Study of Geothermal Energy Potential with Geothermal Doublet: A Case Study for Puga Valley Ladakh

Shibani K. Jha and Harish Puppala

Abstract The growing demands for renewable energy have made geothermal energy a popular option in recent past. The efficiency of such a system depends on the retention and transport capacity of heat. Hence, model studies under different reservoir conditions are essential. This study is concerned about a geothermal doublet to produce hot groundwater, extract heat, and reinject the cooled down water into the subsurface. Studies are performed by computational tool, COMSOL Multiphysics, to estimate the potential of geothermal reservoirs. The study shows the effect of geothermal doublet on coupled heat transport and groundwater flow. Puga Valley in Ladakh district, 1,600 km from New Delhi and at an altitude of about 4,400 m is considered for the study. The transient temperature distribution in the reservoir is discussed. The effect of natural groundwater flow on the temperature distribution and the influence of production and injection wells, the geothermal doublet, are also discussed.

Keywords Geothermal reservoir · Heat transport · Groundwater flow
Geothermal doublet · Injection well · Extraction well

Introduction

Geothermal energy provides an option for renewable energy for base load electricity in alleviating the world's energy and climate predicament (Ekneligoda and Min 2014). Geothermal potential, as regular steam and high temperature water, has been exploited for decades to produce power, and for space warming as well as for industrial purposes. The geothermal electrical plants were installed in the world to

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produce 7974 MW till twentieth century. In the year 2000, with that installed capacity, an electrical energy of 49.3 billion kWh/year was generated, which was nearly 0.3% of the world aggregate electrical energy (Barbier 2002). Prior to 1864, geothermal energy resource in India was nearly unexplored. Beginning with an identification of 99 springs in India (Schlagintweit 1864), it was followed by the monumental work of exploring 340 springs (Rao1997). A major, systematic, multidisciplinary, and multi-Institutional programme (including drilling) was then mounted in India to explore the potential sites during 1972–74, covering the Puga–Chumatang field (Ladakh), India. From the existing literatures and the research works carried by geological survey of India (GSI), it is identified that the Puga geothermal reservoir is rich in hidden energy in the earth's crust which can feed the energy need of India at large scale.

The conventional way of extracting energy from the earth involves the process of injecting cold water through an injection well and extracting hot water from a production well (Schulte et al. 2010). This system of injection and extraction well is known as geothermal doublet. The distribution and frequency of this doublet in a reservoir influence the energy extraction potential. Since 1973, there has been developing interest for geothermal projects to utilize boiling hot water from aquifers which are profoundly covered in sedimentary basins of India. In the areas of normal or close typical temperature gradients, the most extreme temperature accessible in 3000 m wells is prone to be around 100 °C (Hutchence et al. 1986). Extensive research has been carried out on determining the parameters and processes affecting the geothermal extraction potential. Such research includes thermal, mechanical, and hydraulic (Te-Me-H) coupled numerical models as well as analytical studies.

Geological, geophysical, geochemical, geohydrological studies were carried out in the sites of geothermal reservoirs, but very limited studies were carried out to determine the potential of geothermal reservoir with doublet. From the limited studies carried out in India, it was observed that the maximum depth explored through drilling was about 362 m approximately which may not be sufficient to study the commercial feasibility of geothermal reservoir. This paper presents the simulation studies which are performed mainly to understand the movement of thermal front during the reservoir operation period which is also the cold water injection period. The study also presents the estimation of the probable production temperature that can be withdrawn from the production well under the cold water injection. The reservoir flow and energy transport model with doublet proposed in this study is suitable for a system which involves extraction of hot water from a geothermal production well with concurrent injection of cooled tailings water into the same formation in a nearby injection well. The sensitivity study of the energy production with respect to doublet distance and the cold water injection rate is also discussed in this study.

Case Study—Puga Geothermal Reservoir

Puga geothermal field, at an elevation of around 4400 m above mean ocean level, is situated in the northwest of the Himalayan ranges. Lying in the southeast part of Ladakh, the area of Jammu and Kashmir State, it frames a piece of the Himalayan geothermal belt, with topographical coordinates 33° 13′North and 78 °19′East as shown in the Fig. 1.

