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A novel approach to assessing the anisotropic permeability parameters of fractured media

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Abstract. The fracture permeability in is very high and directional, which brings a series of problems for the petroleum reservoir development, such as earlier water breakthrough and low sweep efficiency. It is vital to accurately characterize fractures and acquire the parameters of fracture permeability to alleviate these issues, which are favorable for well pattern design and flow modeling. Permeability tensor is employed to comprehensively and expediently reflect the effect of fracture anisotropy on the fluid diversion. Based on information of fracture log and production, the complete permeability tensors of single group fractures and multiple group fractures are identified, where the coordinate transformation theory and tensor property are used. With the simplified form of the derived full permeability tensor, the anisotropic parameters, principal values and principal directions of permeability for the fractured reservoir, can then be calculated. The proposed method integrates the static characterization and percolation feature of fractures and can be applied merely into field practices of naturally fractured reservoir. This work is beneficial for the management of fractured reservoir and optimization of field development.

1. Introduction

About 50% of the world's remaining conventional hydrocarbons are stored in the naturally fractured reservoirs [1]. But due to the presence of a large number of natural fractures, these reservoirs are always anisotropic and heterogeneous, which brings a lot of difficulties to the development of oil and gas fields. In such reservoirs, the anisotropic fracture permeability plays a significant role. For example, the anisotropic permeability has a destructive impact on the general patterns of wells [2]. Therefore, a precise characterization of anisotropic fracture permeability is the key to make reasonable decisions on the development of the fractured reservoir. The permeability via the conventional Darcy rule fails to properly characterize the percolation features of the fractured reservoir, considering that full tensor permeability in modeling fracture reservoir is a necessity even for reservoirs with initial isotropic permeability [3]. Thus, a nine-component tensor is introduced to capture the anisotropy of the naturally fractured reservoir, where the orientation and magnitude of permeability may vary in the same position. The full permeability tensor is commonly symmetric [4] and its geometric form behavior is similar to that of an ellipsoid [5].

Experimental approaches are generally utilized to measure the anisotropic permeability. After substituting permeability tensor into the conventional Darcy rule, the permeability can be assessed by measuring the flow rate and pressure gradient of different direction [6]. Similarly, the full hydraulic conductivity tensor is computed with a linear least squares algorithm by measuring the average velocity and gradient [7]. However, this approach is not conclusive because the accuracy is not satisfied. Since the sample used for the experiments is heterogeneous, the cubic sample is used to eliminate the effect of heterogeneity when measuring the anisotropic permeability in a tri-axial cell [8]. For the experimental methods, the end effect of the sample always affects the result of the measurement. Besides, the results obtaining from cores cannot characterize the dynamic changes of anisotropic permeability.

Analytical models are also employed to determine the anisotropic permeability. Snow [9] estimated anisotropic permeability by applying means of superposition of parallel plate flow under the assumption of an impermeable rock matrix. An approach incorporating Snow's tensor and permeability tensor calibration to assess permeability tensor is proposed [10]. The models based on material balance [11] and the lowest order finite formula [12] are used to investigate the anisotropic permeability of cross-bedded reservoir. A consistent rock physics model for effective permeability and stiffness tensors of the fractured reservoir are employed to estimate the anisotropic permeability [13]. But this method can deal with the reservoir containing a single set of vertical fractures. From the extended Poiseuille flow approximation of the velocity and pressure field, the analytical model for effective permeability was developed [14]. However, the reliability depends on the fiber's direction, and the anisotropy of the horizontal plane cannot be identified. Chi and Heidari [15] integrated a directional pore connectivity factor into a nuclear-magnetic-resonance-based permeability model to determine directional permeability where the lattice Boltzmann method was used to verify the results. This approach requires micro-CT scans on the rock sample, which prevents the real-time application of this model.

The geophysical method is also applicable for determining anisotropic permeability. The resistivity anisotropy and conventional log derived permeability are used to interpret permeability anisotropy [16]. But it assumes that the formation is transversely isotropic. Frequency-dependent seismic amplitude versus angle and azimuth data and Monte Carlo method performing a Bayesian inversion are utilized to obtain the information of fractures including permeability [17].

