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Development of Hybrid Geothermal Power Plants in Japan

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ABSTRACT

Geothermal energy is the clean and sustainable heat that lies beneath the earth's surface, and it is considered a renewable energy resource. GPP (Geothermal Power Plant) has negligible environmental impact (approximately 0.015kg-CO_2/kWh) and can help reduce carbon dioxide emissions to the atmosphere. Although geothermal energy is potentially a very valuable domestic power source for Japan, much of the geothermal resource base in Japan cannot yet be economically used. Therefore, many industries and research institutes in Japan have researched and developed technologies to harness geothermal energy.

Since 2013 we have started to develop a "highly efficient hybrid GPP" combined with other thermal energy sources such as biomass, solar heat and exhaust heat from fuel cells. It is expected that the thermal efficiency of a GPP can be improved by super-heating the main flow of steam through the use of other energy sources above. Moreover, we have proposed one more hybrid geothermal system, "repowering hybrid GPP". This system can be applied to existing GPPs to recover its power output although the system cannot improve the thermal efficiency of a GPP.

We have also looked into the feasibility of these hybrid GPPs in terms of their engineering, economic performance, environmental laws and regulations. To report the latest status of this project executed by CRIEPI in 2016, we discuss system concepts of these hybrid GPPs and the experimental results performed at the Sumikawa GPP in Japan.

This project has been supported by the New Energy and Industrial Technology Development Organization (NEDO) program (2013 - 2017). NEDO is a semi-governmental organization in Japan set up to promote the development and introduction of new energy technologies.

1. Introduction

Although Japan has about 100 active volcanoes and the world's third largest reserves of geothermal resources after United States and Indonesia, its geothermal generation capacity was ranked only eighth and has not improved in the last decade after the last commercial GPP was built in 1999 on Hachijo Island by Tokyo Electric Power Company.

The main obstacle was environmental protection laws in national parks in Japan. Even though Japan has one of the largest reserves of geothermal resources in the world, more than 80% of them lie within national parks. Therefore, the development of GPPs and the drilling of wells, as well, have been strictly restricted. Rules set in the 1970s suspended the construction of new GPPs inside national parks except for at six sites in operation or under construction at the time. Without reforming the regulations that restrict the development of GPPs within national parks, the geothermal potential that Japan possesses has limited use and cannot be effectively used to produce electricity.

The second obstacle is, until recently, a lack of governmental support for geothermal development. Geothermal energy was recognized as a "new energy" until 1997. However, since then geothermal energy has been excluded from the definition of new energies, subsidies were reduced every year. On the other hand, Japan enacted a RPS (Renewable Portfolio Standard) law in 2003. This law requires electric companies to produce a certain amount of electricity by renewable energy to increase their use and expand the market for renewable energy. However, geothermal energy (flash steam power plants) was also excluded from the RPS law. Since then, geothermal energy has lost support from the government.

In July 2011, the FIT (Feed-in tariff) was adopted by the Japanese parliament. The MoE (Ministry of the Environment) in Japan has gradually relaxed regulations in national parks by 2015. Due to these government policies, in the past four years new GPPs and binary power plants have already been built (totaling 16MWe, as of Mar. 2017). Moreover, in May 2019, J-POWER plans to begin operating the Wasabizawa GPP (42MWe) in the Tohoku region (Yuzawa-chinetsu, 2015). Thus, now it is expected that the usage of geothermal energy will spread more rapidly in Japan in future years. Based on the government estimates, the generation capacity of GPPs can be tripled by 2030.

In Japan, over 10 projects related to geothermal technology are currently in progress. At MoE, three demonstration projects have been conducted to promote social acceptance and to maintain a balance between the development of a GPP and the protection of national parks. Also, at national institutes under the jurisdiction of METI (Ministry of Economy, Trade and Industry), 11 practical studies have been conducted with the aim of reducing the cost and development risk of GPPs. Currently, when some projects under local coordination are added, we have 21 big projects in Japan and their total generation capacity is approximately 560 MWe (NEDO, 2016) .

We have started to develop a highly efficient hybrid GPP combined with other thermal energy sources such as biomass, solar heat and exhaust heat from fuel cells. It is expected that the thermal efficiency of these systems can be improved by super-heating the main flow of steam through the use of other energy sources. Although a Japanese patent was obtained for this technology more than 30 years ago, a detailed study of a system based on this technology has never been carried out in Japan (Nakao et al., 2015).

