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Original article

Parallel numerical simulation for a super large-scale compositional reservoir

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Abstract:
A compositional reservoir simulation model with ten-million grids is successfully computed using parallel processing techniques. The load balance optimization principle for parallel calculation is developed, which improves the calculation speed and accuracy, and provides a reliable basis for the design of reservoir development plan. Taking M reservoir as an example, the parallel numerical simulation study of compositional model with ten million grids is carried out. When the number of computational nodes increases, message passing processes and data exchange take much time, the proportion time of solving equation is reduced. When the CPU number increases, the creation of Jacobian matrix process has the higher acceleration ratio, and the acceleration ratio of I/O process become lower. Therefore, the I/O process is the key to improve the acceleration ratio. Finally, we study the use of GPU and CPU parallel acceleration technology to increase the calculation speed. The results show that the technology is 2.4∼5.4 times faster than CPU parallel technology. The more grids there are, the better GPU acceleration effect it has. The technology of parallel numerical simulation for compositional model with ten-million grids presented in this paper has provided the foundation for fine simulation of complex reservoirs.

1. Introduction

The key issue of reservoir numerical simulation is to solve the large sparse linear algebraic equations, which are composed of large partial differential equations. In order to accurately describing the formation and fluid properties, complicated processing techniques, such as dual porosity, multiple composition simulation, have been developed. As a result, the established equations have more unknown variables, and more computational time is required. In the past, due to the limitation of computation capacity, the parallel simulation of large-scale integrated reservoir could not be well applied, and the development of fine numerical simulation technology is inhibited (Jiang et al., 2001; Cao et al., 2002; Pan et al., 2002; Yang et al., 2003). The appearance of high-performance parallel computer brings the reservoir numerical simulation technology into a new era, and makes the research of parallel numerical simulation a hot spot (Dogru et al., 2003; Liu et al., 2011; Tolstolytkin et al., 2014; Lian et al., 2018).

In recent years, many international oil companies and consulting companies adopt parallel processing technology to reduce production costs and improve work efficiency (Killough and Bhogeswara, 1991; Killough et al., 1997; Zhang et al., 2001; Ehtesham et al., 2013; Lian et al., 2019). Parallel numerical simulation technology not only helps to realize the integrated process of large-scale oilfield development, but also improves the precision of reservoir simulation, saves computational resource, reduces simulation cost, speeds up decision-making, optimizes development plan, improves overall efficiency of oilfield development, and reduces decision risk (DeBaun et al., 2005; Dogru et al., 2008; Al-Saadoon et al., 2013; Li et al., 2015). Petroleum industry in China has imported parallel computers and parallel processing systems, which have played important roles in the scientific research and production of Daqing Oilfield, Shengli Oilfield, etc (Zheng et al., 2001; Che et al., 2002; Zhao et al., 2003; Yang et al., 2004; Li et al., 2012; Li et al., 2018).

Based on the properties of the reservoir fluid, the dynamic model is mainly grouped into black oil model or compositional model. The black oil model has fewer unknown variables, and the numerical simulation technology of ten-million grids has been widely applied around the world. The compositional model, on the other hand, is different from the black oil model. Because of the complexity of flash calculation, the computational speed of the compositional model is much slower than the black oil model. The more compositions there

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are, the more computational time the compositional model requires. By now, the application of numerical simulation of compositional model with ten-million grids is few reported, and is only limited to the CPU parallel. CPU and GPU parallel acceleration numerical simulation is still in research. In this study, the ten-million grids numerical simulation technology is developed for the compositional model, and CPU and GPU parallel is used to accelerate the computational speed. The result of this study can provide insight for numerical simulation of complex reservoirs.

