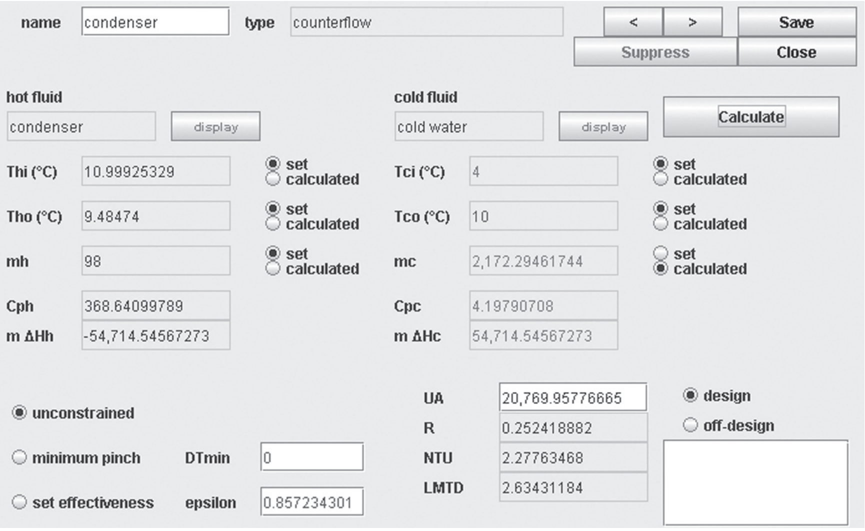


name: condenser
type: counterflow

hot fluid: condenser
Thi (°C): 10.99925329 ● set ○ calculated
Tho (°C): 9.48474 ● set ○ calculated
mh: 98 ● set ○ calculated
Cph: 368.64099789
m ΔHh: -54,714.54567273

cold fluid: cold water
Tci (°C): 4 ● set ○ calculated
Tco (°C): 10 ● set ○ calculated
mc: 2,172.29461744 ○ set ● calculated
Cpc: 4.19790708
m ΔHc: 54,714.54567273

● unconstrained
○ minimum pinch DTmin: 0
○ set effectiveness epsilon: 0.857234301

UA: 20,769.95776665
R: 0.252418882
NTU: 2.27763468
LMTD: 2.63431184

● design
○ off-design

FIGURE 31.2.9
Condenser screen

31.3 GEOTHERMAL CYCLES

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/m^2), 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.

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

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.

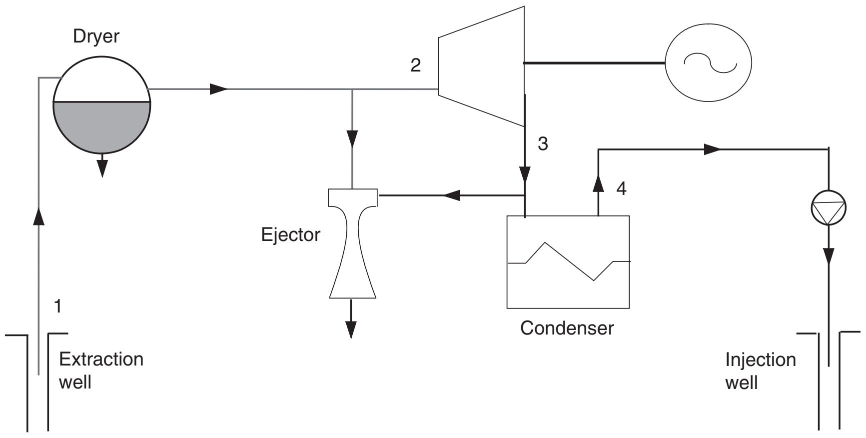


FIGURE 31.3.1
Direct-steam plant

Mixed or combined cycles can use both a direct or flash system and a binary system. In what follows, we present these different cycles modeled in Thermoptim.

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.

31.3.1 Direct-steam plants

Direct-steam cycle 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.

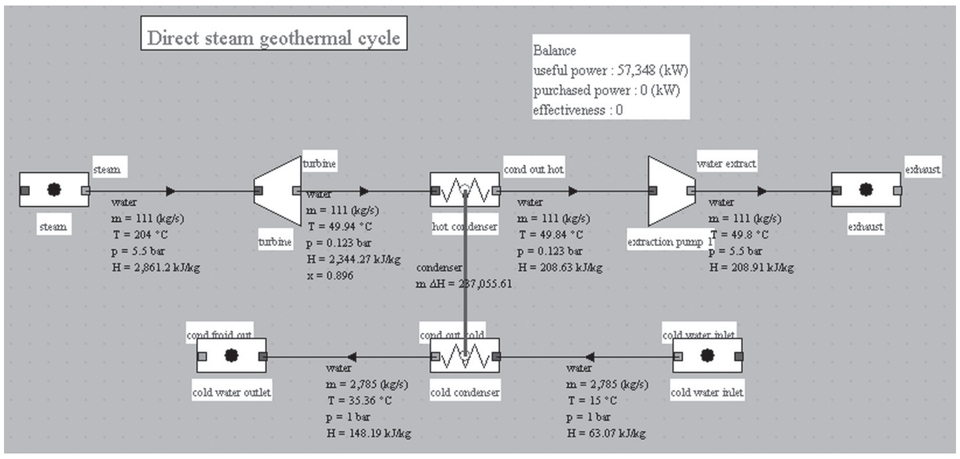
Generally, the condenser cooling is provided by a cooling tower whose makeup water may be taken from the condensate itself.

