Chapter 9
Geothermal Energy

Abstract Geothermal energy is the primordial energy of the Earth, produced in the interior of the Earth by nuclear reactions. It is a thermal form of energy that is conveyed by the magma to the crust of the planet. In the crust, some of the Earth's heat is advected by the water of deep aquifers to the surface. While, high-quality, high-temperature geothermal resources are met in regions that are close to the tectonic boundaries, other lower temperature resources are abundant in all geographic locations. Geothermal energy is primarily utilized by extracting dry steam or high-temperature liquid water from an aquifer and by using the steam or the vapor of another substance for the production of power with a turbine. Depending on the type and the characteristics of the geothermal resource, flashing or binary power plants are used for the production of steam and electricity. The geothermal electric power plants are simpler than fossil or nuclear power plants, i.e. they have a lesser number of components. Because the geothermal fluid emanates from the Earth's interior and carries other substances, including solids and non-condensable gases, the design of the equipment of a geothermal power plant poses several challenges, such as the avoidance of scale in the well and flashing chambers; and the removal of non-condensable gases from the condenser.

9.1 Introduction

Geothermal energy is the thermal energy convected from the interior of the Earth. Approximately 44 TW ($44*10^{12}$ W) of heat power is transferred from the interior to the surface of the Earth. Of this amount, 30 TW is generated by the radioactive decay of elements in the core of the Earth.[1] Given that the average power

[1] The implied power deficit of 14 TW (= 30–44 TW) is an indication that the earth cools continuously and its interior temperature decreases. Therefore, geothermal power will decrease in the future and, eventually, will cease. This is expected to take place in a geological time scale, of the order of billions of years.

E. E. (Stathis) Michaelides, *Alternative Energy Sources*,
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consumed by the entire Earth's population is approximately 16 TW, it follows that geothermal power alone may satisfy the energy requirements of the humans. However, geothermal is thermal power that appears at the surface of the Earth at low temperatures, and its conversion to electricity is accomplished with significantly low efficiencies. In addition, a great deal of the geothermal power is dissipated in the oceans, which constitute more than 70% of the surface of the Earth. For this reason, geothermal energy may produce small amounts of electricity, but may not be reasonably relied upon to provide a high percentage of the total energy needs of the Earth's population.

Geothermal energy has been used since the ancient times. Among others, ancient Greeks and Romans used the high temperature water from hot springs and fumaroles for baths and even for the heating of public places. Later, therapeutic properties were attributed to these hot springs and a whole resort industry was developed around them, which peaked in the late nineteenth century. Hot geothermal water was used to fill individual or communal baths, to provide high moisture air (steam baths) and, in the winter months to provide heating for the resort.

The harnessing of geothermal energy for the production of electricity commenced in 1904 in the small town of Central Italy, Lardorelo. The local count of Lardorelo, apparently disenchanted with the unreliability and high cost of electricity in his area constructed a well that brought geothermal steam to the ground surface. He connected the steam to a turbine, which produced enough electric power to satisfy the demand of his household. In the 1920s the development of the Geysers field started, to the north of San Francisco, California, and continued in the 1950s and 1960s with the installation of more than 2,200 MW of electric power. Several other electric generation projects from geothermal energy around the world, for example in Wairakei, New Zealand; Tsukuba, Japan; and Reykjavik, Iceland, were completed after 1960. In 2010, there were a total of more than 9,000 MW of installed electric capacity from geothermal power plants in 24 countries. Another 16,000 MW of heat from geothermal origin were produced in 72 countries around the world and were used directly for a variety of purposes, including space heating, fresh water production from snow melting, aquaculture, and agriculture. With the emphasis on renewable energy sources that followed the 2007–2008 increase of petroleum prices, in the summer of 2010 an additional 4,000 MW of electric power installation and more than 20,000 MW of heat utilization projects were in the development and construction stages in the U.S. alone.

The *core* or central part of the Earth is in liquid state at temperatures that are estimated to be between 6,000 and 4,000°C and are maintained at this level from the radioactive decay of nuclear isotopes. The core is surrounded by the cooler layer, the *mantle*, which consists of the *magma,* a hot, semi-glassy, viscoplastic material, with temperatures ranging from 3,000 to 1,500°C. The upper layer of the Earth is a thin solid layer, the *crust,* of 8–10 km thickness, which is made up of six major *tectonic plates,* and several minor plates. The crust of the Earth consists of several solid plates that are floating on a pool of magma. The insulating characteristics of the crust help to maintain the lower temperatures at the surface of the Earth and to limit the heat transfer from the mantle to the atmosphere and the outer

Fig. 9.1 Regions of high geothermal activity are at the boundaries of tectonic plates

space. However, at the boundaries of the tectonic plates, which are referred to as *geological faults,* there are significant intrusions of hot magma into the crust layer. Heat from these pockets of hot magma is conducted to local aquifers, often called *geothermal reservoirs,* where water temperatures may rise to 200–300°C. Because the local static pressure is significantly high, water at these temperatures is below the corresponding saturation temperature and exists in the liquid state.

Figure 9.1 shows the regions of the Earth at the boundaries of tectonic plates, in dark, where magma intrusion and high geothermal activity has been observed. Among these regions is the western Pacific Rim, which encompasses the USA, Mexico, all the Central American countries, Ecuador, Peru, and Chile. The countries of Japan, Indonesia, New Zealand and the Philippines are in the East part of this Rim and have significant geothermal resources. In Europe the Mediterranean countries and Iceland have the majority of geothermal resources and geothermal power plants. The eastern African countries of Ethiopia, Eritrea, Kenya, and Tanzania also have significant geothermal resources and a few geothermal installations. The same regions are also characterized with higher volcanic activity and plate instabilities that generate earthquakes.

Figure 9.2 is a schematic diagram that shows how the intrusion of magma close to the Earth's surface creates a geothermal field in the local aquifer. Geothermal wells, which are drilled deep into the aquifer zone, bring the geothermal fluid to the surface of the Earth and supply a geothermal power plant that produces electric power. Oftentimes, the high pressure in the geothermal reservoir is augmented by the insertion of a *downhole pump,* which supplies a higher volume of geothermal fluid to the power plant.

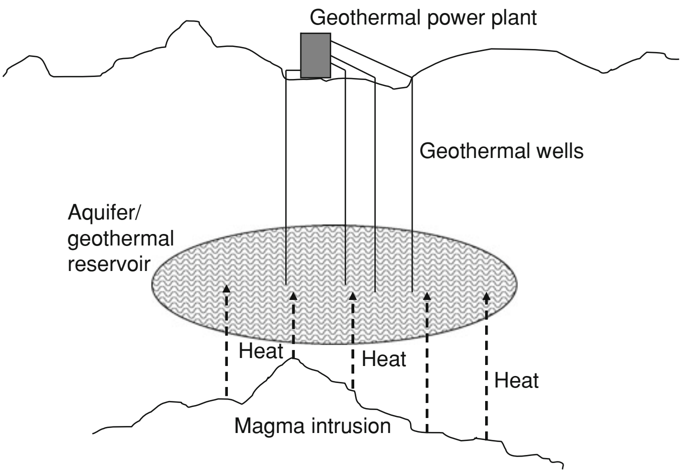

Fig. 9.2 A schematic diagram of geothermal activity

The *geothermal resource* has become almost synonymous with the *geothermal reservoir or aquifer*. Surface water that seeps through the ground and the permeable geological strata replenishes the water carried by the wells. In addition, water that has been used in the power plant is often injected back to the aquifer via *reinjection wells.* Because of the replenishment of the water and the very long time associated with the cooling of the Earth, geothermal resources are considered renewable energy sources. However, it has been observed that, in a period of a few decades, the pressure, temperature and volumetric flow rate of water produced by a specific geothermal well decline. When this occurs, the well may be shut and another well may be drilled at a different location, in the same aquifer. While the temperature of the geothermal reservoir depends to a high degree on the proximity of the reservoir to the heat source of magma, the static pressure of the reservoir is approximately equal to the hydrostatic pressure of a column of liquid water from the surface to the reservoir. This happens because rain or surface water finds its way toward the aquatic reservoir through the fissures of the rocks and other passages. Therefore, there is a continuous column of water from the surface of the Earth to the reservoir level at depth H. As a result, the reservoir pressure P_{res} may be approximately given in terms of the liquid water density, ρ, and the depth from the surface, z, as follows:

$$P_{res} = P_{at} + \int_0^H \rho g dz \approx P_{at} + \rho g H. \tag{9.1}$$

The geothermal fluid is essentially water. Depending on the location of the aquifer, the geothermal fluid contains several minerals, sometimes in significant quantities. For this reason the geothermal fluid is oftentimes referred to as *brine.* $NaCl$, KCl, and $CaCl_2$ are among the most common minerals of geothermal fluids.

