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VISUALIZATION TECHNOLOGY OF THE MICROSTRUCTURE OF RESERVOIR CORE

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Abstract- To solve the problem in conventional technologies of analysis and integration in micro scale of reservoir core, virtual reality and visualization technology can be used in the research of reservoir core microstructure. Integrated with practical research and application works, the modeling method of reservoir core and the database store method of microstructure model are analyzed and discussed. A skeleton extraction algorithm based on maximum circumsphere method is proposed to achieve the skeleton model construction of reservoir core. And the visualization of reservoir core microstructure which includes the visualizations of voxel model, surface model, solid model and skeleton model of reservoir core are realized based on OpenGL graphics library. Taking a carbonate as a case study, we develop a set of software named "visualization system of reservoir core microstructure", which is an effective evidence in the application to scientific research of reservoir core microstructure.

Index terms: Reservoir core, microstructure model, visualization software.

I. INTRODUCTION

Reservoir core is a typical porous medium whose macro physical properties are influenced by many kinds of microcosmic factors [1, 2]. The conventional technologies include thin slice technique and pressure mercury method have some problems in the analysis and decision supporting of reservoir core research, such as low efficiency and poor accuracy. Moreover, it is difficult to observe and study the internal microstructure of reservoir core [3]. In recent years, in order to solve the problem, researchers have adopted advanced CT scanning technology, computer virtual reality technology and numerical simulation method to explore the research method of reservoir core microstructure [4, 5, 6].

At present, the study on microstructural visualization of reservoir core in China is still in its initial stage. There is no comprehensive graphical interface software for microstructural visualization of reservoir core. It is still to be improved in view of the simulation analysis and microstructural visualization of reservoir core. In the process of participating in the national major scientific instrument and equipment development project, we carried out the virtual analysis and software construction of reservoir core microstructure based on an independent development mode.

According to the structural characteristics of reservoir core, we developed a set of software named “visualization system of reservoir core microstructure” to achieve the construction of three-dimensional microstructural models of reservoir core and to realize the visualization of three-dimensional models. The software provides sets of auxiliary tools which image data, achieve the construction of three-dimensional voxel model, three-dimensional surface model, three-dimensional solid model and three-dimensional skeleton model of reservoir core and complete a series of functions including model storage, model operation and model input/output. Aiming at the real microstructural characteristics of the reservoir core and the requirements of the researchers, the software has the advantages of strong data processing, simple operation and realistic visualization effect which achieve the analysis and visualization of reservoir core microstructure conveniently.

II. THREE-DIMENSIONAL MODEL AND SPATIAL DATABASE OF RESERVOIR CORE

In order to observe and study the microstructure of reservoir core, the three-dimensional model of reservoir core should be constructed firstly. In this paper, the three-dimensional models of reservoir core are reconstructed on the basis of voxels which are extracted from the CT image of reservoir core by using digital image technology [7, 8, 9]. And the three-dimensional models of reservoir core include three-dimensional voxel model of reservoir core, three-dimensional surface model of reservoir core, three-dimensional solid model of reservoir core and three-dimensional skeleton model of reservoir core that can realize the full study on reservoir core microstructure. And on the basis of these models, the visualization and operation of reservoir core microstructure are realized.

In order to improve the running efficiency of the software and to achieve the model visualization, we must design a special spatial database to store the data which used to model reconstruction and operation. In this paper, the microstructure models of reservoir core are organized and stored according to the model type. And the data of each model is stored in the corresponding data table. So the same reservoir core has multiple data tables to realize the data storage of its microstructure models.

a. Three-dimensional Voxel Model and Spatial Database of Reservoir Core

a.i Three-dimensional voxel model of reservoir core

The three-dimensional voxel model of reservoir core selects the voxel as the basic unit and the voxel is extracted according to their gray value from CT image after image processing. The image processing includes median filtering to reduce image noise and watershed algorithm to transform the CT image into binarization image [10, 11]. After the image processing, the gray value distribution and regional boundary of CT image are relative concentration which is suitable to voxel extraction. In this spatial data model, the CT image is transformed into two data objects include voxel data object and three-dimensional voxel model data object.

a.ii Spatial database of three-dimensional voxel model

The same reservoir core will get many CT images after CT scanning. And the CT image data of the same reservoir core is recorded in the CT image storage table (Table 1). For the voxel data obtained from the CT image after image processing, the voxel data is recorded in the voxel storage table, as shown in Table 2. The data information of reconstructed three-dimensional voxel model for reservoir core is stored in the three-dimensional voxel model storage table, as shown in Table 3.