2. Methodology of parallel dynamic model

A fine reservoir dynamic model should be able to accurately describe reservoir heterogeneity in detail. If not, the flow characteristics of reservoir fluid will be different from the in-situ situation, and the simulation results will not accurately reflect the reservoir flow characteristics. During static model upscaling, the reservoir properties are averaged, and the heterogeneity is smoothed, resulting in the low accuracy of the simulation results. In other words, the results of high-precision dynamic model that reflects reservoir heterogeneity can help reservoir engineers in better decision-making. However, the high-precision dynamic model has its cost-more grids and more computational time. Besides, compared with the black oil model, the compositional model requires more computational resources. Therefore, an efficient computational platform is necessary for the fine compositional model.

2.1 Computing platform

In order to satisfy the requirement of computing giant reservoir dynamic model, Sinopec Petroleum Exploration and Production Research Institute (PEPRIS) has established a new computing platform that connects multiple Linux clusters. Users have remote access to the ”cloud platform”. The platform is connected to CPUs or nodes in the clusters through high-speed network. Different computers allocate resources or arrange tasks at the same time, and use message passing interface (MPI) to connect adjacent sub domain data. Processor performance and network performance, such as latency and bandwidth, are compatible with the requirements of numerical simulation. The platform can carry out parallel computation of large-scale reservoir numerical simulation, improve the calculation speed and accuracy, and thus provide reliable hardware equipment for the design of reservoir development plan.

2.2 Region partition technology

In parallel computing, the region partition technology is used to decompose the large-scale high-precision reservoir model and map them to a parallel computing platform. During this process, the model is decomposed to each sub domain, which is allocated a MPI. At the same time, many CPUs are called to solve the corresponding sub model. In this way, the simulation time is reduced from several days to several hours, and the dependence on hardware system resources is greatly reduced. The workstation cluster of high-performance reservoir numerical simulation needs high-speed network, such as InfiniBand switch. With the increasing number of clusters, a simulation model can connect to multiple Linux clusters.

3. Example of ten-million compositional model

3.1 Numerical simulation model

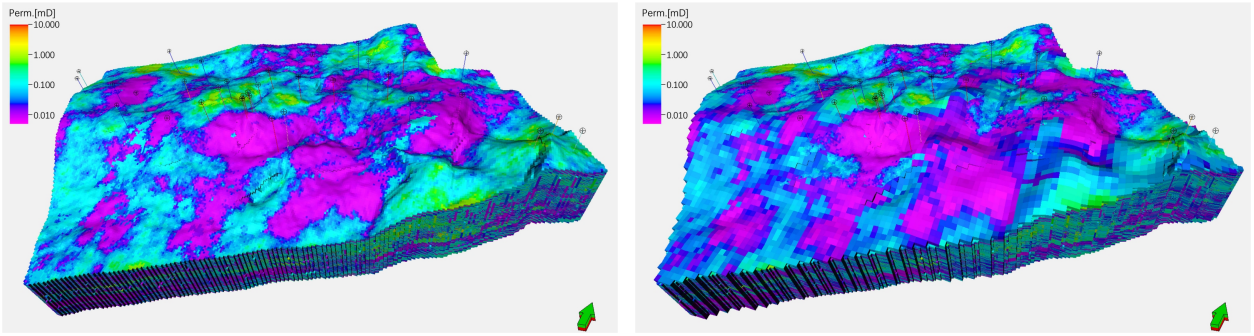
M reservoir is a large integrated porous carbonate reservoir. It has a length of 45 km in the north-south direction, a width of 15 km in the east-west direction, and a thickness of 230 m in the vertical direction. The original reserve is one billion tons. In order to accurately describe the heterogeneity in the formation, a fine geological model is built. The grid number in x, y and z direction is 376 $\times$ 294 $\times$ 281, and the total number of grids is 31,062,864. The average grid size is 100 m $\times$ 100 m $\times$ 1.5 m. Fig. 1a shows the three-dimensional permeability distribution of the fine numerical simulation model. In order to compare the geological characterization effect of the fine model, an upscale model is also built from the fine model. The grid number of the coarse model is 119 $\times$ 92 $\times$ 161, the total grid number is 1,762,628, and the average grid size is 300 m $\times$ 300 m $\times$ 3.0 m. Fig. 1b is the permeability distribution of the coarse numerical model. By comparing Fig. 1a and Fig. 1b, it is clear that the fine model can reflect the heterogeneity of the reservoir better.