The presented numerical simulator can handle the anisotropic issues, but it is assumed that the axial directions of the coordinate system of the girds are aligned with the principal directions of permeability. Under this assumption, the off-diagonal terms of permeability tensor are neglected. The principal directions of permeability do not coincide with the axial direction of simulators' coordinate system which causes significant errors calculating the magnitude and orientation of the Darcy flow rate [18] and the magnitude and direction of velocity [11].

This work focuses on the anisotropic permeability of fractured reservoir. The complete permeability tensor of fractures is first determined by combing the log information and production information. Next, the approach to obtain parameters of anisotropic permeability by the derived anisotropic permeability tensor of fracture is presented. In the final part, an example of the computation of the principal permeability values and principal permeability directions of a practical fractured reservoir is illustrated.

2. Methodology

2.1 The calculation method of anisotropic permeability tensor of fractures
The single group fracture permeability is firstly obtained. Then the permeability tensor of multiple groups of fractures is derived by a simple summation. Next, the approach for calculating the significant parameter average permeability K is introduced.

2.1.1. The anisotropic permeability tensor of single group fractures.

Assume that the azimuth angles are β and the dip angles are α of an arbitrary set of parallel fractures in the reservoir, of which the average permeability is K. At first, the Cartesian coordinate system is established by taking the earth as the reference. As shown in Figure 1, the north, east, and the directions perpendicular to them are considered as the coordinate lines, which correspond to the three unit vectors $\boldsymbol{e}_1$, $\boldsymbol{e}_2$, and $\boldsymbol{e}_3$, respectively. Next, a Cartesian coordinate system is established by taking the fracture as the reference. One of the coordinate lines is the intersection line of the fracture face and horizontal plane, which corresponds to the unit vector $\boldsymbol{f}_2$. Another coordinate line is perpendicular to $\boldsymbol{f}_2$ within the fracture surface and corresponds to the unit vector $\boldsymbol{f}_1$. The direction perpendicular to $\boldsymbol{f}_1$ and $\boldsymbol{f}_2$ is taken as the third coordinate line and corresponds to a unit vector $\boldsymbol{f}_3$.

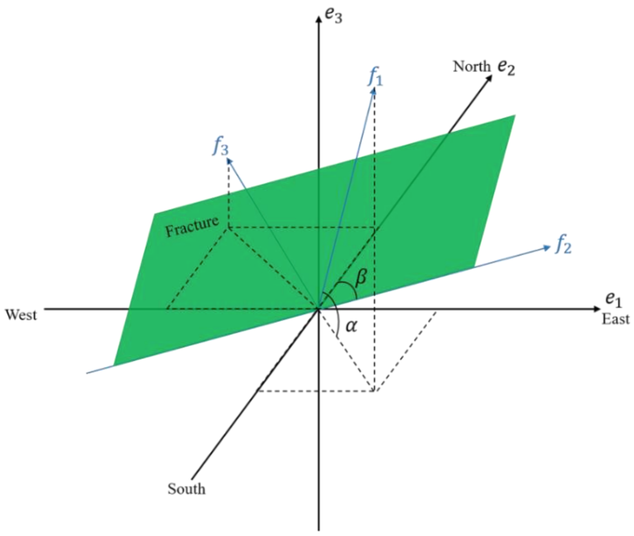

Figure 1. The stereo azimuth of fracture and the coordinate transformation relation.

The expression of permeability tensor $\boldsymbol{K}$ of an arbitrary set of fractures in the coordinate system $(\boldsymbol{e}_1,\boldsymbol{e}_2,\boldsymbol{e}_3)$ will be derived below.

Assume that the expression of permeability tensor $\boldsymbol{K}$ of fractures in the coordinate system $(\boldsymbol{e}_1,\boldsymbol{e}_2,\boldsymbol{e}_3)$ in figure 1 is [19]:

