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Research Paper

A numerical model for transient temperature distribution in an aquifer thermal energy storage system with multiple wells

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ABSTRACT

The present study is concerned about developing a coupled thermo-hydrogeological numerical model for an Aquifer Thermal Energy Storage (ATES) system consisting of a confined porous aquifer underlain and overlain by impermeable rock media with different thermo-hydrogeological properties. Hot water is injected through injection well(s) into the porous medium which is at subsurface temperature. The main motive of the study is to model the movement of the thermal-front which is generated in the aquifer due to hot water injection. First the numerical model is developed for an ATES system with single production well and multiple injection wells and then for a system with multiple production wells and a single injection well, as both the scenario occur in field. Influence of a few parameters involved in the subsurface heat transport process is determined. Parameters of injection rate, permeability of the aquifer and the confining rocks are proved to be very important. A simplified version of the model has been validated using an analytical model developed by the authors. Modeling the movement of the thermal-front is important in designing an injection-production well scheme to avoid thermal-breakthrough which severely affects efficiency of an ATES system.

1. Introduction

As the human civilization advances, the demand for power also rises with it and catering to the increasing demand of power is one of the important challenges of recent times. The production of renewable and sustainable energy is under research for quite some time as the reserve of the fossil fuels in this planet is going to be exhausted in future. With the production of energy, conservation of it is becoming equally important for future use.

The aquifers provide a large volume for storage of thermal energy with low cost of implementation and maintenance and with almost no adverse environmental effects. Using low temperature geothermal resources in an aquifer by circulation of groundwater (Sanner, 2001; Rafferty, 2003) i.e storing the excess thermal energy in water by injecting it into an aquifer and extracting in the time of demand is the main principle of an Aquifer Thermal Energy Storage (ATES) system. Direct use of groundwater with relatively high volumetric heat capacity makes ATES systems more efficient (Kim et al., 2010) than the others. An ATES system works mainly in four stages 1. Injection of hot/cold water, 2. Storage of the hot/cold water, 3. Extraction of water and 4. Using the extracted water for heating or cooling purposes The heat

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of the effluent of a thermal power plant, the excess heat collected in a solar power system (Sila Dharma, 2009) or the excess heat produced by a biogas plant (Yapparova. et al. 2014) can be injected and stored in the aquifer for future use. The demand of the ATES systems is thus growing rapidly since it is practically feasible and economical.

The efficiency of an aquifer to store the thermal energy for long term depends a lot on the capacity of it to retain heat. Efficiency of an ATES system reduces with heat loss. Moreover the thermal injection into the aquifer at a temperature different than the aquifer temperature generates a thermal-front or an interface, across which the temperature varies from the injected water temperature to the initial temperature of the aquifer. The thermal interface spreads with continuous injection process and if the distances between injection and production wells are not sufficient then eventually the thermal-front reaches the production well consequencing the thermal-breakthrough which considerably affects the performance of the thermal recovery.

The chemical composition of the groundwater in the aquifer used for thermal energy storage is also very important for designing an ATES system. Injection of water at higher temperature than the subsurface may involve potential risks and functional problems of the wells and other components of an ATES system (Lee, 2013). The most important problem in an ATES system related to groundwater chemistry is the precipitation and clogging of wells. Chemical precipitation due to thermal injection (mainly carbonates and oxides) within the wells, the gravel pack surrounding the wells and adjacent part of the aquifer results in increased resistance for water to enter the well and thus a lower well capacity. Hence chemistry of the aquifer water must be examined carefully before consideration of an aquifer for thermal energy storage.

