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Investigations of Geothermal Energy Production in Coal Fires Affected Jharia Basin, India

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ABSTRACT

The Jharia Coalfield in India holds significant potential for geothermal energy production due to the presence of high-temperature anomalies resulting from the ongoing coal fires. The persistent coal fires, which have plagued the Jharia basin since 1916, have posed grave threats to the environment and society and created unique thermal conditions. Borehole temperature logging data recorded in the field reveal a notably locally high geothermal gradient within the basin, around 40-45˚C/km. This study aims to harness the untapped thermal energy created by coal fires and convert it into usable geothermal energy. To achieve this, we employ a combination of analytical and numerical simulation techniques to assess the feasibility of extracting geothermal energy. Experimental determination of the thermo-physical attributes like the thermal conductivity and specific heat capacity of the rocks and the injection fluids (water/brines) is employed to enhance our simulations. The current study aims to stimulate the heat transfer process of the injection fluid through a coaxial wellbore in the vicinity of coal fires affecting the Jharia basin. The findings obtained under analytical and numerical simulations indicated the potential of extracting geothermal energy and largely dependent on the well operational flow rate and the geothermal gradient of the basin. Furthermore, the production temperature varied between 128˚F to 135˚F depending on the geothermal conditions, coaxial wellbore dimensions and the thermal characteristics of the injection fluids and the rock formations. The study would enable a comprehensive understanding of the performance of the coaxial wellbore for geothermal energy extraction and pilot-scale operations in the Jharia basin.

1. INTRODUCTION

Worldwide coal fires are a crisis. Renewable energy sources must be used as clean substitutes for the ecologically harmful fossil fuel energy sources in order to reduce greenhouse gas emissions and other environmental harm. Considerable economic loss and environmental problem arises due to the widespread distribution of coal fires in the coal producing countries. The prime example is the burning coal seams of the Jharia coalfield for many decades. Thermal energy due to coal fires is stored underneath which can be tapped to extract heat and produce energy. Globally, coal fires mines are being transformed or studied to produce green energy in the form of geothermal energy (Chiasson et al., 2007; Deng et al., 2020; Shi et al., 2017; Tang et al., 2018). Exploring the extraction of heat from the high-temperature reservoirs could be an alternative in coal fires affected regions. Geothermal energy emerges as a potential solution to reduce reliance on fossil fuels and move towards achieving net-zero emissions. The Jharia basin in India, the sole depository of prime coking coal is infamous for its extensive coal fires, originating from the first outbreak in 1916. The coal fires in Jharia basin mainly ignited from spontaneous combustion, and also influenced by the presence of faults in the area. This work is an first attempt to utilize the wasted heat in the basin and produce a continuous supply of green energy as geothermal energy. The study included an analytical and numerical approach to determine the wellbore outlet temperature in Jharia basin, The present study involved the experimental determination of thermo-physical properties of rocks and fluids, sub-surface temperature variation maps from geophysical logging data of eleven wells, to identify the potential hotspot for geothermal exploration and production in the basin.

