A Distributed Computing CFD Workbench for Porous Media Simulations and Analysis

S. Sengupta*, G.P. Raja Sekhar†
*Department of Aerospace Engineering, IIT Kharagpur,
† Department of Mathematics, IIT Kharagpur, India.
E-mail: shanks.iit@gmail.com

Key Words: Java, parallel algorithm, unstructured mesh, porous flow, cavity analysis

ABSTRACT

This paper addresses the developments of modern software systems in engineering sciences, and more precisely in simulation for industrial applications. Transport in heterogeneous and disordered media has important applications in many fields of science including composite materials, rheology, geophysics, polymer physics, statistical physics, chemical physics, colloid science, petroleum exploration and technology, and also, biotechnology. Progress in the field of heterogeneous media was, until recently, hampered by the difficulties involved in characterizing the complex random microstructure and many more. The problem consists in characterizing the microstructures quantitatively in such a way that the characterization can be used to predict physical transport quantities such as permeability, conductivity or elastic constants. A particularly important subclass of disordered heterogeneous materials is porous media. For porous media, the complete prediction of multiphase fluid flow has remained largely impossible despite many years of research in academia and industry. Solutions to this problem would be of great importance for many applications (e.g. prediction of groundwater flow, chemical reactions in catalysts, and flow through gels, granular media, textiles, construction materials, filtration technology, hydrocarbon production or in situ remediation of contamination areas). Progress towards the solution of these problems requires also advances on some fundamental problems of theoretical physics (e.g. in hysteresis, metastability or non-equilibrium systems, theory of wetting, classification of disordered systems or macroscopic heterogeneity) as well as advances in numerical and computational techniques to analyze the problem much more efficiently and with considerable efficiency. The estimation on the extraction of oil and natural gases is dependent upon the use of computational science to aid in the extraction from the existing oil reserves. Parallel computers permit researchers to create detailed oil reservoir models that help them better predict the effects of well placement and enhanced oil recovery strategies. In the absence of such progress the prediction of water floods /simulation of an oil reservoir or contaminant motion in nuclear waste repositories will remain difficult for a long time to come. Due to its practical importance the study of flow through porous media has attracted much attention for computational modeling. When groundwater studies are made using the LDV (Laser Doppler Velocimeter) by injecting a tracer such as a radioactive isotope, dye or salt into a borehole and the arrival time of the tracer at observation well arranged few meters away is measured, there are several fundamental problems. Some of them are : several observation wells will have to be installed around the injection well, it is difficult to accurately evaluate the arrival time, injection of a large amount of tracer will cause groundwater movement, the presence of the borehole might change the otherwise homogeneous flow, which is particularly important in a single boring method. To overcome some of the obstructions, a new system for measuring the velocity by means of GLDV (Ground water Laser Doppler Velocimeter) has been developed by Momii et. al [1]. Also in this direction Sano [2] and RajaSekhar and Sano ([3],[4], [5]) made significant contributions by studying theoretical models. Sano [2] has studied presence of a void in porous media using Stoke's equation inside the void and Darcy's equation in the porous bed. RajaSekhar and Sano [3] studied the effect of viscous flow in a porous bed using Brinkman's equation in the porous region and Stoke's equation in the void/liquid region. Also they extended their study ([4], [5]) for the case of a slightly deformed void as well as a

void of arbitrary shape and estimated the volume flow coming inside the void and the behavior of velocity profiles for various parameters like permeability, deformation parameter etc. But analytical methods have their own limitations and to study the effect of a void of arbitrary shape or presence of several voids, efficient computational methods are required.

