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The Extraction of Geothermal Energy from Hot Dry Rock: A Potential Green Energy Source

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Abstract. Heat stored in the earth's crust is a potential resource of renewable and green energy to meet the global primary energy needs without producing any greenhouse gases. The majority of the geothermal resources are stored in the Hot Dry Rocks (HDR) at a substantial deep depth as compared to hydrothermal resources. The present study illustrates an overview of the HDR resources available worldwide as well as in India. The article further discussed the available technologies to extract geothermal energy from HDR. A systematic review of the key technologies including Enhanced Geothermal Systems (EGS) and single-well borehole heat exchanger systems are analysed in the article. A 2D Numerical analysis of a single well system with a coaxial wellbore heat exchanger has been carried out to extract thermal energy from the reservoir. In addition, the influence of various parameters on the system's heat extraction capacity has also been investigated. The present work may aid in the development of novel enhanced geothermal systems and single well systems with improved thermal performances.

Keywords: Geothermal Energy, Hot Dry Rock, Numerical analysis.

1 Introduction

Geo-thermal energy is a form of renewable energy that has the potential to be used in various applications such as agriculture drying, space heating, heat pumps, aquaculture heating, swimming, bathing and electricity production. These applications were predicted to replace the utilization of 350 million barrels of oil equivalent and also prevented 148 million tons of greenhouse gas emissions in 2015 [1]. Hence, geothermal energy offers a promising sustainable alternative to fossil fuels with a considerable potential to reduce the planet's carbon footprint.

The earth's crust contains vast geothermal reserves in the form of hydrothermal resources and Hot Dry Rock resources. The geothermal energy reserves are calculated to be 50,000 times the global identified oil and gas reserves [2]. The HDR is a deeply seated crustal rock mass with high temperature and without natural water flow [3]. The extraction of heat from the HDR is a challenging task due to the low porosity and permeability of the reservoir. Hence extraction of heat from the deep resources became a research interest in the energy field.

The aim of the present article is to analyse that data and provide information related to geothermal energy extraction from the HDR reservoir. The study also discusses the effect of well depth, rock thermal conductivity and geothermal gradient on the thermal performance of a single well with a coaxial wellbore heat exchanger through the 2D numerical simulation.

2 Hot Dry Rock Resources

HDR resources in China are classified into four groups such as (a) Reservoirs with high radioactive heat-producing capacities (b) Sedimentary basins with high geothermal gradients (c) Modern volcano HDR, which are having magma as the heat source below the reservoir (d) Intensive tectonic active HDR. The estimated geothermal energy in the top 10 km earth's crust has been predicted equals to 1.3x 10^{27} J, which is equal to the consumption of 3 x 10^{17} barrels of oil [4]. This energy can meet the global energy demands for 19 million years based on the global energy consumed in 2021[5]. China's HDR geothermal energy reserves at 3 km to 10 km depth are more than 8.56 × 10^{8} million tons of coal [6]. In the USA, EGS is expected to have a resource base of 1.3 X 10^{24} J within the 10 km depth, of which 2 x 10^{23} J can be extracted under present available technology. This is equivalent to 1900 times the annual consumption of energy in the USA [7]. In the UK, the accessible HDR resources up to 7 km crustal depth with more than 100 °C reservoir temperature have been estimated to be 36 x 10^{21} J, which is equivalent to the consumption of 13 x 10^{10} tons of coal [8].

3 Indian Perspective

The country's hydrothermal resources are majorly navigated through the granites, which occupy 1.5 million square kilometres and extend to depths of several kilometres [9]. India has plenty of geothermal resources, which can be sufficient to meet the country's primary energy requirements [10]. M/s Geosyndicate Power Pvt. Ltd estimated the electricity generation capacity of geothermal resources over 1000 km^2 area in the Ladakh region and reported as 61x10^{15} kWh [10]. Similarly, they estimated for an area of 1000 km^2 in Andhra Pradesh and Madhya Pradesh granites and reported power generation capacity of 111x10^{15} kWh and 24.5x10^{15} kWh respectively. The exploration and extraction of geothermal energy in India are in the emerging stage. The available information related to India's hydrothermal and HDR resources is limited. Hence, extensive research needs to be conducted on the exploration and exploitation of accessible hydrothermal and HDR resources. Therefore, a brief review has been presented related to heat flow characteristics of various high heat generating rocks located in India.