$$\boldsymbol{K}=(\boldsymbol{e}_1,\boldsymbol{e}_2,\boldsymbol{e}_3)\cdot\overline{K}_{\mathrm{e}}\cdot\begin{pmatrix}\boldsymbol{e}_1\\ \boldsymbol{e}_2\\ \boldsymbol{e}_3\end{pmatrix}=(\boldsymbol{e}_1,\boldsymbol{e}_2,\boldsymbol{e}_3)\cdot\begin{pmatrix}k_{\mathrm{e}11} & k_{\mathrm{e}12} & k_{\mathrm{e}13}\\ k_{\mathrm{e}21} & k_{\mathrm{e}22} & k_{\mathrm{e}23}\\ k_{\mathrm{e}31} & k_{\mathrm{e}32} & k_{\mathrm{e}33}\end{pmatrix}\cdot\begin{pmatrix}\boldsymbol{e}_1\\ \boldsymbol{e}_2\\ \boldsymbol{e}_3\end{pmatrix}=\sum_{i=1}^{3}\sum_{j=1}^{3}K_{eij}\,\boldsymbol{e}_i\boldsymbol{e}_j \tag{1}$$

where $\overline{K}_{\mathrm{e}}$ is the fracture permeability tensor in the coordinate system $(\boldsymbol{e}_1,\boldsymbol{e}_2,\boldsymbol{e}_3)$.

Assuming the expression of permeability tensor $\boldsymbol{K}$ of fractures in the coordinate $(\boldsymbol{f}_1,\boldsymbol{f}_2,\boldsymbol{f}_3)$ in figure 1 is:

$$\boldsymbol{K}=(\boldsymbol{f}_1,\boldsymbol{f}_2,\boldsymbol{f}_3)\cdot\overline{K}_{\mathrm{f}}\cdot\begin{pmatrix}\boldsymbol{f}_1\\ \boldsymbol{f}_2\\ \boldsymbol{f}_3\end{pmatrix}=(\boldsymbol{f}_1,\boldsymbol{f}_2,\boldsymbol{f}_3)\cdot\begin{pmatrix}k_{\mathrm{f}11} & k_{\mathrm{f}12} & k_{\mathrm{f}13}\\ k_{\mathrm{f}21} & k_{\mathrm{f}22} & k_{\mathrm{f}23}\\ k_{\mathrm{f}31} & k_{\mathrm{f}32} & k_{\mathrm{f}33}\end{pmatrix}\cdot\begin{pmatrix}\boldsymbol{f}_1\\ \boldsymbol{f}_2\\ \boldsymbol{f}_3\end{pmatrix}=\sum_{i=1}^{3}\sum_{j=1}^{3}K_{\mathrm{f}\,ij}\,\boldsymbol{f}_i\boldsymbol{f}_j \tag{2}$$

where $\overline{K}_{\mathrm{f}}$ is the fracture permeability tensor in the coordinate system $(\boldsymbol{f}_1,\boldsymbol{f}_2,\boldsymbol{f}_3)$. Based on the known condition, we get:

$$\overline{K}_{\mathrm{f}}=\begin{pmatrix}K & 0 & 0\\ 0 & K & 0\\ 0 & 0 & 0\end{pmatrix} \tag{3}$$

According to the three-dimensional position of the fracture and the spatial relationship between the coordinates $(\boldsymbol{e}_1,\boldsymbol{e}_2,\boldsymbol{e}_3)$ and $(\boldsymbol{f}_1,\boldsymbol{f}_2,\boldsymbol{f}_3)$ in figure 1, the transformation method of the coordinate vector can be expressed as follows:

$$(\boldsymbol{f}_1, \boldsymbol{f}_2, \boldsymbol{f}_3) = (\boldsymbol{e}_1, \boldsymbol{e}_2, \boldsymbol{e}_3) \cdot \boldsymbol{T} \tag{4}$$

where

$$\boldsymbol{T} = \begin{pmatrix} cos\alpha \cdot cos\beta & sin\beta & -sin\alpha \cdot cos\beta \\ -cos\alpha \cdot sin\beta & cos\beta & sin\alpha \cdot sin\beta \\ sin\alpha & 0 & cos\alpha \end{pmatrix}$$

Due to the essential property of tensor, equation (5) can be derived from equations (1) and (2).

$$(\boldsymbol{e}_1, \boldsymbol{e}_2, \boldsymbol{e}_3) \cdot \overline{K}_{\mathrm{e}} \cdot \begin{pmatrix} \boldsymbol{e}_1 \\ \boldsymbol{e}_2 \\ \boldsymbol{e}_3 \end{pmatrix} = (\boldsymbol{f}_1, \boldsymbol{f}_2, \boldsymbol{f}_3) \cdot \overline{K}_{\mathrm{f}} \cdot \begin{pmatrix} \boldsymbol{f}_1 \\ \boldsymbol{f}_2 \\ \boldsymbol{f}_3 \end{pmatrix} \tag{5}$$

