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A STUDY OF FIELD GEOTHERMAL POWER POTENTIAL & THERMODYNAMIC CONCEPTS OF PROSPECTIVE BINARY POWER CYCLE BASED GEOTHERMAL POWER PLANT FOR TATAPANI GEOTHERMAL FIELD

Manoj Chouhan[*1] & Asst. Prof. Rahul Vishwakarma[2]
[*1&2]Department of Mechanical Engineering, Lakshmi Narain College of Technology & Science (RIT), Indore (M.P), India (An institution affiliated to Rajiv Gandhi Proudyogiki Vishwavidyalaya (RGPV), Bhopal (M.P), India)

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ABSTRACT

Tatapani Geothermal field is one of the most promising low-enthalpy geothermal fields in central India, located on Son-Narmada lineament in the state of Chhattisgarh, India. The Tatapani geothermal field geological, geo-chemical & reservoir data has been compiled and analysed for evaluating true power potential & better understanding of the field. The low enthalpy geothermal reservoirs can be utilized for power production using Organic Rankine Cycle (ORC) or binary power cycle. Based on previous research works done, the Tatapani geothermal field has been found to be very prospective and has got huge potential for power generation.
The binary power cycle has been studied in detail along with thermodynamic concepts. In addition, similar low enthalpy geothermal power plants (conceptual & existing both) have been thoroughly studied in order to understand the concepts and methodology to perform technical feasibility based on thermodynamic and exergy analysis. The literature review covers the previous works done on Tatapani geothermal field including works on other geothermal fields in India along with previous research works for Thermodynamic & Exergy Analysis carried-out for binary geothermal power plants across the world for similar low enthalpy prospects.
The methods of performing thermodynamic and exergy analysis for a potential geothermal power plant has been studied and compared. Exergy analysis highlights the areas of primary exergy destruction at various plant components and can be illustrated in the form of exergy flow diagram. The loss of exergy indicates the potential reasons for the inefficiencies within a process and exergic efficiency as conversion of input heat energy from the brine in to useful work output. The exergic efficiencies can be calculated for each component along with exergy destruction. The detailed study has been conducted in order to gather the knowledge regarding conducting the feasibility of setting up binary geothermal power plant at Tatapani from technical point of view using thermodynamic concepts.

KEYWORDS: Geothermal power, Tatapani, ORC, Technical Feasibility, Thermodynamic Analysis, Exergy Analysis, Exergy destruction, Exergic efficiency.

1. INTRODUCTION

India is home to more than 300+ geothermal hot springs across the country. Majority of these geothermal resources are in low to medium temperature range, that is, from 70–150 °C and are suitable for direct heat applications and electric power generation using binary cycle power plant. These hot springs are categorized into seven geothermal provinces, which are as follows:

- Himalayan belt (Puga, Chhumathang)
- Sohana belt in Haryana
- Cambay Graben basin,
- Son-Narmada-Tapi lineament belt (Tatapani)
- West Coast
- Godavari basin
- Mahanadi basin **(Sharma et al, 2013)**

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Tatapani is located 95 km NNE of Ambikapur in the state of Chhattisgarh, India. Tatapani thermal signature consists of hot springs (52-97 °C) in marshy ground area and hydro-thermally altered clay zones covering an area of approximately 0.1 sq. km **(Ravishankar,1987)**. Geological Survey of India (GSI) has carried out prospect evaluation by geochemical and geophysical studies along with exploratory drilling & well testing in association with Oil and Natural Gas Corporation Limited (ONGC), India. Total 26 wells drilled, out of which 5 wells were found to be most successful (with cumulative discharge of 1500 lpm). These completed five wells resulted in to hot water discharge temperature of > 100°C at the maximum depth of 350 ft. However, the silica geo-thermometer predicted an average reservoir temperature of around 157 °C. The Na-K geo-thermometer indicated bottom-hole temperature in the range of 180°C to 200°C and hence, the deeper reservoir are expected to be having higher than 157°C temperature as concluded by silica geo-thermometer. **(Sarolkar et al, 2015 & Chandrasekharam, 1995)** The power potential of Tatapani geothermal field was estimated earlier by ONGC & GSI which evaluated around 11 MWe & 18 MWe power potential respectively. The available data indicates higher reservoir temperature may be 170°C to 200° C or more. Considering above, it is estimated that at the depth of 2000m and temperature of 150°C, Tatapani geothermal field expected to sustain power production of 25 MW to 30 MW depending on porosity range of 2% to 10%, by binary cycle or ORC method considering 10% plant efficiency. The power potential will very as per actual plant efficiency. This requires exploring deeper reservoir to assess true potential of the geothermal reservoir. **(Sarolkar et al, 2015)**

As part of this project, a binary cycle power plant is conceptualized based on power potential available by making use of comparative data from similar capacity existing binary cycle geothermal power plants. Certain assumptions are made for the study wherever there is no data available. A lot of exiting binary cycle plant data has been studied as a part of literature review so as to obtain best possible solution to get option power output & efficiency. The focus has been given to Thermodynamic & Exergy analysis which will provide clarity with respect to power output, efficiency & heat lost or exergy destroyed.

Geothermal Energy Overview

Geothermal energy is basically thermal energy stored inside the Earth's surface. Thermal energy is the energy that determines the temperature of matter. The temperature difference between the core and its surface is called as geothermal gradient which supplies a continuous thermal energy in the form of heat from the core to the earth's surface due to conduction. The word geothermal has Greek roots "Ge" meaning earth and "Thermos" meaning hot.

