PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 13-15, 2017
SGP-TR-212

Utilization of Abandoned Coal Mines as a Low Enthalpy Geothermal Resource and Subsequent Energy Exploitation

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Keywords: Renewable Energy, Geothermal Energy, Abandoned Coal Mines, Energy Exploitation

ABSTRACT

Renewable Energy Investment triggering a debate on clean energy Vs conventional energy. The house of conventional energy i.e. Coal Mines which are abandoned can be serve as a green and clean energy option for the world. Abandoned and flooded coal mines have good potential as low enthalpy geothermal resources, which could be used for small to medium scale power generation and for heating and cooling purposes. The paper describes the exploitation strategies of geothermal energy from abandoned coal mines. In India, the average depth of coal mines is varying from 100 meter to 1500 meter. At this depth, there is an intense heat exchange between the rocks of the caved rock mass and the mine water. This arrangement forms an eco-system similar to that of a geothermal system. The surface temperature of the abandoned coal mines varies from 35 ^{0}C to 95^{0}C for thermal springs and 20 ^{0}C to 25 ^{0}C for cold springs. The reservoir temperature is in the range of 120 ^{0}Cto 260 ^{0}C, which favors low to medium enthalpy geothermal reservoirs. Both thermal spring and cold spring can be utilized for direct and indirect applications of geothermal energy. The paper also describes the utilization of thermal source using Organic Rankine Cycle (ORC) for production of electricity. A simulation program has been developed in EES for the calculation total power through the ORC system. The results have been calculated by changing evaporator temperature & pressure ratio and observing the effects on other parameters. A trade-off is done to select the working fluid among turbine outlet volume flow rate, volume flow ratio, network output, first law efficiency, total irreversibility and second law efficiency of the system. This paper critically reviews implementation of this low to medium enthalpy geothermal energy recovery strategy from the abandoned coal mines of the central parts of India Son-Narmada-Tapti belt.

1. INTRODUCTION

Abandoned and flooded mines present a huge potential for geothermal energy and utilization of low temperature water from remaining underground spaces. Water cut in many mature coal fields is very high, up to almost 98%. The produced water is usually considered a nuisance to coal producers because it is required to dispose or re-inject the water into reservoirs. This process costs a lot and reduces the net profit value of the coal producers. The water produces from the coal mines at low to medium enthalpy range. The surface temperature varies from 350 ºC to 1000 ºC and reservoir temperature varies from 120 ºC to 200 ºC. This water can be utilized for low to medium enthalpy geothermal reservoirs. In addition to that, there are many other sources of heat in underground mines. Some of them are major contributors of heat addition and some of them are minor contributors to heat addition MNRE, (2014). The major sources of heat in underground mines are:

1. Strata heat
2. Auto-Compression
3. Underground water

The minor sources of heat in mines include (Vutukuri and Lama, 1986)

1. Human metabolism
2. Oxidation
3. Blasting
4. Rock movement
5. Pipelines
6. Energy losses in airflow

The paper mainly focuses on geothermal exploitation of coal mines. In mines, we generally make use the term geothermal step which is defined as the depth per degree centigrade rise in temperature. The geothermal step is the inverse of geothermal gradient.

$Geothermal\ Gradient = \Delta T/\Delta Z$ ℃/m and $geothermal\ step = \Delta Z/\Delta T$ m/℃ ΔT = Change in temperature (℃) ΔZ = Change in depth (m)

Both geothermal step as well as geothermal gradient may vary from place to place depending upon the types of the rocks found in the area, thermal properties of the rock, presence of underground water reservoirs, etc. It is also greatly influenced by the age of the rock, and igneous activities going in the region. At around 100 ft to 300 ft depth from the earth surface, temperature is constant, as at this depth, there will be no significant variation of temperature with the change in the climatic conditions observed on the surface of the earth. After approximately 300 ft, it starts showing a uniform increase in the temperature with depth at a particular place. Table 1 gives a brief idea about the variation of geothermic gradient in different mine districts of the India

