Simulation Studies of Various Extraction Schemes and Recovery Factors of a Geothermal Reservoir

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ABSTRACT

The response of a generic geothermal reservoir under various extraction schemes is studied to understand the relative significance of various extraction schemes. Multiple variants in each of the considered extraction schemes are synthesized by varying the distance between injection and extraction wells. The temporal variation of extraction temperatures for all proposed schemes are evaluated using series of simulation works. The findings of simulation results are further used to estimate the extractable energy that can be drawn throughout the reservoir operation period which consequently helped in the evaluation of recovery factor. The transients of cold water plume are studied to understand the thermal dispersion and to evaluate the areal extent of cold water plume. This indicates the possible number of extraction schemes, if needed, to be installed without any thermal inferences. Besides the extractable temperature, the variation in recovery factor with the change in extraction scheme is also discussed. It has to be noted that, although the results help to understand the relative significance of extraction schemes, it is not always possible to install the scheme with highest recovery factor, due to extent of reservoir and economic constraints of exploitation.

1. Introduction

The consumption of energy has been growing rapidly in India for which renewable sources are being used conventionally to meet the required demand. From the report of Lakshmi et al. (2017), it is observed that coal is the major source for the generation of electricity. Energy generation through combustion of coal has an adverse impact on environment (Jha and Puppala 2017). In view of environmental concerns and countries dependency of coal import, there is a great need to alter the present energy breakup by emphasizing the growth of renewable energy. Studies of Jha and Puppala (2017) ratified that the thrust on development of geothermal energy could be a promising option to alter the present energy breakup with least negative impact on environment. Geothermal energy is the stored heat within the earth’s crust and is considered as inexhaustible source of energy in a human time scale (Puppala and...
Jha, 2019). It is clean, renewable, and sustainable source of energy. Radioactive decay of Thorium (232Th), Potassium (40K) and Uranium (238U, 235U) is one of major contributor of enormous heat within the continental crust (Stober and Bucher 2013). Although this heat energy is spread all over the world beneath the feet, the energy is intense at few locations which are referred as geothermal fields (Puppala and Jha, 2019). These geothermal fields are suitable for the installation of geothermal power plants. Success and lifetime of any geothermal plant depends on the total heat stored within it. Under these prevailing conditions, prior to industrial exploitation, there is a great need to assess the stored thermal energy.

2. Methodology

A detailed insight on the governing equations representing the physical processes involved in harnessing entrapped heat from a geothermal reservoir are evident from literature (Puppala and Jha, 2019). A detailed overview of all parameters influencing the energy extraction are discussed below.

2.1 Injection and Production rate

Geothermal borewells are typically used to exploit the entrapped heat within the reservoir. Generally, these are drilled to a depth of 2-3 km, where the thermal fluids encounter. The rate at which the thermal water is extracted is referred as production rate. The terminology production rate and extraction rate are used interchangeably. Similarly, the rate at which the extracted thermal water is reinjected back into the reservoir is referred as injection rate.

2.2. Doublet distance

As discussed in the aforementioned sections, reinjection of extracted thermal water helps to maintain the initial condition of the reservoir in terms of pressure. To reinject, typically another borewell which is located close to extraction well is used. The separation distance between the injection and extraction well is refereed as doublet distance.

2.3. Injection and extraction temperature

The temperature of extracted fluid is referred as extraction temperature, which is a transient parameter. Generally, the extraction temperature decreases with time from the moment of reservoir initiation. Further, the temperature of reinjected water is referred as injection temperature.

2.4. Thermal breakthrough and Reservoir lifetime

The term ‘thermal breakthrough’ is defined as the time after which the production temperature slashes below the initial temperature of the reservoir. It can be considered as a measure of success. Depending on the initial condition of the reservoir, even after attaining thermal breakthrough, reservoir can still be exploited based on the requirement. In most of the cases where sustainability is of prior importance, the terminology reservoir lifetime and thermal breakthrough are used interchangeably. In this manuscript, thermal breakthrough is used consistently to avoid confusion.

2.5. Thermal front

Due to extraction of thermal water and injection of cold water, the initial condition of the reservoir is expected to alter. The movement of cold-water plume is responsible for this alteration. This phenomenon is restricted to few meters radially, from the injection and
extraction wells and may vary in the order of kilometers, depending on the thermo-hydro-
geological properties of the reservoir. Evaluation of production license area helps in planning
the adjacent extraction wells. If these wells fall within production license area of operating
well, due to interference, same efficiency is not expected.