Table 1: The storage table of CT image

Field Name	Data Type	Illustration
PicNumber	long	The number of CT image
Width	int	The length of CT image
Height	int	The width of CT image
Layer	int	The layer of CT image
Data	BYTE	The voxel of CT image

Table 2: The storage table of voxels

Field Name	Data Type	Illustration
PointNumber	long	The number of voxels
x	long double	The X axis coordinate in the plane of CT image
y	long double	The Y axis coordinate in the plane of CT image
z	long double	The layer of CT image
Property	int	The property of voxel
Border	int	The border of CT image

Table 3: The storage table of three-dimensional voxel model

Field Name	Data Type	Illustration
MinCorner	long double	The minimum data of bounding box
MaxCorner	long double	The maximum data of bounding box

CutHeight	double	The profile height of model
Scale	double	The scale of model

b. Three-dimensional Surface Model and Spatial Database of Reservoir Core

The three-dimensional surface model of reservoir core selects the triangular mesh as the basic unit and the three-dimensional surface model which consisted of series of triangular meshes is generated based on voxels by using Marching Cubes algorithm [12, 13] which has advantages of high efficiency and high robustness. And the triangular meshes which generated by using Marching Cubes algorithm keep a good topological relationship between triangular meshes which is very important for the establishment of three-dimensional solid model of reservoir core. In this spatial data model, the voxels are transformed into two data objects include the data object of triangular meshes and the data object of three-dimensional surface model. The data storage table of three-dimensional surface model for reservoir core is shown in Table 4.

Table 4: The storage table of three-dimensional surface model

Field Name	**Data Type**	**Illustration**
Vertex	long double	The vertex of triangle mesh
Normal	long double	The normal vectors of triangle mesh
TriNumber	long	The number of triangle mesh
PointNumb	long	The number of voxels in triangle meshes
ImageNumb	long	The number of CT image
Border	int	The border of triangle mesh
CutHeight	double	The profile height of model
Scale	double	The scale of model

c. Three-dimensional Solid model and Spatial Database of Reservoir Core

The three-dimensional solid model of reservoir core selects the tetrahedron element as the basic unit. Taking the three-dimensional surface model of reservoir core as constraints, the three-dimensional solid model is constructed by using Delaunay triangulation algorithm [14, 15]. In this spatial data model, the triangular meshes of the three-dimensional surface model are transformed into two data objects include the data object of tetrahedron elements and the data object of three-dimensional solid model. And the topological relationship between the tetrahedron elements lays foundation to generate three-dimensional skeleton model of reservoir core. The data storage table of three-dimensional solid model for reservoir core is shown in Table 5.

Table 5: The storage table of three-dimensional solid model

Field Name	Data Type	Illustration
TetraNumber	long	The number of tetrahedron elements
Tetra[4]	int	The number of adjacent tetrahedron elements
NodeNumber[4]	int	The number of tetrahedral vertices
Face[4][3]	int	The number of tetrahedral faces
TetraHeight	double	The height of tetrahedron elements
CutHeight	double	The profile height of model
Scale	double	The scale of model

d. Three-dimensional Skeleton Model and Spatial Database of Reservoir Core

d.i Skeleton extraction algorithm based on maximum circumsphere method

In the research of reservoir core microstructure, the application of network model which can be used to analyze the model parameters, such as the pore shape and spatial distribution, is very extensive. And the skeleton model of reservoir core is the basis of network model construction. At present, there are three main types of skeleton extraction algorithms include Voronoi algorithm, thinning algorithm and distance transform method [16, 17, 18]. And these methods are most of aiming at the two-dimensional image which has some defects, such as low efficiency and inaccurate results of skeleton extraction. Therefore, a skeleton extraction algorithm based on maximum circumsphere method which is suitable for reservoir core is proposed.

Let A denote the modeling space. Let T denote the tetrahedron element of three-dimensional solid model for reservoir core, let ST denote the circumsphere of T and the volume of ST is V_{ST}. Let $ST_1 \wedge ST_2$ denote the intersection between circumspheres of tetrahedron element T_1 and tetrahedron element T_2 . There are some important definitions in the algorithm should be proposed.

(1) Master ball: if $\forall T_1 \in A$, $V_{ST_1} > V_{ST}$, the ST_1 is defined as a master ball.

(2) Slave ball: if $ST_1 \wedge ST_2$ and $V_{ST_2} < V_{ST_1}$, the ST_1 is defined as a slave ball which stored as $ST_2 \subset ST_1$.