The first two are soluble in water, while the last is essentially insoluble at lower temperatures and is carried in the fluid as small particles that may deposit in the piping. The geothermal fluids also contain a number of gases, among which are CO_2, CH_4, the malodorous H_2S, and oftentimes traces of the radioactive Ra, which is produced from the nuclear reactions in the core of the Earth. When modeling the flow and characteristics of the geothermal wells, the properties of pure water are typically used as an approximation. More accurate modeling would require the exact composition of the geothermal fluid as well as knowledge of the influence of all the constituents/impurities on the properties of the water substance.

9.1.1 Geothermal Resources

The type and quality of the geothermal resources depends on the type of fluid the wells produce and is intricately related to the specific exergy of the geothermal fluid. In general, geothermal resources are classified in the following types:

1. *Dry steam*: The water in these aquifers is at a significantly high temperature, typically in the range 200–280°C. As the water flows through the porous medium that constitutes the aquifer, its static pressure drops and a great deal of steam is produced inside the aquifer by local flashing. The steam, with a small fraction of droplets is carried in the geothermal well, where the pressure is further reduced and most or all of the droplets evaporate to produce a higher amount of steam. Thus, wells from a dry steam resource supply the power plant with saturated or superheated steam, which may be fed directly to a turbine for the production of power. The fields at Lardorelo and the Geysers are primarily dry steam geothermal fields. The specific exergy of the steam produced is significantly higher than the exergy of the other types of geothermal resources and, for this reason dry steam resources are considered to be of high quality.
2. *Liquid water*: When the reservoir temperature is lower, liquid hot water at high pressure is produced at the bottom of the well. As the water rises in the well, its static pressure decreases due to the gravitational and frictional losses in the pipe. The temperature of the geothermal fluid is also reduced because of heat losses to the surrounding rock. However, given the insulating properties of the rocks, the rate of temperature reduction is very low. The continuous reduction of pressure in the well may cause the static pressure of the fluid to become lower than the saturation pressure of the fluid at the prevailing temperature. At this level of the well, flashing of the water occurs and some steam is produced. As the fluid moves upwards to the wellhead, more steam is produced by flashing. A mixture of steam and liquid water is directed to the power plant, where additional steam may be produced by flashing. The dryness fraction (quality) of the fluid at the wellhead steam depends to a great extent on the characteristics (pressure and temperature) of the geothermal reservoir as well as on the depth of the well. From the thermodynamic properties of water and

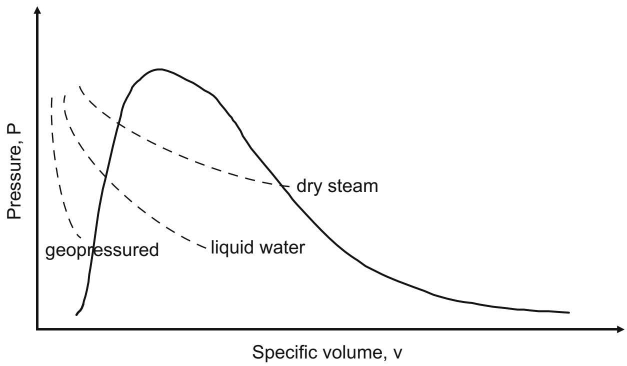

Fig. 9.3 Geothermal fluid processes on a P,v diagram

steam, one may easily deduce that the specific exergy of the fluid produced by liquid water resources is lower than that of the dry steam type.

3. *Geopressured*: Temperatures in the geopressured reservoirs are very low, typically in the range 120–160°C, which correspond to low saturation pressures. These reservoirs are typically located at greater depths than the dry steam and liquid water resources and, hence, the reservoir pressures are significantly higher. At all levels in the well, the pressure of the geothermal fluid is significantly higher than the saturation pressure. Thus, flashing does not occur and vapor is not produced. Liquid, hot water is produced and may be directed to the power plant. The exergy of the liquid water is significantly lower than that of steam and, hence, these resources are considered to be of significantly lower quality than the dry steam resources. The utilization of geopressured geothermal resources or the production of electricity is usually accomplished by a binary power conversion system, which will be described in Sect. 9.2.5. Figure 9.3 shows the pressure–volume diagram of the thermal processes that occur in the reservoirs and the wells of the dry steam, the liquid water and the geopressured resources. Since the amount of heat lost in the wells is very low, these processes are considered to be isenthalpic.
4. *Hot, dry rock*: As the name implies, these resources are hot rocks at a significant depth from the Earth's surface without a nearby aquifer to produce geothermal brine. Despite the fact that there is no local fluid to be carried to the surface, one may develop an engineering system to harness the thermal energy of the rock by drilling a number of wells, injecting a fluid to the wells, bringing this fluid to the surface and using the thermal energy of this fluid for the production of electric power. The working fluid is not necessarily water and may be another fluid with convenient thermodynamic properties, such as butane, pentane or a refrigerant. Figure 9.4 shows a map of the United States with the temperatures that are expected to be found at depths of 3,000 m. It is apparent that most of the high temperature resources are in the Rocky Mountains and the western part of the country. It is also apparent in this figure that, at

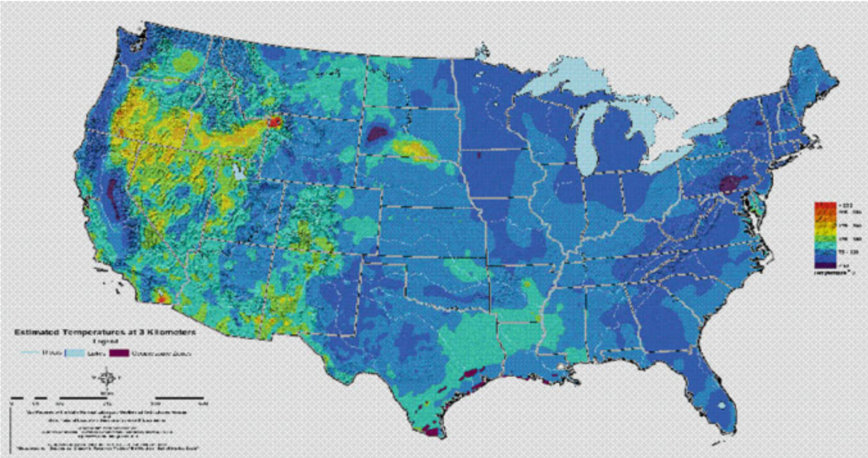

Fig. 9.4 A map of the United States, showing the expected temperatures at a depth of 3,000 m (Prepared by the Idaho National Laboratory Geothermal Technologies Program and Idaho National Laboratory Geospatial Science & Engineering)

a depth of 3,000 m there are several regions in the USA, where the temperature exceeds 150°C, Engineering systems may be designed and constructed in these areas to convert the Earth's thermal power to electricity.

While the dry steam type of geothermal resources are the most desirable for the production of electric power, these resources are scarce and most of them have already been utilized. Similarly, a high percentage of high temperature liquid water resources have been utilized economically and the few that remain will be developed in the near future. Geopressured resources and hot, dry rock resources are abundant on the planet. Despite the fact that the temperatures of these resources are lower, they represent the overwhelming majority of the geothermal resources on the planet, they have the capacity to produce economically a good amount of the electric power of several nations and they should be seriously considered as significant energy resources.

9.2 Geothermal Power Plants

All geothermal power plants utilize resources at moderate to low temperatures and rarely exceed 200°C. For this reason, they are built differently than fossil fuel and nuclear power plants, with an emphasis on higher second law efficiencies and high rate of exergy utilization. The type of geothermal resource that supplies the thermal energy dictates to a large extent the type of power plant that is built. A list of such plants from the simplest to the more complex ones is given in the following subsections.

