Guidance page for practical work electricity production from geothermal energy

1) Objectives of the practical work

The project objective is to study the operation of power plants using geothermal energy and show how to model them realistically with Thermoptim

The thermodynamic conversion of geothermal energy uses four main techniques:

- plants called “direct-steam” can be used if the geothermal fluid is superheated steam that can be directly expanded in a turbine. Historically, this type of plant was first implemented in Larderello in Italy since 1904;
- flash vaporization power plants can exploit sites where geothermal fluid is in the form of pressurized liquid or liquid-vapor mixture. Today it is the type of plant most used. Geothermal fluid begins by being expanded in a chamber at pressure lower than that of the well, thereby vaporizing a portion, which is then expanded in a turbine;
- systems known as binary use a secondary working fluid, which follows a closed Hirn or Rankine cycle, the boiler being a heat exchanger with the geothermal fluid;
- fluid mixture systems, such as Kalina cycle, a variant of binary systems where the working fluid is no longer pure but consists of two fluids to achieve a temperature glide during vaporization.

Mixed or combined cycles can use both a direct or flash system and a binary system.

In this practical work, students deal with these different cycles modeled in Thermoptim.

Students are asked to perform an initial setting of the model based on values provided in the setting out, and then perform sensitivity studies by varying parameters.

This practical work is intended for students who have modeled a simple steam cycle (if it is not the case, they must begin by working on the sessions S25En and S26En), the only difficulty is the construction and configuration of the three part heat exchanger.

Immediately note a small feature of some of these models: in a geothermal cycle calculating purchased energy is not always immediate, since the geothermal fluid (which will be treated as water) is most often distributed in several streams, reinjected or not. We can therefore rarely directly estimate the enthalpy it provides. When this happens, it is preferable not to declare in Thermoptim a process as “purchased energy”, and simply compare cycles on the basis of mechanical power produced.

To estimate an efficiency on a comparable basis, we may consider as a reference a cycle that would allow the entire geothermal fluid to be reinjected at a temperature of 50 °C. We will talk then of reference efficiency.

Note that temperature and pressure levels of the geothermal fluid considered in the examples that follow are not necessarily the same, leading us to temper these comparisons.

2) References

R. DIPIPPO, *Small geothermal power plants: design, performance and economics*, GHC Bulletin, June 1999.

R. DIPIPPO, *Second law assesment of binary plants generating power from low-temperature geothermal fluids*, Geothermics 33, pp. 565-586, 2004.

P. BOMBARDA, E. MACCHI, *Optimum cycles for geothermal power plants*, Proceedings World Geothermal Congress 2000, Kyushu-Tohoku, Japan, June 10 2000.

La géothermie, une énergie d'avenir, Georama n° 12, journal d'information du BRGM, juin 2004.

3) Main practical work

3.1 Setting out

Geothermal energy comes from the gradual temperature increase as one penetrates deeper into the earth’s crust, either because of the natural gradient (3└ C/100 m, with an average flux of 60 mW/m2), or because of geophysical singularities (high temperature natural geothermal reservoirs of porous rock).

It is customary to distinguish three broad categories of reservoirs, according to their temperature levels:
- high temperature (>220 °C);
- intermediate temperature (100–200 °C);
- low temperature (50–100 °C).

In the first case, the geothermal fluid can be essentially composed of water or steam, in the other two it is water, optionally under pressure. A special feature of geothermal fluid is that it is never pure water: it also includes many impurities, corrosive salts (the concentration limit for an operation to be possible is equal to 1.5 mol/kg) and non-condensable gas (NCG) in varying amounts (0.1-10%). We shall see that this feature imposes constraints on thermodynamic cycles that can be used.

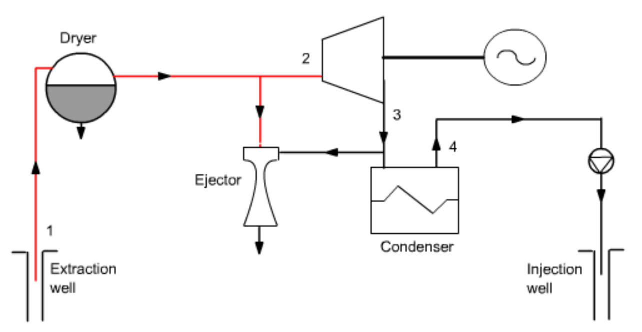

Figure 3.1: Direct-steam cycle

For environmental reasons, the geothermal fluid should generally be reinjected into the reservoir after use, but it is not always the case.