(3) Share ball: if $ST_2 \subset ST_1$ and $ST_2 \subset ST_3$, the ST_2 is defined as a share ball of ST_1 and ST_3 which stored as $ST_2 \subset (ST_1, ST_3)$.

And the transitive relationship of slave balls as shown in Figure 1 is: if $ST_2 \subset ST_1$ and $ST_3 \subset ST_2$, then $ST_3 \subset ST_1$.The relationship between master balls, slave balls and share balls is shown in Figure 2.

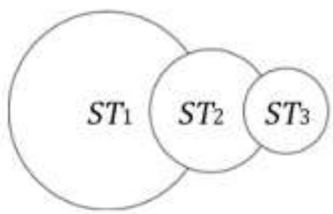


Figure 1. The transitive relationship of slave balls

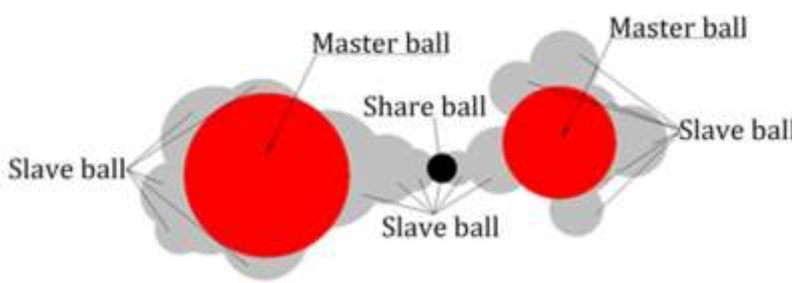


Figure 2. The relationship between master balls, slave balls and share balls

The skeleton extraction algorithm based on maximum circumsphere method is a geometric modeling method which according to the topological adjacency relationship between circumspheres to realize skeleton extraction. And the algorithm is described in details as follows:

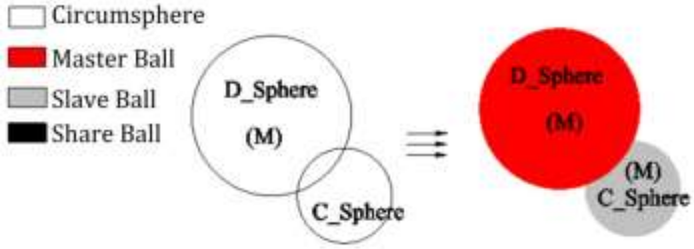
(1) Calculate the circumsphere of each tetrahedron element of three-dimensional solid model.

(2) Sort the circumsphere from big to small according to the radius of circumsphere.

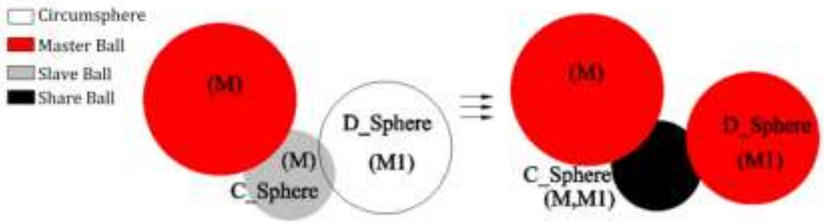
(3) Initialize the master ball (denoted as D_sphere). And determine the affiliation relationship between master ball and adjacency circumsphere (denoted as C_sphere) according to their topological adjacency relationship.

(4) Connect the center of share ball to the center of master ball by skeleton line.

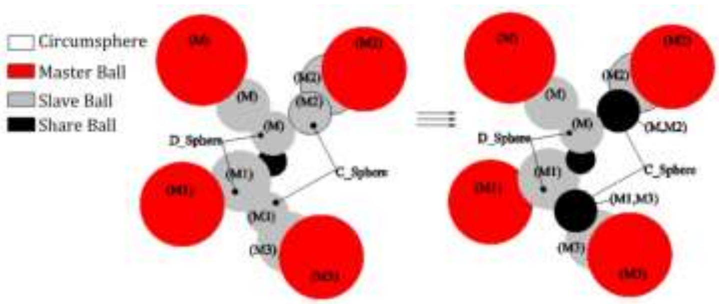
In the step (3), in the process of judging topological adjacency relationship between master ball and adjacency circumsphere, there are 9 cases presented as shown in Figure 3. And the judgment table of circumsphere affiliation is shown in Table 6.



