The Latest Geothermal Steam Turbines

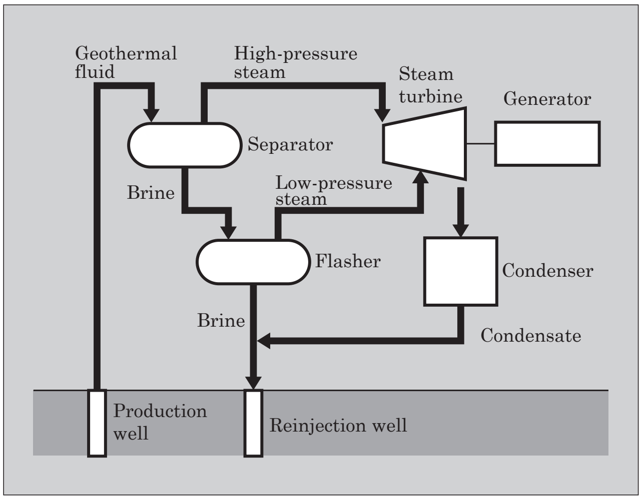
Yoshihiro Sakai †
Yoshiki Oka †
Hideo Kato †

1. Introduction

Geothermal power generation technology extracts a mixture of steam and brine (geothermal fluid) that has been heated by geothermal heat from a well dug deep underground, and then uses that thermal energy to generate power (Fig. 1). Since there is no need to burn fuels such as oil, coal and natural gas, there is almost no emission of such environmental pollutants as carbon dioxide (CO_2), nitrogen oxides (NO_x) and sulfur oxides (SO_x) which are a cause of global warming. Moreover, the steam, after having been used for power generation, can be fed to a condenser and converted into water and then reinjected underground and subsequently reused as geothermal steam. Geothermal energy is reusable clean energy, and its usage is expected to increase in the future to help prevent global warming.

In 1960, Fuji Electric delivered Japan's first commercial geothermal power generating facility to Fujita Tourist Enterprises Hakone Kowakien. Since then, Fuji has delivered a total of approximately 60 geothermal turbines within Japan and overseas, and is considered to be one of the top manufacturers of geothermal turbines in the world. This paper presents an overview of the recent technologies used in Fuji Electric's latest geothermal steam turbines.

Fig.1 Principles of geothermal power generation (double flash cycle)



2. Recent Technologies for Geothermal Steam Turbines

2.1 Technology for improving corrosion resistance

Geothermal steam contains large quantities of chloride, sulfate, hydrogen sulfide and carbon dioxide and other such corrosive chemicals. The majority of these corrosive substances are removed by a separator (water/steam separator), a flasher (reduced pressure evaporator), demister (moisture separator), and so on located upstream from the turbine. Nevertheless, the corrosive substances contained in the steam that enters the steam turbine are 100 to 1,000 times more plentiful than in steam turbines for fossil fuel power plants where the feed water has been chemically treated. Therefore, measures are needed to prevent general corrosion, stress corrosion cracking (SCC), corrosion fatigue and erosion corrosion of parts and materials. In response to these needs, Fuji Electric has continued to develop technology and applied it successively to actual turbines[(1)]. Examples of the latest technologies applied to recent geothermal steam turbines are described below.

(1) Coating technology

Parts such as the rotors and stationary blade holders that are exposed to highly corrosive geothermal steam are particularly susceptible to general corrosion and erosion corrosion, which may lead to the problem of dropout of the seal fin between blades. As one solution, a thermal spray coating technology for the parts' surface has been developed. Basic tests in the laboratory and corrosion tests at geothermal sites were conducted to establish a practical technology using a HVOF (high-velocity oxygen-fuel thermal spray coating, high-velocity frame spraying) process to apply a coating of WC-CoCr thermal spray material. Using this technology, spray coating was applied to the seal fin area between blades of the turbine rotor at the Wayang Windu Unit 2 in Indonesia and resistance to

† Fuji Electric Systems Co., Ltd.

corrosion and erosion was improved (Fig. 2).