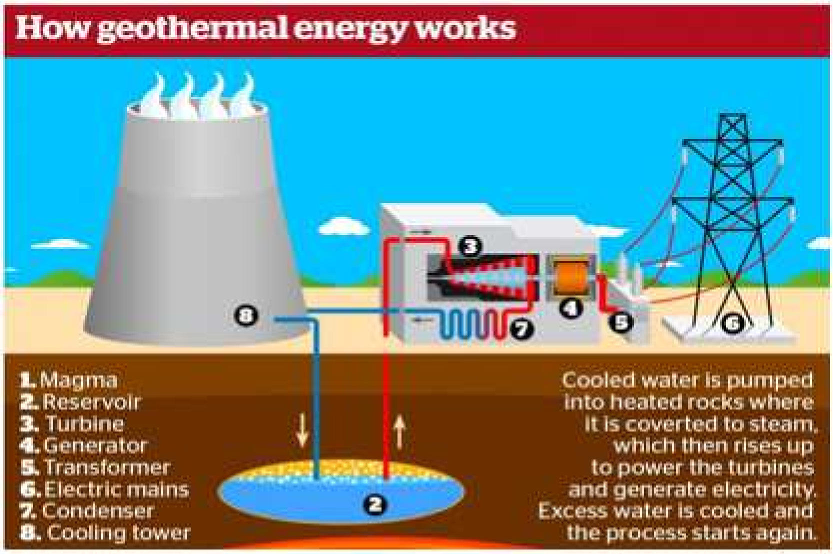

Figure: 1 Basic working of a geothermal power plant

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Earth's internal heat is basically generated from radioactive decay & continual heat loss from its formation. The temperatures at the core–mantle boundary are in the range of 4000 °C. The high temperature and pressure in Earth's interior cause some rocks to melt and to behave plastically, resulting in some portions of the mantle convecting towards surface since it is lighter than the surrounding rock. The water and rock is heated inside the crust, sometimes up to 370 °C. Since Paleolithic times, the hot water from hot springs has been used for bathing and space heating applications, but it is now better known for electricity generation.

Geothermal electricity generation is currently being utilized in 26 countries, while geothermal space heating is in use in almost 70 countries. Worldwide, total installed geothermal electric capacity is close to 12,800 megawatts (MW) as of 2015. Out of which 3,550 MW or 28% are installed in USA alone. The countries generating more than 15% of their electricity from geothermal sources includes Philippines, El Salvador, Kenya, Iceland, New Zealand and Costa Rica.

Geothermal power is reliable, sustainable, environmentally friendly and cost-effective. Latest technological advances have dramatically expanded the range of feasible resources, especially for the applications such as house heating, opening a large potential for widespread exploitation.

Prospects of Geothermal Energy in India
Worldwide share of geothermal energy is around 6.5% which is continuously seeing upward tread due to more & more countries are taking huge interest in geothermal energy and making investments. Geothermal energy is still in nascent stage in India but it has got huge potential. Ironically until now there is no commercial power plant operating in the country.

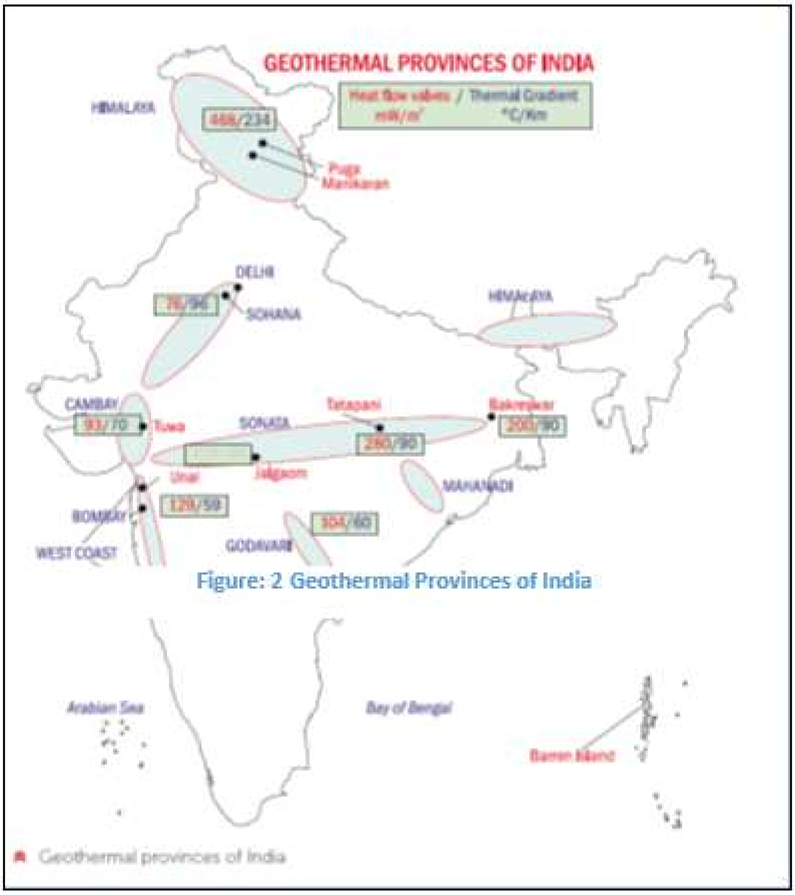

Figure: 2 Geothermal Provinces of India

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Most prospective geothermal fields include the Puga valley and Chhumathang in J&K, Manikaran in Himachal Pradesh, Ratnagiri in Maharashtra, Tapovan in Uttarakhand & Tatapani in Chhattisgarh. In addition to these, Gujarat is also planning to tap its geothermal resources available in Cambay between the rivers Narmada and Tapi. As per Ministry of New and Renewable Energy (MNRE), the total geothermal production capacity of 1,000 MW in India through 340 hot springs across seven geothermal provinces. **(Sharma et al, 2013)**

Applications of Geothermal Energy

- **District or Space Heating**: Hot water can be channelized directly to heating applications (for homes or office buildings) in areas where hot springs or geothermal reservoirs are near the earth's surface.
- **Agriculture, Aquaculture & Mushroom Culture:** Fish growth can be obtained by heating soils in fish ponds or greenhouses by the use of geothermal heat.
- **Power Generation:** Hot water or steam obtained from geothermal wells can be used to generate electricity in a geothermal power plant. The Geothermal power generation has been very successful in countries where dependence on imported fossil fuels is more.

