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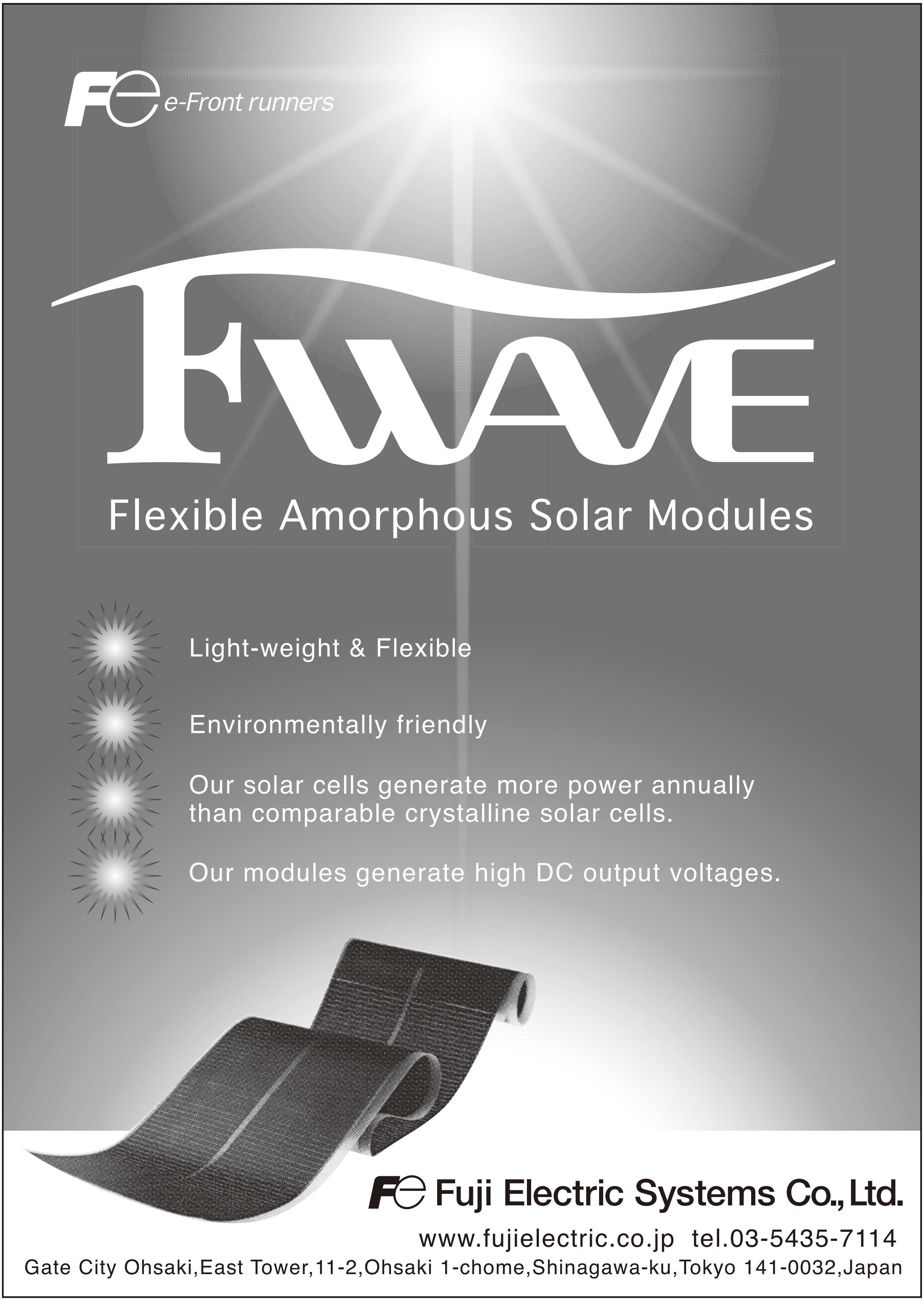
Energy-Creating Technologies

Fuji Electric Group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CONTENTS

Energy-Creating Technologies

Supplemental Explanation

Cover photo:

Japan has made an international pledge to reduce its CO_2 emissions by 25% from 1990 levels by 2020. However, this figure will be unachievable unless additional energy savings are realized and highly efficient energy is utilized.

Leveraging its power generation system technology that employs efficiency-improving techniques accumulated over many years and that utilizes natural energy sources, Fuji Electric intends to contribute to efforts to curb global warming through reducing CO_2 emissions and to help protect the environment and realize a sustainable society.

Based on the keyword of "Energy Creation," the cover photograph depicts geothermal and thermal power equipment, film-type amorphous solar cells, and the new 100 kW fuel cell launched in 2009 as helping to reduce the environment load and fulfilling our corporate social responsibility (CSR).

