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# Effect of heat loss in a geothermal reservoir

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**Abstract**

This paper reports a three-dimensional (3D) numerical study to determine the effect of heat loss on the transient heat transport and temperature distribution in a geothermal reservoir. The operation of a geothermal power plant, which is essentially an injection-production process, involves reinjection of heat-depleted water after extraction of heat for power production which results in gradual cooling of the reservoir. This study aims at determining the influence of the heat loss from the geothermal reservoir to the surrounding rock media on the temperature distribution due to injection-production operations. Results show that the advancement of the cold-water thermal-front becomes slower due to heat loss which helps in delaying thermal-breakthrough at the production well. The permeability and the thermal conductivity of the confining rocks are found to be crucial parameters influencing the heat loss phenomenon and thus the thermal-front movement in the reservoir. In light of the importance of heat loss, a new strategy of reinjection is discussed here. Injection of cold water in a zone capped by rocks with significant permeability at a finite distance away from production zone is proven here to be a good strategy to avoid premature thermal-breakthrough while maintaining pressure balance.


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*Keywords:* Geothermal reservoirs; ; Heat loss; Reinjection; Heat transport in porous media; Thermal-front.

## 1. Introduction

Heat loss from a geothermal reservoir is inevitable. A geothermal reservoir loses its heat energy to the surrounding rock media mainly by conduction and sometimes by convection, which becomes irrecoverable and results in the cooling of the reservoir. Hence the most potential geothermal reservoirs which are suitable for power production are

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found confined by impermeable rocks where heat loss is small. In designing the injection-production well scheme for a geothermal power plant, transient temperature distribution due to injection-production is to be considered. Reinjection of the geothermal water after power generation is an essential procedure in maintaining the reservoir pressure. But this in turn is responsible for cooling of the reservoir with the passage of injection time [1,2]. Geothermal reservoirs are found frequently to be confined by impermeable rock layers from above and below which play a crucial role in the heat transport process that takes place due to the cold water injection. Besides advective and conductive heat transfer in the geothermal reservoir, another heat transfer process involved physically is the heat loss to the confining rock layers.

The present study addresses the effect and the importance of the heat transfer or the heat loss from the geothermal aquifer to the confining rocks which is not well addressed in geothermal literature. This numerical study presents 3D temperature distribution in the geothermal aquifer due injection-production operations and determines the effect of heat loss in it. The heat transfer processes considered here includes advection and conduction in the geothermal reservoir and heat transport from the aquifer to the confining rocks. Study on a few parameters which have important influence on the heat loss phenomenon is also performed. In light of the importance of heat loss in the transient heat transport phenomenon, a strategy is discussed to avoid the premature thermal-breakthrough and cooling of production wells while serving the main purposes of reinjection.

## 2. Numerical modeling

The fluid flow and heat transport in a geothermal reservoir is described by a 3D coupled thermo-hydrogeological model for temperature distribution in the subsurface non-isothermal flow system of a geothermal reservoir, due to injection-production. A 3D schematic diagram of the geothermal reservoir system is presented in Fig. 1. The numerical modeling of the geothermal reservoir here has been carried out using software code DuMu$^x$ [3]. DuMu$^x$ has been applied on subsurface non-isothermal flow problems [4,5,6] and the results have also been validated with field data or analytical solutions. The model domain for the geothermal reservoir considered here is of dimensions ($L$×$B$×$H$) 400 m× 100 m × 120 m. The confined geothermal aquifer is 50 m deep, which is underlain and overlain by impermeable rock bodies of depth 40 m and 30 m, respectively. Permeability of the aquifer is fixed as $10^{-13}$ m$^2$. Dirichlet boundary conditions of specified temperature and pressure are assumed at the longitudinal and lateral boundaries. A pressure gradient of +0.04 is considered between the longitudinal ($x$) boundaries and +0.02 between the lateral ($y$) boundaries. Regional groundwater flow takes place driven by pressure gradient along those directions. Due to negligible permeability of the confining rocks heat loss occurs only by heat conduction. The geothermal reservoir system here consists of one injection and one extraction well which are fully penetrating (Fig. 1). The initial temperature of the aquifer top surface prior to the injection is assumed to be at an initial temperature of 80 °C and increases downwards due to a geothermal gradient of 0.02 °C/m. The injection and production wells are situated along the positive $x$-axis at the mid width, i.e. $y$=50 m. Cold-water at a temperature of 20 °C is injected through the injection well at a distance 150 m from the $x$=0 boundary at a rate 200 m$^3$/day and hot geothermal water is extracted through a production well 250 m from that the same boundary. All the physical and thermal properties used for modeling study are listed in Table 1.