Types of geothermal power plants:

a) **Dry Steam Plant**: It uses use very hot (>235 °C) steam from the geothermal well/reservoir. The steam goes directly to a steam turbine to rotate a generator that generates electricity.

b) Flash Steam Plant: It uses hot water to produce steam when the pressure is reduced. Flash steam power plants use hot water (>182°C) from the geothermal reservoir. The drop in pressure causes some water to vaporize to steam, which rotates a turbine to generate electricity.

c) Binary Cycle Plant: It uses low to moderate temperature water (107–182°C) from the geothermal well. Hot geothermal fluids are passed through one side of a heat exchanger to heat a working fluid in binary geothermal power plant. The working fluid is normally organic fluid with low boiling point, such as isobutene or isopentane. The working fluid is than vaporized and passed through a turbine to generate electricity.

2. LITERATURE REVIEW

A lot of field studies have been conducted in last 3 decades for the geothermal fields of India but none of the potential geothermal power projects really kick started due to slightly higher cost of electricity generated per KWh, lack of bureaucratic interest, remote locations (in some cases) & lack of local expertise. Present global warming concerns, climate change awareness & international pressure to reduce carbon foot print & CO2 discharge are in top priority goals globally by adopting the renewable energy sources such as geothermal energy. There have been a lot of works carried out on Tatapani geothermal field by various researchers as well as organizations such as GSI & ONGC. These studies includes Geophysical surveys, research on Geological aspects, Isotope & geochemical studies, Reservoir characteristics, wellbore drilling & testing and evaluation of geochemistry of thermal water from production wells. Additionally, few studies have also been conducted to estimate the power potential of Tatapani geothermal field.

The last study on Tatapani Geothermal field was by P B Sarolkar **(Sarolkar et al, 2015)**. Accordingly to this study, the maximum power production potential of 30 MWe is estimated for the depth of 1500-2000m (500m reservoir thickness) considering field area of 8 Sq. Km for a period of 20 years, at the base temperature of 150°C. In this project, an attempt has been made to re-evaluate technical feasibility along with estimation of power potential of Tatapani geothermal field based on thermodynamic & exergy analysis. This study will boost the future works in the field to drill & explore deeper reservoirs for greater geothermal resources.

- ✓ **Literature review of previous research works on Tatapani Geothermal Field**
  - o **Ravishankar et al, 1987:** The geothermal studies were carried out & interpretations drawn for hot spring area of Tatapani geothermal field. Hot spring discharge was studied along with chemical composition study. Heat flow & heat generation data reviewed. Geological studies included possible geological model for geothermal anomaly of Tatapani.
  - o **Pitale et al, 1995:** Pilot geothermal power plant idea was conceived and scope of commercial utilisation of Tatapani geothermal field has been done as part of this study. It was projected that

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considering 1500ft reservoir depth, geothermal body extent would be 7.2 Sq. Km is capable to sustain 3.1 MW power output.

- **Chandrashekhram, 1995:** The chemical composition of Tatapani thermal springs discussed in detailed. The surface temperature values along with various estimated values using different methods were discussed.
- **Sarolkar, 2005:** All the field related data studied such as geology, formation structure, discharge of drilled wells, chemical characteristic of thermal water, isotope study, reservoir temperature study result, geophysical survey including fluid inclusion study & well testing results. The discharge fluid temperature was recorded up to 138°C during monitoring. Different geo-thermometer surveys showed reservoir temperature potential of 160°C to 190°C. Aquifer zone identified at 300m & 600m depth.
- **Sarolkar et al, 2015:** Re-estimation of power potential of Tatapani geothermal field was carried out considering 150°C base temperature at estimated depth of 2000m. The estimated power potential to sustain 28 MWe to 30 MWe was concluded. There is a need to explore deeper reservoir zones to establish actual potential of the field.
- **Chandrasekharam et al, 2015:** Geothermal energy resources potential for India was given in great details along with latest update of recent works carried out in the field of geothermal energy including government future plans regarding the same.

✓ **Literature review of previous research works for Thermodynamic & Exergy Analysis Works Carried-out for binary geothermal power plants recently**

- **Kanoglu, 2002**: Exergy analysis of an actual working duel level binary geothermal power plant has been studied in detailed. The points of exergy destruction were identified. The results of the study are as follows :

Table 1

Plant	Inlet brine temperature (°C)	Mass flow rate, Kg/s	Net Power Output (MW)	First law efficiency (%)	Exergic Efficiency (%)
Unit -1	163	48.42	1.76	5.8	29.1

Isopentane was used as working fluid. Seven such units were operating together to generate total power output of 12.4 MWe from total 4 production wells. There were 3 reinjection wells supporting the operations.

- **Yildirim et al, 2012**: Working of two power plants Dora-1 & Dora-2 in Aydin-Salavati geothermal field in Turkey has been studied. The thermodymic & exergy analysis were conducted for the actual plant data. The points of exergy destruction were identified and improvement suggestions were recommended. The exergo-economic analysis were also covered. Organic working fluid used was n-pentane in both the plants.

Table 2

Plant	Inlet brine temperature (°C)	Mass flow rate, Kg/s		Net Power Output (MW)	First law efficiency (%)	Exergic Efficiency (%)
Dora-1	165	75		6.10	5.9	34.7
Dora-2	176	112.5		9.67	5.6	31.2

- **Kanoglu, 2008:** The binary cycle geothermal power plant of capacity 27 MW was analyzed for performance & parametric evaluation. The exergy analysis of an actual working duel level binary geothermal power plant has been studied in detailed. Exergy flow diagram was drawn & the points of exergy destruction were identified. The effects of turbine inlet pressure and the condenser pressure

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along with turbine inlet temperature on the exergy effiency, the net power output of the plant and the reinjection temperature of brine were investigated.

