_i + \left\{ \frac{I_1(k)}{3k_i} - 1 \right\} (S_{(i)}^* - S) \right] \left[\frac{S - S(i)^*}{S_{(i)}^* - S(i)^*} \right] - \text{for water} \tag{7}$$

$$\varphi_1^2 = \left[b_i + \left\{ \frac{I_1(k)}{3k_i} - 1 \right\} (S - S(i)^*) \right] \left[\frac{S_{(i)}^* - S}{S_{(i)}^* - S(i)^*} \right]^\beta - \text{for oil or gas} \tag{8}$$

where $\alpha_i, b_i, \varepsilon_i, \beta$ are parameters experimentally determined; in which case $\alpha_i = \varphi_1^1(S_{(i)}^*)$, $b_i = \varphi_1^2(S(i)^*)$.

That the indices ε_i and β_i should be represented through invariant values defining the filtration-volumetric param-

eters of media, and it's value should correspond to known approximations in going from anisotropy case to isotropic case.

Traditional relative phase permeability representation for isotropic media is a particular case for (7), (8). For the general case of triclinic symmetry of filtration properties the approximations of the relative phase permeability function can be represented as:

$$K_{ij}^1 = \left[\alpha_{ij} + \left\{ \frac{I_i(k)}{3k_3} - 1 \right\} (S_{(ij)}^* - S) \right] \left(\frac{S - S(ij)^*}{S_{(ij)}^* - S(ij)^*} \right)^{\varepsilon_{ij}} \cdot k_e - \text{for water}$$

$$K_{ij}^2 = \left[b_{ij} + \left\{ \frac{I_i(k)}{3k_e} - 1 \right\} (S - S(ij)^*) \right] \left(\frac{S_{(ij)}^* - S}{S_{(ij)}^* - S(ij)^*} \right)^{\beta_{ij}} \cdot k_e - \text{for oil (gas)} \tag{9}$$

where when $i \neq j$ the indexes i, j, l form a cyclic rearrangement of 1, 2, 3, and when $i = j$ all indexes are equal ($i = j = l$); but summation with respect to i is not taken. Note, that to get relative phase permeability the diagonal components of K_{ij}^α -tensor are divided by corresponding components of K_{ij} -tensor. This approach is impossible for the non-diagonal components, because the corresponding non-diagonal component of K_{ij} -tensor equals zero.

Therefore relative phase permeability for a nondiagonal component is obtained by division by one of the main components of K_{ij} -tensor. In eg. (9) there's one of the possible variants in i, j, l - indices forming cyclic rearrangement.

Equ. (9) determine phase permeability for triclinic symmetry of filtration properties, so they are the most general, and phase permeabilities for all anisotropy types (symmetry classes) can be obtained through them. For monoclinic symmetry it's needed to set $k_{13}^\alpha = k_{23}^\alpha = 0$ in equations (9), for orthotropic symmetry, $k_{13}^\alpha = k_{23}^\alpha = k_{12}^\alpha = 0$, for transversal - isotropic symmetry it's needed to add the equality $k_{11} = k_{22}$ to the latter condition.

The analysis of the dependence of the main axes of phase permeabilities tensor on saturation

To keep our following considerations more visualized, an analysis of the dependence of the main axes on saturation for tensors with monoclinic symmetry of filtration properties is done. It's well known, that any symmetric tensor of

2nd rank can be reduced to the main axes, in which it takes a diagonal form. In particular, for monoclinic symmetry of filtration properties the position of one main axis is known. So, reducing the main axes is realized by rotation around

that principle axis. Assuming that a principle axis coincides with axis Z , then a rotation angle is defined by

$$\operatorname{tg} 2\varphi = \frac{2k_{12}}{k_{11} - k_{22}} \quad (10)$$

By analogy reducing the phase permeability tensors K_{ij}^α to the main axes it's needed to turn the coordinate system at angles φ^α , so:

$$\operatorname{tg} 2\varphi^\alpha = \frac{2k_{12}^\alpha}{k_{11}^\alpha - k_{22}^\alpha} \quad (11)$$

However, if in equation (10) all the component values are constant and angle φ is fixed, then in equation (11) the tensor component values depend on saturation and change; therefore the angles φ^α values can change also. Indeed, as it was shown in experiment [8], the phase and relative phase permeability values in anisotropic media are dependent on direction, and higher absolute permeability values correspond to higher phase and relative phase permeability values. In the representation of the relative phase permeability functions it's taken into consideration by determination of the different values of experimental constants and degrees in equ. (9) for different directions.

