A Numerical Coupled Model for an Aquifer Thermal Energy Storage (ATES) System
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Tri Nguyen-Quang[1], Zineddine Alloui[2], Ilhami Yildiz[1] and Jin Yue[1]
[1] Dalhousie University, Nova Scotia, Canada
[2] Ecole Polytechnique de Montreal, Quebec, Canada

Abstract

Aquifer Thermal Energy Storage (ATES) systems are conceived to conserve the waste heat from industrial processes. The ATES system at Bio-Environmental Engineering Center (Dalhousie University Agriculture Campus), utilizing a naturally occurring subsurface aquifer as heat storage, has been under operation since 2003. Based on a system of Darcy's equation for fluid flow in porous aquifer systems and energy conservation equation for heat transfer and storage, our coupling mathematical model will predict the effects of the flow regime on efficiency and reliability of the subsurface heat storage system. The equations will be solved by the finite difference method. This study intends to provide a viable pumping and injection strategy for an ATES system to function effectively for a greenhouse system in the future.

Keywords: ATES (aquifer thermal energy storage), Darcy's equation, Boussinesq equation, water table equation, coupled model, finite difference method.

Résumé

Les systèmes ATES (Aquifer Thermal Energy Storage) sont conçus pour conserver la chaleur résiduaire des procédés industriels. Le système ATES au Bio-Environmental Engineering Center (Campus d'Agriculture de l'Université Dalhousie) qui utilise un réservoir aquifère naturel pour le stockage de la chaleur a été en fonctionnement depuis 2003. Notre modèle mathématique, basé sur un système de couplage des équations de Darcy pour un écoulement de fluide dans les couches poreuses et de conservation de l'énergie pour le transfert et de stockage de chaleur, permet de prédire les effets du régime d'écoulement sur l'efficacité et la fiabilité du système de stockage de chaleur souterrain. Les équations seront résolues par la méthode de différences finies. Cette étude visera à fournir une stratégie d'injection et un pompage viable afin de fonctionner avec efficacité dans l'avenir note système ATES associé à une maison écologique.

Mots clés: Système de stockage de l'énergie aquifère, équation de Darcy, équation de Boussinesq, équation de la nappe phréatique, modèle de couplage, méthode de différences finies.

1. Introduction

The aquifer thermal energy storage (ATES) systems are used to heat greenhouses, keeping optimum temperatures for plant growth in greenhouses cost effectively. The ATES system at Dalhousie University's Bio-Environmental Engineering Center (BEEC) is currently being used for research, as it is the only geothermal heat pump used to heat a greenhouse in Nova Scotia.

Before being able to suggest a viable pumping and injection strategy for an ATES system to function effectively for a greenhouse, one of the important tasks is to understand transfer processes leading to the spatial temperature distribution in the aquifer layer. This paper, which is the first one of our series of future studies related to heat transfer processes in the ATES system in Dalhousie Agricultural Campus, theoretically investigates the relationship between the ground water table equation and the temperature distribution in the aquifer layer. Ground-water flow in shallow, unconfined aquifers can be based on the Dupuit assumption and mathematically described by the work of Bear (1972) [1]. Hence, our suggested mathematical model in this article is a system of coupled partial differential equations (PDE): Darcy's equation for the fluid flows in porous medium, equation of convection-diffusion for heat transfer and the Boussinesq equation for the hydraulic head. The numerical approach for these coupled PDEs is the finite difference method with the T.D.M.A. (Tri-diagonal matrix algorithm) scheme of resolution.

Through our study, it is shown that the stability of the model can be adequately controlled and the code can be expeditiously performed and economically used for the mini or micro personal computers. More interestingly, the outcome of our results can be applied to the situation in which the short-term responses (such as from pumping) of an ATES are simulated.

2. Mathematical Formulation

Considering an unconfined aquifer layer, the model for groundwater flow is considered as a continuum model. The differential equations describing ground water flow are coupled with the energy conservation equation in porous medium, which is assumed as a homogenous and isotropic area. Although the problem is investigated on a two-dimensional framework, the following governing equations are presented herein under the 3D spatio-temporal general form.

2.1 Governing equations

Equation for conservative hydraulic head:

$$S\frac{\partial h}{\partial t} = \nabla(K\nabla h) + W \tag{1}$$

Equation for ground-water velocity or specific discharge:

$$\vec{V} = -K\nabla h \tag{2}$$

Equation of energy conservation:

$$\rho C_s \frac{\partial T}{\partial t} + \rho C_W \nabla(\vec{V}T) = \nabla(D\nabla T) + R \tag{3}$$

The heat transfer in a ground water system can be described mathematically assuming that i) the thermal equilibrium between the liquid and soil particles is achieved instantaneously; ii) the density of the soil particles is constant; iii) the heat capacity is constant; and iv) the chemical system is inert [2]. One other important assumption is that the density effects are neglected in the model.