(2) Shot peening technology

Corrosive material, which is likely to accumulate and concentrate in gaps between the blade root and rotor grooves, is a cause of SCC and corrosion fatigue. Therefore, based on the results of materials testing in the laboratory and at geothermal sites, the materials used for the rotor and the blade are selected from materials that are highly resistance to SCC and corrosion fatigue, and in addition, shot peening technology capable of withstanding even severer environments has been developed and applied to actual equipment. Shot peening technology bombards the high-stress areas of the blade and rotor with steel balls at high speed so that compressive residual stress is generated in the surface of the part, thereby enhancing the capability to withstand SCC and corrosion fatigue. SCC and corrosion fatigue tests were conducted on blade and rotor materials having been treated with shot peening, and a significant improvement in resistance was confirmed. The shot peening treatment parameters such as projection velocity and angle were optimized in advance, and the work was performed with a robot so as to realize stable quality (Fig. 3).

Fig.2 Spray coating of rotor

Fig.3 Shot peening of rotor blade

(3) Material technology

Steam turbines at geothermal power plants operate under environmental conditions that are much more severe than those of ordinary steam turbines at fossil fuel power plants. Evaluation of the corrosion resistance of materials is crucial for the stable long-term operation of devices under such environmental conditions. Therefore, in the laboratory, Fuji Electric has systematically tested materials in corrosive environments with simulated geothermal fluid, and based on the results, has selected materials and working stress levels that are suitable.

On the other hand, because the material properties of geothermal fluid vary by region, it is important to verify the behavior of materials at the actual geothermal site. Fuji Electric already has installed test equipment at geothermal sites throughout the world, and has been testing materials in geothermal fluid. Recently, over the course of approximately 1-year at Reykjanes, Iceland, Fuji Electric has performed onsite testing of materials for use in geothermal turbines. In onsite testing, corrosion tests, SCC tests, erosion corrosion tests, scaling tests and the like are performed by using actual geothermal steam. The appearance of the test equipment is shown in Fig. 4. The geothermal steam at Reykjanes is at a higher temperature and pressure than at a usual geothermal steam site, Therefore, materials were expected to exhibit different behavior than usual, but good results corroborating the efficacy of the original design were obtained.

Fig.4 Onsite materials testing at Reykjanes

Table 1 Standard materials for geothermal turbines

Part	Standard material
Blade material	13% Cr steel 16% Cr-4% Ni steel Ti-6% Al-4% V alloy
Rotor material	1% Cr-MoNiV steel 2% Cr-MoNiWV steel

Based on the verification results from various material tests, the materials of Table 1 were selected as standard materials for geothermal turbine-use, and optimal materials were selected according to the working environment, stress and other usage conditions.

2.2 Technologies for efficiency improvement

To improve the economic efficiency of geothermal power plants, increased reliability against the problems of corrosion, scaling and the like which are specific to geothermal power generation, and improved turbine efficiency are needed. Fuji Electric has applied its latest technologies, based on know-how acquired with fossil steam turbines, to geothermal turbine blades, and has realized a significant improvement in turbine efficiency. The latest technologies for efficiency improvement are introduced below.

(1) Development of a new generation low-pressure blade series

The design must be made in consideration of the high corrosiveness of geothermal steam, and SCC, corrosion fatigue and the like. Fuji Electric has developed a new generation low-pressure blade series for application to geothermal steam turbines, and is sequentially applying this series to actual turbines. Main features of the new generation low-pressure blade series are as follows.

Table 2 Series of new-generation low-pressure blades for geothermal steam turbines

50 Hz use (nominal annular area)	60 Hz use (nominal annular area)
348 mm blade (1.6 m^2)	290 mm blade (1.1 m^2)
487 mm blade (2.5 m^2)	406 mm blade (1.7 m^2)
555 mm blade (3.2 m^2)	462 mm blade (2.2 m^2)
612 mm blade (4.0 m^2)	510 mm blade (2.8 m^2)
697 mm blade (5.0 m^2)	581 mm blade (3.5 m^2)
798 mm blade (6.3 m^2)	665 mm blade (4.4 m^2)

Fig.5 Rotational vibration test of new-generation low-pressure blade for geothermal steam turbine

(a) Designed for high reliability in consideration of the corrosive atmosphere of geothermal steam
(b) High-efficiency blades incorporate the latest computational fluid dynamics (CFD) technology
(c) High-load design enables the realization of a more compact turbine size

Fuji Electric's lineup of new generation low-pressure blades for geothermal steam turbines is listed in Table 2. The 798 mm blade for 50 Hz-use and the 665 mm blade for 60 Hz-use are the world's largest class low-pressures blades for geothermal steam turbines and contribute to increased unit capacity. Rotational vibration tests were performed on prototype blades and the vibration characteristics verified (Fig. 5).