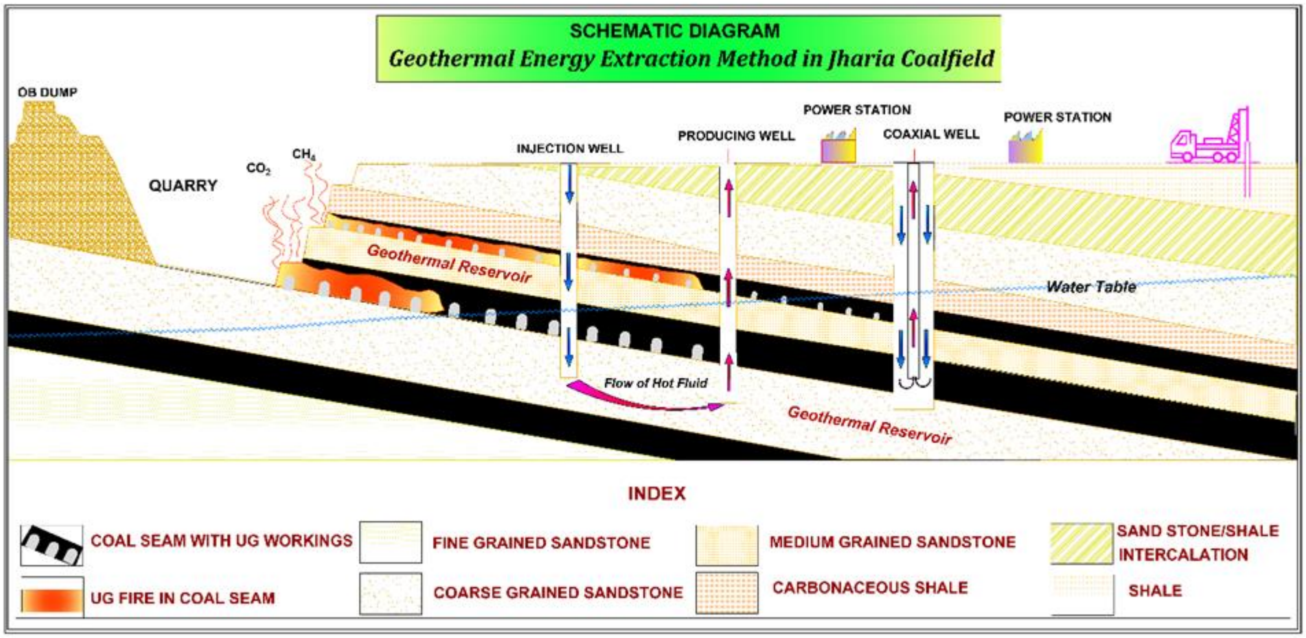


Figure 1: Schematic diagram explaining the release of poisonous greenhouse gases (CO_2. CH_4, etc) to the atmosphere through spontaneous combustion in the coal seams and the geothermal energy technology of coaxial wellbore design (closed loop system) and injecter-producter wellbore design (open loop system) to extract the wasted heat for energy production

GEOLOGICAL SETTINGS AND STUDY AREA

The Jharia Coalfield (JCF) extends over a region of about 450 km^2 from 23˚37′N TO 23˚52′Nto 86˚06′E to 86˚30′E is located in the Singbhum Craton in the Dhanbad district of Bihar. Geologically, the JCF is a sickle-shaped basin, extending bout 19km in N-S direction and 38km in E-W direction, and is deposited in a half graben structure (Basu and Shrivastava, 1981)and its southern boundary is demarcated by a fault zone.

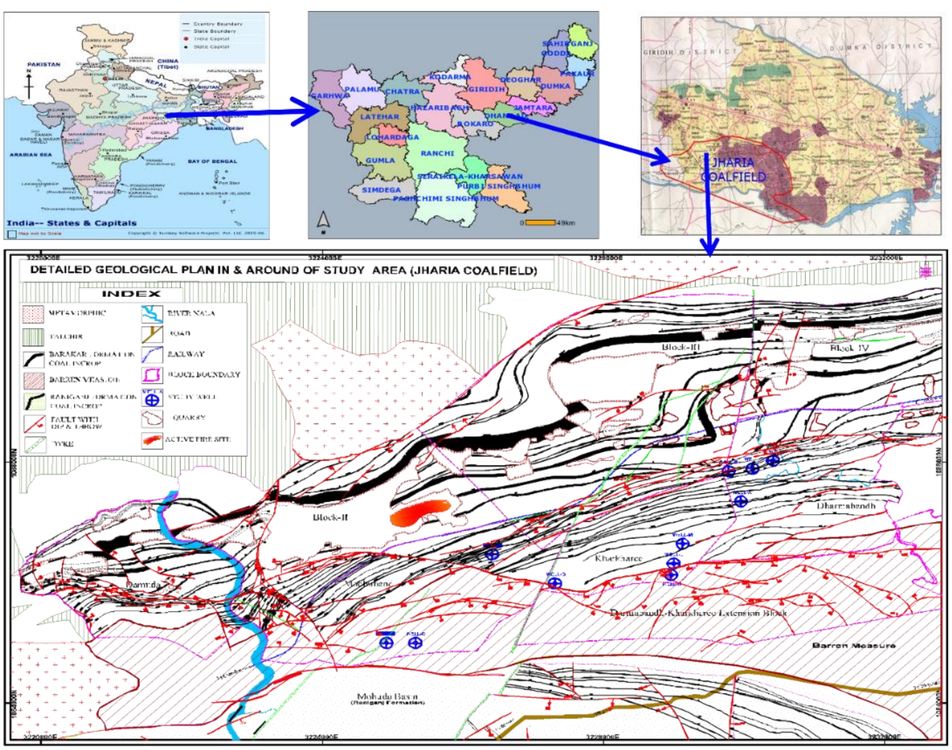


Figure 2: Geological Plan indicating the location of Jharia basin in India and location of geophysical logging wells and active fire site in the Jharia basin.

