Geothermal Power Generation Options and Technologies

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Abstract

Geothermal energy has a potential for several applications including geo-exchange, direct thermal application, and power generation. Whereas the untapped capacity is over 100 GW globally, its growth realizes only 3-4% growth per year. Limitations of geothermal energy includes scarcity of exploitable sites, remote locations often far from load centers and undesirable gaseous emissions. Project development faces challenges of poor funding, technology, and long gestation periods of between 5 and 10 years for conventional power plants. Smooth implementation of geothermal project requires, social acceptance, through minimization of environmental effect, avoidance of adverse effects on the people and giving direct benefits to local communities. It is through both subsurface and power plant technologies that environmental challenges of geothermal power plants are addressed. Research and development into new, efficient and cost-effective technologies will enhance safety and environmental integrity with respect to geothermal energy and electricity development. A geothermal power plant project generally goes through exploration or prefeasibility stage, drilling or feasibility stage and development stage which involves development of production wells, reinjection wells, steam gathering system and power plant construction and commissioning. The last phase is power plant operation and maintenance before the plant is finally retired upon end of the generation contract or license. These phases of the cycle before generation combined take relatively long and there is need to improve. The use of Wellhead power plants currently provides a quick access to geothermal electricity ahead of full development of a conventional power plant hence enabling quicker access to geothermal electricity. Better technology in upfront activities will significantly reduce the high risks and costs while power plant conversion technologies and better reservoir management and engineering will increase output, resource availability and efficiency of resource exploitation.

Keywords
Geothermal, Technologies, Remote locations

1. Introduction

Geothermal energy resource is a renewable form of energy extracted as heat from the ground for various applications in heat and power (Dipippo 2007). As a renewable source of energy, geothermal, heat and electricity have an important role to play in the realization of the Paris agreement (Kabeyi and Olanrewaju 2022). Since, most of the geothermal resources are classified as low and medium temperature reservoirs, the organic Rankine cycle will prove useful for maximum power generation from geothermal fluids (Quoilin et al, 2013). Geothermal energy contributes less than 1% of the global power generation output hence the need to identify more feasible geothermal resources while efficiently exploiting discovered or developed resources for electricity generation. Various technologies can be used to generate electricity from geothermal all employing flash steam technology. They include dry steam technology, flash steam, organic Rankine cycle or a combination of the basic technologies depending on costs required and financing as well as the resource (Kabeyi et al, 2019).

Geothermal energy is produced by drilling deep into the Earth's crust for harnessing to generate electricity or thermal energy. Feasible geothermal resources are available where the thermal gradient is above 30°C/km, permeable rock structure, natural or artificial water replenishment, and an impervious cap rock. Geothermal contributes less than 1% of global electricity generation even though we have significant potential such that it can meet the entire energy needs of humanity at current rates of consumption. As a renewable energy resources, geothermal energy is constantly replenished from neighboring hotter regions and the radioactive decay of naturally occurring isotopes deep in the Earth's crust. The greenhouse gas emissions from geothermal-based electricity are less than 5% of total emissions from coal-based electricity generation. The risks associated with geothermal energy exploitation include the risk of inducing earthquakes, water and soil pollution from brine, and releases toxic emissions like hydrogen sulphide and greenhouse gas emissions like carbon dioxide. The main challenge facing geothermal electricity generation is long project development period, high upfront risks and huge project costs for conventional technologies which also have low electricity conversion efficiency. The adoption of wellhead generators as a project development option can reduce the period and risks involved in development of geothermal power plants (Kabeyi and Olanrewaju, 2022)

For largescale exploitation of geothermal energy, geothermal wells or bore holes are drilled to a depth of up to 1,000 m for steam and water extraction at temperatures generally between 200–300°C and pressure up to 3,000 kN/m^2. Steam from the wellhead is transmitted in pipes of about 1 m diameter over distances up to 3,000 m to the power plant to run steam turbines after separation in water separators or flash systems to separate moisture and solid particles from steam (Hegde 2015, Usman et al, 2020). Geothermal energy is an environmentally friendly power although development processes like drilling, have potential impact on the environment once it is exploited. Other impacts include water and air pollution as well as the potential degradation of ecosystems and alteration of the habitats of fauna and flora. While countries like Iceland, and Kenya have readily available geothermal resources, geothermal resource development requires location for accessibility of use, and careful exploration in needed for drilling of productive wells making the process costly and time consuming. Injection of used geothermal fluid back to the reservoir and use of binary cycles can reduce emissions from geothermal power plants, making renewable resource greener. Overall, geothermal energy systems remain significantly cleaner and more ecologically friendly fossil fuel sources, but has some unfavorable environmental impact effects (Androniceanu and Sabie 2022)

Some countries like Iceland, El Salvador, New Zealand, Kenya and the Philippines, generate large portion of their electricity needs from geothermal with Iceland, generating 90% of the heating demand from geothermal. Geothermal power plants can supply baseload power and, because of being weather-independent and having extremely high-capacity factors of 95-99%Geothermal resources have high potential to generate renewable, reliable and cheap and leave a favorable impact on the economies of the surrounding areas including provision of wide variety of job skills and labor categories comparable to those used in the fossil energy industry, mining, manufacturing, building and construction and other fields. These workers also find it easier to transition between industries due to many shared skill set (Kabeyi and Oludolapo 2020).

The world community is striving to reduce greenhouse gas emissions and limit global warming below 2 °C as agreed in the 2015 UN Climate Change Conference, at Paris. Geothermal energy is renewable, sustainable, and green energy source for power generation, but it remains underutilized globally. As an example, in 2018, the globally installed generation capacity was 13.3 GW accounting for just 0.57% of total renewable energy capacity, hence the need to optimize any developed geothermal resources for maximum power production (Alimonti et al, 2020). Waste heat recovery is a feasible option to reduce greenhouse gas emissions and hence diminish the environmental impact energy systems and processes. Waste heat recovery has a huge potential globally, for example energy wasted by the U.S. industrial systems has potential to produce about 20% of U.S. electricity capacity without burning any fossil fuels. Various countries committed to reduce emissions in line with Paris agreement, for example the EU countries have a target to reduce emissions by about 20%, which makes waste heat recovery a very attractive option.

Heat recovery from wastes and low grade heat sources like solar is an important strategy in reducing greenhouse gas emissions through efficiency measures (Alimonti, et al, 2020). In addition, given the target of reducing about 20% the emission of the EU countries, increasing efficiency and heat recovery from industrial processes will be crucial. Energy from waste heat conversion could be up to 2% of the European Industry energy use, which can effectively reduce emissions (Castelli et al, 2019). The basic ORC has significantly improved over years through research and development to operate over various conditions of the heat source. Countries like Kenya which are developing their geothermal resources for the last four decades mainly using flash conversion technology, should consider the binary power cycle for optimum exploitation of geothermal fields especially in Olkaria waste brine has s significant energy content (Castelli et al, 2019, Ahangar, 2012).

The organic Rankine cycle is a system that can be used to exploit low and medium enthalpy geothermal resources which are the most dominant. The cycle has also proved to be more efficient in the extraction of low grade geothermal fluid which may be difficult to exploit with the conventional Rankine cycle technology (Gitobu 2016, Kabeyi and

Oludolapo 2020). As for the case of the operating Olkaria power plants, brine with temperature above 170ºC and pressure of about 16 bars is return to the underground through the injection well (Valdimarsson 2011). Studies have shown that the cost for double flash plants is 5% higher than that of single flash; however, the plant output increased by 20 to 25%. The efficiency of double flash system is about 3% greater than that of single flash system. Flash steam power plants have low efficiency despite their simple construction structure and low cost.