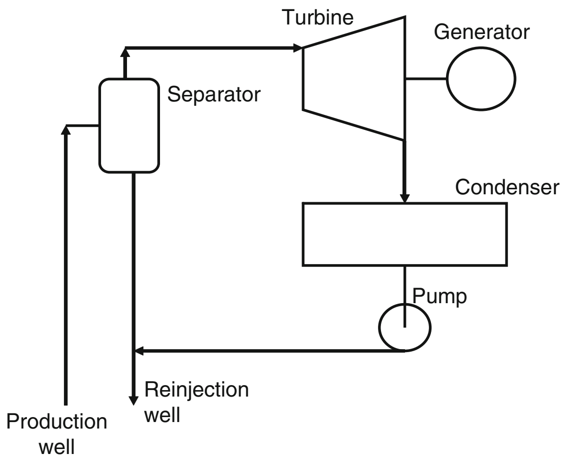

Fig. 9.5 Schematic diagram of a dry steam geothermal power plant

9.2.1 Dry Steam Units

These are the simplest geothermal power plants and utilize resources that produce dry steam. The original geothermal plant at Lardorelo and several of the units at the Geysers geothermal field in California are of this type. Essentially, the geothermal well produces dry (or almost dry) steam, which may be fed directly to a steam turbine that drives the electric generator. A schematic diagram of a dry steam power plant is depicted in Fig. 9.5. The steam from the well is fed to the *steam dryer* or *separator* where any water droplets that are present are removed. The steam is then directly fed to a turbine, which drives the electric generator, and finally exhausts in the condenser. The condensate, which is almost pure water, is then re-injected to the geothermal reservoir or is used locally as a water source. If the mass flow rate of the steam produced is denoted by $\dot{m}$ and the exergy of the steam by e_1, the maximum amount of power such an electric power unit may produce is:

$$\dot{W}_{\max} = \dot{m}e_1 = \dot{m}[h_1 - h_0 - T_0(s_1 - s_0)]. \tag{9.2}$$

The subscript 0 denotes properties at the *dead state*, which is characterized by the ambient temperature and the atmospheric pressure. In the actual operation of the plants, the turbine is not isentropic and the temperature in the condenser is slightly higher than the ambient, 35–45°C. Such thermodynamic irreversibilities would reduce the actual power produced by this power plant to:

$$\dot{W}_{act} = \dot{m}\eta_T(h_1 - h_{2s}) = \dot{m}(h_1 - h_2) \tag{9.3}$$

where 1 and 2 are the states of the steam at the entrance and exit of the turbine as shown in Fig. 9.5. For the calculation of the enthalpy at state 2 one uses the isentropic efficiency of the turbine, η_T, and the state 2s, which is the state that would be reached in an isentropic expansion 1–2s, that is, state 2s has equal

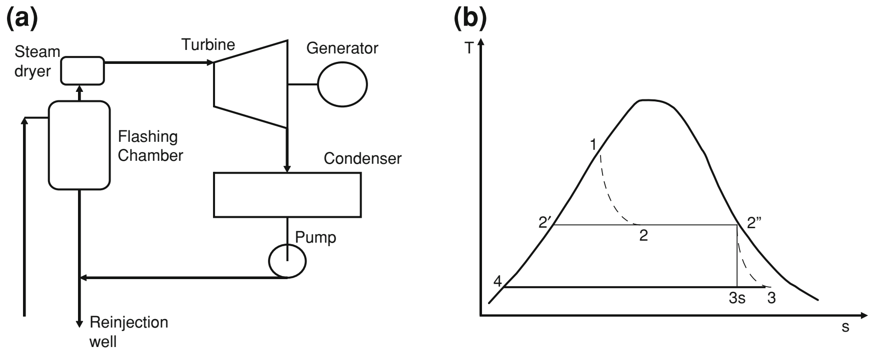

Fig. 9.6 **a** Schematic diagram of the single-flashing geothermal power plant. **b** Thermodynamic diagram of the single-flashing geothermal power plant

entropy to that of state 1 and its pressure is equal to the turbine exhaust pressure (Eq. 3.23).

Dry steam geothermal power plants are the simplest of all steam plants, require a modest amount of capital to construct and are very inexpensive to maintain. For this reason, the electric power produced by dry steam geothermal power plants is significantly less expensive than power produced by most of the other alternative energy sources.

9.2.2 Single-Flashing Units

A schematic diagram of a single-flashing geothermal power plant is shown in Fig. 9.6a. Geothermal fluid from the well at state 1, which may be liquid or two phase mixture (saturated steam and liquid water) enters a flashing chamber, where its pressure is reduced significantly. The flashing process takes place at constant enthalpy and, as a result a significant amount of steam vapor is produced. The vapor is separated from the droplets in the *steam drier* and then fed to the turbine where it expands to the pressure of the condenser, thus producing power. The condensate and the flashing chamber effluent are discarded or re-injected to the reservoir.

The operation of a single-flashing geothermal power plant is shown in the T-s diagram of Fig. 9.6b, where the state of the fluid produced by the well is assumed to be in the two phase region, state 1. At the flashing chamber, the prime symbol ($'$) denotes saturated liquid and the double-prime symbol ($''$) denotes saturated vapor. Flashing chambers are sufficiently insulated for the process 1–2 to be at constant enthalpy. Hence, the fraction of steam produced by this process is obtained by the expression:

$$h_1 = h_2 = (1 - x_2)h_{2'} + x_2 h_{2''} \Rightarrow x_2 = \frac{h_1 - h_{2'}}{h_{2''} - h_{2'}}. \tag{9.4}$$

Typically, 10–25% of the geothermal fluid is converted to steam in the flashing chamber. If the total mass flow rate of the geothermal fluid from the well is denoted by $\dot{m}$, the amount of steam fed to the turbine is $\dot{m}x_2$ and the total power produced is calculated from the expression:

$$\dot{W}_{act} = \dot{m}x_2\eta_T(h_{2''} - h_{3s}) = \dot{m}x_2(h_{2''} - h_3). \tag{9.5}$$

The pressure at state 2 is a parameter in the operation of the single-flashing geothermal units and may be optimized in order to yield maximum power. When the pressure P_2 is very close to the pressure P_1 the steam produced has higher exergy but the fraction of steam produced, x_2, is low. Since the power produced is proportional to this fraction, the total power produced would be low. On the other hand, when the pressure P_2 becomes very low, the exergy of the steam produced (or the isentropic enthalpy difference h_2-h_{3s}) is very low and the total power produced would be, again, very low. Between these two extremes there is an optimum value where the total power produced, as given by Eq. (9.5), is maximized. This optimum value may be obtained by a parametric study, in which the pressure P_2 or equivalently the saturation temperature $T_2 = T_{sat}(P_2)$ is the optimization parameter. From such an optimization study, it was concluded that, when the well produces saturated liquid or compressed liquid at temperature T_1 and the condenser temperature is T_3, then the optimum temperature and pressure for the flashing chamber are given by the expressions:

$$T_{2opt} = \frac{T_1 + T_3}{2} \quad and \quad P_{2opt} = P_{sat}(T_{2opt}), \tag{9.6}$$

that is, the flashing temperature separates the available range of temperatures in two equal parts.

With typical geothermal resource temperatures near 200°C and condenser temperatures of 40°C, the optimum temperature of the flashing chamber is typically 120°C and the pressure of the flashing chamber is close to 2 bar. Because only 15–25% of the geothermal fluid is converted to steam, 75–85% of the mass of this fluid is discarded or reinjected at this high temperature, thus, wasting a significant amount of the exergy of the geothermal fluid. Clearly this high-temperature fluid may be utilized to produce more steam and, consequently, more power. This is accomplished in the dual-flashing geothermal power plants and the binary plants.

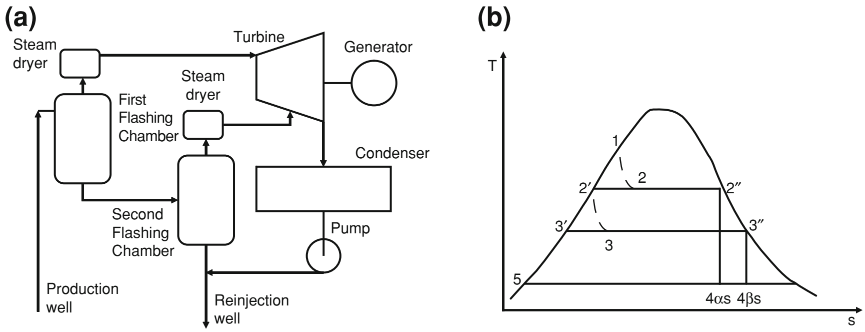

Fig. 9.7 **a** Schematic diagram of the dual-flashing geothermal power plant. **b** Thermodynamic diagram of the dual-flashing geothermal power plant

9.2.3 Dual Flashing Units

The dual flashing geothermal power plants utilize a second flashing chamber, which admits the liquid effluent from the first flashing chamber. The reduced pressure and temperature of the second flashing chamber causes a second, additional quantity of steam to be produced, at the reduced pressure P_3. This steam is also passed through a *steam drier/separator* and subsequently directed to the low-pressure part of the turbine, where it produces an additional amount of power. The schematic diagram of the dual flashing geothermal power plant is shown in Fig. 9.7a and the thermodynamic diagram of the power plant in Fig. 9.7b. As in the case of the single flashing unit, the quantity of steam, x_2, produced in the first flashing chamber is calculated by an energy balance and is given by Eq. (9.4). Following a similar analysis in the second flashing chamber, the steam fraction at state 3 may be calculated from the expression:

$$h_{2'} = h_3 = (1 - x_3)h_{3'} + x_3 h_{3''} \Rightarrow x_3 = \frac{h_{2'} - h_{3'}}{h_{3''} - h_{3''}}. \tag{9.7}$$

It must be noted that the mass flow rate of the effluent from the first flashing chamber is not $\dot{m}$, but $\dot{m}(1 - x_2)$. Hence, the vapor mass flow rate from the second flashing chamber to the turbine is: $\dot{m}(1 - x_2)x_3$. The total power produced by the dual-flashing geothermal power plants emanates from the two streams with dryness fractions x_2 and x_3 and is given by the expression:

$$\begin{aligned} \dot{W}_{act} = \dot{m}\eta_T\left[x_2(h_{2''} - h_{4\alpha s}) + (1 - x_2)x_3\left(h_{3''} - h_{4\beta s}\right)\right] = \\ \dot{m}\left[x_2(h_{2''} - h_{4\alpha}) + (1 - x_2)x_3\left(h_{3''} - h_{4\beta}\right)\right] \end{aligned}, \tag{9.8}$$

where the symbols α and β denote the different states at the end of the expansion processes of the two streams of steam that are fed into the turbine.