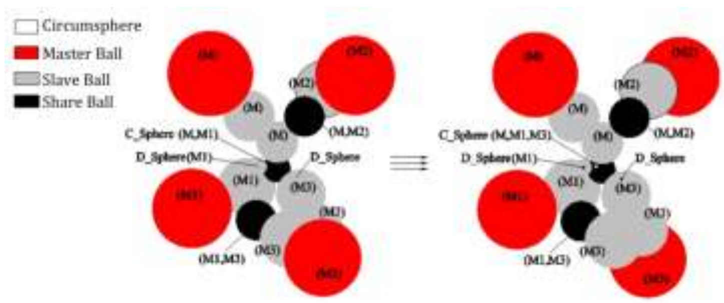
(a)



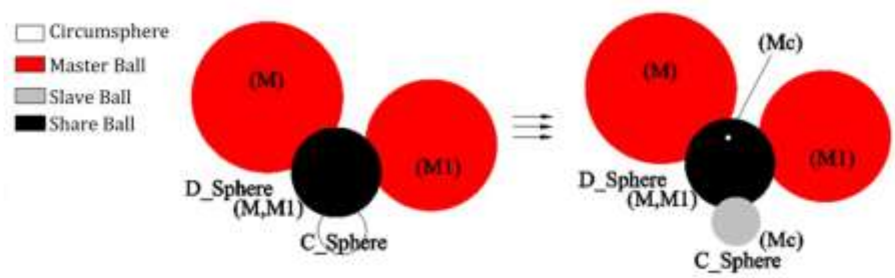
(b)



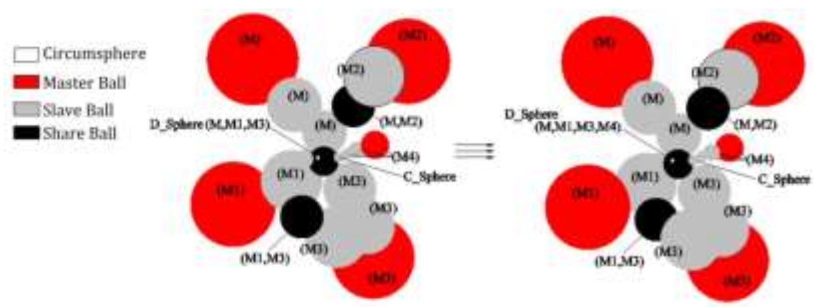
(c)


Circumsphere
Master Ball
Slave Ball
Share Ball

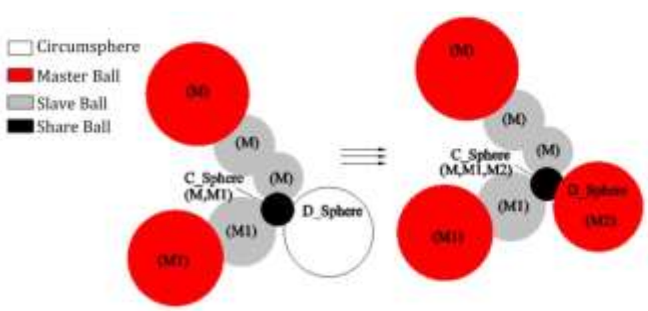
(d)


Circumsphere
Master Ball
Slave Ball
Share Ball
(M)
(M1)
D_Sphere
(M,M1)
C_Sphere
(Mc)
(M)
(M1)
D_Sphere
(M,M1)
(Mc)
C_Sphere

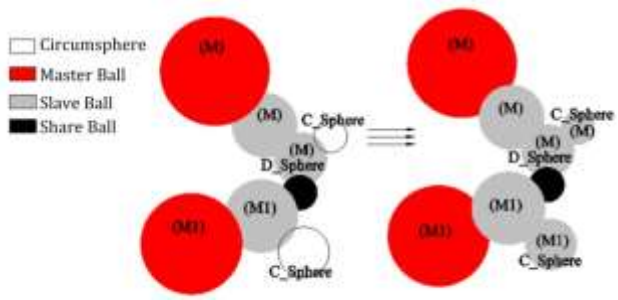
(e)


Circumsphere
Master Ball
Slave Ball
Share Ball

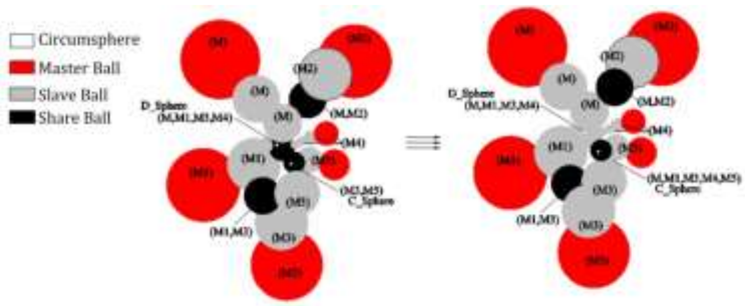
(f)