The JCF basin is an half graben structure, with normal faults varying from NW-SE to NNE-SSW, and the basin profile suggests fault-controlled subsidence. The sedimentary succession of the Jharia basin unconformably lies over the Archaean basement beginning with Talchir Formation, followed upwards by sediments of Barakar, Barren Measure, and Raniganj Formation deposited within an intracratonic extensional setting**.**

The structure of the JCF is a gently plunging syncline with a regional E-W to NW-SE strike and having a gentle dip of about 3-8˚ towards South. The sedimentary lithotypes belong to the Gondwana Supergroup are of Permo-Carboniferous age. The generalised stratigraphic succession is described below:

Table 1: A generalised stratigraphic table of Jharia coalfield (after Chandra, D, 1992)

Age	**Formation**	**Lithotype**	**Maximum thickness**
Jurassic	Igneous Intrusives	Dolerite dyke	
Lower Jurassic	Igneous Intrusives	Mica Peridotite sills and dykes	
Upper Permian	Raniganj	Fine grained feldspathic sandstone, medium to coarse grained sandstone, shale, carbonaceous shale and coal seams	840 m
Middle Permian	Barren Measures	Massive buff colored sandstone, grey shale, carbonaceous shale with or without very thin lenses of coal	625 m
Lower Permian	Barakar	Buff colored medium and coarse grained sandstone, grits, shale, carbonaceous shale, siltstone and coal seams	1250 m
Upper Carboniferous	Talchir	Greenish shale, very fine grained sandstone, sandy shale, conglomerate and basal tillite.	245 m
Unconformity			
Archean	Metamorphic Basement	Granite gneiss, mica schist, quartzite, amphibolite	

The Jharia basin with an estimated coal-bearing area of 350 km^2, vary from medium to high volatile sub-bituminous to bituminous range coal containing 0.13% to 2.81% of moisture, 12.0% to 26.63% of fixed carbon (Karmakar et al., 2013). Surface and sub-surface fires burning through out the Jharia coalfield, comprise one of the largest coal mine-fire complexes in the world (Prakash and Gupta, 1999). The Jharia basin is a hometown for naturally occurring fire within in situ coal seam or in stored coal. Coal is primarily composed of carbon, owing to its inherent property to self–ignite and undergo spontaneous combustion (Feng et al., 1973), has been posing a serious threat to the environment and the society for more than a century. Coal has been the prime source for power generation in India for thousands of years, but the haphazard manner of mining activities led to uncontrolled coal fires in Jharia coalfield. All most
all the coal mine fires ignited due to spontaneous combustion are restricted to the Barakar Formation where major coal producing seams are exposed.

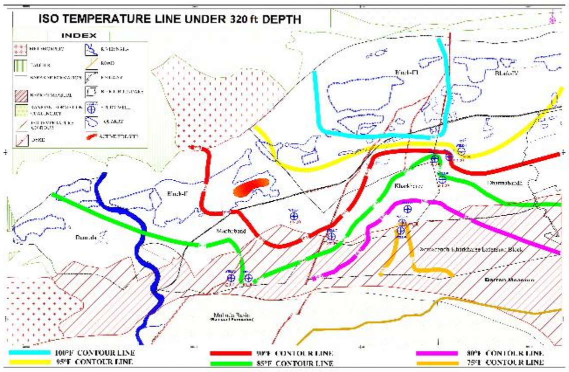
Jharia basin is rich in coal resources, both coking and non-coking type. High surface temperature are resultant of the spontaneous combustion in the coal seams which dissipates the heat to the surface. The coal fires are controlled by the faults as seen in the map (*Figure 1*) and their spatial distribution and subsequent temperature variation at surface and sub-surface depths presented in later section of this paper. The marked circles in the map, are the location of eleven geophysical logging wells in the basin and an active fire site located nearby the wells is also shown in the Map as shown in the Figure 2.