As in the case of the single flashing power plants, the pressures and temperatures of the two flashing chambers are free parameters that may be optimized.

When the geothermal well produces compressed liquid or saturated liquid water the optimum temperatures for the flashing chambers are given approximately by the following expressions:

$$T_2 = T_4 + \frac{2(T_1 - T_4)}{3} \quad and \quad T_3 = T_4 + \frac{T_1 - T_4}{3}, \tag{9.9}$$

In analogy with the single-flash units, the flashing temperatures of the dual-flash units separate the available range of temperatures in three equal parts. The corresponding pressures of the two flashing chambers are the saturation pressures of the last two temperatures: $P_2 = P_{sat}(T_2)$ and $P_3 = P_{sat}(T_3)$.

9.2.4 Several Flashing Processes: A Useful Theoretical Exercise

While the dual flashing power plants utilize a higher fraction of the exergy of the geothermal fluid than the single flashing units, still the effluent of the second flashing chamber is liquid water at an elevated temperature. In principle, a third (and then a fourth) flashing chamber may be employed to extract a higher amount of the available power in the geothermal fluid. The isenthalpic flashing process is a highly irreversible process that produces a significant amount of entropy. The inclusion of several flashing processes and the production of small amounts of vapor that are fed to the turbines for expansion, reduces the amount of entropy generated and also reduces the total irreversibility of the power producing processes. The addition of more flashing chambers would decrease the amount of energy destroyed and, as a consequence, would increase both the first and second law efficiencies of geothermal power plants.

An interesting exercise in the theory of thermo-mechanical energy conversion is to consider the multi-flash system, which is shown in Fig. 9.8: The vapor from the kth flashing process is fed to the kth turbine and the liquid is fed to the $(k + 1)$th flashing chamber. The vapor from this chamber is fed to the $(k + 1)$th turbine, the liquid to the $(k + 2)$th flashing chamber etc. If a total of n flashing chambers is used, the total power produced by the geothermal power plant is:

$$\dot{W}_{tot} = \sum_{k=1}^{n} \dot{m}_{k-1} (\Delta h)_k \eta_k, \tag{9.10}$$

where $\dot{m}_{k-1}$ is the amount of vapor produced in the $(k-1)$th flashing chamber, $(\Delta h)_k$ is the isentropic enthalpy difference in the kth turbine and η_k is the efficiency of the kth turbine. Since steam is produced by an isenthalpic process, the mass flow rate of the steam produced in the $(k-1)$th chamber is given by the expression:

$$\dot{m}'_{k-1} = \dot{m}'_{k-2} \frac{h_{(k-1)\prime} - h_{k\prime}}{h_{fg}} = \dot{m}(1 - x_1)(1 - x_2)\ldots(1 - x_{k-2})x_{k-1}. \tag{9.11}$$

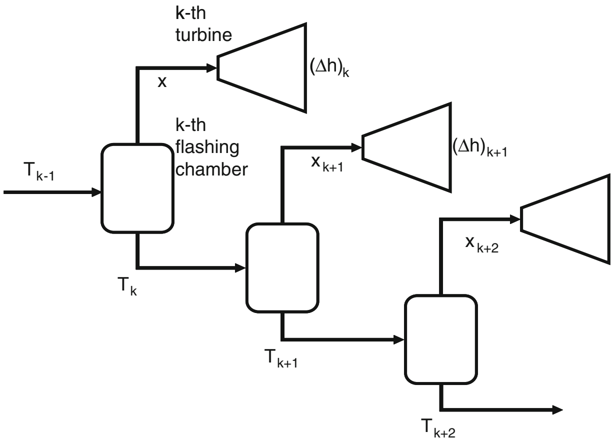

Fig. 9.8 Schematic diagram of three consecutive stages of the multi-flashing geothermal power plant

In Eq. (9.11) $\dot{m}$ is the mass flow rate supplied by the geothermal wells to the first flashing chamber; the prime symbol ($'$) denotes the saturated liquid state and the double prime ($''$) the saturated vapor phase; h_{fg} is the latent heat of vaporization, which is almost constant over small ranges of water/steam temperature. Hence, the total power from the entire series of flashing and expansions may be written as follows:

$$\dot{W}_{tot} = \dot{m} \sum_{k=1}^{n} \left[\prod_{i=1}^{k-2} (1 - x_i) \right] x_{k-1} (\Delta h)_k \eta_k. \tag{9.12}$$

When the number of the flashing processes is very large, only a very small amount of steam is produced in each flashing chamber and, hence $(1-x_i) \approx 1$. In addition, the isentropic enthalpy drop and the liquid to liquid enthalpy drop shown in Eq. (9.11) may be approximated in terms of the specific heats for the saturated water vapor, $c_{p''}$, and the saturated liquid, $c_{p'}$, as follows:

$$(\Delta h)_k \approx c_{p''} (T_k - T_0) \quad and \quad h_{(k-1)'} - h_{k'} = c_{p'} (T_{k-1} - T_k), \tag{9.13}$$

where T_0 is the condenser temperature. Assuming that the properties h_{fg}, $c_{p'}$, and $c_{p''}$ are constant, one may derive the following approximation for the total power produced by the multiple flashing systems, solely in terms of the flashing temperatures, T_1, T_2, $T_3 \ldots T_k$:

$$\dot{W}_{tot} \approx \frac{\dot{m} c_{p'} c_{p''}}{h_{fg}} \sum_{k=1}^{n} (T_{k-1} - T_k)(T_k - T_0) \eta_k \tag{9.14}$$

One may use the theory of Lagrange undetermined multipliers to maximize the total power produced, when the geothermal water enters the plant at temperature

T and the condenser temperature is at T_0. As with the single- and the dual-flashing units, the optimization process will yield that the available range of temperatures be divided in n equal parts. The optimization process yields the following expressions that determine all the intermediate temperatures, T_1, T_2, $T_3 \ldots T_k$, $\ldots T_n$:

$$T - T_1 = T_1 - T_2 = T_2 - T_3 = \ldots = T_{k-1} - T_k = \ldots T_{n-1} - T_n = T_n - T_0, \tag{9.15}$$

Equations (9.6) and (9.9), may be considered as special cases of this general expression, derived for $n = 1$ and $n = 2$ respectively.

At the limit, $n \to \infty$, which is practically approximated by introducing a very large number of flashing chambers, the total amount of power produced by the geothermal power plant becomes equal to the theoretical maximum power. The latter is expressed by the product of the mass flow rate and the exergy of the geothermal fluid with respect to an environment at temperature T_0:

$$\lim_{n\to\infty}\left(\dot{W}_{tot}\right) = \dot{W}_{\max} = \dot{m}[e(T) - e(T_0)]. \tag{9.16}$$

In principle, the maximum amount of work may be extracted by an isentropic *two-phase turbine*, which makes possible the expansion of hot liquid fluids. Although there is considerable engineering research going on in this area, such a turbine is far from becoming reality in the near future. Common turbines operate with vapor expansion and, for this reason, geothermal energy is currently utilized by producing vapor in a flashing or a binary power plant.

In practice, there are diminishing returns in the marginal amount of power that may be extracted by having more than two flashing chambers. The added cost of such installations does not justify the additional energy that may be produced. For this reason, there are not any known geothermal power plants, which utilize more than two flashing chambers. Instead, binary power plants are used, which typically utilize a higher fraction of the exergy of the geothermal fluid and, as a consequence, have higher Second Law efficiencies.