Table 3

Plant	Inlet brine temperature (°C)	Mass flow rate, Kg/s	Net Power Output (MW)	First law efficiency (%)	Exergic Efficiency (%)
Unit -1	160	555.9	16.4	4.5	21.7

- **Budisulistyo et al, 2015**: The pre-feasibility study of binary cycle geothermal power plan described detailed procedure for investigative design. Thermodynamic & economical analysis for multiple working fluid options such as n-pentane, R-245fa and R-134a. the result concluded that the 2-stage turbine using n-pentane is most thermo-economical design out of discussed options.

- **Basaran et al, 2013**: The study reviews the suitability of different refrigerant for binary geothermal power plant based on performance parameters. The net work output, thermal efficiency, exergic efficiency & energy destruction were compared. R-600 (Butane) indicated best performance & hence hydrocarbon (HC) refrigerents are normally best choice for binary cycle.

- **Dipippo, 2004**: The second law assessment done for OCR & kalian cycle for low enthalpy geothermal resources proved that kalian cycle had very little advantage over ORC with about 3% improvement in power output. ORC technology is mature with hundreds of MW power plants worldwide has commercial & technological edge over kalian cycle. There are very few kalian cycle commercial plants operational worldwide.

- **Fernando et al, 2013**: The principles of binary geothermal plant explained in this report have been very helpful in designing. The thermodynamic analysis explained in great details component wise, was very useful in understanding. The costing part also was well explained. The description of various plants worldwide discussed thoroughly & it was crucial to understand actual plant operation & maintenance aspects.
  Below plants were discussed in detailed -

Table 4

Plants	Working fluid	Inlet brine temperature (°C)	Mass flow rate, Kg/s	Net Power Output (MW)
Svartsengi Binary Unit, Iceland	Isopentane	103	5	1.2
Berlin Binary Power plant, Germany	Isopentane	180	221	9.2

- **Erdeveghe et al, 2018**: The feasibility study of low enthalpy geothermal plant were discussed for multiple economical scenarios. The thermo-economical concepts helped build the necessary knowledge base to complete the project.

- **Koroneos et al, 2017**: In this paper, the experimental data was utilized for Greek Island of Nisyros, located in the south of the Aegean Sea, in order to estimate the maximum available work and the efficiency of a potential binary cycle power plant. This helped in defining experimental data & assumptions in order to evaluate overall performance of the plant. The exergic efficiency calculated than compared with various operational plants globally to support technical feasibility of the proposed geothermal power plant.

- **Kahramana et al, 2019**: The thermodynamic and thermo-economic performances of a working 21MW geothermal power plant working with two level binary type ORC was investigated using actual plant operating data. The plant investigated was Sinem Geothermal Power Plant in

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Germencik, Aydin (Turkey). This research papar provides detailed comparison of the exergetic performance of this plant with other type of geothermal power plant units, which make use of geothermal resources with similar specific exergies.

- **Ahanger, 2012:** The Feasibility Study of Developing A Binary Power Plant In Puga Geothermal field was carried in out including the costing of various plant components. The selection of working has been done & five working fluids (isobutane, n-butane, isopentane, n-pentane and propane) were considered for the model to obtain the optimum net power output. The Isopentane resulted highest thermal efficiency & net power output & hence normally is best choice as working fluid for any binary cycle geothermal power plant. A thermodynamic model of a binary power was created in the Engineering Equation Solver (EES) software. The study has been very helpful in conceptualizing the feasibility for Tatapani geothermal power plant.

3. CHARACTARISTICS OF TATAPANI GEOTHERMAL FIELD

Tatapani Geothermal field is a promising geothermal reservoir in the state of Chhattisgarh. The Tatapani hot springs are having surface temperature range of 50°C -97°C in marshy ground, and hydro thermally altered clay zones covering an area of about 0.1 sq km (Ravishanker, 1987). Geological Survey of India Tatapani Geothermal field is located 95 km from Ambikapur city and is connected by black top road from Bilaspur. Total 26 wells were drilled by ONGC as part of exploration campaign out of which wells Tat/6, Tat/23, 24, 25 & Tat/26 proved to be highly successful having hot water flow of 100°C on surface at 270 lpm to 425 lpm. The wells Tat/23, 24, 25 and 26 were drilled & completed as production wells with cumulative discharge from these wells of 1500 lpm. The feasibility study of binary geothermal power plant by using stated flow rates was established in collaboration with ONGC **(Pitale et al, 1995).**

Various studies have showed possibility of very high temperature (160° to 190°C) reservoir at deeper level. Geological & reservoir surveys have suggested low resistivity zones at a depth range of 300m to 600m which might relate to deep aquifer. The various survey methods are mentioned below along with indicated temperature range –

Table 5

Sr. No.	Method of survey	Indicated Temperature
1	Geochemical aqueous Geo-thermometers	160 °C to 200°C
2	Hydrothermal alteration	180°C to 250°C
3	Fluid inclusion study	140°C to 250°C

(Sarolkar, 2005)

At Tatapani geothermal field, along with high flow rate, water at near boiling point at atmospheric pressure but in association with a gas-phase of meteoric signature, indicates very well established convective circuit. The effluent water coming out of from proposed binary plant could be utilized for direct heating purposes such as spa and tourism etc. The estimated reservoir power potential is around 11 MWe with base temperature of 140°C covering an area of 2 sq km to 18 MWe with base temperature of 112°C over an area of 7.2 sq km at the estimated depth of 1500m. **(Pitale et al, 1995)**

4. THERMODYNAMIC CONCEPTS AND SOLUTION METHODOLOGY

Estimation of Stored Heat (Geothermal Power Potential)

In this method, it is assumed that we are extracting the heat from a specific volume of rock, by cooling it down from its original state to a certain base temperature. The based considered is basically the lowest temperature at which it is viable to produce electricity commercially. However practically it is not possible to tap the heat resources contained in the rock fully due to uneven distribution of permeability & porosity of the rock. Due to this reason only, the stored heat is multiplied by a factor called recovery factor. The recovery factor varies between 10-50%, where average value of 25% for hydrothermal resources & 40% for enhanced geothermal resources depending upon the local geological conditions.