Substituting equation (4) into (5), the following result can be obtained:

$$(\boldsymbol{e}_1, \boldsymbol{e}_2, \boldsymbol{e}_3) \cdot \overline{K}_{\mathrm{e}} \cdot \begin{pmatrix} \boldsymbol{e}_1 \\ \boldsymbol{e}_2 \\ \boldsymbol{e}_3 \end{pmatrix} = (\boldsymbol{e}_1, \boldsymbol{e}_2, \boldsymbol{e}_3) \cdot \boldsymbol{T} \cdot \overline{K}_{\mathrm{f}} \cdot \boldsymbol{T}^{\mathrm{T}} \cdot \begin{pmatrix} \boldsymbol{e}_1 \\ \boldsymbol{e}_2 \\ \boldsymbol{e}_3 \end{pmatrix} \tag{6}$$

Apparently,

$$\overline{K}_{\mathrm{e}} = \boldsymbol{T} \cdot \overline{K}_{\mathrm{f}} \cdot \boldsymbol{T}^{\mathrm{T}} \tag{7}$$

Substituting equation (3) into (7), the final expression can be derived:

$$\overline{K}_{\mathrm{e}} = K \begin{pmatrix} cos^2\alpha \cdot cos^2\beta + sin^2\beta & sin^2\alpha \cdot cos\beta \cdot sin\beta & cos\alpha \cdot sin\alpha \cdot cos\beta \\ sin^2\alpha \cdot cos\beta \cdot sin\beta & cos^2\alpha \cdot sin^2\beta + cos^2\beta & -cos\alpha \cdot sin\alpha \cdot sin\beta \\ cos\alpha \cdot sin\alpha \cdot cos\beta & -cos\alpha \cdot sin\alpha \cdot sin\beta & sin^2\alpha \end{pmatrix} \tag{8}$$

2.1.2. The anisotropic permeability tensor of multiple groups of fractures.

The azimuth of the fractures is β_i and the dip angle is α_i ,respectively, i=1, 2, …, N. The density and aperture of every single group of fracture are d_i and b_i respectively and setting $c_i = b_i \cdot d_i$. The average permeability of each group of fractures is K_i . Assume that the permeability of fracture is proportional to c_i and the permeability is K_0 per unit c_i for each group of fractures. The average permeability of an arbitrary single group among the N groups of fractures is $K_i = c_i \cdot K_0$

According to equation (8), the permeability tensor of the i*th* group in the earth coordinate system is:

$$\overline{K}_{\mathrm{ei}} = K_0 \overline{K}_i \tag{9}$$

where,

$$\overline{K}_i = c_i \begin{pmatrix} cos^2\alpha_i \cdot cos^2\beta_i + sin^2\beta_i & sin^2\alpha_i \cdot cos\beta_i \cdot sin\beta_i & cos\alpha_i \cdot sin\alpha_i \cdot cos\beta_i \\ sin^2\alpha_i \cdot cos\beta_i \cdot sin\beta_i & cos^2\alpha_i \cdot sin^2\beta_i + cos^2\beta_i & -cos\alpha_i \cdot sin\alpha_i \cdot sin\beta_i \\ cos\alpha_i \cdot sin\alpha_i \cdot cos\beta_i & -cos\alpha_i \cdot sin\alpha_i \cdot sin\beta_i & sin^2\alpha_i \end{pmatrix}$$

The summation of permeability tensor of N groups is:

$$\overline{K}_{eN} = \sum_{i=1}^{N} \overline{K}_{ei} = K_0 \sum_{i=1}^{N} \overline{K}_i \tag{10}$$

2.1.3 Approach to calculate the average permeability.

It can be found that the average permeability value K is crucial for assessing the full permeability tensor for fractured reservoirs. The average permeability K is the mean value of the permeability of different directions, which can be obtained by using production data.

