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Development and Case Study of a Geothermal Power Generation System

Norihiro Fukuda[1], Katsuki Norito[1], Atsushi Fujii[1], Kan Ogata[1] and Shojiro Saito[2]

[1] Mitsubishi Heavy Industries, Ltd.

[2] Mitsubishi Hitachi Power Systems,. Ltd.

E-mail: norihiro_fukuda@mhi.co.jp

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ABSTRACT

Since Mitsubishi Heavy Industries, Ltd. (MHI) developed the 12.5MW Otake Geothermal Power Plant (Kyushu Electric Power Co.,Inc.) which started operation in 1967 as Japan's first geothermal power plant with water-dominated production wells, we have supplied more than one hundred geothermal power plants over the course of half a century. In addition to our flash geothermal power plants, we have entered the binary geothermal power plant business in the Japanese market, collaborating with Turboden s.r.l., a European ORC supplier and MHI group company. Because the characteristics of geothermal resources are quite different depending on the geothermal well, it is important to optimize the system configuration for each site in order to maximize economic efficiency. A case study was undertaken with respect to possible configurations such as flash, binary and hybrid (flash + binary), and appropriate matching with the heat source was considered in this context. This paper describes the methodology, together with the results in terms of optimizing the power plant configuration.

1. INTRODUCTION

The first known use of geothermal energy for power generation was 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 an environmentally-friendly energy source independent of fossil fuel. Geothermal power generation capacity has reached approximately 11 GW globally as of 2011[(1)]. In Japan, however, the number of geothermal facilities has not increased since the start of operations at the Hachijojima Geothermal Power plant in 1999 when total capacity reached approximately 500 MW in the 1990's. One of several reasons for this has to do with the environmental regulations governing large-scale geothermal power generation facilities (including site preparation and changes in environment and local scenery resulting from geothermal steam discharge), since many geothermal reservoir areas suitable for power generation are located in national parks.

Intense discussions on this issue have taken place in recent years, and conditional notification allowing 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 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 40 yen (0.40USD @1$=100yen), domestic demand for small-scale binary power generation facilities is expected to grow in the future.

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. Only a small amount of the earth's immense energy can be observed at the surface, such as in erupting volcanoes. However, this energy cannot be easily used directly; it is generally used indirectly through groundwater. Groundwater, which originates from water soaking into the ground, is heated underground by geothermal heat. Groundwater existing at relatively shallow depths emerges to the surface, and in some cases is used "as is" in the form of hot springs.

When groundwater reaches greater depths (around 1,000 m or deeper), some of it is confined under a hard stratum (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. Accordingly, the potential for a geothermal power generation typically depends on the availability of a geothermal heat source and an appropriate water circulation cycle within the geothermal reservoir. Identifying and developing areas suitable for geothermal power generation can thus requires much time, and it is a business accompanied by risks. Recent years have seen advances in research and development work on hot dry rock geothermal power generation, which artificially creates a geothermal reservoir artificially by injecting water from the surface.

2.2 Flash geothermal power generation system

Geothermal fluid that is brought to the surface by drilling wells can be classified largely into steam-dominated and hot water-dominated types, depending on the proportion of steam and hot water. In the case of the steam-dominated type, a steam turbine can be driven nearly directly by the steam. Simpler systems can therefore be used, as seen in earlier geothermal power generation systems. However, such convenient geothermal sources are rare. Most geothermal power generation plants in service around the world are the water-dominated type.

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

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, including separators, direct contact condensers, two-phase flow transportation piping, and gas extractors. Based on the data, the Otake Power Plant (11 MW) of Kyushu Electric Power Co., Inc. was designed and constructed, starting operations 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 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.

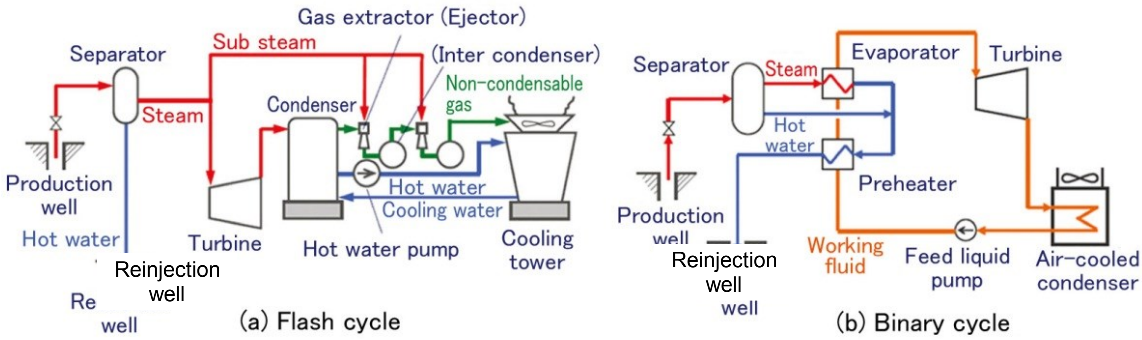

Figure 1 System diagram of typical geothermal power generation systems

2.3 Binary geothermal power generation system

Figure 1(b) shows a conceptual system diagram for a binary geothermal power generation plant. This system is an indirect power generation system that introduces geothermal fluid into the heat exchanger to evaporate the working fluid in the secondary cycle in order to drive the turbine. The main characteristics of the binary geothermal power generation system are described in Table 1 and the additional explanations that follow.