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The estimation of geothermal potential for electricity generation is evaluated based on below equation:

Stored Heat $E_s = [(1-\emptyset).\rho_r.C_r + \emptyset.\rho_w.C_w].V.(T_r - T_b)$ Eq. 1

Recoverable Heat $E_r = E_s.R$ Eq. 2

Installed Power $N = \frac{E_r.n}{f.t}$ Eq. 3

(Mendrinos et al, 2008)

Table-2 represents the values of various geological parameters required for geothermal resource calculations based on previous works by **Sarolkar et al, 2015** & **Pitale et al, 1995**. These values are used to evaluate geothermal power potential in this study.

Table 6

Parameter	Assumed Values
Area at the reservoir , m2	8000000
Reservoir Thickness, m	500 & 1000
Rock Heat Capacity , KJ/Kg °C	0.79496
Rock density, kg/m³	2660
Water heat capacity, kJ/kg°C	4.186
Water density, kg/m³	916
Rock Volume Estimated, m³	4000000000
Rock natural state temperature, °C	150
Base temperature, °C	74
Recovery factor, %	0.33

Binary Power Cycle Concepts

As the name suggests, Binary means two working fluids are used in the power generation cycle. The primary fluid is high temperature geothermal fluid coming out of the well & the secondary fluid is basically working fluid (Hydrocarbon or Refrigerants) which circulates in the closed cycle is also called as power fluid.

The selection of cycle is based on the geothermal fluid temperature range. If the geothermal fluid temperature is between 130 to 180 °C ORC is preferred where if it is below 130 °C Kalina cycle is more suitable. ORC mainly uses various hydrocarbons as working fluid where as Kalina cycle works on a mixture of water-ammonia as working fluid. **(Valdimarsson, 2011)**

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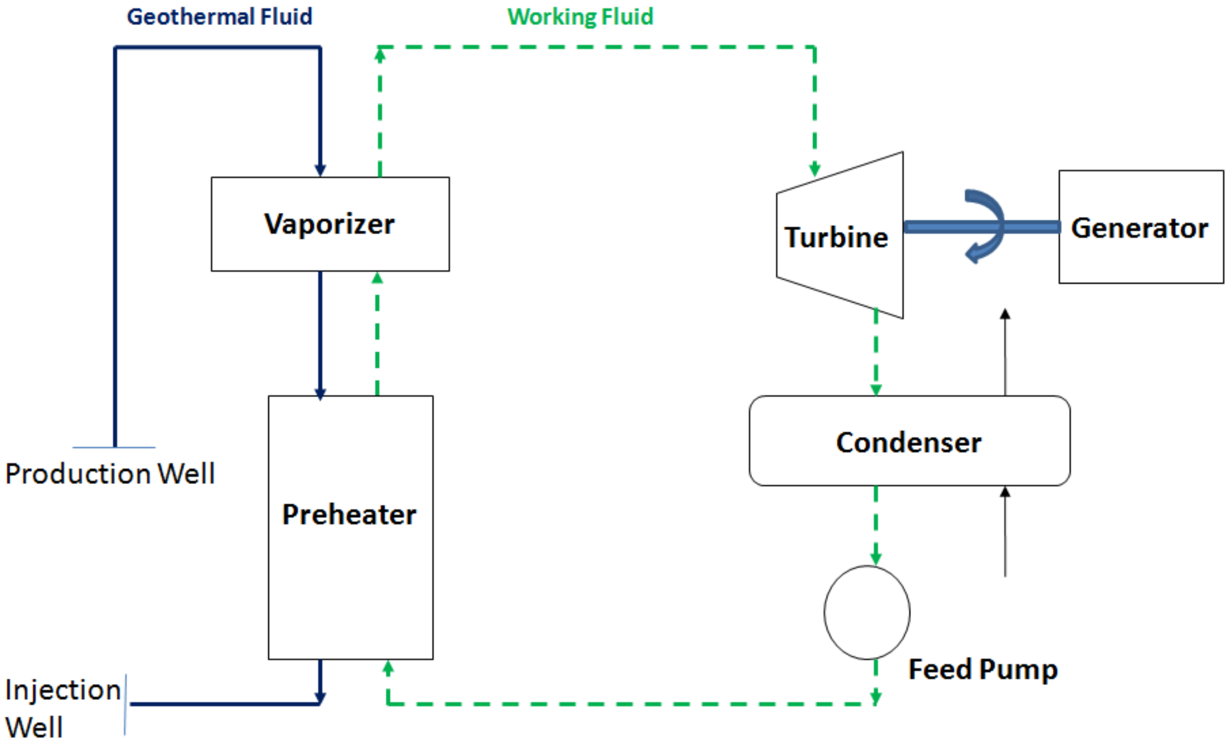

Figure: 3, Basic Binary Power System

In basic binary power system there are two closed loop systems; first heat transfer cycle is of geothermal fluid & second is of the ORC for working fluid. There is no direct contact of geothermal fluid with working fluid; hence heat transfer takes place by means of heat exchangers. The selected working fluid takes heat from geothermal fluid & evaporates, this evaporated vapor than falls on turbine at high pressure & temperature to produce mechanical work. The working fluid is discharged to a condenser where it is again converted into liquid phase using cooling medium such as air or water. The condensed liquid working fluid then pumped using a feed pump to the evaporator again & hence completes the cycle.