The growing concern over emissions and climatic changes have increased the importance of the optimization of conventional thermodynamic systems in power production. Compared with other technologies like, Kalina cycle, Trilateral Flash cycle and Supercritical cycle, the organic Rankine cycle claims to produce 15–50% more power output for the same heat and is ideal for low-temperature heat recovery for power generation with low maintenance costs (Pethurajan et al, 2018)

2. Geothermal Energy Conversion Cycles and Technologies

Geothermal power plants are classified based on the energy conversion system used. Based on the conversion technology, geothermal power plants can be classified as flash dry steam plants, flash steam plants or binary cycle plants. The technology selection is guided by the thermodynamic properties of the steam or geothermal fluid and other factors like cost and size of the steam field (Dipippo 2007). The thermodynamic properties of the resource, especially temperature influences the resource application and the most appropriate energy conversion technology. The conventional Rankine cycle steam turbines normally operate at a temperature above 180°C (350°F) while non-electrical applications can efficiently use geothermal resources with temperatures of 40°C to 180°C, based on specific application (Windrem P. F. and Marr, 1982)

There are three categories of geothermal fluid based on steam temperature, i.e., high temperature for above 150ºC, medium for temperature between 90ºC and 150ºC and low temperature resources if the resource temperature is less than 90ºC (Cao and Ehyaei 2021).

Geothermal power plants function like fossil fuel and nuclear power plants except for the source of heat which is hot water or steam from earth through a series of pipelines to the power plant. The mechanical power is generated by the rotation of the turbine blades upon expansion of steam. The turbine shaft is coupled to a generator which then generates electric power. The condensate is normally reinjected back to the reservoir (Kabeyi and Oludolapo, 2020).

There are three basic types of geothermal heat to electricity conversion technologies globally. These are the dry steam, flash steam, and binary cycles which are selected based on the thermodynamic properties of the geothermal fluid. Dry steam power plants use dry steam, but they are very few because of the scarcity of the dry steam geothermal resources. For hydrothermal fluids with temperature above 170°C, the most used conversion system is the flash steam technolog. In this technology, hot water under pressure comes out of the production well and is sprayed into a flash tank at a lower pressure than the fluid, which causes it to vaporize to steam. In dual-flash plants the fluid that does not vaporize in the first flash tank undergoes a second stage of flashing to generate steam at a pressure lower than the first. Triple and even quad flashing can be done based on the design and geothermal fluid conditions(DiPippo, 2005). For much lower fluid temperature below 150ºC, the binary cycle technology is applied where a secondary low temperature boiling fluid is used to extract heat from the geothermal fluid. The secondary fluid then vaporizes and is used to drive a steam turbine by expanding through the turbine blades (Cao 2021)

2.1 Dry Steam Plants

For conventional steam power plants, water is converted to dry superheated steam and used to expand in a steam turbine to perform mechanical work which spins the turbine rotor coupled to a generator for power generation (Kabeyi and Olanrewaju 2022). For high enthalpy geothermal fluid normally with temperatures above 200^{O}C existing as saturated or dry steam is piped directly to a steam turbine to generate power (Brender 2018). Dry steam geothermal plants are rare because geothermal resources with such favorable conditions are scarce. Such resources are found at Larderello in Italy and The Geysers (USA), Yellowstone National Park in Wyoming (USA) which is in a protected area hence not developed and very few other known places globally (National Renewable Energy Laboratory, 2020). Other sites with dry steam geothermal resources are Lake counties in Northern California, Old Faithful geyser at the Yellowstone National Park in Wyoming, and the Kamojas in Indonesia (Karytsas and Mendrinos 2013)

In dry steam power plants, dry steam is drawn from the production wells and directed to a turbine/generator coupled to a synchronous generator. This technology was first used in 1904 at Lardarello in Italy which is also the oldest geothermal power plant. Figure 1 below illustrates a dry steam power plant.

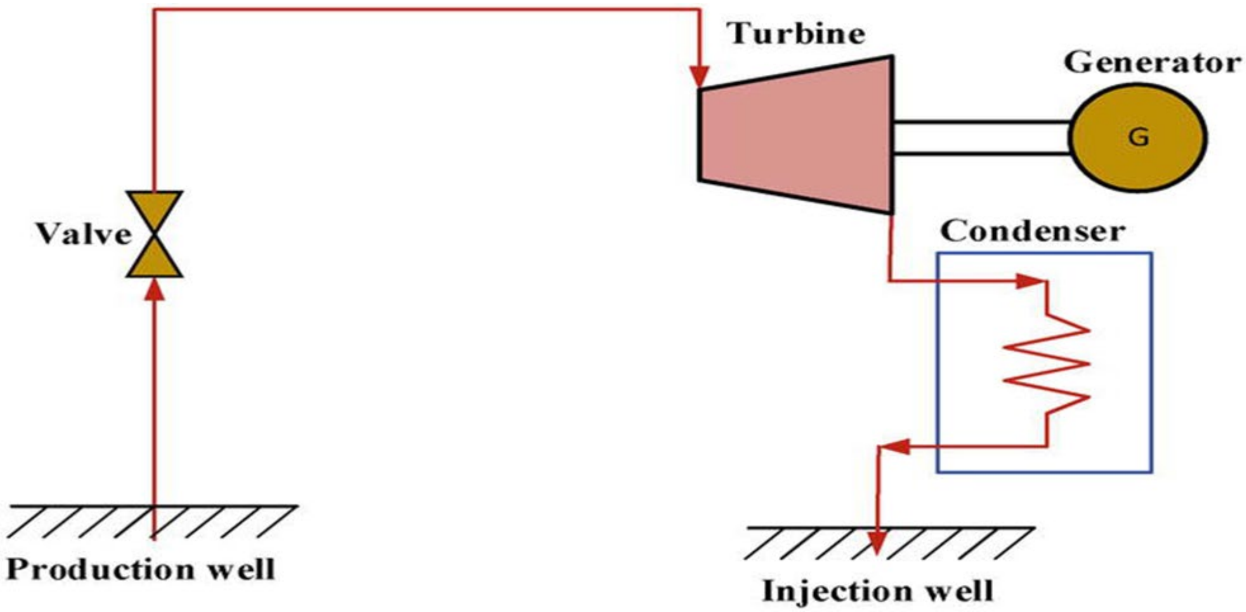

Figure 1. Dry steam power plant

Figure 1 shows a dry steam power plant with steam from the production well piped to the steam turbine through a control valve.

The main features of a dry steam power plant include a production well, injection well, reservoir with dry steam, steam turbine, generator, condenser, and cooling tower. In a dry steam plant, steam is directed from a production well to the turbine from production well is delivered directly to the steam turbine via a strainer to remove any solid impurities while the condensate reinjected through reinjection wells. The average power plant size is 45 MWe.

2.2. The Flash System

A flash system, hot water or wet steam is directed to a separator where it flashes to low pressure steam and a liquid. Pressure reduction of the separator or flash vessel causes the geothermal fluid to flash or vaporizes, into dry steam which is directed to a steam turbine for power generation. The exhaust steam exiting the turbine is condensed and reinjected to the reservoir. Flash systems are used for resources existing as a two-phase mixture at high temperature (Kabeyi et al, 2021). The flash steam power plant systems are equipped with a separator which causes pressure drop that causes steam to be separated from the water. Steam generated is directed to a steam turbine where it expands and condenses. The condensate is collected with the brine and reinjected back into the reservoir (Karytsas C. and Mendrinos, 2013). Flash power plants can be single, double flash, triple flash etc. based on the number of flashing stages (Dipippo 2012).

Single-flash geothermal system is the most prevalent geothermal power generation system globally and remains the most appropriate system of power generation for liquid-dominated geothermal system. In the year 2007, 159 single flash systems were in operation in 18 countries and accounted for 42% of global geothermal generation capacity. The system capacities generally varied from 3 MW to 90 MW while the average capacity for flash power plants was about 25.3 MW. In single flash system, the geothermal fluid from the reservoir is separated in the separator to form steam and brine. The largest single site binary power plant is the 100 MW Ngatamariki power plant in Central North Island of New Zealand, close to Taupo city with average fluid temperature of 193^0C (Valdimarsson, 2011). Figure 3 below illustrates a single flash geothermal power generating system.