The use of aquifer for storing energy for long term started in early 1970s. Robbimov et al. (1971) and Meyer and Todd (1973) did some early studies on the topic which consisted of mainly analytical or semi-analytical solutions and economic considerations. Development of analytical models on this topic have later been performed by researchers like Sauty et al. (1982), Voigt and Haefner (1987), Yang and Yeh (2002), Stopa and Wojnarowski (2006) and Li et al. (2010), which are applicable only for simplified or idealistic scenarios. Tsang et al. (1978) presented an analytical model for fluid flow and heat transport in an aquifer in which they found a heat recovery of about 80%. Bodvarsson and Tsang (1982) developed an analytical model to investigate the movement of the cold water front through an equally spaced horizontal fractured system with impermeable rock separating them. Numerical modeling was also performed by the authors to determine the validity of the assumptions made in the analytical model. Another analytical model was presented by Chen and Reddel (1983) for thermal injection into a confined aquifer with overlying and underlying rock media. Two unsteady solutions were derived by the authors, one for short time period and another for long time period. A finite element numerical model was presented by Molson et al. (1992) for simulating coupled density dependent groundwater flow and thermal energy transport. The authors validated their numerical results with experimental data collected by Palmer et al. (1992), which showed very good agreement. Lee and Jeong (2008) performed another numerical modeling study on the performance of ATES under cyclic mode of operation. The study is based on the computation of the variation of extraction well temperature over seasons for long term injection-production operations. Dickinson et al. (2009) presented the theory of ATES and developed a numerical model using software package HSTWin. The authors compared their results with operational data collected over 12 months period finding a good match between them. Another numerical model study was performed by Kim et al. (2010) on the thermal interference between stored warm water and cold water energy in a two-well ATES system. They studied the influence of some parameters involved in the study, such as the distance between two wells, injection-production rate and hydraulic conductivity but they neglected the important parameter of regional groundwater flow in their study. Ganguly et al. (2013) presented a numerical model for movement of the thermal-front in a heterogeneous two-well ATES system consisted of vertical layers of different thermo-hydrogeological properties. The results revealed that heterogeneity of the aquifer is one of the factors controlling the advancement of the thermal-front through the aquifer. In a recent numerical modeling study by Bridger and Allen (2014) the influence of the geological layering on the heat transport and storage in an ATES system is determined. In another recent paper Sommer (2014) performed an assessment study on the thermal storage performance and heat transport around the wells for an ATES system in the Netherlands.

In spite of existence of several numerical and analytical modeling studies mentioned, the model study of an ATES system with multiple injection and production wells presenting the transient heat transfer phenomenon and transient temperature distribution in the system considering regional groundwater flow and all the modes of heat transport namely the advection, conduction and the heat loss to the overlying and underlying rock media, is rare in literature. The aim of this study is to present a general two-dimensional (2D) coupled thermo-hydrogeological numerical model of an ATES system with multiple injection-production wells to predict the transient temperature distribution in the ATES system due to injection of hot water into the aquifer at subsurface temperature. The main target is to model the movement of the thermal-front which is generated due to hot water injection.

Practically an ATES scheme is constructed with multiple such wells and hence modeling the temperature distribution for such a system is very essential to design the system efficiently. ATES systems employ multiple production or injection wells depending on the energy demand for heating/cooling and the reserve of water in the aquifer. When energy demand is high, multiple production wells are used to extract energy. Sometimes the reserve of aquifer fluid diminishes due to continuous extraction and natural recharge may not be sufficient to replenish it. Hence multiple injection wells are used for recharging the aquifers artificially.

2. Mathematical model for flow and heat transport

The present study is concerned about developing a 2D coupled thermo-hydrogeological model for determining temperature distribution in an ATES system during thermal injection. The fluid flow and heat transport equations in porous media are solved here. The fluid flow in a porous media is described by

$$S\frac{\partial h}{\partial t}-\left(\mathbf{K}_x\frac{\partial^2 h}{\partial x^2}+\mathbf{K}_y\frac{\partial^2 h}{\partial y^2}\right)=q_f \qquad [1]$$

where h is the hydraulic head (in m); $\mathbf{K}_x$ and $\mathbf{K}_y$ are the hydraulic conductivities of the aquifer in longitudinal and vertical directions, respectively (in m/s); S is the specific storage (in m^{-1}); q_f is source term (in sec^{-1}) and x and y represents the distances in longitudinal and vertical directions, respectively (in m).

The governing equation of heat transport in an ATES system is given by a second order partial differential equation for energy conservation in the aquifer domain. The equation is well known form the literature (Stopa and Wojnarowski, 2006; Ganguly and Mohan Kumar, 2014) and for a 2D system is given by

$$\frac{\partial}{\partial t}\left\{(1-\phi)\rho_r c_r T+\phi\rho_w c_w T\right\}+\frac{\partial}{\partial x}\left(u_x\rho_w c_w T\right)+\frac{\partial}{\partial y}\left(u_x\rho_w c_w T\right)=\lambda_x\frac{\partial^2 T}{\partial x^2}+\lambda_y\frac{\partial^2 T}{\partial y^2} \qquad [2]$$

where T is the temperature (in K); c_r and c_w are the specific heats of rock and water, respectively (in J/kg·K); ϕ is the porosity of the aquifer; ρ_r and ρ_w are the densities of the rock and water, respectively (in kg/m^3); u_w is the velocity of groundwater (in m/s); λ_x and λ_y are the thermal conductivities of the aquifer in longitudinal and vertical directions, respectively (in W/m·K) and t is the injection time (in s). The above heat transport equation coupled with the 2D groundwater flow equation given by equation [1], is solved in the model to derive the transient temperature distribution in the model domain.

