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Energy Procedia 110 (2017) 143 – 148

Energy Procedia

1st International Conference on Energy and Power, ICEP2016, 14-16 December 2016, RMIT University, Melbourne, Australia

Numerical investigation of temperature distribution in a confined heterogeneous geothermal reservoir due to injection-production

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Abstract

The present study deals with the modeling of transient temperature distribution in a heterogeneous geothermal reservoir in response to the injection-production process. The heterogeneous geothermal aquifer considered here is a confined aquifer with homogeneous layers of finite length and overlain and underlain by impermeable rock media. The heat transport modes considered are advection, conduction in the geothermal reservoir and heat transfer to the confining rock media. Results show that heterogeneity plays a very significant role in determining the transient temperature distribution and controlling the advancement of the thermal front in the reservoir. A one-dimensional (1D) analytical model for temperature distribution in the geothermal reservoir is also derived in this study. Results from a simpler version of the numerical model are compared with the results from the analytical solution which are in good agreement with each other.

Keywords: Geothermal reservoir; Heat transport in porous media; Thermal front; Heterogeneity; Numerical modeling; Analytical solution.

1. Introduction

Geothermal reservoir operation is essentially an injection-production process where geothermal steam/hot water is extracted for power production. A fraction or the whole waste-water which is produced after heat extraction is then reinjected back into the geothermal reservoir. The purposes of reinjection are safe disposal of the thermal water [1], maintaining the reservoir pressure which gradually declines due to continuous production of geothermal fluid [2] and enhancing the heat extraction efficiency of a reservoir [3]. In spite of these benefits, there lies the possibility of cooling of the production wells due to premature breakthrough of the cold-water thermal front generated by the reinjection

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doi:10.1016/j.egypro.2017.03.119

since the reinjected fluid is much colder than the geothermal reservoir environment [4,5]. Thermal-breakthrough affects the reservoir efficiency to produce power severely. Hence to maintain the reservoir efficiency and for longer life of the reservoir, the injection-production well scheme is to be properly designed and injection and production rates are to be fixed properly. Modelling the transient temperature distribution due to injection-production is thus very important. Heterogeneity of the geothermal aquifer is also an important factor to consider in the heat transport phenomenon in porous media since a homogeneous medium is practically very rare in nature. In the geothermal literature the heterogeneity of the aquifer is not well addressed. [6] derives an analytical solution for temperature distribution in a geothermal reservoir with continuous heterogeneity. Geothermal reservoirs are found which are comprised of a series of homogeneous finite layers. [7] cited literatures based on layered porous media observed in natural environments such as stratified soils [8], aquifers and aquitards [9] or in constructed environments such as estuary sediment caps [10]. One such confined and layered geothermal reservoir is considered in this study. The objective of the present study is to develop a numerical model to predict the transient temperature distribution in a heterogeneous geothermal reservoir system due to injection-production. The numerical modelling is performed using the software code DuMu^x [11]. The heat transfer processes taken into account are the advection, conduction and heat transport to the confining rocks. The aquifer considered here is a confined one and consists of vertical layers with different thermo-geological properties. A simpler version of the numerical model for a 1D heterogeneous geothermal aquifer is compared with an analytical model derived here. The comparison of temperature distributions derived using both the models shows very good match to each other.

2. Mathematical and numerical modeling

The present study is about developing a coupled thermo-hydrogeological model for temperature distribution in a heterogeneous geothermal reservoir due to thermal injection. The three-dimensional (3D) fluid flow equation in porous media is given by

$$S\frac{\partial h}{\partial t} - \nabla \cdot \{K \cdot \nabla h\} = q_f \tag{1}$$

where h: hydraulic head, K: hydraulic conductivity of the aquifer; S: specific storage and q_f : source term.

The confined aquifer considered here consists of two homogeneous layers (although the model can be extended for n number of such layers), overlain and underlain by impermeable rocks. The whole aquifer system with injection-production wells is presented schematically in Fig. 1. 3D heat transport equation for single phase fluid flow in porous media for two layers of the aquifer is

$$\frac{\partial}{\partial t}\left\{\left(1-\phi_{1,2}\right)\cdot \rho_{1,2}\cdot c_{1,2}\cdot T_{1,2}(x,y,z,t)+\phi_{1,2}\cdot \rho_w \cdot c_w \cdot T_{1,2}(x,y,z,t)\right\}+\nabla\cdot\left\{u_w\cdot\rho_w\cdot c_w\cdot T_{1,2}(x,y,z,t)\right\}+q_1-q_2=\nabla\cdot\left\{\left(\lambda_{1,2}\cdot\nabla\right)\cdot T_{1,2}(x,y,z,t)\right\} \tag{2}$$