M reservoir has a serious problem of asphaltene precipitation. In order to accurately characterize the characteristics of different fluid compositions, a large number of laboratory experiments were carried out to study the PVT properties of crude oil. According to the results of the PVT experiment and special fluid analysis data, a multi-composition numerical model considering the precipitation of asphaltene is established. There are nine compositions in the model. In addition to the conventional components, three compositions are added for asphaltene precipitation: soluble composition (PREC), flocculation composition (FLOC) and solid composition (DEPO). The detailed compositions are shown in Table 1. When the formation pressure is high, asphaltene is dissolved in the crude oil. With the decrease in formation pressure, asphaltene begins to precipitate and flocculate. When the flocculation gathers into large particles, it begins to precipitate as solid composition.

3.2 Partition design and optimization

The built ten-million grid numerical model is computed on the parallel computing platform. Firstly, the region partition is optimized. The default partition method is to average the number of grids along X direction, and the total number of grids in each domain is the same. However, due to reservoir heterogeneity and boundary setting, the computation load of each partition often varies a lot. There is ”barrel effect” in parallel numerical simulation speed, which depends on the partition with the largest calculation load. Therefore, it is necessary to optimize the load of each area.

After tremendous attempts and explorations, the fundamental principles of partition design for parallel computation are established:



(a) (b)

Fig. 1. Comparison of permeability distribution in the fine and coarse static models: (a) Fine static model; (b) Coarse static model (the green arrow points to the north).

Table 1. Pseudo-composition for asphaltene numerical simulation.

Pseudo-composition	composition	Mole fraction, %	Molecular weight
SC1N	C_1, N_2, H_2S	0.49	16.2
C2	C_2, CO_2	0.11	32.6
C34	C_3, C_4	0.11	50.0
C56	C_5, C_6	0.05	79.4
PC78	C_7, C_8	0.06	101.5
NC90	C_9, C_{10}	0.05	126.4
PREC	C_{11}+	0.13	366.6
FLOC	Flocculation composition	0.00	366.6
DEPO	Deposition composition	0.00	366.6

(1) The effective grid number in each region is close to each other;

(2) The fault or impermeable zone is set as the boundary of the regions;

(3) Different pressure systems should be in different regions;

(4) The fluid phase characteristics in the same region are similar;

(5) The same injection-production unit should be in the same region;

(6) The same well is located in the same region.

According to the basic principles of region partition, the load balance is optimized for the numerical model of M reservoir. By comparing the computational time of 10 years simulation, it is shown in Fig. 2 that the computational time of the optimized partition is lower than that of the default partition. With the increase of the computing nodes, more computational time is saved.

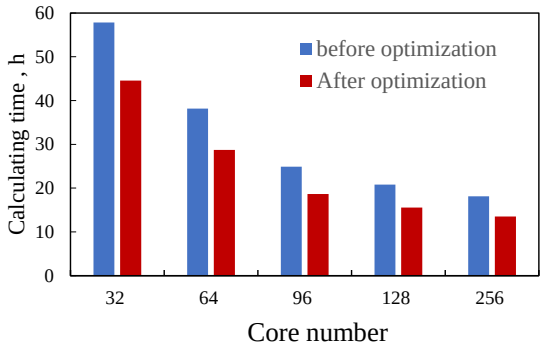


Fig. 2. Results of load balance optimization under different computer cores.

3.3 CPU parallel test

The CPU parallel computing speed of the built numerical simulation model is tested. The calculation tasks of reservoir simulation can be divided into several categories, which are equation solving, well data processing, Jacobian matrix building and data input and output. Generally, the equation solving is the most time-consuming process. Fig. 3 shows the processing time of the modeling using different processes with 32 cores, 64 cores and 128 cores. When using 32-core process to do the simulation, 64% of the time is spent on equation solving. When 64-core process is used for simulation, the percentage of the time for equation solving is reduced, but it still takes about 61% of the time. When 128-core process is used for simulation, the percentage of the time for equation solving is further reduced to 56%. When the number of nodes is large, more MPI processes and data exchange take up a large amount of time compared with conventional solutions. Therefore, with the increase of the number of simulation nodes, the partition of equation solving time is decreased.