2. Concepts of Our Proposed Hybrid GPPs in Japan

In this project, our aim is to develop two types of hybrid GPP by effectively combining geothermal energy and other types of thermal energy. One of them is a highly efficient hybrid GPP and the other is repowering hybrid GPP.

2.1 Highly Efficient Hybrid GPP

2.1.1 System Concept

Figure 1 shows the system configuration of a highly efficient hybrid GPP, and Figure 2 shows the T-s (Temperature-Entropy) diagram of the system. In a typical GPP, the turbine inlet steam is saturated. If there is even only a small heat drop in the turbine, the resulting thermal efficiency of a GPP will be much lower than that of a thermal power plant. Therefore, we have investigated the idea of improving both the power output and the thermal efficiency of a GPP by super-heating the turbine inlet steam. By analyzing the performance of the highly efficient hybrid GPP, we've discovered that the power output increased by 30% and the thermal efficiency was more than 20% higher in prescribed production well steam conditions: 2,721.8kJ/kg at 0.5MPa, and cooling water conditions in winter (Nakao, 2016).

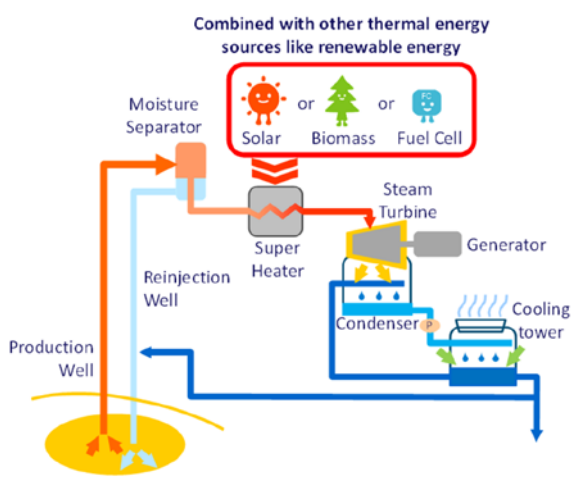

Figure 1: System configuration of a highly efficient hybrid GPP

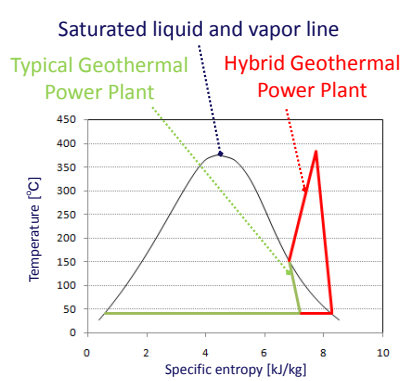

Figure 2: T-s diagram of a highly efficient hybrid GPP

2.1.2 Other Thermal Energy Sources Combined with GPP

We have developed a highly efficient hybrid GPP combined with other thermal energy sources, which are biomass, solar heat, or exhaust heat from fuel cells, and so on. It is expected that the thermal efficiencies of a GPP are improved by super-heating the main steam through the use of other thermal energy sources. We have looked into the system feasibility of highly efficient hybrid GPPs from the point of view of engineering, economic performance, environmental laws and regulations.

As for solar heat, it would be impractical to install solar heat collectors in national parks in Japan, and it is not feasible to gather sufficient solar heat in these environmentally sensitive regions to super-heat the geothermal steam up to approximately 400℃. Fuel cells also have great feasibility in performance and operability, but is quite expensive. As a result, we found that a highly efficient hybrid GPP combined with biomass has greater feasibility than other thermal energy sources in Japan. Thus, we have proceeded with investigating a geothermal-biomass highly efficient hybrid GPP, such as the following:

Table 2: Reliability verification of other thermal energy sources combined with a GPP in Japan

	Biomass	Solar heat	Fuel cell	Micro Gas Turbine
Regulation in national parks	Needs to meet emissions regulations	Needs large site area for solar heat collectors	Needs to store combustible fuel	Needs to store combustible fuel and meet emissions regulations
Performance	✓ Higher than that of biomass power plant	✗ Shortage of direct solar radiation in Japan	✓ Very high efficiency	Lower than that of Combined Cycle Gas Turbine
Cost			✗ Initial cost is still high	✗
	Be able to share power generation facilities such as steam turbine, condenser, cooling tower and ejector			
Others	FIT schemes apply	Combination with GPP has less output fluctuation than PV alone	Wide load range Zero-emission Quick response to load variation	High CO_2 emissions
Comprehensive evaluation	✓	✗	Depends on initial cost	✗

2.1.3 Plant Generation Capacity

In this project, the generation capacity of the geothermal-biomass hybrid GPP was determined to be approximately 4MWe for the following reasons.