Another interesting situation is coupled processes of fluid flow with deformation of the matrices in granular materials. The erosion of soils and some type of rock fracture are examples of such phenomena. When the structure of the matrix is assumed rigid and large scaled dynamical processes are considered, that medium may be treated as a homogeneous porous medium with or without a well-defined boundary, and enormous investigations have been made. Here the term "large-scale" refers to flows or processes whose characteristic length is much larger than any internal structure, and homogeneity of the material is assumed in a statistical sense averaged over the latter. In geological application, however, collapse of the microstructure due to viscous stress is sometimes as cause of macroscopic, irreversible, non-linear and non-uniform motion, such as ground-water network formation, collapse of a river bank or a cliff, landslides etc. at the time of a rainfall. Here a very small initial non-homogeneity in the matrix can alter the local flow field, which leads to the destruction of the cavity boundary, growth of a cavity in a particular direction, and merging of cavities in the presence of many such cavities. If these processes are repeated a large –scaled groundwater channel or network will be formed after thread-like growth of cavities, or large-scale disastrous changes like landslides and collapse of cliffs will happen after a completion of sheet-like discontinuity of the stress chains. Kaneko and Sano ([6], [7]) studied experimentally on the interaction of two circular holes placed in a porous medium and further analyzed the collapse and merging of cavity regions. The current method proposed can handle such complex situations efficiently. The parallel approach allows users to develop time generated flow solutions of such situations thus analyzing the result of viscous flows. Modeling and simulation of such complex cases, stress determination and variation of void geometry and flow properties with time finally leads to the prediction of final geometry and its variation with time. Calculations involved in repeated unsteady computation of coupled Stoke's equation is extremely time consuming and requires much resources. This paper discusses the scopes of software addressing all the above listed problems from a computational point of view and to simulate the exact situations. The authors' provide a CAD interface to efficiently design such situations encountered widely in industry and real-life and thus analyze the solution so that better results and detailed information can be derived by going deeper into investigation which is otherwise impossible due to the lack of similar applications in industry. The JAVA classes inherent in the application takes care of the problem of parallelization and load-sharing by distributing the computational loads almost equally among the participating processors, thus saving time, storage and increasing efficiency and also allowing more problems to be dealt with and addressed much more quickly in a shorter time than waiting for theoretical solutions to come up for specific cases. Figure 1 demonstrates the load sharing by elucidating a manager-worker model. Figure 2 shows a screenshot of the software with an example. Figure 3 illustrates the idea of domain decomposition scheme applied to achieve computational efficiency. Another situation occurring in the field of groundwater flow which might influence the velocity field is the interaction of multiple cylindrical boreholes. In fact, it is common to drill many boreholes (observation well). For example, eight holes are bored symmetrically around the central one when the direction of the groundwater flow is unknown. In this case a certain tracer such as salt, dye or radioactive is measured. There seems, however, no verification to what extent the measured data approximates the flow in natural condition. The authors have also incorporated features to handle multi-porous media both cylindrical as well as any arbitrary void. The paper also focuses on the growing issues concerned with the development of accurate and efficient parallel algorithms for reservoir simulation; development of an understanding of parallel scaling issues in reservoir simulation; investigation of problems in porting reservoir simulators to parallel computers. As an engineer, maintenance of code can become a tremendous problem especially when developing on heterogeneous systems. More than a simple object-oriented language, JAVA has achieved a point where one can expect sufficient efficiency