(2) High-load high-efficiency reaction blades

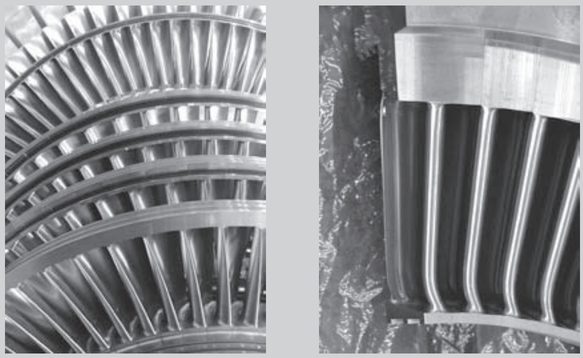
For blade rows that do not include low-pressure blades, the latest blade design technology has been utilized to create high-load high-efficiency reaction blades that maintain high efficiency while increasing the load per row. The application of these high-load high-efficiency reaction blades enables a 1 to 2% improvement in cascade efficiency compared to conventional blades. The reaction blades are all integral shroud blades and achieve high reliability even in the severely corrosive environment of geothermal steam (Fig. 6).

2.3 Compatibility with higher inlet steam pressure

Previously, geothermal steam turbines typically operated with an inlet steam pressure in the range of approximately 0.5 to 1 MPa, but owing to developments in geothermal well exploration technology and drilling technology, and the increased utilization of deep geothermal resources, nowadays the inlet steam pressure can exceed 1 MPa, and in some cases, even approach 2 MPa.

Fuji Electric has previously delivered many geothermal steam turbines compatible with inlet steam pressures of greater than 1 MPa. In recent years Fuji has delivered geothermal steam turbines to the Reykjanes Units 1 and 2 (1.9 MPa inlet steam pressure) and

Fig.6 High-load high-efficiency reaction blades



(a) Moving blades (b) Stationary blades

the Svartsengi Unit 6 (1.6 MPa inlet steam pressure) in Iceland, and these turbines have continued to operate smoothly.

The fluid that flows out of a geothermal well is typically a mixture of steam and brine, and a separator or flasher is used to extract the steam only. The inlet steam is inevitably saturated steam. Accordingly, as a result of the rising inlet pressure, the following issues must be addressed.

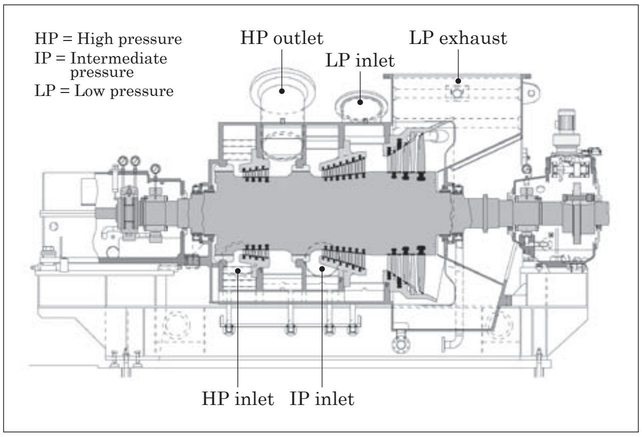
(a) Increased steam wetness of low-pressure stages
(b) Increased steam corrosiveness in dry-to-wet transition zone
(c) Turbine casing design capable of withstanding high pressure

The extent to which the progression of erosion can be limited in low-pressure moving blades is a challenge for (a) above. Fuji Electric provides drain slot midway on the turbine blade stages, and employs a mechanism for capturing and expelling water droplets in order to reduce erosion.

The extent to which erosion corrosion and SCC can be limited in the rotors, stationary holders and blades that face high-pressure and low-pressure steam paths is a challenge for (b) above. It is known that increasing the amount of Cr content in a material will generally reduce erosion corrosion dramatically. Fuji Electric uses 2% Cr steel rotors, stainless steel stationary blade holders, and highly SCC-resistant stainless steel as the blade material to meet the abovementioned challenge.