Table 1 Geothermal Gradient in Coal Mines, India (Banerjee, 2003)

Location	**Geothermic Gradient (m/°C)**
Jharia Coalfield, India, Coal Measure Rocks	17.2-39
Raniganj Coalfields, India, Coal Measure Rock	38.4
Sigareni Coalfield, India, Coal Measure Rocks	30
Kolar Gold Field, India	91.1
Mosabani Copper Mine, India	50-54.8

2. GEOTHERMAL POSSIBILITIES IN INDIA'S ABANDONED COAL MINES

Talking about the central part of India, a huge potential of geothermal energy has found out in these region i.e Son-NarmadaTapti (SONATA) geothermal province. Most part of Son-Narmada –Lineament zone falls in the state of Madhya Pradesh, Jharkhand, and Chhattisgarh. Major geothermal sites are located at Tattapani, Salbardi, Surajkund and Bakreswar sites. The surface temperature of the SONATA belt varies from 30 °C to 93 °C for the thermal springs and 24 °C to 25 °C for the cold springs. The estimated reservoir temperature based on chemical geothermometers is in the range of 132 °C to 265 °C, which favors a medium enthalpy geothermal system MNRE, (2014).

In India, total 574 coal mines have been drilled till date. The total coal productions from the mines are 550 MT tones per year out of which 240 abandoned mines where no reclamation takes place. Indian Bureau of Mines (IBM) had identified 82 abandoned mines out of which 42 mines are under the SONATA lineament zones which are potential locations for geothermal exploitations in the state of Madhya Pradesh, Chhattisgarh and Jharkhand. Godavari provinces also include 8 abandoned mines in the state of Andhra Pradesh and hence can be utilized for power production. Also abandoned and flooded mines have potential which can be utilized for low grade geothermal applications such as space heating and cooling, crop cultivation and fish farming Khanna,(2013).

3. ENERGY ESTIMATION FROM INDIAN COAL MINES

In this work, the "geothermal potential" of a mine is the total amount of geothermal energy or geothermal power which can be utilized from this mine. It is easy to understand that one of the factors influencing geothermal potential is the volume and characteristics of the voids created by mining activity (*i.e.*, these voids can be stable in the long run and remain open, or they can cave in immediately and be filled with rock debris). This value is directly related to coal output. Our goal is to relate the present geothermal potential of an underground coal mine with the total saleable coal production yielded by the mine through its operation history. The main advantage of this proposal is that the coal output of a mine is a well-known parameter, which is always easy to find because it has been recorded over the years by public administration. On the other hand, wide coal mining experience helps us to establish an easy-to-use method .Diez and Aguado, (2014).

Thus, a simple formula is proposed:
$W_t \approx k \times PT$
Where W_t is the value for geothermal power of the mine in MW thermal (MWt);
PT is the total saleable coal production in millions of tonnes (MT);
(Total Saleable quantity in India is 15000 MT)
K is the factor of proportionality which has to be estimated empirically.
Where $K_{min} \approx 0.25$ and $K_{max} \approx 1$.

Table 2 Total Energy Obtained From Indian Geothermal Mines

Sr. No	Production in Million Tonnes	Proptionality factor	Geothermal Power (MW)
Case 1	7500	0.25	1875
Case 2	7500	0.50	3750
Case 3	7500	0.75	5625
Case 4	7500	1	7500

Therefore, average expected geothermal energy extracted from abandoned coal mines will be around 7500MW which is equivalent to 375000 MW of solar PV/thermal

4. LOW TEMPERATURE WATER HEAT RECOVERY TECHNOLOGY

Increasingly, low-temperature resources once used predominantly for direct use applications such as heating, fisheries, and industrial processes can now also be used for power generation in suitable conditions. Low-temperature technologies have the potential to utilize geothermal resources from across the nation, expanding geothermal power potential using various low temperature sources DiPippo R., (2008). Organic Rankine Cycle (ORC) is one such technology which utilizes for power production from low enthalpy geothermal reservoirs. ORC generators pressurize various working fluids which drives the expander to produce electricity. The expander is unique in its configuration, lubrication, and specifications, but uses reliable, proven compressor technology that has existed for more than 20 years. After the working fluid expands across the expander (spinning a generator) the low-pressure vapour must be condensed to a liquid to begin the cycle again Sircar et al. (2016).