2.2 Initial and Boundary conditions

- For the equation of hydraulic head, the conditions are:

At the time t=0: $h(x, y, 0) = H_0$ for all x, y of the considered system (Fig. 2).

At the time t, general condition used for the water table according to [2]:

$$h(x,y,t) = A - B\cos\left(\frac{\pi\, x}{L}\right) \tag{4}$$

Two constants A and B were defined as [3]:

$$A = \frac{L}{2} + B \qquad\qquad B = \cosh\left(\frac{\pi\, H_0}{L}\right) \tag{5}$$

$$\frac{\partial h}{\partial \vec{n}} = 0 \text{ for the rest of boundaries} \tag{6}$$

where H_0 is the initial stable head value, $\vec{n}$ is the normal direction to the no-flow boundary; L is the length in horizontal direction of the considered medium. All other parameters and variables are reported in Nomenclature.

All boundary conditions are shown in Figure 1.

- For the heat flow equation, all boundaries except the upper surface were convective heat flux condition. The upper surface had specified temperature boundaries. Heat transfer at that surface was assumed to be proportional to the difference between the soil temperatures and mean daily air temperature. To simplify the condition, it was assumed that at the upper surface the temperature $T_{upper}=T_o$ and at the lower surface $T_{lower} = \partial T_o / \partial y$.

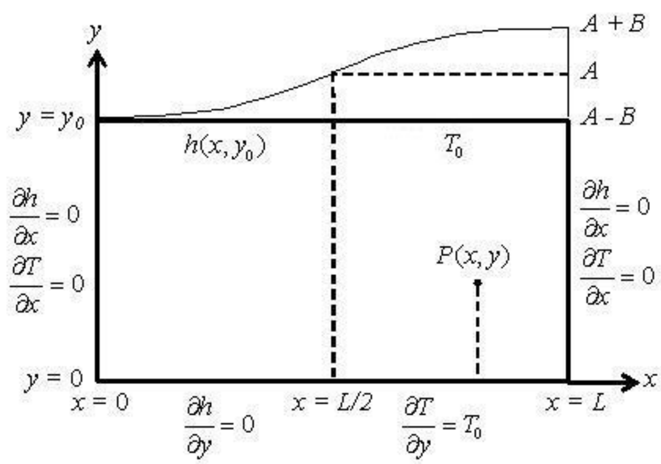

Figure 1. Physical description and boundary conditions of the ATES layer.

3. Numerical approach and code validation

Finite difference method with regular grids was chosen for the resolution of the nonlinear system of partial differential equations coupling with algebraic term (Eqs. 1-3) and equivalent boundary conditions (Eqs. 4-6). The discretized equations were derived using central differences *for spatial derivatives and backward differences for* time derivatives. The scheme T.D.M.A *(*Tri-diagonal matrix algorithm*)* was used to solve the system of governing equations [4,5].

The validation of numerical code was based on analytical results presented in [2] and numerical approach by Finite Volume with non-orthogonal grids of [6].

4. Results and Discussions

The ATES system used in this study is located on the campus of Perennia Innovation Centre in Bible Hill, Nova Scotia. The general geology of the site is approximately provided in Figure 2.

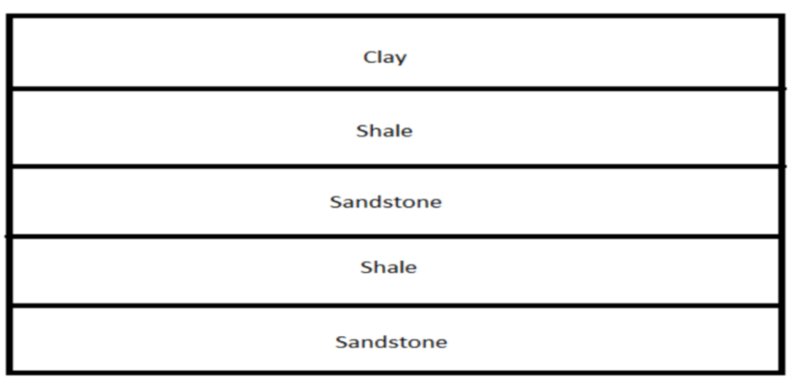

Figure 2. General geology of the aquifer system in Dalhousie Agricultural Campus

Physical parameters used in this study are presented in Table 1.