A pressure of 2 MPa is low compared to that used in fossil power generation. However, because geothermal steam turbines are larger in size than fossil power steam turbines of the same capacity, the magnitude of deformation becomes larger. Additionally, structural design that considers the corrosion allowance over the duration of long-term operation is also needed. Therefore, for (c) above, detailed structural analysis is performed utilizing 3-dimensional CAD and FEM (finite element method) techniques, and also based on the Fuji Electric's long-term experience with actual turbines, the deformation of the turbine casing is ascertained quantitatively and reflected in the design of actual turbines.

Fig.7 Sectional view of Svartsengi Unit 6 geothermal steam turbine



2.4 Utilization of multiple types of steam sources

With the trend towards higher pressures as described above, plants that use a triple flash cycle to flash brine at three stages (high-pressure, intermediate-pressure and low-pressure) and introduce each steam thusly obtained to the geothermal steam turbine have become common. Moreover, configurations in which multiple steam flows are introduced to a single geothermal steam turbine by utilizing surplus steam from existing geothermal steam power plants or by drilling new geothermal wells have also become more popular.

Beginning with the geothermal turbine for the Svartsengi Power Plant Unit 5, and later with the Salton Sea Unit 5 in the US and the Svartsengi Unit 6[(2)] (Fig. 7), Fuji Electric has delivered geothermal steam turbines that combine three or more steam sources.

3. Characteristics of Latest Geothermal Steam Turbines

3.1 Wayang Windu Unit 2

Unit 2 increases the capacity of the Wayang Windu Power Plant in Indonesia and was constructed subsequent to Unit 1 for which Fuji Electric delivered a turbine in 1999. The steam conditions, output, turbine structure and so on for Unit 2 are nearly the same

Fig.8 Sectional view of Wayang Windu Unit 2 geothermal steam turbine

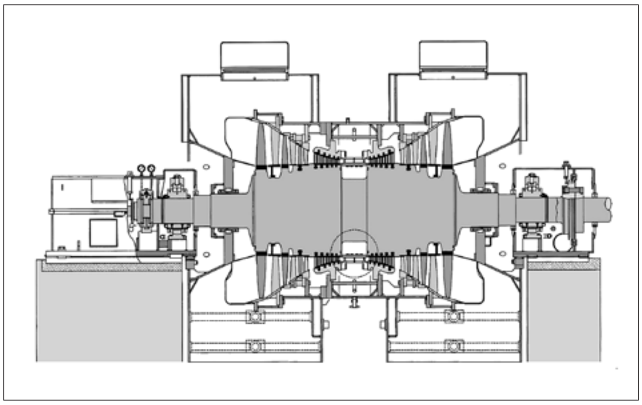


Table 3 Main specifications of Wayang Windu Unit 2 geothermal steam turbine

Turbine type	Single-casing dual-exhaust condensing
Generator output	117.0 MW
Rotating speed	3,000 r/min
Inlet steam condition	1.07 MPa, 182.8 °C (saturated)
Effective strength of last stage blades	697 mm
Nominal annular area	5.0 m^2

as for the existing Unit 1, but in order to provide enhanced corrosion resistance, the coating technology described in section 2.1 has been applied to the rotor and other parts of the turbine. The gross output of 117.0 MW is the world's largest for a single-casing type geothermal steam turbine (Fig. 8). Main specifications are listed in Table 3.

3.2 Svartsengi Unit 6

Unit 6 increases the capacity of the Svartsengi Power Plant in Iceland and was constructed subsequent to Units 3 and 5 for which Fuji Electric had delivered turbines in 1980 and 1999, respectively. At this plant, 1.6 MPa high-pressure geothermal steam had existed prior to constructing the Unit 6 shown in Fig. 9. However, the pressure had been reduced to this lower level prior to usage because the existing turbines had been designed for lower pressure conditions of 0.65 MPa. Moreover, this plant also supplies steam for district heating, and the effective utilization of excess steam generated seasonally was a challenge.

Fuji Electric was involved from the conceptual design stage in the project to expand capacity by adding Unit 6, and in order to optimize the thermal efficiency of the overall plant, collaborated with customers to consider the use of existing steam lines. These efforts resulted in the design and construction of a unique geothermal steam turbine as shown in Fig. 10 that uses controlled extraction and a separator at the turbine intermediate-pressure section.

