



Three-dimensional hydrocarbon migration and accumulation modeling based on finite volume method



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Abstract: Aiming at the issue that the application effect of current 3-D hydrocarbon migration and accumulation modeling technique cannot meet the actual requirement because of over-simplified geologic model, a 3-D dynamic geologic model using PEBI grid in bedding and columnar shape was established, which can be used to solve the heterogeneity in reservoirs of various sedimentary facies, and to reduce the effect of mixed lithologies on modeling accuracy. A 3-D numerical modeling technique based on finite volume method was established, including the construction of variable grid flow equation, decomposition and calculation of full-tensor permeability, and calculation of conductivity etc. Some related processing techniques, such as smoothing of key parameter curves, stability processing of upstream and downstream of grid flow, etc. were used to improve the convergence of Newton's iteration. Automatic adjustment of time step and multi-core parallel computation were taken to enhance the running efficiency of the software. In a case study of Nanpu sag in the Bohai Bay Basin, the hydrocarbon migration and accumulation process, oil saturation and hydrocarbon resources abundance in various periods were simulated, the modeled oil saturation, accumulation quantity and hydrocarbon distribution locations coincide with current exploration status. The results also showed that the proved ratio of hydrocarbon resources in target layers is 84.4%, the majority of the resources are distributed in Block B and Block C, and it is predicted that undiscovered resources are mainly near Well NP2-16 in Block C and in the structure north of Well NP5-4 in Block A.

Key words: 3-D hydrocarbon migration and accumulation modeling technique; finite volume method; PEBI grid in bedding and columnar shape; variable grid flow equation; Nanpu sag

Introduction

Currently, there are three types of hydrocarbon migration and accumulation modeling technologies, i.e., 2-D flowpath method^[1], invasion percolation method^[1–2] and 3-D multi-phase Darcy flow method^[1,3–6]. Among them, the 2-D flow path method is suitable for modeling hydrocarbon accumulations in structural traps on map view; the invasion percolation method is mainly used to model hydrocarbon migration and accumulation pathways, and can be used in 2-D and 3-D spaces. The application prerequisite of the above two methods include static geology models and invariant modeling grids. The 3-D multi-phase Darcy flow method is a relatively mature one that considers the most factors in all the quantitative modeling methods^[7]. This method involves three kinds of core algorithms: finite element method (such as PetroMod and 3-D SEMI), finite volume method (such as Temispack) and finite difference method (such as BasinMod). The 3-D grids used in the three algorithms have some differences. The finite differ-

ence method is only suitable for regular center grid (such as rectangular grid); the finite element method is suitable for regular or irregular corner point grid (such as rectangular grid, corner point grid and tetrahedral grid, etc.); the finite volume method is suitable for regular or irregular center grid (such as rectangular grid, PEBI grid, etc.). These algorithms and corresponding grid modeling techniques have their own advantages and disadvantages. With the deepening of geological cognitions and the development of oil and gas exploration, the requirements on 3-D geological models are becoming higher and higher. The simpler rectangular grid commonly used in modeling cannot meet the modeling requirement in complex areas. As the PEBI (Perpendicular Bisection) grid modeling technique is more flexible, and applicable in a broader scope.

The studies on the 3-D hydrocarbon migration and accumulation modeling techniques based on finite volume method have made great progress in China and abroad. Feng Yong et al. (2001)^[8] proposed the combination of PEBI grid and the

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finite volume method, however, it was not effective in application. Shi et al. (2003) improved this combined method^[3]. Hantschel T and Kauerauf A I (2009) made an in-depth study on this method^[1]. The Watson Laboratory (2009) in IBM proposed a 3-D controlled volume finite element method^[4]. Shi et al. (2010)^[5] developed the finite volume method based on PEBI grid, which has achieved preliminary success in actual application. Except for the IBM method, the geology modeling grids in the above studies are all horizontal columnar PEBI grids, i.e., the vertical grid surfaces are parallel to horizontal planes. The top and bottom surfaces of such columnar grids intersecting with formation planes, are called “trans-formation” or “diachronous” in geology. Though such grid division can accelerate calculation speed, modeling accuracy is undermined, which is unfavorable for fine hydrocarbon migration and accumulation modeling in complicated geological setting.