Table 1. Physical parameters

Parameters	Symbols	Estimated values
Hydraulic conductivity, horizontal/vertical, m/day	K	0.1/4
Thermal conductivity, $W/(m^3.^oC)$	D	0.05-0.65
Storativity	S	0.2
Heat capacity of the aquifer framework, $kJ/(m^3.^oC)$	ρC_W	0.7
Heat capacity of the saturated porous medium, $kJ/(m^3.^oC)$	ρC_S	4.21
Recharge or pumping rate of the wells per unit area, m/day	W	0.01-0.5
Heat source or rate of heat injection, $kJ/(m^3.day)$	R	0.01-0.5
Aquifer type	Sandstone	
Aquifer thickness	≈ 2.8m	

Ground water level (profoundness)	≈ 9.5 m
Undisturbed temperature of ground water	≈ *10* ^oC

Due to the aquifer thickness and undisturbed temperature of the ATES ground water system, the following results were calculated based on a 3mx3m basin configuration with different physical parameters above mentioned and one case of 3mx6m configuration. The temperature was set at $T_0=10\ ^oC$.

It is observed that under the 'natural condition', i.e. $R = W = 0$ (no heat source and no recharge rate), the system is submitted to the conduction regime (Fig. 3). However, the hydraulic conductivity plays the role of convective factor: With the same natural condition $R = W = 0$, the iso-temperature lines in Fig.4 are more curved than the ones in Fig.3 because of the hydraulic conductivity *K* (0.5 versus 0.1). That made the flow regime in Fig.4 more convected.

When there is a presence of disturbance factor such as the heat source *R* or pumping rate *W*, the flow regime is more convected (Fig.5). Different scenario of convective temperature and head distribution in the longer configuration at steady state is presented in Fig. 6. In that case, the length of the basin is double (6m) when the height remains the same. It is obviously observed that the shapes of the iso-temperature contours and head distribution for a specified thermal conductivity, dispersivity and heat capacity are a function of rate of heat output/input. An increasing heat source R can make the contours more convective. Likewise, these convective effects can be regulated by the presence of pumping rate W.

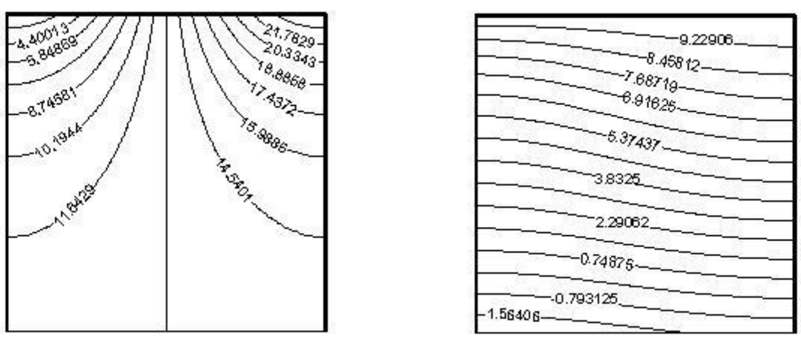

Figure 3. Distribution of the head (left) and temperature in the case *W=0, R=0, K=0.1*.

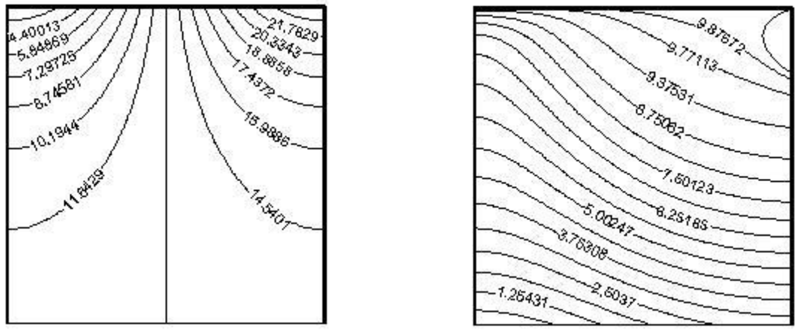

Figure 4. Distribution of the head (left) and temperature in the case *W=0, R=0, K=0.5*

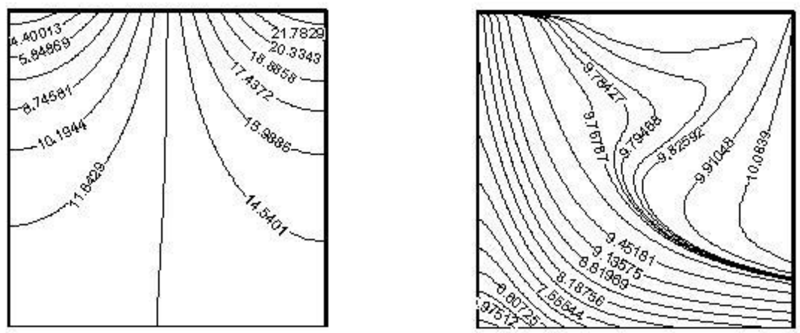

Figure 5. Distribution of the head (left) and temperature in the case
R=0.01,W=0.1,K=0.5,D=0.064