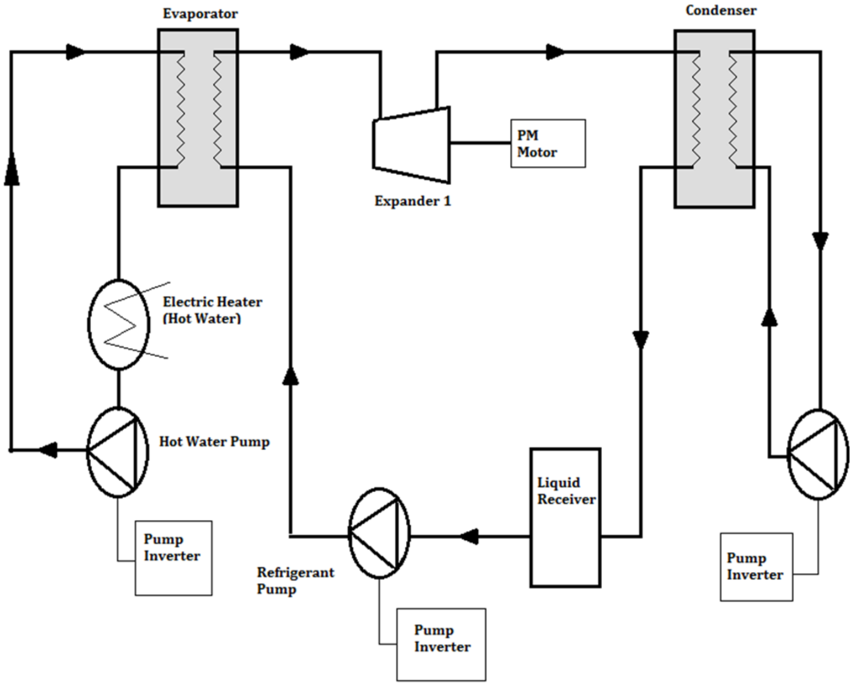

Figure 1: A Schematic of Organic Rankine Cycle Baral et al.(2015)

5. SYSTEM MODELING FOR ORGANIC RANKINE CYCLE

First and second laws of thermodynamics are used to evaluate the performance of ORC system for different preliminary screened working fluids. Internal irreversibility and pressure drops in evaporator, condenser and pipes are ignored. First and second laws of the thermodynamics are applied for each component Dincer and Rosen (2013). Equations so obtained are summarized below.

The pre-described ORC system was simulated by developing the code using the Engineering Equation Solver (EES). The following assumptions were made when analyzing the sub-system and overall system:

(a) All the thermodynamic processes are in the steady state.
(b) The pumps and scroll expander are adiabatic devices.
(c) The pressure drops in the evaporator and condenser can be neglected because negligible pressure occurs in any of the ORC devices.
(d) The dead state temperature and pressure are 25 °C and 1 bar (atmospheric pressure) respectively.

$$e_n = (h_n - h_0) - T_K * (s_n - s_0) \tag{1}$$

$$s_{gen} = s_f - s_i \tag{2}$$

Evaporator:

$$\dot{Q}_{in,e} = \dot{m}_{gf} * c_{gf} * \left(T_{in,e} - T_{out,e}\right) \tag{3}$$

$$s_{gen,e} = \dot{m}_{gf} * (s_6 - s_5) + \dot{m}_{of} * (s_1 - s_4) \tag{4}$$

$$I_e = T_K * s_{gen,e} \tag{5}$$

Turbine:

