POWER PLANT SYSTEM ENGINEERING

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Module 4

Lec 7: Geothermal Energy

Dear learners greetings from IIT, Guwahati. We are in the MOOCs course Power Plant System Engineering module 4 that is Hydro and Renewable Energy Power Generation Systems. In today's lecture we will focus on another category of renewable energy that is geothermal energy. So, we will touch upon topics like origin of geothermal energy, different types of geothermal energy systems and most possible and effective way of harnessing this geothermal energy are of two types & they are mainly on hydrothermal systems. And we call them as vapor dominated system and liquid dominated system. So, they are typically hydrothermal systems and why we say hydro because mostly the working fluid is water. So that is the reason, we say it is a hydro. However this water is not in its purest form it is highly saline and at the same time there are many gaseous components which are already present in this water. So, that water content is called as brine. So, I will talk about those aspects in this lecture.

Now, let us understand that where we are in, if you look at power generation systems through fossil fuel energy as a reference. So, in this fossil fuel based power generation systems that is mostly steam power systems, our main focus was on the energy that comes into this systems through boiler or steam generator is fossil fuel combustions or coal based combustions in presence of air. But due to depletion of fossil fuels, we switch upon to other sources of renewable form of energy they are geothermal, solar, nuclear; these are possible ways. And till this point of time we have covered this passive forms of solar energy which are available in nature. These are called wind energy, then ocean temperature energy conversion OTEC plants, then we have hydroelectric energy that comes by virtue of solar heating and is available in the form of rain, creating a dam we can store the energy of water and that energy is the potential form of energy and through this process we convert them to kinetic energy and subsequently by rotating the turbines, we get to harness the power.

Then we have this tidal energy which is mainly by virtue of the gravitational effects of lunar and solar cycles on the ocean surface. So, basically all these forms of energy, which we have discussed so far, are renewable form because they all of them come from the solar energy and effect of solar energy on this surface itself. So, we will talk about the solar energy much later. But now let us dig into the fact that whatever form of energy, which is available on the surface, is termed as renewable energy, but there are other possible ways like energy is also available in the earth's crust. And that is also renewable form of energy and they comes under the category of geothermal energy.

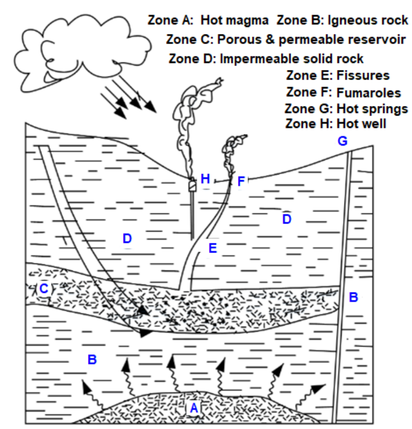
So, basically geothermal energy is also kind of renewable energy, but it is not available on the surface or in the higher atmosphere, but it is underground. So, it is available in the earth's crust. So, we know that formation of earth has started millions years ago and if you take a look inside the crust of earth, there are all the materials and as earth crust is mainly made out of carbon materials, so these are available in plenty within the earth's crust. So, if you dig into the earth, we will find many sources of energy. The energies resources are available in plenty and these are nothing, but your heat source. And if you can tap those heat source then we can get a substantial amount of energy which is capable for running a power plant system.

So, we can say that geothermal energy is a kind of a natural energy resources and these are available since the formation of earth. But till this point of time our main attention was mainly high energy density contents and those are in the form of fossil fuels. So, essentially all the fossil fuels like all the petroleum products are derived from the earth's crust and till this point of time there was no scarcity. But since there is a scarcity of this fossil fuels now because rate at which energy demands are coming, the fossil fuels are no longer in a position to supply for these demands. Although nature makes its own fossil fuel through its ecological processes, yet what happens is that the rate of demand is much higher. So, it cannot supply. So, human attention is now more focused to other sources of natural energy which is again available in the earth's crust, but these may have lesser energy contents and those energy contents are still unattended because with our available technology so far we are not able to reach those energy resources. But now time has come, since the fossil fuels are depleting, we should also dig into those low energy contents which is available in the earth's crust. But these are predominantly available in some localized pockets under the earth surface. So, basically these low energy contents are not available in every places on the earth, rather they are available in specific locations on the earth surface.