Table 1 Characteristics of geothermal power generation system

Item	Flash cycle	Binary cycle
Feature	- High power output - High efficiency (double flash)	- 100% reinjection possible
Working Fluid	- Geothermal steam - Non-flammability	- Hydrochlorofluorocarbon, Hydrocarbon, etc. - Necessary to pay attention to global warming or flammability
Unit capacity	Up to hundreds of MW (high capacity power generation plant)	Up to tens of MW (low capacity)
Turbine corrosion	- Countermeasures necessary including high grade alloys	- Countermeasures unnecessary - Lower grade alloys 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 plume rises)	- No white plume rises when air-cooled condenser is applied

(1) Full reduction of geothermal fluid: This system can return all of the geothermal fluid coming out of the ground back underground, and the mass balance within the reservoir is thus maintained. In addition, this system has little influence on the surrounding environment such as forests, or on local scenery and the landscape, because a white plume, (seen as a symbol of geothermal power generation plants) does not rise into the air when an air-cooled condenser is applied.

(2) Working fluid: Typical working fluid poses a risk to the environment. Two often-used working fluids are a) refrigerants that require consideration of global warming potential, and b) hydrocarbons that require appropriate fire protection systems. Both systems need special precautions against leakage.

(3) Countermeasures for corrosion and scale: In the case of a flash power generation system, geothermal fluids (steam, hot water, and non-condensing gas) pass through nearly all system components including the turbine, and appropriate measures against

corrosion or non-condensing gas are required. In a binary power generation system, however, heat is transferred from the geothermal steam and water to the working fluid by means of a heat exchanger. This means that basically only the part of the system upstream from the heat exchanger is affected by geothermal fluid. However, scale buildup on the heat transfer tubes in the heat exchanger does have a direct effect on performance, and consequently requires attention.

(4) Cooling system: Air-cooled condensers are often used for binary power generation systems which need no cooling water, given that lack of cooling water are common problem in many areas suitable for geothermal power generation plants. While the air-cooled condensers do not emit white plumes, they are typically larger than water-cooled units. As a result, the air-cooled condenser may be the largest structure among the components of a binary power generation system, and appropriate design taking into consideration the initial introduction cost and power of auxiliary equipment (i.e., the cooling fan of the air-cooled condenser) is required. On the other hand, when cooling water is available for the condenser, the application of water cooling makes the condenser size smaller than would be the case with an air-cooled condenser.

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

The binary power generation system use secondary fluid, in contrast to the flash power generation system that uses geothermal steam directly. 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 a pentane. Therefore the secondary cycle is typically referred to as the ORC (Organic Rankine 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 operating temperature range (heat source temperature to atmospheric temperature) can be used as the working fluid for the ORC. In reality, however, there are various restrictions, such that practically applicable working fluids are limited. A working fluid must be selected in light of the major factors below.

(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 methodology for the working fluid from the perspective of cycle characteristics. However, even when there is a material with favorable cycle characteristics, it cannot be selected for long-term operation if the ease of handling or economic efficiency is ignored. A final determination of a working fluid must be taken into account all of the factors described above – in addition to the cycle characteristics –in a balanced manner.

3.2 Latent heat of the working fluid

The latent heat of the working fluid is very important. Figure 2 shows the latent heat for unit mass of several working fluids which are commonly used in the Rankine cycle or refrigerating cycle at the saturation temperature of 35°C, as an example of condensing temperature. This figure shows that the latent heat of water is quite large as it is usually discussed. On the other hand, a factor of primary importance in deciding the economy of a power plant is the size of the facility (especially the extent of piping and heat exchangers), and the volume flow of the working fluid normally has large influence on this. To discuss this characteristics (the volume flow), it is convenient to use the latent heat for unit volume, as indicated in Figure 3. The values in this figure are calculated by multiplying the latent heat in Figure 2 by the corresponding vapor density. These values show the ability for heat transportation; higher is better. Figure 4 shows the latent heat from Figure 3 on the vertical axis and the saturation pressure at the same temperature on the horizontal axis; data at different temperatures (35°C and 100°C as an example of boiling temperature) are also plotted (box symbols). This figure shows that the latent heat per unit volume depends on saturation pressure and has little relation to either the type of working fluid or the saturation temperature. This means that it is advantageous to select a working fluid with higher saturation pressure (low boiling point medium) in order to reduce volume flow from the viewpoint of heat transportation.

3.3 Matching to the heat source characteristics

T-h diagrams are helpful in the evaluation of cycle characteristics. Figure 5 shows an example of a simplified heat source side heat exchange model. In this simplified example, the heat source is assumed to have only sensible heat and no latent heat. In the case of geothermal power generation systems, hot water with no steam corresponds to such a heat source. In other cases (e.g., plant exhaust heat recovery), this could be exhaust heat recovery from exhaust gas. Figure 6 compares the T-h diagrams of butane and water.