Another practical consideration in the design of flashing geothermal power plants is the pressure in the flashing chamber: Flashing chambers have significantly high volume and, over time, develop cracks that allow air to leak from the outside, if the pressure is sub-atmospheric. Air leakage to a flashing chamber would increase the percentage of non-condensable gases to the turbine and the condenser, thus, reducing by a higher percentage the net power of the plant. On the other hand, a limited amount of steam leakage from the flashing chamber to the environment would not decrease by a great deal the net power produced. For this reason, single and dual-flashing power plants are designed with the flashing chambers to be above atmospheric pressure. For example, if the optimum temperature of a dual flashing unit, T_3, is calculated to be less than 100°C, the second flashing chamber is designed in the temperature range 102–105°C. This choice maintains a positive pressure inside the second flashing chamber, $P_3 > P_{atm}$, and prevents the costly leakage of atmospheric air into the second flashing chamber.

9.2.5 Binary Units

The construction of binary units is recommended when the geothermal fluid at the wellhead is at low temperature. Given this low resource temperature and the practical consideration to keep the pressure and temperature of the flashing chambers higher than 1 atm and 100°C respectively, the production of steam by flashing would be very low and a flashing-type power plant would produce very low power. In such cases, it is advantageous to use a heat exchanger for the transfer of the thermal energy from the geothermal fluid to a *secondary* or *working* fluid, which evaporates and undergoes expansion in a turbine and subsequent condensation. Effectively, the heat exchanger becomes the boiler of a simple Rankine cycle that uses the secondary fluid for the production of power. A schematic diagram of a binary geothermal power plant is shown in Fig. 9.9. The geothermal fluid enters the main heat exchanger from the production well and exits at the re-injection well. In the heat exchanger heat is transferred to the secondary fluid, which is the working fluid of the simple Rankine cycle. The secondary fluid exits the heat exchanger as a saturated or superheated vapor at sufficiently high pressure and temperature to power the turbine, which drives the electric generator. The Rankine cycle is completed via the condenser and the condensate pump of the secondary fluid.

Suitable choices for the secondary fluid are substances with high saturation pressures and low corresponding saturation temperatures. Candidate fluids are most of the refrigerants, including ammonia, and several hydrocarbons, such as propane, butane, iso-butane and pentane. Figure 9.10 shows the operation of the heat exchanger in a Length–Temperature (L–T) diagram: The primary geothermal fluid supplies with heat the secondary fluid and, thus, cools between states 1–4. The secondary fluid preheats during the process 4–3, evaporates during the process 3–2 and becomes superheated during the process 2–1. The three processes are separated by the dotted lines in Fig. 9.10. If one denotes by $\dot{m}_p$ the mass flow rate of the primary fluid and by $\dot{m}_s$ the mass flow rate of the secondary fluid, then the energy conservation principle (first law of thermodynamics) in the three parts of the heat exchanger yields the following equations:

$$\begin{aligned}\dot{m}_p\left(h_{p1}-h_{p2}\right)&=\dot{m}_s(h_{s1}-h_{s2})\\ \dot{m}_p\left(h_{p2}-h_{p3}\right)&=\dot{m}_s(h_{s2}-h_{s3})\,.\\ \dot{m}_p\left(h_{p3}-h_{p4}\right)&=\dot{m}_s(h_{s3}-h_{s4})\end{aligned} \tag{9.17}$$

The primary fluid remains in the liquid state and, hence, its enthalpy difference may be approximated using its specific heat capacity in all three processes. The same approximation may be used in the preheating process, 4–3, of the secondary fluid. Also, during the evaporation process, 3–2, the enthalpy difference of the secondary fluid is the latent heat h_{fg}. Hence, the set of the above equations may be

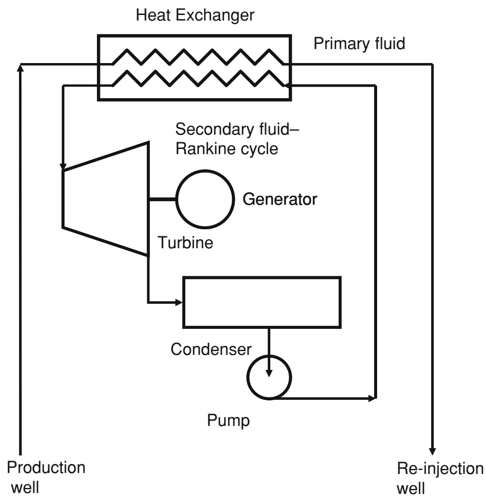

Fig. 9.9 Schematic diagram of a binary geothermal power plant

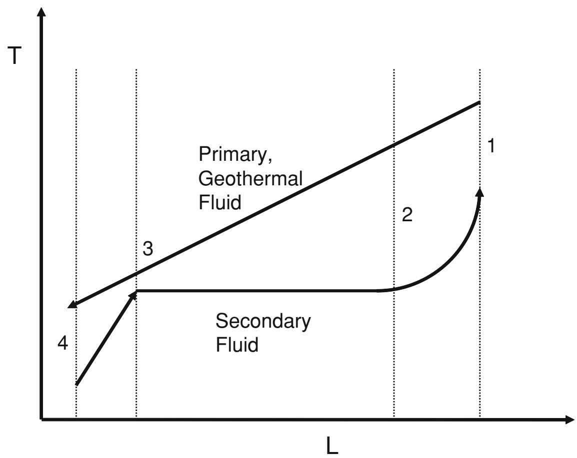

Fig. 9.10 L-T diagram that elucidates the three parts of the main heat exchanger

written in terms of the corresponding temperatures at the primary and secondary side as follows:

$$\begin{aligned} \dot{m}_p c_{pp}\left(T_{p1} - T_{p2}\right) &= \dot{m}_s(h_{s1} - h_{s2}) \\ \dot{m}_p c_{pp}\left(T_{p2} - T_{p3}\right) &= \dot{m}_s h_{fg} \\ \dot{m}_p c_{pp}\left(T_{p3} - T_{p4}\right) &= \dot{m}_s c_{ps}(T_{s3} - T_{s4}) \end{aligned} \tag{9.18}$$

where c_{pp} and c_{ps} are the specific heat capacities of the primary and the secondary fluid, respectively.

The mass flow rate, $\dot{m}_p$and the primary fluid inlet temperature, T_{p1}, of a typical geothermal binary power plant are imposed by the thermodynamic state of the produced geothermal fluid. Also, the evaporation temperature of the secondary fluid, T_{s2}, is decided from design optimization considerations. In addition, heat exchanger design consideration impose a 3–7°C difference at the *pinch point* of the heat exchanger at state 3, that is the difference $T_{p3}-T_{s3}$ is defined to be between 3 and 7°C. These conditions and the three Eq. (9.18) may be used to determine the mass flow rate of the secondary fluid, $\dot{m}_s$, the exiting temperature of the secondary fluid, T_{s1} and the exiting temperature of the primary fluid, T_{p4}. The equations define all the temperatures in the heat exchanger and make its design feasible.

In general, binary geothermal power plants utilize a higher percentage of the exergy of the geothermal fluid than flashing units. Another advantage of the binary power plants is that the suitable choice of a secondary fluid will result in smaller turbines and heat exchangers. In addition, the absence of flashing eliminates any non-condensable in the condenser, which cause a significant decrease of the power, as described in Sect. 9.3. Among the disadvantages of the binary geothermal power plants are:

a) The high cost of the heat exchanger
b) The higher cost of the secondary fluid turbine and
c) The lower temperatures in the primary fluid side may cause significant scaling in the heat exchanger pipes and this may interrupt the operation of the power plant. This may be avoided by the occasional scrubbing and cleaning of the primary side of the heat exchanger.

9.2.6 Hybrid Geothermal-Fossil Power Units

One of the main thermodynamic disadvantages of the geothermal power plants is that the geothermal resources are at moderate or lower temperatures, typically less than 220°C. As a result, the steam produced in the flashing units or the vapor produced in the binary units is at even lower temperatures. For this reason, the first-law efficiency of all the geothermal power plants is lower than the efficiency of fossil fuel and nuclear power plants. A method to increase the temperature and the power produced as well as to improve the efficiency of the geothermal power plants is to use fossil fuels in order to superheat the steam produced by the flashing units, or the vapor of the secondary fluid produced by the binary units. The superheated steam or vapor has higher energy and may produce a higher amount of power in the turbine. A schematic diagram of a single-flash-fossil hybrid power plant is depicted in Fig. 9.11. It is observed that the hybrid plant has all the components/equipment of the single-flashing unit, with the only addition of the steam superheater. Hybrid geothermal power plants have in general higher first- and second-law efficiencies but require the consumption of fossil fuels.