The major components of a binary cycle power plant are as follows:

1. Evaporater (Heat Exchanger)
2. Turbine
3. Condenser (Heat Exchanger, water cooled or air cooled)
4. Feed pump
5. Pre-heater (Heat Exchanger)
6. Generator

Selection of Working Fluid

Selection of the working fluid is of foremost consideration in designing the geothermal power system. There are various factors must be considered in selecting the working fluid. The proper choice of working fluid has got direct impact on the performance of the unit. Due to low temperature of the heat source, irreversibilities within the heat exchangers are very detrimental to the overall efficiency of the cycle. These irreversibilities are highly dependent on the thermodynamic properties of the working fluid. The thermodynamic properties of the working fluid as critical pressure, critical temperature, boiling point, toxicity etc mainly influence the performance of the system. Other essential criteria include the influence of the working fluid on overall cost, Health, safety and environmental effects.

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Table 7

Fluid	Formula	Critical Temp (°C)	Critical Pressure (bar)	Toxicity	Flammability	Molecular Wt.
i-Pentane (iC5)	i-C5 H12	187.8	34.09	Low	Very high	72.15
n-Pentane (nC5)	C5 H12	193.9	32.40	Low	Very high	72.15
i-Butane (iC4)	i-C4 H10	134.9	36.85	Low	Very high	58.12
n-Butane (nC4)	C4 H10	152.0	37.18	Low	Very high	58.12
Propane (C3)	C3 H8	96.6	42.36	Low	Very high	44.1

Past studies concluded that the highest net power output & thermal efficiency is obtained from the isopentane working fluid for the similar temperature range among the hydrocarbon working fluids for a binary ORC **(Ahangar, 2012)**. Hence isopentane has been selected as working fluid for this project.

Thermodynamic & Exergic Analysis

The proposed binary cycle geothermal power plant diagram is designed based on the previous works done by various researchers on this subject in order to carry out detailed thermodynamic & exergic analysis. The basic data has been taken based on actual realistic numbers from previous works and suitable assumptions are made wherever applicable or in case of data unavailability.

i. Thermodynamic Analysis Methodology

In 1961, Harry & Lucien developed a method for make use of low boiling temperature organic fluid as the working fluid for power turbines for producing electricity. Conventionally, electrical power is generated using Rankine power cycle using water as working fluid.

In an Organic Rankine Cycle using an organic fluid as working fluid instead of water. It facilitates heat recovery from lower temperature resources such as industrial waste heat, geothermal heat, solar ponds, etc. The low temperature heat is than converted into useful work that can be converted into power.

The working principle of the Organic Rankine cycle is very much similar to Rankine cycle. In ORC, there is a heat source in the form of hot water coming out of geothermal well instead of boiler.

In the ideal ORC cycle include primarily four processes as explained below w.r.t below figures 2 & 3 as examples:

1. **Isobaric Evaporation (1–4)**. It means that there is no pressure change in the heat exchanger. It can be further divided into three catagories: preheating (1-2), evaporation (2-3) & superheating (3-4).
2. **Isentropic Expansion (4–5)**. Isentropic expansion is anadiabatic (during the process there is no heat exchange with the environment) and is reversible (No pressure drops, no fiction losses or nil leakages).
3. **Isobaric Condensation (5–8)**. It can be subdivided into the de-superheating (5-6), condensation (6-7) and sub-cooling (7-8) processes.
4. **IsentropicPump(8–1)**. For an isentropic compression on a liquid, dS = dT =0.

Where as in the real cycle, due to the presence of irreversibility's reduces the cycle efficiency. Irreversibility's mainly occur due to below:

- **In the expansion:** In the real expansion process, only a part of energy is converted in to useful work. The remaining part is converted into heat and lost to the surroundings.
- **In the heat exchangers:** The pressure drops across the heat exchanger causes reduction in power recovery.
- **In the pump**: This includes internal leakages & electro-mechanical losses.

The expansion work can be given by:

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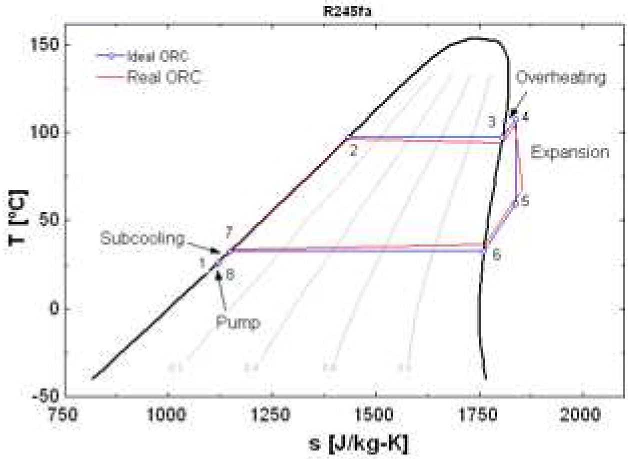

Figure 2

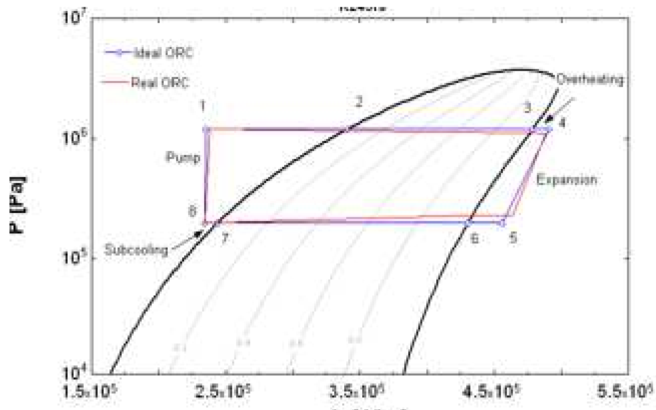

Figure 3

- From the T-s diagram, (assuming the vapor is a perfect gas):
  $w_{exp} = c_p * (T_4 - T_5)$ Eq. 4
- From the p-h diagram,
  $w_{exp} = h_4 - h_5$ Eq. 5

The diagrams show that the irreversibility's considerably reduces the amount of useful work that can be recovered. **(Quoilin, 2008)**

ii. ORC Cycle efficiency

The cycle efficiency is basically net work (the work turbine minus the work of the pump) divided by the amount of heat supplied.