The study area located in the north-western quadrant of Jharia coalfield. The studied wells are mainly located in the Madhuband, Kharkharee and Dharmaband geological blocks of Jharia coalfield. From mining point of view, the above mentioned three blocks are basically underground potential and these blocks are separated from the northern site opencast blocks namely Damuda, Block-II, Block-III, Block-IV etc., by Dhanbad-Chandrapura Railway line. Geologically the study area covered up by the rocks of Barakar formation whereas smaller portion of Barren Measure outcrops in the south of the study area. Structurally, the rocks trending broadly towards NE-SW direction and dips towards SE direction. General dips of the beds range between 8° to 12°, however, the dip may increase upto 30° in the vicinity of major faults.

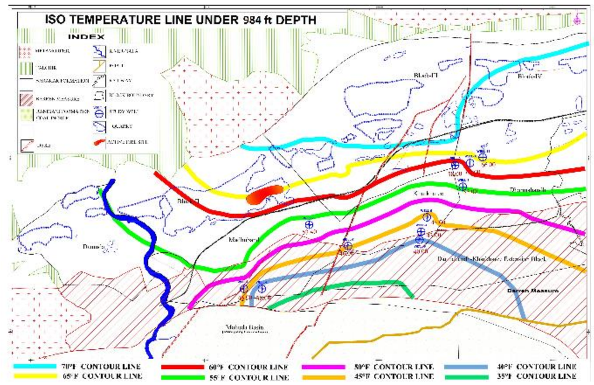
The area dissected by NE-SW trending several dolerites dykes, whereas as sills of mica peridotites has been reported from the association with many coal seams in the area. The area dissected by numerous normal faults of various geometry having throw ranges from 5m to 650m. Dip of these faults ranges between 60° to 70°.One of the major fault having maximum throw of 650m passes towards E-W direction and located almost in the middle of the study area. Almost 40 major Barakar coal horizons which area mostly coking in nature, have been reported in the study area. Total cumulative thickness of these seam are around100m whereas total thickness of Barakar formation is around 1000m. As per normative stratigraphic order, these seams have been named from XVIII to I. Generally upper seams like XVIII to XI/XII are extensively worked by underground methods within the study area. Presently most of the mines are temporarily suspended and most of the worked seams are waterlogged whereas few are affected by underground fire.

3.0 Methodology

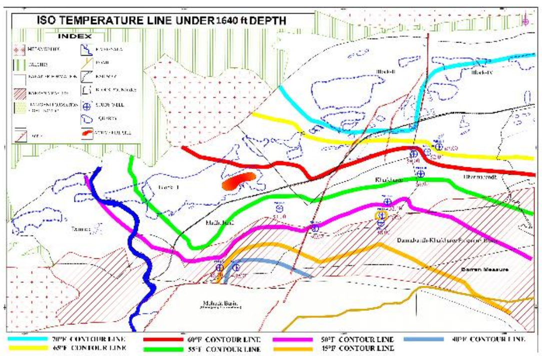
(a) Iso-Temperature Map at 320 ft depth



(b) Iso-Temperature Map at 984 ft ft depth



(c) Iso-Temperature Map at 1640 ft depth map



(d) Iso-Temperature Map at 2625 ft ft depth

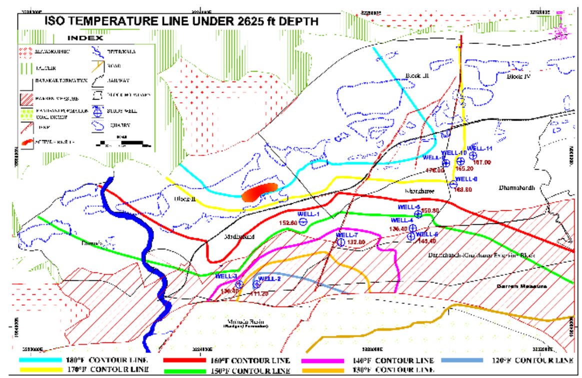


Figure 2: Iso-Temperature Map generated at surface, 320 ft , 984 ft, 1640 ft and 2625 ft depth in Jharia basin