where the subscripts 1,2 stand for the two layers of the geothermal aquifer (Fig. 1), T: temperature; c_r and c_w: specific heats of rock and water; ϕ:porosity of the aquifer; ρ_r and ρ_w: densities of the rock and water; u_w : velocity of groundwater; λ_x and λ_y : thermal conductivities of the geothermal aquifer in longitudinal and vertical directions; t : injection time; x and y : distances in longitudinal and vertical directions and q_1 and q_2 are the heat transfer fluxes to the overlying and underlying rocks. The above heat transport equation (2) coupled with the groundwater flow equation (1), is solved in the model to derive the transient temperature distribution in the model domain.

The model domain considered here is a confined porous aquifer of dimensions ($L\times B$) 600 m×30 m, consisting of two vertical layers of length 260 m (L_1) and 340 m (L_2). The aquifer is underlain and overlain by rock media of thickness 90 m (b_1) and 80 m (b_2), respectively. Initial temperature of the aquifer is 80°C (353K). Cold water at a temperature of 20°C (293 K) is injected at a rate of 300 m^3/day by an injection well at a distance 200 m away from the left end of the aquifer. Hot-water is extracted by a production well at a distance 200 m from the injection well. At the right boundary of the domain a pressure of 30.0 MPa and a temperature of 80^{0}C are considered as boundary conditions whereas a pressure of 31.2 MPa and the same temperature of 80^{0}C are considered to be the boundary conditions for the left boundary. Hence there is an existing regional groundwater flow driven by the gradient from left to right existing prior to the injection. The overlying and underlying rock media are of low permeability and heat loss occurs from the aquifer by only by heat conduction due to the temperature gradient between the aquifer and the rock media. All the physical and thermal properties used in the modeling study are listed in Table 1.

3. Analytical solutions

Eq. (2) in 1D is given by

$$\frac{\partial}{\partial t}\left\{\left(1-\phi_{1,2}\right)\cdot \rho_{1,2}\cdot c_{1,2}\cdot T_{1,2}(x,t)+\phi_{1,2}\cdot \rho_w\cdot c_w\cdot T_{1,2}(x,t)\right\}+\frac{\partial}{\partial x}\left\{u_w\cdot \rho_w\cdot c_w\cdot T_{1,2}(x,t)\right\}+q_1-q_2=\lambda_{1,2}\frac{\partial^2 T_{1,2}(x,t)}{\partial x^2} \tag{3}$$

The differential equations for the heat transport in the overlying and underlying rocks are

$$\rho'_{r1,2}c'_{r1,2}\frac{\partial T'_{1,2}(x,z,t)}{\partial t}=\lambda'_{1,2}\frac{\partial^2 T'_{1,2}(x,z,t)}{\partial z^2} \tag{4}$$

where the subscripts 1 and 2 stand for overlying and underlying rocks, respectively; $T'(x,z,t)$ is the temperature in the rocks; ρ'_r is the density; c'_r is the specific heat; λ_1 is the vertical conductivity of the rocks and z represents the vertical direction.

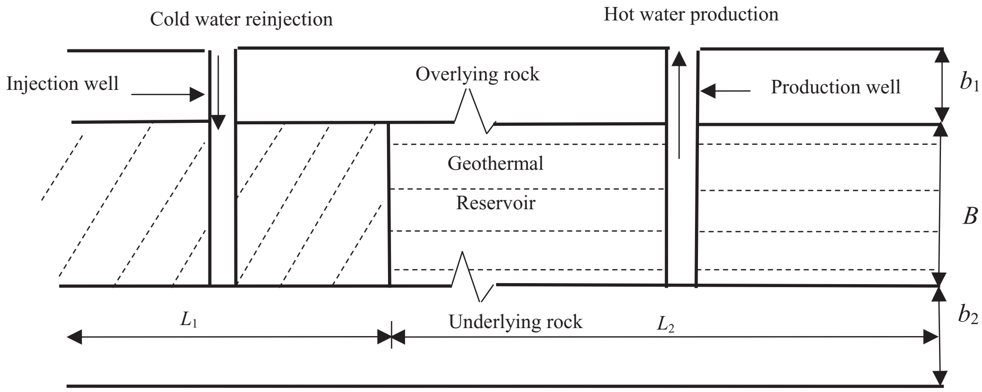

Fig. 1. Schematic representation of the confined heterogeneous geothermal reservoir with injection-production wells.