Pump Work: $w_{pump} = h_1 - h_8$ Eq. 6

Heat Supplied: $q_{boil} = h_4 - h_1$ Eq. 7

In order to get the powers, the intensive variables must be multiplied by the mass flow rate:

$\dot{W}_{exp}\ [W] = \dot{M}\ .\ w_{exp}$ Eq. 8

$\dot{W}_{pump}\ [W] = \dot{M}\ .\ w_{pump}$ Eq. 9

$Q_{boil}\ [W] = \dot{M}\ .\ q_{boil}$ Eq. 10

The ORC cycle efficiency:

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$$\eta = \frac{\dot{W}_{exp} - \dot{W}_{pump}}{Q_{boil}} = \frac{w_{exp} - w_{pump}}{q_{boil}} = \frac{(h_4 - h_5) - (h_1 - h_8)}{h_4 - h_1} \quad \text{Eq. 11}$$

Above equation is only valid for adiabatic expansion and compression. In the case of a heat exchange between the Turbine (or pump) and the surroundings, a heat balance will be shown by:

$$\dot{W}_{exp} = \dot{M} . (h_4 - h_5) - \dot{Q}_{amb,exp} \quad \text{Eq. 12}$$

$$\dot{W}_{pump} = \dot{M} . (h_1 - h_8) - \dot{Q}_{amb,pump} \quad \text{Eq. 13}$$

Where Q_{amb} is the heat exchanged between the turbine (or the pump) and the ambiance.

The cycle efficiency becomes:

$$\eta = \frac{\dot{W}_{exp} - \dot{W}_{pump}}{\dot{M} . (h_4 - h_1)} = \frac{[\dot{M} . (h_4 - h_5) - \dot{Q}_{amb,exp}] - [\dot{M} . (h_1 - h_8) - \dot{Q}_{amb,pump}]}{\dot{M} . (h_4 - h_1)} \quad \text{Eq. 14}$$

(Quoilin, 2008)

iii. Exergy Analysis Methodology

The first law of thermodynamics deals with the quantity of energy and implies that energy cannot be created or destroyed. This law hardly serves as an important tool for the recording of energy during a process and offers no challenges to the engineer. However, the second law deals with the quality of energy. More precisely, it is concerned with the degradation of energy during the process, the entropy generation, and the opportunities lost to do useful work; and it offers plenty of room for improvement. **(Cengel et al, 5th Edition 2017)**

The exergy, which is a property, implies regarding total useful work available, which is also known as availability or available energy. The rest of the energy, which is wasted or discarded to the surroundings & not useful, is termed as unavailable energy.

Exergy analysis is a powerful tool for assessment of a thermodynamic system & focus on wastage of energy at various states of a system. This enables us to determine useful work output for a given state & also for an entire system.

The exergy analysis provides below information regarding a system -

- Provides amount of useful work available & lost/discarded to the surroundings
- Pin points the area of low efficiency or high wastage of energy
- Provides information of overall efficiency of a process

Ignoring kinetic and potential energy changes, the specific flow exergy of geothermal fluid at any state (at geothermal plant location) can be evaluated from below formula

$$e = h - h_0 - T_0(s - s_0) \quad \text{Eq. 15}$$

The exergy rate can be obtained by multiplying specific exergy by the mass flow rate of the geothermal fluid,

$$\dot{E} = \dot{m} . e \quad \text{Eq. 16}$$

Pre-heaters, Evaporators or vaporizers, and condensers in the plant are essentially heat exchangers designed to perform specific tasks. The exergy efficiency of a heat exchanger can be measured by the increase in the exergy of the cold stream of fluid divided by the decrease in the exergy of the hot stream of fluid. That is;

$$\dot{E}_{vap\ (A)} = \frac{\dot{E}_{10} - \dot{E}_9}{\dot{E}_1 - \dot{E}_2} \quad \text{Eq. 17}$$

Exergy distruction is basically difference between the numerator and denominator in above Eq. for a heat exchanger. That is,

$$\dot{I}_{vap\ (A)} = (\dot{E}_1 - \dot{E}_2) - (\dot{E}_{10} - \dot{E}_9) \quad \text{Eq. 18}$$

Exergy efficiency and exergy destruction relations for Level-A vaporizer-preheater system as

$$\varepsilon_{vap-pre\ (A)} = \frac{\dot{E}_{10} - \dot{E}_8}{(\dot{E}_1 - \dot{E}_2) - (\dot{E}_3 - \dot{E}_4)} \quad \text{Eq. 19}$$

$$\dot{I}_{vap-pre\ (A)} = (\dot{E}_1 + \dot{E}_3 + \dot{E}_8) - (\dot{E}_2 + \dot{E}_4 + \dot{E}_{10}) \quad \text{Eq. 20}$$

The exergetic efficiency of the condenser is calculated as explained above. However, the exergy destruction in the condenser is expressed by the exergy drop of isopentane across the condenser.