Obviously, the angles φ^α will not depend on saturation, if in equ. (11) all the parameters, consistency saturation, will be reduced. However it's impossible, because, as it was mentioned above, the experimental constants values are dependent on direction. Therefore, if the values of the

constants in (9) are determined, then it's possible to analyze a change in the position of the main axes in two-phase flows in dependence of saturation.

To illustrate the effect of dependence of the position of the main axes on saturation let's assume, that $k_1:k_2:k_3 = 4:2:1$ and take basic parameters for oil and water in (9) as equal:

for oil:

$$\varepsilon_{11} = 1,4; \varepsilon_{22} = 2; \varepsilon_{12} = 1,8; \varepsilon_{11} = 1,4; \\ S_{(11)^*} = 0,1; \alpha_{11} = \alpha_{22} = \alpha_{12} = 1$$

for water:

$$\beta_{11} = 2; \beta_{22} = 2,5; \beta_{12} = 2,2; \\ S_{22}^* = 0,9; b_{11} = b_{22} = b_{12} = 1$$

and substituting these values into (11), we estimate a cross-section of the related phase permeability demonstrative surfaces $k^\alpha(n_i) = k_{ij}^\alpha n_i n_j$ by the plane XY :

$$k^\alpha(n_i) = k_{ij}^\alpha n_i n_j = k_{11}^\alpha \cos^2 \beta + \\ 2k_{12}^\alpha \cos \beta \sin \beta + k_{22}^\alpha \sin^2 \beta$$

In fig. 5 the calculation results are shown as the cross-sections of the indicatory surfaces of filtration properties. From the polar diagrams shown it's seen, that with increasing saturation a turn of the main axes of the tensors in opposite directions is taking place and that's confirmed by the experimental results [8].

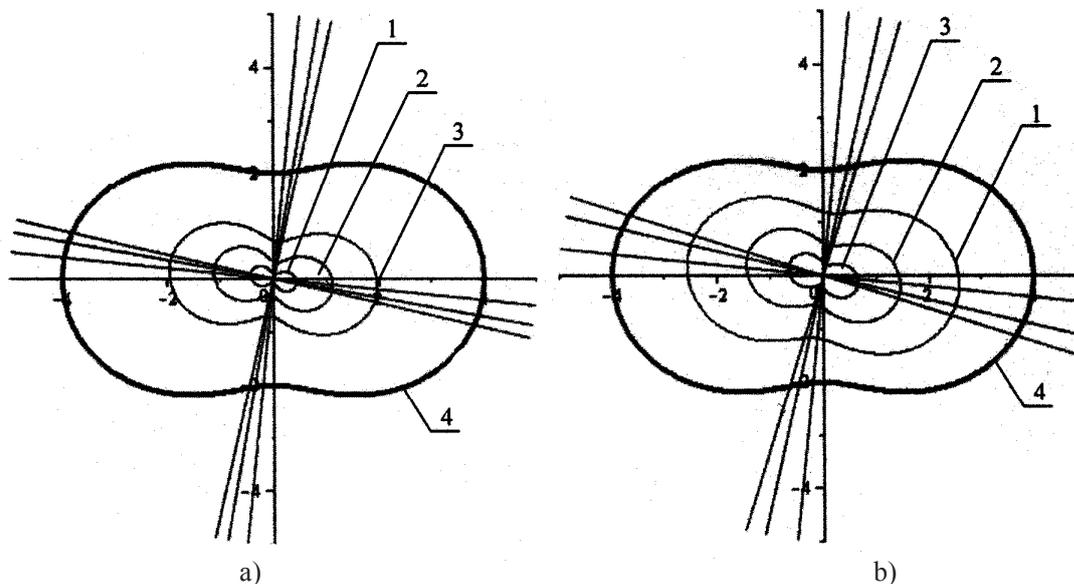


Fig. 5. Cross-section of the absolute and phase permeability tensor directional surfaces for water (a) and oil (b) under saturation values; 1 - $s = 0,2$; 2 - $s = 0,4$; 3 - $s = 0,6$; 4 - absolute permeability

The method for the laboratory determination of non diagonal component phase permeability tensors [2]

Let's assume, that porous media has monoclinic symmetry of filtration properties; obviously, in case of triclinic symmetry the considerations would be analogous. Further we'll assume, that the position of the known main axis of the absolute permeability tensor coincides with the Z-axis. In this case the non-zero non-diagonal components of the phase permeability tensors are the k_{12}^α components.