- In the FIT scheme, geothermal energy is purchased for 40yen/kWh for smaller plants (< 15MWe).

  The bill introducing the FIT scheme (MoE, 2013) for renewable energy was adopted by the Japanese parliament in July 2011. The purchase rate and period are decided every year and depend on the type of energy, the form of installation and the scale of the renewable energy source. All of the generated renewable electricity (excess electricity produced by residential

renewable energy equipment) is purchased at a fixed price. It has been decided that geothermal energy will be purchased for 26yen/kWh for plants with a capacity of 15MWe or larger and 40yen/kWh for smaller plants for the next 15 years.

- As an example of best practice with minimum impact on the environment, MoE is promoting the Hachijo Island GPP in Japan.

Although a GPP should be promoted as an environmentally friendly energy system, more than 80% of Japan's geothermal resources lie in national parks. Therefore, MoE has relaxed regulations on a GPP in national parks. As an example of best practice with minimum impact on the environment, MoE is focusing on the Hachijo Island GPP. On all occasions, maintaining a balance between the GPPs and the national parks has been a very big issue.

The same thing applies to hot springs ("onsen" in japanese). Japan's rich geothermal resources have made it famous for its numerous hot springs and the culture that developed with them. Currently Japan has more than 25,000 hot springs, and 90% of the direct use of geothermal energy in Japan is for hot springs. This means that geothermal development in Japan has been focused on its use for hot springs. Many hot spring owners worry about a reduction or exhaustion of their resources, thus many of them resist or disagree with the development of GPPs or binary power plants. Some of them even refuse to permit research on the geothermal resources near their hot springs.

- Biomass procurement

In Japan, it is difficult to procure lots of biomass from forests at a low cost. If we cut down timber at the forests far from the power plant, the biomass fuel procurement cost would be high because the cost would include the transportation cost. According to our investigation, the maximum amount of biomass from sustainable management is 12,000 ton/year or less for each power plant site. This means that the heat exchange amount of a standard biomass-fired boiler is approximately 3MWth.

2.1.4 Plant Performance of Geothermal-Biomass Highly Efficient Hybrid GPP

The heat-and-mass-balance diagram of a geothermal-biomass highly efficient hybrid GPP was calculated using EnergyWin™ (Koda, 1999; Takahashi, 2007; Nakao, 2011). Table 2 shows major analysis conditions for a GPP, and Figure 3 shows the configuration of a biomass heating facility, which is additionally arranged on a GPP. The main conditions of the saturated geothermal steam were 2,721.8kJ/kg at 0.5MPa, and the flow rate was chosen for a gross power output of 3MWe from the GPP without biomass. The flow rates of the turbine leakage, gland-seal steam, and cooling water in the oil cooler and other system components were estimated from the specifications of existing units in Japan. As for a biomass heating facility, we determined the capacity of each element apparatus by calculating the heat-and-mass-balance of it, and we have made a preliminary estimation of the auxiliary input.

Table 2: Major analysis conditions for a GPP

Variable	Value
Main geothermal steam conditions	
-Flow rate	24.6t/h
-Pressure	0.5MPa
-Specific enthalpy	2,721.8kJ/kg
-NCG	1wt%
Turbine adiabatic efficiency	82%
Vacuum condition	685mmHg
-Cooling water temperature	28°C
-Wet-bulb air temperature	20°C
Pump efficiency	80%
Flow ratio of steam ejector	0.6