Circumsphere
Master Ball
Slave Ball
Share Ball

(g)



(h)



(i)

Figure 3. The topological adjacency relationship between circumspheres

Table 6: Determination of circumsphere affiliation

Reference Diagram	**D_sphere**	**C_sphere**	**Illustration**
Figure 3 (a)	Undetermined	Undetermined	$C\_sphere \subset D\_sphere$
Figure 3 (b)	Undetermined	Slave ball	C_sphere is a share ball
Figure 3 (c)	Undetermined	Share ball	$C\_sphere \subset D\_sphere$
Figure 3 (d)	Slave ball	Undetermined	$C\_sphere \subset D\_sphere$
Figure 3 (e)	Slave ball	Slave ball	C_sphere is a share ball
Figure 3 (f)	Slave ball	Share ball	$C\_sphere \subset D\_sphere$
Figure 3 (g)	Share ball	Undetermined	$C\_sphere \subset D\_sphere$
Figure 3 (h)	Share ball	Slave ball	$D\_sphere \subset C\_sphere$
Figure 3 (i)	Share ball	Share ball	D_sphere is a slave ball

After the above steps, the skeleton model of reservoir core is constructed finally. In this algorithm, we design four data objects include master ball, slave ball, share ball and skeleton line. And the data structure is shown in table 7.

Table 7: Data structure of skeleton extraction algorithm based on maximum circumsphere method

Master Ball	**Slave Ball**	**Share Ball**	**Skeleton Line**

Class CSkeleton
{
double Radius;
// The radius of master ball.
CPoint Center;
// The center of master ball.
int Master;
// The number of master ball.
BOOL IsMaster;
// To Judge whether it is a master ball.
long Number;
//The number of circumsphere.
};
	Class CSkeleton
	{
	double Radius;
	// The radius of slave ball.
	CPoint Center;
	// The center of slave ball.
	int MasterNum;
	// The number of master ball which contains the slave ball.
	BOOL IsSlave;
	// To Judge whether it is a slave ball.
	long Number;
	// The number of circumsphere.
	};
		Class CSkeleton
		{
		double Radius;
		// The radius of share ball.
		CPoint Center;
		// The center of share ball.
		int MasterNum;
		// The number of master ball which contains the share ball.
		BOOL IsShare;
		// To Judge whether it is a share ball.
		long Number;
		// The number of circumsphere.
		};
			Class CSkeleton
			{
			CPoint Center;
			// The center of circumsphere.
			long Number;
			// The number of circumsphere.
			long m_LineID;
			// The number of skeleton line.
			long m_StartID;
			// The number of starting master ball.
			long m_EndID;
			// The number of ending share ball.
			};

d.ii Spatial database of three-dimensional skeleton model

The three-dimensional skeleton model of reservoir core selects the circumsphere and skeleton line as the basic units. The three-dimensional skeleton model is generated by using skeleton extraction algorithm based on maximum circumsphere method which is proposed in this paper on the basis of the three-dimensional solid model. In this spatial data model, the tetrahedron elements in the three-dimensional solid model are transformed into three data objects include the data object of circumsphere, the data object of skeleton line and the data object of three-dimensional skeleton model. The data storage table of three-dimensional skeleton model for reservoir core is shown in Table 8.

Table 8: The storage table of three-dimensional skeleton model

Field Name	**Data Type**	**Illustration**
Center	long double	The center of circumsphere
Radius	double	The radius of circumsphere
Property	int	The property of circumsphere
Master	int	The number of master ball
SNumber	long	The number of slave ball
NShare	int	The number of share ball
Scale	double	The scale of model

III. VISUALIZATION OF RESERVOIR CORE MICROSTRUCTURE

At present, the 2D visualization technology has been relatively mature when the three-dimensional visualization technology is still limited by the real expression of spatial information. The available visualizers mainly include: OpenGL open graphics library and Microsoft DirectX [19], etc. In this paper, the OpenGL open graphics library is adopted to achieve the visualization of models by setting viewpoint and changing light, etc. Based on the three-dimensional space coordinates of models, the model visualization of reservoir core microstructure is achieved after projective transformation and model transformation based on OpenGL [20].

Each unit in the model of reservoir core microstructure can be composed of point, line, or ball in the OpenGL open graphics library. In order to improve the visualization efficiency of the model, according to the structural characteristics of reservoir core, we reform some functions of OpenGL which used to display voxel, skeleton line and model color, as shown in Table 9. And the reformation methods are as follows:

(1) Firstly, add a new parameter that represents property (denoted as Property) in the original function to control the color of different model unit.

