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A Parallelized Model For Simulating A Vertical Closed-Loop Geothermal Heat Pump System

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ABSTRACT

A borehole heat exchanger (BHE) is one of the important factors that can affect performance of the vertical closed-loop geothermal heat pump (GHP) system. Its construction costs are also a large percentage of the overall initial costs of the GHP system. When constructing BHEs, several parameters should be determined, such as length of the borehole heat exchanger, the number of the BHEs, and spacing between BHEs. Numerical simulation can be used to find optimal parameters. However, it takes a long time to find optimal parameters with a large domain. To reduce the calculation time, a massively parallel computing procedure is introduced into the serial simulator for the vertical closed-loop GHP system. It can simulate temperature changes in the BHE with circulating fluid through the U-tubes and compute groundwater flow and aquifer temperature changes. By increasing the number of processors, the total execution time was reduced from 7,031 seconds using two processors to 1,145 seconds using 32 processors. The total execution time of the serial model is 13,902 seconds.

1. INTRODUCTION

Geothermal energy is a renewable energy source that has until recently had little economic potential except in areas where thermal water or steam is found to occur naturally. This has recently changed with developments of geothermal heat pump (GHP) systems and ground source heat pump systems using the ground as a heat source for heating or as a heat sink for cooling, depending on the season (Fridleifsson, 2001). The electrical efficiency of GHP systems is better than that of air-source heat pump systems because ground temperature is higher than air temperature in the heating season and is lower than air temperature in the cooling season. The vertical closed-loop GHP system is the most popular design (Lund et al., 2004). Its advantage lies in its applicability to most geographic locations and to most system sizes. It has good efficiency in heterogeneous media, such as fractured aquifers in Korea.

However, it tends to have the highest installation costs of the various GHP systems because of the expense of borehole heat exchangers (BHEs). This makes the vertical closed-loop GHP system unattractive financially in the short term. The installation costs are typically returned in energy savings within 5–10 years. Therefore, to reduce the installation cost and increase energy savings, BHE design (including the total number of BHEs, length of each BHE, and spacing between BHEs and the ground surface) should be optimized using a quantitative and reliable assessment procedure.

The assessment procedure for the BHE design requires an understanding and corresponding treatment of the physical processes in and around a BHE. In the cooling season, the heat of indoor air is delivered by a heat pump to the circulating fluid. The circulating fluid flows through a U-tube and transports the heat to the ground. The emitted heat is transferred by conduction and advection. The heat raises the temperature of the ground and groundwater and can affect the performance of the other BHEs. The opposite process occurs in the heating season. It can be simulated by a three dimensional numerical model. Numerical models for temperature changes used to investigate the performance of vertical BHEs have been developed (Fujii et al., 2005; Signorelli et al., 2006; Kim et al., 2008). However, it takes a long time to solve the optimization problem with numerical simulations.

In this study, a massively parallel computing procedure is introduced into the serial simulator for the vertical closed-loop GHP system. The parallel computing is expected to reduce the computing time. Detailed discussion on the calculation time of the parallel model compared to that of the serial model is presented.

2. METHOD

2.1 Physical Background

The general form of the basic mass and energy balance equations in a porous medium is given in Equation 1:

$$\frac{d}{dt}\int_{V_n} M dV_n = \int_{\Gamma_n} \mathbf{F}\cdot\mathbf{n}\, d\Gamma_n + \int_{V_n} q\, dV_n\ , \tag{1}$$

where V_n is an arbitrary subdomain bounded by the closed surface Γ_n and $\mathbf{n}$ is a normal vector on the surface element $d\Gamma_n$ pointing inward into V_n. The quantity M denotes the mass or energy per unit volume. $\mathbf{F}$ represents the mass or heat flux and q represents sources and sinks (Pruess et al., 1999).

The mass accumulation term (M_M) is given in Equation 2:

$$M_M = \phi\rho\ , \tag{2}$$

where ϕ denotes porosity and ρ denotes density.

The heat accumulation term (M_H) is defined according to Equation 3:

$$M_H = (1-\phi)\rho_R C_R T + \phi\rho u\ , \tag{3}$$

where ρ_R is the rock density, C_R is the specific heat of the rock, T is temperature, and u is the specific internal energy. The fluid and rock are assumed to have the same temperature.

The advective mass flux ($\mathbf{F}_M$) is given in Equation 4:

$$\mathbf{F}_M = \rho\mathbf{u} = -\frac{k\rho}{\mu}\left(\nabla P - \rho\mathbf{g}\right), \tag{4}$$

where **u** is the Darcian velocity, k is permeability, μ is viscosity, P is pressure, and **g** is the vector of gravitational acceleration.

The conductive and convective heat flux ($\mathbf{F}_H$) is given in Equation 5:

$$\mathbf{F}_H = -\lambda\nabla T + h\mathbf{F}_M\ , \tag{5}$$

where λ is the thermal conductivity, and h is the specific enthalpy.