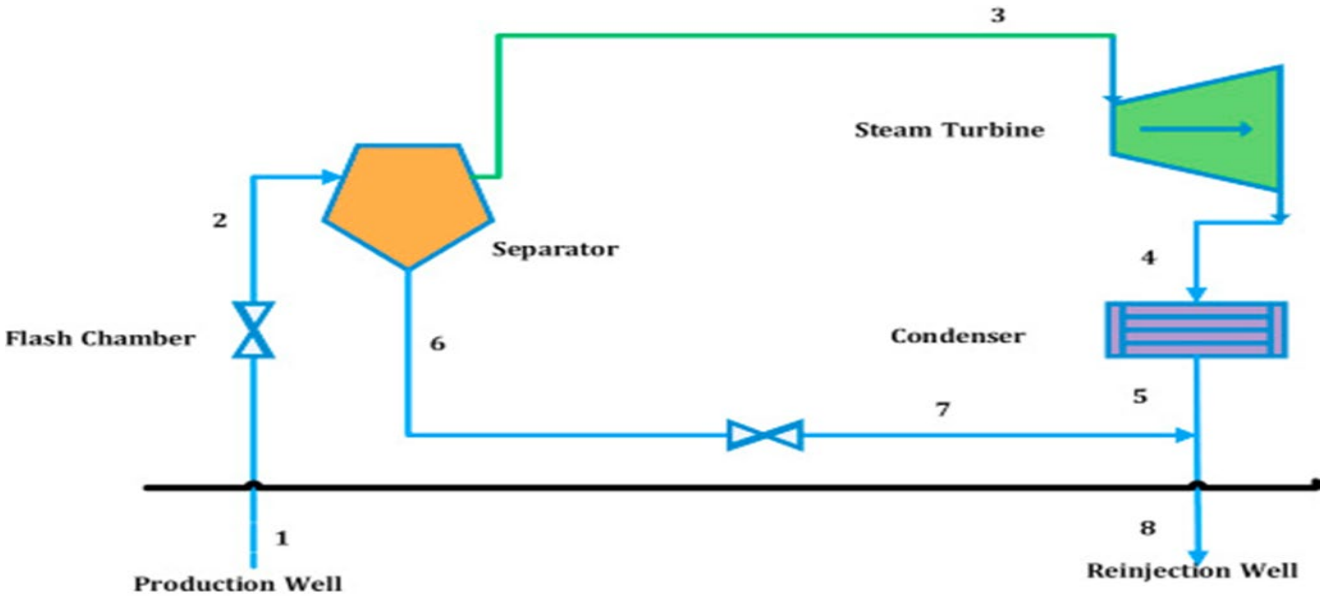

Figure 2. A single flash system

From Figure 2, it is noted that the single flash geothermal system consists of the production well, a single separator which supplies steam to a steam turbine and the injection well which reinjects the brine and condensate to the reservoir**.**

2.3. Binary Power plants

Binary cycles are used to convert medium-low temperature geothermal resources to electric power, mainly as organic Rankine, Kalina cycles and Goswami cycles. Binary cycles use two fluids in a closed loop cycle, one being the geothermal resource fluid and the other an organic working fluid (Meng et al, 2020). The geothermal fluid is passed through a heat exchanger where heat is transferred to a low temperature boiling fluid like Isobutane which acts as a working fluid (Quoilin et al, 2013). The working fluid vaporizes and expands through a turbine which rotates the shaft coupled to a generator for power production. The working fluid is then condensed and recycled through the heat exchanger repeatedly. The geothermal fluid leaving the heat exchanger in a single pass is often reinjected back to the reservoir (WIndrem et al, 1982). Figure 3 shows the general configuration of a binary cycle plant.

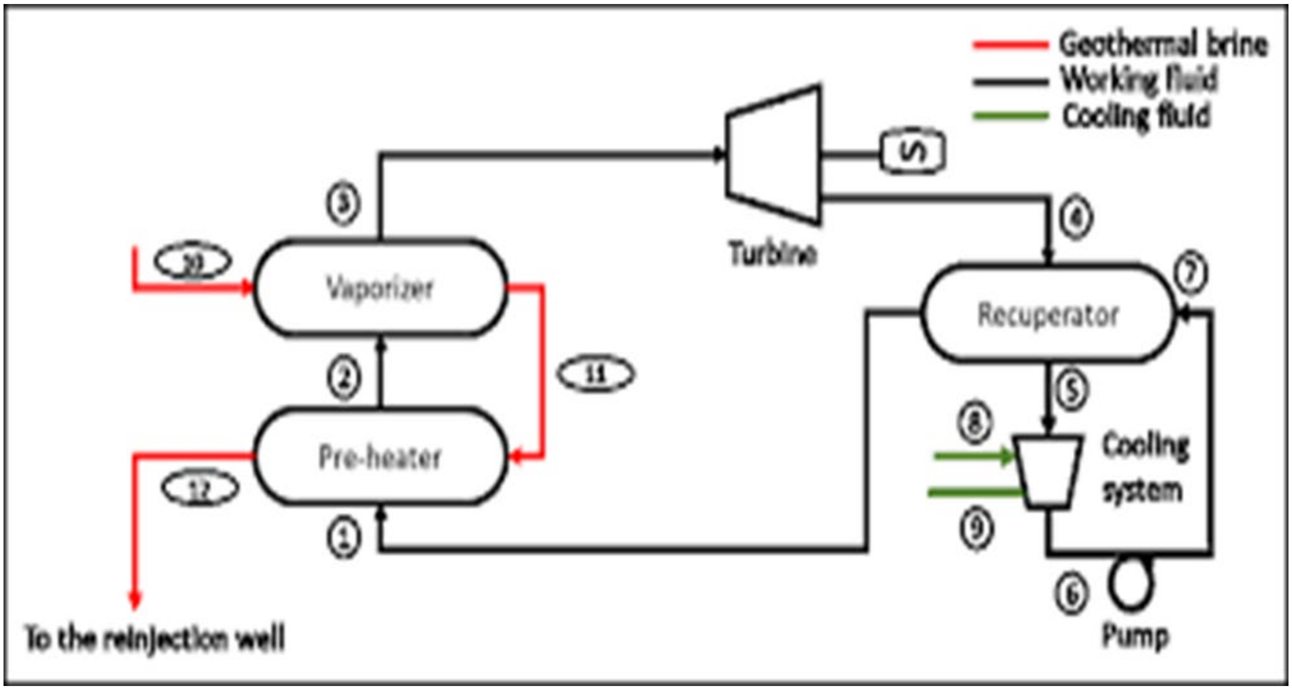

Figure 3. Binary cycle plant

Figure 3 shows that basic construction of a binary cycle with three fluids, namely geothermal fluid, the working fluid, cooling fluid, a preheater, evaporator, turbine/expander and the recuperator. Among binary cycles, the organic Rankine cycle is identified as the best cycle for low temperature thermal energy sources (Herath et al, 2020).

2.3.1. Organic Rankine and Kalina cycles

There are various types of binary cycles used in geothermal power plants based on the selected working fluid. They are mainly classified into Organic Rankine cycles which use refrigerants or organic fluids, Kalina and Goswami cycles which use ammonia mixtures (Dipippo 2007). In Organic Rankine Power plants, the geothermal fluid heats up and pressurizes a low boiling temperature and pressure a secondary fluid like penta-fluoropropane and Isobutane which normally in a closed cycle and hence no mixing. There are various working fluids available for selection influenced by various techno-economic factors. The organic Rankine cycle is a preferred technology for low enthalpy geothermal and for fluid temperatures lower than 150°C. However, with working fluids like R600a/R161 fluids the process can be applied for fluids with temperatures of up to 200^{O}C. The organic Rankine cycle technology is considered mature with many such power plants operating globally, although their sizes are often small hence their lower share of installed capacity (Kabeyi and Oludolapo, 2020). Globally, 162 ORC units were in operation in May 2007 with capacity of 373 MW in 17 countries. This was about 4% of total geothermal power generating capacity yet the in terms of generating units was about 32% of the total. This is because the organic Rankine cycle plants are often small in capacity.

