INTERNATIONAL JOURNAL OF
NUMERICAL ANALYSIS AND MODELING, *SERIES B*
Volume 4, Number 4, Pages 413–424

NUMERICAL MODELING AND ANALYTICAL VALIDATION FOR THE MOVEMENT OF THERMAL FRONT IN A HETEROGENEOUS AQUIFER THERMAL ENERGY STORAGE SYSTEM

SAYANTAN GANGULY, N. SEETHA AND M. S. MOHAN KUMAR

Abstract. The aquifer thermal energy storage system (ATES) owing to growing demands for sustainable energy has become a popular technology in last few decades for long term storing of excess thermal energy. The efficiency of such a system depends entirely on the capacity of the aquifer to retain heat and hence modeling the heat transfer and transient temperature distribution in the aquifer due to hot water injection is essential. The present study is concerned about presenting a two-dimensional numerical model for such an ATES system with block heterogeneities where hot water is injected through an injection well into the heterogeneous porous aquifer with lesser initial temperature. The transient temperature distribution in the porous aquifer or the advancement of the hot water thermal front generated due to hot water injection into the porous aquifer is modeled here using the multiphysics numerical code COMSOL. First the model is developed for the general case including the convective and the conductive heat transport. Since modeling of such complex systems are associated with numerical errors which may lead to possible errors in estimation of temperature distribution in the aquifer, the results derived numerically afterwards are compared and validated with an analytical model derived by the authors.

Key words. ATES, Heat transport, Hot water injection,Thermal front,Heterogeneous porous media and Numerical and analytical modeling.

1. Introduction

Production of renewable and sustainable energy is one of the most important topics of this century since the reserve of the fossil fuels on earth is going to be exhausted in not so far future. The modern research thus concentrates a lot on the exploration and exploitation of alternative sources of energy such as solar, wind power and geothermal etc. With the production of energy the storage of the excess thermal energy is also becoming important to make use of it in future. The Aquifer Thermal Energy Storage (ATES) systems have become popular worldwide for serving this purpose as a practically and economically feasible large scale open energy storage system for heating as well as cooling buildings. Injecting the hot or cold water into an aquifer for long term storage and extracting that in the time of demand is the basic theory of this system. An ATES system operates in a full cycle consisting of mainly four stages. The injection of hot/cold water into the aquifer, storage of the hot/cold water, production and the heating/cooling of buildings (Sila Dharma [1]). Practical feasibility and low cost of implementation and maintenance have been behind the popularity of the system. Moreover it reduces the expense of heating and cooling greatly and has got almost no adverse environmental effects.

Received by the editors October 4, 2012 and, in revised form, August 26, 2013.
2000 *Mathematics Subject Classification.* 35Q79.

The hot water byproduct of thermal power plant or the excess heat collected in the solar energy system during periods of bright sunshine thus can be injected and stored underground and extracted in the time of demand. Direct use of groundwater with relatively high volumetric heat capacity makes ATES system more efficient than any other system (e.g. closed system like borehole thermal energy system or BTES) that can be used for this purpose (Kim et al. [2]). The effectiveness of storing the thermal energy in an aquifer depends on the efficiency of the aquifer to retain heat. Loss of heat from the aquifer to the surrounding media affects the efficiency of the aquifer to be used as an ATES system and hence understanding the heat transfer in the porous aquifer is crucial. Continuous injection of hot or cold water into the natural groundwater in the aquifer generates an interface zone known as the thermal front, across which the aquifer temperature varies from the injection water temperature to the initial aquifer temperature. The thermal front with the passage of time propagates through the porous aquifer medium. Thus modeling the advancement of the thermal front or the transient temperature distribution due to the thermal injection into the aquifer is essential for the effective design of the injection production well system and for fixing the injection and extraction rates into or from the aquifer, respectively.

The use of an aquifer as storage of hot water was first suggested in 1971 (Tsang [3]). Robbimov et al. [4] and Meyer and Todd [5] did some early studies on this topic which mainly present analytical and semi-analytical solutions and economic considerations. Other analytical models and solutions on this topic were developed by Sauty et al. [6], Chen and Reddel [7], Voigt and Haefner [8], Ziagos and Blackwell [9], Li et al. [10] and Yang and Yeh [11], which present solutions for idealistic systems under simplifying assumptions or qualitative estimations. A three-dimensional numerical model for fluid flow and heat transport in an aquifer was presented by Tsang et al. [12]. They found a heat recovery to storage ratio of about 80%. An experimental study was performed by Molz et al. [13] to test the concept of underground heat storage and to collect data for calibration of numerical models. Larson et al. [14] used the data collected by them for numerical simulation of water and heat flow in a heat storage aquifer. Another analytical solution was developed by Bodvarsson and Tsang [15] to investigate the movement of the cold water thermal front through subsurface media with equally spaced horizontal fractures. Numerical simulations were also conducted by them to assess the influence of the assumptions applied in analytical modeling. Another experimental study was performed by Palmer et al. [16] on thermal injection and storage in a shallow unconfined aquifer. The study provides three-dimensional temperature distribution data which allows validating complex numerical models with experimental results. The experimental data also provide the quantification of physical processes like advection, dispersion, retardation, buoyancy and boundary heat loss. Molson et al. [17] developed a three-dimensional finite element model for simulating coupled density dependent groundwater flow and thermal energy transport. They used the experimental data obtained by Palmer et al. [16] to validate their model which showed the model agrees very well with experiment. Mongelli and Pagliarulo [18] derived a model for temperature distribution in an unconfined semi-infinite aquifer. The results derived by them lead to the evaluation of the zone influenced by recharge. Nagano et al. [19] did experimental study and performed numerical simulations to investigate the importance of natural convection on forced horizontal flow through saturated porous medium in an ATES system. Stopa and