Low Temperature Heat Recovery for Geothermal Binary Plant

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The geothermal power plant business of Mitsubishi Heavy Industries, Ltd. (MHI) provides small-capacity binary power generation systems in addition to conventional large-capacity flash power generation systems in order to respond to the needs of all markets and customers. This binary power generation system can be applied to biomass plant or exhaust heat recovery. This paper presents the advantages and thermal system characteristics of binary systems, as well as the technologies of Turboden s.r.l., which is a group company of MHI and Italian binary power generation system manufacturers that has delivered roughly 250 binary systems, mainly for biomass plants.

1. Introduction

It is known that the first use of geothermal energy for power generation occurred in Larderello, Italy, in 1904, where naturally emerging superheated steam was used for 0.75-horsepower power generation. Since then, geothermal power generation has been introduced around the world as a nature-friendly energy source independent of fossil fuel, and its power generation capacity has reached approximately 11 GW around the world as of 2011[(1)]. In Japan, on the other hand, the number of geothermal power plants has not increased since the start of operations at the Hachijojima Geothermal Power plant in 1999 although the capacity reached approximately 500 MW in the 1990's. One of several possible causes for this is the environmental burden of large-scale geothermal power generation facilities (such as land preparation and changes in environment and scenery because of geothermal steam discharge) on geothermal reservoir areas suitable for power generation, many of which exist in national parks.

Recently, vigorous discussions on this issue have been conducted, and a notification that permits the development of "binary power generation that involves small-scale geothermal development work and has little influence on scenery and the landscape or uses existing hot spring water" in national parks (class II, class III, and common areas) was published with conditions in March 2012[(2)]. In addition, responding to the fact that the Feed-in Tariff Scheme for Renewable Energy launched in Japan in 2012 sets the purchase price from geothermal power generation of less than 15 MW at 42 Yen, domestic demand for small-scale binary power generation facilities is expected to grow in the future. The following contents outline binary power generation systems and present MHI's efforts therefor.

2. Features of geothermal power generation

2.1 Geothermal heat source

Geothermal heat emerges from the ground and is considered to originate from decay heat generated by radioactive materials inside the earth. The strength of its huge amount of energy can

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be observed only in a small proportion of the earth's surface, such as in erupting volcanoes. However, human beings cannot use the energy directly. Therefore it is used indirectly through water (groundwater). Groundwater, which originates from water soaking into the ground, is heated underground by geothermal heat. Groundwater existing at relatively shallower depths blows out of the surface, and is used directly as hot springs in some cases.

When groundwater reaches deeper depths (around 1,000 m or deeper), some of it is confined under a hard stratum (referred to as a cap rock) and stays there at high temperatures and under high pressure. This is referred to as a geothermal reservoir. Areas suited for geothermal power generation are selected depending on the capacity of the geothermal reservoir and its accessibility from the surface. In this way, the possibility of typical geothermal power generation depends on the availability of a geothermal heat source and an appropriate water circulation cycle. Therefore searching for and the development of areas suitable for geothermal power generation requires much time, and it is a business accompanied by risks. In recent years, the research and development of hot dry rock geothermal power generation, which creates a geothermal reservoir artificially by injecting water from the surface, has been advanced.

2.2 Flash geothermal power generation system

Geothermal water that is brought to the surface by excavation can be classified largely into steam-dominated and hot water-dominated type, depending on the proportion of steam and hot water. In the case of steam-dominated type, a steam turbine can be driven almost directly by the steam because evaporation completes in the course of rising to the surface. Therefore simpler systems can be used, as seen in earlier geothermal power generation systems. However, such a convenient geothermal source is rare. Most geothermal power generation plants in service around the world are the hot water-dominated type.