3. Numerical modeling for the ATES system

The numerical modeling of this study is performed by software code DuMu^x (developed by Department of Hydromechanics and Modeling of Hydrosystems, University of Stuttgart) which is capable of handling both isothermal and non-isothermal single and multiphase flow through porous and fractured media (Flemisch et al., 2011). DuMu^x is written in C++ language and requires knowledge of the language to code specific problems in the software environment. The model domain considered here consists of a confined aquifer of dimensions 700 m×30 m. The aquifer is underlain and overlain by rock media of thickness 90 m and 80 m, respectively. In the first case hot water is considered being injected by injection wells at a distance 200 m, 300 m and 400 m away from the left end of the aquifer and extracted by a production well at a distance 500 m away from the left end (Fig. 1A). In the second case the well at 200 m is considered as injection well and the rest are considered as production wells (Fig. 1B). The rectangular aquifer domain is discretized by 2800 elements in horizontal direction and 800 elements in vertical direction. The domain is open in the longitudinal (x) direction i.e. it allows regional groundwater flow in positive x-direction which is driven by the pressure gradient in that direction. The overlying and underlying rock media are of low permeability. Heat loss from the aquifer to the confining rocks occurs by only mode of heat conduction due to the temperature gradient between the aquifer and the rock media. The permeability of the aquifer (k) is fixed as 10^{-13} m^2. Initial temperature of the aquifer is 293 K (20°C). Hot water is injected through the injection well(s) at a temperature of 323 K (50°C) which is assumed as constant throughout the injection time. All the physical and thermal properties used in the modeling study are listed in Table 1.

A few assumptions are made in developing the numerical model: (1) the geothermal aquifer and the overlying and underlying rocks are homogeneous and isotropic in nature, (2) the viscosity and density of the fluid are not functions of temperature, which is a valid assumption when the change of temperature in the porous media and subsurface fluid is small (Stopa and Wojnarowski 2006), (3) thermal equilibrium exists, i.e. the study holds good under the assumption of local thermal equilibrium, which states that the temperature of each phase present in a Representative Elementary Volume (REV) equals to the average temperature of the REV.

4. Analytical solution for transient temperature distribution

The analytical solution for the transient temperature distribution in a homogeneous aquifer due to hot water injection is given by (Ganguly and Mohan Kumar, 2014)

$$T = T_0 - \frac{2}{\pi^{1/2}}\left(T_0 - T_{in}\right)\exp\left(\frac{Ux}{2\lambda}\right)\int_{l_1}^{\infty}\exp\left(-\zeta^2 - \frac{U^2x^2}{16\lambda^2\zeta^2}\right)d\zeta \qquad [3]$$

where $U=\rho_w c_w u_w$. The lower limit of the integral equation is given by

$$l_1 = \frac{x}{2}\left(\frac{C}{\lambda t}\right)^{1/2} \qquad [4]$$

where $C=(1-\phi)\rho_r c_r+\phi\rho_w c_w$. It is to be noticed that the variation in the temperature field in the aquifer arises due to the second term in the integral equation [3], which results from the difference in temperature of the injected water (T_{in}) and the aquifer temperature prior to the injection (T_0).

5. Results and discussions

A schematic diagram of the ATES system with three injection wells and one production well is shown in Fig. 1(A). Schematic of the same with one injection well and three production wells is presented in Fig 1(B). At the right boundary of the domain a pressure of 39.5 kPa and a temperature of 293K are considered as boundary conditions whereas a pressure of 30 kPa and the same temperature of 293 K are considered to be those for the left boundary. This means the existence of a regional groundwater flow from right to left existing prior to the injection. Boundaries of the domain are considered far away from the injection-production zone such that the effect of the boundary conditions on the temperature distributions is minimum.

In the first case the ATES system consists of three injection wells and one production well. The injection wells are situated at a distance 200 m, 300 m and 400 m, respectively from the left boundary. The production well is considered to be at 500 m from the left boundary. The injection wells inject water at 323 K (which is kept constant during the injection period.) at a rate 100 m^3/day and the production well extracts water the water at a rate of 300 m^3/day which is equal to the accumulated amount of water injected by three injection wells.