2.6. Total available heat energy

The total heat energy that is stored within a considered volume of reservoir can
mathematically be expressed as Eq 1 (Gupta et al. 1979).

\[ H = (1 - \phi)C_r \rho_r V_r (\Delta T) + \phi C_{gr} \rho_{gr} V_r (\Delta T) \]

where, \( H \) is the total heat energy that is stored within the reservoir; \( \phi \) is the effective porosity
of the reservoir; \( C_r \) and \( C_w \) is the specific heat of rock and water respectively; \( V_r \) is the
volume of reservoir, \( \Delta T \) is the difference in reservoir characteristic temperature and reference
temperature. Although the theoretical estimate using Eq 1 aid as a preliminary assessment to
determine the significance of a geothermal field in terms of total heat energy stored, it often
over glorifies the potential of a geothermal reservoir, since it is not always possible to extract
the estimated theoretical potential within the accessible depths under economic and technical
constraints.

2.7. Recovery factor

The ratio of heat that can be recovered to the available total heat energy that is stored under a
considered volume is referred as recovery factor (Gringarten 1978). It can mathematically be
expressed as Eq 2 (Gringarten 1978).

\[ RF = \frac{\dot{m} c_p (T_{ext} - T_{inj}) \cdot t}{(1 - \phi)C_r \rho_r V_r (\Delta T) + \phi C_{gr} \rho_{gr} V_r (\Delta T)} \]

where, RF is the recovery factor; \( \dot{m} \) is the production rate at a given time; \( \rho_w \) is the density
of water; \( c_w \) is the specific heat of water, \( T_{ext} \) is the extraction temperature and \( T_{inj} \) is the
injection temperature; \( \Delta T \) is the difference in reservoir characteristic temperature and reference
temperature; \( \phi \) is the effective porosity of the reservoir; \( C_r \) and \( C_w \) is the specific
heat of rock and water respectively; \( V_r \) is the volume of reservoir \( \Delta t \) is the time interval
between starting time and application abandonment time of the reservoir. From Eq 2, it can
be noted that the recovery factor is a function of reservoir characteristics and the mass
extraction rate. Explicitly it can be stated that for a chosen geothermal reservoir, recovery
factor is closely associated with extraction rate, which depends on the production scheme
adopted for developing a geothermal reservoir.

3. Numerical simulations and extractions schemes

The dynamic response of a generic geothermal reservoir under various extraction is studied
numerically. The proposed extraction schemes are distinguished based on number of
borewells, their functioning, and spacing between them. To study the significance of
proposed extraction schemes precisely, considering the findings of Cho, Augustine, and
Zerpa (2015), a larger generic geothermal reservoir is created so that the influence of
boundary conditions on extraction temperature in case of all the proposed extraction schemes
is negligible. In this study, the radius of borewell is considered as 0.2 m for all the proposed
extractions schemes. Under these proposed extraction schemes, the transient extraction
temperature for 60 years is estimated by solving the coupled heat transfer and fluid flow
equations. Although, 60 years of reservoir lifetime is relatively higher, the rationale for adopting it is to observe the thermal breakthrough period even for lower injection rates, which is expected to be relatively higher. From the temperature vs time plots, thermal breakthrough time, recovery factor and cumulative energy generation is evaluated for all the proposed schemes.

To study the superiority of the proposed configurations, a generic reservoir is developed, and the reservoir region is defined as the permeable layer surrounded by the impermeable layers. The schematic representation is shown in Fig 1. The demarcated region of reservoir is assumed as a homogenous porous medium which implicates that the thermo-hydro-geological properties are constant throughout the reservoir. The dependency of thermo-hydro-geological properties on temperature is neglected in this study and the attributes are shown in Table 1. It has to be noted that the reservoir temperature is assumed to be constant throughout the thickness by neglecting the thermal gradient. The design aspects of injection and extraction wells are presented in Table 1. The proposed extraction schemes are distinct just in terms of number of bore wells, whereas the design aspects such as radius of the bore well and length of injection are same for all the extraction schemes. Since the study of minimum distance to be maintained between bore wells is not focused in the earlier literatures, parametric study is conducted in this work by varying the well separation ranging between 300 m to 1700 m with intermittent separation distances of 200 m step size. This helps in understanding the influence of well separation distance on extraction temperature and thermal breakthrough period. Cold water is injected \( Q(t)_{\text{injection/production}} = 848 \text{ m}^3/\text{day} \) for \( 0 \leq t \leq 60 \) along entire thickness of reservoir through an injection well. Since the demarcated reservoir is assumed to be surrounded by cap rock and base rock, which is merely impermeable, top and base of the computational domain are considered as no fluid flow boundary conditions, in case of fluid flow.