Technically, the binary power plants are designed to operate with two thermodynamic cycles consisting of a geothermal fluid loop and a power cycle loop and are classified as either organic Rankine Cycle plants or Kalina plants based on the working fluid used. Kalina cycles use a mixture of 70% ammonia and 30% water as the working fluid with higher efficiency and exergy potential compared to the Organic Rankine cycles (Koroneos and Rovas , 2013). The Kalina cycle is a modified Rankine cycle uses a distillation separator and absorption recuperator and was invented by Alex Kalina in 1980s. These power plants are safer, have lower capital costs and are simpler with possible applications in both small and big power plants sizes 50-100 MW. With adequate optimization, Kalina cycles can be as high as 2.1 more efficient and generate 14.7% more power output than the Rankine cycle power plants can (Shehata 2019).

The thermal gradient between the geothermal fluid and the working fluid facilitates heat transfer via a heat exchanger. The working fluid is heated, vaporizes, and expands through a turbine which rotates turning a synchronous generator coupled to it for power generation. For power generation. The geothermal fluid from the heat exchanger is then injected in a closed loop, to the reservoir hence lowering emission rates as compared to other technologies of geothermal power generation (Kabeyi 2019). Figure 2 below illustrates an organic Rankine geothermal power system.

The organic Rankine system is a state-of-the-art technology used for conversion of medium–low temperature geothermal energy into electricity. The cycle consists of four main elements or components namely the boiler or evaporator, turbine, with generator, the condenser, and a pump. The fluid is vaporized in the boiler before it goes to drive a turbine or expander for mechanical work production (Meg et al, 2020). Electricity is generated by a synchronous electric generator coupled to the expander. The exhaust from the expander is directed to a condenser where it condenses to a saturated liquid which is pumped to the boiler for another cycle to start in a closed system.

The lifetime of the organic Rankine Cycle power plant is on average 30 years, ORC power systems usually could be up to 30 years, and generally higher than conventional Rankine cycle power plants. The main threat in Organic Rankine cycle plants is condensation of the working fluid in the turbine which can lead to turbine blade corrosion. This can be reduced by working fluid superheating and proper selection of the working fluid for optimum operation.

An organic Rankine cycle generating system has got the main elements being the reservoir, production and used fluid injection well, cooling water feed pump, working fluid feed pump, working fluid condenser and preheater unit, power turbine and a generator unit for power generation. The secondary loop fluid exits the turbine at a lower pressure after expansion in the turbine and goes to the condenser where it is condensed and recirculated (Kabeyi et al, 2021).

Globally today, the binary plants are one of the most widely used geothermal power plants with 155 units in operation in July 2004, that produced 274 MWe of electricity in 16 countries that accounted for 33% of the installed units (Kopuničová 2009). However, because of size limitations as they are usually small in capacity with average size of .8 MW, they accounted for about 3% of the total installed generation capacity of geothermal power. However bigger units of sizes f 7–10 MW have been developed. Most power plants globally use the conventional steam turbines, while about 20%, use the binary cycles. In plant design any power station configuration chosen should seek to maximize the exergy efficiency of the whole system i.e. the resource and plant use not just the system thermal efficiency of the plant.

2.3.2 Organic flash cycle (OFC)/Regenerative cycles

An organic flash cycle (OFC) is said to be a modified trilateral cycle that avoids the state of isothermal evaporation and avoids a two-phase expander in the cycle and as a result the organic flash cycle significantly reduces the irreversibility during the evaporation of the working (Kabeyi and Oludolapo 2020). The working fluid is heated to saturation and flashed by throttling. The saturated vapor from the flash separator then expands through a turbine hence doing some work and rotating it. In a basic organic flash cycle, the working fluid in saturated form from the separator and turbine exhaust are responsible for the largest part of the total heat input. System performance can be improved by recovery of heat from the saturated liquid or the turbine exhaust to preheat the working fluid (Ho et al, 2012).

Organic Flash Cycles (OFCs) are used to achieve a good temperature match between the two fluids to minimize heat loss from a saturated liquid in the flash separator which reduces the cycle efficiency. Thermodynamic performance can be improved by regeneration through recovery of more heat from the saturated liquid to be used in preheating the working fluid [35]. In regeneration, the evaporation and flash temperatures are optimized for maximum net power generation for geothermal fluid temperatures between 120 °C to 180 °C having reinjection temperature of 70 °C. The optimal flash temperatures for organic flash cycle with regenerator (ROFC), the organic flash cycle with regenerator and organic flash cycle with internal heat exchanger (ROFC + IHE) as well as the modified organic flash cycle (MOFC) low compared with that of a basic organic flash cycle (BOFC) because of the limits of the preheat load and the pinch point which lead to a higher vapor mass flow rates. The net power output increases and the decreases in the evaporator exergy losses by ROFC, ROFC + IHE and MOFC compared with those of BOFC tend to decrease with increasing geothermal water inlet temperature. A modified organic flash cycle (MOFC) can produce maximum net power which is up to 66.2% greater than power from the basic organic flash cycle (BOFC) for a geothermal fluid temperature of 120 ℃. The main limitation of the modified organic flash Rankine cycle (MOFC) is that it requires more evaporator area of about 51–78% , less condenser area by 13–42% less to produce same power as the BOFC (Meng et al, 2020)

In the study by Ho et al, (2012) involving the use of a double flash Organic flash cycle O(FC), a modified OFC, two-phase OFC and a 2 phase MOFC showed that modified OFC (MOFC) generated 10–12% extra power compared to a conventional ORC. To reduce throttling irreversibility, a two-phase expander was adopted in the place a high-pressure throttling valve in the two-phase OFC. A two- phase MOFC produced up to 20% more net power compared to an ordinary ORC (Ho et al, 2012). In terms of thermodynamic efficiency and economics of OFC and regenerative cycles (OFRC) (Baccioli et al, 2017), it was established that the unit cost of the OFRC was reduced and the efficiency of a double-flash OFRC was better than that of conventional ORCs (Fischer 2011). Figure 4 shows an organic flash cycle.

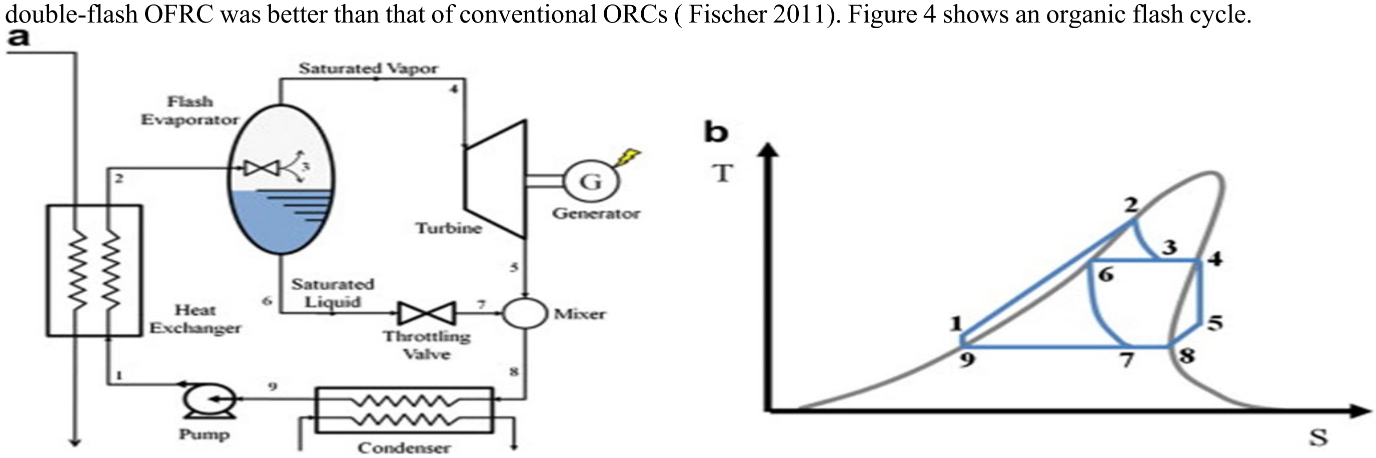

Figure 4. Organic flash cycle/Regenerative cycle

Figure 4 shows the main elements of an organic flash cycle in 5a and a T-S thermodynamic representation of the cycle in 5b. The main elements are the flash evaporator, heat exchanger, condenser, pump, mixer, and throttling valve.

