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RESEARCH PAPER

Water flooding flowing area identification for oil reservoirs based on the method of streamline clustering artificial intelligence

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Abstract: For the case of carbonate reservoir water flooding development, the flow field identification method based on streamline modeling result was proposed. The Ocean for Petrel platform was used to build the plug-in that exported the streamline data, and the subsequent data was processed and clustered through Python programming, to display the flow field with different water flooding efficiencies at different time in the reservoir. We used density peak clustering as primary streamline cluster algorithm, and Silhouette algorithm as the cluster validation algorithm to select reasonable cluster number, and the results of different clustering algorithms were compared. The results showed that the density peak clustering algorithm could provide better identified capacity and higher Silhouette coefficient than K-means, hierachical clustering and spectral clustering algorithms when clustering coefficients are the same. Based on the results of streamline clustering method, the reservoir engineers can easily identify the flow area with quantification treatment, the inefficient water injection channels and area with developing potential in reservoirs can be identified. Meanwhile, streamlines between the same injector and producer can be subdivided to describe driving capacity distribution in water phase, providing useful information for the decision making of water flooding optimization, well pattern adjustment and deep profile modification.

Key words: water flooding; water flooding efficiency; flow field identification; streamline simulation; cluster algorithm; artificial intelligence

Introduction

Terrestrial sedimentary clastic rock and marine sedimentary carbonate reservoirs in China are characterized by strong heterogeneity. At present, the distribution of remaining oil in many high water cut sandstone reservoirs is disorder and scattered after long-term water flooding, making it difficult to understand the producing pattern of water flooding reservoirs and resulting in inefficient water-injection. Meanwhile, dominant channels are likely to form in the formation after long time fluid flush, resulting in ineffective water circulation[1] and low water flooding efficiency. In order to better describe the features of water flooding reservoirs, the water flooding flow field was characterized by the water drive characteristic curve[2] and the cross-well connectivity model before[3]. Hou et al.[1, 4-5] did a lot of research on flow field identification, established the flow field evaluation system, and used AHP to evaluate the flow field. However, AHP requires artificially setting the evaluation weight and will cause uncertainty in decision-making. On the basis of geologic model, previous researchers tried to fit the production data through the streamline simulation and analyze the fluid migration rules and flow trajectories[6–10]. Compared with the conventional method of determining the flow field strength based on the distribution of porosity, permeability and saturation, streamline simulation can accurately and directly show the main fluid flow area, so the water injection optimization, water flooding control and well-pattern optimization can be done according to the contribution of water injection to the oil recovery[11–18]. Although the mainstream reservoir numerical simulation software such as Petrel RE can accurately calculate the streamline distribution and optimize the solution according to the above method, it lacks method for flow field quantitative analysis, and the discrete streamline distribution can't represent the actual flow field, nor can it distinguish the mobility areas with different water phase driving capacities. In this study, based on the secondary development of the commercial software Petrel RE, we have come up with the streamline clustering method to distinguish and analyze the streamlines with different water-phase driving abilities, which provides a new means for

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water flooding flow field identification.

Clustering method is also called unsupervised learning, which is a branch of artificial intelligence method. Different from the way of analyzing injection-production cross-well coordination, streamline clustering[19] is used to cluster streamlines according to their spatial position and properties, and extract the potential distribution structure of flow field. Clustering algorithm clusters streamlines according to the principles of maximizing the difference between clusters and minimizing the difference within a cluster, ensuring that every kind of streamline can characterize the flow field it is in at the most extent and distinguish different kinds of streamlines. With minor dependency on empirical formula and artificial evaluation, this kind of algorithm without supervision is applicable to different types of reservoirs.

In this study, with a carbonate reservoir as an example, the streamline clustering method was used to distinguish the streamlines with different driving abilities in the water phase and further subdivide the streamlines between an injector and producer pair, to find out the potential preferential flow field and provide scientific basis and technical support for the decision-making of water flood flow field adjustment and oil recovery enhancement.