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 31.3.2. 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%.

31.3.2 Simple flash plant

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



Balance
useful power : 57,348 (kW)
purchased power : 0 (kW)
effectiveness : 0

FIGURE 31.3.2

Synoptic view of a direct steam geothermal cycle

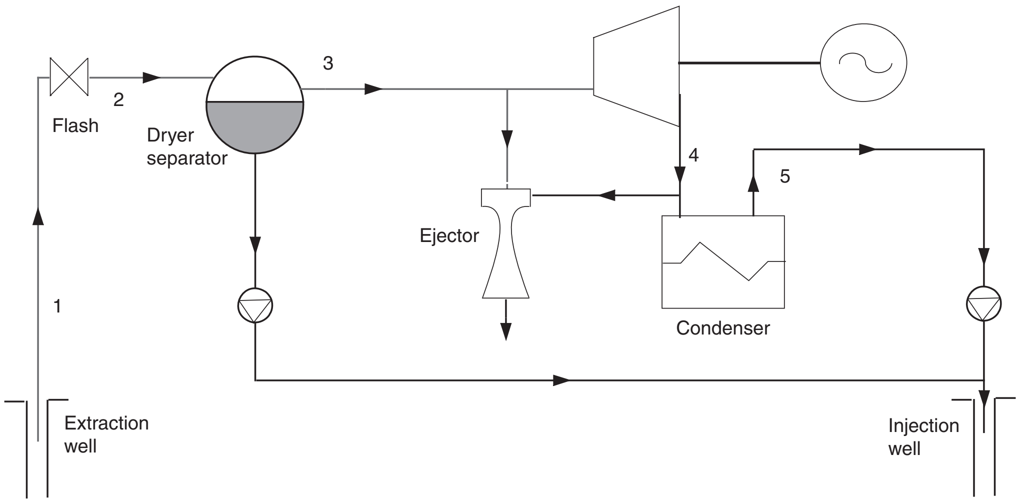


FIGURE 31.3.3

Single 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 31.3.4 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.