Figure 1(a) shows a schematic system diagram of a flash geothermal power generation plant as one of the typical power generation system using hot water-dominated geothermal heat. Geothermal power generation technology using a hot water-dominated-type production well was developed in New Zealand for the first time and then actually applied to the Wairakei Geothermal Power Generation Plant in 1958. Following this success, MHI started the development of a geothermal power generation system using a hot water-dominated-type production well jointly with Kyushu Electric Power Co., Inc. In this development, the foundation of material selection was laid through chemical analyses of geothermal fluid and material tests of main equipment such as turbines in a geothermal steam atmosphere.

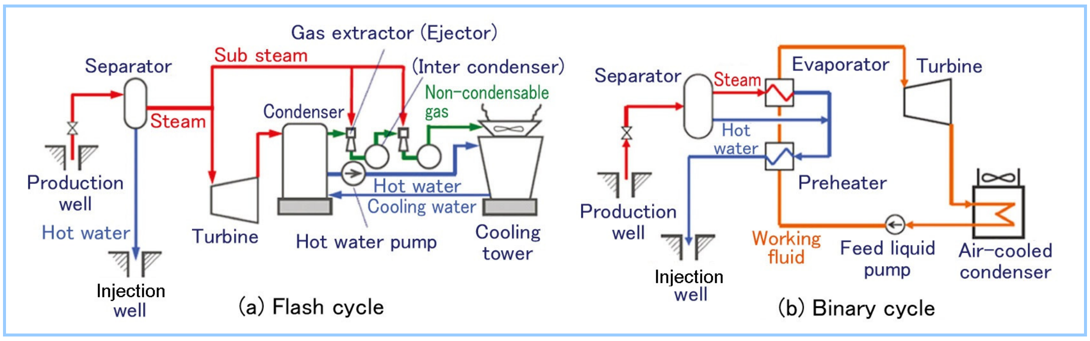

Figure 1 System diagram of typical geothermal power generation systems

In addition, basic data for equipment design was accumulated through analyses and verification tests of the characteristics of the main equipment necessary for a geothermal power generation plant such as separators, direct contact condensers, two-phase flow transportation piping, and gas extractors. Based on the data, the Otake Power Plant (output 11 MW) of Kyushu Electric Power Co., Inc. was designed and constructed, and started operation in 1967 as the first hot water-dominated-type geothermal power generation plant in Japan. Since then, MHI has produced 103 geothermal power generation plants, with a total output of 3108 MW, in 13 countries including Japan, while developing and applying various technologies for the improvement of performance, economic efficiency and reliability.

2.3 Binary geothermal power generation system

Figure 1(b) shows a typical system diagram of a binary geothermal power generation plant.

The binary geothermal power generation system is an indirect power generation system that introduces geothermal fluid into the heat exchanger to evaporate the working fluid in the secondary cycle to drive the turbine. The main characteristics of the binary geothermal power generation system are described in **Table 1** and the following additional explanations.

Table 1 Characteristics of geothermal power generation system

Item	Flash cycle	Binary cycle
Feature	- High power output - High efficiency (double flash)	- 100% injection possible
Working Fluid	- Geothermal steam - Non-flammability	- Chlorofluorocarbon, hydrocarbon, etc. - Necessary to pay attention to global warming and ozone depletion (chlorofluorocarbons) and flammability (hydrocarbon)
Unit capacity	Up to hundreds of MW (high capacity power generation plant)	- Up to tens of MW (low capacity)
Turbine corrosion	- Countermeasures necessary	- Countermeasures unnecessary - Low grade materials can be used
Scaling (countermeasure)	- First stage nozzle of turbine (turbine cleaning equipment) - Injection line (pH adjustment)	- Heat transfer surface of preheater and injection line (pH adjustment)
Cooling system	- Wet cooling tower - White smoke rises	- Air-cooled condenser - No white smoke rises

(1) Full reduction of geothermal fluid: This system returns geothermal fluid coming out of the ground back underground. Therefore the mass balance within the area is maintained. In addition, this system has little influence on the surrounding environment such as forests, as well as on scenery and the landscape, because white smoke (steam), which is considered the symbol of geothermal power generation plant, does not rise into the air.