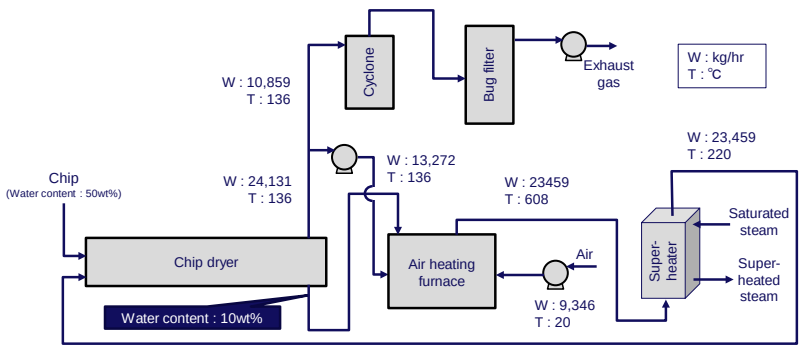

Figure 3: Configuration of a biomass heating facility

Figure 4 shows an advantage of a geothermal-biomass highly efficient hybrid GPP. In our analysis, the gross power output increased by 928 kWe owing to an increase in the temperature of the turbine inlet flow and the gross thermal efficiency is approximately two points higher than that of a GPP without biomass. Then, the net power output increased by 863kWe, and the net thermal efficiency (biomass) of the system was calculated to be 22.2% (HHV: Higher Heating Value of a biomass). It is much higher than that of a biomass-fired power plant.

Here, the net thermal efficiency (biomass) was defined as follows:

Net thermal efficiency (Biomass) [%] =

(Increased net power output [kWe] – Biomass auxiliary input [kWe]) / HHV of biomass fuel [kWth]

Compared to a biomass-fired power plant, the geothermal-biomass highly efficient hybrid GPP would lead to effective utilization of biomass chips. The net power output of the system has increased by about 10% due to combining a GPP with a biomass-fired power plant. In the case of operating a typical GPP and standard biomass-fired power plant respectively, the net power output was 3,399 kWe altogether. Whereas, in the case of a geothermal-biomass highly efficient hybrid GPP, the net power output was 3,716 kWe, because the auxiliary input for biomass heating facility would be reduced by half in comparison to that of a standard biomass-fired power plant. Moreover, the geothermal-biomass highly efficient hybrid GPP has an advantage in efficiency and economics as both systems share a large-scale turbine and generator.

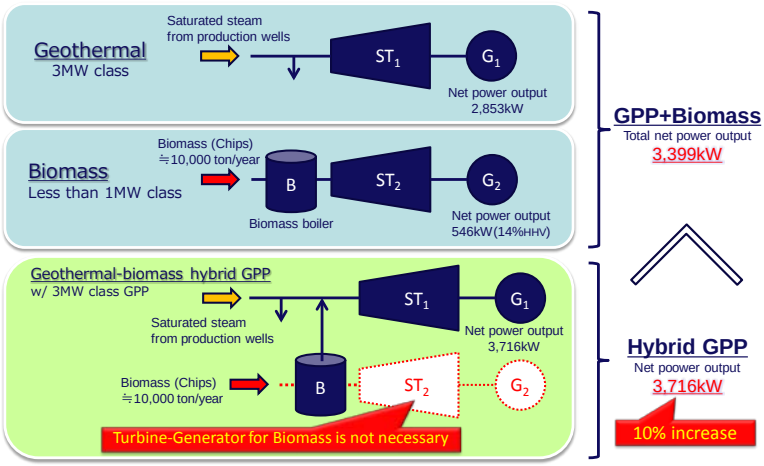

Figure 4: Advantage of a geothermal-biomass hybrid GPP

2.2 Repowering Hybrid GPP

2.2.1 System Concept

Figure 5 shows a system concept of a repowering hybrid GPP combined with other thermal energy sources. Although the repowering hybrid GPP cannot improve the thermal efficiency of a GPP, this concept can be applicable to existing GPPs to improve the power output. On the left part of Figure 5, the power output is 10% lower from the design point. In this case, as by heating two-phase geothermal fluid until the quality of the fluid rises to 0.22 from 0.2, the power output can be increased by 10%, as shown by the system on the right. Also,although the thermal efficiency cannot be improved, the repowering hybrid GPP contributes to reduce the initial cost required for the construction of a biomass-fired power plant while utilizing nearly all of the conventional power facilities of the GPP, such as the moisture separator, steam turbine, condenser, circulating pump, cooling tower, ejector and so on.