$$\dot{W}_t = \dot{m}_{of} * (h_1 - h_2) \tag{7}$$

$$s_{gen,t} = (s_2 - s_1) * \dot{m}_{of} \tag{8}$$

$$I_t = T_K * s_{gen,t} \tag{9}$$

Condenser:

$$\dot{Q}_{out,c} = \dot{m}_{of} * (h_2 - h_3) \tag{11}$$

$$s_{gen,c} = \dot{m}_{of} * (s_3 - s_2) + \dot{m}_{cf} * (s_8 - s_7) \tag{12}$$

$$I_c = T_K * s_{gen,c} \tag{13}$$

Pump:

$$w_p = v_3 * (P_e - P_c) \tag{15}$$

$$s_{gen,p} = (s_4 - s_3) * (\dot{m}_{of}) \tag{16}$$

$$I_p = T_K * s_{gen,p} \tag{17}$$

Total Irreversibility:

$$I_{total} = I_e + I_t + I_c + I_p \tag{19}$$

Net work output:

$$\dot{W}_{net,out} = \dot{W}_t - \left(w_p * \dot{m}_{of}\right) \tag{20}$$

First law efficiency:

$$\eta_{I,cycle,p} = \left(\frac{\dot{W}_t - (\dot{m}_{of} * w_p)}{\dot{Q}_{in,e}}\right) * 100 \tag{21}$$

Mass flow rate:

$$\dot{m}_{of} = \frac{\dot{Q}_{in,e}}{h_1 - h_4} \tag{22}$$

$$\dot{m}_{cf} = \left(\frac{\dot{Q}_{out,c}}{(c_{cf} * (T_8 - T_7))}\right) \tag{23}$$

Second law efficiency:

$$\eta_{II,cycle} = \left(1 - \left(\frac{I_{total}}{(e_{heat,in} + (w_p * \dot{m}_{of}))}\right)\right) * 100 \tag{24}$$

$$e_{heat,in} = \left(1 - \left(\frac{T_c + 273}{T_e + 273}\right)\right) * \dot{Q}_{in,e} \tag{25}$$

Total UA

$$UA_{total} = UA_e + UA_c = \left(\frac{\dot{Q}_{in,e}}{T_{LMTD,e}}\right) + \left(\frac{\dot{Q}_{out,c}}{T_{LMTD,c}}\right) \qquad 26)$$

Where, e is specific exergy, kJ/kg; h is specific enthalpy, kJ/kg; T_K is ambient temperature, K; s is specific entropy, kJ/kg-K;$\dot{Q}$ is heat transfer, kW; $\dot{m}$ is mass flow rate, kg/sec; c is specific heat, kJ/kg-K; T is temperature, °C; I is irreversibility, kW;$\dot{W}$ is work, kW; w is specific work, kJ/kg; v is specific volume, m3/kg; P is pressure, kPa; η_I is first law efficiency; η_{II} is second law efficiency;subscripts 0,in, out, gen, gf, of, cf, e, t, c, pand LMTD denotes dead state condition, injected(inlet), rejected(outlet), generated, geothermal fluid, organic fluid, cooling fluid, evaporator, turbine, condenser, pump and logarithmic mean temperature difference respectively**.**

6. RESULTS AND DISCUSSION

Operating conditions for the system are given in Table 2. Based on the above equations, the results evaluated for different working fluids for a particular set of condition is tabulated in Table 3. All the parameters used in the calculation are derived from software EES, Academic Professional V9.969-3D, having a good accuracy. High network outputs were given by R600a, R600, R134a, R227ea, and R236fa.Good second law efficiency was shown by R600a followed by 134a, R227ea, R236fa and RC318. Fluids having lesser total UA are R600a, R600, R134a, R227ea, R236fa and RC318.There has to be a trade-off among the criteria to find the optimum working fluid. R600a followed by R600, R134a, R236fa and R245fa are more appropriate working fluid candidates for low temperature low enthalpy geothermal reservoirs Bao and Zaho, (2013)