When the number of computing cores increases from 32 to 128, the computing speed of the model should ideally increase 8 times. Fig. 4 shows the time of the equation solving process of the whole model. Although the computing speed is improved when the number of CPU cores increases from 32 cores to 256 cores, the computing speed only increases by

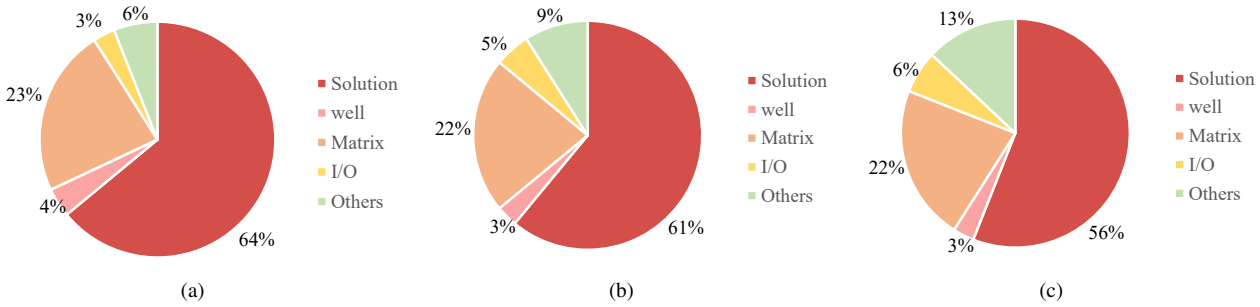


Fig. 3. Processing time of different processes in the 32, 64 and 128 cores: (a) 32 cores; (b) 64 cores; (c) 128 cores.

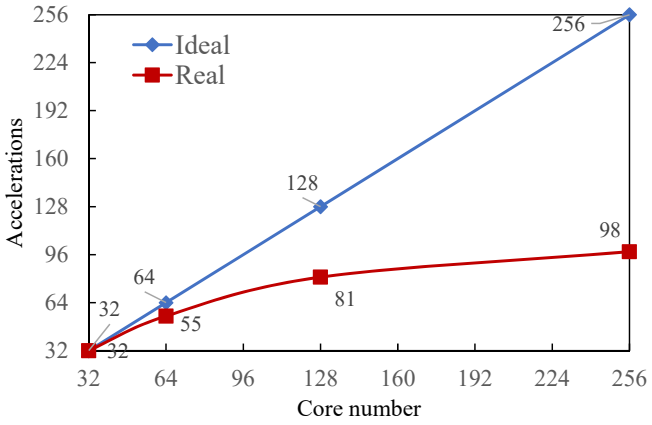


Fig. 4. Comparison of ideal and actual acceleration ratio.

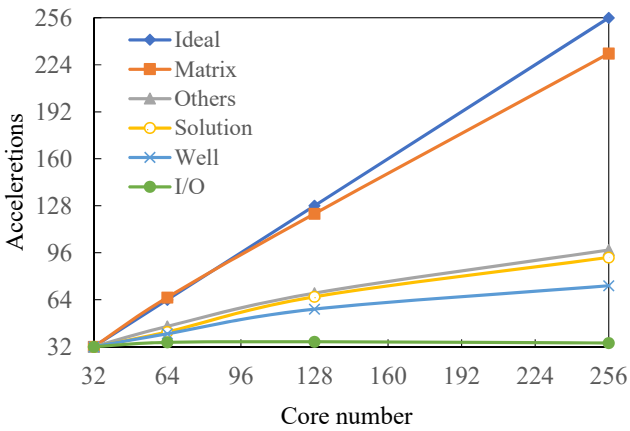


Fig. 5. Comparison of acceleration of each process.