The initial condition for the whole geothermal aquifer is

$$T(x,0)=T_0 \tag{5}$$

The boundary condition for the first layer in the aquifer is

$$T_1(0,t)=T_{in} \tag{6}$$

where T_{in} is the temperature of the injection water.

Continuity of temperature is considered to be the boundary condition for the second layer and is given by

$$T_2(0,t)=T_1(L_1,t) \tag{7}$$

The initial and boundary conditions for equation of heat transfer in the overlying and underlying rocks (Eq. 4) are

$$T'_{1,2}(x,z,0)=T'_{01,02} \tag{8}$$

$$T'_{1,2}(x,B,t)=T_{1,2}(x,t) \tag{9}$$

$$T'_1\{x,(B+b_1),t\}=T'_{01} \tag{10}$$

$$T'_1(x,-b_2,t)=T'_{02} \tag{11}$$

The heat flux from the geothermal aquifer to the overlying and underlying rocks at the interface ($z=B$,0) is modeled by Fourier's law of heat conduction

$$q_{1,2} = -\lambda'_{1,2} \left. \frac{\partial T'_{1,2}}{\partial z} \right|_{z=B,0} \tag{12}$$

Laplace transform technique is applied here to solve the heat transport Eq. (3). First Eq. (4) is solved in Laplace domain and the solution is differentiated to obtain the source terms. These terms are then substituted in the Laplace domain equation of heat transfer obtained by applying Laplace transform to Eq. (3). Finally the transformed solution in Laplace domain is inverted to obtain the tran sient temperature distribution in the geothermal aquifer.

Table 1. Values of parameters of different layers in the reservoir

Parameter name	Symbol (unit)	Layer 1	Layer 2
Length	L(m)	260	90
Specific heats of rock	c_r (J/kg·K)	850	1560
Density of the porous aquifer	ρ_r(kg/m^3)	2650	1047
Thermal conductivity of the aquifer (longitudinal)	λ_x (W/ m·K)	2.8	0.6
Thermal conductivity of the aquifer (vertical)	λ_y (W/ m·K)	1.0	0.3
Porosity of the aquifer	ϕ	0.15	0.20
Density of the fluid	ρ_w (kg/m^3)	985	985
Specific heats of fluid	c_w(J/kg·K)	4180	4180

The solution for transient temperature distribution in the first layers of the geothermal aquifer, given as

$$T_1 = T_0 - \left(T_0 - T_{in}\right) erfc\left\{ \frac{\alpha x}{2U\left(t - \frac{C_1 x}{U}\right)^{1/2}} \right\} - \frac{(\omega - \alpha T_0)}{\alpha} \cdot \left[erfc\left\{ \frac{\alpha x}{2U(t - \frac{C_1 x}{U})^{1/2}} \right\} \right. \tag{13}$$

$$\left. - \exp\left\{ \frac{\alpha^2 x}{C_1 U} + \frac{\alpha^2}{C_1^2}(t - \frac{C_1 x}{U}) \right\} \cdot erfc\left\{ \frac{\alpha x}{2U(t - \frac{C_1 x}{U})^{1/2}} + \frac{\alpha}{C_1}(t - \frac{C_1 x}{U})^{1/2} \right\} \right] + \frac{(\omega - \alpha T_0)}{\alpha}\left\{ 1 - \exp\left(\frac{\alpha^2}{C_1^2} t \right) \cdot erfc\left(\frac{\alpha}{C_1} t^{1/2} \right) \right\}$$

where $C_{1,2,3} = (1-\phi) \cdot \rho_{r1,2,3} \cdot c_{r1,2,3} + \phi \cdot \rho_w \cdot c_w$ and $U = \rho_w \cdot c_w \cdot u_w$, $\alpha = (C_1\lambda_1)^{1/2} + (C_2\lambda_2)^{1/2}$, $\omega = (C_1\lambda_1)^{1/2} T_{01} + (C_2\lambda_2)^{1/2} T_{02}$, $C'_{1,2} = \rho'_{r1,2} \cdot c'_{r1,2}$

