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Project Report

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Rock fracture modelling for hot dry rock enhanced geothermal systems

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Project title: Rock fracture modelling for hot dry rock enhanced geothermal systems

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Area of proposed study: Geothermal reservoir characterisation – fracture modelling

Executive Summary
The main purpose of the project was to conduct preliminary work to improve the application of an ARC discovery project of the same title to increase its chance of success. One postdoctoral research fellow was employed under the project and one international collaborator visited Adelaide and worked for one month for the project. Outcomes of this project include the award of $330k for the ARC discovery project in 2010 and several research publications.

Background
The funding was requested initially to support a post-doctoral research fellow for four months to conduct some preliminary work for an ARC discovery project. Such a short-term contract turned out to be inadequate to attract a suitably qualified candidate. Some additional funding from the Faculty of Engineering, Computer and Mathematical Science (ECMS) was secured for the project which, together with the tied grant, provided support for a research fellow for six months. The position was advertised in June 2010 and as a result Dr. Rosemarie Mohais was appointed to the RA position on Aug. 2, 2010 for a seven-month contract (80% FTE) until Feb. 28, 2011.

In addition, Dr. Pardo-Igúzquiza, from the Spanish Geological Survey, spent the month of July, 2010 in Adelaide working on the project with the support of the funding. Dr. Pardo-Igúzquiza has extensive research experience in the area of spatial statistics and stochastic modelling.

Five papers have been produced from the project and we are currently working on two more ARC discovery projects covering the next steps in modelling for hot dry rock (HDR) geothermal applications.

Work done

Dr. Mohais has a strong background in flow and heat modelling and geophysics. She completed her PhD in 2007 at the University of the West Indies with a thesis entitled *Heat transfer studies of coupled fluid flow in porous media*, which received a High Commendation from the thesis examiners. She worked in the School of Mathematics and Statistics at UniSA and the School of Mathematical Sciences at the University of Adelaide before taking up the position. Dr. Mohais has made some significant progress in the research. A paper entitled Fluid Flow and Heat Transfer within a Single Horizontal Fracture in a Hot Dry Rock System has already been generated as part of her research and has been accepted for publication subject to revisions (ASME Journal of Heat Transfer). Another paper entitled *A first estimation of maximum attainable temperature in EGS reservoirs with porous-walled fractures* has been submitted to the XXV IUGG General Assembly and is currently under review. A detailed technical report for this part of the research can be found in Appendix A.

As a result of Dr. Pardo-Igúzquiza's visit, a paper entitled *Stochastic simulation of karst conduit networks using a signal based random walk approach* is in the final stages of editing prior to submission.

A collaboration with Geodynamics under the project produced a paper entitled *Optimised fracture model for Habanero reservoir* which was presented at the 2010 Australian Geothermal Conference held in Adelaide.

Future Research Plans

We are now in the process of recruiting a postdoctoral research fellow and a PhD candidate to work on the ARC discovery project. The construction of realistic fracture models is the first step in effective modelling of flow and heat transfer in EGS reservoirs.

We are currently preparing an application for an ARC discovery project entitled *Large scale reservoir flow modelling for hot dry rock enhanced geothermal systems*. The project will combine the latest fracture network modelling techniques with coupled hydro-thermal conditions to achieve more realistic flow and heat exchange modelling for hot dry rock geothermal systems. Dr. Mohais is also working on an ARC early career research (ECR) discovery project entitled *Coupled fluid flow and heat transfer models of fractures in enhanced geothermal systems*, which will focus on the theoretical investigation of the coupled fluid flow in EGS reservoirs.

Outcomes of the Project

Apart from the success of the ARC discovery project, the following papers were produced as part of the research output related to this project:

1. Mohais, R, Xu, C. and Dowd, P. A., A first estimation of maximum attainable temperature in EGS reservoirs with porous-walled fractures, submitted to XXV IUGG General Assembly (under review).
2. Mohais, R, Xu, C. and Dowd, P. A., Fluid Flow and Heat Transfer within a Single Horizontal Fracture in a Hot Dry Rock System, submitted to ASME *J. Heat Transfer* (accepted Jan. 27, 2011 for publication subject to revisions)
3. Eulogio Pardo-Igúzquiza, Peter A. Dowd, Chaoshui Xu and Juán José Durán-Valsero, Stochastic simulation of karst conduit networks using a signal based random walk approach, (in preparation).

4. Xu, C., Dowd, P. A. and Wyborn, D. (2010) Optimised fracture model for Habanero reservoir, Proceedings of the Australian Geothermal Conference 2010, Adelaide, Nov., 2010, ISBN 978-1-921781-38-4, pp. 98-103.
5. Xu, C. and Dowd, P. A. (2010), A new computer code for discrete fracture network modelling, *Computers and Geosciences*, **36**, 292-301.

Conclusions

All original objectives of the project have been met. The funding has also enabled us to expand the objectives further to cover the next stage of our long-term research plan, i.e., flow and heat modelling for hot dry rock enhanced geothermal systems.

Appendix A: Progress and Technical Advances

This section gives a brief outline of the research in flow modelling undertaken for the project. The main aim of this part of the research is to examine the fluid flow and heat transfer in fractures in hot dry rock enhanced geothermal systems (EGS). The motivation behind the study is to develop mathematical models that are representative of the fluid mechanics and the thermodynamics associated with the transfer of heat within single fractures and within simple fracture combinations. These models can then be used in the development of fracture models of the entire fracture network.