So, essentially geothermal energy is available at some locations, where we used to see volcanoes, we used to see lavas. That means, energy from earth's crust tries to come up in the form of fire or high density gas from the earth's crust through some passage or vents. So, if you can tap those kind of energies then it becomes a better usage of our natural resources in the form of renewable energy.

So, now let us see what is this geothermal energy? Let us try to understand the origin of geothermal energy. So, what we can claim like this is that geothermal energy is the energy resources available in the form of heat and this heat has to be transported from the interior earth through steam or hot water. That means, if we can tap this in the form of hot water or steam, then we can harness this. So, it is also a form of renewable, but these are not available in plenty at every location of earth's interior, but geographically these are available at some specific locations. But unfortunately with our available conventional technology we are not even able to extract that energy. But how can you say that the location is a geothermal site? We will find those locations which are more prone for volcanoes, lavas flows, hot springs, geysers, like some hot spray of water that comes out from the underground and that is the location which can be treated as a geothermal energy resources. So, just to give some history of this resources, earth is said to have been created by a mass of liquids and gases out of which 5 to 10% are the steam. So, when this fluid cooled down by losing heat at the surface that means, these steam when tried to come out of the surface, these tried to cool down by losing heat surface, the outer solid crust is formed with an average thickness of 32 km. So, these are the realistic numbers that has been taken from the book. So what happens is that inside the solid crust when those energy find some passage to come out, these come through certain vents or some passages and through that passage when these come out, they try to cool down. When they cool down they condenses as water and the water we see in the sea or oceans is nothing, but that has come from the earth crust and that is what is claimed. Now if you actually dig into the earth crust, we have molten mass that is called magma and till now also these magmas are in the process of cooling. So when they cool on the earth surface they forms seas or lakes and oceans. Another point I would like to mention is that the historical background tells about many earth tremors. That means, whenever there is some kind of an earthquake, so we will find some kind of disturbances in the different layers of earth surface. So, due to these disturbances in layers, there are some passage or cracks which starts developing inside this earth crust and those are the kind of the passages that gets initiated for this formation of this volcanoes or lavas. Now through this process what happens whatever materials are stored inside the earth, they try to come out. So, initially it starts with this magma, so when the magma tries to come out through this, we will have steam, brines. And during this, they come out by mixing with different parts of earth crust. So, thereby many gases are also diffused within that component and we call the entire thing as a brine. So, essentially when you dig into earth surface and if you go much much deeper, then whatever liquid material that we are going to extract will be called as a brine because it is a mixture water and so many other gas components. So, that is the main reality of this geothermal systems.

Now with geothermal point of view these cracks or vents are called as fissures. So, these are the passages through which the inside materials of earth tries to come out. Now let us see the pictorial representation of a typical geothermal field. So, we will try to see the geothermal resources which are available. So, essentially speaking this picture shows one particular geothermal field at a given geographical location. Now in a geothermal field there are different zones. So, these are mentioned as A, B, C, D, E, F, G and H. So, what we see here is much below this earth crust. So, we are going deep into this earth crust. So, we say it is underground.



Typical Geothermal Field

Now if you go much deeper, we will find the zone A. So, zone A is known as hot magma zone. So, this hot magma zone is the main resources where these things are available as molten materials. So, these are like some kind of boiling materials which starts boiling inside the crust. These try to come out, but are unable to come because there are so many different layers through which it has to pass. So, when these try to come, this molten mass tries to radiate or diffuse heat. So, they try to make the nearby vicinity area either solidify them or entire earth crust which is available in the rock form, these try to heat them. Other way is that if there is some water deep inside the earth crust, these try to become hot and hot. So, they form steam which tries to come out from the earth crust.