Borehole geophysical logging conducted in the study area obtained temperature logs to determine the sub-surface temperature variations in the basin. Sub-surface temperature value obtained from the geophysical logging has been plotted at various depth interval i.e. at 100 m, 300m, 500 m depth. Surface temperature variation is mainly due to the dynamics of coal fires in the Jharia basin. Sub-surface temperature maps generated to visualize and understand the anomalous temperature variations in the basin. Contour map for the same has been generated in QGIS and MINEX software and shown in *Figure 2*. From the contour plan, it is observed that, there is an increasing trend of geothermal gradient/sub-surafce temperature towards the North, i.e. in the direction of open cast region within the study area. It can also be inferred that relatively higher sub-surface temperature values reflected in the map at comparatively shallower depth i.e, at 320 ft depth. This observance of higher sub-surface temperature at shallower depth may be related to underground fires, which has been observed at different quarries in the region. This anomalous nature of high local thermal gradient in the basin is mainly due to the spontaneous combustion in the basin.

The thermo-physical properties(thermal conductivity and specific heat capacity) of rock formations (Sandstone and Coal) and fluids is experimentally determined. The thermal conductivity is calculated using TEMPOS Sensors (*KS-3*, *RK-3*) for rocks and fluids shown in and incorporated in the simulations. The specific heat capacity for rocks and fluids (*DW*, *3% KCl* brine) is determined using NETZSCH DSC 204F1 Phoenix. The experimentally determined thermal conductivity of dominant rock strata (sandstone and coal) in the basin and injection fluids are presented in the below *Figure 3*.

(a) Coal and Sandstone

(b) 3% KCl Brine and DW

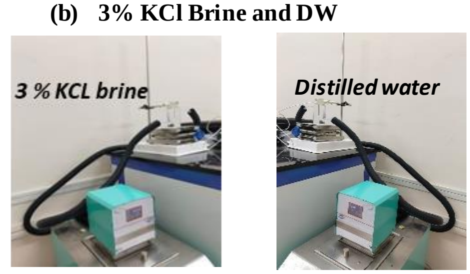


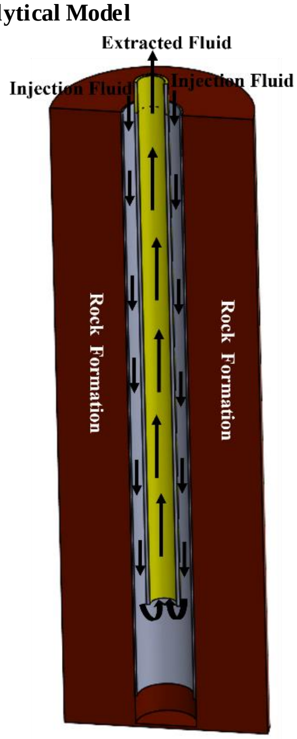
Figure 3: Experimental determination of thermal conductivity of rocks (sandstone, coal) and brines (distilled water, 3% KCl)

Table 2: Thermo-Physical properties of rocks and fluids in the study

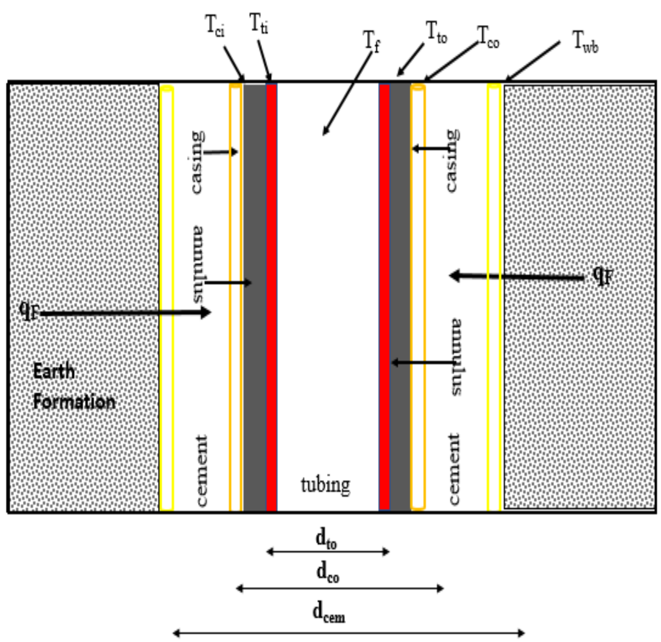
Sample	Thermal Conductivity (W/m.K)	Specific Heat Capacity (BTU/ lb.˚F)
3%KCl Brine	0.556	0.8598
Distilled Water (DW)	0.541	1.0032
Rock Formation (Sandstone)	2.42	0.2388
Rock Formation (Coal)	0.46	0.3105