To determine k_{12}^α it's necessary first to determine the diagonal components values k_{11}^α and k_{22}^α . Therefore to perform laboratory studies it's necessary to cut out three samples. Two of them are cut out along two main directions of the tensor k_{ij} in the XY-plane. To make our calculations more convenient, the third sample can be cut out along the bisectrix of the angle between two main directions. The determination of phase and relative phase permeabilities for diagonal components of the tensors can be done by conventional methods [6]. After termination of phase and relative phase permeabilities along the main directions of the tensor k_{ij} , the determination of the component k_{12}^α can be as follows. For doing it, we'll use two model problems: flow through a «thin» plate and movement in a «long» bar [6]. In the first case a directional permeability value can be defined, and in the second case – a directional filtration resistance. Laboratory equipment enables to create a flow in samples, which are neither a thin plate, nor a long bar. Therefore to define the debit dependence on pressure drop we can use an approximate formula based on the above mentioned solutions:

$$\frac{Q^\alpha \mu^\alpha L}{S \cdot \Delta p} \sqrt{\frac{k_{ij}^\alpha n_i n_j}{r_{lm}^\alpha n_l n_m} \left[\frac{1 + k_{ij}^\alpha n_i n_j r_{lm}^\alpha n_l n_m (D/L)}{k_{ij}^\alpha n_i n_j r_{lm}^\alpha n_l n_m + (D/L)} \right]} \quad (12)$$

where

Q^α is debit of α^{th} phase, Δp – pressure drop at distance L , S is area of sample cross-section, D – sample diameter, n_i – vector components, setting a direction of symmetry axis of core, r_{ij}^α -tensor of filtration resistance.

Since the tensor r_{ij}^α and k_{ij}^α are inter-convertible, then we have:

$$k_{ij}^\alpha \cdot r_{ii}^\alpha = \delta_{ij} \quad (13)$$

where δ_{ij} – Kroneker symbol, $\delta_{ij} = \begin{cases} 1, & \text{if } i = j \\ 0, & \text{if } i \neq j \end{cases}$

Using equ. (12) we calculate tensor r_{ij}^α components by the known tensors k_{ij}^α components. Then from (13) we get an equation, where the only unknown value is a component k_{12}^α . Assuming that k_{12}^α lies between 0 and 1, the component value can be found by fitting with minimization of the difference between experimental and theoretical debit value. Theoretical debit value is obtained by the calculation of component k_{12}^α .

The generalization of a model with dual porosity on anisotropic fractured-porous media is presented in ref. [3].

Allowance of anisotropy of the reservoir and filtration properties enables more adequate description of filtration flows, and this, in turn, allows optimization of oil recovery processes.

Conclusion

Tensor nature of absolute and relative phase permeabilities (RFP) is shown theoretically and is confirmed by experiments. General representation of the component RFP tensors is given for different anisotropy types. A new method for complex laboratory studies of anisotropic core-samples

is suggested for the determination of filtration properties of anisotropic porous media. For two-phase flows, the analysis of new effects due to anisotropy is given. This knowledge enables more adequate simulation of filtration flows and allow optimization of oil-gas recovery processes.

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ZAKŁAD OCENY WŁAŚCIWOŚCI EKSPLOATACYJNYCH

Zakres badania:

- badania właściwości użytkowych paliw silnikowych w testach stanowiskowych (LO, LC, Mercedes M102 i M111, Peugeot XUD9);
- oznaczanie stabilności oksydacyjnej biopaliw (test Rancimat);
- ocena właściwości użytkowych paliw i olejów smarowych w badaniach eksploatacyjnych;
- ocena wybranych, fizykochemicznych właściwości użytkowych paliw i środków smarowych (oddziaływanie na metale i elastomery, odporność na działanie wody, odporność na utlenianie, skłonność do pienienia, stabilność podczas przechowywania);
- ocena właściwości smarnych olejów napędowych (test HFRR) oraz środków smarowych i cieczy hydraulicznych;
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- oznaczenia właściwości reologicznych olejów w szerokim zakresie temperatur (testy CCS, HTHS, MRV, Brookfield);
- ocena kompatybilności dodatków do paliw i olejów smarowych;
- ocena stopnia degradacji olejów smarowych w badaniach stanowiskowych i podczas eksploatacji u użytkownika;
- badania pasywnej regeneracji filtrów cząstek stałych na stanowisku z silnikiem o zapłonie samoczynnym.

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