2.87 times. When the number of nodes is large, there are more MPI processes and more time for data exchange, resulting less the acceleration ratio. With the development of technology, the speed of processor and network is also increased, and the time of data exchange is reduced, which is beneficial to improve the speed up ratio.

Different process accelerations of the model are shown in Fig. 5. The process of equation solving and Jacobian matrix building increases the most (close to the ideal acceleration ratio). On the other hand, the I/O process is not increased. Other processes, such as model initialization, are not as fast as Jacobian, but is better than the I/O processes. Therefore, I/O process is the key factor that restricts the acceleration ratio. The further work is to develop hardware equipment to improve the acceleration ratio of I/O process.

3.4 GPU and CPU hybrid acceleration

The architecture of CPU and GPU is quite different. CPU has many functional modules, and can adapt to the complex computing environment. The composition of GPU is relatively simple. At present, stream processor and video memory controller occupy the majority of transistors. The CPU architecture is conducive to the serial architecture of X86 instruction set. The CPU is designed to complete a task as quickly as possible. GPU, on the other hand, has millions of tasks to be processed in parallel at the same time. Therefore, GPU is designed to handle many tasks in parallel instead of completing a single task like CPU.

The heterogeneous hybrid parallel computing of CPU + GPU is based on CUDA (Compute Unified Device Architecture) parallel computing architecture. GPU and CPU work together, CPU handles parallel computing, while GPU handles operating system and instruction logic control. The cooperation between CPU and GPU is dozens or even hundreds of times faster than that of the CPU merely. Fig. 6a shows the accumulation curve of the computational time when the fine model is computed using the parallel acceleration of CPU and GPU. It is shown that the parallel acceleration technology of 64 CPUs and 1792 GPUs is 3.6 times faster than that of 64 CPUs only. When the number of GPUs is increased to 3840, the acceleration ratio increases to 5.4, and the growth rate decreases. Fig. 6b shows the cumulative time curve of the coarse model using the parallel acceleration simulation. The parallel acceleration technology of 64 CPUs and 1792 GPUs is 2.4 times faster than that of 64 CPUs alone. As the number of grids is small, the computation load of GPUs is reduced, so the acceleration ratio is reduced.

Fig. 7 shows the CPU and GPU usage time with different CPU number. The number of GPUs is 1792. It is shown that the more CPU cores there are, the shorter CPU computing time it requires. Due to the more data exchange between partitions, the GPU computing time will increase. When the CPU increases to a certain number, the GPU calculation time will not increase any more.

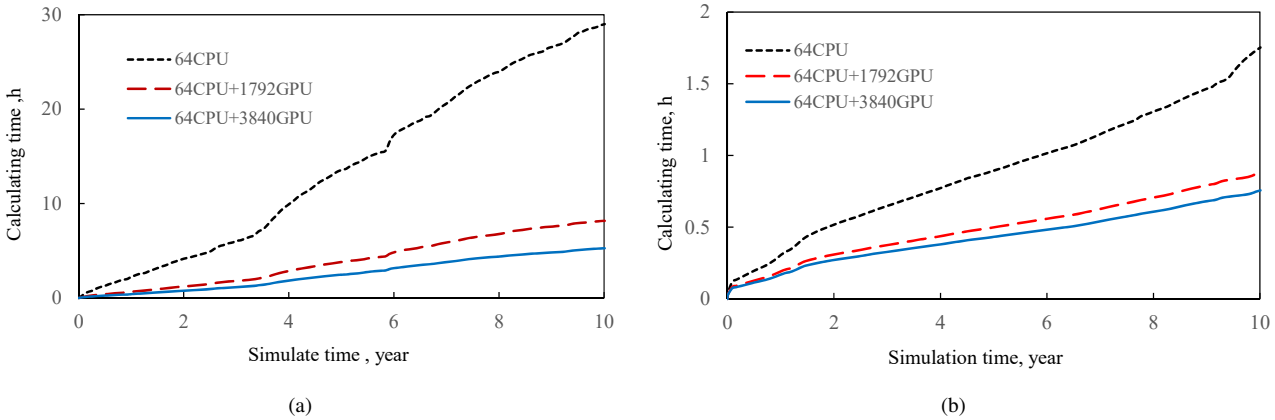


Fig. 6. Comparison of calculating time of CPU and GPU + CPU: (a) Fine model; (b) Coarse model.