## 3. Results and discussion

A quantity $\alpha$ is defined, here to measure the movement of the thermal-front, which is given by the ratio between the length of the thermal-front in the direction of the production well to the distance between the injection and production wells. The temperature distributions in the aquifer at injection times of 30 days and 90 days are presented in Fig. 2 for both general transient case (with heat loss) and without heat loss case (where confining rocks are impermeable with very low thermal conductivity). The longitudinal and vertical cross section planes of the geothermal reservoir shown in Fig. 2 are taken at $y$=50 m (i.e. at the mid width) and $z$=40 m (i.e. the bottom of the aquifer), respectively. The figures show the generation and growth of the cold water thermal-front due to continuous injection of heat depleted water. Comparison between the figures showing the temperature distribution for the general transient case (Fig 2(a) and (b)) with those of no heat loss case (Fig. 2 (c) and (d)) makes it evident that due to heat loss in general transient case the advancement of the thermal-front is lesser than that of no heat loss case. This is due to the fact that a part of the cold energy which is injected into the aquifer is transferred to the confining rocks cooling them down and hence the lesser cold thermal energy propagates in the geothermal aquifer slowing down the movement of the cold thermal-front. In Fig. 2 (a) and (b) the value of the parameter $\alpha$, are 0.24 and 0.41, respectively whereas in Fig. 2 (c) and (d) the value of the parameter $\alpha$ are 0.29 and 0.51 respectively. So it is evident from the results that the heat loss delays the thermal-breakthrough. The phenomenon of heat loss involves a few parameters like the permeability and thermal conductivity of the confining rocks. The importance of these parameters is discussed in the next section.

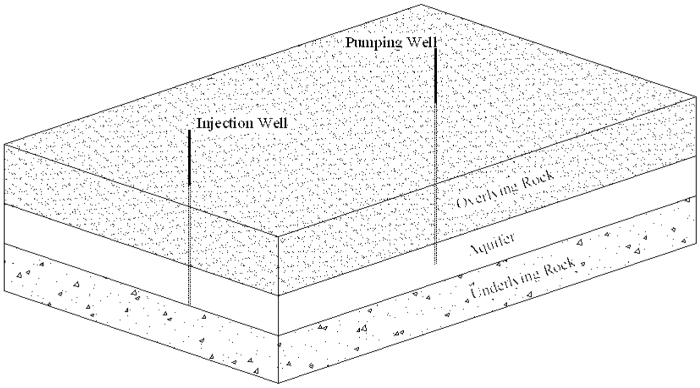


Fig. 1. 3D schematic of the confined geothermal reservoir with injection and production wells.

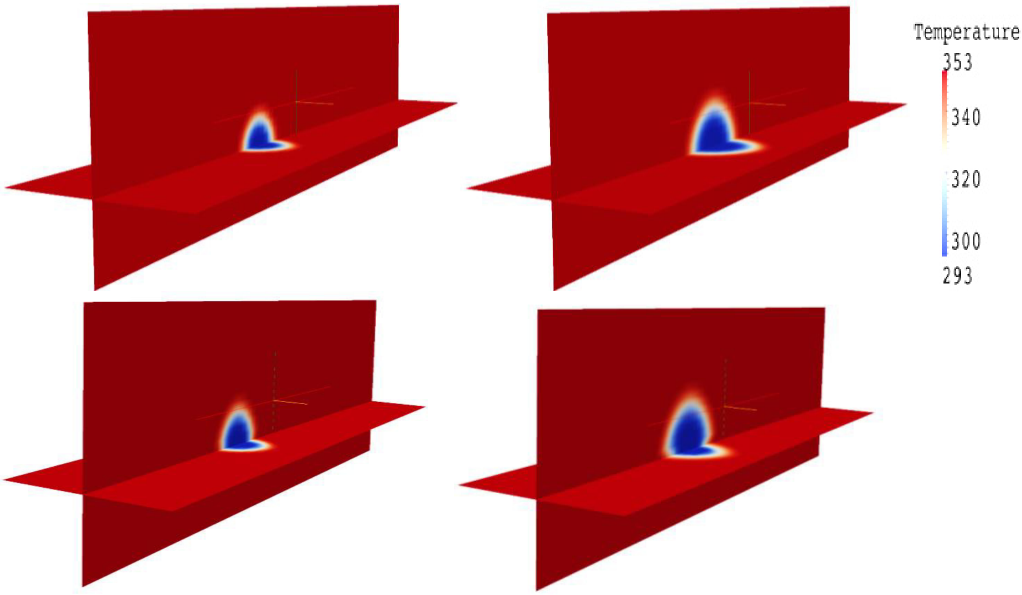


Fig. 2. Temperature distribution in the geothermal reservoir with heat loss at (a)30 days, (b)90 days; without heat loss at (c)30 days, (d)90 days.