3.1 Malani Igneous Suite

The Malani Igneous Suite (MIS) region is encompassed various high heat generating rocks, which are spread around an area of 55,000 km^2 in India as well as Pakistan. These rocks are located in Siwana, Barmer, Tosham, Jalore, Jhunjhunu, Jaisalmer and Pali regions [11].

Siwana Ring Complex (SRC) is a part of the MIS, located in Barmer district, Rajasthan. SRC encompasses an area of 800 sq. km with dolerite, gabbro, basalt, trachyte, granite and rhyolite in the ascending order of abundance. SRC contains ring dykes of medium to coarse-grained Siwana granite composed of high-temperature minerals like bipyramidal quartz, sanidine and orthoclase [12]. The granites present in the complex have radioactive elements like Uranium (U), Thorium (Th) and Potassium (K), which are responsible for producing radioactive heat ranging from 4.3 to 41.68 $\mu W/m^3$ [13]. The produced radioactive heat increases the temperature of the circulating fluids, which is the main reason for the thermal springs in the region. The thermal springs in the SRC regions can produce 30 to 40 ℃ surface temperatures [12]. The projected reservoir temperature in this region is ranging from 76 to 220 ℃ with the higher heat flow values ranging between 83 to 440 mW/m^2.

Siner Valcono-Plutonic Region is comprised of high heat-producing rocks such as Granite, Micro-Granite dykes, Trachyte and Rhyolite. These rocks have a high concentration of Th along with U and K. The estimated heat production of the Siner region is ranging between 3 to 33 $\mu W/m^3$ in Granites and up to 41 $\mu W/m^3$ in Micro-Granite dyke with an average of 12.73 $\mu W/m^3$ [11].

Jodhpur Granites - The Northeast part of Jodhpur city has pink and grey colour granite with a high concentration of Th compared to U and K, which are responsible for producing an average radioactive heat of 6.69 $\mu W/m^3$ [14].

Tusham region is located in the trans-Aravalli province, Haryana. The region is occupied by volcanic and pre-volcanic rocks such as granite, porphyry, rhyolite and metasediments. The estimated geothermal gradient of the region is around 26 ℃/km. The thermal conductivity of the Tusham granites is 3.55 $\pm$ 0.26 W/ (m.K). In addition to the high thermal conductivity, Tusham granites reported high heat flow around 96$\pm$ **3.2** mW/m^2 [15]. Sharma et al. (2019) reported the high radioactive heat generation capacity of the Tusham granites as 13.88 $\mu W/m^3$ [16].

3.2 Bundelkhand Craton

The Bundelkhand craton is spread in a semi-circular shape over an area of 29,000 km^2 in the Central Indian Shield. The granites present in the craton are having high heat generating capacity an average of 4.56 $\mu W/m^3$ surface heat production due to radioactive elements [17]. The thermal conductivity of the Bundelkhand granites is reported in the range of 3.1 to 3.6 W/(mK) [18].

3.3 Himalayan Province

The Himalayan province is the major geothermal province in India with the majority of the thermal springs [19]. The Himalayan region also has a substantial mass of hot dry rock at accessible depths. The thermal water present in the region has surface temperatures up to 98 ℃. The estimated geothermal gradient from the shallow well explorations is greater than 100 ℃/km. The region also reported high heat flows between 70 to 180 mW/m^2 [20]. The main reasons behind these high thermal discharge and heat flow are the high radioactive heat production capacity of the granites and also the presence of seismic bright spots in the region [21].