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Similarly, The exergetic efficiency of a turbine:

$$\varepsilon_{turb(A)} = \frac{\dot{W}_{turb\ (A)}}{(\dot{E}_{10} - \dot{E}_{11})}$$ Eq. 21

The exergy destruction in the turbine:

$$\dot{I}_{turb\ (A)} = (\dot{E}_{10} - \dot{E}_{11}) - \dot{W}_{turb\ (A)}$$ Eq. 22

The exergetic efficiency and exergy destruction for the Level-A pump:

$$\varepsilon_{pump(A)} = \frac{\dot{E}_8 - \dot{E}_7}{\dot{W}_{pump\ (A)}}$$ Eq. 23

$$\dot{I}_{pump\ (A)} = \dot{W}_{pump\ (A)} - (\dot{E}_8 - \dot{E}_7)$$ Eq. 24

The exergetic efficiency of Level-A isopentane cycle can be determined as below:

$$\varepsilon_{level(A)} = \frac{\dot{W}_{net\ (I)}}{(\dot{E}_1 - \dot{E}_2) + (\dot{E}_3 - \dot{E}_4)}$$ Eq. 24

Total exergy distruction in Level-A cycle can be determined by

$$\dot{I}_{level(A)} = \dot{I}_{pump\ (A)} + \dot{I}_{vap\ (A)} + \dot{I}_{pre\ (A)} + \dot{I}_{turb\ (A)} + \dot{I}_{cond\ (A)}$$ Eq. 25

The exergetic efficiency of the plant, **based on total brine exergy drops across the vaporizer-preheater systems of Level-A and Level-B cycles** (i.e. total exergy inputs to Level-A and Level-B cycles), can be given as below

$$\varepsilon_{plant} = \frac{\dot{W}_{net\ plant}}{(\dot{E}_1 - \dot{E}_2) + (\dot{E}_3 - \dot{E}_4) + (\dot{E}_2 - \dot{E}_3 - \dot{E}_5) + (\dot{E}_5 - \dot{E}_6)}$$ Eq. 26

The First Law thermal efficiency of the plant, can be calculated from

$$\eta_{plant} = \frac{\dot{W}_{net\ plant}}{\dot{m}_1(h_1 - h_2) + \dot{m}_3(h_3 - h_4) + \dot{m}_2(h_2 - h_5) + \dot{m}_5(h_5 - h_6)}$$ Eq. 27

Where the terms given in the denominator are heat transfer rates in vaporizer A, preheater A, vaporizer A, and preheater A, respectively. **(Kanoglu, 2002 & Koroneosa et al, 2017)**

7. CONCLUSION

A lot of research work has been done on Tatapani geothermal field till date which includes geological-geochemical analysis, drilling & testing of wells to assess reservoir capabilities for sustainable production. Below are the key conclusions from the study -

1. Last feasibility study of setting up binary power plant has been carried out by P.B. Sarolkar in 2015. This study was very brief & does not cover details of binary power plant such as components involved, proposed schematic, working fluid selection etc. Hence, there has been an urgent need to carryout detailed thermodynamic analysis considering all the potential aspects related to proposed binary power plant at Tatapani Geothermal field.
2. There have been no studies carried out related to exergy (available energy) calculations for proposed binary cycle power plant at Tatapani geothermal field. The overall exergy analysis will provide in-depth overview of actual operating parameters & energy losses within the system. Maximum power output and thermal conversion efficiency shall be the primary goals of ORC thermodynamic analysis.
3. The drilling & well testing activities performed during 1995-1999 by ONGC in coordination with GSI. The wells were drilled up to 350m for assessing geothermal gradient & flow characteristics. Hence, there is an immediate need to drill deeper to explore deeper reservoir in order to estimate the true potential of Tatapani Geothermal field.
4. Based on the available thermal gradient data and the temperatures measured in the boreholes, it is estimated that at the depth of 2000m the temperatures may rise to around 200°C. The geothermal potential will have to be re-evaluated considering different porosity, plant efficiency and load factors along with reservoir thickness & field area.
5. Geothermal energy has the potential to play a very significant role in improving quality of life of millions of people in region. It is one of the few renewable power technologies which are capable to supply continuous, base-load power to an electric grid. The Binary geothermal plants have the capability to ramp

up or down production multiple times each day ranging from 100% to as low as 10-15%. The unit cost of electricity from geothermal plants is also becoming increasingly competitive with respect to conventional energy resources. As a source of heating, for millions of homes and businesses at any location makes its future even brighter.

8. FUTURE SCOPE

There is huge scope for future works for the Tatapani Geothermal field potential evaluation and feasibility study, below is the brief summary:

1. Estimation of geothermal potential for electricity generation considering different scenarios of porosity %, conversion efficiency %, load factor etc.
2. Thermodynamic analysis can be carried out for the proposed design of a binary cycle geothermal power plant for Tatapani geothermal field with suitable working fluid option.
3. Evaluate maximum available work generated & efficiency for prospective installation using basic concepts & equations of ORC Thermodynamic cycle along with field geothermal resource potential estimation.
4. The exergy analysis can be done which facilitates plant performance evaluation along with highlight locations of primary exergy destruction. The exergic efficiency of various plant components can be calculated to evaluate their individual performances.
5. The above analysis will provide a strong technical basis for the implementation of the proposed binary cycle geothermal power plant at Tatapani. This will reaffirm the technical feasibility of the proposed plant using thermodynamic & exergic analysis.
6. The research will further pave the way for the technical design aspects & economic feasibility of the plant

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NOMENCLATURE

Ø	Porosity, (%)
ρ_r	Rock density, kg/m³
ρ_w	Water density, kg/m³
C_r	Rock heat capacity, kJ/kg°C
C_w	Water heat capacity, kJ/kg°C
V	Rock Volume, m³
T_r	Rock natural state temperature, °C
T_b	Base temperature, °C
R	Recovery factor
n	Conversion efficiency
f	Load factor
t	Commercial life span of the plant, msec
E_s	Stored Heat, KJ
E_r	Recoverable Heat, KJ
N	Installed power, MWe
P	Pressure, bar
T	Temperature, °C
h	Specific Enthalpy, KJ/Kg
s	Specific Entropy, KJ/Kg-K
$\dot{W}$	Power, KW
η	First Law Efficiency, %
$\dot{I}$	Exergy destruction, KW
ε	Exergic Efficiency, %
$\dot{E}$	Exergy Rate, KW

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ṁ	Mass flow rate, Kg/s
e	Specific flow exergy, KJ/Kg

SUBSCRIPTS

0	Dead state
A	Level-A
B	Level-B
Cond	Condenser
Pre	Pre-heater
Turb	Turbine
Vap	Vaporizer

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