For the second case the flow in the middle two wells are reversed. I.e. The well at 200 m from the left boundary acts as an injection well whereas rest are used as production wells. The hot water is considered being injected through the injection well situated 200 m away from the left end. The injection well injects hot water at a rate 300 m^3/day and the three production wells extract water at a rate 100 m^3/day each. Hence the injection rate is considered equal to the cumulative amount of water extracted. The wells are considered fully penetrating the aquifer and injection and production take place at the bottom of the aquifer.

The temperature distribution plots in the aquifer domain at different injection times have been shown in Fig. 2 for the first case with three injection wells and one production well. The 2D plots show that owing to continuous injection of hot water into colder aquifer environment, a thermal interface or a thermal-front is set up which propagates through the aquifer with time in both the directions. The temperature of the aquifer also increases gradually with the passage of injection time due to the advancement of the thermal-front. The injection of hot water is performed at the bottom of the aquifer. The hot injected water being lighter than the aquifer water rises up and due to heat transport phenomenon the thermal influence area stretches in the longitudinal directions. Hence the thermal influence areas are pyramid shaped. Further analysis of the plots also show that at 44.2 days the thermal-front from the well at 400 m reaches the production well which indicates the thermal-breakthrough and implies that the production temperature increases affecting the system performance.

The temperature distribution plots at different injection times for the second case with one injection well and three production wells have been shown in Fig. 3. Here also the thermal-front is generated at the injection well and propagates with time. The thermal-front reaches the nearest production well at 34.5 days. The thermal-breakthrough in this case is much faster than the first case since the injection rate is much higher here.

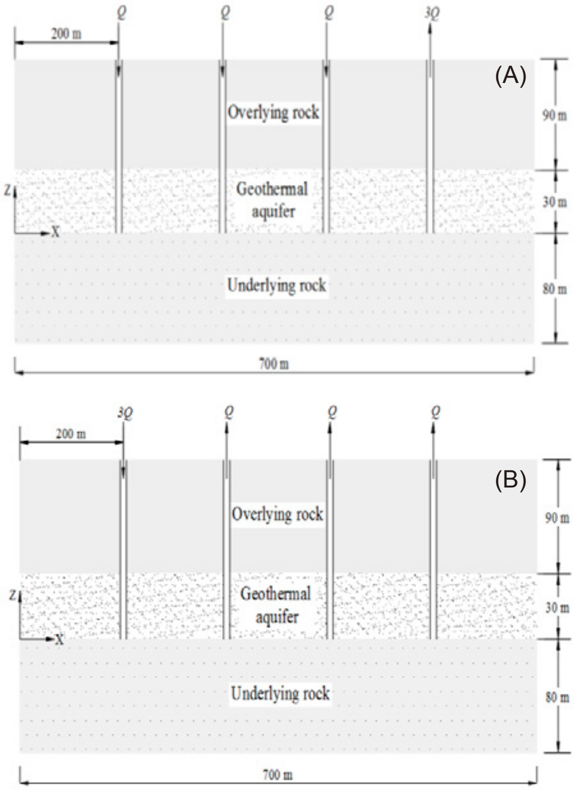

Fig. 1. Schematic diagram of the ATES systems with (A) three injection wells and one production well (B) one injection well and three production wells.

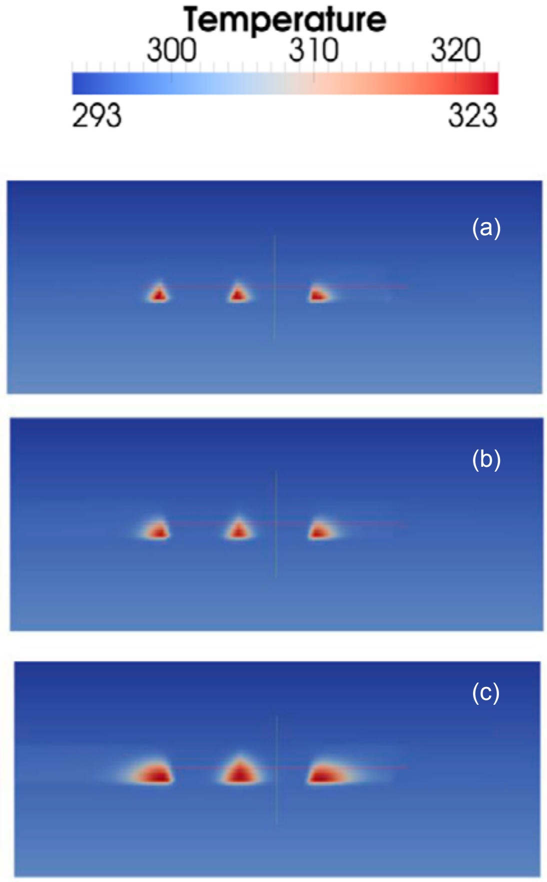

Fig. 2. Temperature distribution plots for multiple injection wells and single production well at (a) 5 days, (b) 10 days and (c) 20 days showing the advancement of the thermal-front.