4 Geothermal energy extraction methods from Hot Dry Rock

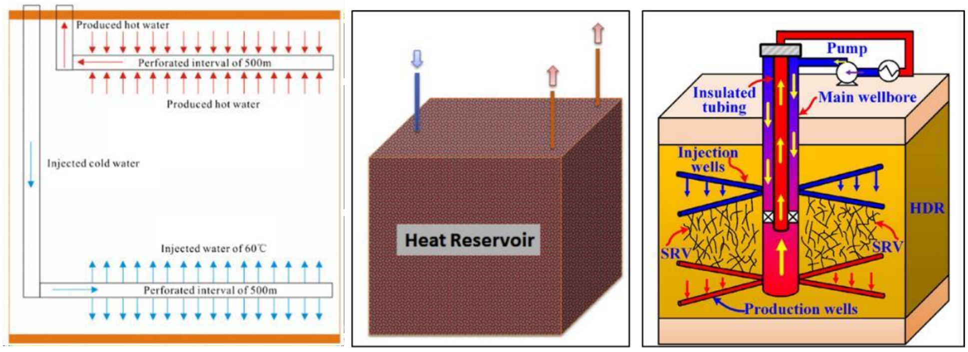
4.1 Enhanced Geothermal System

EGS is an engineered geothermal system with two or multiple wells situated in an artificially fractured thermal reservoir. The cold fluid mainly water is circulated through the fractured reservoir for economical harvesting of geothermal energy from HDR. In the year 1970, Los Alamos National Laboratory proposed a plan to exploit heat from the HDR. A site in Fanton Hill, New Mexico was selected to develop the first-ever HDR geothermal project. The project was executed in three phases by drilling the different injection and production wells but the results show poor hydraulic conductivity between the wells [22]. From this project, Zhang and Zhao (2020) concluded that, in the field application of the HDR project, the production well should be drilled in the hydraulic fractured region after the installation of the injection well and hydraulic fracturing to establish a good hydraulic connection between wells [23].

In the year 1989, another HDR project was started in Ogachi, Japan. Three boreholes (OGC-1, OGC-2, OGC-3) were drilled up to 1017 m, 1100 m and 1300 m deep into the HDR. Initially, OGC-1 was drilled and stimulated at two locations and then OGC-2 was drilled in the stimulated region but failed to establish a good hydraulic connection between wells. Later OGC -3 was drilled and attained good hydraulic conductivity but reported a huge quantity of water loss [24].

In addition to the field studies, researchers also conducted numerical investigations to exploit the heat energy from the HDR. The numerical simulation is carried out to extract the geothermal energy by generating a fractured reservoir between two horizontal wells (Refer Fig. 1a). The analysis was conducted for the geological of the Desert Peak geothermal field [25]. The results showed an acceptable electricity production of 6.2 to 8.6 MW with an efficiency of 10.8 to 30.6. Chen and Jiang (2015) carried out a 3D numerical simulation to analyse the heat extraction from the HDR resource with the help of the doublet, triplet in a straight line, triplet in a triangular pattern (Refer Fig. 1b) and quintuplet [26]. The results indicated that the triplet in a triangular pattern with an injection wellbore and two production wells performed better than the other patterns. Song et al. (2018) proposed a multilateral well system connected to a single main vertical well [27]. The system contains multiple lateral injection wells and production wells with a fractured reservoir between them (Refer Fig. 1c). The study concluded that the multilateral well HDR system has a high heat extraction capacity.

The development of HDR geothermal projects involves huge challenges regarding the development of the fractured zone, attaining a good hydraulic connection between the wells, restricting the water loss and getting high thermal efficiency. The major hurdle to the establishment of HDR reservoir system is the high initial cost of the project in terms of drilling multiple wells to deeper depths and also the hydraulic stimulation process. Hence, many researchers proposed single well systems with heat exchangers to overcome these challenges [6, 28-30]



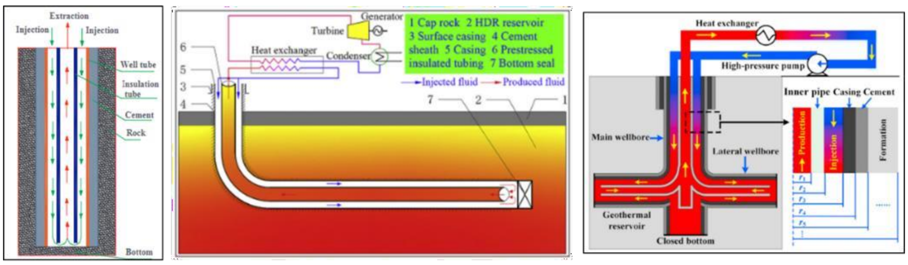
(a) (b) (c)

Fig. 1. (a) Two horizontal wells EGS [25] (b) Triplet with triangular pattern [26] (c) Multi-lateral well system [27]

4.2 Single Well System with heat exchanger

A single well geothermal system consists of a pipe heat exchanger installed in the wellbore to extract the geothermal heat from the HDR reservoir. This system does not require any hydraulic stimulation process, which ultimately reduces the initial cost and complexity of the EGS. The working fluid such as water is circulated inside the wellbore heat exchanger to extract the heat.