(2) Working fluid: Typical working fluid poses a risk to the environment. Two often-used working fluids include an alternative chlorofluorocarbon that requires consideration of its ozone depletion and global warming potential, and a hydrocarbon working fluid that requires appropriate fire extinguisher l equipment. In this case, the system needs to have special measures against leakage.

(3) Countermeasures to corrosion and scale: In the case of a flash power generation system, geothermal fluid (steam, hot water, and non-condensing gas) passes through almost all system components including the turbine, and therefore all of them require measures against corrosion or non-condensing gas depending on the characteristics of the geothermal fluid. In the case of a binary power generation system, on the other hand, heat is transferred from the geothermal steam and water to the working fluid by the heat exchanger, and therefore basically only the upstream system of the heat exchanger requires measures to deal with geothermal fluid. However, scaling of heat transfer tubes of the heat exchanger has a direct effect on performance and therefore requires attention.

(4) Cooling system: Generally many of areas suitable for a geothermal power generation plant have difficulty in the availability of cooling water for turbine condensate. In the case of a flash power generation system, condensed water of geothermal steam can be used as makeup water for cooling water. In the case of a binary power generation system, on the other hand, this method cannot be used, and therefore an air-cooled condenser, which is typically larger than a water-cooled one, is used. As a result, the air-cooled condenser may be the largest structure among the components of the binary power generation system. Therefore appropriate design in consideration of the initial introduction cost and power of auxiliary equipment (i.e., the cooling fan of the air-cooled condenser) is required.

(5) Low volume flow rate: When a low boiling point working fluid is used for the secondary cycle, the condensate pressure can be set higher than that of the steam. This allows for a lower volume flow rate and more compact turbine design.

As described above, a binary power generation system has both advantages and disadvantages. There is no conclusive definition of whether a flash or binary power generation system is better. What is important is to study each site individually in terms of economic efficiency and environmental friendliness before making the final determination of the system to be introduced.

3. Mechanism of binary power generation system

The word “binary” means “two.” The binary power generation system is a system that uses secondary fluid, in contrast to the flash power generation system that directly uses geothermal fluid. The secondary fluid used for a binary power generation system is typically a low boiling point working fluid, in most cases an organic compound such as alternative chlorofluorocarbon. Therefore the secondary cycle is typically referred to as the ORC (Organic Rankin Cycle). The following contents outline the mechanism and features of the ORC.

3.1 Working fluid for ORC

In principle, any material having vapor pressure that can be commonly handled over the operation temperature range (heat source temperature to atmospheric temperature) can be used as the working fluid for the ORC. In fact, however, there are limitations from various aspects, and therefore practically applicable working fluid are limited. A working fluid to be used needs to be selected in consideration of the following major factors.

(1) Cycle characteristics (power generation efficiency)
(2) Ease of handling (including safety, stability and environmental friendliness)
(3) Economic efficiency

The following sections describe the selection policy of a working fluid from the perspective of the cycle characteristics. However, even when there is a material with favorable cycle characteristics, it cannot be selected in terms of long-term operation if the ease of handling or economic efficiency is ignored. It is necessary to make a final determination of a working fluid taking all of the factors described above – in addition to the cycle characteristics – into consideration in a balanced manner.

3.2 ORC characteristics

For an evaluation of the cycle characteristics, the use of a T-h diagram is an easily comprehensible method. **Figure 2** shows an example of a simplified heat source side heat exchange model. In this example, the heat source is assumed to have only sensible heat and no latent heat for simplification. In the case of geothermal power generation system, hot water including no steam corresponds to such a heat source. In cases other than a geothermal heat source (e.g., plant exhaust heat recovery), exhaust heat recovery from exhaust gas corresponds to such a heat source. **Figure 3** compares T-h diagrams of butane and water, for example.