The subsurface heat transport phenomenon involves a lot of parameters which have important influence on the transient temperature distribution in the aquifer. Injection rate into the aquifer, permeability of the aquifer, permeability of the confining rocks etc are to name a few. To judge the importance of these parameters two values of the parameters are taken in each case and the temperature distribution in the aquifer is plotted at different injection times. The sensitivity of the parameter is judged by observing the variation of the results. The case of one injection and three production wells is considered for all parameter studies.

Temperature distribution in the aquifer for an injection rate Q=150 m^3/day is presented in Fig. 4 for three different injection times 5 days, 10 days and 20 days. The production wells are considered to be extracting water at a rate 50 m^3/day. The permeability of the aquifer is fixed as 10^{-13} m^2. The temperature distribution plots in Fig. 4 are compared with those in Fig. 3 where the injection rate is Q=300 m^3/day. The figures show that the advancement of the thermal-front is faster when the injection rate into the aquifer is higher. This apparently has two reasons. First when the injection rate into the aquifer is higher, input of the hot water thermal energy is also higher, which leads to greater advective heat flux in the aquifer. Secondly, to inject greater amount of fluid into the aquifer larger injection pressure is required. This induces a higher pressure gradient along the direction of the injection to production well which in turn consequences in higher advective fluid flow through the porous medium and higher advective heat flux resulting in faster thermal-front movement in the aquifer. E.g. for an injection rate 300 m^3/day the thermal-breakthrough at the nearest production well takes place at 34.5 days whereas that for injection rate of 150 m^3/day takes place at 41.3 days. The flow rate has to be maintained in the ATES system keeping the system safe from the interference caused by the thermal-breakthrough during its period of operation. The wells cannot be placed far away for each other arbitrarily (to avoid thermal-breakthrough) which may be physically and economically infeasible. Hence optimizing the flow rate through the injection-production wells with the well spacing is a very important issue. It is also to be mentioned here that the pressure gradient and thus the movement of the thermal-front depends not only on the injection rate, but also on the production rate and the extraction head at the production well which also influences the pressure gradient and thus the advection flux of heat.

Table 1. Parameters of the rock and fluid used.

Parameter name	Symbol (unit)	Magnitude
Specific heat of the aquifer	c_r (J/kg·K)	2713
Specific heat of the overlying rock	c_{r1} (J/kg·K)	1046
Specific heat of the underlying rock	c_{r2} (J/kg·K)	800
Density of the aquifer (dry)	ρ_r (kg/m^3)	1047
Density of the overlying rock	ρ_{r1} (kg/m^3)	2650
Density of the underlying rock	ρ_{r2} (kg/m^3)	2600
Thermal conductivity of the aquifer	λ (W/m·K)	2.4
Thermal conductivity of the overlying rock	λ_1 (W/m·K)	1.5
Thermal conductivity of the underlying rock	λ_2 (W/m·K)	2.59
Porosity of the aquifer	ϕ	0.3
Porosity of the overlying rock	ϕ_1	0.10
Porosity of the underlying rock	ϕ_2	0.15
Density of the geothermal fluid	ρ_w (kg/m^3)	985
Specific heat of the geothermal fluid	c_w (J/kg·K)	4180
Initial temperature of the overlying rock	T_{01} (K)	293
Initial temperature of the underlying rock	T_{02} (K)	293
Thickness of the aquifer	B (m)	30
Thickness of the overlying rock	b_1 (m)	90
Thickness of the underlying rock	b_2 (m)	80