2.2 Model Development

The vertical closed-loop GHP system consists of heat pumps, fluid pumps and BHEs. The heat pump is located indoors and in the cooling season, moves heat from indoor air to the circulating fluid using mechanical work. The fluid pump sends the circulating fluid through the BHE and the heat pump. The BHE transfers heat to the ground. A developed model is focused on the temperature variation of the circulating fluid and in the vicinity of the BHE. The developed model is based on the TOUGH2-MP code (Zhang et al., 2008). TOUGH2-MP is a massively parallel (MP) version of the TOUGH2 code (Pruess et al, 1999), a widely accepted three-dimensional numerical simulator for heat and fluid flow in geothermal systems. It can consider fluid flow occurring under viscous, pressure, and gravity forces according to Darcy's law and heat transport by means of conduction and convection, including both sensible and latent heat. To take thermal and hydraulic processes related to the vertical closed-loop GHP system into account, three modules were developed and added to TOUGH2-MP. The developed model was validated by comparing actual data sets with simulated results (Kim et al., 2008).

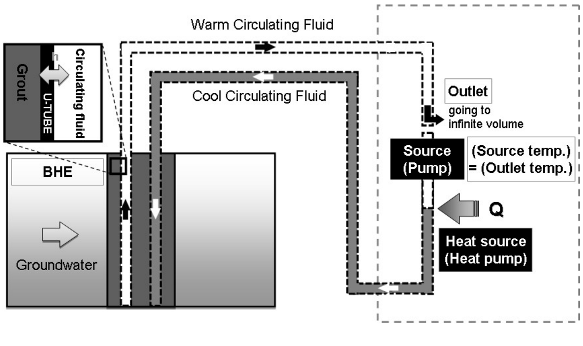

Figure 1: A schematic diagram of the vertical closed-loop GHP system. (Kim et al., 2008).

Parallel computing improves memory distribution requirements and computational efficiency for solving large simulation problems with millions of gridblocks, such as the optimization problem for the BHE design within a fractured medium. The TOUGH2-MP code, a massive parallel version of the TOUGH2 code, was developed and has been successfully applied to large-scale simulations with up to several million gridblocks. In performing a parallel simulation, the TOUGH2-MP code first subdivides a simulation domain, defined by an unstructured grid of a TOUGH2 mesh, into a number of subdomains using the partitioning algorithm from the METIS software package (Karypsis and Kumar, 1998). The parallel code then relies on the MPI (Message-Passing Interface; Message Passing Forum, 1994) for its parallel implementation. Parallel simulations are run as multiple processes on a few or many processors simultaneously. Each processor is in charge of one portion of the simulation domain for updating thermophysical properties, assembling mass and energy balance equations, solving linear equation systems, and performing other local computations. The local linear equation systems are solved in parallel by multiple processors with the Aztec linear solver package (Tuminaro et al., 1999). Although each processor solves the linearized equations of subdomains independently, the entire linear equation system is solved together by all processors collaboratively via communication between neighboring processors during each Newton iteration step (Zhang et al., 2008).

3. RESULTS

The TOUGH2-MP is based on the integral finite difference method (IFDM; Edwards, 1972; Narasimhan and Witherspoon, 1976). Spatial discretization was accomplished using the U-mesh program (Kim et al., 2008). It generated the IFD mesh and input files of the developed model, which are suitable to simulate the vertical closed-loop GHP system. The IFD mesh used in simulations is illustrated in Figure 2. Domain size was set to be 30 m in both horizontal directions and 110 m in the vertical direction from the ground surface. 16 BHEs that consist of a closed circuit with a double U-tube in a grouted 100-m-deep borehole were considered in numerical simulations. Spacing between BHEs was 5 m.

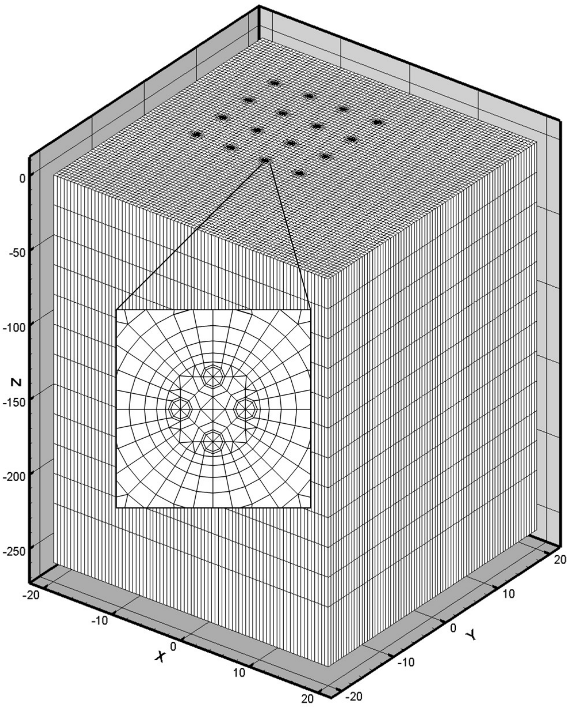

Figure 2: IFD mesh (x to z ratio = 5).