![Figure 1: Schematic illustration of reservoir with doublet](image)
Table 1: Thermo-hydro-geological properties of geothermal reservoir

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>0.32</td>
<td>-</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>1.16</td>
<td>W/mK</td>
</tr>
<tr>
<td>Specific heat</td>
<td>853</td>
<td>J/kg. K</td>
</tr>
<tr>
<td>Density</td>
<td>2197</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Permeability</td>
<td>750</td>
<td>mD</td>
</tr>
<tr>
<td>Reservoir temperature</td>
<td>440</td>
<td>K</td>
</tr>
<tr>
<td>Radius of borewell</td>
<td>0.2</td>
<td>meters</td>
</tr>
<tr>
<td>Length of injection</td>
<td>55</td>
<td>Meters</td>
</tr>
<tr>
<td>Injection/Extraction rate</td>
<td>848</td>
<td>m³/day</td>
</tr>
</tbody>
</table>

The temperature of injected water is assumed to be 283 °K throughout the operation phase of reservoir. It has to be noted that the assumed injection temperature is considered to be constant with time, which illustrates the negligence of seasonal temperature variation. The initial reservoir temperature is assumed to be constant at 440 °K.

Discretizing the entire reservoir domain using a similar mesh may involve huge computational effort. In this regard, the entire domain is divided into three sub-domains as shown in Fig 2. These domains are termed as eastern domain, central domain and western domain. Eastern and western domains are discretized using swept meshing. The applied swept mesh is structured in both the sweep direction and in the direction orthogonal to sweep direction. The element volume ratio of eastern domain and western domain is 0.08 and 0.07 respectively. Since the central domain in which the wells of proposed production schemes are situated is the area of interest, tetrahedral meshing is adopted for the central domain with a minimum element size of 0.06 m (which is 1/3rd of the radius of borewell). The element volume ratio of the central domain is 1E-10. This enables to evaluate the variation in a fine spatial scale. The variation in the elemental volume for western, eastern and central domain is maintained by varying the type of meshing to trade-off between precision and computational effort. It has to be noted that the interface of adopted meshes for the eastern and western domain contains quadrilateral elements, which are divided diagonally to convert into tetrahedral elements. This ensures adjacent free tetrahedral mesh. The coupled equations as shown in aforementioned sections are solved at each and every vertex of the discretised computational mesh to determine the transient production temperature that can be extracted from the shallow geothermal reservoir and also to map the transient temperature variation within the reservoir.
4. Results and Discussions

The extraction temperature over 60 years with a time step of 0.1 years is estimated from simulations for all the proposed extraction schemes and the findings are discussed below.

4.1. Heat extraction using doublet extraction scheme

Two borewells are used in this extraction scheme. Water is considered as a geothermal fluid to drive the entrapped heat. One well is used as an extraction well and the other is used to re-inject the extracted thermal water from the reservoir. Cold water at a temperature of 283 K is injected at a rate of 848 m$^3$/day, through the injection well which is located towards the west of reservoir. Due to the injection of cold water, the temperature of the rock adjacent to injection well decreases. This decrease in temperature results in the formation of low temperature zone around the injection well. The extent of this zone increases with time and progresses towards the production well, which results in the lowering of extraction temperature. The time after which this cold plume strikes the extraction zone depends on the doublet distance and the thermo-hydro-geological parameters of the reservoir. The variation in temperature distribution within the reservoir is obtained. This helps in mapping areal extent of cold-water region at all intermittent time steps. The mapped areal extent of plume is further used to determine the area of influence. The evaluated attributes are presented in Table 2. The temperature variation due to the injection of cold water after 5 years is shown in Fig 3. From Fig 3, it can be inferred that the cold-water plume has advanced till the extraction well after 5 years in case of doublet distance of 500 m. This results to the drop-in extraction temperature significantly. In contrast, for a doublet distance of 1500 m, the extraction temperature remains unaltered till 25 years. The transient extraction temperature for under doublet extraction scheme with well separation distances ranging between 300 m and 1700 m with intermittent well separation distances of 200 m step size are obtained which is shown in Fig 4. The results used to deduce the thermal breakthrough periods for all the well spacing’s is presented in Table 2.
From the Table 2, it can be stated that thermal breakthrough period is sensitive to well spacing. It can also be noted that the extraction temperature during the initial stages of exploration for all well separation distances is equal to the reservoir temperature (440 K). This fact can be correlated with Fig 4, where the cold-water plume has not advanced till the extraction well. But due to the advancement of cold plume from injection well towards the production well, it is observed that the production temperature has decreased beyond the reservoir temperature. From Fig 4, it can be observed that for a well separation distance of 500 m, the cold-water plume reached the extraction end after 2.4 years, which results in the variation of reservoir temperature surrounding the extraction well. The variation is observed to be substantial after 5.7 years where the temperature has slashed to 420 K. From the temperature variation curve corresponding to well separation distance of 1500 m, it can be stated that thermal breakthrough time has increased nearly by 10 times with the increase in doublet distance by 3 times. From the extraction temperature vs time plots, corresponding to a well separation distance of 300 m as shown in Fig 4, it is observed that the production temperature decreased drastically in the initial phases of the operation i.e. till 12 years and has declined gradually during the operation phase of the reservoir. In contrast to this, production temperature in case of a well separation distance of 1500 m has maintained at 440 K till 24.9 years and then it is observed that extraction temperature has decreased gradually.
Besides evaluating the transient temperature distribution, the total heat energy stored within the reservoir is evaluated using Eq 1. However, it would not be practically possible to extract the entire heat stored within the reservoir. In this regard, as discussed in aforementioned sections, the amount of extractable energy is evaluated using the estimated transient extractable temperature and the corresponding stats for few of the operating cases are presented in Table 2.