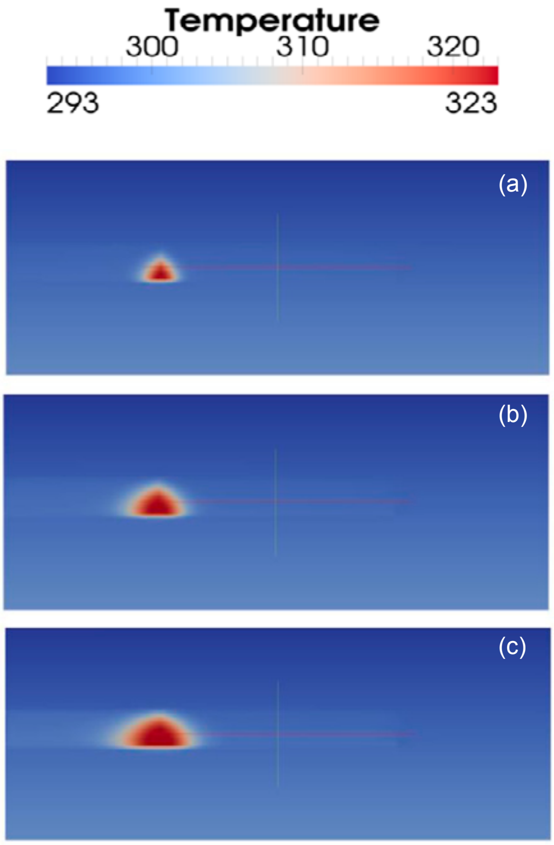

Fig. 3. Temperature distribution plots single injection well and multiple production wells at (a) 5 days, (b) 10 days and (c) 20 days showing the advancement of the thermal-front.

To determine the sensitivity of the parameter, the permeability of the aquifer (k), the temperature distribution in the aquifer is plotted for k=10^{-12} m^2 in Fig. 5 at three different injection times. The figures are compared with the temperature plots in Fig. 3, where the permeability of the aquifer is k=10^{-13} m^2. The injection rate used for this sensitivity analysis is 150 m^3/day. The figures show that the advancement of the thermal-front is greater for higher value of permeability of the aquifer. The aquifer permeability controls the advective flow velocity in the aquifer and thus the advective heat flux. Thus higher the value of k, faster is the thermal-front movement in the aquifer and higher is the possibility of a premature thermal-breakthrough. Hence the spacing between the injection and production wells has to be fixed according to the properties of the aquifer used for thermal energy storage purpose. In this case the hot water thermal-front reaches the nearest production well at 35.6 days for the aquifer with k=10^{-12} m^2 consequencing in premature thermal-breakthrough at the well, whereas that for the aquifer with k=10^{-13} m^2 takes place at 41.3 days. Hence aquifer permeability is a very important parameter to consider in the design of an ATES system.

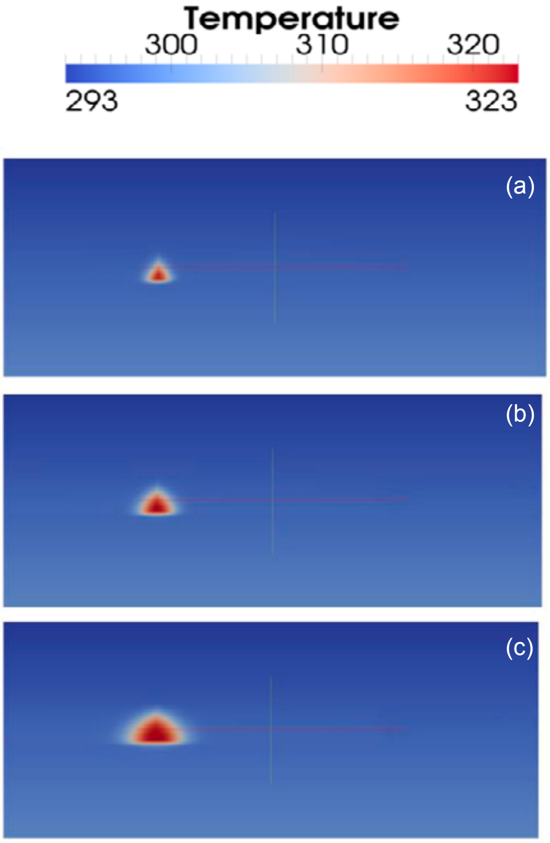

Fig. 4. Temperature distributions for single injection well and multiple production wells for injection rate Q=150 m^3/day at (a) 5 days, (b) 10 days and (c) 20 days showing the advancement of the thermal-front.