2.3.3 Supercritical Organic Rankine Cycles

Supercritical ORCs, the Organic Rankine cycles applying zeotropic mixtures, trilateral cycles as well as the organic flash cycles (OFCs) can improve the temperature matching and thermal efficiencies. In a supercritical Organic Rankine cycle, the evaporation pressure for a supercritical ORC should be made greater than the critical pressure of the working fluid to avoid the isothermal evaporation which improves temperature matching between the working fluid and the heat source fluid. However, higher turbine inlet pressure causes an increase in pump power consumption, increases the investment cost, as well as operational safety requirements. The use of a non-isothermal phase change of a zeotropic mixture allows for a good match of the temperature profiles in the process of evaporation and condensation. The main challenges of zeotropic mixtures are the uncertainty over the thermodynamic properties of the fluid which inhibits accuracy of computational models and efficient system design. Additionally, the heat transfer coefficients of zeotropic mixtures are lower hence require larger surface areas for adequate heat transfer. In a trilateral cycle, the liquid-phase working fluid absorbs heat from heating fluid in the cycle. Desired reduction in heat transfer irreversibility by adaptive temperature matching between the working fluid and the heat heating fluid. However, the design of two-phase expanders with high isentropic efficiencies is still challenging. Figure 5 shows the main processes and stages in a supercritical cycle.

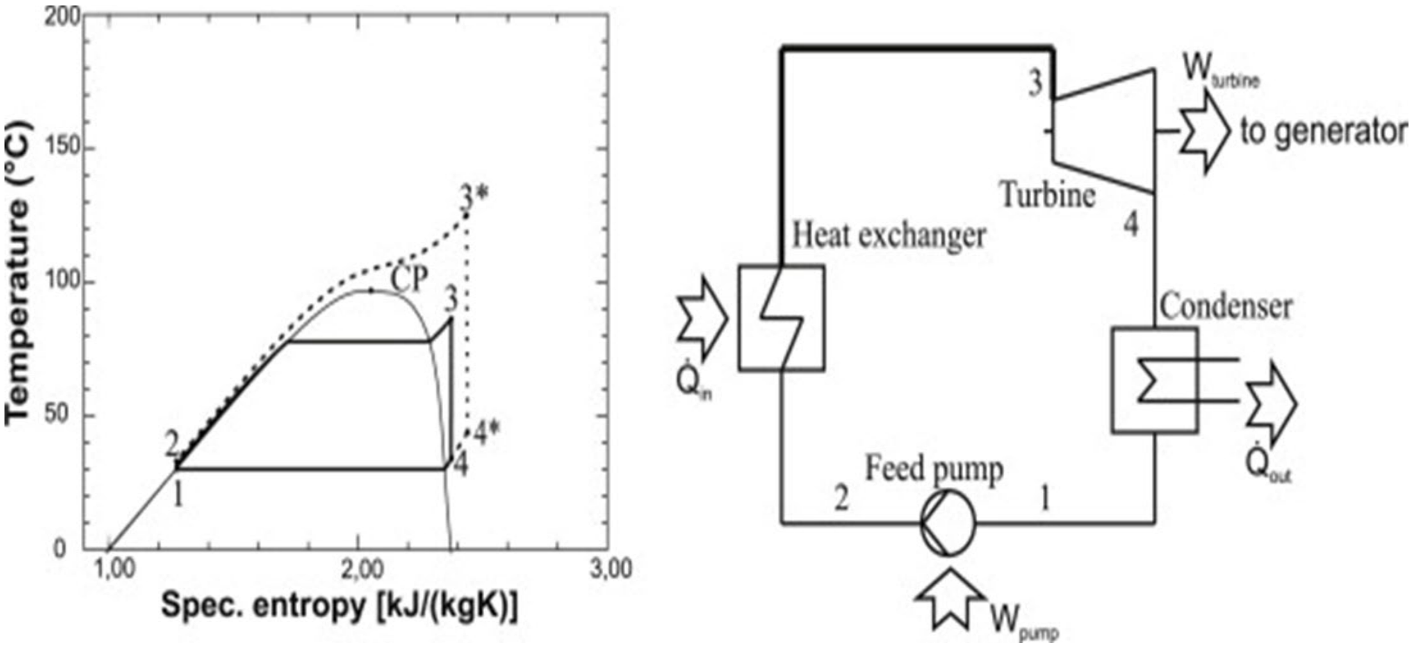

Figure 5. The Supercritical Rankine cycle

From Figure 6, the main process of a typical supercritical cycle which include, regeneration, boiler superheating, reheating, expansion, and condenser heat rejection.

2.4 Combination Cycles

Combination conversion cycles constitute a combination two or more of the basic conversion cycles i.e., dry steam, flash, and the binary cycles (Kabeyi et al, 2019). The suitable combination is selected based on the steam temperature and pressure conditions, reservoir and fluid characteristics, investment cost, and application among others. Combinations include flash and binary, dry steam and binary, flash, and binary combined. Where a flash/binary hybrid plant is used, the fluid is first flushed to steam in a separator then steam is fed to the turbine as the separated liquid is directed to a binary cycle plant for extra power generation (Geothermal Energy Association , 2020). Other examples of combinations are single flash/binary, Any combination adopted should guarantee a higher efficiency, list cost and maximum out (Dipippo 2020).

2.4.1 Flash/binary combined cycle

Depending upon of field characteristics, a geothermal power plant design can be such that it starts with a flash cycle followed by a binary unit which uses waste geothermal fluid to as the heat source and a secondary fluid on the working cycle to generate extra power. This will form a combined or hybrid flash-binary plant. In the first cycle, a flash plant is operated by geothermal fluid from the production which acts as the working fluid and is directed to reinjection well after exiting the turbine but with possible heat recovery before it goes back to the reservoir (Spadacini et al, 2017). The waste leaving the separators can be sent directly to injection wells or can be send to the binary station for heat recovery. This improves overall generation since extra electricity is generated from the same geothermal fluid (Dincer et al. 2020). Figure below illustrates a combination power plant.