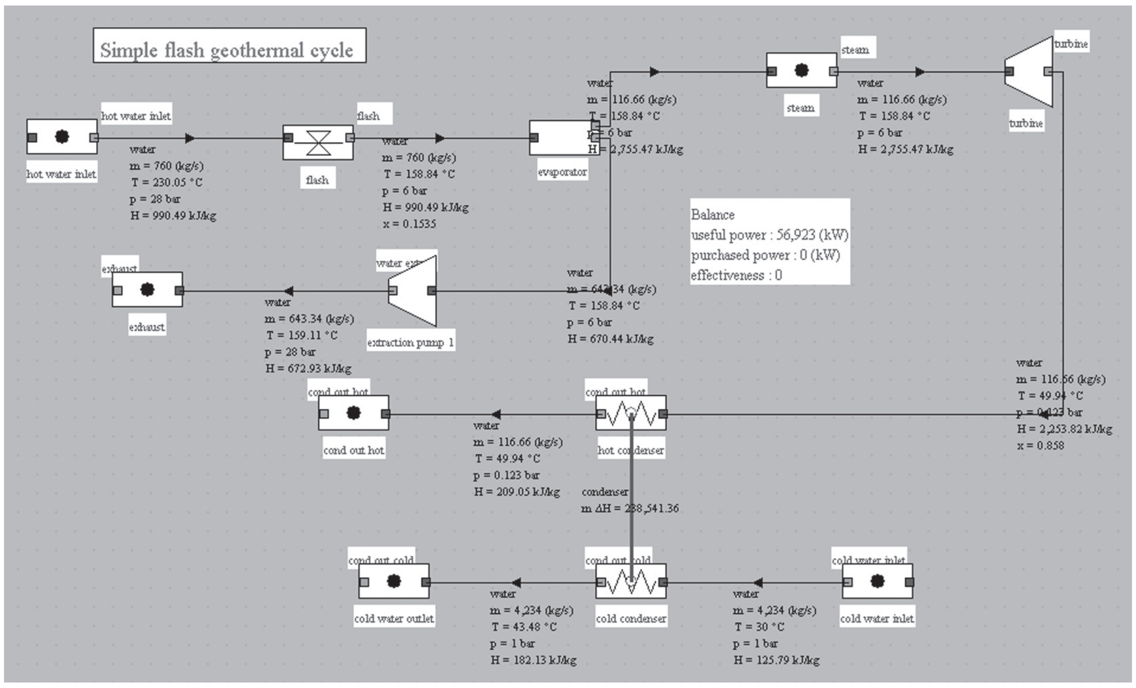


FIGURE 31.3.4

Synoptic view of a single flash geothermal cycle

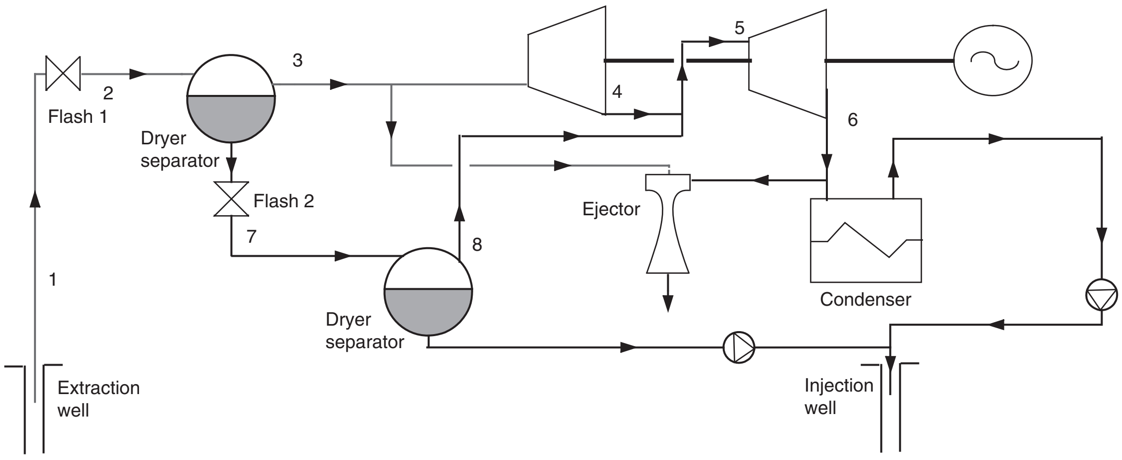


FIGURE 31.3.5

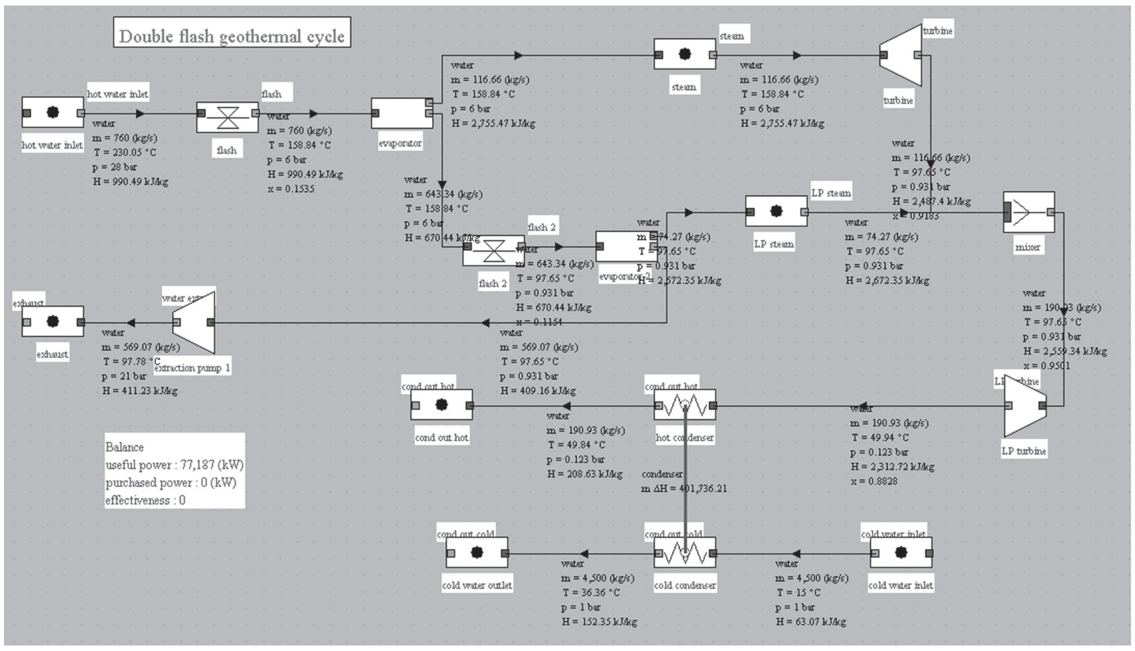
Double flash plant

31.3.3 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.

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 31.3.6, 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.