So, through this there has to be some passage for the steam to come out. Since there is no passage, but over the years there are different cracks are developed due to the earthquake or any other geographical accident, through this process there are vents or cracks developed, through which these materials try to come out. So, basically we have one region which is called as magma, second region is called as igneous rock because these are like volume of crust which are available. So, we call this as igneous rock which means nothing, but your hot rock. Then third category is the region C. So, region C is like a permeable reservoir. So, basically it is a permeable water reservoir. So, whatever water come out from this earth crust, they try to get stored in this particular belt which you call as a permeable reservoir. But this permeable reservoir is also tapped in another area and that is called as solid rock. So, basically B is called as igneous rock, that is fire rock and D is nothing, but the heat rock or solid rock that is also hot. So, E is nothing, but we can say it is a passage or vents and in geothermal category, we call this as fissures. So, these are nothing, but the passages.

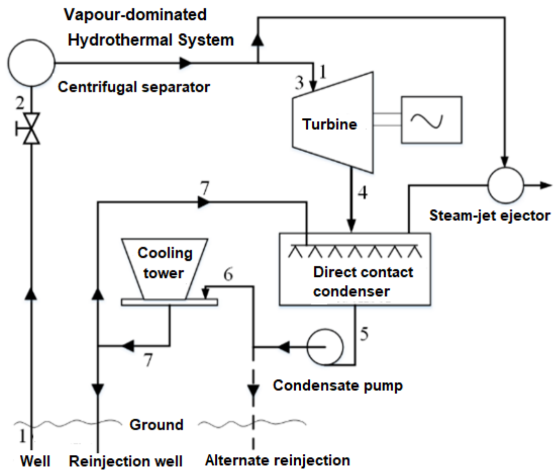
Now through these passages when the inside earth materials try to come, we land of having the net effect as hot springs or hot well and also in the form of geysers. Geyser means it is a supply of hot water. So, all these things we see on the earth surface. So, essentially these are the areas we see as the effect of underground earth crust on the surface. However actually for this geothermal systems, we can categorize the type of heat which they contain in two ways, one is called as magmatic steam, which originates from the magma & the other is meteoritic steam, which originates from the groundwater heated by magma. So, some materials that comes directly through some passage. So, it is like a hot spring. Other thing is that earth crust that comes through this fissures passages.

So, there are two ways to harness this geothermal energy. So, what you do? From the earth surface you go underground, try to reach hot rock or this fire rock and put your fluid from the outside or from the ground and then try to heat up that fluid. That means we need to go maybe 32 km deep to arrive at this zone B. This is one way. The other way is that, in case you are unable go deep into this region that is around 32 km then we can go for let us say the region D, which is the impermeable hot rock or the region C, that is the porous & permeable reservoir, where we can extract these fluids. Because these are actually reservoir heat source which are available and we can extract these fluids to the ground and again re-inject. So, that is what essentially the entire geothermal system does.

So, through this process we classify different types of geothermal resources; one is hydrothermal systems, second geo pressurized systems, and third is petro thermal systems. So, in the geothermal systems we mainly target the liquid regions. So, we can tap the fluid which is inside the earth crust. These are either completely high temperature liquids or they can be high temperature vapors. So, of course, pressure is much higher. So, they are stored in that regions. So, that is what we call as a hydro thermal systems that means, we are extracting the fluid from the earth crust.

Other category is geo pressurized systems, in which we trap water from the underground aquifer. So, basically we are going to that water reservoir that is zone C which was shown in the picture. So, there we have this permeable rock, gravels, sand. So, when you go close to 2.5 km to 9 km depth, we reach this particular point, where the energies are available in pressurized form through rock gravels or sand. So, we plan to trap them. So, geo pressurized systems thought to be at temperature of 160℃ pressure can be 1000 bar which is too high, but with high salinity. High salinity means it is saline water and of course, it is saturated with natural gas which is mainly methane. And often we call this water as brine because it is not in its purest form. The water can be either liquid dominated or vapor dominated and is diffused with natural gases. So, considering all of these, we call this as a brine.