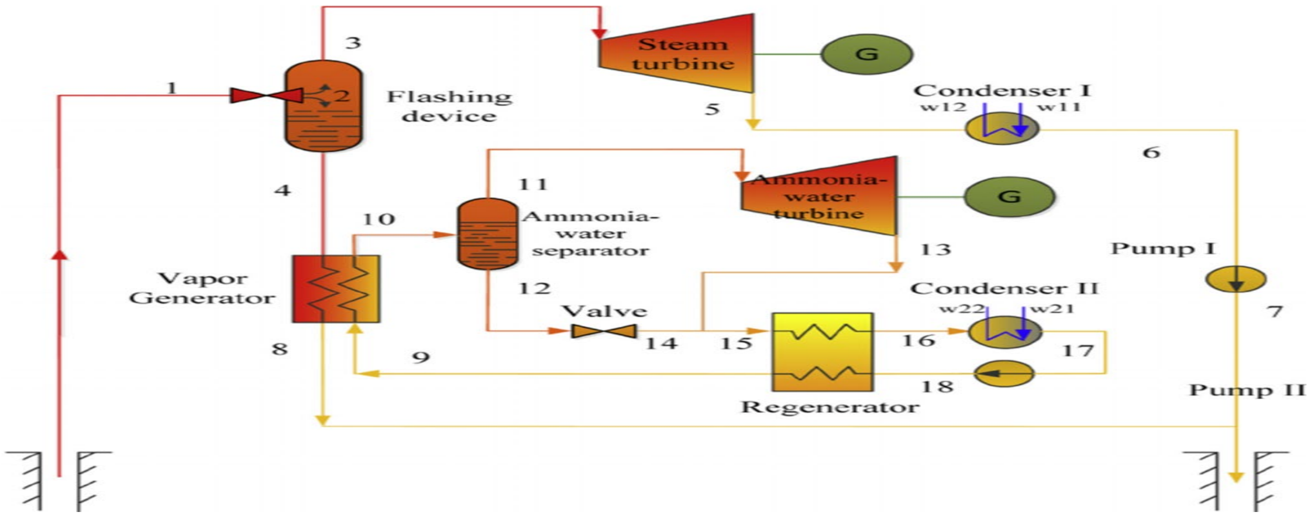

Figure 6. A combination flash-binary plant

Figure 6 above shows a combination flash-binary power plant with two turbines, one driven by steam from the production well flashed in the separator while the second one uses a binary fluid heated by separated brine on its way to the injection well. Steam turbine exhaust is condensed and before injection back to the reservoir via the injection well.

2.5 Hybrid/Combined Cycles

These are integrated geothermal energy conversion systems i.e. hybrid or geothermal system in combination with at least one other different source of energy like solar, coal, etc. (hybrid). The overall objective in either arrangement is to achieve synergy and hence realize superior performance compared to separate or individual arrangement. The benefits include higher utilization, higher thermal efficiency, increased net power output or more financial and economic benefits. Geothermal combined systems may consist of different types of flash-steam units and/or binary plants in an integrated combination that achieves advantages and benefits not realizable in separate units. Examples of hybrid systems include fossil-fueled plants, such as coal-fired central stations, gas turbines, biomass, or waste-to-energy plants, or concentrating solar thermal or photovoltaic plants working in conjunction with geothermal power plant cycles like flash, binary or dry steam systems (Dippo 2016).

2.5.1 Solar-Thermal combination plant

An example of a combination plant is the solar–geothermal plant whose main challenge in designing and managing the intermittent nature of solar energy versus the continuous nature of geothermal energy. Solar energy can supplement both geothermal binary and flash-steam plants by means of superheating and/or preheating of the working fluid. A basic binary cycle plant with a solar array of parabolic collectors is used to superheat the binary working fluid before it is fed to the turbine. The main challenge is the intermittence nature of solar availability and hence heating. Figure 7 below illustrates a basic binary cycle with solar heating of working fluid.

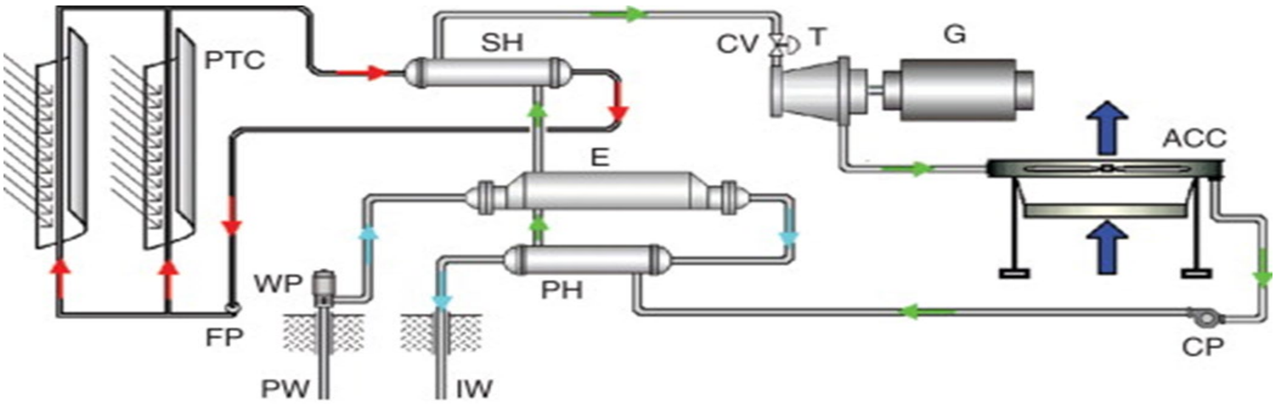

Figure 7. Basic binary cycle with solar heating

Figure 7 above shows the main elements of a basic solar thermal power plant. They are the geothermal production well (PW), the solar concentrator (PTC), the flash separator (SH), control valve (CV), steam turbine (T) electric generator (G), coolant pump (CP), evaporator (E), preheater (PH), feed pump (FP) and the condensate cool (ACC) (Dincer and Abu-Rayash 2020).

In the case of a more complex flash-binary plant with solar-brine heating, a moderate-temperature geothermal brine is heated with solar energy to the design flash temperature. This is followed by a topping up back pressure turbine to generate power to augment the binary cycle power coming from turbine the first turbine. The condensate of the solar power-driven turbine is used as feed to the condenser/preheater (C/PH) before being reinjected. The hot-separated brine is then used to heat up the binary working fluid, then mixed with steam condensate before reinjection. When used with an air-cooled condenser as shown below in figure 8, this operation provides 100% reinjection of the geothermal fluid.

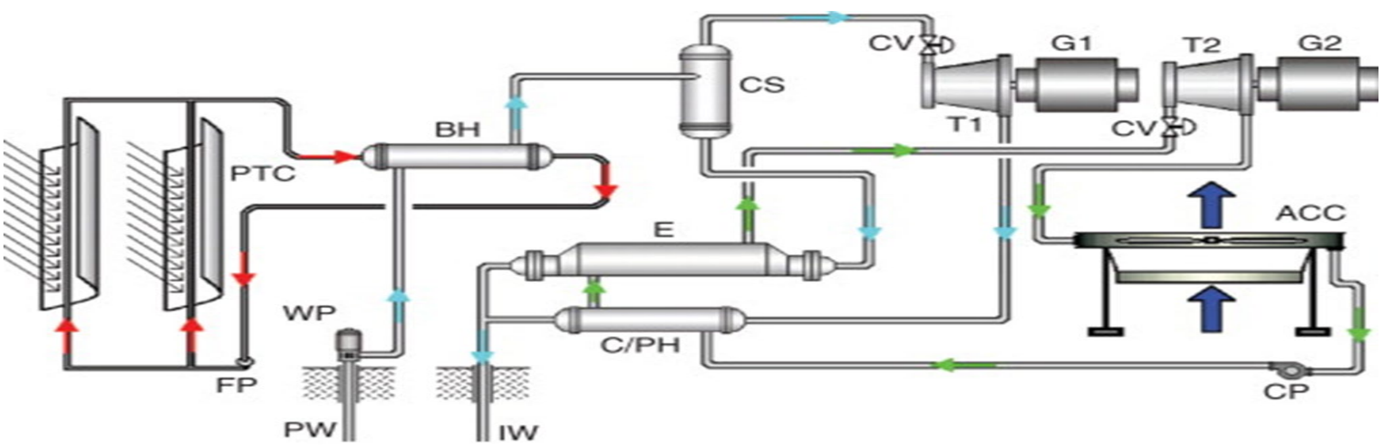

Figure 8. A binary cycle with solar-brine heating of working fluid

Figure 8 shows a binary solar combination power plant where the solar is used to superheat the working fluid before it goes to the first turbine T1 whose exhaust is preheated by the waste geothermal fluid leaving the separator (CS). The exhaust of the second turbine (T2) is mixed with exhaust of the first turbine (T1) before the mixture is heated by brine and used to run the second turbine as the working fluid.