For vertical wells, K can be derived from the production formula of plane radial flow:

$$Q = \frac{2\pi Kh(P_e - P_w)}{\mu B_O (ln\frac{R_e}{R_w} + S)} \tag{11}$$

For horizontal wells, K can be obtained according to production formula:

$$Q = \frac{2\pi Kh(P_e - P_w)}{\mu B_O (ln(\frac{a + \sqrt{a^2 - (\frac{L}{2})^2}}{\frac{L}{2}}) + \frac{h}{L}(\ln(\frac{h}{2\pi R_w}) + S))} \tag{12}$$

where Q is the liquid production, m^3/d; μ is the viscosity of fluid, $\mathrm{mPa \cdot s}$; B_O is the oil volume factor, m^3/ m^3; P_e is initial pressure of reservoir, MPa; P_w is bottom hole pressure, MPa; h is the height of the reservoir, m; R_e is supply radius, m; R_w is the radius of wellbore, m; S is the skin factor; L is the length of the horizontal well, m; a is the semi-major axis of the elliptical oil drainage region , m.

Log data gives the information of fracture orientation including azimuth, dip angle, density, and aperture. Production data can determine the average permeability K. Combing the two, anisotropic permeability tensor of an arbitrary set of fractures $\overline{K}_e$ and that of multiple groups of fractures $\overline{K}_{eN}$ can be identified.

2.2 Approach to calculate the anisotropic permeability parameters

During the field practice, the most concerned issue is the anisotropic permeability parameters, which are the principal directions and principal values of permeability for fractured media. For the principal direction, it can be determined by the fracture orientation data from logging. The method to obtain the three principal values in the permeability tensor will be discussed below.

2.2.1. A simplified form of permeability tensor.

Based on the identified principal directions, the axis direction of the global coordinate is set to be aligned with the principal direction. In this case, off-diagonal terms of the permeability tensor can be eliminated.

Accordingly, when the principal directions are east, north and vertical direction in the coordinate system (Sec. 2.1.1) taking earth as a reference, equation (8) for single group fractures can be simplified into:

$$\overline{K}_e = K\begin{pmatrix} cos^2\alpha \cdot cos^2\beta + sin^2\beta & 0 & 0 \\ 0 & cos^2\alpha \cdot sin^2\beta + cos^2\beta & 0 \\ 0 & 0 & sin^2\alpha \end{pmatrix} \tag{13}$$

Equation (9) for multiple groups of fractures can be reduced to the following form:

$$\overline{K}_{eN} = \sum_{i=1}^{N}\overline{K}_{ei} = K_0\sum_{i=1}^{N}\overline{K}_i$$

$$= K_0\sum_{i=1}^{N}c_i\begin{pmatrix} cos^2\alpha_i \cdot cos^2\beta_i + sin^2\beta_i & 0 & 0 \\ 0 & cos^2\alpha_i \cdot sin^2\beta_i + cos^2\beta_i & 0 \\ 0 & 0 & sin^2\alpha_i \end{pmatrix} \tag{14}$$

According to equation (14), it is evident that the ratio of the three principal permeability values can be written as:

$$k_{xx} : k_{yy} : k_{zz} = S_x : S_y : S_z \tag{15}$$

where

$$\begin{cases} S_x = \sum_{i=1}^{N} c_i(cos^2\alpha_i \cdot cos^2\beta_i + sin^2\beta_i) \\ S_y = \sum_{i=1}^{N} c_i(cos^2\alpha_i \cdot sin^2\beta_i + cos^2\beta_i) \\ S_z = \sum_{i=1}^{N} c_i(sin^2\alpha_i) \end{cases}$$

2.2.2. Approach to calculate the principal permeability values.

After collecting log data and getting the average permeability K, the permeability tensor of each fracture can be calculated by equation (8). The macroscopic permeability tensor of the fractured reservoir can be computed by equation (9). The eigenvalue and eigenvector of the tensor are the principal permeability values and principal permeability directions of fractured media respectively. For the scenario where the principal directions have been confirmed, the three principal values can be calculated by the following method.

The average permeability K can be derived via the anisotropic seepage theory [20]:

$$K = (k_{xx} \cdot k_{yy} \cdot k_{zz})^{1/3} \tag{16}$$

Substituting (15) into (16), the three principal permeability values can be obtained as:

$$\begin{cases} k_{xx} = K / (\frac{S_y \cdot S_z}{S_x{}^2})^{1/3} \\ k_{yy} = K / (\frac{S_x \cdot S_z}{S_y{}^2})^{1/3} \\ k_{zz} = K / (\frac{S_x \cdot S_y}{S_z{}^2})^{1/3} \end{cases} \tag{17}$$

Therefore, the anisotropic permeability parameters, principal directions and principal values of permeability, are identified, which can be employed to optimize the pattern design and infilling of the well.