Balance
useful power : 77,187 (kW)
purchased power : 0 (kW)
effectiveness : 0

FIGURE 31.3.6

Synoptic view of a double flash geothermal cycle

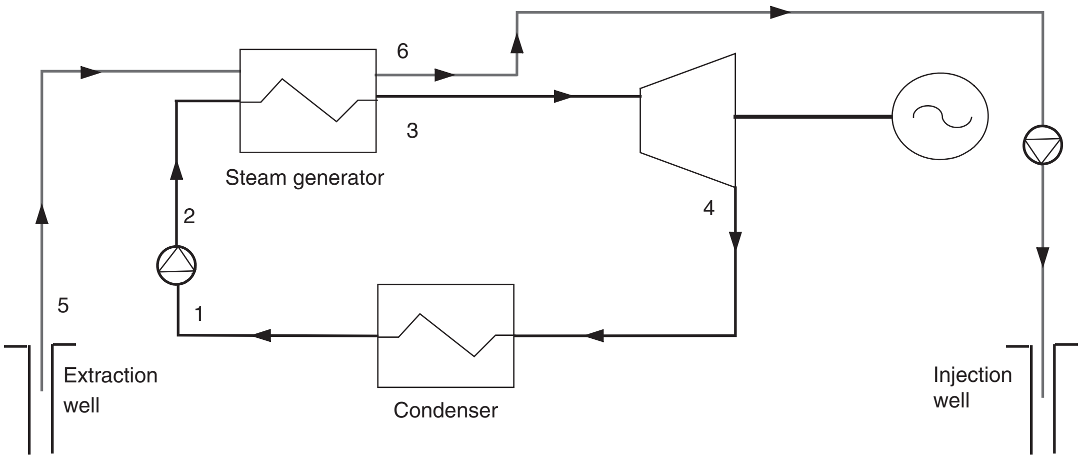


FIGURE 31.3.7

Binary cycle

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.

31.3.4 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).

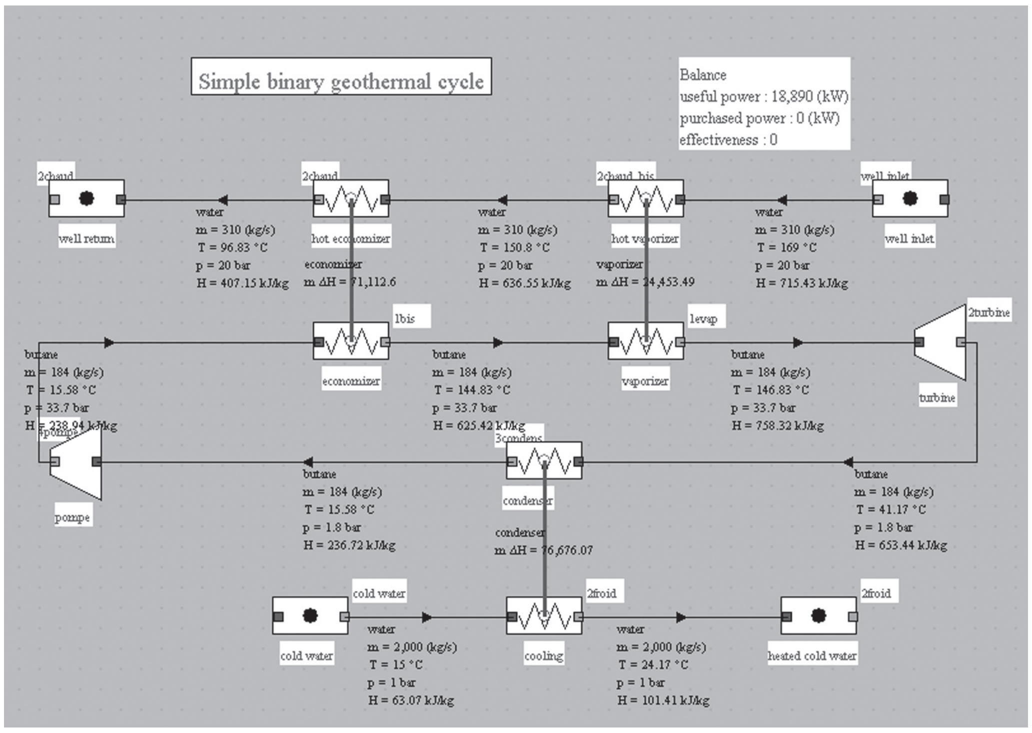


FIGURE 31.3.8

Synoptic view of a butane binary geothermal 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 31.3.8 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.

31.3.5 Kalina cycle

The Kalina cycle, which was presented in detailed manner in section 25.4, uses as working fluid system "water – ammonia", which has an important temperature glide.

The Kalina cycle replaces the ORC cycle of the previous example.

Given the temperature glide, irreversibilities in heat exchanger between the geothermal fluid and the working fluid are reduced, and geothermal heat better used. Compared to the binary cycle, mechanical power produced rises from 19 to 23.5 MW, and the efficiency reaches 18.9%.