Here, “Other thermal energy sources combined with GPP” and “Plant generation capacity” of a repowering hybrid GPP are the same as that we mentioned 2.1 above.

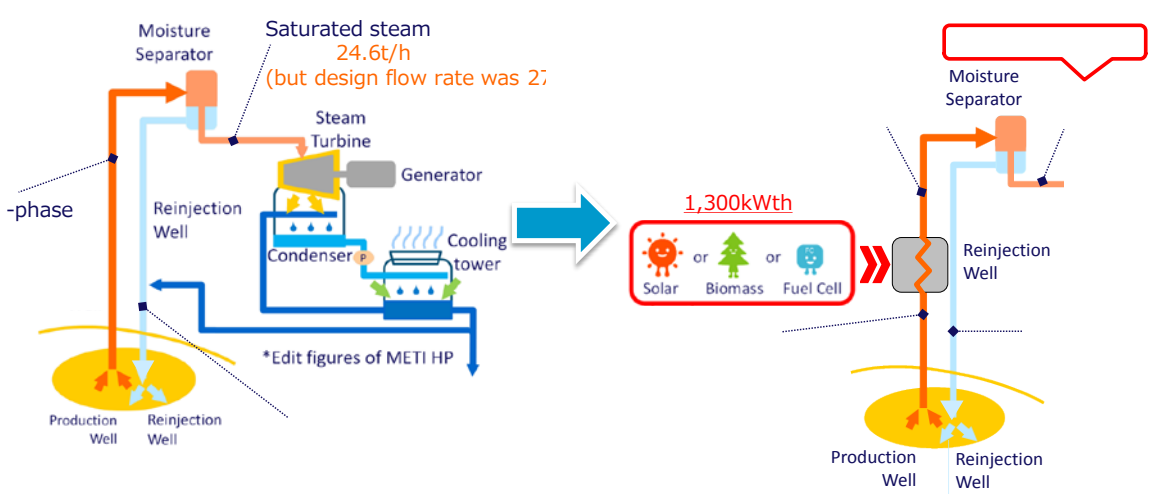

Figure 5: System concept of a repowering hybrid GPP

2.2.2 Plant Performance of Repowering Hybrid GPP

For situation 2.2.1 above, a power output that is 4 times that of a biomass-fired power plant using the same amount of biomass chips can be generated by adopting the repowering hybrid GPP.

To raise the quality of two-phase geothermal fluid (24.6t/h w/ 1wt% NCG) to 0.22 from 0.2, it is necessary to supply latent heat of approximately 1,300kWth. Here, the net thermal efficiency of an existing GPP is assumed to be 15% (HHV) and the biomass heating facility of Figure 3 is installed as an evaporator (here, the system efficiency of the biomass heating facility was assumed to be 75%), the power output of a repowering hybrid GPP can be increased over 230kWe, and the net thermal efficiency (Biomass) defined as in section 2.2.1 above can be approximately 13% (HHV), respectively. On the other hand, generally, it is said that the net thermal efficiency of a small-scale biomass-fired power plant is several percent (HHV). In this case, this means that the power output of approximately only 60kWe is generated by a biomass-fired power plant.

Thus, in the case of a small-scale system, a repowering hybrid GPP can utilize biomass chips more economically than a biomass-fired power plant. Moreover, it is expected that the thermal efficiency of a repowering hybrid GPP is enhanced by combining with a highly efficient hybrid GPP system as described in Section 2.1.

3. Geothermal Fluid Heating Experiments

In order to assess the feasibility of a highly efficient hybrid GPP and a repowering hybrid GPP, saturated geothermal steam super-heating and geothermal water evaporating experiments were performed in the Sumikawa geothermal field in the Tohoku region of Japan in August 2016. As a result, we confirmed that both types of hybrid GPP can be realized, although demonstration testing directed towards practical use is needed in the future.

Figure 6 shows an experimental apparatus with arrows indicating the flow in the case of the saturated geothermal steam super-heating experiment. Two-phase geothermal fluid was provided to the moisture separator from an actual production well directly and saturated steam separated from the two-phase geothermal fluid. The saturated steam (saturated water in the case of the evaporating experiments) was flowed into the bottom of the heat exchanger and while flowing through the heat exchanger it was super-heated until its temperature became equal to an arbitrary temperature. Then, the super-heated steam was condensed at a cooler, in order to measure its flowrate and analyze its properties. After the super-heating experiments, we have observed a quantity of silica scale adhesion on the inside wall of the heat exchanger.