Expanded steam at the turbine's high-pressure section is exhausted once outside the steam turbine; a portion is extracted to the existing steam lines and the remainder is re-introduced via a separator to the turbine intermediate-pressure section. In the case of excess steam in the 0.12 MPa existing steam lines, that excess portion is introduced to the turbine's low-pressure section. This turbine is connected to input piping and exhaust piping at total of 9 locations. The design employed 3-dimensional CAD-based structural design and piping design in order to ensure reliability.

This turbine achieved its rated load in December 2007, all design values such as controllability and thermal efficiency were confirmed to have been satisfied,

Fig.9 External view of Svartsengi Unit 6

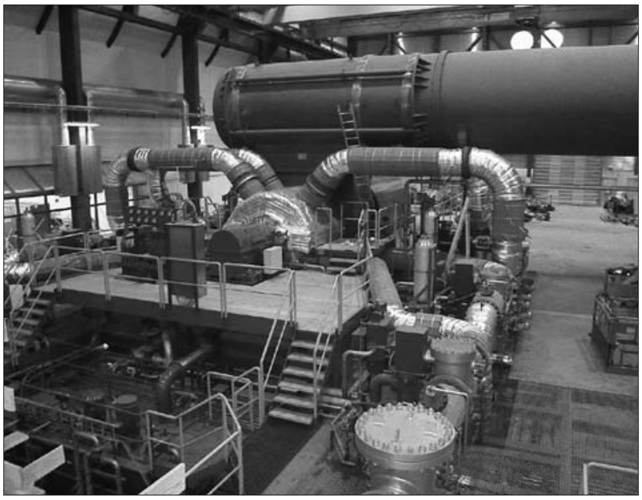


Fig.10 Svartsengi Unit 6 steam line drawing

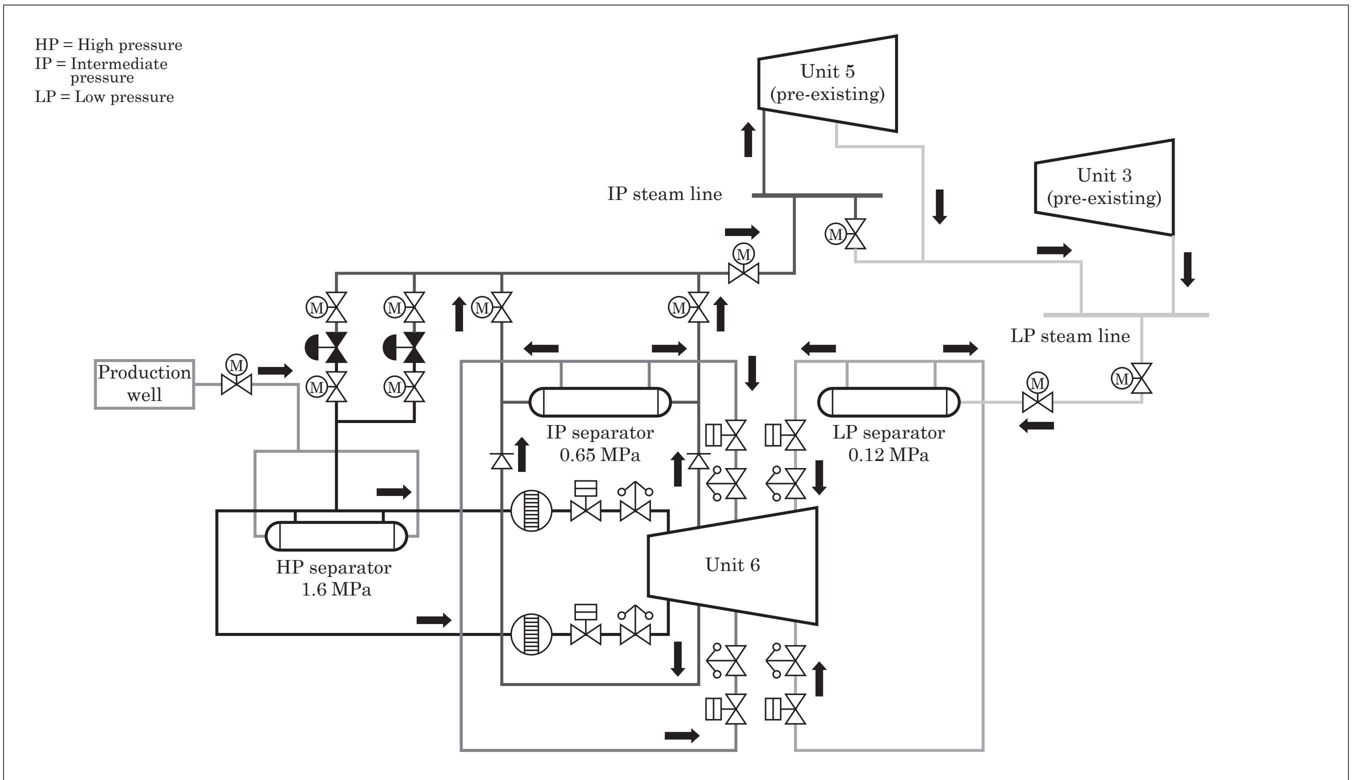
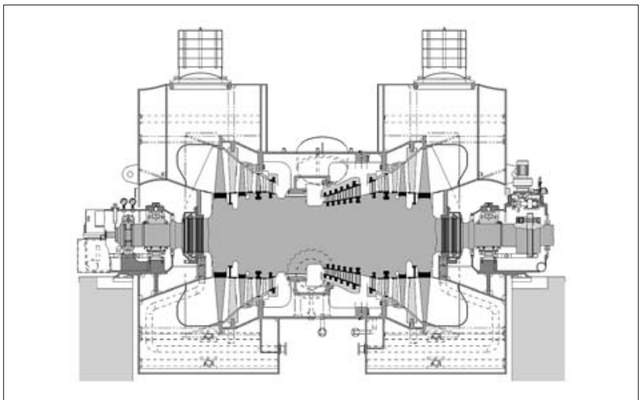