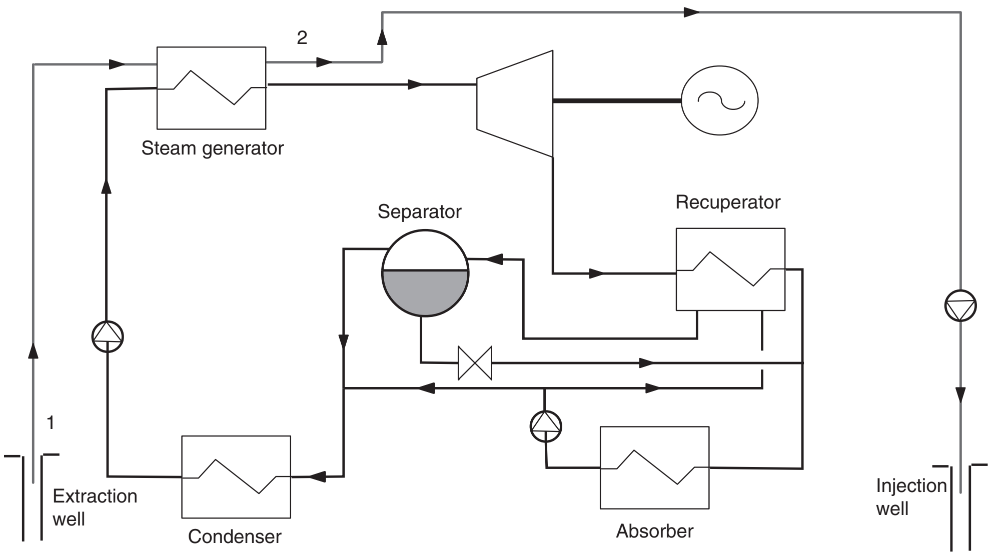


FIGURE 31.3.9
Kalina geothermal cycle

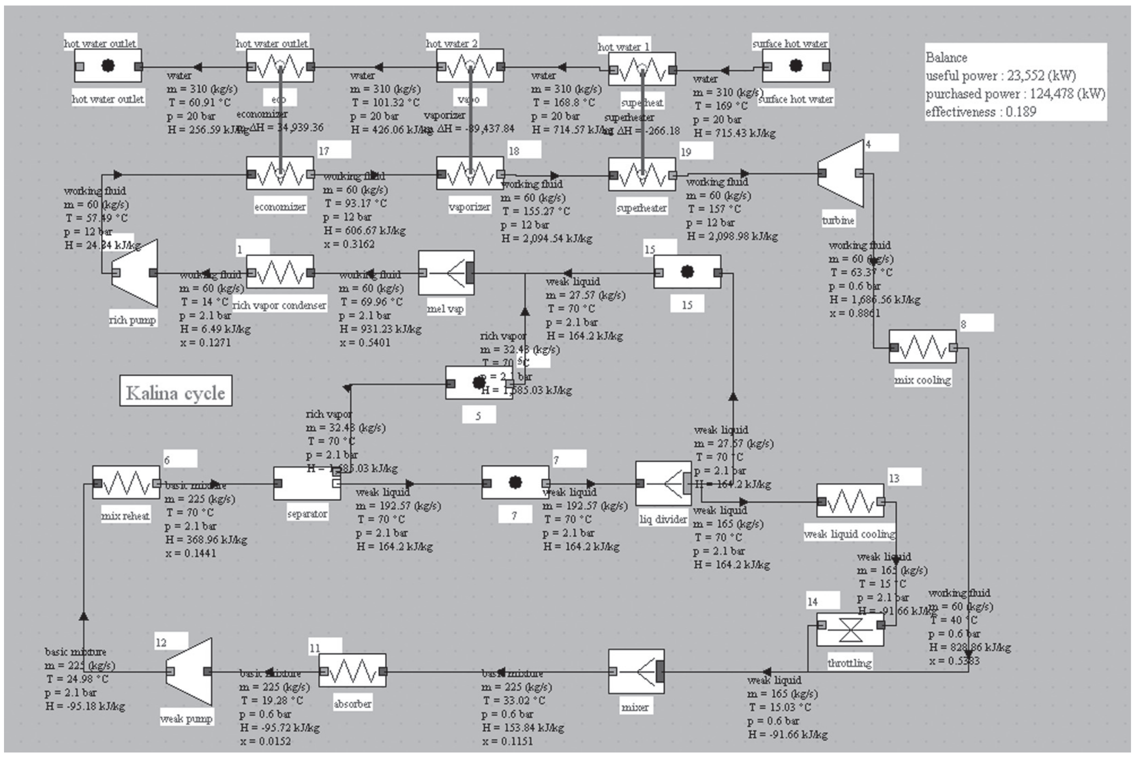


FIGURE 31.3.10
Synoptic view of a Kalina geothermal cycle

31.3.6 Combined cycles

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.