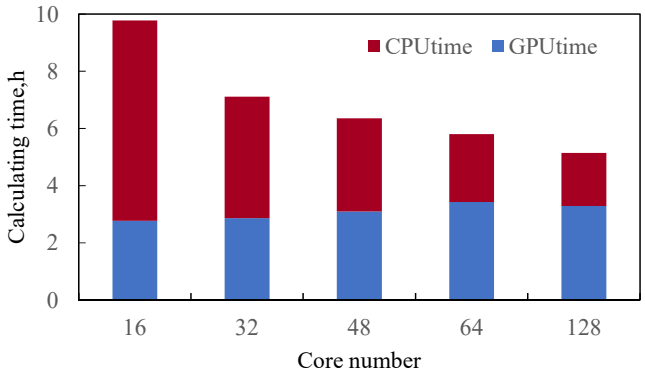


Fig. 7. The GPU and CPU time under different CPU cores.

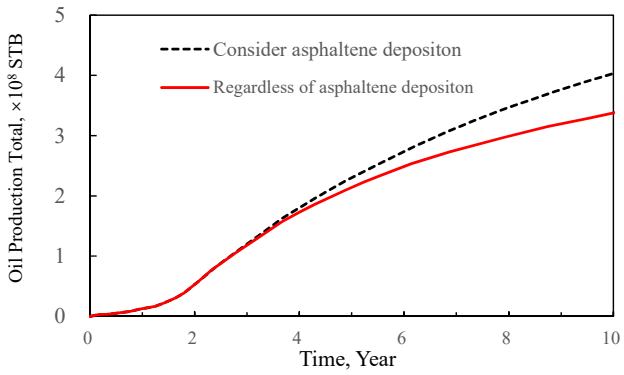


Fig. 8. The cumulative production curves with and without asphaltene deposition.

3.5 Field application

The effect of asphaltene precipitation on cumulative production in M reservoir is calculated using parallel simulation. The model is very large, and the CPU + GPU parallel acceleration technology is applied to improve the calculation speed of the model, thus saving the calculation time. Fig. 8 shows the influence of asphaltene precipitation on cumulative production. It is clear that the production decreases rapidly and the cumulative oil production gap is large when asphaltene deposition is considered. The reason is that the solid asphaltene precipitation results in the plugging of formation pores, which leads to the decrease of permeability, and affects the single well production. Therefore, the asphaltene precipitation must be considered in the actual reservoir simulation, otherwise the predicted production index will be overestimated.

4. Conclusions

(1) With the help of parallel acceleration technology, the numerical simulation of ten-million compositional model is successfully conducted. According to the reservoir condition, the load balance optimization principle is established. With the basic principle and method of region partition, the load balance optimization of M reservoir numerical model is carried out, which significantly improves the computational efficiency.

(2) For CPU parallel computing, when the number of computing nodes is large, more MPI processes and data exchange take up much time, and the proportion time of equation solving is reduced. I/O process is the key factor that restricts the improvement of acceleration ratio. In the further, hardware equipment can be developed to improve the acceleration ratio of I/O process.

(3) By using CPU + GPU parallel acceleration, the computing speed can be greatly improved, and the example shows that it can be increased by 5.4 times. The more CPU cores there are, the shorter CPU computing time it will take. Because of the increasing data exchange between partitions, the GPU computing time becomes longer. When the number of CPUs increases to a certain number, the GPU calculation time will not increase any more.

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