(2) Then, adopt small balls to replace voxels that achieve a more obviously three-dimensional voxel model of reservoir core microstructure.

(3) Finally, select cylinders to replace skeleton lines that realize a more obviously three-dimensional skeleton model of reservoir core microstructure.

Table 9: The reformation methods of OpenGL

Function	**Function Reformation**
Point rendering	pView->EsDrawPointBall (Center, Radius, 1, Property);
Line rendering	pView->EsDrawCylinder(Center, pTera->Center, 0.15);
Color control	pView->EsDrawWithProperty(EsView *pView)

IV. THE VISUALIZATION EXAMPLE OF RESERVOIR CORE MICROSTRUCTURE

In order to display the visual effect of the software, in this paper, the reservoir core specimen of a carbonate rock with complex structure is taking as the research object to achieve the three-dimensional models construction and visualization in the visualization software. The three-dimensional models of carbonate rock include three-dimensional voxel model, three-dimensional surface model, three-dimensional solid model and three-dimensional skeleton model are constructed in the visualization software and the user can achieve some operations, such as zoom, pan, rotate and sectioning, through the visualization software to realize comprehensive observation of reservoir core microstructure.

The three-dimensional voxel model of carbonate rock which is composed of voxels extracted from the CT image is shown in Figure 4. The three-dimensional surface model of carbonate rock which is composed of a series of triangular meshes is shown in Figure 5 and Figure 6. The three-dimensional solid model of carbonate rock core which is composed of tetrahedron elements that generated under the constraint of three-dimensional surface model is shown in Figure 7 and

Figure 8. According to skeleton extraction algorithm based on maximum circumsphere that proposed above, the three-dimensional skeleton model of carbonate rock core is constructed and the model is shown in Figure 9 and Figure 10.

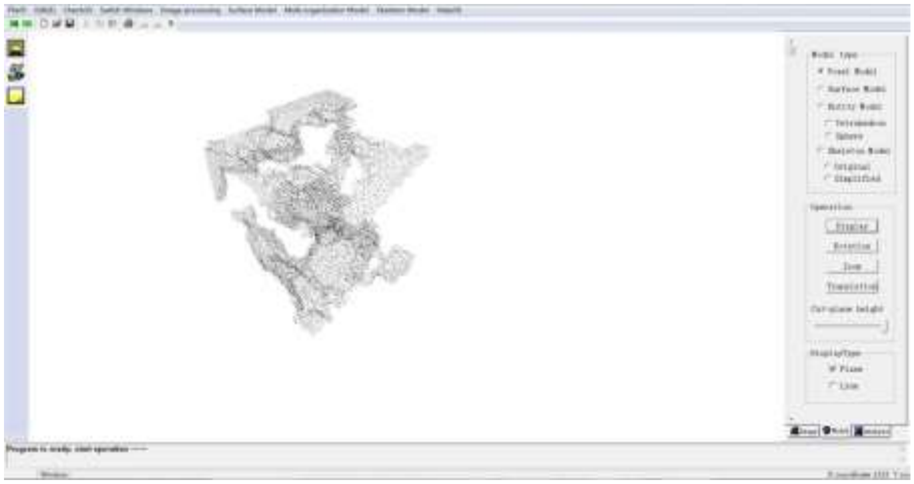


Figure 4. The visualization of three-dimensional voxel model of carbonate rock core

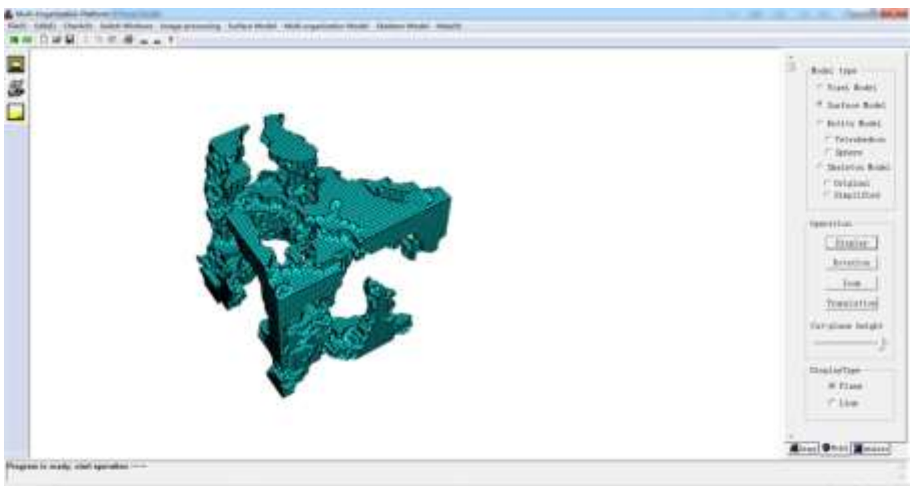


Figure 5. The visualization of complete three-dimensional surface model of carbonate rock core