Table 3 shows analysis results of geothermal water and condensed water of saturated geothermal steam. The geothermal fluid in the Sumikawa GPP has the property of being slightly acidic (average pH is 5.9). We found that the silica concentration of the geothermal water was remarkably high (average of 1,512mg/L) during our experiments, and a small amount of silica was contained in saturated geothermal steam at an outlet of the moisture separator.

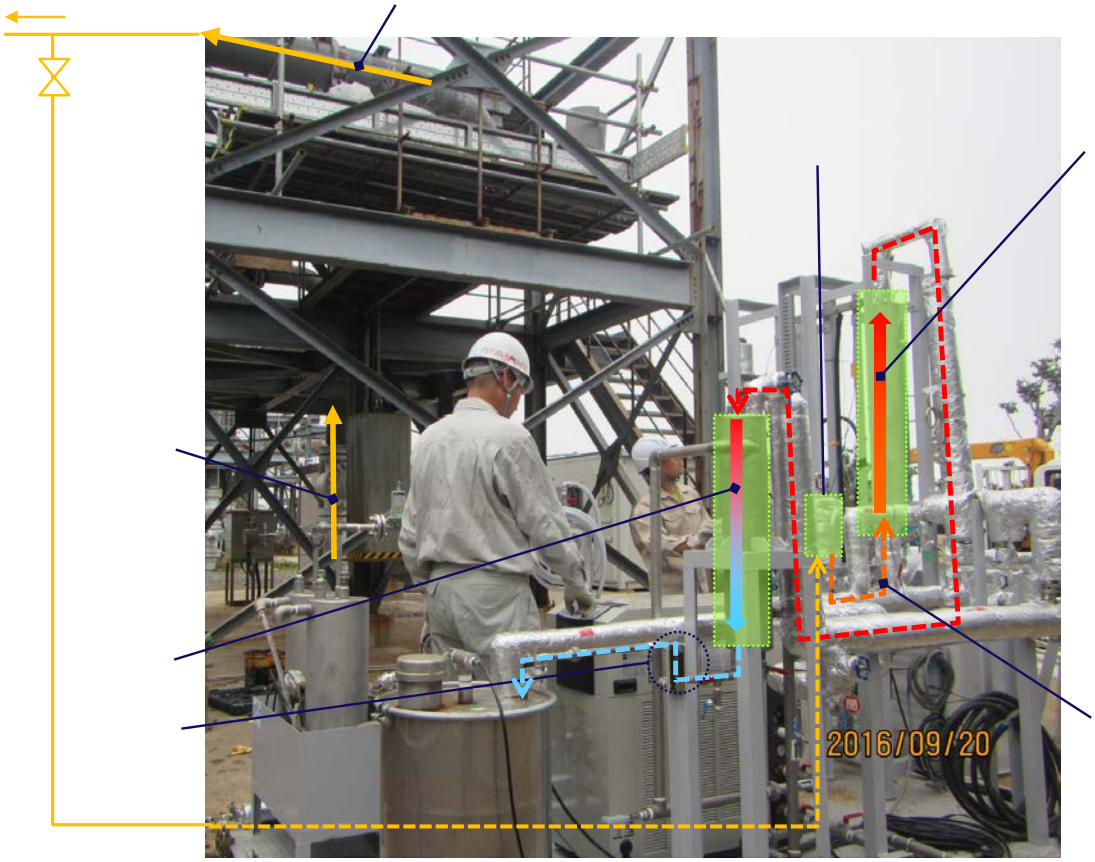

Figure 6: Experiment apparatus for the saturated geothermal steam super-heating experiment

Table 3: Analysis results of geothermal fluid in the Sumikawa GPP

(a) Geothermal water

DATE	pH	SiO2	Cl−
	−	mg/L	mg/L
2016/8/26 15:22	6.6	1606	1788
2016/8/26 18:02	5.6	1462	4805
2016/8/28 10:45	5.8	1488	1936
2016/8/28 12:30	5.9	1535	1697
2016/8/30 9:25	5.7	1494	1260
2016/8/30 11:00	5.9	1487	1423
AVERAGE	5.9	1512	2151

