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Original paper

Parallel numerical simulation of two-phase flow model in porous media using distributed and shared memory architectures

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Resumen

En este trabajo se estudia un modelo de flujo bifásico (agua-aceite) en un medio poroso homogéneo considerando un desplazamiento inmiscible e incompresible. Este modelo se resuelve numéricamente usando el Método de Volumen Finito (FVM) y se comparan cuatro esquemas numéricos para la aproximación de los flujos en las caras de los volúmenes discretos. Se describe brevemente cómo obtener los modelos matemático y computacional aplicando la formulación axiomática y programación genérica. También, implementa dos estrategias de paralelización para reducir el tiempo de ejecución. Se utilizan arquitecturas de memoria distribuida (clusters de CPUs) y memoria compartida (Tarjetas gráficas GPUs). Finalmente se realiza una comparación del desempeño de estas dos arquitecturas junto con un análisis de los cuatro esquemas numéricos para un patrón de flujo de inyección de agua, con un pozo inyector y cuatro pozos productores (five-spot pattern).

Palabras clave: flujo bifásico, medios porosos, recuperación de hidrocarburos, método de volumen finito, cómputo paralelo, Cuda.

Abstract

A two-phase (water and oil) flow model in a homogeneous porous media is studied, considering immiscible and incompressible displacement. This model is numerically solved using the Finite Volume Method (FVM) and we compare four numerical schemes for the approximation of fluxes on the faces of the discrete volumes. We describe briefly how to obtain the mathematical and computational models applying axiomatic formulations and generic programming. Two strategies of parallelization are implemented in order to reduce the execution time. We study distributed (cluster of CPUs) and shared (Graphics Processing Units) memory architectures. A performance comparison of these two architectures is done along with an analysis of the four numerical schemes, for a water-flooding five-spot pattern model.

Key words: two phase flow, porous media, oil recovery, finite volume method, parallel computing, Cuda.

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Introduction

New recovery techniques (for example Enhanced Oil Recovery) are essential for exploiting efficiently oil reservoirs existing around the world. However, before these techniques can be successful applied, it is fundamental to develop mathematical and computational investigations to model correctly all the processes that can occur. General procedures for constructing these mathematical and computational models (MCM) are presented in [1, 2], where it is shown that with an axiomatic formulation it is possible to achieve generality, simplicity and clarity, independently of the complexity of the system to be modeled. Once we have an MCM of the oil recovery process we are interested in, an efficient implementation of computer codes is required to obtain the numerical solution in short times.

Nowadays, the oil reservoir characterization technologies can produce several millions of data, in such a way that an accurate well-resolved simulation requires an increase on the number of cells for the simulation grid. The direct consequence is that the calculations are significantly slow down, and a very high amount of computer resources (memory and CPU) are needed. Currently, fast simulations on commercial software are based on parallel computing on CPU cores using MPI [3] and OpenMP [4]. On the other hand, since the introduction of the CUDA language [5], high-performance parallel computing based on GPUs has been applied in computational fluid dynamics [6, 7], molecular dynamics [8], linear algebra [9, 10], Geosciences [11], and multi-phase flow in porous media [12, 13, 14, 15, 16] among many others.

The water-flooding technique is considered as a secondary recovery process, in which water is injected into some wells to maintain the field pressure and to push the oil to production wells. When the oil phase is above the bubble pressure point, the flow is two phase immiscible and there is no exchange between the phases, see [17]. Otherwise, when the pressure drops below the bubble pressure point, the hydrocarbon component separates into oil and gas phases. The understanding of the immiscible water-flooding technique is very important and still being studied as a primary benchmark for new numerical methods [18] and theoretical studies [19]. Besides, some authors have started to investigate parallel technologies to reduce the execution time of water-flooding simulations, see for example [7, 13, 15, 20].

The incorporation of the GPUs into the floating point calculation of the oil reservoir simulation, has been considered in several studies. For example, in [20] a model for two-phase, incompressible, immiscible displacement in heterogeneous porous media was studied, where an operator splitting technique, and central schemes are implemented on GPUs producing 50-65 of speedup compared with Intel Xeon Processors. In [13], a very similar study as ours is presented, where the IMPES method is used to linearize and decouple the pressure-saturations equation system, and the SOR method is applied to solve the pressure equation implicitly. Their implementations was done considering a partition of the domain and then distributing each subdomain to blocks of threads. They obtain considerable accelerations (from 25 to 60.4 times) of water-flooding calculations in comparison with CPU codes. Multi-GPU-based double-precision solver for the three-dimensional two-phase incompressible Navier-Stokes equations is presented in [7]. Here the interaction of two fluids are simulated based on a level-set approach, high-order finite difference schemes and Chorin's projection method. They present an speed-up of the order of three by comparing equally priced GPUs and CPUs.

The numerical application studied in this paper, is the well known five-spot pattern model, and we work this model in the limit of vanishing capillary pressure, applying Darcy's law coupled to the Buckley-Leverett equation. This assumption generates an hyperbolic partial differential equation which can presents shocks in its solution. Our approach for solving this equation is to use four numerical schemes for approximating the fluxes adequately on the faces of the discrete volumes. We are interested in to study the numerical throwput of these four numerical schemes. We also focus our attention in the comparison of two parallel implementations written to run on a high-performance architecture consisting of CPUs and GPUs. We made this comparison in equality of conditions in order to do an objective analysis of the performance. The parallel implementations we present, are based on the use of well established opensource numerical libraries for solving linear systems. We use PETSc [21, 22] for distributed memory and CUSPARSE [24, 23] for GPU shared memory. We coupled these two libraries to our software TUNAM [25, 26], which implements FVM from a generic point of view. With this software we can easily implement, incorporate and evaluate the four numerical schemes for the approximation of the fluxes on the faces. Our objective is to give a quantitative reference that can be reproduced easily, and applied to other applications.

This paper is structured as follows. In section 2, we discuss the mathematical modeling of multiphase flows in porous media. The presentation is based on the axiomatic formulation introduced in [1, 2], and a pressure-saturation formulation is described for the two-phase flow. In section 3, the FVM is applied to the mathematical model, and the four numerical