3.2 Direct-steam plants

Direct-steam cycle (figure 3.1) is very close to that of Hirn or Rankine. The main difference comes from the need to extract the NCG in order to condense water at the turbine outlet, which allows the steam to be expanded at pressure below the ambient. Depending on circumstances, the extraction is done using an ejector driven by geothermal steam, or a compressor coupled to the turbine.

Generally, the condenser cooling is provided by a cooling tower whose makeup water may be taken from the condensate itself.
As mentioned above, this type of plant requires the existence of dry steam in production wells, which is exceptional: the only known sites that have this property are Larderello in Italy and the Geysers in NW California.

The synoptic view of such a cycle is given in Figure 3.2. We considered available 111 kg/s of steam at 5.5 bar and 204 °C, which represents approximately a 50°C superheating. This steam is expanded at 0.123 bar, 50°C and then condensed and recompressed before reinjection. In this case, the mechanical power produced is 57.3 MW, the cycle efficiency being 20.9%.

3.3 Simple flash plant

Generally, the well contains a low quality (below 0.5) liquid-vapor mixture, which cannot be sent directly to the turbine.

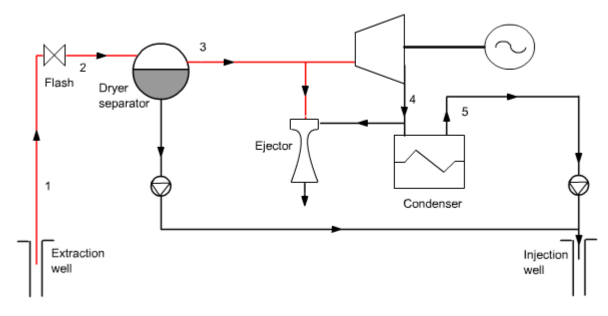

Figure 3.3: Simple flash plant

If the initial pressure is sufficient, a solution is to partially expand the mixture in order to vaporize a portion, which is then sent to the turbine, while the liquid fraction is reinjected.

As in the case of direct-steam plant, the vapor phase typically contains a significant amount of NCG to be extracted if we want to condense water at the turbine outlet.

Note that steam through the turbine is distilled water which can sometimes be valorized notably as drinking water.

Figure 3.4 shows the synoptic view of such a cycle modeled in Thermoptim. We assumed that we had 760 kg/s of hot water in the saturated liquid state at 230° C and 28 bar.

This water undergoes a flash at 6 bar, leading to a 0.15 quality. The liquid and vapor phases are then separated, the first being recompressed before reinjection, whereas the latter is expanded at the pressure of 0.123 bar (50 °C) and then condensed. The mechanical power produced is 57 MW and efficiency 9.6%.

Note that the pressure at which the flash is performed (6 bar) has not been optimized. The condensing pressure and temperature are relatively high because of noncondensable gases present in the geothermal fluid.

3.4 Double flash plant

In some cases, if the pressure at the well outlet is sufficient, it is possible to achieve a double flash, which allows steam to be obtained at two different pressure levels and increases plant performance.

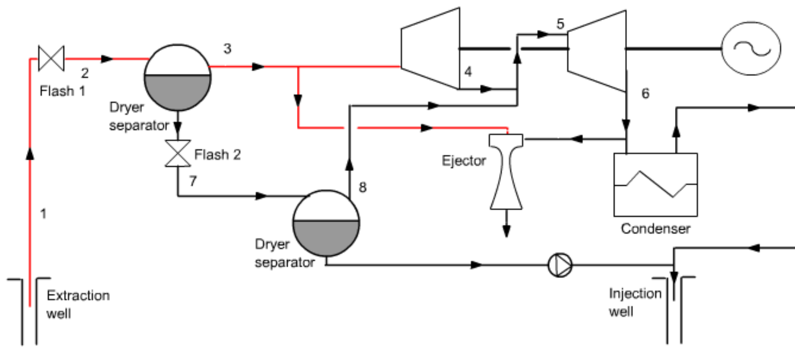

Figure 3.5: Double flash plant

Theoretically, we could thus increase the number of flashes, but technological and economic constraints limit them in practice to 2.