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Present Status and Future Outlook of Energy-Creating Technologies

Naoto Yoneyama   Satoru Ohsawa   Hiroshi Yoshioka

ABSTRACT

Fuji Electric is promoting a new type of business management based on the keywords of "energy and the environment" and has adopted the following approaches to the creation of green energy. For geothermal power generation, Fuji is focused on developing technology for improving the corrosion resistance of turbines and on binary power generation. In the nuclear power field, Fuji is researching and developing a next-generation high-temperature gas cooled reactor that can be used for power generation, hydrogen production and the like. For solar cells, Fuji has begun full-scale mass-production aiming to popularize lightweight, flexible, film-type cells capable of being installed at a wider range of sites. Fuji has also commercialized a 100 kW phosphoric acid fuel cell named the FP-100i, and is expanding its range of applications to include disaster prevention, digestion gas use, hydrogen stations, etc.

1. Introduction

The global demand for energy is expected to continue to increase significantly in the future, particularly with the economic development of emerging countries and the growing population worldwide. The increase in demand for electrical power will be especially large, and in the International Energy Agency's (IEA) report for 2009 (World Energy Outlook 2009), demand through 2030 for electric power is forecast to increase at an annual rate of 2.5%, and 4.8 TW (terawatts) of additory generation capacity will be needed(1).

Meanwhile, in order to prevent climate change and realize a sustainable society, the reduction of greenhouse gas emissions has become a subject of paramount importance. If the consumption of fossil fuels continues to increase unabated, the atmospheric concentration of greenhouse gases will inevitably exceed 1,000 ppm CO_2-equivalent, and a 6 °C rise in global mean temperature and large-scale climate change are predicted to occur. According to the IEA report, in order to maintain a sustainable global environment, the global temperature rise must not exceed 2 °C, and in order to limit to 50% the probability of occurrence of a greater than 2 °C rise in global mean temperature, the atmospheric concentration of greenhouse gases must be stabilized at 450 ppm CO_2-equivalent. To reduce greenhouse gas emissions, efforts to create a global framework and to promote governmental policies for reducing greenhouse gas emissions have been actively advanced as a matter of urgency at the 15th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP15) in Copenhagen. For government policies to address the serious threat of the climate change that is becoming apparent, economic stimulus policy has incorporated initiatives to promote a low carbon economy, and specific measures are being advanced.

To realize a low carbon society, the amount of energy consumption must be reduced and a green society established. In the energy creation sector where electrical energy is produced, more efficient thermal power using fossil fuels and using nuclear power generation that is free of CO_2 emissions is being promoted. Additionally, the adoption of power generation using renewable energy sources such as geothermal power, hydropower, wind power and solar light/thermal power, is actively being sought.

Fuji Electric is promoting a new type of business management based on the themes of "energy and the environment." In the energy solutions sector, Fuji is focused on the creation of green energy and on grid solutions, while in the environmental solutions sector, Fuji provides solutions for demand-side energy savings and for environmental policies. This special issue introduces some representative initiatives for energy creation in order to establish a low carbon society, and discusses the future outlook for energy creation.

2. Geothermal Power Generation

Geothermal resources are present in regions where the plates of the earth collide with each other and where volcanoes are common. Such areas are found in the Pacific Rim region, northeastern Africa, and in Europe in the Mediterranean region and Iceland. Thus far, geothermal power generation has been actively developed in the USA, Mexico, Europe (Italy and Iceland), Asia (Indonesia and the Philippines), Oceania (New Zealand), and so on (Fig. 1). In these regions, the development of geothermal power as a renewable energy source is expanding further. Moreover, even

† Energy Solution Group, Fuji Electric Systems Co., Ltd.

Fig.1 Promising areas for geothermal power generation

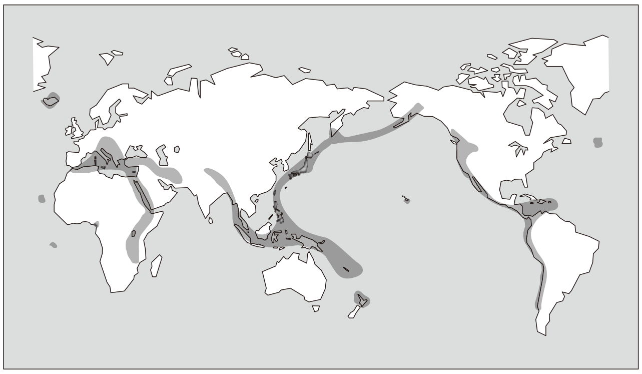
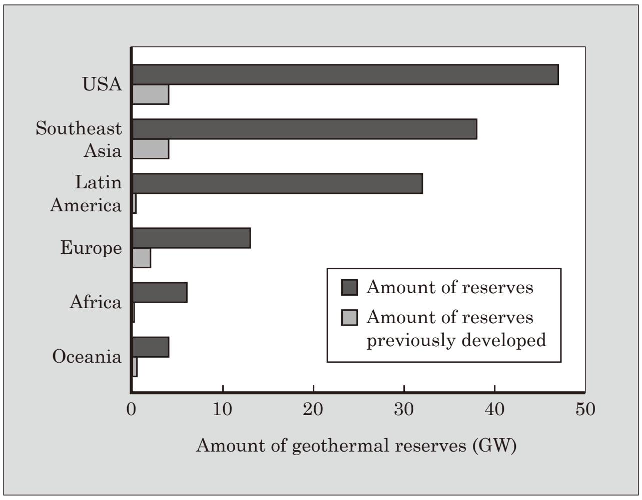