The horizontal axis represents the amount of heat (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 to adjust 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, or pinch point. As shown by geometric considerations, if fluid having a high ratio of latent heat to the entire heat exchange amount (such as water), is used, the heat source outlet temperature is high, and the fluid is therefore discharged without sufficient heat exchange. Typically, the larger the gap between the operating temperature (pressure) and the critical temperature (pressure) of the working fluid ratio, the greater the latent heat ratio.

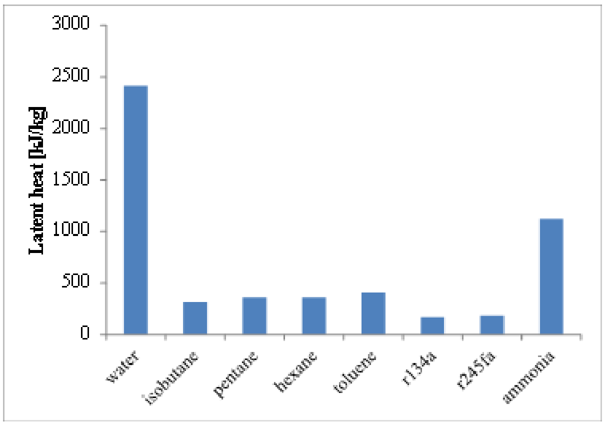

Figure 2 Latent heat for unit mass

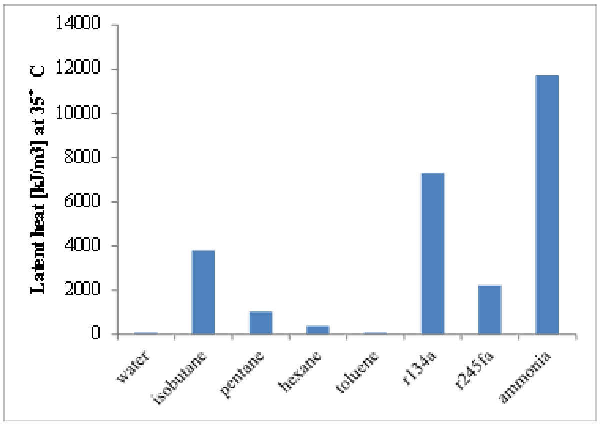

Figure 3 Latent heat for unit volume

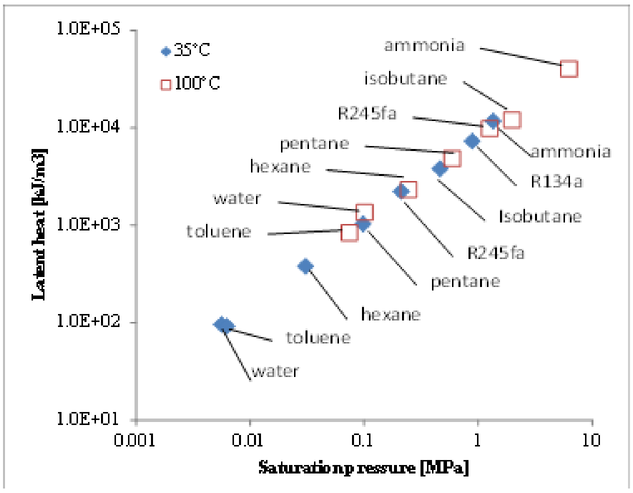

Figure 4 Relation between latent heat and saturation pressure

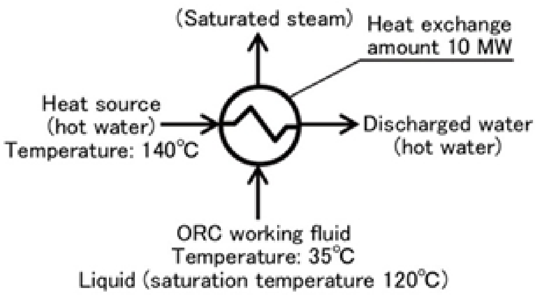

Figure 5 Heat exchanger model of ORC

Figure 7 shows the calculation results for the ratio of latent heat assuming that the condensate temperature in the ORC is 35°C. In addition to isobutane, normal pentane and R245fa, which are often used as ORC working fluids, water is shown in the figure for the purpose of comparison. In all of these working fluids, the ratio of latent heat drops sharply to zero around the critical temperature.

The above description is based on the assumption that a simple sensible heat source is used, and that the ratio of latent heat for the ORC can be set with relative flexibility. Nevertheless, since some actual geothermal heat sources 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 constraints on the injection temperature for scale suppression. Thus, constraint conditions vary significantly depending on the characteristics of the geothermal heat source, making it important to undertake optimization according to each heat source.