Table 3: Operating Conditions and Input Parameter for ORC System

Geothermal water inlet temperature	$T_{in,e}$	80 °C
Geothermal water outlet temperature	$T_{out,e}$	70 °C
Mass flow rate of geothermal fluid	$\dot{m}_{gf}$	8 kg/sec
Pinch temperature difference	-	5 °C
Dead state temperature	T_0 or T_K	25 °C or 298 K
Dead state pressure	P_0	101.325 kPa
Pressure ratio	PR	1.9-2.2
Isentropic efficiency of turbine	$\eta_{t,\ isen}$	80%
Isentropic efficiency of pump	$\eta_{p,\ isen}$	80%

Table 4: Comparison of Performance of Different Fluids for a Set of Condition of PR = 2.2

FLUID	P_E (KPA)	P_C (KPA)	$\dot{V}_2$ (M^3/SEC)	VFR	$\dot{m}_{of}$ (KG/SEC)	$\dot{W}_{net,out}$	η_I	I_{TOTAL} (KW)	η_{II}	UA_{TOTAL}(KW/°C)
R600	721	327.7	0.1084	2.248	0.8566	21.51	6.412	24.59	19.4	80.41
R600A	972.9	442.2	0.08512	2.3	0.9338	22.28	6.639	25.65	21.04	80.32
R134A	1891	859.5	0.04421	2.375	1.871	21.41	6.38	26.01	20.12	80.46
R227EA	1325	602.1	0.06028	2.364	2.728	20.18	6.015	26.39	16.59	80.63
R236FA	867.9	394.5	0.08505	2.341	2.158	19.76	5.889	24.55	15.17	80.66
R236EA	690.4	313.8	0.1024	2.288	2.006	19.3	5.753	23.94	13.72	80.72
R245FA	531.9	241.8	0.127	2.232	1.678	18.79	5.601	22.92	12.32	80.78
RC318	949	431.4	0.07907	2.423	2.859	19.6	5.841	25.94	14.4	80.69

Table 5: Irreversibility Of Individual Components For Different Fluids (Percentage In Brackets)

FLUIDS	I_C	I_E	I_P	I_T	I_{TOTAL}
R600	7.797 (31.70)	11.42 (46.44)	0.145 (00.58)	5.232 (21.27)	24.59
R600A	7.857 (30.63)	12.05 (46.97)	0.2231 (0.86)	5.517 (21.50)	25.65
R134A	7.676 (29.51)	12.35 (47.48)	0.3977 (1.52)	5.594 (21.50)	26.01
R227EA	8.354 (31.65)	12.6 (47.74)	0.3574 (1.35)	5.083 (19.26)	26.39
R236FA	7.779 (31.68)	11.76 (47.90)	0.186 (0.75)	4.824 (19.64)	24.55
R236EA	7.853 (32.80)	11.32 (47.28)	0.1306 (0.54)	4.634 (19.35)	23.94
R245FA	7.471 (32.59)	10.87 (47.42)	0.08933 (0.38)	4.493 (19.60)	22.92
RC318	8.252 (31.81)	12.66 (48.80)	0.245 (0.94)	4.788 (18.45)	25.94
RANGE	(32.80- 29.51)	(48.80- 46.44)	(1.35- 0.54)	(21.50- 18.40)	

7.CONCLUSION

This paper overall discusses importance and possibilities of utilizing abandoned coal mines as an alternative geothermal resource As India is focusing on renewable energy sector in recent times geothermal energy is emerging as a viable alternative. However, current exploration activities focus on conventional geothermal systems. However, if abandoned coal mines are explored properly as mentioned in this paper, a new dimension in Indian geothermal sector can be opened. These resources can be well utilized by existing exploitation methods as well as developing new techniques by integrating with different energy sources such as solar, wind and biomass. Various agencies in India have been recently working on developing such technologies. These efforts may result in combating issues like global warming at large in the long run.

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