Then third category is the petro thermal systems. These make use of hot dry rock for which the temperature is available in the range of 150 to 300°C with close proximity. And of course, these contribute 85% of geothermal resources. These rocks are also available at moderate depth, but they are highly impermeable. So, in order to extract this energy, we require a carrier fluid which has to be injected or pumped into the ground. So, basically petro thermal system uses outside fluid which is pumped into those rock regions and we try to harness the energy. The hydro thermal systems is on other side of story, where we do not inject any fluid from outside rather we take out the inside fluid to the ground, make use of it and then re-inject it. So, in our discussions we will mostly focus on the hydro thermal systems that makes some similarity with our steam power plant in which we have discussed about the thermodynamic cycles that can be useful for this course.



So, in our discussions we will try to focus only on hydro thermal systems. There of two types, one is vapor dominated geothermal system & the other is liquid dominated geothermal system. So, first we will discuss about this vapor dominated geothermal systems. So, you refer to this thermodynamic circuit. The circuit represented here is a vapor dominated hydro thermal systems. We can say we have dug a well on the earth surface. Keep entering into the earth crust and through this well, we extract the fluid and this fluid is nothing, but typically this brine. When you take out this fluid, there is a throttle valve which of course regulates the pressure and of course, we have the centrifugal separator. So, the centrifugal separator takes all unwanted corrosive products from this brine. And ideally vapor has to expand in the turbine. So, whatever purest form of water is available that goes. So, we say whatever goes into the turbine is nothing, but water vapor and rest of the things gets discharge outside.

Rest of the processes are similar to a Rankine cycle, where after expansion in the turbine it goes to the condenser, which is a heat rejection system. So, heat rejection system means we have a cooling tower that supplies the feed water system to this condenser. So, it is also water and as well as vapor, so we can have a direct contact type condenser. Then there is the condensate pump. Whatever left out water is there, that is again re-injected through this well. So, through the well we extract, purify, use it and then we dump into the well again.

So, this is how this thermal circuit works. Now, if you represent this in a temperature entropy diagram, with a relative comparison we can say, we do not have a boiler or steam generator as we see in a Rankine cycle. So, we start with a location where already steam is available to us. So, that means, we are at some particular point that is state point 1, but at state point 1 we cannot directly expand in the turbines. So, it has to go through the state 3. So, state 3 means through some separation process, only vapor comes to the turbine. So, it tries to expand. So, when it expands we have this isentropic process 3-4s. If it is a non-isentropic, it follows 3-4. Then next things is the condensation process that is from 4-5. So, of course, there is no pump work, but even though there is a condensate pump, the pump work is very negligible as compared to the other thing that normally happens and again the supply for the condenser or feed water system is achieved through point 7. So, the point 7 is the cooling tower exit and that supply necessary water to this cooling medium. So, this is all about the operations. So, we will try to put some numbers because those numbers for your working fluid is already available.

So, in this system water is vaporized into steam & it reaches to the surface in a relatively dry conditions at temperature 205℃ and 8 bar pressure. And if you can tap those kind of working fluid then only that will be suitable for turbo electric power plants. So, here these processes that I have already explained are like the dry steam comes in a saturated conditions at 35 bar and 200℃. There is a drop in pressure. That 1-2 process is throttling. Again this drop gives slightly super heat condition. So initially it comes at higher pressure, but at saturated conditions. But when it actually enters into the turbine, there is a drop in pressure, but we reach in a superheated conditions and that we expand in the turbine. So, this is what we achieve for a vapor dominated systems.

So, other important thing is that the mass flow rate of re injection is of course less than that of originating from well because there are losses in the centrifugal system, steam jet ejector, evaporation, drift and blow down in cooling tower. So, whatever mass of water available in the form of brine, in that the content of water gets reduced when it is re injected. Of course that is quite obvious.

Now, there is another category of geothermal system in which the system is liquid dominated. So, if you refer our previous figure, we started the expansion in the turbine when the water availability or brine availability is already in the saturated vapor. So, this is nothing but saturated vapor and this side we have saturated liquid line. So, here in a vapor dominated system, the availability of your working fluid is already in the saturated vapor line. But if you look at the liquid dominated system, the availability of working fluid is not at saturated vapor line rather it is close to saturated liquid line. This is the essential difference between a liquid dominated system and vapor dominated system. There are two types of methods that we use; either we use the same working fluid and make it vapor and then use in the turbine or instead of taking that as working fluid which is not at all suitable for expansion, we normally use a binary cycle system. So, in a binary cycle systems, we use the underground energy available in the brine as a heat source and that heat source is being used to vaporize our secondary working fluid. Since we are using a secondary working fluid, so we call that cycle as a binary cycle.