The transient temperature distribution in the second layer given by

$$T_2 = T_0 - \left(T_0 - T_{in}\right) \cdot erfc\left[\frac{\alpha\left(L_1 + x\right)}{2U\left\{ t - \frac{\left(C_1 L_1 + C_2 x\right)}{U} \right\}^{1/2}} \right]$$

$$- \frac{(\omega - \alpha T_0)}{\alpha}\left[erfc\left\{ \frac{\alpha\left(L_1 + x\right)}{2U\left\{ t - \frac{\left(C_1 L_1 + C_2 x\right)}{U} \right\}^{1/2}} \right\} - \left[\exp\frac{\alpha^2\left(L_1 + x\right)}{C_1 U} + \frac{\alpha^2}{C_1^2}\left\{ t - \frac{\left(C_1 L_1 + C_2 x\right)}{U} \right\} \right] \cdot erfc\left[\frac{\alpha\left(L_1 + x\right)}{2U}\left\{ t - \frac{\left(C_1 L_1 + C_2 x\right)}{U} \right\}^{-1/2} + \frac{\alpha}{C_1}\left\{ t - \frac{\left(C_1 L_1 + C_2 x\right)}{U} \right\}^{1/2} \right] \right]$$

$$+ \frac{(\omega - \alpha T_0)}{\alpha}\left[erfc\left\{ \frac{\alpha x}{2U\left(t - \frac{C_2 x}{U}\right)^{1/2}} \right\} - \exp\left\{ \frac{\alpha^2 x}{C_1 U} + \frac{\alpha^2}{C_1^2}\left(t - \frac{C_2 x}{U}\right) \right\} \cdot erfc\left\{ \frac{\alpha x}{2U}\left(t - \frac{C_2 x}{U}\right)^{-1/2} + \frac{\alpha}{C_1}\left(t - \frac{C_2 x}{U}\right)^{1/2} \right\} \right]$$

$$- \frac{(\omega - \alpha T_0)}{\alpha}\left[erfc\left\{ \frac{\alpha x}{2U\left(t - \frac{C_2 x}{U}\right)^{1/2}} \right\} - \exp\left\{ \frac{\alpha^2 x}{C_2 U} + \frac{\alpha^2}{C_2^2}\left(t - \frac{C_2 x}{U}\right) \right\} \cdot erfc\left\{ \frac{\alpha x}{2U}\left(t - \frac{C_2 x}{U}\right)^{-1/2} + \frac{\alpha}{C_2}\left(t - \frac{C_2 x}{U}\right)^{1/2} \right\} \right]$$

$$+ \frac{(\omega - \alpha T_0)}{\alpha}\left\{ 1 - \exp\left(\frac{\alpha^2}{C_2^2} t \right) \cdot erfc\left(\frac{\alpha}{C_2} t^{1/2} \right) \right\} \tag{14}$$

In the equations (13) and (14) it is to be noticed that the second term originates due to the difference in the initial aquifer temperature (T_0) and the injection water temperature (T_{in}). Rest of the terms (3rd to last) emerge due to the difference in the intial temperature of the aquifer (T_0) and intial temperature of confining rocks (T'_{01}, T'_{02}).

4. Results and Discussion

The temperature distribution plots in the heterogeneous aquifer domain at different injection times are shown in Fig. 2. The two-dimensional plots show that owing to continuous injection of cold-water into hot aquifer environment a thermal interface or a thermal front is generated which propagates through the aquifer with time in both directions. The temperature of the aquifer also decreases gradually with the passage of injection time due to the advancement of the thermal front, the effect of which is most pronounced around the injection well. Sharp changes in the temperature plots are visible when the thermal front enters the second and third layers. The change in trend of the temperature distribution is triggered by the change in thermo-hydrogeological properties of different layers present in the geothermal aquifer. This implies the properties and thus the heterogeneity have profound effect on the temperature distribution and movement of the thermal front in the porous media. The temperature plots also show that the cold-water thermal front reaches the production well at 63 days for the given conditions, which implies the occurrence of thermal-breakthrough. After the breakthrough the temperature of the geothermal fluid at the production well decreases and the geothermal reservoir loses its efficiency for power production.