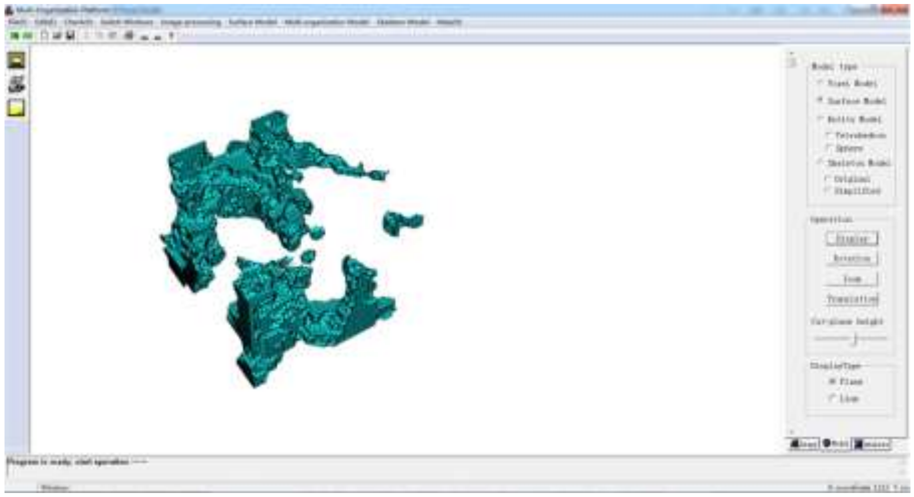


Figure 6. The visualization of sectional three-dimensional surface model of carbonate rock core

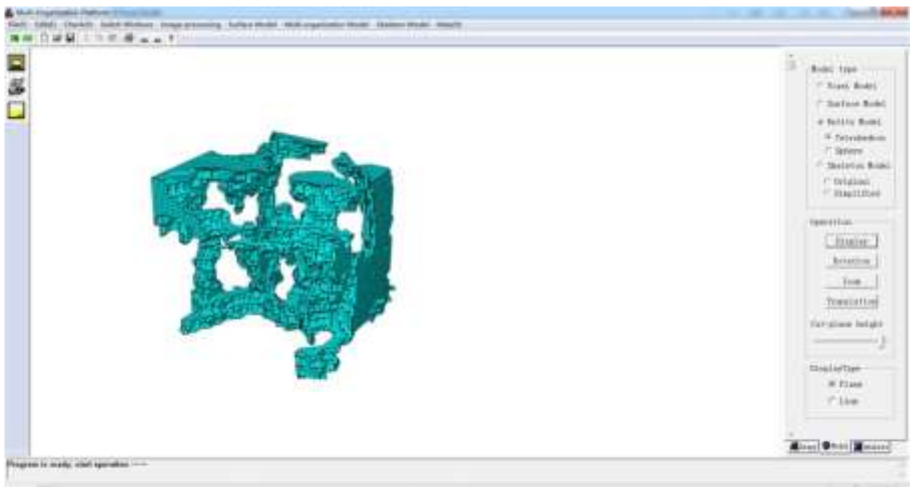


Figure 7. The visualization of complete three-dimensional solid model of carbonate rock core

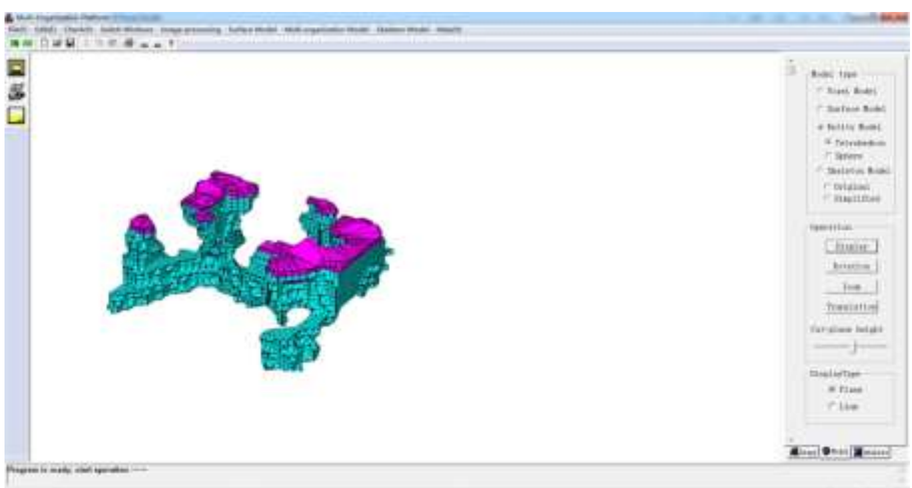


Figure 8. The visualization of sectional three-dimensional solid model of carbonate rock core