A Coaxial double pipe heat exchanger (CDHE) was installed inside the wellbore to extract the thermal energy by circulating the cold working fluid shown in Fig. 2a [6, 28]. Further, the CDHE performance was also analysed for the horizontal wells (Refer Fig. 2b) [29]. The results indicate that the horizontal well heat exchanger system provides better heat transmission between the working fluid and the formation due to the presence of a long horizontal flow path in the high-temperature reservoir. The heat transfer area is limited in both vertical and horizontal wells with the CDHE system. To increase the heat transfer area, Wang et al. (2021) proposed a vertical well connected to the multilateral wells with a coaxial double pipe heat exchanger (Refer Fig. 2c) to extract heat from the HDR [30]. The results concluded that the thermal capacity of the system increases by connecting more lateral wells to the vertical well. The thermal capacity for 6 lateral wells increased by 116% compared to the 2 lateral wells.



(a) (b) (c)

Fig. 2. HDR reservoir with CDHE (a) Vertical well [6] (b) Horizontal well [30] (c) Multi-lateral wells [31]

5 Effect of various parameters on the heat extraction capacity

The heat extraction capacity of the geothermal system will depend on many factors such as thermophysical properties of the reservoir rock, geothermal gradient of the formation rock, depth of the well, reservoir dimensions, inlet fluid temperature, flow rate, and type of the geothermal system etc. A 2D numerical simulation of a single well system with a CDHE is conducted to study the influence of some of the above-mentioned factors on heat extraction. The influence of well depth, geothermal gradient of the formation rock and rock thermal conductivity on the heat extraction from the HDR has been studied in the present analysis. The homogeneous rock strata with 288 K surface temperature and 0.07 K/m geothermal gradient is considered for the analysis. The thermophysical properties of the reservoir rock, heat exchanger and working fluid are considered from the available literature [31].

5.1 Numerical modelling

A 2D numerical model of a single well system with a CDHE is modelled in COMSOL Multiphysics 5.6 for heat extraction. The geometry and boundary conditions of the model are axially symmetric; hence the model is built as a 2D axisymmetric model with cylindrical coordinates (r, z), as shown in Fig. 3 a. The simmulation has been carried out by employing a conjugate heat transfer module with the turbulent k-ε model to extract the heat from the formation rock. The Non-isothermal flow multi-physics of the conjugate heat transfer module is used to couple the heat transfer and fluid flow inside the domain.

The domain consists of a CDHE with an outer steel casing of 0.18 m diameter and an inner tubing of 0.12 m diameter. The length of the heat exchanger has been considered equal to the depth of the wellbore. The heat exchanger is surrounded by the 200 m wide dry sedimentary rock strata to provide a sufficient buffer between the boundary conditions and the well domain. The dimensions of the rock strata are considered based on previous studies [32]. The analysis is carried out for 1000 m, 2000 m, and 3000 m deep wells with geothermal gradients ranging from 0.03 K/m to 0.1 K/m. The initial and operational conditions like inlet temperature, inlet flow rate, pressure, initial rock temperature, formation geothermal gradient and heat flux are taken as boundary conditions as shown in Fig. 3a.

5.2 Validation

The identification and validation of the numerical model is an essential step in the simulation process, as it demonstrates that the designed model can accurately represent the geological body and the coaxial wellbore heat exchanger system. The results obtained in the present analysis have been compared with the available literature to validate the numerical approach employed in this work [31]. The details of the geometrical parameters and operating conditions used for the validation are given in Table 1. The material properties considered for the present study are listed in Table 2. The triangular mesh has been used for the numerical simulations of heat extraction, as shown in Fig. 3b. The computational analysis has been carried out for a 1000 m deep well with various combinations of minimum and maximum element sizes to find out the optimum mesh size. It was noted from Fig. 4 that the outlet fluid temperature decreases with an increase in the number of elements up to 4.55 lakh elements and attains stability. This indicates that further refinement is not required as the results become independent of the number of grid points at a mess size of 4.55 lakh elements.