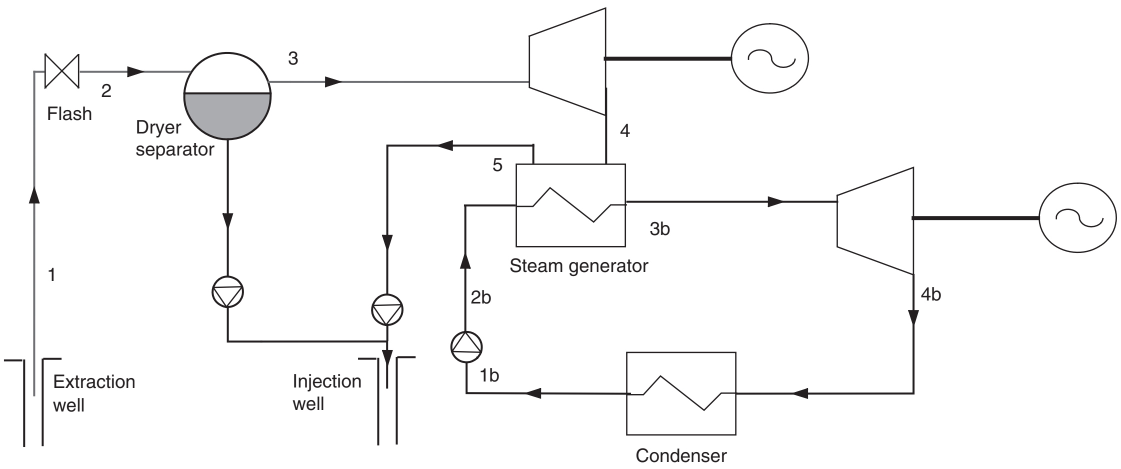
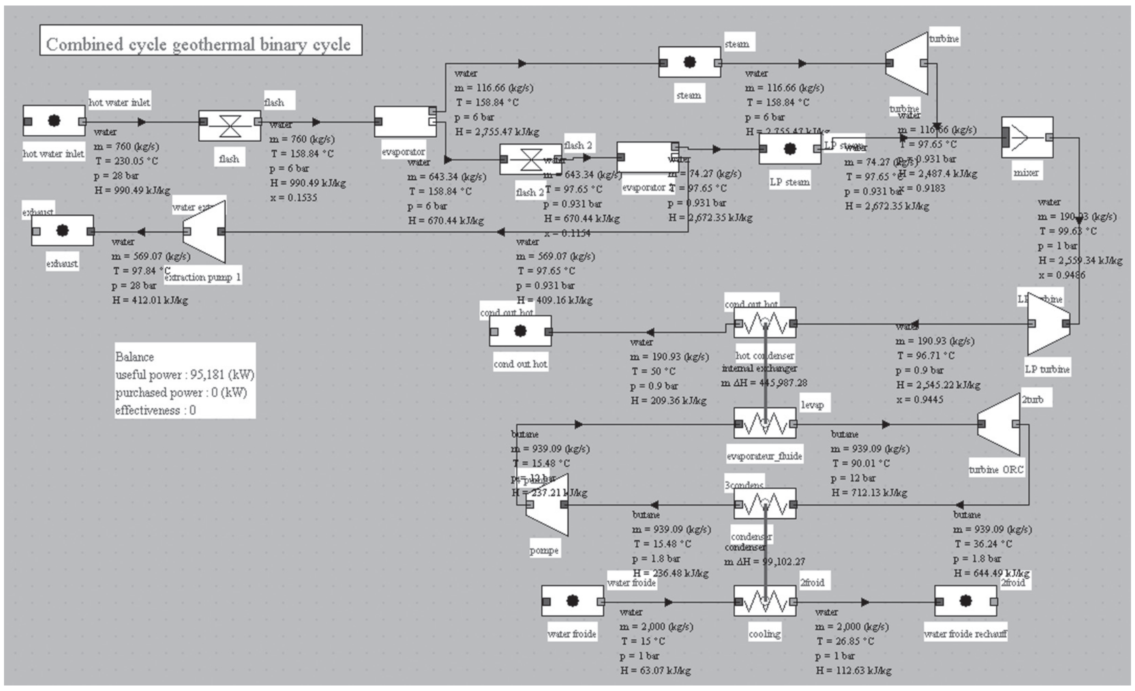