### *3.1 Permeability and thermal conductivity of confining rocks*

Permeability of a porous media is a parameter that directly influences the flow velocity and thus the advective heat transport through the media. To judge the importance the permeability of the underlying rock on heat loss, three values of the parameter $10^{-15}$, $10^{-17}$ and $10^{-20}$ $m^2$ are considered and temperature distributions in the system are plotted in Figs. 3 (a), (b) and (c), respectively after 60 days of injection. The vertical plane shown in the figures is the cross section taken at $y$=50 m. i.e. at mid-width and the line through the vertical plane indicates the plane passing through the bottom of the aquifer at $z$=40 m. Other parameters considered to be same as Fig. 2. It can be seen from the figures that thermal-front has penetrated larger area in the underlying rock with higher permeability. The values of $\alpha$ for the thermal-front propagation in Figs. 3(a), (b) and (c), are 0.33, 0.39 and 0.43, respectively. As heat loss helps in slowing down the cold thermal-front movement in the direction of the production well, more permeable the confining rock is, slower is the thermal-front movement which in turn helps in delaying the thermal-breakthrough.

The conductive heat transport flux, although smaller than the convective part has also influence on the heat loss from the aquifer to the rocks and the movement of the thermal-front. Figs. 4(a), (b) and (c) show temperature distribution in the geothermal reservoir at an injection time of 60 days for a thermal conductivity of the underlying rock equal to 2.8 W/m·K, 1.4 W/m·K and 0.5 W/m·K, respectively. The values of $\alpha$ in the figures 4(a), (b) and (c) are computed as 0.39, 0.41 and 0.43, respectively which implies in an aquifer confined by an underlying rock with larger thermal conductivity, advancement of the thermal-front is smaller. Hence confining rocks with significant permeability also helps in slowing down the cold water thermal-front.

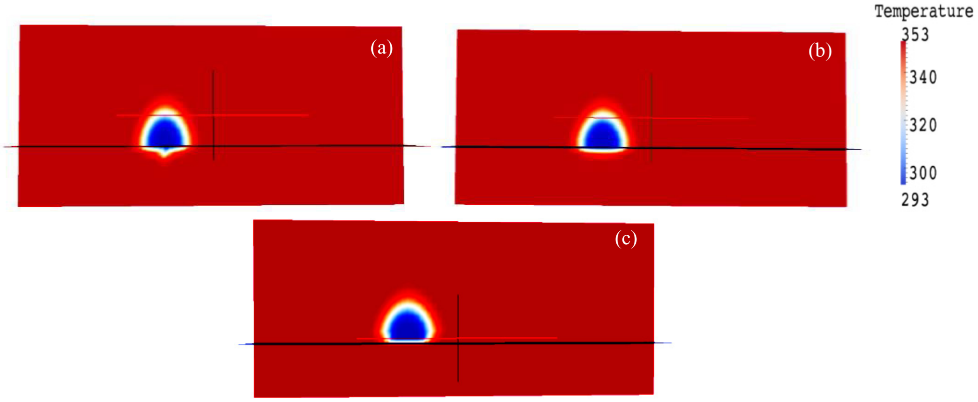


Fig. 3. Temperature distribution in the geothermal reservoir at 60 days for underlying rock permeability (a)$10^{-15}$ $m^2$, (b)$10^{-17}$ $m^2$ and (c)$10^{-19}$ $m^2$.

Table 1. Thermal and fluid properties of the aquifer and rocks used in the modelling.

| Parameter name | Value (unit) |
|---|---|
| Density of the aquifer | 2000 ($kg/m^3$) |
| Density of the overlying rock | 2670 ($kg/m^3$) |
| Density of the underlying rock | 2200 ($kg/m^3$) |
| Density of the fluid | 1000 ($kg/m^3$) |
| Specific heat of the aquifer | 800 (J/kg·K ) |
| Specific heat of the overlying rock | 1850(J/kg·K ) |
| Specific heat of the underlying rock | 2010 (J/kg·K ) |
| Thermal conductivity of the aquifer (longitudinal) | 2.0 (W/m·K) |
| Thermal conductivity of the aquifer(lateral) | 1.2 (W/m·K) |
| Thermal conductivity of the overlying rock | 1.5(W/m·K) |
| Thermal conductivity of the underlying rock | 2.59 (W/m·K) |
| Porosity of the aquifer | 0.3 |
| Porosity of the overlying rock | 0.10 |
| Porosity of the underlying rock | 0.15 |
| Permeability of the aquifer (longitudinal) | $10^{-13}$ $m^2$ |
| Permeability of the aquifer (lateral) | $10^{-14}$ $m^2$ |
| Permeability of the overlying rock | $10^{-19}$ $m^2$ |
| Permeability of the underlying rock | $10^{-20}$ $m^2$ |