1. Streamline clustering

Streamlines represent the dominant channels formed by long-term flush of fluids, and are the flow trajectory of formation fluid during streamline simulation. In this study, streamline simulation was used to characterize the flow field, the basic assumption was that the reservoir fluid flew along the streamline within a certain time step; the streamline trajectory was obtained by the streamline tracking algorithm[20], and solving the one-dimensional mass conservation equation along the streamline gave the distribution of the saturation, which shows the fluid flow pattern in the reservoir.

The result of streamline simulation can only represent the distribution of fluid properties on the discrete streamline trajectory. Therefore, it is necessary to extract the streamline information to obtain a detailed description of the flow field. In this study, the flow field was divided into different flow regions by streamline clustering method, and the features of flow fields were evaluated, thus the follow-up reservoir development plans can be made according to the information obtained. Streamline clustering steps include feature parameters extraction, clustering analysis and clustering evaluation.

1.1. Feature parameters extraction

The clustering algorithm needs to cluster the samples according to their features, so the distinctive features of streamline easy to be used in actual application need to be extracted, the streamline features extracted and the formulas are shown in Table 1. Among them, the oil-water volume ratio is represented by V_{ow}, a larger value represents more oil not swept by water. Oil-water flow rate ratio is represented by v_{ow}, higher value means higher water driving ability.

Table 1. Streamline characteristics and formulas.

Description	Formula
x position of midpoints in streamline	$X_a = \sum_{b=1}^{n_a} x_{ab} \Big/ n_a$
y position of midpoints in streamline	$Y_a = \sum_{b=1}^{n_a} y_{ab} \Big/ n_a$
Oil-water volume ratio	$V_{\mathrm{ow}} = \sum_{b=1}^{n_a} S_{\mathrm{o}ab} \Big/ \sum_{b=1}^{n_a} S_{\mathrm{w}ab}$
Oil-water flow rate ratio	$v_{\mathrm{ow}} = \sum_{b=1}^{n_a} v_{\mathrm{o}ab} \Big/ \sum_{b=1}^{n_a} v_{\mathrm{w}ab}$

The span of streamline position in z-axis is not significant, thus we chose x, y positions of the streamline midpoints to represent the positions of streamlines. Meanwhile, due to the numerical dissipation in streamline simulation, some of the streamlines may show both oil and water flow velocities close to zero. Therefore, it is difficult to characterize the water-phase driving ability through the fluid flow velocity. In addition, for the flow field in the late stage of water flooding, the water permeability is often high, while the fluid saturation is increasing linearly, so they can't distinguish the water driving ability effectively. Thus the oil-water volume ratio and oil-water flow rate ratio were adopted to represent water-phase driving capacity of streamlines, this method can identify streamlines with lower water saturation and higher oil saturation, and highlighten streamlines with water saturation higher than a certain value, so as to reflect the distribution of flow fields with different water driving capacities.

The significance of parameter selection lies in that the streamlines can be clustered according to their spatial position, displacement efficiency, and sweep efficiency thus the streamlines with similar properties are clustered into one category, so as to find the reservoir area with development value and provide information and technology support for the water flooding optimization, well pattern adjustment, deep profile control and other programs.

After feature extraction, the feature parameters of each streamline need to be normalized for the following clustering analysis.

1.2. Cluster analysis

Clustering analysis is a technique for finding the internal structure between data. The clustering algorithms include density peak, K-means, spectral clustering and hierarchical clustering algorithm etc. The density peak algorithm was adopted in this study for its excellent capability in distinguishing data structure and non-random results. The basic principle of density peak clustering algorithm[19] is to set the number of samples that have similar features as the local density of these samples, and the point with the highest density in a local part is taken as the clustering center, meanwhile, it must be far to the other samples with larger local density. The flow chart of density peak clustering algorithm is shown in Fig. 1.

The local density of sample i is calculated as[19]:

$$\rho_i = \sum_j \chi\left(d_{ij} - d_{\mathrm{c}}\right) \quad \left(i = 1, 2, \cdots, n_{\mathrm{p}}\right) \tag{1}$$