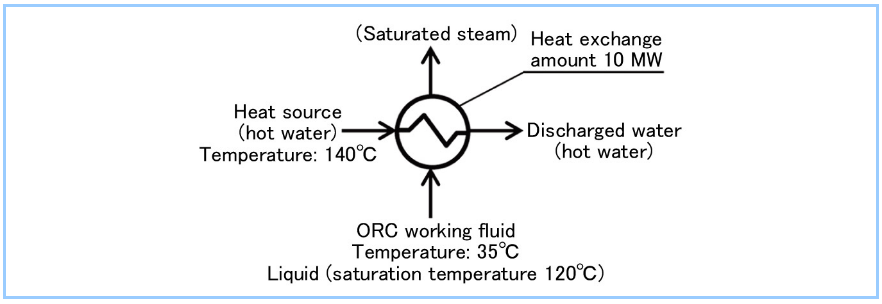

Figure 2 Heat exchanger model of ORC

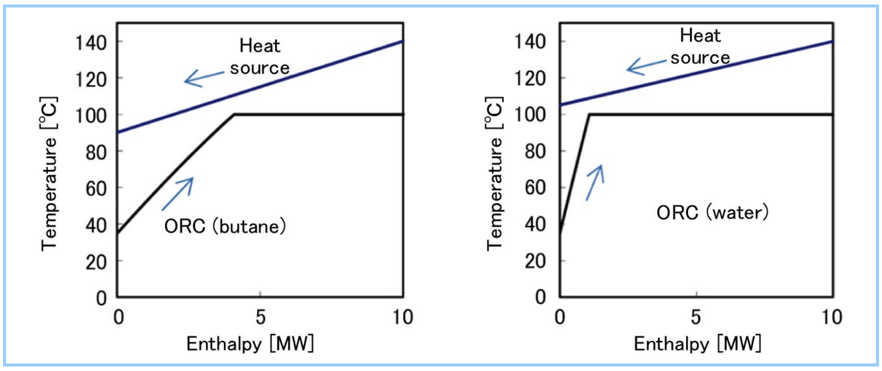

Figure 3 T-h diagram examples of butane and water

The horizontal axis represents the heat amount (W) obtained by multiplying the specific enthalpy of each fluid (J/kg) by the flow rate (kg/s). However, the flow rate of the heat source varies in each case because it is obtained by heat balancing for adjustment of the heat exchange amount. In a heat exchange process, the temperature of the heat source fluid decreases along with the release of heat. However, the cycle outlet temperature is determined by the boiling start temperature of the cycle fluid, which acts as a constraint (pinch point). As shown by geometric considerations, if fluid having a high ratio of latent heat to entire heat exchange amount, such as water, is used, the heat source outlet temperature is high, and therefore the fluid is discharged without sufficient heat exchange. Typically, the larger the gap between the operation temperature (pressure) and the critical temperature (pressure) of the working fluid ratio becomes, the more the latent heat ratio increases.

Figure 4 shows the calculation results of the ratio of latent heat with the assumption that the condensate temperature in the ORC is 35°C. In addition to isobutane, normal pentane and R245fa, which are typically used as ORC working fluid, water is shown for comparison in this figure. All of these working fluid show the characteristics that the ratio of latent heat sharply drops to zero around the critical temperature.

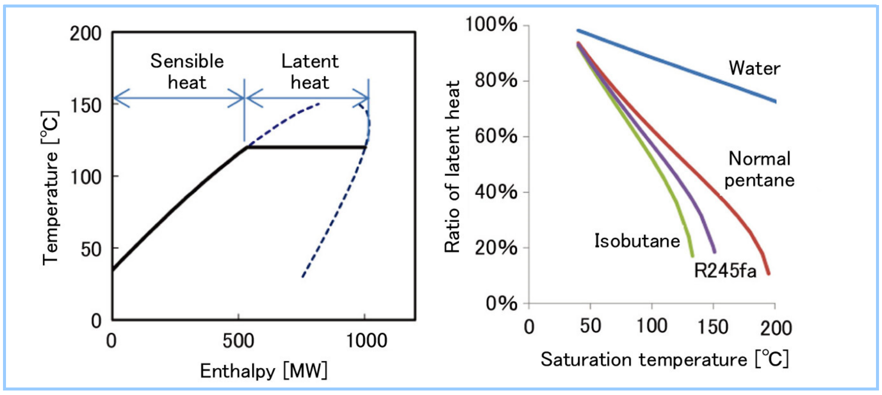

Figure 4 Ratio of latent heat in ORC
The ratio of latent heat is defined as (latent heat) / (sensible heat + latent heat)