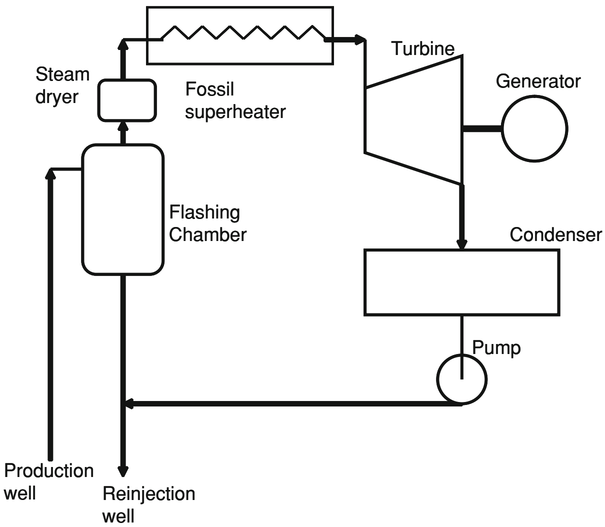

Fig. 9.11 Schematic diagram of a geothermal flashing hybrid power plant

The amount of fossil fuel, $\dot{m}_f$, to be used in such a hybrid plant is determined by the amount of steam vapor produced $\dot{m}_v$ heat balance in the fossil superheater and the superheat temperature:

$$\dot{m}_f \Delta h_f = \dot{m}_v (h_e - h_i), \tag{9.19}$$

where Δh_f is the heat of combustion (heating value) of the fuel and the parenthesis in the right hand side of the equation represents the enthalpy rise of the vapor in the superheater.

9.3 Effects of Impurities in the Geothermal Fluid

Because the geothermal fluid emanates from natural aquifers in the crust of the Earth, it carries several substances other than pure water. These substances are characterized as:

a) *Solids*, which are typically dissolved in the form of ionic salts and primarily consist of NaCl, KCl, Ca_2Cl, Ca_2HCO_3, and $CaCO_3$ and
b) *Non condensable gases*, primarily CO_2, H_2S, CH_4, NH_3, N_2 and C_2H_6. Among the gases CO_2, is the most common constituent and accounts for at least 85% of the mass of the non-condensable gases.

The main effect of dissolved solids on the operation of geothermal power plants is that at lower pressures and temperatures their solubility decreases and they come out of solution. The kinetic considerations of the solution process favor the separation of solids, at the level where steam is initially produced. This often occurs inside the geothermal well, at a level where the static pressure becomes less than the saturation pressure. At this level, the so-called *flashing point* of the geothermal well, steam is produced in the form of bubbles. The evaporation process induces some of the solids to come out of the water solution. Naturally, a fraction of the solids will be deposited on the walls of the pipe. If left untreated, the continuous deposition of salts in the pipe forms scales, which over time will result in pipe restriction and eventual well "clogging." Well clogging may be avoided by treating the affected part of the well with an acid solution or by regularly "scrubbing" the well with metallic brushes. Other parts of the power plant, where scales may be formed from salt deposition are the flashing chambers, where a large amount of steam separates from the geothermal fluid, the remaining water solution becomes supersaturated and solids come out of the solution.

Despite the absence of flashing processes and steam separation, scaling may also become a problem in the heat exchangers of the binary power plants, because ionic solubility is a strong and monotonic function of temperature. Between the entrance and the exit of the binary unit heat exchanger there is always a significant drop of the fluid temperature, typically in the range of 120–150°C. This implies a significant decrease of the salt solubility along the heat exchanger, which leads to the separation of part of the solids from the solution. A high percentage of the solids is carried by the flow, but a small part is driven to the pipe wall by thermophoresis and is deposited. Pipe fouling and "clogging" may occur with the continuous operation of the equipment. This is detrimental in the transfer of heat and the overall operation of the heat exchanger. The solids may be removed and the heat transfer coefficient may be improved by the periodic scrubbing of the heat exchanger pipes or treatment with a mild acid (e.g. HCl) solution.

Non-condensable gases, which emanate from the Earth's magma, account for up to 10% in dry steam installations and up to 2% by weight of the liquid brine resources. The latter, when used with a flashing unit may produce steam that contains up to 35% non-condensables. It has been observed that these gases are flashed out in the initial stages of operation of the geothermal reservoir and, hence, the amount of non-condensable gases in the geothermal wells decreases significantly after the first few months of operation. CO_2 is the main constituent of these gases. Traces of the malodorous hydrogen sulfide (H_2S) are often present and easily detected in the vicinity of geothermal power plants.

The presence of the non-condensable gases has significant effects in the net work the power plant produces and the design of the condenser. As their name implies, these gases do not condense in the condenser and, hence, may not be removed by the condensate pump, which only carries liquid. If left in the condenser, the gases will accumulate over time and will cause a significant increase of the condenser pressure. Since the condenser pressure determines the back-pressure of the turbine, this would imply a significant decrease of the power produced by the turbine. Therefore, the non-condensable gases must be continuously removed from the condenser at the expense of a high amount of power. Among the equipment used for the removal of the gases from the condenser are steam ejectors, pressurized water ejectors, rotary compressors or systems of steam ejectors, and radial blowers (ERR systems).

For a thermodynamic analysis of the gas removal from the condenser, we must recall that the gases and water vapor form a homogeneous mixture in the condenser under a total pressure P_t and a common temperature T. Since there are two vapor constituents in the homogeneous mixture, steam and gases, the total pressure of the mixture, P_t, is equal to the sum of the saturation pressure of the steam, $P_{sat}(T)$, and the partial pressure of the non-condensable gases, P_g:

$$P_t = P_{sat} + P_g. \tag{9.20}$$

The condensation process liquefies most of the water vapor and the condensate is removed by the condensate pump. The remaining steam becomes part of the homogeneous mixture with the non-condensable gases and must be removed by the mechanical gas removal equipment. Let us consider a volume V of the steam-gas homogeneous mixture in the condenser. The partial pressure of the gas, $P_g = P_t - P_{sat}(T)$, is low enough for the gas to be considered as an ideal gas. Therefore, if the apparent molecular weight of the non-condensable gas is denoted by M_g, the mass of the gas in the volume V would be:

$$m_g = \frac{(P_t - P_{sat})VM_g}{\mathbf{R}T}, \tag{9.21}$$

where $\mathbf{R}$ is the universal gas constant, 8.314 kJ/kmol K, and the apparent molecular weight of the gases is often assumed to be equal to the molecular weight of CO_2, 44 kg/kmol.

For better accuracy, the thermodynamic properties of the steam may be obtained from steam tables. Thus, the mass of steam in the same volume, V, would be equal to:

$$m_s = V\rho_s = V/v_s, \tag{9.22}$$

where v_s is the specific volume of the saturated steam at the temperature T (usually denoted as v_g in most steam tables). Hence, the ratio of steam to gas masses in the homogeneous mixture that occupies the volume V is:

$$\frac{m_s}{m_g} = \frac{\mathbf{R}T}{(P_t - P_{sat})M_g v_s}. \tag{9.23}$$

In order to avoid the accumulation of the non-condensable gases the entire mass flow rate of them, $\dot{m}_g$, must be removed. Because this mass is in a homogeneous mixture with the steam, a corresponding mass flow rate of steam must be also removed continuously from the condenser. From Eq. (9.22) the mass flow rate of steam that must be removed with the gases is [1]:

$$\dot{m}_s = \dot{m}_g \frac{\mathbf{R}T}{(P_t - P_{sat})M_g v_s}, \tag{9.24}$$

The corresponding volumetric flow rate the gas extraction equipment must remove from the condenser is:

$$\dot{V} = \dot{m}_g \frac{\mathbf{R}T}{(P_t - P_{sat})M_g} = \dot{m}_s v_s. \tag{9.25}$$

A glance at the last two equations proves that the condensation process in the presence of non-condensable gases is not isothermal at the saturation temperature $T_{sat}(P_t)$ that corresponds to the turbine back pressure, P_t. If $P_t \approx P_{sat}(T)$, a very large amount of steam must be extracted in the vapor form at the expense of a large amount of power. The amount of steam is reduced significantly by designing the condenser temperature, T, to be a few degrees lower than $T_{sat}(P_t)$. Usually, a difference of 3–6°C is sufficient for the condensation to proceed smoothly. This practice effectively increases the total condenser pressure, P_t, to values higher than those the cooling system would otherwise support. In addition to the power used for the gas extraction equipment, the pressure rise in the condenser implies that the back pressure of the turbine, P_t, must be higher than the corresponding back pressure in the absence of the non-condensable gases. This causes a reduction of the isentropic work as well as the actual work the turbine produces.

The presence of non-condensable steam fed to the turbine and the need for the operation of gas extraction equipment uses a significant fraction of the power produced by the plant. Hence, the main effect of the presence of the non-condensable is a significant reduction of the net power produced by the geothermal power plant. Table 9.1 shows the net work produced under ideal conditions when the amount of CO_2 present in the steam fed to the turbine is in the range 0–40%. The actual percentage of work reduction will be higher because of irreversibilities in the equipment.