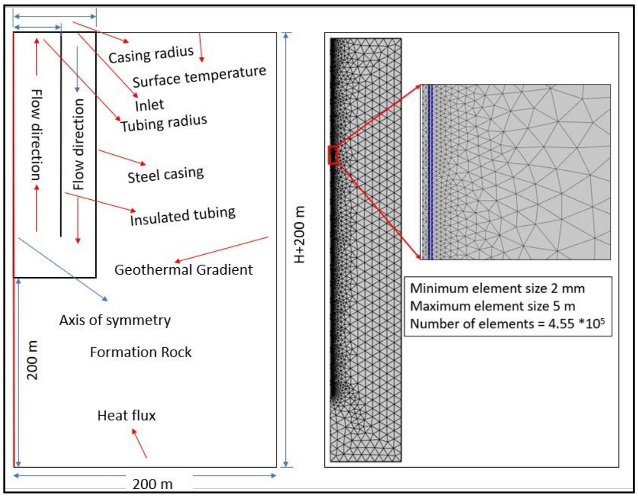


Fig. 3. Numerical modelling (a) Axisymmetric model domain (b)Triangular elemental mesh

Table 1. Geometrical and operational parameters [31]

S. No	Quantity	Value
1	Wellbore depth, m	1000 to 3000
2	Casing diameter, m	0.18 m
3	Casing thickness, m	0.01 m
4	Tubing diameter, m	0.12 m
5	Insulation thickness, m	0.01 m
6	Inlet mass flow rate, l/s	1 to 10
7	Inlet temperature, K	288
8	Surface temperature, K	288
9	Geothermal gradient, K/m or °C/m	0.07

Table 2. Thermo-physical parameters [31, 32]

Parameter	Rock	Casing	Water
Thermal conductivity, W/(m.K)	2.9	50	0.58
Density, kg/m^3	2600	7850	968
Specific heat capacity, J/(kg K)	824	475	4200

The results obtained from the present analysis are compared with the numerical simulation results of Caulk and Tomac (2017) for the same geometric and operational parameters with similar boundary conditions. The analysis has been carried out for 1000 m, 2000 m and 3000 m deep wells with various flow rates such as 1 l/s, 4.4 l/s and 10 l/s. The outlet temperature of the circulating fluid has been plotted against well depth for various flow rates, as shown in Fig. 5. The results obtained from the numerical analysis clearly exhibit good agreement with the results from previous literature**.**