(b) Condensed water of saturated geothermal steam

DATE	pH	SiO2	Cl−
	−	mg/L	mg/L
2016/8/26 15:22	8.5	6	4
2016/8/26 17:57	7.8	3	4
2016/8/26 19:50	3.8	8	2
2016/8/27 10:45	4.5	0	2
2016/8/29 12:25	5.1	7	2
AVERAGE	5.9	5	3

3.1 Experimental Results of Saturated Geothermal Steam Super-Heating

Figure 7 shows the observation results of a transverse cross section of the heat exchanger (super-heater) for saturated geothermal steam by electron microscopic photography. The saturated geothermal steam separated at the moisture separator flowed into the bottom of super-heater pipe (Length 1,000mm × Inner diameter 4mm). The inlet steam condition was 100℃ at atmospheric pressure, and the flowrate of the steam was 2.8kg/h. Then, the outlet steam temperature was 315 ℃ for this experiment. Thus, the top of the super-heater pipe had been exposed for 25 hours to the super-heated steam that was at least over 300℃. After the super-heating experiments, we observed the inside wall of the super-heater pipe by electron microscopic photography, and found that no silica scale formation observed on it.

This result suggests that saturated geothermal steam can be super-heated without worrying about scale adhesion; that is, the geothermal-biomass highly efficient hybrid GPP has high feasibility. Thus, in the summer of 2017, we are planning a demonstration test using a super-heater pipe that is the same size as that of commercial-sized facility, in order to confirm the durability of the super-heater and obtain more information to design a biomass heating facility.

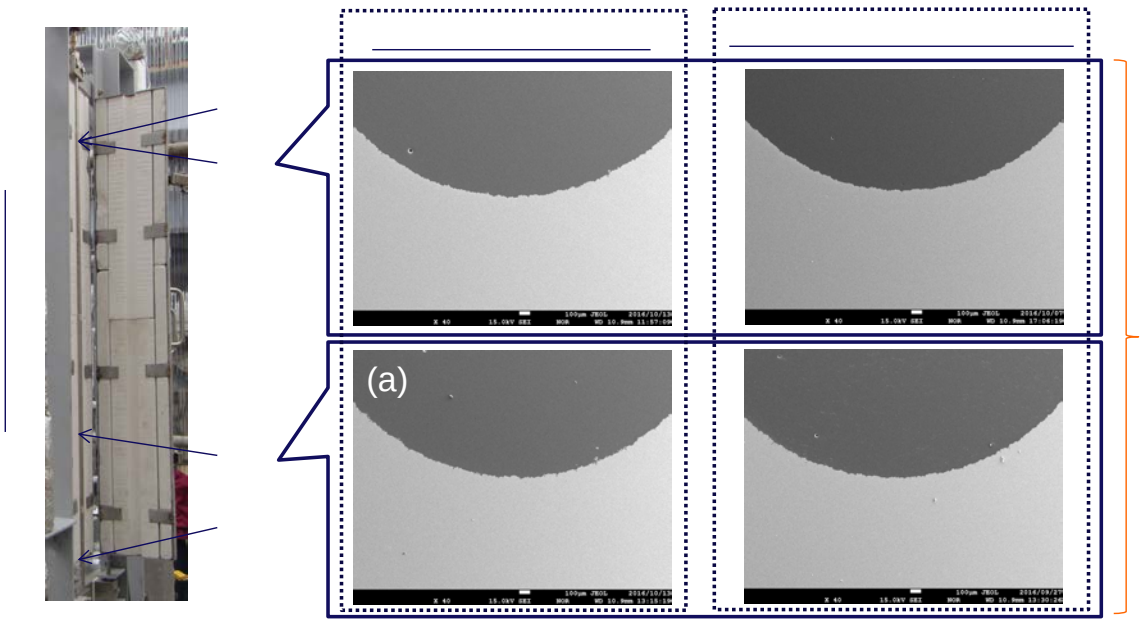

Figure 7: Observation results of a transverse cross section of the heat exchanger (super-heater) for saturated geothermal steam by electron microscopic photography (25 hours later)