As shown in the synoptic view of Figure 3.6, the liquid stream, which in the previous cycle was recompressed and re-injected, undergoes this time a second flash at a pressure of 0.931 bar, which leads to a 0.115 quality.

The liquid phase is recompressed and reinjected, while the vapor is mixed with the steam flow from the first flash expanded at the same pressure. The whole is then expanded at the condenser pressure in a LP turbine. Mechanical power produced rises from 57 to 77 MW, representing an increase of 35%. Efficiency becomes 13%.

Here too the flash pressures (6 and 0.931 bar) have not been optimized.

3.5 Binary cycle plants

When the temperature or pressure at the well outlet is low, it becomes impossible to make use of direct-steam or flash cycles. We then use a second working fluid, which follows a closed Hirn or Rankine cycle (with or without superheating, figure 3.7).

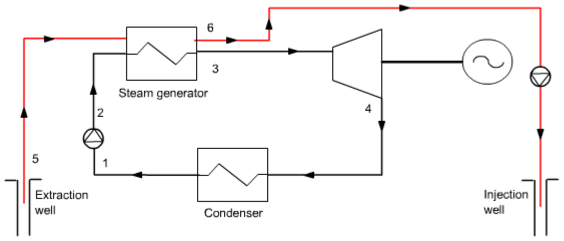

Figure 3.7: Binary cycle

The geothermal fluid then transfers its heat to the fluid before being reinjected.

A cooling tower ensures condensation of the working fluid, whose choice depends on many considerations, technological, economic and environmental. Since this is often an organic fluid, it is customary to speak of Organic Rankine Cycle (ORC).
Figure 3.8 shows the synoptic view of such a cycle modeled in Thermoptim. We assumed we had 310 kg/s of hot water in the subcooled liquid state at a temperature of 169 °C and pressure of 20 bar.
This water is used to vaporize with a very low superheating (2 °C) butane, which is then expanded in a turbine and condensed in an entirely conventional Hirn cycle. The mechanical power produced here is 18.9 MW, and the efficiency 12%.

The condensation pressure and temperature of butane may be here lower than for the geothermal fluid in flash cycles because of the absence of noncondensable gases in the second cycle.

Like any Hirn cycle, this cycle can be improved by judiciously introducing reheats and/or extractions.

3.6 Combined cycle

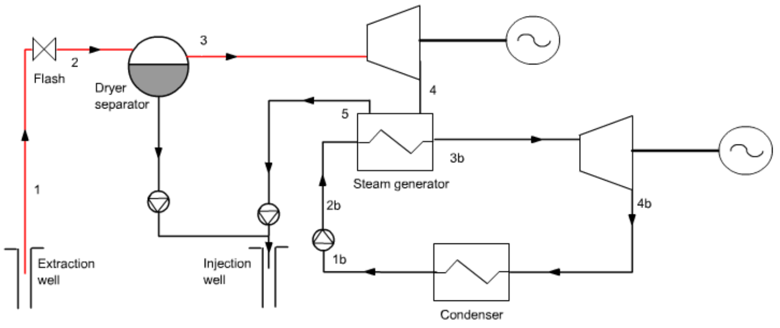

Figure.3.9: Combined cycle

As we have seen, one of the constraints encountered in condensation of direct-steam or flash cycles is the need to extract NCG, resulting in significant parasitic energy consumption.

An alternative is to use a combined cycle, combining direct-steam or flash cycle with an ORC, the steam leaving the turbine being at a pressure higher than atmospheric, and being cooled in the boiler of the second cycle.

Let us for example consider the case of the double-flash cycle studied previously, the steam being expanded this time at only 0.9 bar instead of 0.123 bar and then cooled at 50 °C in a heat exchanger used as vapor generator for a butane Hirn cycle.