So, the main demerit in the liquid dominated systems is when water comes from underground in the form of brine, there are various degrees of salinity and that range from 3000 to 280000 ppm dissolved solids. So, separation is a big task. So, that is the reason, we a separator system where a flash separator is normally used. So, we call this as a flashed-steam systems. But the advantage of a liquid dominated system is that the underground temperature which are available to us is closely in the range of 175℃- 315℃. And of course, they are at high pressure and we take them for our use.

Now, let us try to understand some basic difference that we get in a flashed steam system, which is liquid dominated. So, we see that from the underground reservoir we get this brine and this brine enters into the flash separator. And this is the most critical part for a liquid dominated system because brine contains high salinity water. So, in a single flashed steam system, same working fluid will be used in our thermodynamic cycle which is supposed to be fed to the turbine. So, water or brine is available in the saturated liquid form that is at state 1 and when you take out this brine there is a drop in pressure. So, first pressure drop takes place from 1-2. Now, from 2-3, there is a flash separator. So, basically the separator take out whatever vapor contents available in this brine and sends back the liquid part. This is the job of the flash separator. So, point 3 which is somewhere in the liquid vapor region. So this is saturated liquid, this is saturated vapor, and this is liquid vapor regions in the T-S diagram.

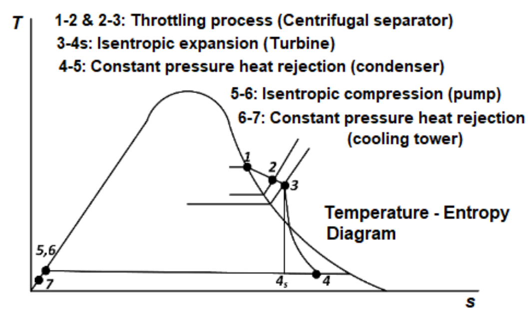
So, initially we have this brine comes from point 1. Then the flash separator separate the brine. After this separation, water vapor is taken out and it goes to state 4 that is the inlet condition for the turbine where it expands to point 6 then it goes to condenser. And here also the working fluid is same, so we can use the direct contact type of condenser. Then the rest of the cycle is simple. And again at point 3, the unused brine that comes out is again re injected into the well. So, this is how single flashed steam based system works and it is a liquid dominated geothermal system.

Now, in a binary cycle what we do? Here also we have the same brine but we do not use the same brine in the working fluid. If you look closely, there are 2 parts; one is that the brine comes from the underground reservoir and through appropriate throttling it enters to a heat exchanger. And, through this heat exchanger the brine releases heat to the secondary fluid. So, this secondary fluid constitutes the working fluid for our thermal cycles. So, those working fluids are organic fluids which mainly have low boiling point. And these are typically isobutene- boiling point -10℃ and Freon 12- boiling point -29.8℃. We can operate these fluids at relatively high pressure corresponding to source water and heat sink temperature. So, this liquid dominated system use a secondary fluid and we call this as a binary cycle. Other parts are almost similar because it also follows the conventional Rankine cycle for this power generation systems.

So, this is all about the lecture contents that I am supposed to discuss. Now, based on our discussions we will try to solve some numerical problems. So, this numerical problems we have is similar to what we solved in a Rankine cycle system, where we have superheated steam & saturated steam. But the only difference between them is that we try to bypass what happens in the boiler or steam generators. So, basically speaking we already have steam which is available either in the saturated liquid line or saturated vapor line. So, we have to use the same steam tables or temperature entropy diagrams for water systems.