The Puga range is encompassed by slopes ascending to a height of around 6000 m, shaping a valley. This region is around 700 km far from Srinagar city and around 190 km from Leh Town, the district headquarters. Puga valley, situated in the northernmost territory, and is in the remotest and coldest part of the country and is around 15 km long with a most extreme width of 1 km inclining almost east west in bearing between Sumdo town in the east and Pologongka Lake in the west. The geothermal activity, which is spread over a range of 5 km^2 is confined to the two N–S drifting faults, known as Kaigar Tso flaw toward the west and Zildat shortcoming toward the east. From the studies carried out by the geological survey of India, it was identified that the Puga geothermal region is the most prominent geothermal field in the nation, which has an expected capacity of 20–100 MW as found by the geo scientific studies for the zone.

The bore holes in the Puga valley is distributed at irregular intervals. The temperature gradient obtained in different well is different. However, due to the unavailability of proper temperature distribution for the entire valley, the decision maker finds it difficult to select the location of injection and extraction well. The

Fig. 1 Geographical location and the terrain of Puga Valley

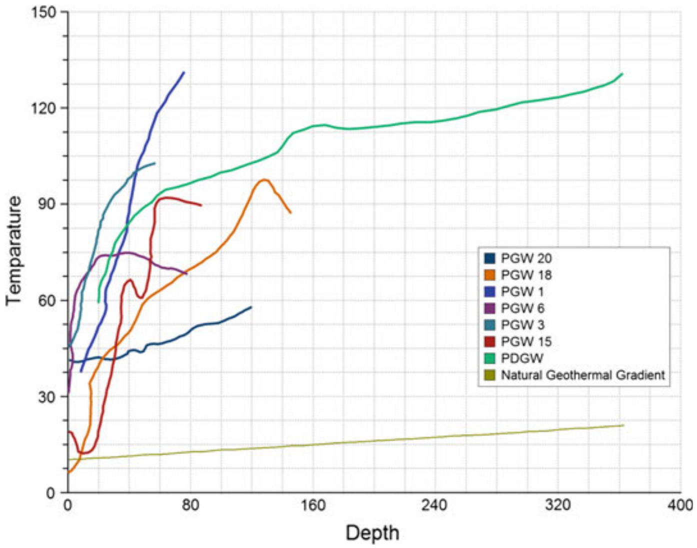


Fig. 2 Variation of temperature with depth at the corresponding bore holes

limited data of thermal gradient is available from the geothermal atlas of India (Geological Survey of India 1991) as shown in Fig. 2. For the present study the natural geothermal gradient (linear profile) as shown in Fig. 2, has been considered for the initial temperature distribution of the reservoir.

Conceptual Model of the Reservoir

The geophysical studies conducted in the Puga geothermal basin uncovered the presence of conductive features at shallow depths below 500 m, yet the deeper part of the geothermal valley remains unmapped. The wide band magneto-telluric studies were conducted in the Puga geothermal basin, to explore the data with respect to the vicinity of geothermal action and assets in that region (Harinarayana et al. 2006) and the computer model developed earlier by Absar et al. 1996. These studies were taken into consideration in the preparation of the present conceptual model of Puga geothermal valley. As the deep geothermal reservoir is emphasized in this study, the block heterogeneity is considered for the computer model to represent the Puga valley, approximately. To study the thermal front propagation under the injection and extraction wells, 3-D model of the valley is considered as shown in the Fig. 3.