This gives the combined cycle in figure 3.10: mechanical power increases from 77 to 95 MW and efficiency from 13 to 16.1%.

3.7 Mixed cycle

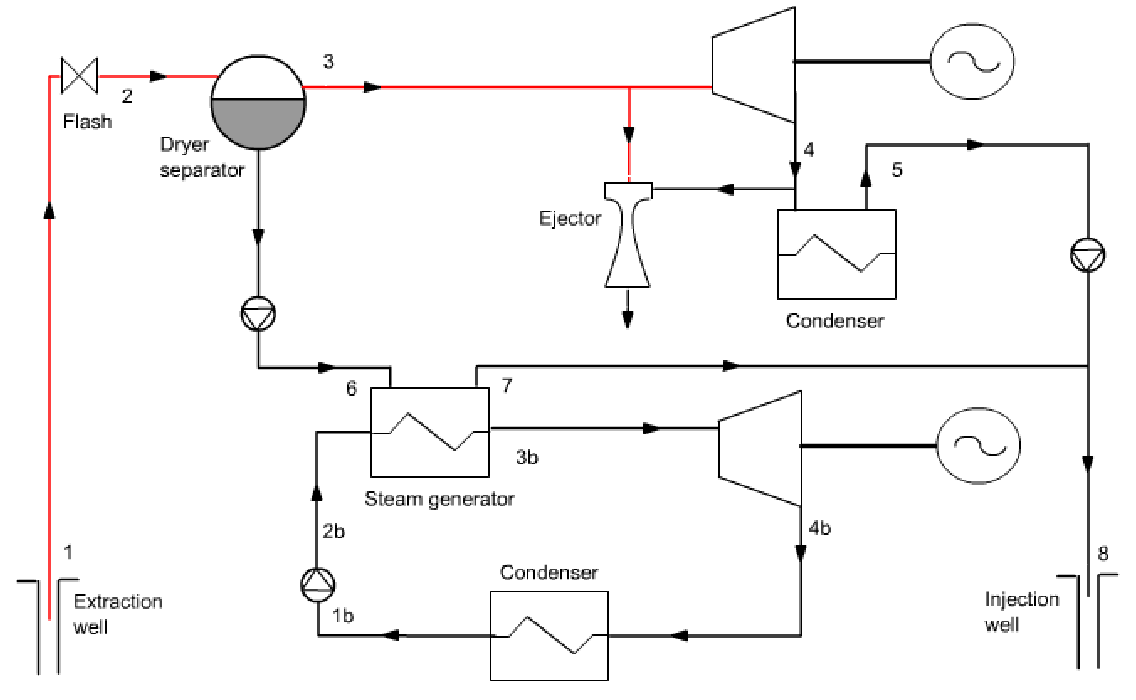

Figure 3.11: Mixed cycle

One major drawback of flash cycles is that they exploit only a small share of the total flow of geothermal fluid, the one corresponding to the vapor fraction after the flash, the liquid fraction being reinjected.

Mixed cycles valorize the geothermal fluid, using the liquid fraction to provide the energy necessary for an ORC cycle.

One can thus obtain a total efficiency well above that of a flash cycle. Of course, if the topping cycle of a combined cycle is the flash type, it is possible to associate a second ORC cycle of the mixed type.

Let us consider again the double flash cycle studied previously, and add a butane Hirn cycle, no longer on the circuit of expanded steam, but this time on the circuit before reinjection of geothermal fluid. The diagram of Figure 3.12 shows the result: mechanical power produced increases from 77 to 94 MW and efficiency from 13 to 15.8%. The gain is somewhat lower than that obtained in the combined cycle, but already quite significant. Note that it would indeed be quite possible to add this butane cycle on the combined cycle, which would improve performance

4) Variants

Given the number of cycles already presented in this guidance pages, we do not propose alternatives, but it would be very easy to do so, including combining mixed cycles and combined cycles with single or double flash.

It is interesting to ask students to build-up the exergy balance of these cycles, if they have enough time.

Diapason session S06En will provide necessary explanations on how to proceed.