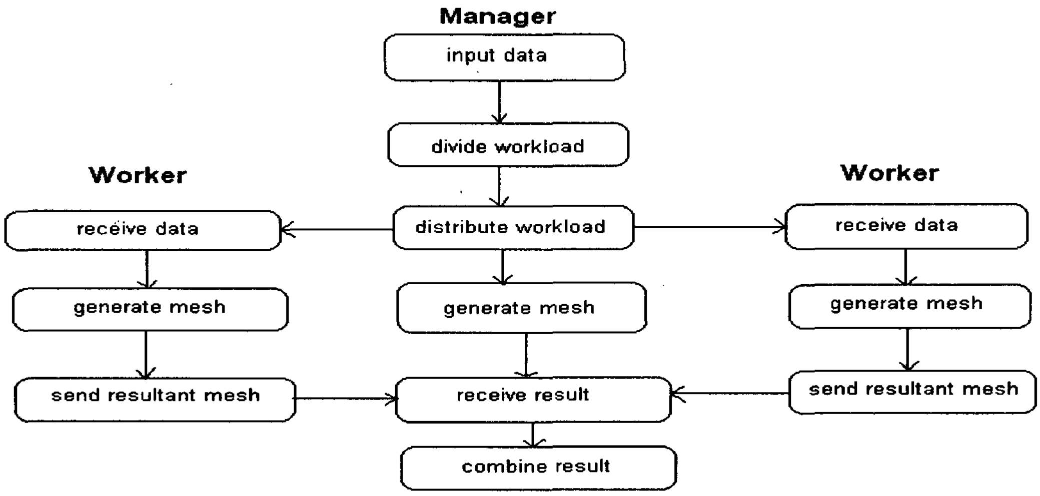

Figure 1: Manager-Worker model to distribute computational load.

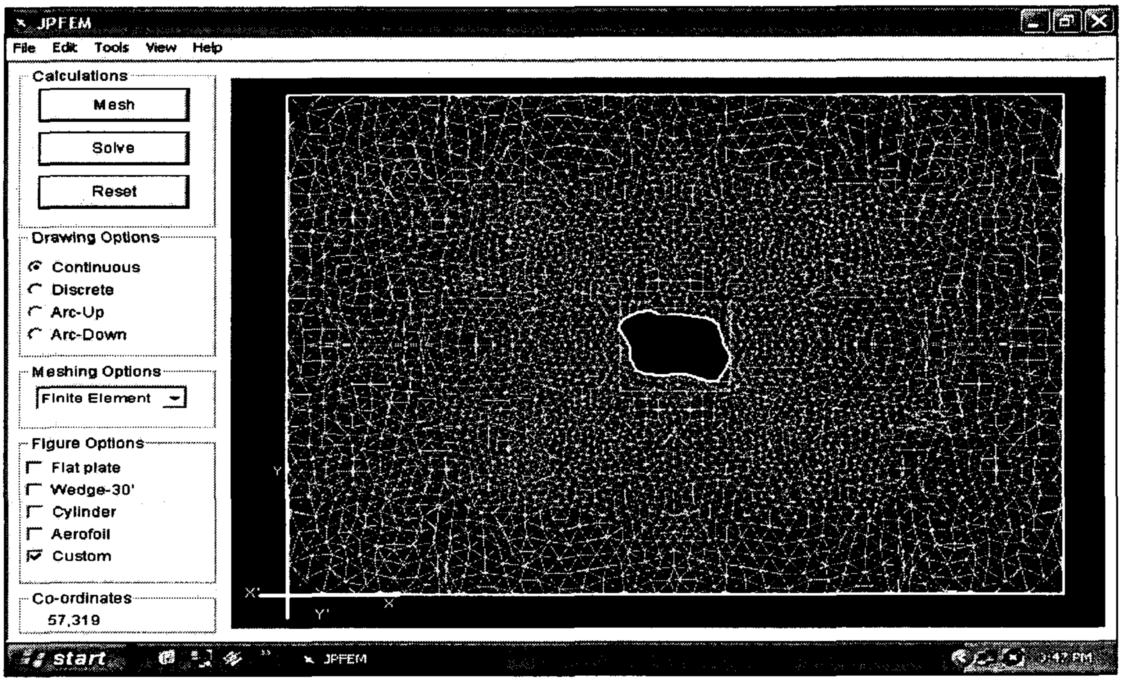

Figure 2: Screenshot of the application demonstrating unstructured mesh generation around an arbitrary shaped void embedded in a rectangular porous bed.

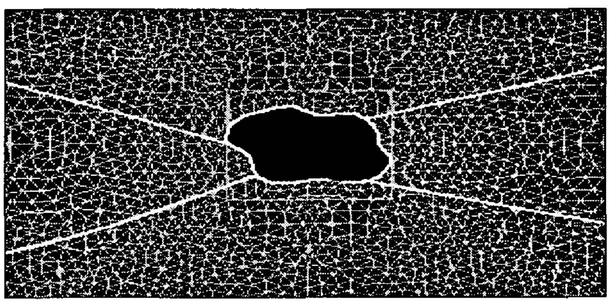

Figure 3: Domain decomposition method employed to achieve distributed mesh generation. The white lines indicate the artificial inter-zonal boundaries dividing the computational region among the processors