The reservoir permeability is considered in terms of block heterogeneity based on the type of existing rocks in the Puga geothermal reservoir. From the literature (Absar et al. 1996) it is observed that the Puga geothermal valley is distributed with

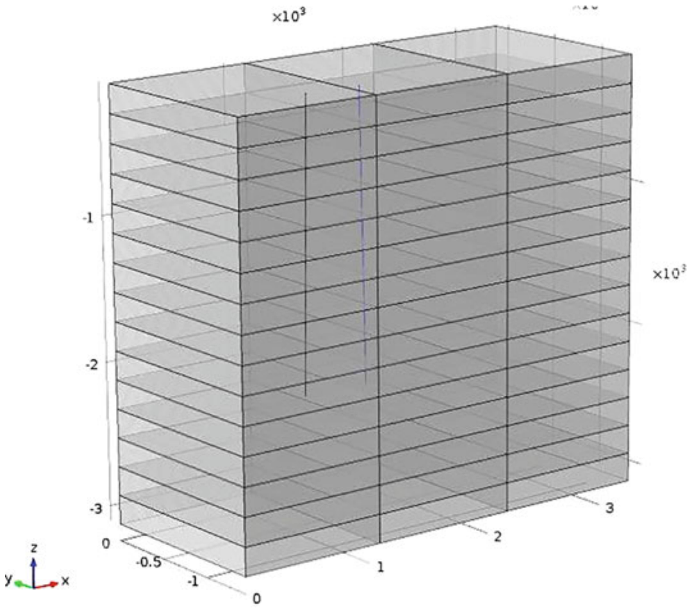


Fig. 3 Model approximation of entire Puga geothermal reservoir

Gneiss, Gneiss V, Gneiss III, Gneiss IV, Breccia, and Granite in the deep layers. Also the literatures suggest that the permeability of porous matrix follows log-normal distribution. Therefore, by considering the proper permeability range for the corresponding rocks, values are generated by following lognormal distribution which was further assigned for each of the blocks. The values of required properties for existing type of rocks are adopted from the literature (Robertson 1988; Manger 1963; Davis 1969; Sperl et al. 2008). Similarly, porosity, conductivity, density, and the specific heat capacity of each block is estimated and assigned to the respective block. Natural geothermal gradient is considered in determining the initial condition of the geothermal reservoir.

From Ahangar 2012, it is observed that the groundwater recharge to the Puga basin is mainly from the snow fed Puga–Nala and its tributaries. Puga valley has a stream coursing through it. This river streams from west to east and is nourished by ruling glacier, located at a distance of 15 km west of Puga. In the significant part of the area, with the exception of a small stretch in the western part, no point in the valley is more than 1000 m far from the stream. In the eastern part, the distances are much smaller. Flow in the Puga–Nala River is variable, i.e., 250 litres/s in the maximum peak summer and 4–6 L/s during December–January when the river is frozen.

Flow and Energy Transport Model with Doublet

As the Puga geothermal valley has alluvium and Breccia in its depth, the flow velocity is very less due to the less permeable and low porous material. In this study, time-dependent analysis is executed using Darcy's law. Darcy's law states that the velocity field is a function of pressure gradient, viscosity, and the soil properties of the porous medium which can be expressed mathematically as shown is Eq. 1.

$$u = \frac{K}{\mu} \nabla p \tag{1}$$

where k is the permeability of the medium, μ is the dynamic viscosity and ∇p is the pressure gradient. Equation 1 is used in the continuity equation given by Eq. 2 below.

$$\frac{\partial}{\partial t}\left(\rho \varepsilon_p\right) + \nabla.(\rho u) = Q_m \tag{2}$$

The side boundaries of the model are assigned with the Dirichlet boundary condition with specified hydraulic head. Bottom boundary is specified as no flow boundary. The model presented in this study considers the existing deep geothermal well of Puga valley as the injection well which is located at 740 m from left boundary of the model considered. And the extraction well is considered at a distance of 1033 m from the injection well.

Inlet condition to the injection well is assigned during the computation using the expression as shown in the Eq. 3.

$$-n \times \rho u = \rho U_0 \tag{3}$$

U_o represents the Darcy's velocity considered to be positive when the flow is inward and is considered to be negative when the flow is outward.