In the simulation, 5,000 W of heat was transferred to the circulating fluid of each BHE over a 90 day period. The flow rate of the circulating fluid was 0.2 L/sec. A pressure field is shown in Figure 3. The porous medium and fractured medium have the same pressure field. A temperature field after 90 days of heat injection is shown in Figure 4.

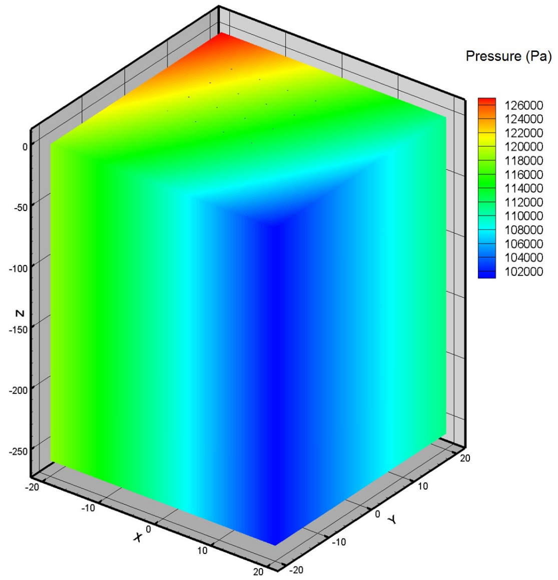

Figure 3: Pressure field.

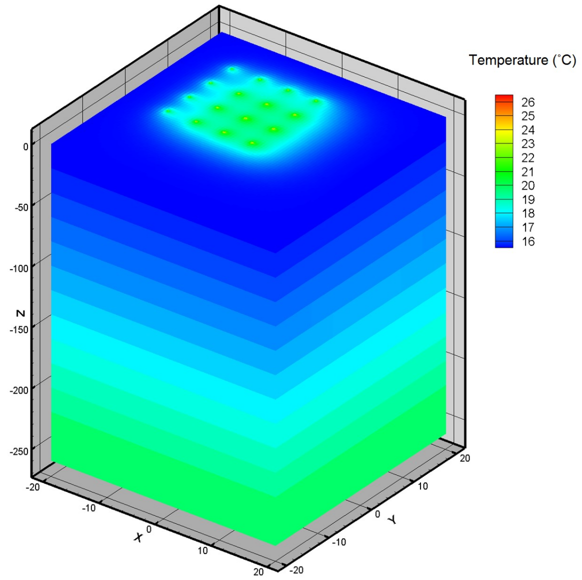

Figure 4: Temperature field after 90 days of heat injection.

Simulations were run on a Linux cluster equipped with 8 nodes using a gigabit Ethernet switch connection, and each node consisted of an Intel quad-core CPU. For testing the parallel code performance, the model was run using either 2, 4, 8, 16, or 32 processors for the same simulation time period. The speedups obtained for different numbers of processors and for different parts of the simulation are shown in Figure 5. By increasing the number of processors, the total execution time was reduced from 7,031 seconds using two processors to 1,145 seconds using 32 processors. The total execution time of the serial model was 13,902 seconds. The original TOUGH2-MP code demonstrates much better performance than ideal linear speedup (Zhang et al., 2008). Because of a bottleneck in our Linux cluster when the data were transferred between nodes, the modified code could not achieve the original speedup.

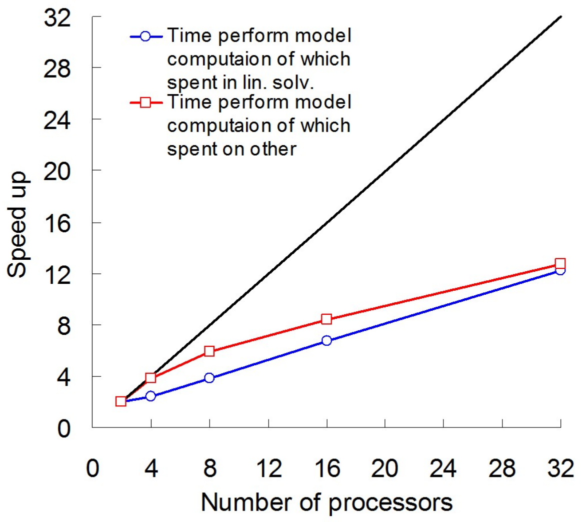

Figure 5: Speedups for the different parts of the parallel simulations.

4. CONCLUSION

To reduce the calculation time of BHE simulations, massively parallel computing procedure were introduced into the serial simulator for the vertical closed-loop GHP system. The total execution time was reduced from 13,902 seconds using the serial model to 1,145 seconds using the parallel model with 32 processors. Numerical simulators can be used to find optimal BHE design parameters

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