It is apparent from Table 9.1 that the non-condensable gases may consume a very high percentage of the available geothermal power because they have to be extracted. When the amount of non-condensable gases from the flashing chamber exceeds 8–10%, a good engineering practice is to feed them to a turbine that exhausts to the atmosphere and does not have a condenser. The power forgone by the atmospheric expansion compensates for the power needed to extract the gases from the condenser. Since almost all the non-condensable gases are released at the first flashing chamber, dual flashing plants may use an atmospheric turbine for the expansion of the vapor and gases from the first flashing chamber and a condensing turbine for the expansion of the vapor from the second flashing chamber.

In addition to the power lost for their extraction, a second drawback of the presence of non-condensable in a condenser is the significant drop of the overall heat transfer coefficient. Figure 9.12 shows schematically how the reduction of the heat transfer coefficient occurs. The turbine exhaust, which is composed of steam and non-condensable gases, is fed directly to the cooling tubes of the condenser.

Table 9.1 Power reduction in a flashing unit because of the presence of non-condensable gases

Percent CO_2	Net work (kJ/kg)	Percent reduction
0	620	0
10	485	21.8
20	417	32.7
30	362	41.6
40	324	47.7

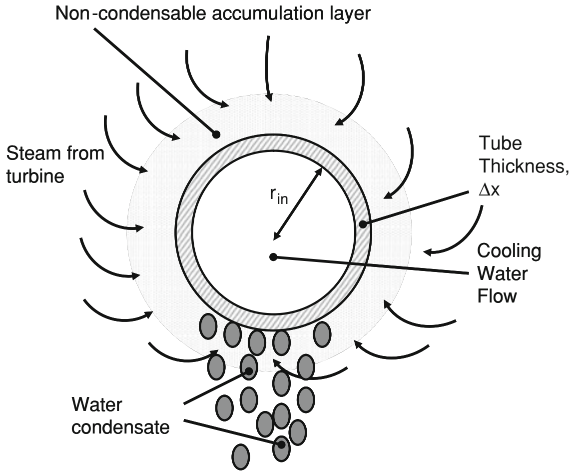

Fig. 9.12 Formation of the gaseous layer at the outer surface of condenser tubes, that causes the reduction of the outside heat transfer coefficient h_{out}

Steam condenses at the outer surface of the tubes but the non-condensable do not condense and, thus, form a gaseous layer at the external surface of the tubes. Even though the non-condensable are continuously removed from the condenser, the gaseous layer surrounding the external surface of each tube becomes a permanent presence. Steam that is directed to the external surface of the tubes must diffuse through this outer layer before it cools sufficiently to condense. The diffusion process is very slow and impedes the heat transfer to the cooling fluid. This causes a large drop of the outside heat transfer coefficient, h_{out}, of the condenser tubes. It has been observed experimentally that a 2% fraction of non-condensable gases would reduce the outside heat transfer coefficient of a tube by more than 50%. This effect causes a corresponding reduction of the overall heat transfer coefficient of the tube, U, which is given by the following expression:

$$\frac{1}{U} = \frac{1}{h_{in}} \frac{r_{in} + \Delta r}{r_{in}} + \frac{\Delta r}{k} + \frac{1}{h_{out}}. \tag{9.26}$$

In this expression h_{in} is the inside heat transfer coefficient, which pertains to the cooling water and is unaffected by the presence of non-condensable; k and Δr are the conductivity and thickness of the tube respectively; and r_{in} is the inside radius of the tube. Accordingly, the rate of heat transfer for the heat exchanger tubes is given by the expression:

$$\dot{Q} = UA(LMDT). \tag{9.27}$$

LMDT is the logarithmic mean temperature difference. The consequence of the significant reduction of h_{out} and U because of the presence of the non-condensable gases is that condensers, which are typically designed to make possible the steam condensation with non-condensable gases, must have a significantly higher surface area, A, than condensers that operate with steam vapor alone. This practice increases significantly the capital cost of the power plant.

9.4 Cooling Systems

Fossil fuel and nuclear power plants use energy sources (fuel) that have very high energy density (in kJ/kg) and may be readily transported to the location of the power plant. As a result, nuclear and fossil fuel plants are located close to the regions of electric power demand and close to sources of available cooling water, usually rivers or lakes. On the contrary, the energy density of geothermal resources is rather low and transportation of the geothermal fluid far from the point of production is neither economical nor thermodynamically sound, because the resource will cool during the transportation. One of the characteristics of geothermal power plants is that they are built very close to the geothermal resource in order to minimize energy losses upon transportation. More often than not, the area where the geothermal resource is located does not have a source of cooling water, such as a river or a lake. For this reason, alternative cooling methods must be used to supply the condenser of a geothermal power plant with cooling water.

Artificial lakes or ponds are probably the best and most economical way to supply the condenser of the geothermal power plants with cooling water. The pond is constructed on location and its water is supplied from the geothermal wells or from local water wells. Since the condensate is not reused or re-injected, it may be discharged to the artificial pond in order to replenish the losses from natural evaporation in the pond.

Mechanical or natural draft wet cooling towers are also used with geothermal power plants. The water needed for the operation of the wet cooling towers may be supplied by the condensate and, hence, no other source of water is needed. If the condensate water is used for another purpose, some of the effluent from the last flashing chamber may also be used after a suitable treatment.

Dry cooling towers, either mechanical or natural have also been used, where the condensate may not be used or is consumed as a source of water for other reasons. However, the large overall temperature difference needed for the operation of the dry towers results in higher condenser temperature and, hence, lower efficiency and lower power production. Because, in general, geothermal power plants have

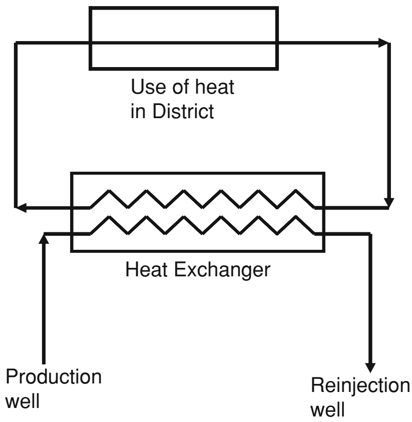

Fig. 9.13 District heating system

lower efficiencies than fossil fuel plants, this additional reduction of the overall power plant efficiency makes the dry cooling towers the least desired option for the production of geothermal power.

9.5 Geothermal District Heating: An Example of Exergy Savings and Environmental Benefit

The earliest use of geothermal energy was to provide hot water for baths and houses. When geothermal resources are available near the population centers, this practice continues today with the heating of entire districts of houses and businesses. This is called *district heating* and has been successfully practiced in several locations in Iceland, Japan, New Zealand as well as in Oregon, USA. The engineering system for district heating is very simple and is shown in Fig. 9.13. The geothermal water from the production well passes through a heat exchanger, where it transfers its enthalpy to a cleaner secondary fluid, which is often clean water. The latter is distributed via well-insulated pipes to the district, where it transfers its enthalpy to raise the interior temperature of the group of houses and commercial establishments. Fluid valves at the entrance of the main heat exchanger control the amount of geothermal water used and balance the demand for heating with the supply. Since the geothermal fluid does not exit the heat exchanger, dissolved gases or solids are re-injected and, hence, do not pose any environmental problem. Some of the carried solids may come out of solution and deposit at the pipe walls of the heat exchanger. For this reason, periodic cleaning of the main heat exchanger—e.g. during the summer season when heating is not needed—is highly recommended.

The use of geothermal water for district heating is an excellent example of how exergy and primary energy sources are saved by the use of alternative energy sources. Let us consider two alternatives for the heating of a group of houses, which require a heating load of 10 MW-t. The first is burning a hydrocarbon fuel, such as methane and the second is the use of a low temperature geothermal resource that provides water at 90°C and may be cooled in the heat exchanger to 45°C. If the heating load is met by the geothermal water, a mass flow rate $\dot{m}_w = 52.9\mathrm{kg/s}$ would be used according to the energy balance equation:

$$\dot{Q} = \dot{m}_w c_p (T_{in} - T_{out}). \tag{9.28}$$

If geothermal water were not available and the heating load were met solely by the combustion of methane in conventional household burners with 70% combustion efficiency and given that the heat of combustion of methane, $-\Delta H$, is 50,020 kJ/kg, we would need for the same task of space heating 0.29 kg/s of methane. Thus, the use of geothermal district heating results in the conservation of a significant quantity of methane.