In this study, a 3-D numerical modeling technique is developed for hydrocarbon migration and accumulation based on finite volume method, from the aspects of the establishment of geology model, construction of flow equation, calculation of full-tensor conductivity, and improvement of iteration stability and calculation efficiency of the Newton’s method, etc. Specifically, (1) a 3-D dynamic geology model with bed-parallel columnar PEBI grid is established to finely characterize formation evolution, which preliminarily solves geologic problems such as special flow features caused by formation heterogeneity and faults etc., and mixed lithologies; (2) flow equations in variable grids are constructed to replace the fixed grid flow equation, which achieves mass conservation more efficiently; (3) vector permeability (i.e., full-tensor permeability) is introduced to solve complex flow problems. This technique has been successfully applied in the Nanpu sag with good effect.

1. Grid division and key geology problem processing

1.1. Division methods of 3-D geologic body grids

1.1.1. Bed-parallel columnar PEBI grid

For the PEBI grid, the central ligature between any adjacent two grid blocks is perpendicularly bisected by their common surface. Such grid division method can improve flow modeling speed. Currently, the commonly used grid is horizontal columnar PEBI grid, namely, PEBI grid on plane, horizontal grids in vertical direction, in which grid surfaces intersect with formation planes (“diachronous”), geologic model accuracy will be negatively impacted. This study adopts bed-parallel columnar PEBI grid with PEBI grid on plane, and formation plane grid in vertical direction. Using such grid, the optimum planar grids can be constructed according to the distribution of known data points on plane to maximize modeling efficiency. In vertical direction, such grids can be divided according to stratigraphic surfaces to keep the grid sur-

face consistent with stratigraphic surface, so that “diachronous” phenomenon is avoided and the accuracy of geological model is improved.

1.1.2. Dynamic grid

The conventional modeling grids are static^[9]. In this paper, dynamic grids are adopted in various geologic periods, i.e., grids show consistent variations with strata during the burial process, and formations in grids are constant, only their attributes change because of some geology processes (compaction, etc.) (Grid volume changes, but their contents have no change). The advantage of dynamic grids lies in that the geologic model is closer to the reality, while their disadvantage is that the grid volume is significantly affected by formation thickness and calculation speed can be reduced.

1.2. Processing of key geologic parameters

1.2.1. Processing method for heterogeneity of formation physical properties

Random sampling is utilized to address heterogeneity. Firstly, the maximum, minimum, mean values and variance of porosity, permeability and pore throat radius were counted according to types of sedimentary facies, and their distribution models were established. Secondly, samples were taken randomly according to their distribution models to get the porosity, permeability and pore throat radius of different grids.

1.2.2. Processing method for permeability in specific direction (such as fault and river channel etc.)

Firstly, the permeability was divided into three directions, namely, principal-direction permeability (k_x , the strike direction of river channel and fault), minor-direction permeability (k_y) and vertical permeability (k_z). Then, the principal direction was expressed by a vector or azimuth, while the minor direction was vertical to the principal direction. Here, the vertical direction refers to the direction perpendicular to the stratigraphic surface (stratigraphic dip direction). Finally, the grids where the river channel and fault zone were located were assigned with k_x , k_y , k_z and the vector values (or azimuth angle).

1.2.3. Processing method for mixed lithologies

The grids for hydrocarbon migration modelling are bigger, generally covering several types of lithologies, thus special processing is necessary in grid parameter assignment. In this paper, means such as introducing the parameter “effective reservoir ratio”, and setting lower limit value of effective reservoir were taken to lower the effect of mixed lithologies on the modeling accuracy. Taking sandy and muddy layers as an example, the processing method is to set the effective reservoir ratio of each grid (f), and give the lower limit value of effective reservoir existence (f_{\min}). If $f > f_{\min}$, this grid is in “reservoir bed or conducting bed”, the physical properties in this grid are the physical properties of sandstone, and the ef-

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