Q1. In a vapour-dominated geothermal system with 100 MW capacity, the saturated steam is extracted from a well with a shut-off pressure of 30 bar. Steam enters the turbine at 7 bar and condenses at 0.2 bar. The isentropic efficiency for the turbine is 0.8 while the combined efficiency of turbine-generator unit is 0.9. The temperature at exit of cooling tower is 22°C and the reinjection occurs prior to cooling tower. Calculate the steam flow rate, cooling-water flow rate, heat rate and efficiency of the system.

So, let us and try to understand the first problem. It is a vapor dominated geothermal system with a capacity of 100 MW. The saturated steam is extracted from the well with a shut-off pressure at 30 bar. Since it is saturated steam obviously, the state point 1 in this thermal circuit lies on the saturated vapor line. If you refer this T-s diagrams, so it is the critical point, this side is saturated vapor line, & this line is saturated liquid line in between it is liquid plus vapor line. So, we locate the point that means point 1 is at 30 bar. Steam enters the turbine at 7 bar and condenses up to 0.2 bar. So, point 3 is at 7 bar, but this pressure is available at let us say 30 bar. So, 1 -2 and further 3, is a throttling process that is already defined & in this enthalpy remains same. 3-4s is an expansion process in turbine. So, we are given with an isentropic efficiency of 0.8, then we have this combined efficiency of turbine generator as 0.9 that means, the combined efficiency of turbine & generator is 0.9. So, effectively whatever power developed by the turbine, 90% of that is converted to electricity.



Then other information is available for this feed water systems or through this cooling tower. So, we have this cooling tower conditions which is at 22℃ and re injection occurs prior to cooling tower. So, this is the problem and we are essentially asked to find the steam flow rate in the turbine, cooling water flow rate in the condenser, then heat rate and efficiency of the system. Heat rate means how much heat we are actually tapping from this brine.

So for this problem you have to refer steam table.

State − 1: $p_1 = 30$ bar (saturated)

$$\Rightarrow h_1 = \left(h_g\right)_{30\text{bar}} = 2804.2\,\frac{\text{kJ}}{\text{kg}}$$

Then we have state 3, state 3 means inlet to turbine and in between of course, we have this throttle valve, but again there is initial drop in pressure, so we can directly say 1 -3 as constant enthalpy process. So, when you say constant enthalpy process, we can use this h_1 data to calculate the enthalpy at state 3 which is slightly superheated region.

State − 3: 1 − 3 → Constant Enthalpy process

$$h_3 = h_1 = 2804.2\,\frac{\text{kJ}}{\text{kg}};\, p_3 = 7\text{ bar},$$

Referring the superheated Table, ⇒ $T_3 = 180°\text{C}$; $(T_{sat})_{7\text{bar}} = 165°\text{C}$; $s_3 = 6.9656\,\frac{\text{kJ}}{\text{kg. K}}$

So, we can say degree of superheat that means this drop in pressure gives rise to a degree of superheat which is about 15°C that is difference between T_3 & $(T_{sat})_{7\text{bar}}$.

Now, we are already in the state 3 then we will look into the expansion process in the turbine then we have to see for state 4 and 4 s.

State − 4 & 4s; Isentropic process, $p_{4s} = p_4 = 0.2$ bar

The process is isentropic, so $s_3 = s_{4s} = \left[s_f + x_{4s}\left(s_g - s_f\right)\right]_{0.2bar}$

So we have data using saturated table for pressure,

$$s_g = 7.9085\,\frac{\text{kJ}}{\text{kg. K}};\, s_f = 0.832\,\frac{\text{kJ}}{\text{kg. K}}$$

So, we have s_3, s_g, s_f, so this will give you

$$\Rightarrow x_{4s} = \frac{s_3 - s_f}{s_g - s_f} = 0.866$$

So, at this point so, at the point 4 s we calculate $x_{4s} = 0.866$.

Now, $h_{4s} = (h_f)_4 + x_{4s}(h_g - h_f)$

State – 4; $p_4 = 0.2$ bar, From saturated table, $h_{fg} = 2358.3\ \frac{\text{kJ}}{\text{kg}}; h_f = 251.4\frac{\text{kJ}}{\text{kg}}$

Now, $h_{4s} = (h_f)_4 + x_{4s}(h_g - h_f) = 2293.7\frac{\text{kJ}}{\text{kg}}$

So, now we can calculate isentropic work.