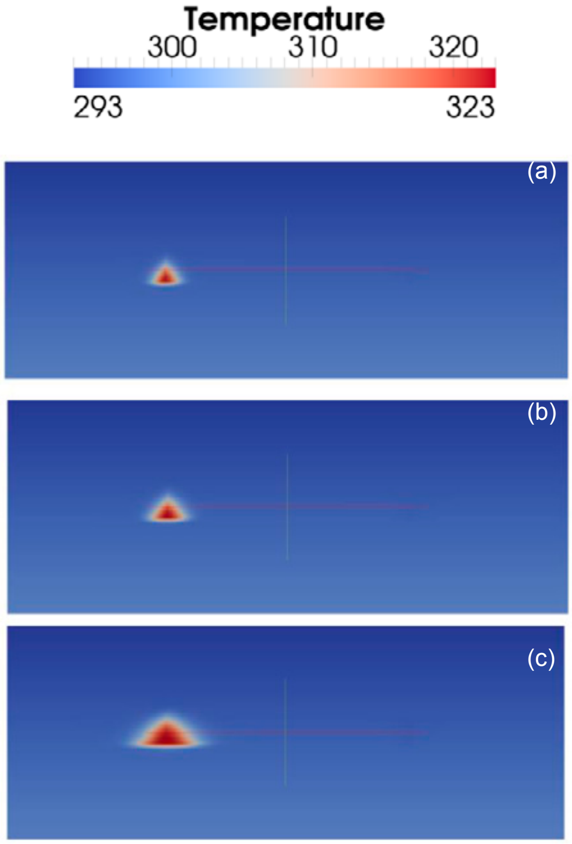

Fig. 5. Temperature distribution plots for single injection well and multiple production wells for aquifer permeability k=10^{-12} m^2 at (a) 5 days, (b) 10 days and (c) 20 days showing the advancement of the thermal-front.

Besides the permeability of the aquifer used for thermal energy storage the permeability of the underlying and overlying rocks also influences the movement of the thermal-front. To judge the influence of the permeability of the underlying rock (k_1), temperature distributions in the system are plotted in Fig. 6 for a value of the parameter 10^{-15} m^2 at three different injection times and the results are compared with temperature distributions in Fig. 3, in which the underlying rock permeability is considered to be 10^{-18} m^2. The injection rate into the aquifer and the permeability of the aquifer are fixed as 150 m^3/day and 10^{-13} m^2, respectively. The figures show that the thermal-front movement in an aquifer confined by rocks with higher value of permeability is slower. The thermal-breakthrough in an aquifer with underlying rock permeability k_1=10^{-18} m^2 takes place at 41.3 days whereas that for k_1=10^{-15} m^2 takes place at 47.7 days. The figures also make it evident that higher value of permeability of the underlying rock allows flow into it and thus induces heat loss to the rock body. The pressure head in the aquifer also plays a role in this heat loss phenomenon. It can be seen from the Figs. 6 (a), (b) and (c) that thermal-front has penetrated some area in the underlying rock near the injection well (at a distance 200 m from the left end of the domain). The thermal injection causes heating of the porous medium near the injection well predominately and hence the thermal-front penetrates the underlying rock near the injection well itself. The conductive heat loss in case of an aquifer confined by impermeable aquifer in Fig. 3 is negligible within the time range shown. The efficiency of an ATES system depends on the capacity of the aquifer to retain heat energy. The loss of heat from the aquifer used for the ATES system is inevitable. But loss of heat in large magnitude makes the aquifer inefficient and ineffective for the purpose of heat energy storage. Although the advancement of the thermal-front in the ATES system with higher value of permeability of the underlying rock is slower, the large heat loss makes such an aquifer inefficient for heat storage. Hence to minimize the heat