The transient heat transport model with conduction, convection, and heat source through porous media is taken into consideration to study the thermal front movement within the Puga geothermal basin as given by the Eq. 4.

$$d_z (\rho C_p)_{\text{effective}} \frac{\partial T}{\partial t} + d_z \rho C_p u.\nabla T = \nabla.(d_z k_{\text{eff}} \nabla T) + Q \tag{4}$$

where $(\rho)_{\text{effective}}$ is the effective density of the porous medium (fluid and solid), $\left(C_p\right)_{\text{effective}}$ is the heat capacity of the porous medium, k_{eff} is the effective thermal conductivity of porous medium, and Q is the heat source or a sink. The boundary

Table 1 Input parameters for the computer model

Parameter	Value	Units
Pumping rate	40	[L/s]
Radius of bore hole	0.5	[m]
Injection length	20	[m]
Production length	20	[m]
Injection velocity	0.0002	[m/s]
Production velocity	0.0002	[m/s]
Injection well inclination	1	[degree]
Extraction well inclination	1	[degree]
Hydraulic head gradient	0–5	[mm/m]
Surface temperature	290	[K]
Injection temperature	280	[K]
Mass influx	10	[Kg/s]
Heat source	60,000	[Watts]
Doublet distance	500	[m]

condition for heat transport model as given by Eq. 5 is geothermal gradient assigned to all the side boundaries of the model.

$$T = T_0, \text{ if } n \cdot u < 0; \quad -n \cdot q = 0, \text{ if } n \cdot u \geq 0 \tag{5}$$

The Darcy's flow model is coupled with the heat transport in porous medium model to study the temperature distribution under the operation of doublet.

Following the studies of (Blocher et al. 2010; O'Sullivan et al. 2001), this study is further extended to capture the behavior of geothermal reservoir as a 3-D model and the entire domain is divided into finer elements. The set of governing equations discussed above are solved numerically using COMSOL Multiphysics with the boundary conditions and input parameters discussed in the paper. To present the comprehensive model, all the parameters which had an impact on heat transport and fluid flow are also discussed. The concerned input parameters as well as geometrical parameters of the Puga geothermal reservoir are mentioned in the Table 1. The natural ground water flow is considered in terms of the specified hydraulic gradient as mentioned in the Table 1.

Results and Discussions

The governing flow and transport models are solved numerically using computational tool, COMSOL Multiphysics. As this study focus on the influence of geothermal doublet on the movement of thermal front, initially, the spacing

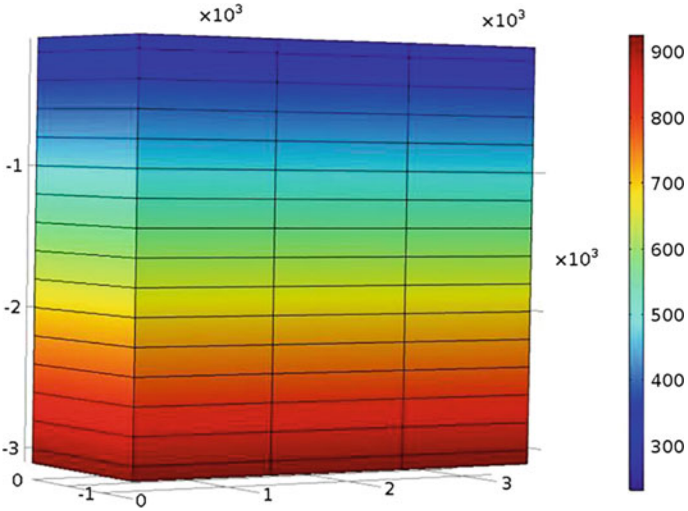


Fig. 4 Initial temperature distribution of the reservoir (natural geothermal gradient)

between injection and the extraction well is maintained at a distance of 500 m and then the thermal front variation is studied by varying the doublet distance to a lower value of 250 m and next to a higher value of 700 m, respectively. In addition to the well spacing or doublet distance, the impact of the injection rate of cold water is also studied by considering different injection rates of 50 and 30 L/s and compared with base simulation of 40 L/s.

It is observed that the scope of the most extreme and least temperature of the extracted water from the production well is increased with increase in the doublet distance. The initial temperature distribution is shown in Fig. 4. The movements of thermal front during the operation period for the different cases simulated are shown in Figs. 5 and 6. From the simulation studies, it is observed that the range of maximum temperature and the minimum temperature is increased with decrease in injection rate of cold water and also it is observed that with increase in the doublet distance, the time for which the cold water is in contact with porous structure which is initially at higher temperature increased which enhances the exchange of temperature for longer time, which apparently helps in extracting the water with high temperature at production well. The results of such study can help the decision maker in deciding the identification of proper locations of injection as well as the extraction wells in addition to the proper injection rates.