**Table 2. Thermal breakthrough period and extractable energy till thermal breakthrough for doublet**

<table>
<thead>
<tr>
<th>Doublet distance (m)</th>
<th>Thermal breakthrough (Years)</th>
<th>Area of Influence (Km²)</th>
<th>Extractable energy (Joules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>0.8</td>
<td>0.10</td>
<td>1.86E+14</td>
</tr>
<tr>
<td>500</td>
<td>2.4</td>
<td>0.25</td>
<td>5.35E+14</td>
</tr>
<tr>
<td>700</td>
<td>4.7</td>
<td>0.51</td>
<td>1.09E+15</td>
</tr>
<tr>
<td>900</td>
<td>7.8</td>
<td>0.81</td>
<td>1.82E+15</td>
</tr>
<tr>
<td>1100</td>
<td>12.2</td>
<td>1.21</td>
<td>2.84E+15</td>
</tr>
<tr>
<td>1300</td>
<td>17.0</td>
<td>1.62</td>
<td>3.96E+15</td>
</tr>
<tr>
<td>1500</td>
<td>24.9</td>
<td>2.25</td>
<td>5.79E+15</td>
</tr>
<tr>
<td>1700</td>
<td>34.9</td>
<td>2.86</td>
<td>8.12E+15</td>
</tr>
</tbody>
</table>

It has to be noted that the reservoir can be operated even after thermal breakthrough, till a considerable extraction temperature is drawn. But in this study, in view of sustainability, exploitation is stopped after reaching thermal breakthrough. From the attributes of Table 2, it can be inferred that the thermal breakthrough period is strongly correlated with well spacing with a linear correlation coefficient of 0.96. This can be inferred with the fact that the time...
taken by the cold-water plume is to reach extraction end would increase with the increase in well spacing as it can be observed that the time taken by cold water plume to reach extraction end which is at a distance of 300 m and 1700 m is 0.8 years and 34.9 years respectively.

4.2. Heat extraction using triplet, quadruplet and quintuplet extraction schemes

The extractable energy and thermal breakthrough period of the extraction schemes are estimated in case of all the proposed extraction schemes. Although, various production schemes have been proposed, it has to be noted that the total injection rate and extraction rate is maintained constant in all the extraction schemes to understand the relative significance of each extraction scheme. All the attributes observed in case of doublet extraction scheme are examined for all the studied extraction schemes as presented in Fig 5 and Table 3. From Fig 5, it can be inferred that, for a smaller well separation distances, the variation in extraction schemes does not alter the thermal breakthrough period. In contrast, it is observed that installation of multiple wells for the extraction of entrapped heat helps in enhancing the cumulative energy extraction. However, for a well spacing of 1700 m, thermal breakthrough period is observed to be same in quadruplet and quintuplet extraction schemes. In view of the findings corresponding to all the proposed extraction schemes, conclusively it can be stated that utilization of multiple wells for the exploitation of reservoir would help in extracting more energy, relatively than using a doublet extraction scheme.

Although same number of injection and extraction wells are used in case of triplet collinear and triplet triangle production schemes, from the estimations shown in Table 3, it can be noted that the energy extraction in case of triplet collinear is relatively higher than triplet triangle extraction scheme. The rationale for this variation is due to the interference of thermal plumes in case of triplet triangle. These comparative results implicate that the selection of extraction scheme and well spacing is crucial in setting up a geothermal plant. The mapped thermal distribution in case of all the proposed extraction schemes is further used in evaluating the area of influence. The evaluated attributes in case of all extraction schemes is shown in Fig 6. The measurement of area of influence may help the planners to
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find the possibility of installing more than one specific extraction scheme in a geothermal field. This helps to extract the heat entrapped in the entire area of reservoir, effectively.