FIGURE 31.3.11
Combined cycle



Combined cycle geothermal binary cycle

water
m = 760 (kg/s)
T = 230.05 °C
p = 28 bar
H = 990.49 kJ/kg

water
m = 760 (kg/s)
T = 158.84 °C
p = 6 bar
H = 990.49 kJ/kg
x = 0.1535

water
m = 116.66 (kg/s)
T = 158.84 °C
p = 6 bar
H = 2,755.47 kJ/kg

water
m = 116.66 (kg/s)
T = 158.84 °C
p = 6 bar
H = 2,755.47 kJ/kg

water
m = 643.34 (kg/s)
T = 158.84 °C
p = 6 bar
H = 670.44 kJ/kg

water
m = 643.34 (kg/s)
T = 97.65 °C
p = 0.931 bar
H = 670.44 kJ/kg
x = 0.1154

water
m = 74.27 (kg/s)
T = 97.65 °C
p = 0.931 bar
H = 2,672.35 kJ/kg

water
m = 74.27 (kg/s)
T = 97.65 °C
p = 0.931 bar
H = 2,672.35 kJ/kg

water
m = 116.66 (kg/s)
T = 97.65 °C
p = 0.931 bar
H = 2,487.4 kJ/kg
x = 0.9183

water
m = 190.93 (kg/s)
T = 99.63 °C
p = 1 bar
H = 2,559.34 kJ/kg
x = 0.9486

water
m = 569.07 (kg/s)
T = 97.65 °C
p = 0.931 bar
H = 409.16 kJ/kg

water
m = 569.07 (kg/s)
T = 97.84 °C
p = 28 bar
H = 412.01 kJ/kg

water
m = 190.93 (kg/s)
T = 96.71 °C
p = 0.9 bar
H = 2,545.22 kJ/kg
x = 0.9445

water
m = 190.93 (kg/s)
T = 50 °C
p = 0.9 bar
H = 209.36 kJ/kg

internal exchanger
m ΔH = 445,987.28

Balance
useful power : 95,181 (kW)
purchased power : 0 (kW)
effectiveness : 0

butane
m = 939.09 (kg/s)
T = 15.48 °C
p = 12 bar
H = 237.21 kJ/kg

butane
m = 939.09 (kg/s)
T = 90.01 °C
p = 12 bar
H = 712.13 kJ/kg

butane
m = 939.09 (kg/s)
T = 36.24 °C
p = 1.8 bar
H = 644.49 kJ/kg

butane
m = 939.09 (kg/s)
T = 15.48 °C
p = 1.8 bar
H = 236.48 kJ/kg

condenser
m ΔH = 99,102.27

water
m = 2,000 (kg/s)
T = 15 °C
p = 1 bar
H = 63.07 kJ/kg

water
m = 2,000 (kg/s)
T = 26.85 °C
p = 1 bar
H = 112.63 kJ/kg

FIGURE 31.3.12
Synoptic view of a geothermal combined cycle

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 31.3.12: mechanical power increases from 77 to 95 MW and efficiency from 13 to 16.1%.

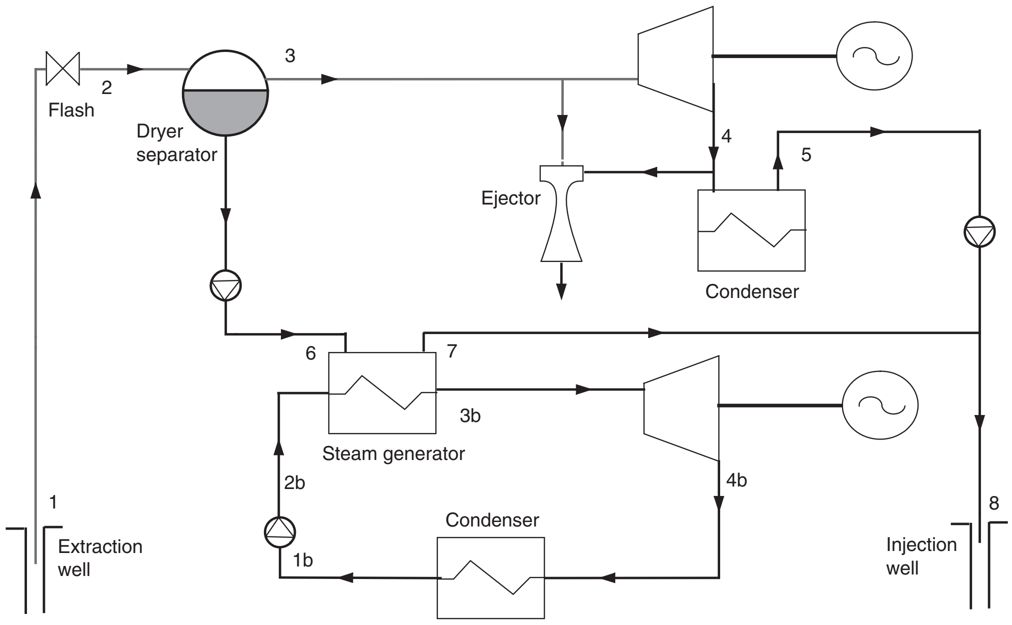
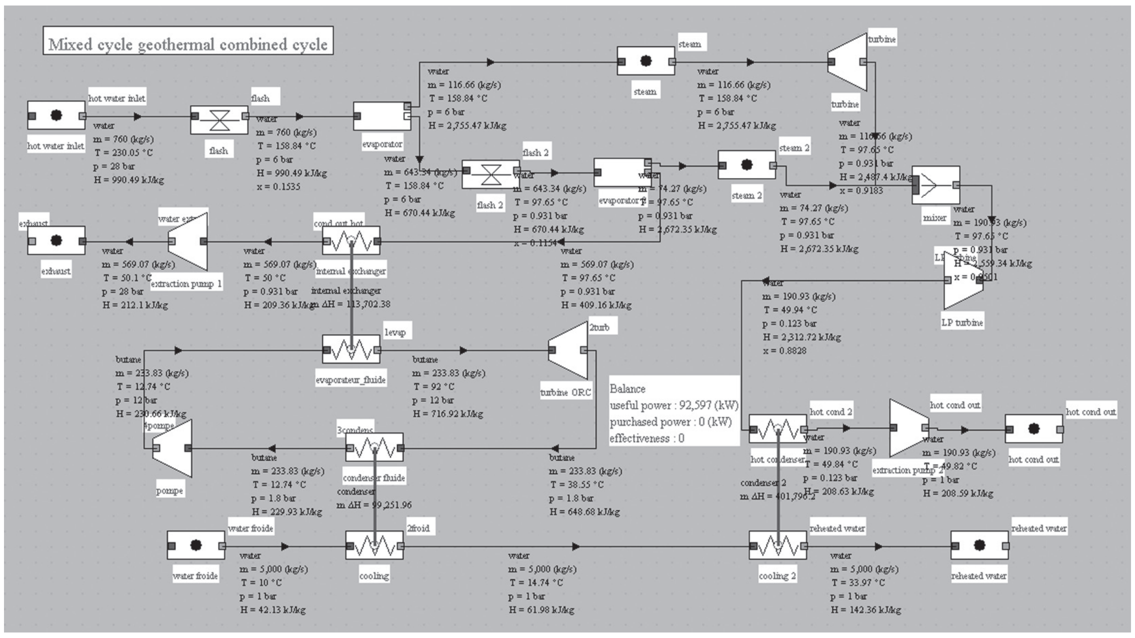