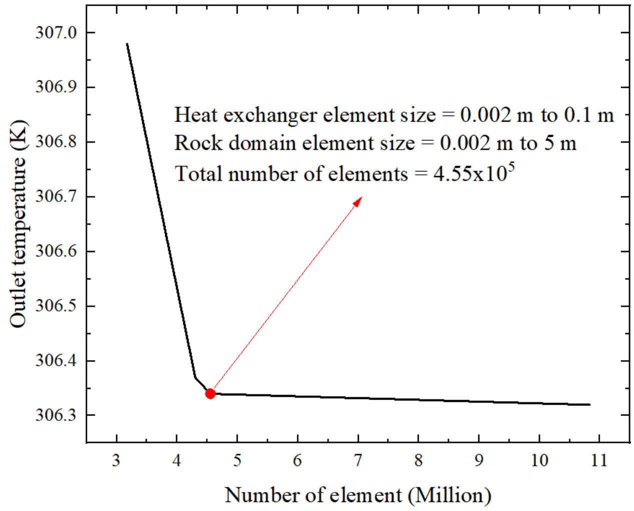


Fig. 4. Grid independence study for 1000 m length CBHE

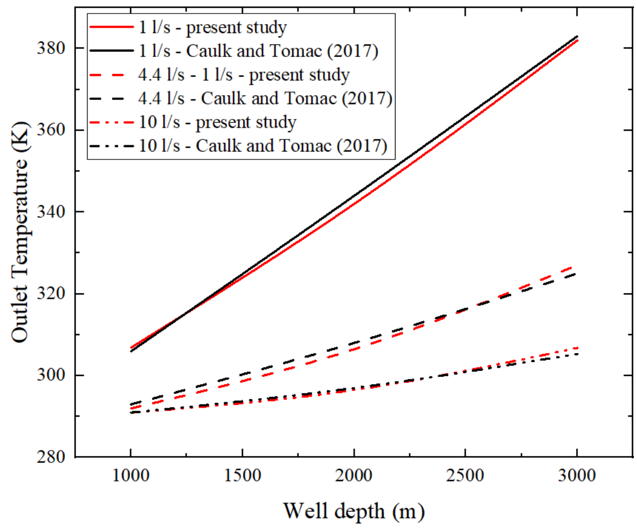


Fig. 5. Borehole heat exchanger outlet temperature for various well depths, mass flow rates at 0.07 K/m

6 Results and Discussions

The present study investigates the extraction of heat from the earth's crust with 1000 m, 2000 m, and 3000 m deep single well systems by means of the CDHE. To extract the heat, water at an initial temperature of 293 K is circulated inside the well with 1 kg/s mass flow rate. The CDHE with 0.18 m outer casing and 0.12 m inner tubing has been employed for the analysis. The thermophysical properties of the materials considered for the study are listed in Table 2. The results from the 2D axisymmetric finite element analysis are presented in Fig. 6. It was observed from the results that, the outlet temperature of the well with a 1000 m length of heat exchanger is equal to 309 K, whereas the well with a 3000 m length heat exchanger is attaining the outlet temperature of 382 K under the same geological and process conditions. It shows that the outlet temperature of the circulating fluid increases with an increase in the depth of the wellbore. This is mainly due to the increase in the temperature of the heat exchanger wall with an increase in the earth's crust depth at a constant inlet flow rate, the circulation time of the working fluid increases with increasing the well depth which ultimately leads to the increase in the outlet fluid temperature.

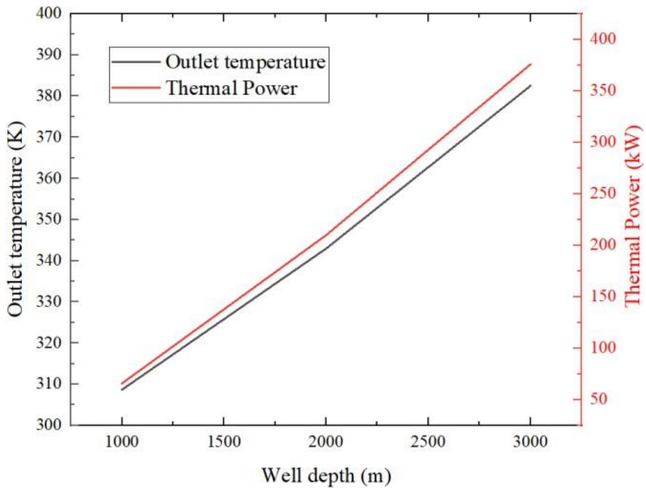


Fig. 6. Variation of outlet fluid temperature and thermal power with well depth

6.1 Effect of Geothermal Gradient

The geothermal gradient is the critical geological parameter that affects the heat extraction in the vicinity of the geothermal well. It indicates the quality of the thermal resources in a region. Various geothermal gradients between 0.03 - 0.1 K/m have been used in this work to investigate the influence of the formation of geothermal gradient on the thermal performance of the system. The variation of thermal power and fluid outlet temperature concerning the geothermal gradient is shown in Fig. 7. It has been noted that, with an increase in geothermal gradient, the thermal power and fluid outlet temperature also increase. This is due to the fact that a region with the higher geothermal gradient has higher temperature along the well facing and thus higher bottom hole temperature leading to the higher heat transfer. In the present study, the model with geothermal gradients up to 0.04 K/m are producing a maximum outlet temperature of 345 K, which can be utilized for direct heat applications. For a 3000 m deep wellbore, the thermal power and outlet temperature of the system with a 0.1 K/m geothermal gradient are 541.8 kW and 422 K, which is approximately 248 % and 162 % more than the thermal power and outlet fluid temperature of the system with the rock of 0.03 K/m geothermal gradient.