The study above suggest that the heat transfer to the confining rocks indeed helps in slowing down the movement of the cold water thermal-front and delay the thermal-breakthrough. But the heat loss from the geothermal reservoir to the confining rocks also has detrimental effects on the capacity of the reservoir. Due to heat loss in significant quantity the reservoir gradually loses its heat content. Hence the geothermal reservoirs found all over the world are suitable for heat extraction when they are capped by impermeable rock formations such that the heat loss is small. The injection of the heat depleted cold water could be done at a distance far away from the production well zone such that the advancement of the thermal-front takes a very long time to reach the production well and the chances of thermal-breakthrough can practically be avoided. But then the main purpose of the reinjection, which is meant to counteract the decline of pressure due to continuous extraction of geothermal fluid, is lost. Optimizing the distance between the injection and the production well is thus a challenging task. The local geophysical constraints, land access and operational and business decisions often control the siting of the wells.

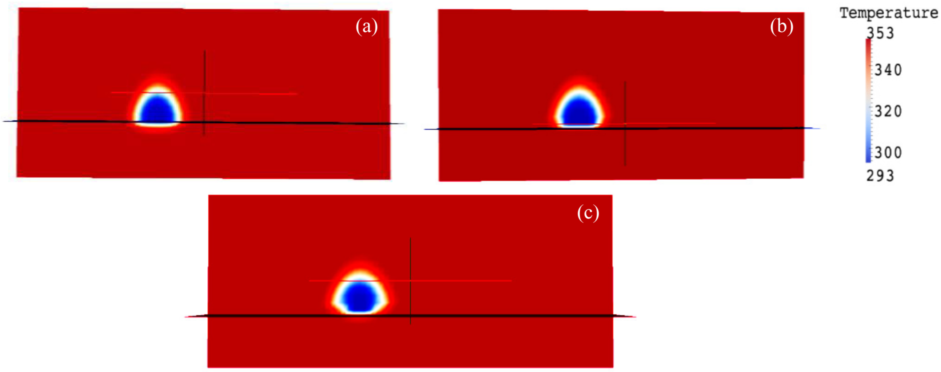


Fig. 4. Temperature distribution in the geothermal reservoir at 60 days for an underlying rock thermal conductivity (a) 2.8 W/m·K, (b) 1.4 W/m·K and (c) 0.5 W/m·K.

In this regard it is suggested here that if there is a region near the geothermal reservoir which is of considerably high permeability and/or thermal conductivity or bounded by rocks having considerable permeability and/or thermal conductivity and which is at a finite distance away from the production zone will be suitable for reinjection. The finite distance of the injection well from the production zone will help in maintaining the reservoir pressure while a significant part of the cold energy injected into the reservoir will be transferred to the confining rocks near the injection zone (due to advective heat transport in the rocks). This will slow down the cold water thermal-front movement, delaying the thermal-breakthrough. The situation here is demonstrated in Fig. 5. Here the cold water is injected at that part of the geothermal aquifer, which is confined by rocks having higher permeability than the rocks confining the original geothermal aquifer. The permeability of the underlying and overlying rocks are $2\times10^{-15}$ $m^2$ and $7\times10^{-15}$ $m^2$, respectively. The injection well is also at a finite distance, 350 m away from the production well, such that the pressure decline in the reservoir can be counterbalanced. Fig. 6 shows the pressure distribution in the aquifer for three cases (a) only production, without injection (b) injection in the confined geothermal aquifer after 60 days of injection and (c) injection in the region confined with permeable rocks after 60 days of injection. The sudden rise and fall in the pressure distribution in the figures denote the injection and extraction pressure points, respectively. The figures show that the pressure in the geothermal aquifer declines with passage of time without reinjection. Reinjection helps in keeping the pressure intact. E.g. the pressure at a point midway in the aquifer (i.e. at a distance 50 m from the injection well) is 3.725 MPa when there is no injection. The pressure at the same point is 3.81 MPa when there is injection in the confined aquifer, whereas in case of injection in the aquifer part with permeable capping, pressure is 3.775 MPa. The value of the parameter $\alpha$ at injection times of 60 and 90 days are 0.31 and 0.35 and the thermal-breakthrough happens after 240 days of injection when cold water is injected in the confined aquifer. The value of $\alpha$ become 0.28 and 0.32 when reinjection is done in the permeable zone and the thermal breakthrough happens after 275 days. Hence it is evident that this new strategy of injection helps in retarding the thermal front movement and thus delaying the premature thermal-breakthrough, while counteracting the pressure decline in the geothermal reservoir.