3. Results and Discussion

The target area is a volcanic reservoir in Liaohe Oilfield. Natural fractures are well developed in this block, which leads to a strong heterogeneity and anisotropy. The objective is to obtain the principal permeability directions and the three principal permeability values of the area. Sixteen wells are drilled, and the pay zone is divided into three layers in the vertical direction.

The flow chart of the solution is devised as Figure 2. Taking well 18-30 as an example, the detailed procedures are given as follows.

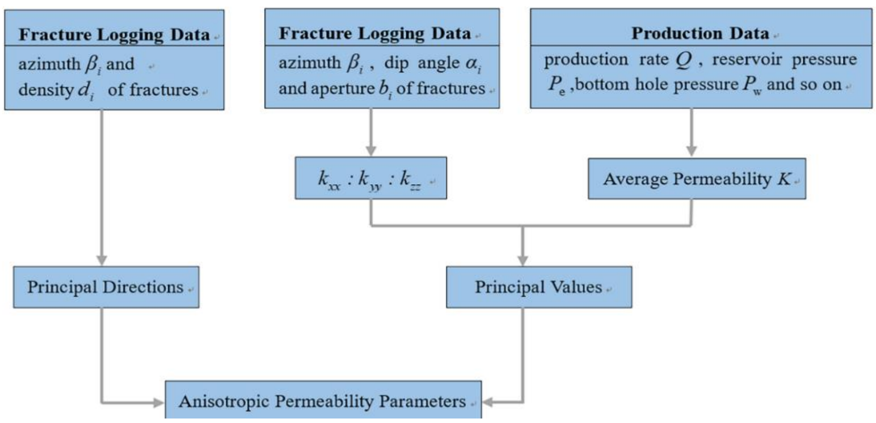

Figure 2. Illustration of workflow to compute the anisotropic parameters.

Step 1: The identification of principal directions. The azimuth of 1969 fractures are shown in Table 1 and statistically analyzed in Figure 3, where the length of the radius represents the number of fractures of different directions. And an adjacent ellipse of data points is drawn in Figure 3. The directions of the major axis and minor axis of the ellipse indicate that the fractures distribute mostly in 25° north by the west but least in 65° north by east. Since the fracture permeability is dominated by the orientation and density of fractures, 65° north by east, 25° north by west, and the direction perpendicular to the two are used as the three principal permeability directions, and they are taken as x-, y-, and z-axis of the Cartesian coordinate system, respectively.

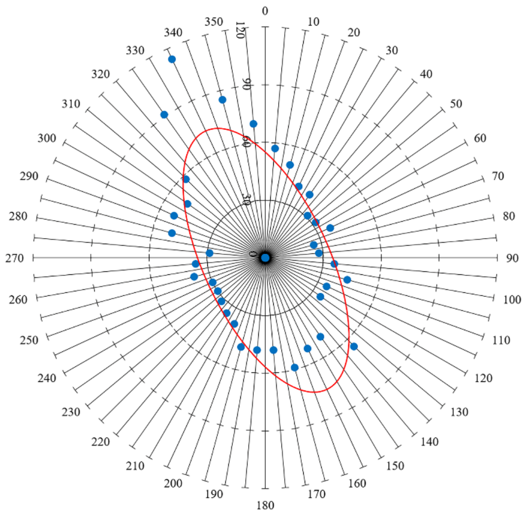

Figure 3. Fracture azimuth distribution circle diagram.