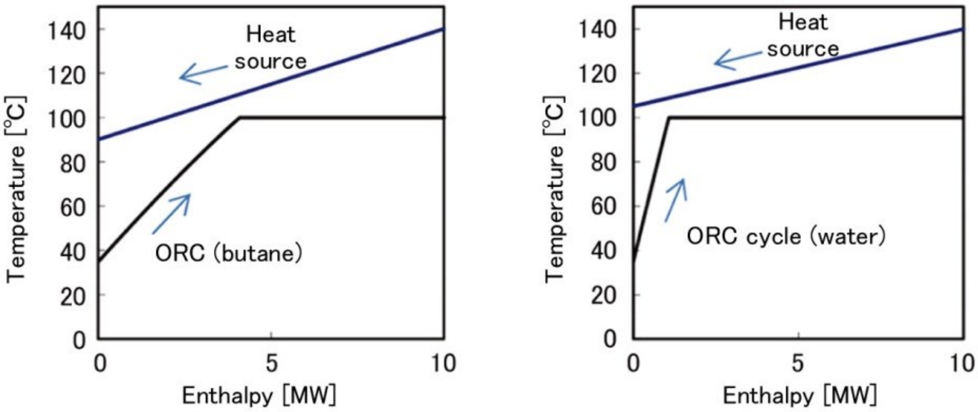

Figure 6 T-h diagram examples of butane and water

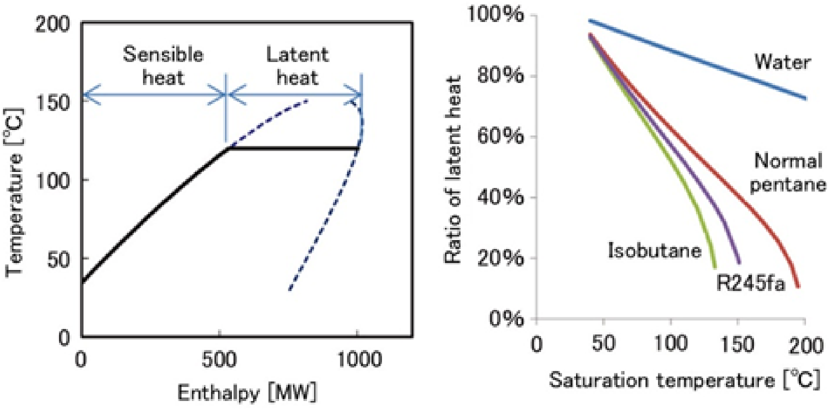

Figure 7 Ratio of latent heat in ORC

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 8 shows the Rankine 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 condensing temperature as 35°C. Here, 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. For water, the lower part of the T-s diagram on the steam side (the low temperature side of the steam saturation line) protrudes substantially 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 the dry area and appears to be favorable. However, the high degree of superheat at the turbine outlet causes a certain amount of high temperature waste heat to the condenser. In such cases, a feed liquid heater (known as a “regenerator” or “recuparator”) is sometimes added for heat recovery, depending on the conditions of the heat source.

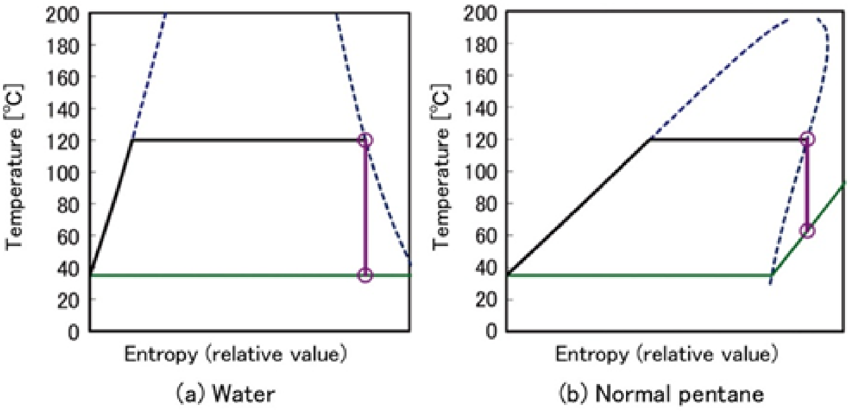

Figure 8 Wetness of turbine outlet

3.5 Points of concern for design of binary power generation systems

Beyond the typical characteristics of an ORC, there are some additional points of concern when used in geothermal binary power generation systems.

(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 scale buildup. Scaling speed varies significantly depending on the silica concentration in hot water, pH and temperature. It is therefore important to take measures to prevent scaling as necessary, such as reducing the pH or injecting a chemical inhibitor, as well as control of injection temperature. In this case, the cycle outlet temperature is sometimes constrained as described above, and ORC design needs to take this into consideration.

(2) Sufficient attention must also be paid 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, and appropriate study of the hot water will be needed in order to select the appropriate material, and in consideration of the cost. The components of an ORC, other than the heat exchangers, do not 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, measures must be taken against corrosion according to the gas concentration.