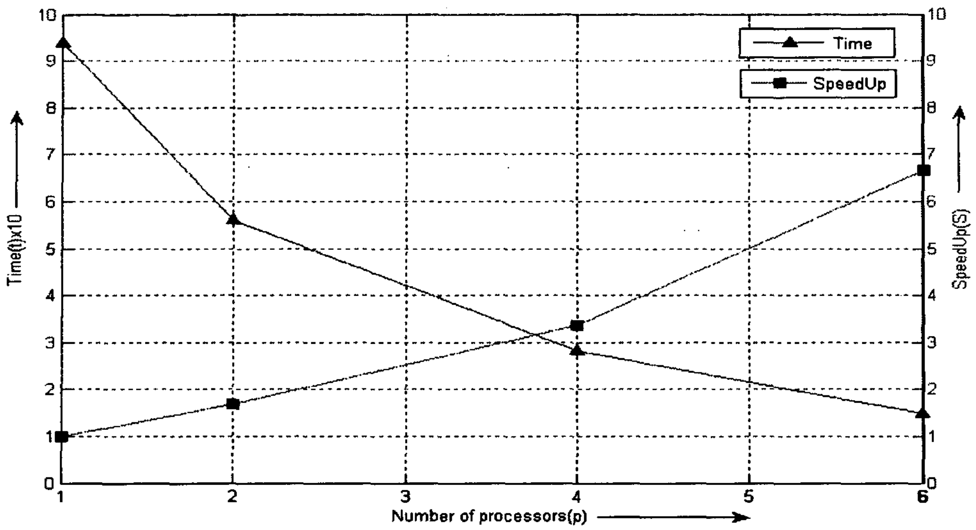

Figure 4: Computational efficiency (Speedup) achieved in case of time dependent solutions over increasing number of processors.

to solve large problems on multi-processors computers (clusters or networked workstations/single processor systems). The aim of this paper is to develop such a workbench capable of simulating porous flow regions either multiphase/single-phase and to analyze the region of flow using efficient and fast algorithms revealing important data related to porous media flow often required in industry. Figure 4 shows the speedup achieved when the program is executed over 2, 4 and 6 processors. The software is implemented entirely in Java and comes with an extra advantage of being portable as Java is a platform independent language. The software does not require extra modifications to the JVM or the working OS but takes care of the distributed computing paradigms linked with the execution of the code by enabling its own distribution and communication methods. The workbench is equipped with an easy to use GUI which enables users to create simulation regions consisting of voids of arbitrary shape; to analyze deformations, retrieve other information etc. The entire simulation domain is also discretized for unstructured FEM calculations of the coupled Stoke's and Darcy's equations using parallel algorithms with substantial gain over sequential situations in storage as well as computational overhead.

References

[1] K.Momii, K.Jinno, T.Ueda, H.Motomura, F.Hirano and T.Honda:J.Groundwater Hydrol.32 (1989) 13 [in Japanese].

[2] O.Sano: J.Jpn.Soc.Fluid.Mech.(1983) 252 [in Japanese].

[3] G.P. Raja Sekhar, O.Sano : Viscous Flow past a Circular/Spherical Void in Porous Media-Journal of Physical .Society of Japan (2000).

[4] G.P.Raja Sekhar, O. Sano : Two dimensional viscous flow past a slightly deformed circular in a porous medium. Fluid Dynamics Research ,Vol.28 (2001).

[5] G.P. Raja Sekhar, O.Sano : Two dimensional viscous flow in a granular material with a void of arbitrary shape. Physics of Fluids, Vol.15 (2003).

[6] Y.Kaneko, O.Sano : Experimental study on the interaction of two two-dimensional circular holes placed in a uniform viscous flow in a porous medium. Fluid Dynamics Research,Vol.32(2003).

[7] Y.Kaneko, O. Sano : Collapse and merging of cavity regions in a granular material due to viscous flow. Physics of Fluids. Vol.17 (2005).