6.2 Effect of the Rock Thermal Conductivity

The thermal conductivity of the formation rock is another important geological parameter that can influence the location optimization of the geothermal system. The analysis is carried out for various thermal conductivities ranging from 2.5 to 3.5 W/(m.K). The results shown in Fig. 8 indicate that the thermal power and outlet fluid temperature of the system increases with an increase in the thermal conductivity of rock. For a 3000 m deep wellbore, the thermal power and outlet temperature of the system with 3.5 W/(m.K) thermal conductivity is 407.4 kW and 390 K, which is approximately 16 % and 13 % more than the thermal power and outlet fluid temperature of the system with the rock having a thermal conductivity of 2.5 W/(m.K).

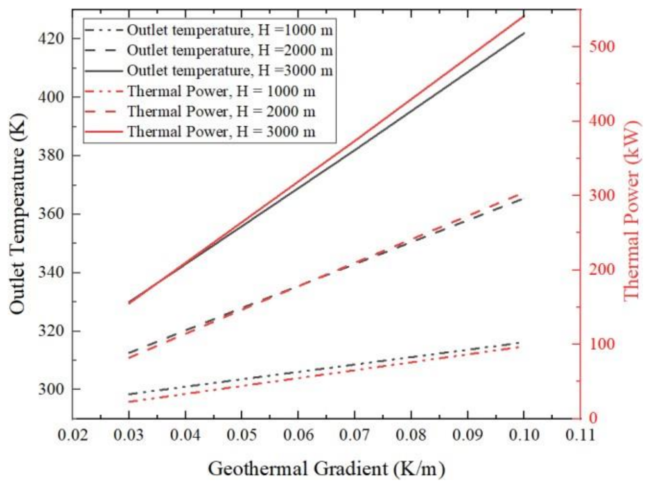


Fig. 7. Variation of outlet fluid temperature and thermal power with geothermal gradient

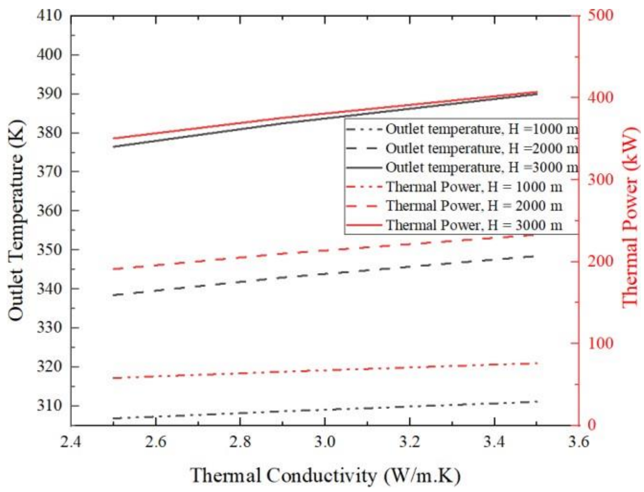


Fig. 8. Variation of outlet fluid temperature and thermal power with rock thermal conductivity

7 Conclusions

The Hot Dry Rock geothermal resources are widespread across the globe in an accessible depth with a capacity to replace fossil fuel energy sources. India has plenty of geothermal resources, which are sufficient to meet the country's primary energy requirements. The available information related to India's hydrothermal and HDR resources is limited. The existing HDR projects showed the complexity in achieving good hydraulic connectivity between wells. Hence, extensive research needs to be conducted on the exploration and exploitation of accessible hydrothermal and HDR resources.

The numerical analysis results indicate that the depth of the well, thermal conductivity of the formation rock and geothermal gradient have a greater influence on the thermal performance of the system. For a 3000 m heat exchanger, the thermal power and outlet temperature of the system with a 0.1 K/m geothermal gradient are approximately 248 % and 162 % more than the system with the rock of 0.03 K/m geothermal gradient. The reservoir with 3.5 W/(m.K) thermal conductivity yields approximately 16 % and 13 % more thermal power and outlet fluid temperature than the reservoir with 2.5 W/(m.K) thermal conductivity. Hence, these are the key geological parameters that need to be considered for the geological location optimization of the wells.

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