4. CYCLE EFFICIENCY AND CASE STUDY OF THE GEOTHERMAL POWER GENERATION SYSTEM

4.1 Cycle efficiency and available energy loss

This section considers cycle efficiency of the ORC from the perspective of entropy. First, we introduce the theoretical efficiency with the ideal and reversible Rankine cycle. The relationship between heat and entropy change in the reversible process is given by:

$$dS = \frac{dQ}{T} \tag{1}$$

where Q (kW) is the heat power, T (K) is temperature, and S (kW/K) is entropy defined by multiplying specific entropy by the flow rate. The transferred entropy through the exothermic process (temperature change from T_H to T_L) is given by integrating the formula (1)

$$\Delta S_H = \int_{T_H}^{T_L} \frac{dQ}{T} = \int_{T_H}^{T_L} \frac{-C_p G dT}{T} = C_p G \ln\left(\frac{T_H}{T_L}\right) \tag{2}$$

where Cp (kJ/kg K) is the specific heat and G (kg/s) is the flow rate of the heat source fluid. Because the specific heat changes according to temperature, then the averaged value of specific heat should be used for Cp. The transferred heat is also given by:

$$\Delta Q_H = C_p G (T_H - T_L) \tag{3}$$

Due to the characteristics of the ideal and reversible cycle, there is no entropy increase inside the cycle and received entropy from the heat source must be discharged into the low temperature heat sink (temperature is T_{amb}(K)) without change. Assuming the ideal heat sink, the temperature change is negligible during the heat discharge process and discharged heat is calculated using formula (2) by:

$$\Delta Q_L = T_{amb} \Delta S_H = T_{amb} C_p G \ln\left(\frac{T_H}{T_L}\right) \tag{4}$$

We can then write the work output from the ideal cycle (referred to as "available energy" in the following sections) and its efficiency as:

$$W_{ideal} = \Delta Q_H - \Delta Q_L = C_p G \left[(T_H - T_L) - T_{amb} \ln\left(\frac{T_H}{T_L}\right) \right] \tag{5}$$

$$\eta_{ideal} = W_{ideal} / \Delta Q_H = 1 - \frac{T_{amb}}{T_H - T_L} \ln\left(\frac{T_H}{T_L}\right) \tag{6}$$

Figure 9 shows the temperature dependency of the cycle efficiency calculated using Formula (6) with ambient temperature T_{amb}=25°C. The horizontal axis represents the lower temperature limit of the heat source (T_L), and three different heat source temperature cases (T_H=150°C,200°C,250°C) are illustrated. The right end of each line correspond to T_H=T_L (i.e. assuming isothermal heat source) which corresponds to Carnot cycle efficiency. This left downward slope indicates that the cycle efficiency is lower than the Carnot cycle when the heat source temperature changes during the heat release process.

4.2 Entropy increase in the actual process and available energy loss

Whereas the above discussion concerns the ideal process without entropy change, the reality is that entropy always increases because of the irreversibility of the actual process. An example of the irreversible process specific to geothermal power systems is the heat transfer process. In order to observe the entropy increase in this process, we go back to heat exchange model shown in Figure 5. Heat amounts released by the heat source side and received by the heat-receiving side are represented by the formulas below using entropy. (Hereinafter entropy is a relative value and entropy for the lowest temperature of each fluid is defined as zero.)

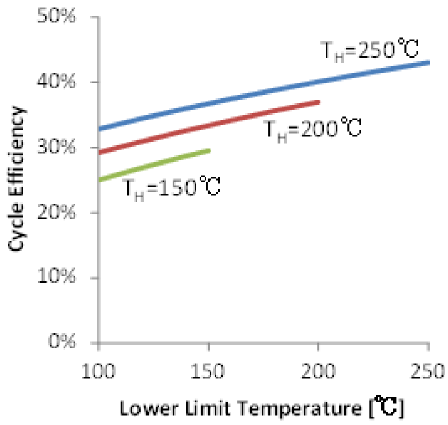

Figure 9 Cycle efficiency of ideal system when heat source temperature change from TH to TL

(Heat release side)

$$Q_1 = \int_0^{S_1} T_1 dS \tag{7}$$

(Heat-receiving side)

$$Q_2 = \int_0^{S_2} T_2 dS \tag{8}$$

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

Figure 10 shows the heat exchange process schematically. Q_1 in Formula (7) 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 S_1 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 9(b). This intuitively represents the increase of entropy in the heat exchange process. This serial cycle can be explained thermodynamically as follows. In the irreversible process, the conversion from mechanical energy to thermal energy occurs, and the driving power of this conversion is the scattering of mechanical energy into thermal energy; and this is the reason why the process is irreversible. Converted energy accumulates as entropy increase in the process, and this accumulated entropy must be exhausted to a low temperature heat sink (or the environment).As for the heat exchanger model shown in Figure 5, it is necessary to decrease the temperature difference between the heat release side and the heat-receiving side, and this needs a larger heat transfer area in the heat exchanger. In designing a heat exchanger, it is important to set the temperature profile appropriately to balance efficiency and cost.