Isentropic Work, $W_{isen} = h_3 - h_{4s} = 2804.2 - 2293.7 = 510.5\frac{\text{kJ}}{\text{kg}}$

Actual Work = Turbine work, $W_T = \eta_t W_{isen} = 0.8 \times 510.5 = 408.5\frac{\text{kJ}}{\text{kg}}$

But you have the power generated as 100 MW at combined efficiency of turbine-generator unit as 0.9.

Power Transmitted, $W = W_T \times 0.9 = 367.56\frac{\text{kJ}}{\text{kg}}$

So, this is the power we should be working on to calculate the rest answers of the questions. So, we also know power which is developed, P=100MW. And the power which is we get per cycle is 367.56 kJ/kg.

Steam production or required mass flow rate of steam, $\dot{m}_{st} = \frac{P}{W} = \frac{100 \times 10^3}{376.56}$

$$= 272\frac{\text{kg}}{\text{s}}$$

Volume Flow rate of steam, $\dot{V}_{st} = v_3 \times \dot{m}_{st}$

So, v_3 is calculated based on the state point 3. $v_3 = 4045\ \text{m}^3/\text{kg}$

Volume Flow rate of steam, $\dot{V}_{st} = 110\ \text{m}^3/\text{s}$

So, this is what we required that is the steam flow rate and volume flow rate of the steam. Now, we will move on to this condenser part.

Condenser + Cooloing tower; $\dot{m}_7(h_5 - h_7) = \dot{m}_4(h_4 - h_5)$

So, we know that this cooling tower exit condition is 22°C. So, condition 7 has to be found out from this data.

At $T_{sat} = 22°\text{C}$, From steam table → $h_7 = 92.33 \frac{\text{kJ}}{\text{kg}}$

And we also know already $h_3 = 2804.2\ {}^{\text{kJ}}/_{\text{kg}}$.

Turbine Work, $W_T = h_3 - h_4 = 408.4 \Rightarrow h_4 = 2395.8 \frac{\text{kJ}}{\text{kg}}$

$h_5 = \left(h_f\right)_{0.2\text{bar}} = 251.4 \frac{\text{kJ}}{\text{kg}}$

So, from these equations, all the numbers are known h_5, h_4, h_7. So, this will give you

Cooling water requirement, $\dot{m}_7 = 3667 \frac{\text{kg}}{\text{s}}$; & Volume flow rate for water, $\dot{V}_7$

$$= 3.667 \frac{\text{m}^3}{\text{s}}$$

Then next job is to find out heat added. So, we started with point 1 ended at point 7.

So, heat added per unit mass, $q_{in} = h_1 - h_6 = 2804.2 - 251.4 = 2552.8 \frac{\text{kJ}}{\text{kg}}$

Then we need to find the efficiency of the system.

So efficiency of the system, $\eta = \frac{W}{q_{in}} = \frac{367.54}{2552.8} = 0.15 = 15\%$

So, the next thing that is required is the heat rate.