FIGURE 31.3.13
Mixed cycle



water
m = 760 (kg/s)
T = 230.05 °C
p = 28 bar
H = 990.49 kJ/kg

water
m = 760 (kg/s)
T = 158.84 °C
p = 6 bar
H = 990.49 kJ/kg
x = 0.1535

water
m = 116.66 (kg/s)
T = 158.84 °C
p = 6 bar
H = 2,755.47 kJ/kg

water
m = 116.66 (kg/s)
T = 158.84 °C
p = 6 bar
H = 2,755.47 kJ/kg

water
m = 116.66 (kg/s)
T = 97.65 °C
p = 0.931 bar
H = 2,487.4 kJ/kg
x = 0.9183

water
m = 643.34 (kg/s)
T = 158.84 °C
p = 6 bar
H = 670.44 kJ/kg

water
m = 643.34 (kg/s)
T = 97.65 °C
p = 0.931 bar
H = 670.44 kJ/kg
x = 0.1154

water
m = 74.27 (kg/s)
T = 97.65 °C
p = 0.931 bar
H = 2,672.35 kJ/kg

water
m = 74.27 (kg/s)
T = 97.65 °C
p = 0.931 bar
H = 2,672.35 kJ/kg

water
m = 190.93 (kg/s)
T = 97.65 °C
p = 0.931 bar
H = 2,559.34 kJ/kg
x = 0.9501

water
m = 569.07 (kg/s)
T = 97.65 °C
p = 0.931 bar
H = 409.16 kJ/kg

water
m = 569.07 (kg/s)
T = 50 °C
p = 0.931 bar
H = 209.36 kJ/kg

internal exchanger
m ΔH = 113,702.38

water
m = 569.07 (kg/s)
T = 50.1 °C
p = 28 bar
H = 212.1 kJ/kg

water
m = 190.93 (kg/s)
T = 49.94 °C
p = 0.123 bar
H = 2,312.72 kJ/kg
x = 0.8828

butane
m = 233.83 (kg/s)
T = 12.74 °C
p = 12 bar
H = 230.66 kJ/kg

butane
m = 233.83 (kg/s)
T = 92 °C
p = 12 bar
H = 716.92 kJ/kg

Balance
useful power : 92,597 (kW)
purchased power : 0 (kW)
effectiveness : 0

butane
m = 233.83 (kg/s)
T = 12.74 °C
p = 1.8 bar
H = 229.93 kJ/kg

condenser
m ΔH = 99,251.96

butane
m = 233.83 (kg/s)
T = 38.55 °C
p = 1.8 bar
H = 648.68 kJ/kg

water
m = 190.93 (kg/s)
T = 49.84 °C
p = 0.123 bar
H = 208.63 kJ/kg

condenser 2
m ΔH = 401,796.2

water
m = 190.93 (kg/s)
T = 49.82 °C
p = 1 bar
H = 208.59 kJ/kg

water
m = 5,000 (kg/s)
T = 10 °C
p = 1 bar
H = 42.13 kJ/kg

water
m = 5,000 (kg/s)
T = 14.74 °C
p = 1 bar
H = 61.98 kJ/kg

water
m = 5,000 (kg/s)
T = 33.97 °C
p = 1 bar
H = 142.36 kJ/kg

FIGURE 31.3.14
Synoptic view of a geothermal mixed cycle

31.3.7 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.