In geothermal systems, the wellbore's structure and the underlying rock formation's geological characteristics determine how heat flows through the well at different flow rates producing different outlet temperatures for energy generation. The pioneering work on the wellbore heat transfer process (Hasan et al., 1996; Hasan and Kabir, 2012; Ramey, 1962; Raymond, 1969) provided solutions for fluid circulation through inner pipe and exiting through the annulus (forward circulation); fluid circulation through annulus and exiting through the inner pipe (reverse circulation). The present study considers the reverse circulation fluid flow process through the wellbore in the Jharia basin. The analytical solutions based on the earlier work (Kabir et al., 1996) is compared with the transient numerical solutions based on the recent work (Abdelhafiz et al., 2020) for a geothermal well in Jharia basin. The schematic diagram explaining the mechanisms of wellbore heat transfer in the analytical and numerical approach adopted in this study is shown in *Figure 3*. A single coaxial vertical wellbore is considered with the pipe dimensions (*O.D*: 0.55 ft, *I.D*: 0.42 ft), with a geothermal gradient (g_G: 0.055˚F/ft) for an 1850ft wellbore depth operating at a flow rate of 5 gpm (gallons per minute) for a circulation time of 24 hrs.

(a) Analytical Model



(b) Schematic of wellbore heat transfer process in analytical model



(c) Numerical Model **(d) Schematic representation of the numerical model**

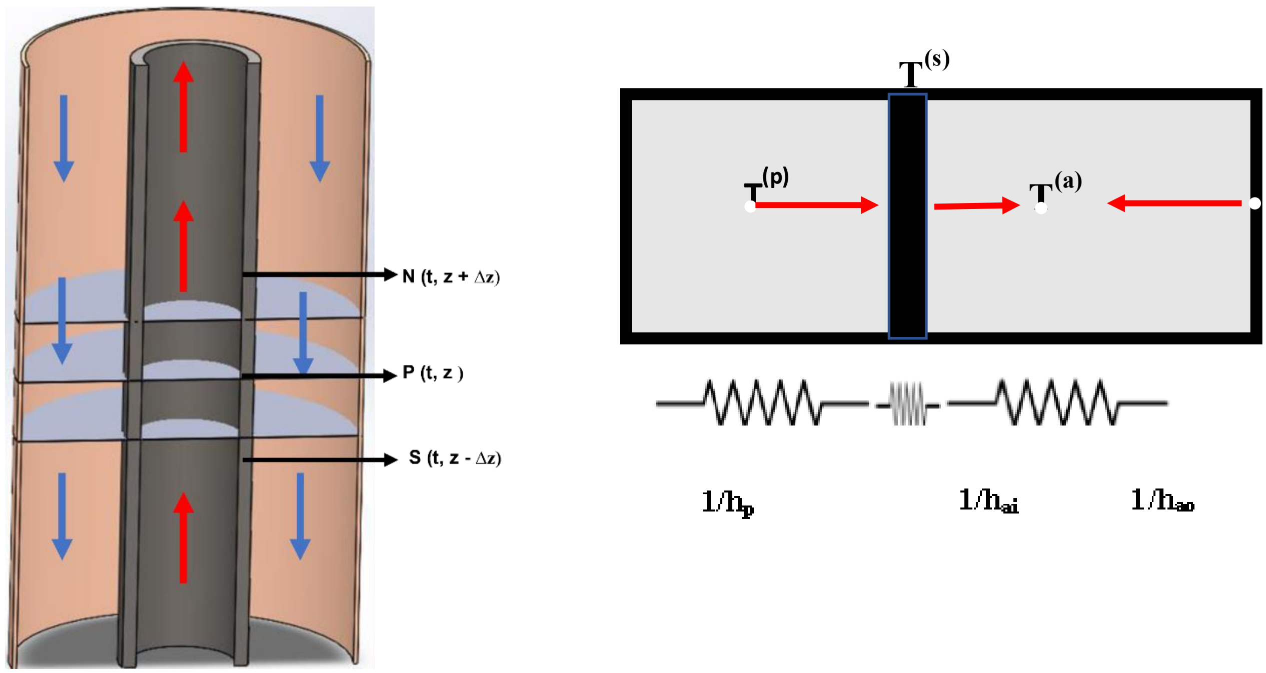


Figure 3: Schematic representation of wellbore heat transfer process in analytical model and numerical model for Jharia basin