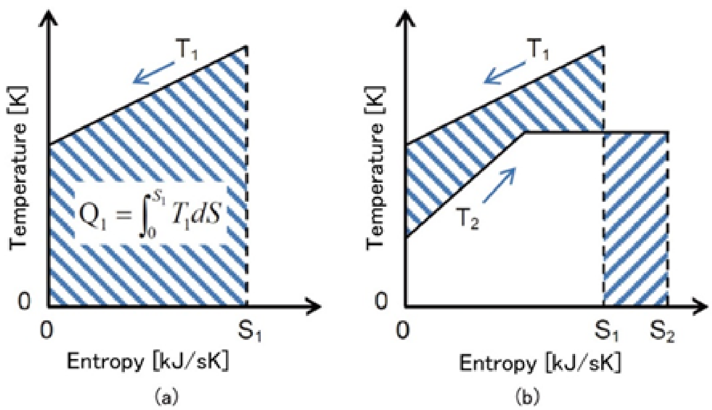

Figure 10 Schematic diagram of energy loss. In graph (b), exergy loss corresponding to entropy increment (S1 - S2) occurs

Various irreversible processes are incorporated in geothermal power generation systems, such as the flasher, turbine and condenser. To evaluate the entire available energy loss, the increase in total entropy must be calculated as shown below.

$$\Delta S_{irr} = \sum_{i=all irreversible process} \Delta S_i \tag{9}$$

This whole entropy increase also increases the heat exhaust to ambient as mentioned previously, such that Formulas (4) and (5) become:

$$\Delta Q_L' = T_{amb}\left(\Delta S_H + \Delta S_{irr}\right) \tag{10}$$

$$W_{irr} = \Delta Q_H - \Delta Q_L' = W_{ideal} - T_{amb}\Delta S_{irr} \tag{11}$$

Then available energy loss W_{loss} is defined as follows:

$$W_{loss} = W_{ideal} - W_{irr} = T_{amb}\Delta S_{irr} \tag{12}$$

Formula (12) means that we can estimate the available energy loss by determining the entropy increase in each process. In the next section, we note the results of an investigation using a geothermal power generation model.

4.3 Output evaluation of a simple geothermal power model

A simple geothermal power generation model is used to evaluate the available energy (W_{ideal}) and available energy loss (W_{loss}). The schematic process model is shown in Figure 11. This model is configured by combining the flash and binary system, in which the binary system utilizes the drain water from the separator. For simplification, the geothermal fluid is assumed here to be pure water which contains neither non-condensable gas nor impurities, and pressure loss and heat emission are considered to be negligibly small. The parameters and conditions are summarized in Table 2. In this discussion the work output refers to turbine shaft power, and if necessary, mechanical loss and electrical loss must be considered outside this model to evaluate the electrical output. The work output is estimated in two ways: one is derived from the enthalpy drop in the turbine estimated from the process calculation, and the other is derived from the difference between available energy and available energy loss. Figure 12 and Table 3 present a schematic representation of the calculation results. The values given in parentheses show the results from the process calculation, and both results agree within 1% error. Accordingly, with this availability energy methodology, we can identify the approximate amount of available energy loss.

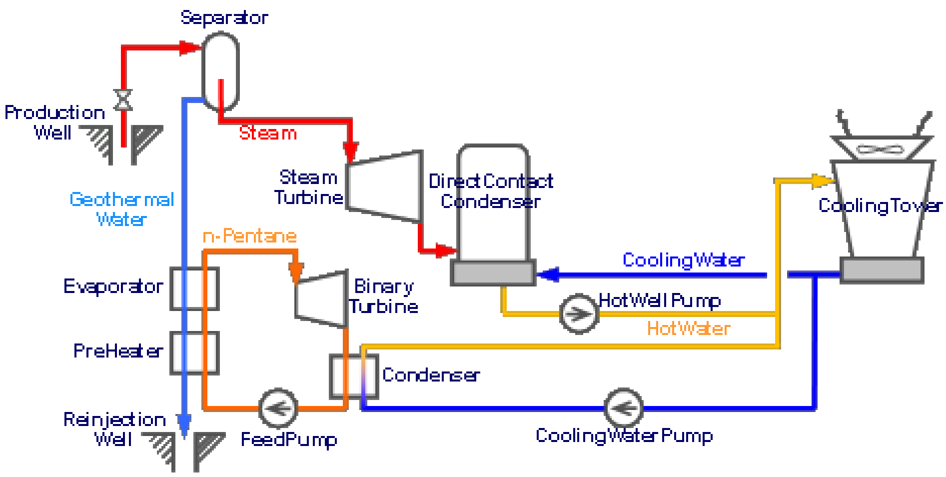

Figure 11 Calculation model for hybrid system

Table 2 Process parameters

Environment	
Bottom hole temperature	200°C
Flow rate	100t/h
Reinjection temperature	100°C
Environment temperature	20°C
Flash System	
Separator pressure (Saturation temperature)	0.36MPa-a (140°C)
Steam turbine efficiency	0.8
Condenser pressure	0.01MPa-a
Binary System	
Working fluid	pentane
Evaporator temperature	110°C
Condenser temperature	35°C
Turbine efficiency	0.8
Fluid pump efficiency	0.6
Cooling water system	
Cold water temperature	25°C
Flow rate (for flash system)	400t/h
Flow rate (for binary system)	400t/h