Table 3: Thermal breakthrough period and extractable energy till thermal breakthrough for triplet collinear, triplet triangle, quadruplet and quintuplet

<table>
<thead>
<tr>
<th>Extraction Scheme</th>
<th>Well spacing (m)</th>
<th>Thermal breakthrough (Years)</th>
<th>Extractable energy (Joules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triplet Collinear</td>
<td>300</td>
<td>1.2</td>
<td>$2.79 \times 10^{14}$</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>3.5</td>
<td>$7.91 \times 10^{14}$</td>
</tr>
<tr>
<td>Triplet Triangle</td>
<td>900</td>
<td>11.6</td>
<td>$2.7 \times 10^{15}$</td>
</tr>
<tr>
<td></td>
<td>1100</td>
<td>15.9</td>
<td>$3.7 \times 10^{15}$</td>
</tr>
<tr>
<td>Quadruplet</td>
<td>700</td>
<td>7.6</td>
<td>$1.84 \times 10^{15}$</td>
</tr>
<tr>
<td></td>
<td>900</td>
<td>13.2</td>
<td>$3.14 \times 10^{15}$</td>
</tr>
<tr>
<td>Quintiplet</td>
<td>1500</td>
<td>54.5</td>
<td>$1.27 \times 10^{16}$</td>
</tr>
<tr>
<td></td>
<td>1700</td>
<td>60</td>
<td>$1.4E \times 10^{16}$</td>
</tr>
</tbody>
</table>

Fig 6. Area of Influence for different extraction schemes and well spacing
5. Recovery factor and sustainable extraction schemes

The extractable energy within thermal breakthrough period for each exploitation scheme is evaluated as presented in Table 2 and Table 3. The total energy stored in the reservoir is $2.2 \times 10^{18}$ Joules which is evaluated by using Eq. 1. The total stored energy and extractable energy during operation are further used to determine the fraction of recoverable heat energy i.e. the recovery factor of each scheme using Eq 2 and the evaluated stats are shown in Fig 7. The lower recovery factor in case of all the extraction schemes for the lower well spacing is in correlation with smaller area of influence. For instance, if the well spacing in any of extraction scheme is less, the area of influence from which it extracts the heat reduces, which will have a significant effect on cumulative energy extraction and recovery factor. This is evident from Fig 7. As discussed earlier, it can be inferred that triplet collinear is preferred over triple triangle. Although same effort is involved for triplet collinear and triplet triangle, in terms of economic aspects, considerable deviation in terms of energy extraction is observed which is interpreted with the thermal plume inferences. Although, the results in Fig 7 reflects the hierarchy in terms of recovery factor, it may not always be possible in real field situations to install the multi-well extraction scheme with highest recovery factor due to spatial constraints of the reservoir. The heuristic knowledge between recovery factor and well spacing is used to deduce the mathematical relation between recovery factor and well spacing, for each of the proposed extraction schemes. The deduced relations are shown in Fig 8. From Fig 8, it is evident that a strong nonlinear correlation is observed between recovery factor and well spacing for all extraction schemes. Although a similar trend between these two parameters is observed, different coefficient is noticed for different scheme, which is evident from Fig 8. The mathematical relations shown in Fig 8 help planner to estimate the probable recovery factor for intermittent well spacing’s without performing the simulation studies.

![Fig 7. Recovery factor of extraction schemes](image-url)
6. Conclusions

In this work, various reservoir extraction schemes and the response of geothermal reservoir for the sustainable exploitation of entrapped heat are studied. The extraction temperature vs time is estimated for all the schemes by numerical simulations of the coupled fluid flow and heat transfer processes during operation of geothermal reservoir. Also, thermal breakthrough periods for all the extraction schemes are obtained and are further used in estimating the amount of recoverable heat from various schemes. The results of this study helps to understand the dominance of extraction schemes in terms of possible recovery factor. The nonlinear relation is obtained between recovery factor and well spacing for all the five extraction schemes studied in this work, which can further be used by planner to estimate the probable recovery factor for intermittent well spacing’s. From the relative comparison, it is observed that with the increase in number of extraction wells, there is an enhancement of thermal breakthrough period. However, in practical application, the economic considerations and the spatial extent of reservoir may also play a vital role in selecting a proper scheme for the extraction of entrapped heat in a geothermal reservoir. This study acquires the significance in policy making decisions while proposing extraction scheme for the effective exploitation of a geothermal reservoir.

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