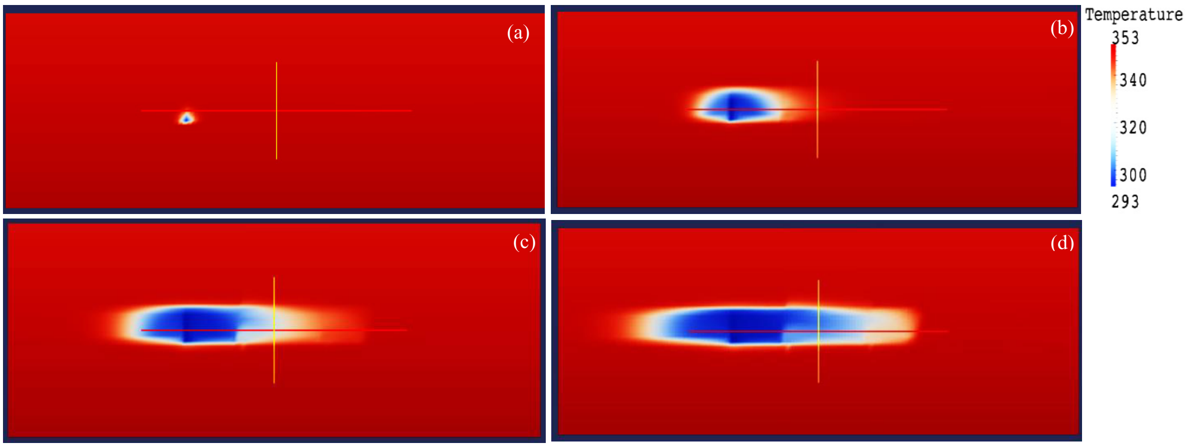

Fig. 2. Temperature distributions in the heterogeneous geothermal reservoir at (a) 1 day; (b) 30 days; (c) 60 days; (d) 90 days .

The present numerical model needs to be validated to check the efficiency and accuracy of the model to predict of transient temperature distribution in the geothermal reservoir. The temperature distributions derived in the geothermal aquifer derived by the numerical model is compared with analytical solutions given by Eqs. (13) and (14). For this the thickness of the geothermal aquifer is considered negligible such that the temperature in it can be approximated as 1D. The other geological conditions and boundary conditions are kept same as that of the analytical model. The 1D temperature plots are derived by both analytical (Eqs. 13 and 14) and numerical model (DuMu^x) for thre different injection times of 30 days, 90 days and 200 days and shown in Fig. 3. The plots of temperature distribution derived by both the methods match well with each other, implying that this model is suitable for determining the transient temperature distribution in a geothermal reservoir due to cold-water injection. Change in trend in the temperature distribution plots can be noticed when the thermal front enters the second layer which is shown by curves derived by both the methods.

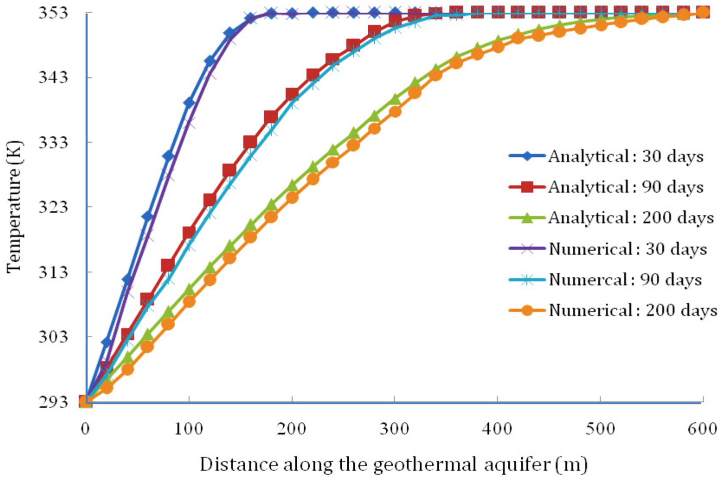

Fig. 3. Comparison of temperature distributions derived by numerical and analytical methods at different injection times.

5. Conclusions

With the continuous injection of cold-water a thermal front is set up in the geothermal reservoir and proceeds with passage of injection time. The aquifer temperature thus decreases gradually with time at a fixed distance. The thermo-hydrogeological properties in a heterogeneous porous aquifer influence the transient heat transfer phenomenon. The temperature distribution in a heterogeneous geothermal aquifer changes trend when the thermal front enters layers of different properties. Thus heterogeneity plays a vital role in controlling the movement of the thermal front and determination of the properties of different layers is very essential. The results for trasient temperature distribution in heterogeneous aquifer due to thermal injection derived numerically agrees with the results derived from the analytical solution very well. Lastly the present model gives insight into the problem of transient heat transport phenomenon in a heterogeneous porous geothermal aquifer due to cold-water injection. The results presented here can be effectively used in design of the injection-production well scheme in a heterogeneous geothermal reservoir system. The numerical model can also serve as a reference solution to more complex numerical models. The analytical model for temperature distribution presented here can be used as a benchmark solution for heterogeneous porous aquifers like the present one.

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