Analytical Solution

The steady state analytical solutions for the reverse circulation process is given below:

$$T_t = \alpha e^{\lambda_1 z} + \beta e^{\lambda_2 z} + g_G z + Bg_G + T_{es} \quad 1$$

$$T_a = (1 - \lambda_1 B)\alpha e^{\lambda_1 z} + (1 - \lambda_2 B)\beta e^{\lambda_2 z} + g_G z + T_{es} \quad 1$$

where T_t represents the tubing temperature in °F, T_a the annular temperature in °F, g_G the geothermal gradient in °F/ft, z refers to the wellbore depth, and α , β , λ_1 , λ_2 are constants.

Numerical Solution:

At each time step, the wellbore is discretized vertically, and the three numerical solutions for each circulation are explicitly calculated before being simultaneously computed. This is done before the wellbore is vertically discretized. After switching the direction of the circulation, a higher temperature was observed at the output. For fluid flowing down the tubing, considering a space step size, Δz and time step, Δt, the numerical solutions based on the work (Abdelhafiz et al., 2020) is provided below:

(a) For fluid in the tubing:

2

$$T_P^p = T_P^{(p)0} - \frac{2h_P\Delta t}{r_{p,i}\rho_f c_{p,f}}\left(T_P^{(p)0} - T_P^{(s)0}\right) - \frac{u_z\Delta t}{\Delta z}\left(T_P^{(p)0} - T_S^{(p)0}\right) + \frac{k_f\Delta t}{\Delta z^2\rho_f c_{p,f}}\left(T_N^{(p)0} + T_S^{(p)0} - 2T_P^{(p)0}\right)$$

(b) For fluid in the annulus:

$$T_P^{(a)} = T_P^{(a)0} - \frac{2h_{a,i}r_{p,o}\Delta t}{(r_a^2 - r_{p,0}^2)\rho_f c_{p,f}}\left(T_P^{(a)0} - T_P^{(s)0}\right) - \frac{2h_{a,0}r_a\Delta t}{(r_a^2 - r_{p,0}^2)\rho_f c_{p,f}}\left(T_N^{(a)0} - T_P^{(r)0}\right) - \frac{u_z\Delta t}{\Delta z}\left(T_N^{(a)0} - T_P^{(a)0}\right) + \frac{k_f\Delta t}{\Delta z^2\rho_f c_{p,f}}\left(T_N^{(a)0} + T_S^{(a)0} - 2T_P^{(a)0}\right) \quad (3)$$

(c) For tubing thickness:

$$T_P^{(s)} = T_P^{(s)0} - \frac{2h_{p,i}\Delta t}{(r_{p,0}^2 - r_{p,i}^2)\rho_f c_{p,s}}\left(T_P^{(s)0} - T_P^{(p)0}\right) - \frac{2h_{a,i}r_{p,0}\Delta t}{(r_{p,0}^2 - r_{p,i}^2)\rho_f c_{p,s}}\left(T_P^{(s)0} - T_P^{(a)0}\right) - \frac{u_z\Delta t}{\Delta z}\left(T_N^{(a)0} - T_P^{(a)0}\right) + \frac{k_s\Delta t}{\Delta z^2\rho_f c_{p,f}}\left(T_N^{(s)0} + T_S^{(s)0} - 2T_P^{(s)0}\right) \quad (4)$$

where T_P^p is the fluid temperature (˚F) in the inner tubing, $T_P^{(a)}$ is the fluid temperature (˚F) in the annulus and $T_P^{(s)}$ is the tubing pipe thickness temperature (˚F), h_p is the convective heat transfer coefficient (BTU/hr.ft^2.˚F) for the flow inside the tube; h_{ai} & h_{a0} is the convective heat transfer coefficient (BTU/hr.ft^2.˚F) for the flow inside and outside the annulus; k_f is the thermal conductivity (BTU/hr.ft.˚F) of the fluid, $r_{p,i}$ & $r_{p,0}$ is the inner and outer tubing radius (ft), r_a is the radius (ft) of the annulus, ρ_f is the fluid density (lb/ft^3), $c_{\rho,f}$ is the fluid specific heat (BTU/lb˚F) and u_z is the average fluid velocity (ft/s) inside the tubing.