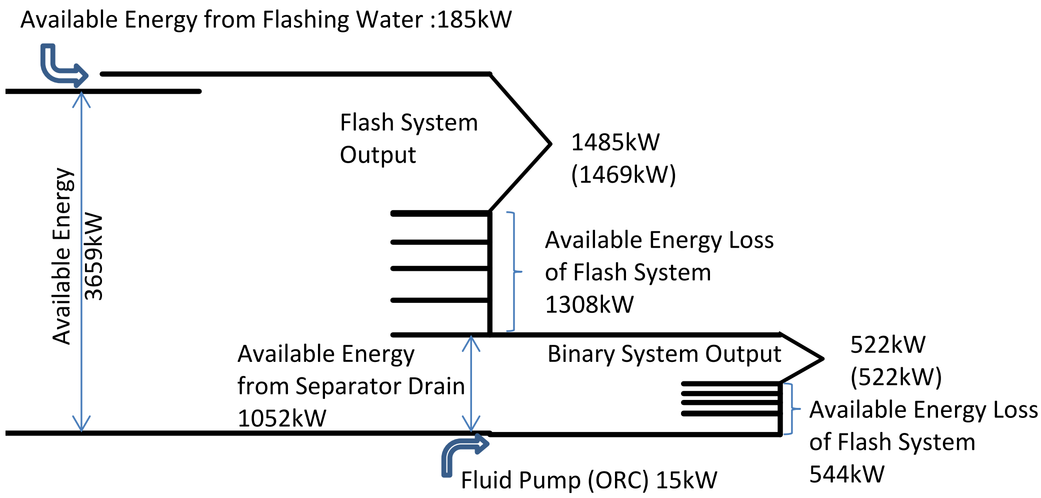

Figure 12 Calculation results

Table 3 Breakdown of available energy loss in Fig. 12

Flash System	Available Energy Loss
Cooling water system	314kW
Condenser	284kW
Turbine	338kW
Separator	372kW
Separator drain	1052kW
Binary System	Available Energy Loss
Cooling water system	107kW
Condenser	97kW
Turbine	114kW
Fluid pump	6kW
Heat exchanger	221kW

4.4 Case study of geothermal power generation

This section presents the process model of the geothermal power generation system and case study results considering the foregoing discussion. The process simulation tool PRO/II is employed, and two types of geothermal power generation system, i.e. flash and hybrid, are examined. The case study conditions are shown in Table 4, and the outline of this model is described below.

(i) Production Well Model

- Geothermal source is assumed to be hot water at the bottom hole of the geothermal production well and the bottom hole temperature is set as a parameter to investigate characteristics of the system.

- Geothermal fluid is introduced to the separator and separated into steam and water. The separator pressure is the parameter to be optimized.

(ii) Flash Power Generation Model

- The process model is the same as shown in Figure 1 (a).

- The combination of direct contact condenser and wet cooling tower is adopted as the turbine exhaust condensing system with two stage ejector as non-condensable gas extraction.

(iii) Hybrid Power Generation Model

- Hybrid system utilizes geothermal hot water from the separator as the heat source for the ORC cycle as shown in Figure 13.

- The additional binary process model is the same as shown in Figure 1 (b) except for the cooling system. The water-cooled condenser is selected in this study in order to have the condensing condition correspond to flash systems

- Normal pentane is adopted as the working fluid, showing comparably good performance in our preparation work.

Figure 14 shows the results of this study. This figure also contains available energy calculated by means of Formula (5). The difference between the available energy and actual work output is availability energy loss as mentioned in the previous section. This shows that even the hybrid system can achieve only half of the ideal system. Although available energy corresponds to the highest limit of the work output thermodynamically, various limitations due to actual process equipment constrain actual work output to around half of the maximum. From the perspective of engineering, the effort to reduce irreversibility often leads to higher equipment cost. It is thus important to consider the balance between available energy loss and cost in optimizing the process.

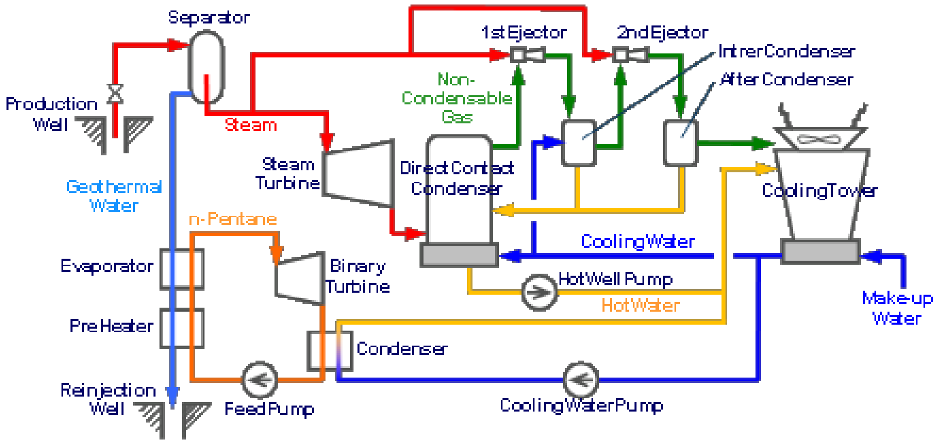

Figure 13 Calculation model for the hybrid system

Table 4 Main terms of calculations

Item	Flash	Binary	Hybrid
Heat Source	Saturated Hot Water temperature Ranging Bottom Hole Temperature Range of 160 ~ 250 °C		
Pressure of Separator	Optimized parameter		
Working Fluid	Geothermal Steam	n-Pentane	Geothermal Steam + n-Pentane
Pinch Point	-	10 °C (Evaporator) 10 °C (Condenser)	10 °C (Evaporator) 10 °C (Condenser)
Air Temperature	20 °C (wet bulb)	20 °C (wet bulb)	20 °C (wet bulb)
Cooling Water Temperature	25 °C	25 °C	25 °C
Reinjection Temperature (Lower Limit)	100 °C	100 °C	100 °C