The pattern of thermal front along the vertical cross sections studied at different locations of the Puga geothermal region is shown in Fig. 7. The sections near to production well show higher temperature, as hotter fluid moves upward along the production well. Also the upward coning of the thermal front which is expected

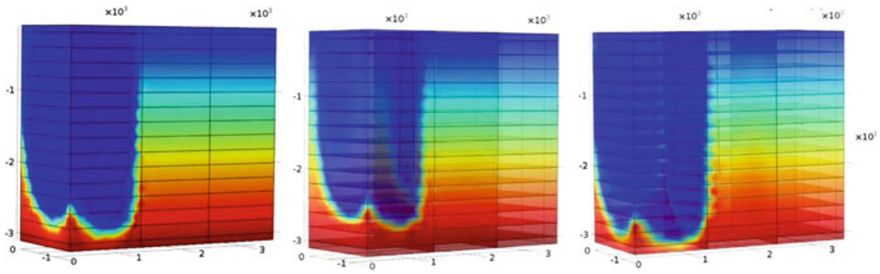
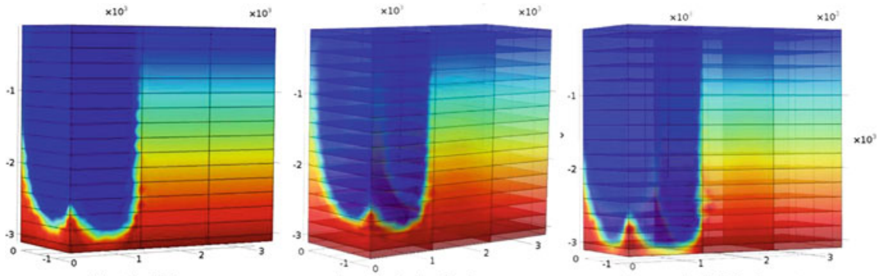


Fig. 5 Pattern of thermal front after 30 years and the impact of doublet distance (*left* 500 m, *center* 250 m, *right* 700 m)



Base Condition

Decrease in the injection rate

Increase in the injection rate

Fig. 6 Pattern of thermal front after 30 years and the impact of injection rate (*left* 40 L/s, *center* 30 L/s, *right* 50 L/s)

near the production well is shown by the results studied. The temperature of hot water at the production well over the operation period of 30 years in all the different cases is examined and is presented in Fig. 8. The temperature of extraction is higher in case of higher doublet distance and lower injection rate in comparison with the base condition considered in this study.