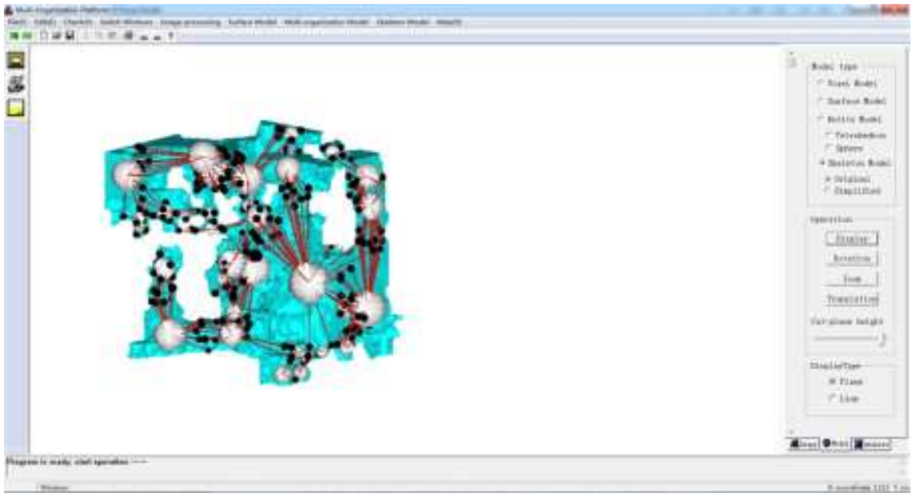


Figure 9. The visualization of complete three-dimensional skeleton model of carbonate rock core

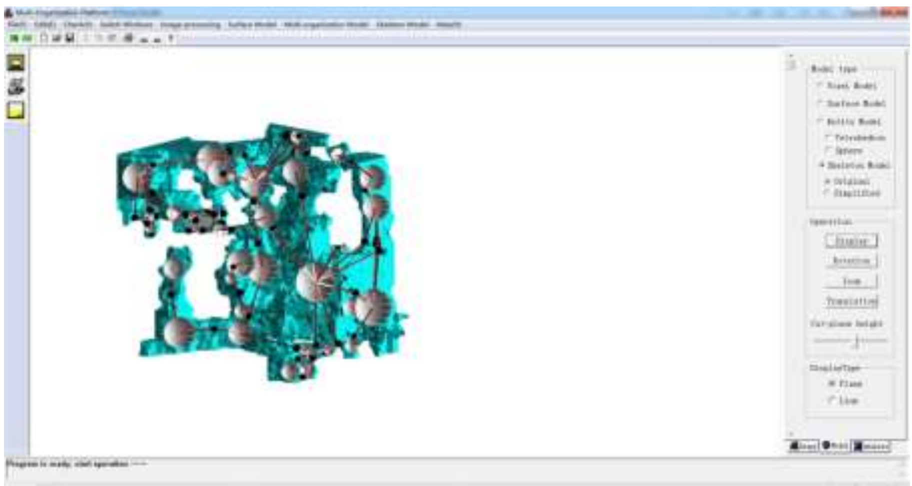


Figure 10. The visualization of sectional three-dimensional skeleton model of carbonate rock core

With reference to above Figure 4 to Figure 10 we can see that the visualization effect of three-dimensional model of carbonate rock core is comprehensive and meticulous which can help researchers to observe and analyze the microstructure of carbonate rock core with much more convenience.

V. CONCLUSIONS

By using three-dimensional visualization technology and computer virtual reality technology, the visualization software of reservoir core is built based on a reasonable spatial data model. The software takes full consideration of the characteristics of the original data and the application requirements of real-time, efficient and flexible at the time of technology implementation which achieved good practical results. The software can be used to study and observe the microstructure of reservoir core which improves the research efficiency. In the future, the numerical analysis and calculation of relevant parameters of reservoir core will be carried out to improve the practicality of software which provides a more comprehensive and effective support for the research on the microstructure of the reservoir core.

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