The above description is based on the assumption that a simple sensible heat source is used, and that the ratio of latent heat of the ORC can be set with comparative flexibility. On the other hand, in the case of an actual geothermal heat source, some of which emerge as a two-phase flow of steam and hot water due to high bottom hole temperature, it is necessary to match the ratio of latent heat of the ORC with the ratio of latent heat of the heat source. In addition, some geothermal heat sources cause higher silica concentration in hot water, resulting in the constraint of the injection of temperature for the suppression of scaling. In this way, constraint conditions vary significantly depending on the characteristics of the geothermal heat source. Therefore optimization according to each heat source is important.

3.3 Exergy loss in heat exchange process

This section considers exergy loss occurring in the heat exchange process as one of the factors that influence the economic efficiency of an ORC, using the heat exchange model shown in Figure 2. Heat amounts released by the heat source side and received by the heat-receiving side are represented by the following formulas using entropy. (Hereinafter entropy is a relative value and entropy for the lowest temperature of each fluid is defined as zero.)

(Heat release side) $$Q_1 = \int_0^{S_1} T_1 dS \qquad (1)$$

(Heat-receiving side) $$Q_2 = \int_0^{S_2} T_2 dS \qquad (2)$$

where the suffix “1” represents the heat source side, the suffix “2” represents the ORC side, Q (kW) is the heat amount, G (kg/s) is flow rate, T (K) is temperature, and S (kJ/sK) is entropy (defined by multiplying specific entropy by the flow rate).

Figure 5 shows the heat exchange process schematically. Q_1 in the formula (1) is geometrically equal to the area surrounded by the horizontal lines S=0 and S=S_1, the operation temperature curve, and the horizontal axis (absolute zero temperature). If there is no heat release loss, Q_1 is equal to Q_2. And S1 is smaller than S_2 considering that T_1 is larger than T_2. When the graphs of the two formulas are shown in an overlapped manner, S_2 protrudes to the right (toward the higher entropy side) so that the two shaded areas have the same area, as shown in Figure 5(b). This intuitively represents the increase of entropy in the heat exchange process. Considering the entire ORC, the increases of entropy at the turbine, the condenser, etc., are added to this, and then finally the heat is released to the outside of system.

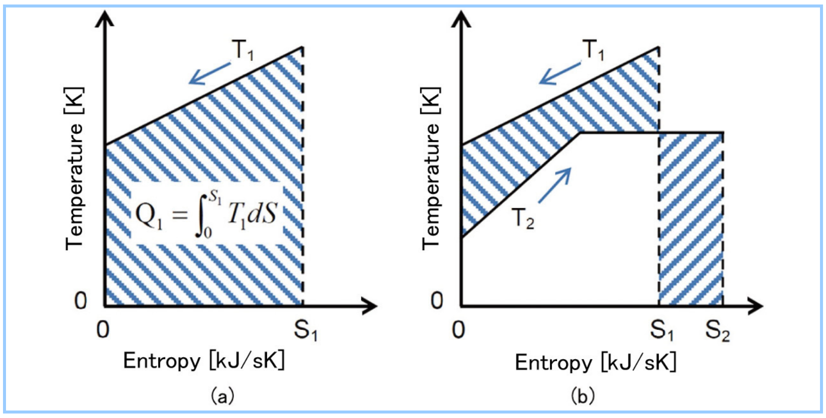

Figure 5 Schematic diagram of energy loss
In graph (b), energy loss corresponding to entropy increment (S_1 - S_2) occurs