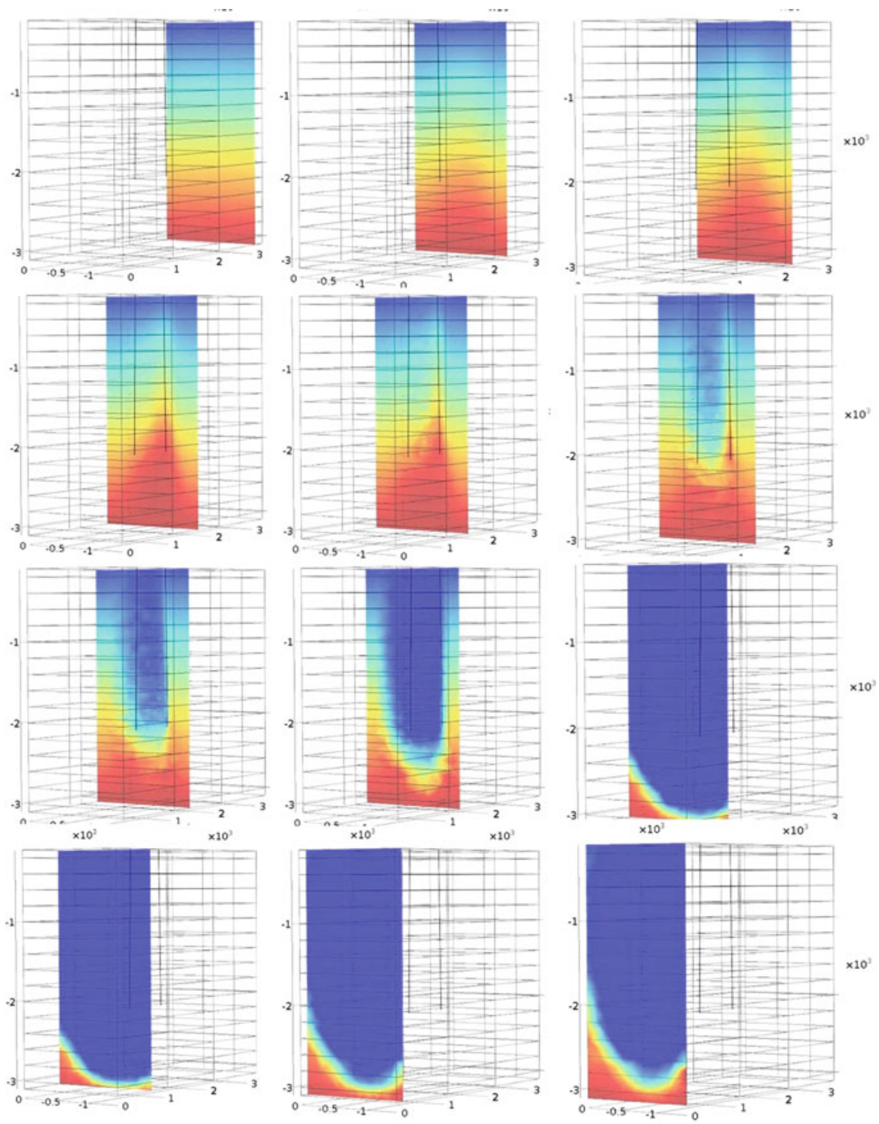


Fig. 7 Pattern of thermal front at different sections along the geothermal reservoir after 30 years

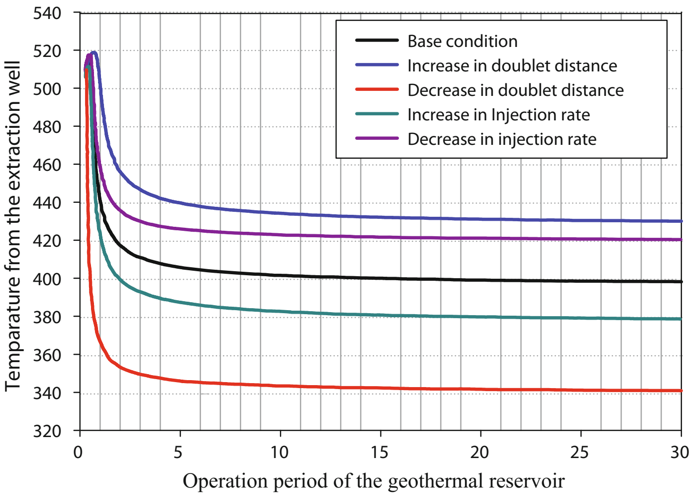


Fig. 8 Temperature of water that can be extracted through the production well

Conclusions

The primary focus of this study is to understand the thermal front movement under the doublet operation so that the potential of energy extraction in terms of temperature can be predicted for the geothermal reservoir of Puga region, Ladakh. This study helps in estimating temperature of water that can be withdrawn from the production well. The production temperature is required for further estimation of commercial energy generation purposes. It is found that the temperature extracted from the production well is proportional to the scale of electricity that can be generated. The behavior of Puga geothermal reservoir for the operation period 30 years is studied by considering some of the existing data for structural geometry and geological properties which is further studied by coupling the different physics of flow and energy transport involved during the operation period of geothermal reservoir. The results presented by such study will be helpful for the decision maker, to further plan and manage the injection and production rates, and the doublet distance, which has an impact on potential of geothermal reservoir.

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