(a) analytical solution for 1850 ft wellbore   (b) numerical solution for 1850 ft wellbore

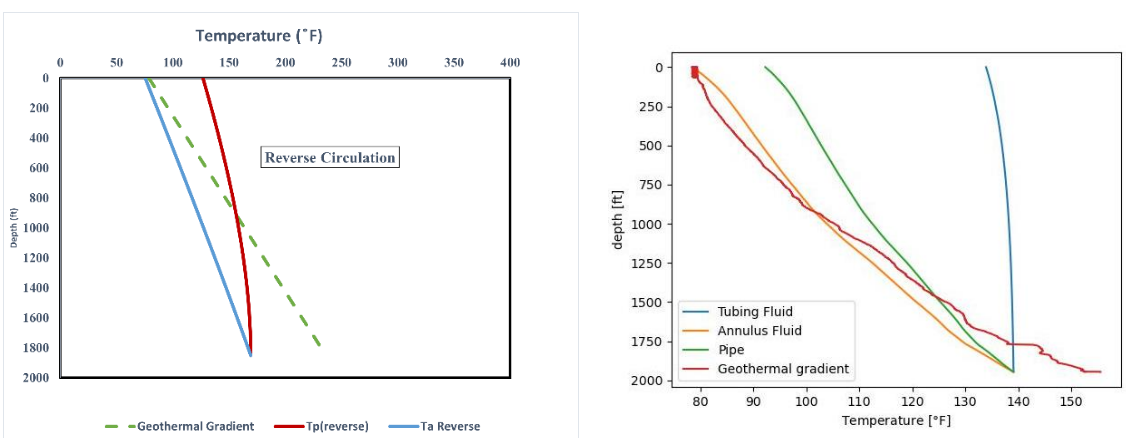


Figure 5: (a) Temperature profile of reverse circulation using analytical solutions for an 1850 depth well at 5 gpm at an constant gradient of 0.055˚F/ft for 24 hrs (b) Temperature profile of reverse circulation using numerical solutions for an 1850 depth well at 5 gpm for a transient geothermal gradient for 24 hrs

4.0 Results and Conclusions

The geothermal simulations that were performed in the current study to investigate the effect of coal fires for geothermal energy extraction demonstrated the variation of fluid temperature in a wellbore. The result obtained through analytical solutions from Equation **Error! Reference source not found.**. and Equation *1* produced an outlet temperature of ≈128˚F shown in *Figure 5(a)* for a linear geothermal gradient of 0.055˚F/ft for an 1850 wellbore depth and for a circulation time period of 24 hrs.

The numerical solutions utilizing Equation *2*, Equation 3 and Equation *4* for a single vertical wellbore in Jharia coalfield produced an outlet temperature of ≈135˚F demonstrated in *Figure 5(b)* for a transient geothermal gradient for a circulation time of 24 hrs. The temperature profiles generated from reverse circulation are analysed, and so is the impact that wellbore operating parameters have on those temperature profiles.

The economic limitations on geothermal energy as per literature studies, the development of geothermal energy covers a very wide range of capacities—from shallow, single wells for which heat pumps are used, to multiple injection-production wells as in the case of super hot rock system. Correspondingly, the range of costs for research, evaluation, development, operation and decommissioning is also very wide.

Critical to the advancement of the field at this stage is the development of datasets from experiments of geothermal reservoir rock, pilot scale studies that are promising enough to be used for geothermal field development. Such extensive pilot scale and experimental studies could pave the way for designing of fluids and wellbore infrastructure that can achieve the heat transfer and thus geothermal energy production objectives while making robust predictions of risk and long term performance of Jharia coalfield as hotspot of geothermal reservoir in India as a stepping stone towards green energy.

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