The first phase of the study focused on understanding the problem of EGS from a fluid mechanics point of view. From the literature, it seems that the most convenient and popular model used to describe a fracture is that of plane Poiseuille flow, where Newtonian fluid flows through a channel comprised of two stationary parallel plates. Past research focused on only one-dimensional modelling using the reduced form of the Navier-Stokes equation containing only the non-linear terms (Stokes equation). There have also been attempts at modelling fractures as circular cracks, using cylindrical polar coordinates. A choice was made, in the first instance, to use the model of the parallel plate channel to describe a fracture.

Once the main equations that govern the problem were determined, the next phase involved finding appropriate boundary conditions. Past attempts at the flow problem within fractures yielded the well-known cubic law by using no-slip boundary conditions at impermeable walls. This condition implies that when fluid flows through a channel there is a thin layer of fluid that adheres to the impermeable walls. However it is debatable whether the walls of the channel are in fact completely impermeable as they may contain many fine cracks as a result of the hydro-fracturing process. Fluid flowing through the main channel may then be able to seep into the walls of the channel, which can act as a permeable medium. Mathematically, this implies that the use of no-slip boundary conditions at the walls is inadequate to model the flow and instead slip boundary conditions must be used. A literature search revealed that some authors (Berkowitz, 1989) have incorporated slip boundary conditions in one-dimensional modelling of fractures. Berkowitz showed that the omission of slip leads to underestimation of volumetric flow by as much as 19%. Numerical modelling of flow using slip boundary conditions in fractures was also attempted (Crandall, Ahmadi, & Smith, 2010). The results showed that if slip is neglected in the model, then results may vary by as much as 10%.

Our first model designed to study flow within a fracture sought to upgrade the channel problem to a two-dimensional time-independent problem using the full Navier-Stokes equation. Slip boundary conditions were applied at the fracture walls using the Beavers-Joseph slip boundary conditions (Beavers & Joseph, 1967). Heat transfer was incorporated into the study by using the energy equation. This meant that there were four coupled equations to be solved: the continuity equation, two Navier-Stokes equations and the energy equation. The variables were first non-dimensionalised using the channel width and entrance velocity. Then a similarity solution was determined using a suitable similarity parameter, which after some effort reduced the non-linear Navier-Stokes equation to a fourth order linear differential equation that was solved via a perturbation solution in increasing orders of Reynolds numbers. Once the velocity was determined, perturbation was used to determine a solution for the energy equation. The flow profiles and heat transfer profiles showed that the effect of the slip boundary conditions in the fracture cannot be ignored. This work (Fluid flow and heat transfer in a single horizontal fracture in a Hot Dry Rock system) has been accepted for publication in ASME *Journal of Heat Transfer* subject to revisions (accepted Jan. 27, 2011).

A second approach to the problem was to model fractures as single channels with thin porous walls. These channels are aligned horizontally within a heat-generating block. The flow in each channel was solved using a simplified one-dimensional model with slip at the walls. The exit temperature of the fluid is determined by using the volumetric flow rate in the channels and the energy equation governing a heat-generating body taken from Bejan and Errera (2000). This approach is described in *A first estimation of maximum attainable temperature output in EGS reservoirs with permeable-walled fractures*, which has been submitted for review for the XXV IUGG General Assembly to be held in Melbourne later this year.

The problem we are currently working on is based on Berkowitz's previous work in which flow within the channel is studied simultaneously with flow within the channel walls to determine a net flow at the exit of the channel (Berkowitz, 1989). Berkowitz used the Brinkman extension of Darcy's law to model the flow with porous walls involving slip. His boundary conditions were set up to describe fractures with porous walls of infinite extent. We are currently in the process of modifying these conditions to a more realistic wall width to examine the flow profiles within the channel as well as the walls. In the first instance, this will be attempted for the one-dimensional Berkowitz model using the concept of a transition layer, defined as that the distance measured from the permeable interface at which the velocity approaches 1% of the Darcy velocity (Goharzadeh, Khalili, & Jorgensen, 2005). The transition layer has been investigated experimentally and it has been shown that above the transition layer, the velocity increases monotonically, whereas below it the velocity fluctuates randomly within the limit of error for velocity for porous media flow (Goharzadeh, Khalili, & Jorgensen, 2005). A preliminary solution may be obtained by the end of February 2011.

Other areas that can be explored are the non-dimensionalisation of the variables in the complete equations (in two dimensions) governing flow within a channel with permeable walls using other quantities, such as the superficial Reynolds number, pore scale Reynolds number, characteristic Reynolds number, and various length scales determined by experimental work (Goharzadeh, Khalili, & Jorgensen, 2005). The exploration of these areas would clearly enhance the model by using parameters that are unique to the specific system under study. This work will be considered when time permits.

In summary, significant advances have been made in the modelling of flow and heat transfer through fractures modelled as channels with porous walls. This area of study has potential for extensive, sophisticated mathematical modelling that will improve the modelling of flow and heat transfer for hot dry rock enhanced geothermal systems.

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