This serial cycle can be explained thermodynamically as the following. In the heat transfer process from a high temperature heat source to a low temperature heat source (temperature of T_L (K)), only the portion corresponding to $T_L(S_2 - S_1)$ of physical energy that can be ideally drawn (in a reversible manner) is converted to thermal energy (i.e., released) as an increase of entropy. This is the so-called exergy loss. As for the heat exchanger model shown in Figure 5, it is necessary for the reduction of exergy loss to decrease the temperature difference between the heat release side and the heat-receiving side. To decrease the temperature difference, however, a larger heat transfer area of the heat exchanger is required, which leads to increased cost. For the design of a binary cycle, it is important to determine the temperature profile appropriately while balancing exergy loss and the cost of each piece of equipment.

3.4 Wetness of turbine outlet

Characteristics with respect to wetness of the turbine outlet differ significantly between water and a low boiling point working fluid. **Figure 6** shows the Rankin cycle (T-s diagram) of water (a) and normal pentane (b) as an example. This figure defines the high operation temperature as 120°C and the low operation temperature as 35°C. In this figure, turbine loss is considered as zero for simplification. The adiabatic expansion curve of the actual cycle protrudes slightly to the right, and is not a vertical line. The lower part of water's T-s diagram on the steam side (the low temperature side of the steam saturation line) protrudes largely to the right, and enters into a wet area after adiabatic expansion. It is well known that this causes harmful effects such as efficiency degradation and erosion due to liquid droplets. In contrast, that of the working fluid (b) represented by pentane enters into a dry area and seems to be favorable. However, the high degree of superheat at the turbine outlet causes much waste of the heat amount to the condenser. In such cases, a feed liquid heater is sometimes added in order to recover the heat amount corresponding to the superheat, depending on the conditions of the heat source.

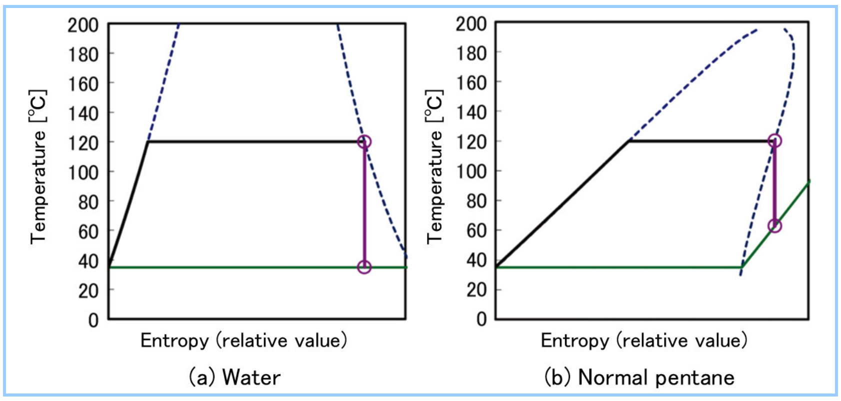

Figure 6 Wetness of turbine outlet

3.5 Points of concern for design of binary power generation system

The above describes the typical characteristics of an ORCe, but there are some points of concern for application to a geothermal binary power generation system.

(1) When silica supersaturation occurs due to the characteristics of geothermal water, it is necessary to be aware of piping blockages and performance deterioration of the heat exchanger caused by scaling. Scaling speed varies significantly depending on the silica concentration in hot water, pH and temperature. Therefore it is important to take measures to prevent scaling as necessary, such as the management of pH (including the injection of an inhibitor) and the control of injection temperature for underground injection. In this case, the cycle outlet temperature is sometimes constrained as described above. Therefore the design of an ORC needs to take this into consideration.