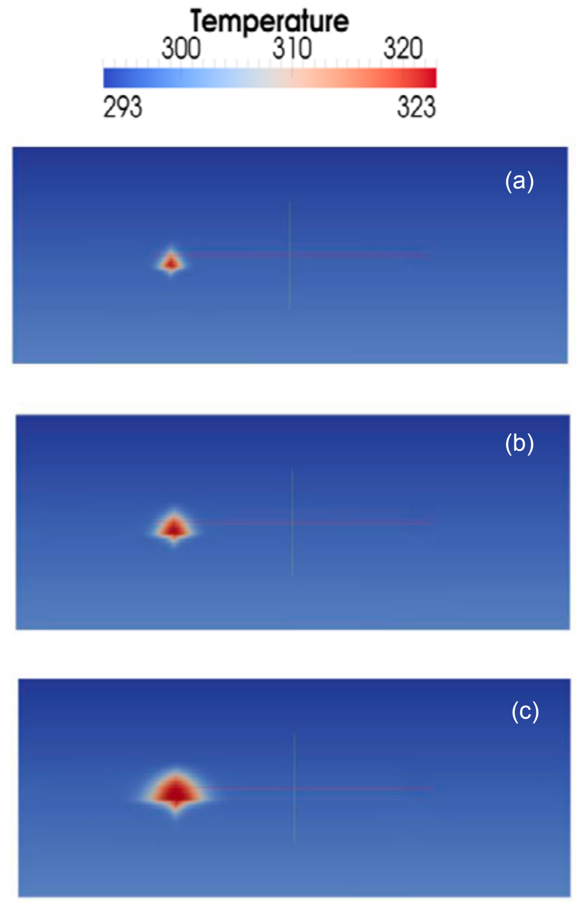

Fig. 6. Temperature distribution plots for single injection well and multiple production wells for underlying rock permeability k_1=10^{-15} m^2 at (a) 5 days, (b) 10 days and (c) 20 days showing the advancement of the thermal-front.

loss a confined aquifer with impermeable confining rock bodies is always preferred.

A simple one-dimensional (1D) version of the present numerical model with only one injection well and one production well is derived and the results have been compared with the 1D analytical model in equation [3]. The breakthrough curve at a fixed distance of 50 m from the injection well has been presented in Fig. 7 derived both numerically and analytically. Breakthrough curves derived by both the approaches match very well with each other. The R^2 value for the fit of the curves is 0.91.

6. Conclusions

A 2D numerical model for heat transport and transient temperature distribution in a porous aquifer thermal energy storage system with multiple injection and production wells and confined by impermeable rock bodies is presented here. The target was to model the movement of the thermal-front with time, which is

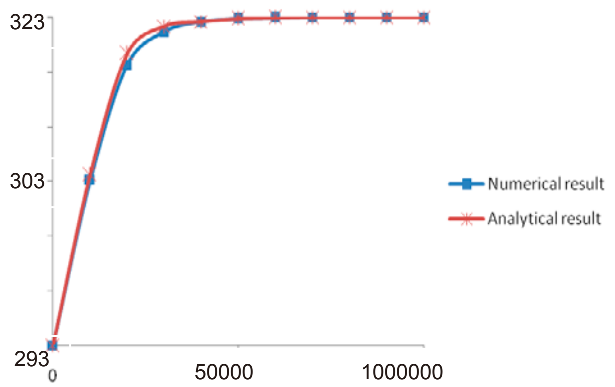

Fig. 7. Comparison of breakthrough curves derived analytically and numerically.

generated in the aquifer due to the thermal injection. The numerical code used in this study is compared with an analytical model. It is evident that with the continuous thermal injection a thermal-front is set-up around the injection well(s) which advances with injection time. The thermal-front may eventually reach the production well affecting the production temperature and the efficiency of the thermal energy storage system. Hence sufficient distance between the injection and production wells should be maintained and the injection-production rates are also to be fixed such that the thermal-breakthrough does not occur during the injection period of an ATES system. Some parameter sensitivity studies are also performed to judge the influence of them on the transient temperature distribution. The injection rate, permeability of the aquifer and the confining rocks turned out to be parameters influencing the advancement of the hot water thermal-front gravely. The breakthrough curve for a 1D version of the present numerical model agrees excellently with the 1D analytical model.

Lastly the present model gives valuable insight on the problem of transient heat transport phenomenon in the porous media due to hot water injection into it. The results presented here can be effectively used in design of the ATES scheme or can serve as a reference solution to more complex numerical models.

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Symbols and abbreviations

c_r, c_w	Specific heats of rock and water, respectively (J/kg·K)
h	Hydraulic head (m)
k	Aquifer permeability (m^2)
k_1	Permeability of the overlying rock
K_X, K_Y	Hydraulic conductivities of the aquifer in longitudinal and vertical directions, respectively (m/s)
Q	Injection rate (m^3/day)
q_f	Source term (sec^{-1})
S	Specific storage (m^{-1})
x, y	Distances in longitudinal and vertical directions, respectively (m).
t	Injection time (s).
T	Temperature (in K)
T_{in}	Temperature of injected water (K)

T_0	Initial aquifer temperature (K)
u_W	Velocity of groundwater (m/s)
ϕ	Porosity of the aquifer
ρ_r , ρ_w	Densities of the rock and water, respectively (kg/m^3)
$\lambda_{,x}$ λ_x	Thermal conductivities of the aquifer in longitudinal and vertical directions, respectively (in W/m·K)