Step 2: Calculating the ratio of the three principal permeability values. As shown in Figure 4, the established system $(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})$ having an $\theta = 25^{\circ}$ included angle with the coordinate system $(\boldsymbol{e}_1,\boldsymbol{e}_2,\boldsymbol{e}_3)$ mentioned, equation (15) should be transformed into the present coordinate system. Thus, the ratio of the three principal permeability value should be written as:

$$k_{xx} : k_{yy} : k_{zz} = S_x^{'} : S_y^{'} : S_z^{'} \tag{18}$$

where

$$\begin{cases} S_x^{'} = cos\,\theta(\sum_{i=1}^{N} c_i(cos^2\alpha_i \cdot cos^2\beta_i + sin^2\beta_i)) - sin\,\theta(\sum_{i=1}^{N} c_i(sin^2\alpha_i \cdot cos\,\beta_i \cdot sin\,\beta_i)) \\ S_y^{'} = sin\,\theta(\sum_{i=1}^{N} c_i(sin^2\alpha_i \cdot cos\,\beta_i \cdot sin\,\beta_i)) + cos\,\theta(\sum_{i=1}^{N} c_i(cos^2\alpha_i \cdot sin^2\beta_i + cos^2\beta_i)) \\ S_z^{'} = \sum_{i=1}^{N} c_i(sin^2\alpha_i) \end{cases}$$

It is assumed that the azimuth of fractures is the primary direction 25° north by west, and the secondary direction 65° north by east. The weights of the primary and secondary directions account for 66.67 and 33.33%, respectively, according to the number of fractures. The inclination angles of fractures are summarized in Table 2. Then, substituting the related data into equation (18), the result can be obtained as:

$$k_{xx} : k_{yy} : k_{zz} = 0.5712 : 0.6295 : 0.7348 \tag{19}$$

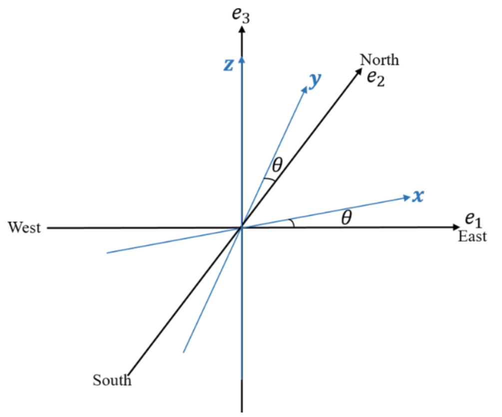

Figure 4. The coordinate system of this field problem.

Table 1. The distribution of fracture azimuth of well 18-30.

Angle (°)	Number	PCT (%)	Angle (°)	Number	PCT (%)	Angle (°)	Number	PCT (%)	Angle (°)	Number	PCT (%)
0-10	2	2.47	90-100	0	0	180-190	3	3.70	270-280	2	2.47
10-20	6	7.41	100-110	0	0	190-200	2	2.47	280-290	2	2.47
20-30	4	4.94	110-120	3	3.70	200-210	1	1.23	290-300	4	4.94
30-40	4	4.94	120-130	1	1.23	210-220	2	2.47	300-310	6	7.41
40-50	1	1.23	130-140	0	0	220-230	1	1.23	310-320	3	3.70
50-60	1	1.23	140-150	1	1.23	230-240	2	2.47	320-330	2	2.47
60-70	3	3.70	150-160	2	2.47	240-250	1	1.23	330-340	3	3.70
70-80	1	1.23	160-170	0	0	250-260	0	0	340-350	5	6.17
80-90	0	0	170-180	6	7.41	260-270	2	2.47	350-360	5	6.17

Table 2. The distribution of fracture dip angle of well 18-30.

Angle (°)	Number	PCT (%)	Angle (°)	Number	PCT (%)	Angle (°)	Number	PCT (%)	Angle (°)	Number	PCT (%)
10-15	2	2.47	30-35	4	4.94	50-55	9	11.11	70-75	11	13.58
15-20	1	1.23	35-40	4	4.94	55-60	3	3.70	75-80	7	8.64
20-25	2	2.47	40-45	5	6.17	60-65	10	12.35	80-85	4	4.94
25-30	4	4.94	45-50	3	3.70	65-70	10	12.35	85-90	2	2.47

Step 3: Calculating the average permeability. According to equation (11), the average permeability $K = 57.03\times10^{-3}\mu\text{m}^2$. The used production data are listed in Table 3.

Table 3. The relevant production data to calculate average permeability of well 18-30.