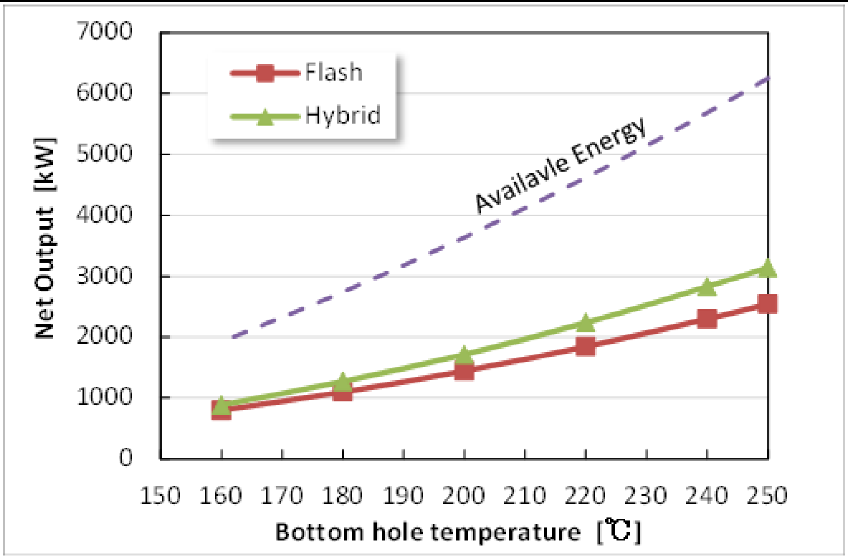

Figure 14 Calculated net output of the system

5. ACTIVITY IN DEVELOPMENT OF GEOTHERMAL BINARY SYSTEM

Mitsubishi Hitachi Power Systems, Ltd. (MHPS) has been working on the commercialization of geothermal binary systems jointly with MHI group company Turboden s.r.l., an Italian manufacturer specializing in ORC, in order to meet market needs in Japan as quickly as possible. Turboden s.r.l., founded in 1980, has delivered around 250 ORC systems mainly for biomass plants. In recent years, they have provided several geothermal binary power generation plants (maximum output 5.6 MW) in Europe. Figure 15 schematically indicates the structure of the geothermal binary system. Part of the heat source can be used for local heat supply. An air-cooled type, water-cooled type, or a combination of the two can be selected for the design of the condensate system. Figure 16 shows a general view of an existing binary 5.6MW power generation plant in Germany as an example, using a hot water heat source.

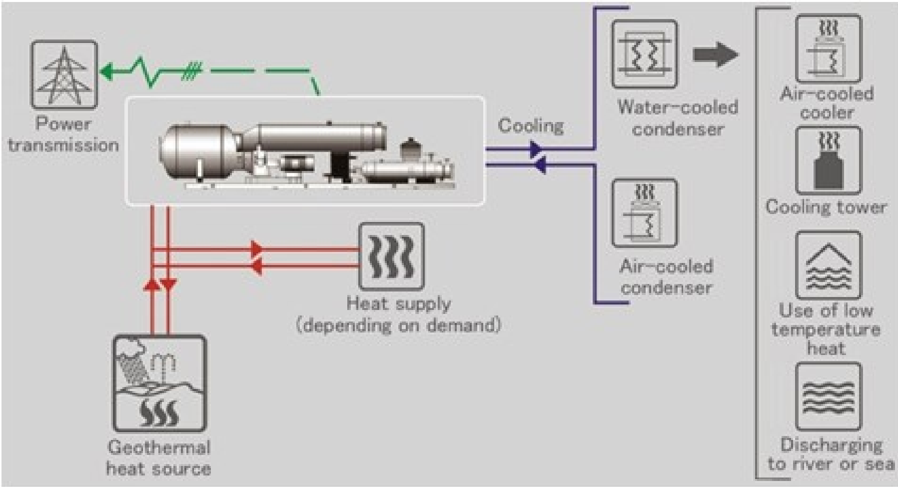

Figure 15 Schematic diagram of the geothermal binary structure

Figure 16 Existing binary plant in Germany designed by Turboden (MHI group company)

6. CONCLUSION

Although geothermal energy plays a very important role as a renewable energy source, it can also be challenging in terms of utilizing natural resource itself. The many restrictions include thermal conditions, chemical components and local regulations. There is no conclusive theory for the design of geothermal power generation systems that will be valid for every geothermal source. The important thing is to investigate the most effective configuration for each geothermal site, based on a proper understanding of the characteristics both of the geothermal resource and the power generation system. These efforts will help to expand geothermal resource utilization.

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