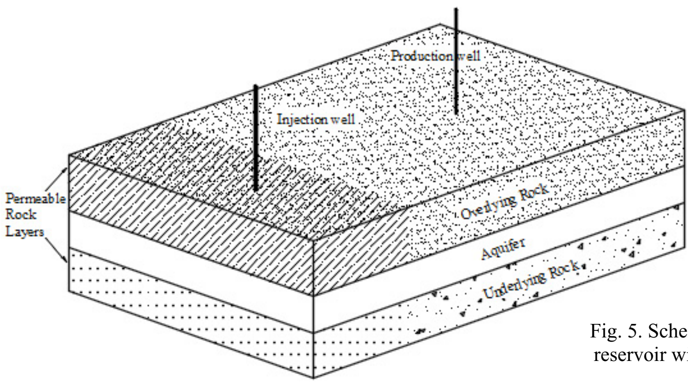


Fig. 5. Schematic diagram of a geothermal reservoir with the permeable zone beside.

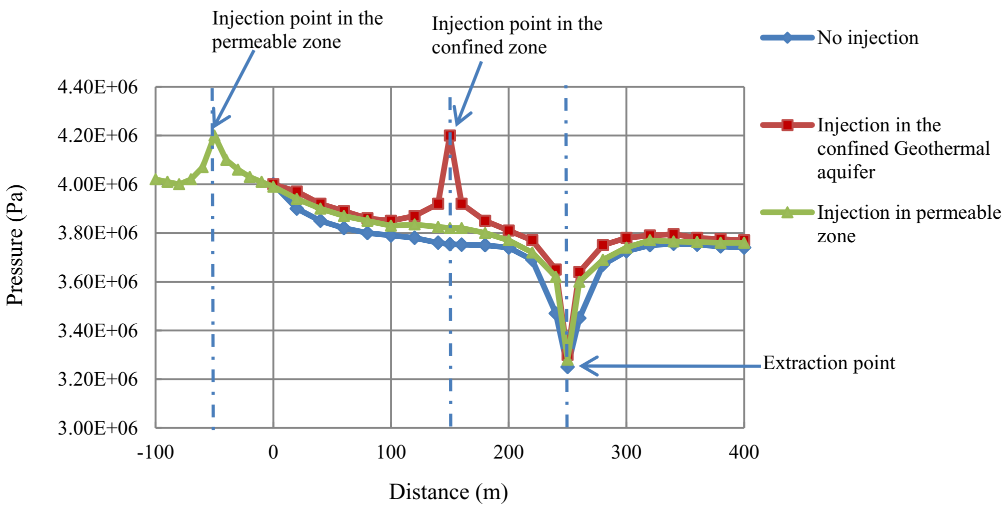


Fig. 6. Pressure distribution in the geothermal reservoir for different cases.

## 4. Conclusions

Modeling the transient heat transport in a geothermal reservoir is of utmost necessity for the purpose of designing a geothermal power plant and determining the effect of heat loss in the heat transport phenomenon is very essential since it directly influences the transient temperature distribution in the geothermal reservoir. The study in this paper finds the heat loss to be a very important parameter influencing the temperature distribution in the geothermal aquifer. The movement of the cold-water thermal-front in a geothermal aquifer with heat loss is always lesser than an aquifer having no heat loss. Hence heat loss from the aquifer delays the thermal-breakthrough. Permeability and thermal conductivity of the confining rocks are found to be controlling parameters for the heat loss phenomenon. Higher value of permeability and thermal conductivity of the confining rocks also causes larger heat loss. In light of the influence of the heat loss on temperature distribution, a new strategy of reinjection is discussed. Reinjection of cold water in the part of aquifer at a finite distance away from the injection well which has significant permeability and/or thermal conductivity or in the part of aquifer bounded by rocks with significant permeability and/or thermal conductivity has been proved to delay the premature thermal-breakthrough at the injection well and counteracts the pressure decline in the aquifer due to continuous extraction, which is the main purpose of reinjection.

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