2.5.2 Fossil-Geothermal power plants

It is possible to develop a combination of fossil fuel power plant and geothermal energy source for electric power generation. This combination of geothermal energy and fossil fuels for power generation offers many thermodynamic advantages compared to individual technology approach. Different approaches that can be used include fossil superheating of geothermal steam, use of geothermal heat in preheating of fossil fuel power plants feed water which then replaces some high grade steam which can be used for extra power generation, and development of a compound geothermal fossil power plants (Liu et al. 2016).

2.6 Combined Heat and Power/Cogeneration Cycles

Combined heat and power is simultaneous generation of electricity with heat or thermal applications which significantly improves the overall cycle efficiency (Bruhn et al, 2019). Use of cogeneration systems leads to higher thermodynamic and environmental performance and reduction in unit cost of energy. CHP is increasingly applied in geothermal energy exploitation as well as other renewable sources of energy like solar, wind and biomass. With huge quantities of low grade heat in geothermal fluid, cogeneration has a special role in geothermal energy utilization (Kabeya and Oludolapo 2021).

Cogeneration systems are classified into topping and bottoming up based on the sequence of energy exploitation adopted. In topping cycles, the energy supplied is first used for power generation followed by heat energy application, hence heat is a by-product of the cycle. Topping cycle is the most ideal for geothermal energy (Bhatia et al. 2014). For a bottoming cycle, the energy is first used in thermal processes while rejected heat is used in power generation. These cycle are ideal in manufacturing like cement, iron and steel, ceramic production , gas production and petrochemical industries (Dincer et al, 2020).

3. Technical Considerations in Geothermal Power Plant Design

3.1. Fouling/Scaling Effect

The chemistry of the geothermal fluid has significant concentrations of minerals and gases which can cause scaling and corrosion of the installations which the geothermal fluids flow through. Geothermal resources have a very high mineral content dissolved in water to form brine. Some of the minerals contained in the geothermal fluid include magnesium, potassium, calcium, and sodium with actual composition varying from one geothermal field to another. The chemistry off the geothermal fluid varies mainly according to temperature, but generally the fluid is dilute for low-temperature fields (Gunnlaugsson et al. 2014). However, upon flashing, the concentration of the minerals increases to very higher level hence the risk risks of fouling or scaling. The process of removing heat from the brine using preheater and evaporator further increases the risk of fouling as scaling increase with reduction of temperature. Solubility of the materials reduce as the temperature reduces hence the fouling menace for heat exchangers in organic Rankine Cycle power plants.

The various types of scales realized in geothermal fields include carbonate minerals (calcite and aragonite), metal oxides, amorphous silicates, and sulphide. The most common geothermal scales are silica (SiO_2), and calcite ($CaCO_3$) are the most common scales in geothermal installations. These scales are white colored and visually difficult to distinguish from one another but in some cases the silica scales are grey or black due to small amounts of iron sulphide, which is a corrosion product in all geothermal pipelines (Boch et al. 2017). In a quick test, a calcite scale is identified putting a drop of hydrochloric acid on a scale sample, and appearance of bubbles will confirm the presence of calcite scales (Gunnlaugsson et al. 2014).

The measures proposed to contain the effect of fouling in the heat exchangers include.

i.) The heat exchanger is designed such that the working fluid i.e., pentane will flow through the shell side while the hot brine is contained in the copper tubes of the evaporator. This makes maintenance easier since the fouling fluid is on the easier to clean shell side.

ii.) The temperature of the brine should not be cooled below 130^0C. Below this temperature, precipitation will occur leading to formation of an insoluble calcium carbonate salt that will yield up to form scales that may cause pipe blockage or even pipe burst.

iii.) To design against scaling in the heat exchanger, the flow direction and variables are considered to increase the velocity of the brine in the heat exchanger. The heat exchanger is tilted at an angle to allow brine flow to flow at higher velocity in the copper tubes.

iv.) Furthermore, any formed scales can be wiped out and carried away by gravity as the brine flows in the copper tubes of the heat exchanger.

v.) Use of chemical additives such as scale inhibitors and anti-scalants to reduce the carbonate concentration in the brine to reduce the Calcium carbonate formation.

Careful material selection is very important in original design of geothermal plants for long and reliable service. However, geothermal fluids are in most cases not corrosive and hence the main casing and pipe material selection is using mild steel. Experience has however shown many cases of manageable localized corrosion challenges in many geothermal installations, which require proper material selection, as well as good engineering practices operation and maintenance. The condensate is corrosive and hence stainless-steel pipes or fiberglass are required. Due to the presence of H_2S, Copper material is not recommended. There is additional requirements to for the air control room to filter H_2S from in the ambient air to protect the copper wiring and switchgears(Boch et al, 2017, Corsi et al, 1986). The use of surface-active inhibitors to prevent the formation of deposits and erosion–corrosion processes is another measure that can enhance corrosion and scaling control in geothermal power plans and can be considered in the detailed design phase (Tomarov et al, 2015).

3.2. Cavitation in the ORC Turbines/expanders and Pumps

Cavitation is a phenomenon that occurs when part of liquid suffers encounters vaporization when the absolute pressure in a local fluid field is reduced to saturated vapor pressure(Li et al, 2020). Cavitation is common in Organic Rankine cycles due to the low boiling temperature of most organic fluids. Cavitation occurs in pumps, turbines, and other rotating machines. The main cause of cavitation is dynamic variations of pressures and temperatures in the fluid system. In a pump, it occurs in the suction stage when pressure in the liquid is instantaneously reduced to or close to the fluid saturation pressure that corresponds to the liquid temperature. Cavitation in pumps degrades performance, causes noise, vibration, and mechanical damage. Cavitation can be reduced in pumps by providing adequate net positive suction head (NPSH), or net positive suction head available (NPSHa). This is the total energy of a fluid at the inlet of the pump less saturated vapor pressure at the operating temperature (Li et al, 2020).

Cavitation can degrade the evaporator performance and system instabilities during operation. It is important to establish the correct net positive suction head or sub cooling for the pump in ORC system design and operation as a strategy in cavitation management. Cavitation is encountered whenever the vapor pressure is higher than the fluid pressure which the liquid at higher pressure to flash into vapor and the bubbles formed are carried by condensing water streams to higher pressure zones where they condense into liquid form. The surrounding fluid then rushes into the cavity giving rise to a very high localized pressure reaching about 7000 atmospheres. This may occur repeatedly in hundreds of times per second. This phenomenon is thus termed cavitation, and it is accompanied by considerable noise and vibrations. This calls for less durability of turbines and lower turbine operating efficiency.

Ultra-high expander torques lead to attainment of saturation vapor at the turbine/expander inlet which causes the liquid droplets induced shock wave to cause deterioration of expander performance. To avoid this, it is necessary to operate within an optimal range of torques for the expanders to ensure better expander performance. In pumps, sub cooling of the liquid working fluid by 20 °C can minimize pump cavitation (Tomarov et al, 2015).

Some design measures that can be applied to reduce cavitation ad its impact include.

i.) The match between pump and expander*:*

There is need to match the expander and pump parameters like capacities, state parameters, efficiencies, working pressures, enthalpies Matching of thermodynamic parameters for the pump and expander applies to both steady and unsteady organic Rankine operating conditions (Li et al, 2020).

ii.) The match between evaporator and condenser

Heat transfer and phase change takes place during evaporation and condensation creating considerable pressure drops often neglected during thermodynamic analysis which calls for careful design analysis in the design of heat exchangers. Evaporation and condensation heat transfer take place in the two heat exchangers. The phase change heat transfer coefficients of organic fluids are significantly lower than those of water. The heat exchanger design should match the two-phase flow and heat transfer between evaporator and condenser (Yang et al, 2015).

iii.) The match between heat source and ORC

Organic Rankine cycles are significantly affected by the heat supply. Increase in heat source temperature increases pressure and so is increase in flow rate of heat carrier leading to more power output. These changes should be matched with equivalent increase pumping to adapt to changes in temperature and flowrate. On the other hand, a decrease in heat supply reduces cycle power r output and system efficiency hence the need to match the cycle parameters to changes in heat supply (Li and Yu 2021)

iv.) proper material selection (either alloy steels or stainless steels), adequate polishing of turbine surfaces (proper machining)

v.) Selecting turbines with low specific speeds. This being a design. consideration, impulse turbine is selected because it operates at lower specific speeds.

