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A scalable parallel black oil simulator on distributed memory parallel computers

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ABSTRACT

This paper presents our work on developing a parallel black oil simulator for distributed memory computers based on our in-house parallel platform. The parallel simulator is designed to overcome the performance issues of common simulators that are implemented for personal computers and workstations. The finite difference method is applied to discretize the black oil model. In addition, some advanced techniques are employed to strengthen the robustness and parallel scalability of the simulator, including an inexact Newton method, matrix decoupling methods, and algebraic multigrid methods. A new multi-stage preconditioner is proposed to accelerate the solution of linear systems from the Newton methods. Numerical experiments show that our simulator is scalable and efficient, and is capable of simulating extremely large-scale black oil problems with tens of millions of grid blocks using thousands of MPI processes on parallel computers.

1. Introduction

Nowadays, large-scale reservoir simulations often have millions of grid blocks, particularly those involving thermal recoveries such as SAGD (Steam Assisted Gravity Drainage) simulations, which require that grid block sizes are of order of around one meter, which results in an extremely large number of grid blocks for full field scale simulations. Furthermore, when dealing with models with complex geology, high resolution simulations with a large number of grid blocks are required to capture fine-scale phenomenon. Most available commercial reservoir simulators were developed for personal computers and workstations. Limited by the memory size and CPU performance, using these reservoir simulators, simulations with tens of millions of grid blocks may take weeks or even longer to complete. Parallel reservoir simulators should be considered to improve simulation efficiency.

Various techniques have been invested to accelerate reservoir simulations, including new models [1], numerical methods [1], linear solvers and preconditioner techniques [2–7]. In the 1980s, parallel computation was considered in reservoir simulations [8–10]. Killough et al. developed a parallel compositional simulator, which demonstrated that a highly efficient parallel model could be generated for an n-component, three-phase, EOS (equations of state) reservoir simulator in a distributed-memory parallel computer [10]. Rutledge et al. implemented an IMPES (implicit-pressure explicit saturation) compositional simulator using massive SIMD computers, which yielded reasonable computational performance with a straightforward data structure and a simple approach to handle multiple phases [11]. Kaarstad et al. presented a two-dimensional two-phase (oil and water) simulator, which could solve problems with one million grid blocks [12]. Shiralkar et al. developed the parallel production quality simulator FALCON, which could run effectively on a variety of computing platforms [13]. Killough et al. used locally refined grids in their parallel simulator [14]. Parashar et al.'s parallel simulator

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successfully handled multiple fault blocks with multiple physics [15]. In 2009, Dogru et al. developed a parallel simulator GigaPOWERS, which was capable of simulating one billion grid blocks [16]. Linear systems from black oil model are ill-conditioned, and proper preconditioners are essential to parallel simulators. Many preconditioners for reservoir simulation have been proposed, including point-wise and block-wise incomplete factorization [3,4,17], domain decomposition [18,17], constrained pressure residual (CPR) [5,6,19], multi-stage [20] and fast auxiliary space preconditioners (FASP) [21,22]. Recently GPU computing techniques have been applied to reservoir simulations. Chen et al. developed GPU-based linear solvers and preconditioners to speed the Krylov subspace linear solvers, algebraic multigrid solvers and preconditioners [23,24]. These techniques have been applied to black oil simulations [25,19]. Klie and Saad implemented their GPU-based linear solvers and applied them to reservoir simulation [26,27].

In this paper, we present our work on developing a parallel black oil simulator. The black oil simulator is based on an in-house parallel platform we are developing, which is designed for general purpose simulators. The black oil model has three mass conservation equations for the water component, the oil component and the gas component. Here the finite difference method is applied to discretize the equations due to its simplicity. The schemes are conservative and an upstream weighting technique is employed for fluid and fluid–rock properties. The black oil model is highly nonlinear. Usually Newton–Raphson methods (or Newton methods) are used to solve the model system, which is solved relatively accurately. The Krylov subspace solvers [28], such as BICGSTAB and GMRES, and algebraic multigrid solvers (AMG) are widely used to solve linear systems from the Newton methods. The problem is that when the sizes of the linear systems derived from these methods are large and the condition numbers of these linear systems are large, the standard Newton method can be very expensive. To our knowledge, when a linear system is large enough, 70% or more of the whole simulation time can be spent on linear solvers [1]. In our simulator, both the Newton methods and inexact Newton methods are implemented. For the inexact Newton methods, the termination tolerance for the linear solvers is loosed, which saves the simulation time. Even with these methods, the solution of a large linear system in reservoir simulation is still challenging. Commonly used preconditioners are implemented to accelerate the linear solvers, including domain decomposition, algebraic multigrid and Constrained Pressure Residual (CPR) preconditioners. Here, a new three-stage preconditioner is proposed, which is more efficient than the classical CPR preconditioner. The number of average linear iterations is around 10 for the challenging problems studied. It also shows excellent performance and parallel scalability. Numerical experiments are carried to study the performance of the black oil simulator, linear solvers, preconditioners and Newton methods. The benchmarks demonstrate that our methods are fast, our simulator is scalable, and our linear solver techniques are efficient and robust.

The rest of the paper is organized as follows: In Section 2, the mathematical equations of the black oil model and the numerical methods used to discretize these equations are presented. In Section 3, the methods of solving the coupled non-linear systems for the black oil model are introduced. In Section 4, techniques for the solution of the linear systems resulted from Newton methods are studied. In Section 5, numerical results are presented.

2. Black oil model and its numerical discretization

The black oil model assumes that the flow in a reservoir has three phases and three components (oil, gas and water), there is no mass transfer between the water phase and the other two phases, and the reservoir is isothermal. Combining Darcy's law and mass conservation law, the black oil model is written as follows [1]:

$$\begin{cases} \dfrac{\partial}{\partial t}(\phi s_o \rho_o^o) & = \nabla \cdot (\dfrac{K K_{ro}}{\mu_o} \rho_o^o \nabla \Phi_o) + q_o, \\ \dfrac{\partial}{\partial t}(\phi s_w \rho_w) & = \nabla \cdot (\dfrac{K K_{rw}}{\mu_w} \rho_w \nabla \Phi_w) + q_w, \\ \dfrac{\partial (\phi \rho_o^g s_o + \phi \rho_g s_g)}{\partial t} & = \nabla \cdot (\dfrac{K K_{ro}}{\mu_o} \rho_o^g \nabla \Phi_o) + \nabla \cdot (\dfrac{K K_{rg}}{\mu_g} \rho_g \nabla \Phi_g) + q_o^g + q_g, \end{cases} \tag{1}$$

where ϕ and K are porosity and permeability, for phase α ($\alpha = o, w, g$), Φ_α is potential, and s_α, μ_α, p_α, B_α, ρ_α, $K_{r\alpha}$ and q_α are the saturation, viscosity, pressure, formation volume factor, density, relative permeability and production rate, respectively. ρ_o^g is the density of solution gas, ρ_o^o is the density of the oil component, and $\rho_o = \rho_o^g + \rho_o^o$. These variables have the following relations:

$$\begin{aligned} &\Phi_\alpha = p_\alpha + \rho_\alpha \wp z, \\ &s_o + s_w + s_g = 1, \\ &p_w = p_o - p_{cow}(s_w), \\ &p_g = p_o + p_{cog}(s_g), \end{aligned}$$

where $\wp$ is the gravitational constant and z is the reservoir depth. With proper boundary and initial conditions, a close system is given.

In this paper, the fully implicit method (FIM) and a first-order upstream finite difference method are applied to discretize the black oil model, where pressure δp, water saturation δs_w and δX (gas saturation δs_g or bubble point pressure δp_b) are