Parameters	Liquid production (Q) t/d	Reservoir pressure (P_e) MPa	BHFP (P_w) MPa	Area of reservoir (A) Km^2	Radius of well (R_w) m	Skin factor (S)	Perforation height (H) m	Oil viscosity (μ) mPa.s	Volume factor (B_o)	Oil density (ρ_o) g/cm^3
Value	63.2	29.33	28.08	7.40	0.12	68.55	75	0.50	1.47	0.84

Since the permeability is proportional to the fracture density, the average permeability of each layer can be obtained, as is shown in Table 4.

Table 4. The fracture density and average permeability of well 18-30.

Layer	II layer	II-1 Layer	II-2 Layer	II-3 Layer
Density (1/m)	0.3122	0.4000	0.2485	0.1765
Average permeability ($10^{-3}\mu m^2$)	57.03	73.07	45.39	32.24

Step 4: Calculating principal permeability. Substituting (19) and the average permeability value *K* of each layer into (17), the corresponding principal permeability values of well 18-30 can be identified. Similarly, the principal permeability values of other 15 wells are calculated. The results are shown in

Table **5**, which lists single wells' parameters of anisotropic permeability of three layers. It can be concluded that principal values vary with different positions due to the non-uniform distribution of fractures.

Table 5. Principal permeability values of different wells of three layers ($10^{-3}\mu m^2$)

Well number	II-1 layer			II-2 layer			II-3 layer		
	x	y	z	x	y	z	x	y	z
18-30	65.05	71.68	83.67	40.41	44.53	51.97	28.70	31.63	36.92
22	1.49	2.04	1.81	1.50	2.02	1.83	1.49	1.90	1.95
23	19.66	27.04	23.99	15.96	21.48	19.45	8.26	10.54	10.80
24	0.95	0.84	0.54	1.44	1.38	0.52	0.34	0.36	0.21
25	0.61	0.79	0.52	1.02	0.92	0.36	2.56	2.41	2.28
14-14	3.28	3.68	3.02	2.69	3.07	2.54	2.92	4.54	3.62
14-18	8.00	16.86	17.23	6.46	14.28	12.63	2.89	4.25	4.70
14-26	1.44	1.56	0.87	1.52	2.17	1.89	0.81	1.74	1.32
16-22	4.20	3.06	3.45	4.17	3.10	3.42	4.20	3.29	3.21
16-24	9.36	23.86	19.34	11.50	20.81	16.09	13.47	17.20	17.62
16-26	17.26	23.73	21.06	17.38	23.40	21.20	17.29	22.07	22.61
16-32	0.87	0.91	0.41	1.40	1.42	0.86	0.98	2.33	2.28
18-24	3.98	5.79	4.58	1.80	3.15	4.19	2.33	2.06	1.22
18-34	3.73	4.97	3.37	6.42	7.57	2.19	3.49	3.41	2.29
18-36	2.26	2.03	1.22	0.29	0.24	0.22	1.76	1.88	1.11
20-38	3.58	3.06	1.98	3.99	4.45	1.65	0.57	4.00	3.54

In this study, the derived complete tensor permeability calculated using the static log data and dynamic production data not only characterizes the fracture permeability quite accurately but also provides reliable simulation results. On the other hand, after the identification of the principal direction with log data, the simplified form also gives a good performance. With the calculation results, the principal permeability direction of fractures helps one to design the direction of the array of the vertical wells and the wellbore direction of horizontal wells. The principal value of the permeability gives a guidance to determine the well spacing. These designs, decisions, and adjustments based on the calculation results are of great significance and are instrumental in retarding the water breakthrough time, improving the displacement effect, and increasing the ultimate oil recovery.

4. Conclusions

The results obtained made it possible to draw the following major conclusions.

- ✓ The expression of full permeability tensor of fractures is derived by converting the fracture permeability values from different local coordinate systems into one global coordinate system based on the tensor theory, which offers a comprehensive and accurate description of the flowability. Upon this approach incorporation into simulators, the precision of the simulation is significantly improved.
- ✓ The proposed method for assessing the parameter of anisotropic permeability is expedient and applicable. Principal directions are derived based on the log data. Principal values are identified using log data and production data. This approach can be used for adjusting well patterns properly and precisely.
- ✓ The field application strongly indicates that the methodology proposed in this paper is effective in assessing the anisotropic permeability parameters. Thus, it can facilitate the production system management and identification of the optimal well pattern layout.

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