(2) It is necessary to pay sufficient attention to the corrosion of heat exchangers, which act as contact points with the environment, in particular on the heat source side (i.e., the preheater and evaporator), because they come into contact with geothermal water. The characteristics of geothermal water vary considerably depending on the site. Therefore it is necessary to sufficiently study the characteristics of the hot water to select the appropriate material, also in consideration of the cost. The components of an ORC, other than the heat exchangers, have no possibility to come into contact with geothermal water. However, they may be surrounded by corrosive gas such as hydrogen sulfide depending on the location. In such cases, it is necessary to take measures against corrosion according to the gas concentration.

4. Activity in development of geothermal binary system

MHI has been working on the commercialization of geothermal binary systems jointly with Turboden s.r.l., an Italian manufacturer specializing in ORC, in order to meet the market needs in Japan as quickly as possible. Turboden s.r.l., founded in 1980, has past records of around 250 ORC systems delivered mainly for biomass palnts. In recent years, they have delivered several geothermal binary power generation plants (maximum output 5.6 MW) in Europe as shown in **Table 2**. Among them, the 1000kW plant in Austria has been running stably for more than 10 years since its delivery, demonstrating the reliability of the system.

Table 2 Delivery records of Turboden s.r.l. geothermal power generation systems

Country	Power generation capacity	Remarks
Austria	1000kW	Operation launched in 2001; Cogeneration
France	1500kW	Operation launched in 2008; Dedicated to power generation
Germany	200kW	Operation launched in 2009; Cogeneration
Italy	500kW	Operation launched in 2012; Supercritical (prototype)
Germany	5600kW	Operation launched in 2013; Dedicated to power generation
Germany	5600kW	Operation launched in 2013; Dedicated to power generation
Germany	5000kW	Operation launched in 2013; Cogeneration

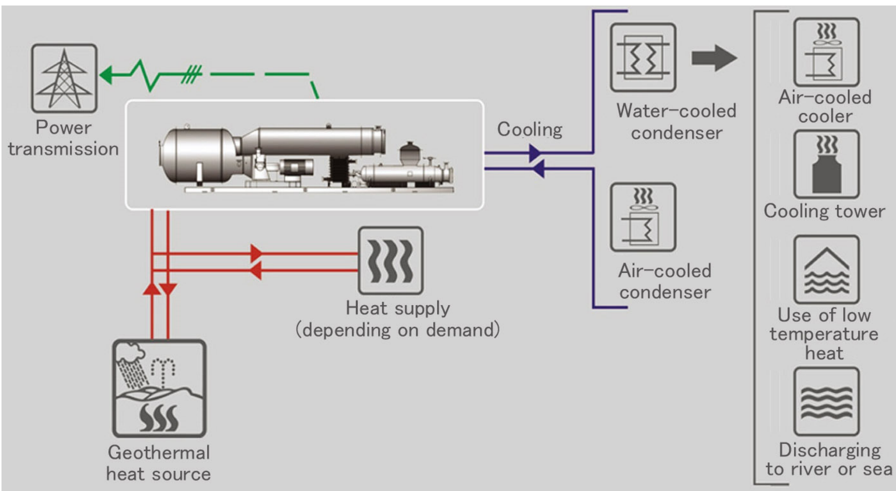

Figure 7 Schematic diagram of geothermal binary structure

Figure 7 schematically shows the structure of the geothermal binary system. Part of the heat source can be used for local heat supply. Air-cooled type, water-cooled type, or a combination of the two can be selected for the design of the condensate system. **Figure 8** shows a general view of the existing binary power generation plant in Germany as an example. This plant is a 5.6MW power generation plant using a hot water heat source.

Figure 8 Existing binary plant in Germany

5. Conclusion

MHI has mainly promoted the commercialization of flash geothermal power generation plants as activities in the geothermal power generation field. However, actions related to binary geothermal power generation plants have been limited to the accumulation of basic technologies and the development of a prototype. In the future, MHI will develop products that can effectively utilize low temperature heat sources previously unused for power generation and realize community-based geothermal power generation plants, and prepare many applications such as increasing the output of existing geothermal power generation plants jointly with Turboden s.r.l., to contribute to the effective utilization of renewable energy and local revitalization.

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