Table 4 Main specifications of Svartsengi Unit 6 geothermal steam turbine

Turbine type		Single-casing single-exhaust mixed pressure condensing
Generator output		33.3 MW
Rotating speed		3,000 r/min
Steam conditions	HP inlet	1.6 MPa, 201.4 °C (saturated)
	HP exhaust	0.67 MPa, 163.2 °C (wet)
	IP inlet	0.65 MPa, 161.8 °C (saturated)
	LP inlet	0.12 MPa, 104.8 °C (wet)
Effective length of last stage blades		487 mm
Nominal annular area		2.5 m^2

Fig.11 Sectional view of Kawerau Power Station geothermal steam turbine



and the turbine continues to operate in good condition. The main specifications are listed in Table 4.

3.3 Kawerau Power Station geothermal power plant

This turbine is produced for the Kawerau Power Station in New Zealand. As a primary EPC (engineering, procurement and construction) contractor, Fuji Electric is responsible not only for the geothermal steam turbine, but also for the design, fabrication and construction of the entire power plant.

The inlet steam is at a high pressure of 1.33 MPa (max.), and the geothermal steam turbine is characterized by its use of the world's largest 798 mm last stage rotor blades. In order to improve reliability in a geothermal steam environment, the shot peening technology described in section 2.1 is applied to the last 3 stages, and 2% Cr steel rotors are used. Moreover, high-efficiency 3-dimensional blades are used in all stages (Fig. 11). Main specifications are listed in Table 5.

Table 5 Main specifications of Kawerau Power Station geothermal steam turbine

Turbine type		Single-casing single-exhaust mixed pressure condensing
Generator output		113.67 MW
Rotating speed		3,000 r/min
Steam conditions	HP inlet	1.33 MPa, 192.5 °C (saturated)
	HP exhaust	0.22 MPa, 124.4 °C (wet)
Effective length of last stage blades		798 mm
Nominal annular area		6.3 m^2

4. Postscript

The utilization of geothermal energy which is a reusable and clean is attracting attention worldwide as a means to help preventing global warming. With international cooperation, the Iceland deep drilling project (IDDP) is being advanced to drill a well 5,000 m below ground, and utilization of 400 to 600 °C geothermal steam is planned for the future. Moreover, Germany, which had previously not been considered a source of geothermal power generation, is moving ahead with a project to dig wells 3,000 to 5,000 m deep and to generate geothermal power. The utilization of geothermal resources is expected to become increasingly important in the future.

As a pioneer of geothermal power generation, Fuji Electric intends to continue to advance the development of geothermal power generation technology and to help facilitate energy utilization that is environment-friendly.

Reference

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(2) Nishimaki, K. Application of Controlled Extraction to Geothermal Steam Turbine. Proceedings of International Conference on Power Engineering 2007. 2007, p. 281-285.

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