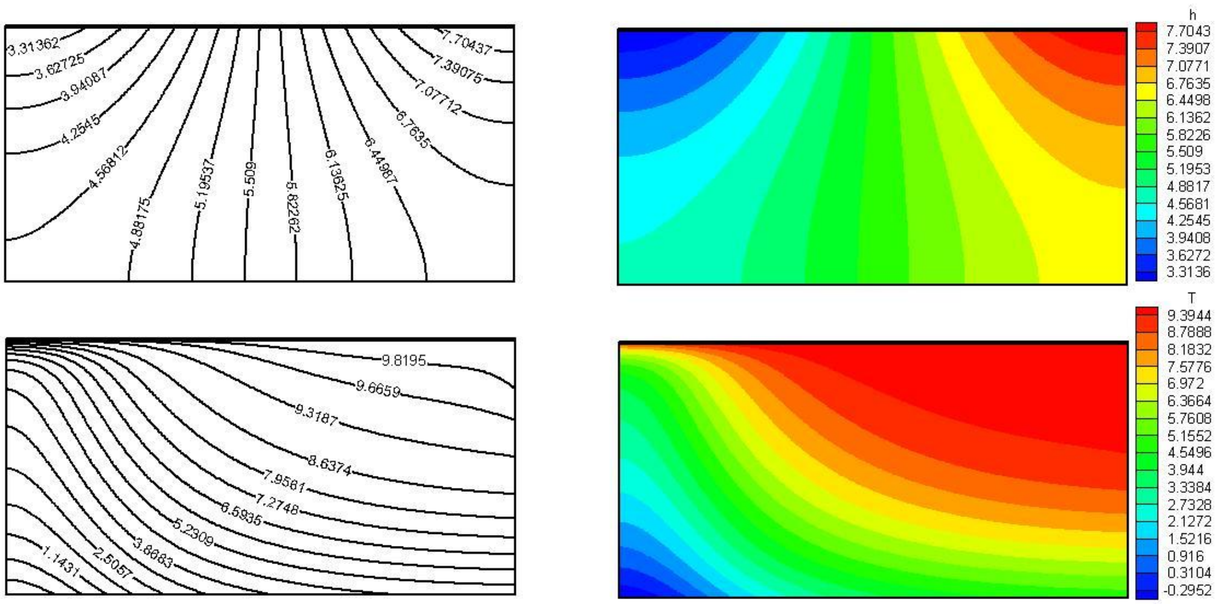

Figure 6. Distribution of the head (above) and temperature (below) in the case of the basin (3x6)m and *R=0.01,W=0.1,K=0.5,D=0.064*

5. Conclusions

Different scenarios presented in this article illustrate that there are many factors affecting the steady state distribution of temperature in an ATES system. They can be summarized into i) intrinsic properties of the medium and contained fluid (i.e. thermal diffusivity and hydraulic conductivity); ii) water-table configuration, and iii) the geometric configuration (i.e. the ratio between the basin depth and length). Therefore, to take the coupling effects of these factors into account, a dimensionless group would have to be formulated from dominating parameters of the ATES system, and would provide a relative measure of the simultaneous transport of heat by the bulk motion of the fluid. In such a case, the whole picture of relationships between different individual parameters affecting the transfer processes in an ATES system would be much clearer and systematically understood. The effects of density would also be taken into account in the system. Based on these premises, mathematical models with the adequate numerical approach are necessary for predictions and suggestions of a viable pumping and injection strategy for an ATES system to function effectively for a greenhouse system. That will be topics of our next study.

Nomenclature

b	elevation of the aquifer bottom, L
D	coefficient of dispersion, H/tTL. This is a combined thermal conductivity and dispersion tensor which is derived from the thermal conductivity, porosity and thermal dispersion.
h	hydraulic head, L
H	height of the basin, L
K	hydraulic conductivity tensor, L/t
L	length, L
S	the storage coefficient
W	recharge or pumping rate of the wells per unit area, L/t
t	time
T	temperature, ^oC
ρC_W	heat capacity of water, H/L^3T
ρC_S	heat capacity of saturated porous medium, H/L^3T
R	heat source or rate of heat injection, H/L^3t

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7. Acknowledgments

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8. Biography

Dr. Tri Nguyen-Quang is a faculty member at Engineering Department. His expertise is on biosystems modeling and coupling models applied in porous and fluid media. Dr. Zineddine Alloui, postdoctoral researcher, has expertise in coupling thermal-hydrodynamic systems. Dr. Ilhami Yildiz, Professor at Engineering Department, is a controlled environment systems engineer, and has expertise in energy, environment and sustainability issues. Dr. Jin Yue is an instructor at the Engineering Department with expertise in applied PDE and probabilistic modeling.