3.2 Experimental Results of Geothermal Water Evaporating

Figure 8 shows the observation results of a transverse cross section of the heat exchanger (Evaporator) for geothermal water by electron microscopic photography. The saturated geothermal water separated at the moisture separator flowed into the bottom of the evaporator pipe (Length 2,000mm × Inner diameter 4mm) through a preheater. The inlet water condition was 95℃ at atmospheric pressure, and the flowrate of the saturated geothermal water was 8kg/h. The quality of outlet two-phase fluid was 0.18 for this experiment. The evaporator pipe had been exposed for 15 hours to the two-phase fluid of approximately 100℃. After the evaporating experiment, we observed the inside wall of evaporator pipe by electron microscopic photography. We found that no silica scale formation observed on the lower part of evaporator pipe, i.e., regions (a), (b), (c) and (d) that were exposed to the two-phase fluid having quality 0.09 or less, but silica scales were attached to the upper part of the evaporator pipe, such as regions (e), (f) and (g).

This result suggests that geothermal water can be evaporated without worrying about scale adhesion if the heat amount is very small, that is, the repowering hybrid GPP has high feasibility. Therefore, in the summer of 2017, we are planning a demonstration test using the same apparatus as that of super-heating demonstration test.

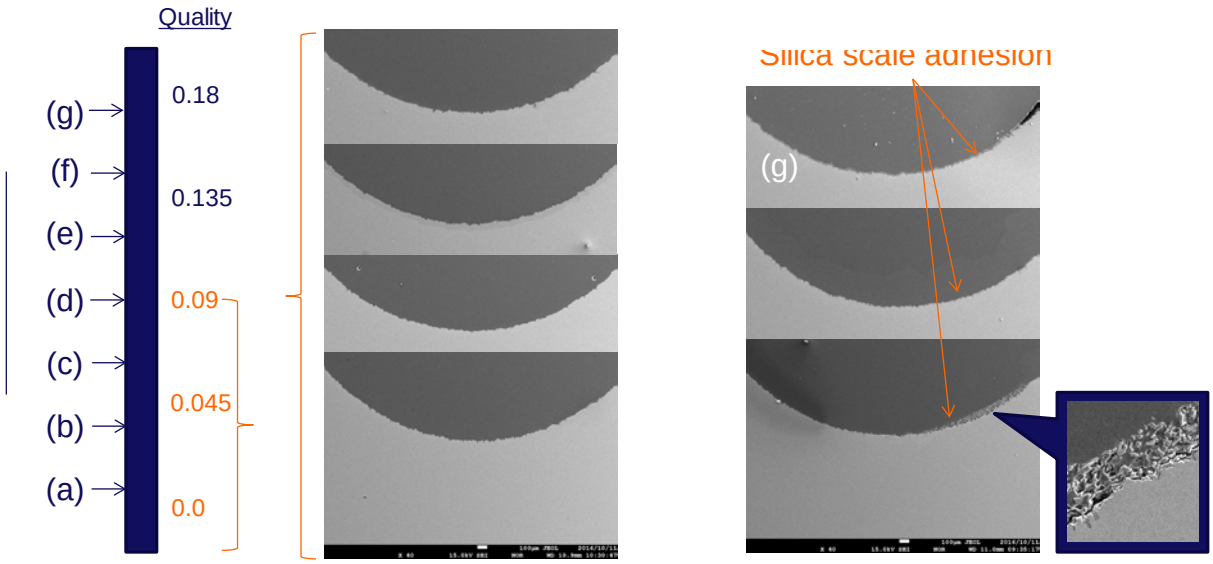

Figure 8: Observation results of a transverse cross section of the heat exchanger (Evaporator) for geothermal water by electron microscopic photography (15 hours later)

4. Conclusion

We have started to develop a geothermal-biomass highly efficient hybrid GPP and a repowering hybrid GPP combined with biomass heating facility. It is expected that the thermal efficiency or the power output of a GPP can be improved using this combination. Therefore, we have looked into the feasibility of these hybrid GPP systems in terms of their engineering, economic performance, environmental laws and regulations.

In August 2016, saturated geothermal steam super-heating and geothermal water evaporating experiments were performed in the Sumikawa GPP in the Tohoku region of Japan. As a result, we confirmed that both types of hybrid GPP (highly efficient hybrid GPP and repowering hybrid GPP) can be realized. However, in order to confirm the durability of the super-heater or evaporator and obtain more information to design a biomass heating facility, demonstration tests directed in practical use are needed.

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