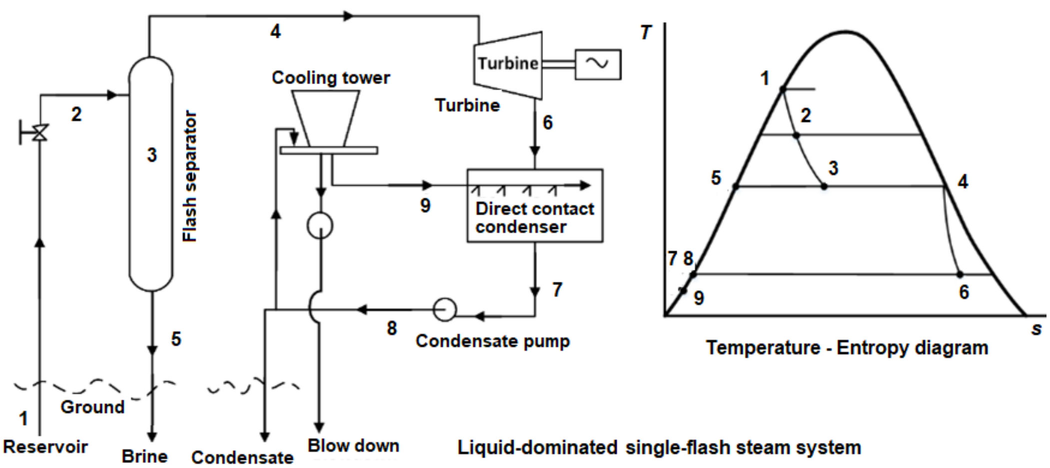
$$\text{Heat rate}, HR\left(\text{in} \frac{\text{kJ}}{\text{kWH}}\right) = \frac{q_{in} \times \dot{m}_{st} \times 3600}{\eta \times P(\text{in kW})} = \frac{2552.8 \times 272 \times 3600}{0.15 \times 100 \times 10^3}$$

$$= 156231 \frac{\text{kJ}}{\text{kWH}}$$

So, this is about the big problem which is for vapor dominated systems. Now, we will look into a small problem in which we will look into a liquid dominated system.

Q2. A flashed steam liquid-dominated geothermal system uses hot water reservoir that contains water at 240°C and 11 bar. The separator pressure is 7 bar. Find, (a) the mass flow rate of water from the well and re injected brine per unit mass flow rate into the turbine; (b) enthalpy ratios of spent brine and steam.

So, the problem statement is for a liquid dominated geothermal system. So, we started with same diagram temperature entropy diagram.



Liquid-dominated single-flash steam system

So, we have liquid here, we have vapor here. And it is given in the question that we have an instrument which is called as cyclone separator or flash separator and that flash separator separates the brine that enters into the circuit and that separation happens at point 3. So, it is said in the question that the geothermal system uses a hot water reservoir it contains water at 240°C and 11 bar.

State $-$ 1; $h_1 = (h_f)_{240°\text{C}}$

Since it is already in saturated liquid region, so here we have to use this temperature as benchmark. So, at this temperature we can calculate the enthalpy from the saturated temperature table.

So $h_1 = (h_f)_{240°\text{C}} = 1037.3\,\frac{\text{kJ}}{\text{kg}}$

Process 1 − 2 − 3 → Constant enthalpy process; $h_3 = h_1 = (h_f + x_3 h_{fg})_{7\text{bar}}$

From saturated steam table, at 7 bar; $h_f = 697.22 \frac{\text{kJ}}{\text{kg}}$; & $h_f = h_5$; $h_g = 2763.5 \frac{\text{kJ}}{\text{kg}}$

$$h_3 = h_1 = (h_f + x_3 h_{fg})_{7\text{bar}} \Rightarrow x_3 = \frac{1037.3 - 697.22}{2763.5 - 697.22} = 0.16$$

So, the question was asked that we need two parts, one is the mass flow rate of water from the well and re injected brine per unit mass flow rate into the turbines.

So mass flow rate into the turbines, $\dot{m}_t = 1 \frac{\text{kg}}{\text{s}}$

$$\dot{m}_w = \frac{1}{x_3} = \frac{1}{0.16} = 6.2 \frac{\text{kg}}{\text{s}}$$

So, the mass flow rate from the well per unit mass flow of the turbine would be 6.2 kg per second. Then we need to find mass of the brine that is re injected. So, that is 6.2 unit comes at point 3, from that 1 unit goes to turbine and rest of the thing comes out as brine.

$$\dot{m}_b = \dot{m}_w - \dot{m}_t = 6.2 - 1 = 5.2 \frac{\text{kg}}{\text{s}}$$

Now, what is the enthalpy ratio?

So Enthalpy ratio of spent brine to the steam, $Y = \left(\frac{h_5}{h_4}\right) \dot{m}_b = \left(\frac{697.22}{2763.5}\right) \times 5.2 = 1.32$

So, enthalpy ratio turns out to be 1.32. So, with this I conclude this geothermal section in this lecture. Thank you for your attention.