3.3. Cooling for Organic Rankine Cycle

Power plants have high cooling water requirements and account for a significant amount of fresh water requirements. For example, about 41% of US fresh water consumption goes to cooling in power plants, of which 90% is employed in condenser cooling (Roy and Chen 2011). A simple and low-cost water-to-steam is historically applied for condensers and account for about 43% of the US power plant cooling systems (Bustamante et al. 2016).

It is necessary to cool the turbine or expander exhaust fluid before recirculation. This is usually done in condensers. An ideal coolant is needed to extract heat to desired temperature before recirculation usually by use of air or water. Air has lower heat transfer which leads to a larger heat transfer areas and volumetric flows compared to water. If water is used as a coolant for the Organic Rankine cycle, a shell and tube heat exchanger is preferred since it offers greater flexibility in design, and they are ideal for some liquid coolants. If air is the coolant used then a cross-flow finned tube heat exchanger is the preferred choice because it has high heat transfer area densities thus reduces the mass and volume flow rate requirements (de la Fuente et al, 2018). Since water has got a higher heat transfer area, its use as the coolant reduces the size of the heat exchanger. The finned tube condenser can be made of aluminum (Bustamante et al, 2016).

The use of air cooled condensers in power plants leads to a 5–10% plant-level efficiency penalty when compared to power plants applying a once-through cooling systems or wet cooling towers where water is often the coolant. The use of air-cooled condensers also requires substantially higher capital than wet-cooled condensers because of the use of large, finned surface areas which additionally need more in support structures (Park and Jacobi, 2009).

Air-cooled condensers have common applications in geothermal power plants. The Air-cooled condensers are flexible compared to water cooled condensers, they require less maintenance than water cooled than water cooled condensers and cannot cause undercooling or unnecessary over cooling. In air-cooled condensers operate by rejecting heat directly surrounding air. Therefore, the condensing temperature is a function dry-bulb temperature of the ambient air. The main advantage of air-cooled condensers in geothermal power generation is the low water requirements making them ideal for application in water scarce like deserts (Zachary 2012).

3.4 Non-Condensable Gases

Non condensable gases (NCGs) are gases which cannot condensed in normal operation. These gases include ordinary air and nitrogen. Non condensable gases exist in four mains. Firstly, can permeate the system through poorly sealed pipes and valves. The second method is through generation from the decomposition of the working fluids at temperature and action of corrosion of devices during operation (Bao and Zhao 2013). Thirdly, some non-condensable remain in the system after vacuum-pumping. Finally, non-condensable gases may infiltrate the organic Rankine cycle during repair and replacement of components. With application of silicone oils as favorably choice for high temperature applications, the ORC system can be troubled due to low saturation pressure of silicone oils at room temperature.

It is very difficult to have total sealing of the system for long-term working conditions, making control of non-condensable gases in the Organic Rankine cycle a complicated undertaking. Non-condensable gases (NCGs) are present in organic Rankine cycle (ORC) system, with adverse effects (Bao and Zhao 2013). In the study, it was observed that the accumulation of non-condensable gases led to unexpected expander backpressure, which was as high as 0.68 bar higher more than saturation pressure. The non-condensable gases have overall effect of reducing the power output of the Organic Rankine cycle (Li et al. 2018).

Therefore, since non condensable gases in the Organic Rankine cycle have a negative impact operation, maintenance and output, they should be controlled through proper operation, maintenance, selection of the correct working fluids and provision for removal of the gases from the system through well designed and located venting outlets. The cycle operating conditions should also be monitored and well designed to limit entry and generation of non-condensable gases.

4. Results and Discussion

4.1. Binary Versus Open cycle power Plants

It is both economical and technically feasible to generate electricity from low-temperature heat sources generally 80–300 °C like geothermal, waste heat, solar, biomass, cooling water, etc. The Organic Rankine Cycle (ORC) as applies organic working fluids get higher efficiency than the conventional Rankine cycle which uses water as the working fluid.

This study showed that brine leaving a single flash geothermal power plant has significant quantities of recoverable energy for extra power generation using binary thermodynamic cycles. Various binary cycles and working fluids can be used based on the condition of the geothermal fluid mainly in the form of fluid temperature. The organic Rankine cycle for geothermal power generation is a mature technology preferred for use in low and medium enthalpy geothermal. This study shows that different working fluids have differences in performance characteristics, making selection of an organic fluid a very important function in the design of an organic Rankine system. Comparison between, Isopentane and n-pentane similarly exhibited differences in properties with n-pentene exhibiting superior performance in terms of power plant thermal efficiency and power output, but research on use of mixtures of organic working fluids tend to yield attractive results in terms of cycle performance. The main cost item in the proposed expansion is cost of plant and equipment, although other costs are installation costs like transport, construction, staff training and development and operation and maintenance of plant. Technical evaluation shows that the investment is technically viable while projected economic performance proved that the plant is economically viable. Overall, the power plant efficiency will improve, revenue will increase, and extra green power means reduced carbon emissions and sustainability in power generation through fossil fuel substitution in power generation from renewable, low carbon and reliable geothermal power generation.

It may be concluded that the ORC is ideal for low-grade heat recovery, but optimum performance requires a careful selection of the working fluid based on the thermodynamic conditions of the heat source, required exit temperature and the expected work output within existing budget outlay.

5. Conclusion

Geothermal energy is renewable energy resource found in the earth's surface with potential for several application including geo-exchange, direct application, and power/electricity generation. With high load factors, geothermal power plants are ideal for base load electricity generation. Geothermal energy systems have proved to have minimal environmental footprint, won't be affected by climate change, and have potential to become the global cheapest source of sustainable renewable energy with zero-emission, with ability to supply direct thermal use and power generation. With geothermal energy, displacement of more emissive and hence polluting fossil energy supplies is expected to play a crucial role in enabling both energy security and climate change mitigation strategies. Although, geothermal energy is now considered a mature technology but only realizes growth of 3-4% per year with global untapped capacity of more than 100GW.

Geological factors make it impossible for some countries or geographical locations to realize geothermal energy. Slow growth is due to natural disasters in some countries, permitting and regulatory problems and processes, cheap fossil fuels which makes it harder to get financing and general nature of available technologies. Effort should be made to increase the rate at which this significant potential is tapped into. Technologically hydrothermal geothermal systems with wells down to 2-3 km provides a mature technology, enhanced geothermal systems at 3-5 km depth provides new technology while supercritical systems at 5 -10 km depth are a future technology in geothermal development. Wellhead technology currently provide a quick access to geothermal electricity ahead of full development of a conventional power plant as demonstrated by several operating wellhead plants in Olkaria steam fields in the Kenyan Rift Valley. The attitude of local communities at geothermal project areas significantly influences success rates of the project. Strategies used to obtain acceptance, agreement, or at least the tolerance on the project works by the people residing in the project area also called social acceptance, or social consensus of the project include prevention of adverse effects on people's health, minimization of environmental impact, and creation of direct benefits for the resident communities. During project execution, effort should be made to create local social benefits to the community like employing locals and providing incentives to the community through sponsoring community projects and infrastructure. Legal framework can be put in place to enforce environmental, health and safety issues related to geothermal energy development and exploitation. Close monitoring and control of environmental issues and effective social responsibility initiatives can be used to mitigate negative environmental and social effects of geothermal development.

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