An exergy analysis of the two alternatives also gives an informative example of the benefits of geothermal heat utilization: assuming an environment at 25°C (298 K), the rate of exergy content in the 90°C (363 K) water, which is needed for this energy consuming task is:

$$\dot{E} = \dot{m}_w (e_{90} - e_{25}) \approx \dot{m}_w \left[c_p (363 - 298) - 298 c_p \ln \frac{363}{298} \right], \tag{9.29}$$

or 11,331 kW. Given that the exergy loss (change in the Gibbs free energy) of methane is $-\Delta G = 51{,}978$ kJ/kg, the exergy usage from the combustion of 0.29 kg/s methane is 15,074 kW. This is significantly more than the exergy use of the geothermal fluid.

It is apparent that, even though the geothermal water is only partially cooled to 50°C and not to the environmental temperature of 25°C, the use of the geothermal water for district heating still has a thermodynamic advantage in comparison to the use of fossil fuels, such as methane or other hydrocarbons. Because fossil fuels may produce very high temperatures upon combustion, it is best to use them with high-temperature Rankine cycles with first-law efficiencies in the range 35–40%, and not for the production of relatively low-temperature water for space heating or household water use. In addition to the thermodynamic advantages, there is always the environmental advantage that the combustion of 0.29 kg/s of methane would have continuously released approximately 0.80 kg/s of CO_2 in the atmosphere during the heating season. Therefore, the substitution of the fossil fuels with geothermal water for district heating saves precious natural resources (methane in this case) and prevents environmental pollution.

9.6 Environmental Effects

Geothermal energy is a clean source of energy. The operation of the geothermal power plants causes minimal environmental impact. The main source of atmospheric pollution from geothermal units is the discharge of the non-condensable gases, primarily CO_2. The quantity of CO_2 released to the atmosphere is by far less than that produced by an equivalent fossil fuel plant. Geothermal power plants produce 1,000–5,000 times less CO_2 per kWh produced than fossil fuel plants. Hydrogen sulfide, H_2S, is another gas that is released from the condenser of a geothermal power plant. At very small concentrations, less than 1 ppm, H_2S is malodorous (it smells like rotten eggs) and leaves a distinct odor near geothermal power plants. At higher concentrations, H_2S desensitizes the olephatic nerves and may not be detected by its odor. Sulfur abatement methods may be used to eliminate the release of H_2S. The Geysers field, north of San Francisco, California uses these methods to eliminate a very high percentage of H_2S and to comply with the air standards of the state of California, which are among the strictest in the world. Other gases that are released by a geothermal power plant, such as NH_3, are in traces and do not pose environmental problems.

Soil subsidence may become a problem in the vicinity of geothermal power plants: As steam or water is removed from the geothermal aquifers, open cracks shrink and the permeability of the aquifers decreases. The surrounding rocks and soil are displaced to fill all major voids and the soil surface subsides, but not always in a uniform manner. Uneven soil subsidence on the surface may pose problems to structures and buildings. Water re-injection and rainwater seepage mitigates to a large degree the soil subsidence. Since most of the geothermal resources and power plants are located far from the major population centers, soil subsidence does not pose a significant problem to large populations. A beneficial effect of this geological volume reduction is that mechanical stresses that are caused from geological plate movements are released. The stress release in the interior of the Earth's crust alleviates earthquakes or significantly mitigates their strength and their effects on the structures.

Thermal pollution, which is caused by the heat released to the environment as a result of the operation of the cooling system, is another environmental effect. Because, geothermal power plants operate at lower temperatures, their first-law efficiency (W/Q_{in}) is significantly lower than that of fossil fuel or nuclear power plants. Subsequently the thermal pollution per unit energy produced (kJ/kWh) is higher (about 1.7–2.5 times more) than that of the fossil fuel plants.

Finally, noise, which is always a problem with all power plants, is also an environmental concern for the geothermal units. Ejectors of non-condensable gases, especially steam ejectors, add significantly to the noise pollution. However, since the vast majority of geothermal power plants are isolated and far from population centers, noise pollution is not a significant environmental concern and only affects the wildlife in a way that is similar to the noise effect of wind turbines.

Problems[2]

1*. A geothermal well produces 60 kg/s of saturated liquid water at 210°C. What is the maximum power (in kW) this well may produce? The atmospheric temperature is 27°C.

2*. A geothermal well has a diameter 25 cm and produces dry steam at an average velocity of 9 m/s. The steam is at 5 bar pressure and 200°C. The steam is supplied to a turbine with an isentropic efficiency $\eta = 0.78$ and exhausts in a condenser at an average temperature 36°C. Calculate: a) the mass flow rate of steam; b) the power produced by the turbine; c) the total amount of kWh the plant produces annually; and d) the annual revenue to the operator, if the average sale price of energy is $0.087/kWh.

3*. Typical dry steam wells are 25 cm in diameter and produce continuously at a typical average steam velocity of 10 m/s at the wellhead. The wellhead steam conditions at a particular location are T = 200°C and P = 7 bar. It is proposed to build a 60 MW geothermal power plant in this location. The turbines to be used have an isentropic efficiency $\eta = 0.80$ and enough cooling water is available in this location to maintain the condenser of a power plant at 38°C. What is the power that a single well may produce and how many wells must be drilled to supply sufficient steam to this geothermal power plant?

4*. Five geothermal wells produce together 310 kg/s of a mixture of water and steam at 180°C with a dryness fraction 12%. What is the maximum power a power plant may produce from the five wells? The atmospheric temperature is 27°C.

5*. A geothermal well produces 68 kg/s of saturated liquid water at 230°C. The water is used in a single-flash unit and the isentropic turbine efficiency is 80%. What is the total power produced and what are the first and second-law efficiencies of this power plant?

6*. A geothermal well in Warakei, New Zealand produces an average of 56 kg/s of a two-phase mixture of steam and water at 190°C. The dryness fraction at the well head is x = 0.15. The steam is separated at the wellhead and fed to a turbine with isentropic efficiency $\eta = 0.82$. The rest, which is saturated liquid water is flashed and the steam produced is fed to a low pressure turbine with $\eta = 0.80$ and back pressure 8 kPa. Determine: a) the amount of power produced by the two turbines; and b) the first and second law efficiencies of the power plant.

7*. A geothermal well produces 65 kg/s of saturated liquid water at 230°C. The water is used in a dual-flash unit. What is the total power produced and what are the first and second-law efficiencies of this plant?

[2] Steam tables or other water properties are needed for the solution of the problems marked with an asterisk (*).

8*. A geothermal resource/aquifer has been tested and confirmed to continuously produce saturated liquid water at 230°C. It is desired to construct a 60 MW geothermal power plant, which will utilize this resource. Two designs are proposed: a) a single flash unit and b) a dual-flash unit. A nearby cooling pond may supply sufficient cooling water to keep the condenser of the plant at 40°C. For the two types of units under consideration calculate:

a) The total amount of steam that needs to be produced.
b) The total amount of water the wells must provide.
c) If each well produces 60 kg/s of water, what is the number of wells that must be drilled?

9*. A geothermal well produces 60 kg/s of liquid water at 20 bar and 160°C. What is the maximum power you can get from this resource? Design a binary cycle with R-134 or another refrigerant to produce power from this resource.

10*. Two geothermal wells produce 110 kg/s of water at 170°C, 15 bar. A binary plant, operating with refrigerant-134, is to be designed to extract power from this resource. Ample cooling water is available to maintain the condenser temperature at 40°C. A temperature difference of 5°C must be maintained at all points of the main heat exchanger. What is the optimum power this cycle may produce?

Hint: you will need to optimize using an iteration process for the boiling temperature in the secondary cycle.

11*. The average apartment in Paris, France needs 1.2 kW of heat power in the winter months. It is proposed that geothermal district heating be used in the 15th District (15th Arrondisement) for a number of buildings with a total of 1,260 apartments. How much heat power is required? If the geothermal water enters the district heating plant at 70°C and is re-injected at 42°C, how much water volumetric flow rate, in m^3/s, is required for this plant?

12*. A geothermal district project in Iceland has a continuous water supply of 7,200 tons of water per hour. The water enters the district at 73°C and is re-injected at 40°C. This geothermal heat district operates for 285 days per year. Determine: a) the heat power in kW, this project delivers; b) if the only other heating alternative is propane, the annual amount of propane that is saved because of this type of heating; and c) the amount of CO_2 emission avoidance annually because of this project.

13. "Because the interior of the Earth is cooling fast, geothermal energy will not be available. Therefore, there is absolutely no reason to invest in geothermal projects." Comment in a short essay of 250–300 words.

14. "$44*10^{12}$ Watts of power are continuously produced from geothermal resources and this represents three times the entire energy consumption by humans. Therefore, if we concentrate on developing our geothermal resources, we will not need any other form of energy." Comment in a short essay of 250–300 words.

Reference

1. Michaelides EE (1982) The influence of noncondensable gases on the net work produced by the geothermal steam power plants. Geothermics 11(3):163