Fig.2 Amount of geothermal resource reserves(2)



on the Eastern Coast of Africa and in Latin American countries where the development of geothermal power is lagging, plans for geothermal power development are being advanced. Japan's geothermal resources are said to be the third largest in the world, but development has stagnated due to constraints imposed by the Natural Parks Law and so on, and the generating capacity developed thus far has remained at about 500 MW. In the future, the governmental adoption of policies that support development is expected to promote new development.

Fuji Electric delivered its first geothermal power facility in 1960 and, since then, has continued to focus on geothermal power, researching and developing high-efficiency geothermal turbines and specific anti-corrosion measures for geothermal turbines. Geothermal steam, in particular, contains substances that corrode turbines, and degrades performance as a result of scaling that adheres to the turbine blades. Fuji Electric has researched and developed turbine materials, coating technology and the like, which are strongly resistant to corrosion and wear, achieving good results. Furthermore, Fuji Electric has also established anti-corrosion technology for generators and electronic control equipment installed in a geothermal gas atmosphere, and has manufactured and delivered high performance, highly reliable geothermal power facilities. Recently, in addition to turbine power generating equipment, Fuji Electric has also been designing and manufacturing steam generating facilities for producing the optimal steam for turbine operation, as well as auxiliary equipment for these steam generating facilities, and is also working to realize a turn-key solution for the engineering of an entire geothermal power plant.

Fuji Electric has worked to develop large-capacity flash generators that generate electric power from geothermal steam fed directly to a turbine. In addition, Fuji Electric also developed binary power generation technology capable of effectively utilizing low temperature geothermal resources that had previously been unusable. Geothermal binary power is generated using the heat from geothermal steam to evaporate a medium that has a lower boiling point than water, such as pentane, and to drive a turbine. Binary power plants are medium or small-capacity geothermal power plants that can be used at sites where the geothermal resources are at a low temperature or the amount of steam is small, and they hold promise for the efficient utilization of idle energy that had been previously unused.

Enhanced Geothermal Systems (EGS) are attracting attention as a new type of geothermal power generation technology. Existing geothermal power generation extracts the resources of geothermal steam and hot water from high-temperature natural reservoirs underground. With EGS technology, hydraulic fracturing of hot rock is performed artificially by pumping water into the rock and capturing the resulting steam and hot water. EGS is being researched in the USA, Australia, Germany and elsewhere, and holds promise as a means for expanding geothermal usage in the future. The generation of power from geothermal resources is capable of providing stable power that is unaffected by weather, and as a renewable energy source capable of a high utilization rate, the development of geothermal resources is expected to become more active in the future (Fig. 2).

3. Nuclear Power (High-Temperature Gas-Cooled Reactor)

As a form of energy that does not emit CO_2, nuclear power is being developed throughout the world. Particularly in the US, the adoption of nuclear power is being planned to provide a stable supply of power and to help prevent global warming. The adoption of nuclear power is also been actively promoted recently in the Middle East and Asia. The nuclear power generation currently planned involves mostly light water reactors, but high-temperature gas-cooled reactors (HTGR) hold promise as next-generation reactors capable of using distributed resources and that will expand the range of applications for nuclear energy.

HTGRs can use high-temperature heat in the range of 700 to 950 °C, and as power generation plants, can therefore realize power generation with nearly 50% efficiency using a direct gas-turbine cycle. HTGRs are also capable of producing hydrogen directly from water using a thermo-chemical process, or can be used as a source for the high-temperature steam supplied as process heat to a chemical plant. HTGRs have potential for expanding the range of uses of nuclear power, which has been limited to generating electricity in the past, and by positioning nuclear power as a primary energy source that replaces fossil fuels, to reduce CO_2 emissions dramatically. For this reason, HTGR technology is actively being developed in Japan and overseas. The modular HTGR, which has limited output and is able to take advantage of the inherent safety characteristics of HTGRs, has become the mainstream nuclear reactor being developed in countries throughout the world. Because the maximum heat output of the reactor is limited to about 600 MWt (300 MWe electric power), in the case of an accident, the reactor will shutdown naturally and remove heat naturally, and has no risk of releasing massive amounts of radioactive matter that would require evacuation of the public. Accordingly, HTGRs can be constructed in proximity to the regional demand for electric power and can also be constructed as distributed power sources.

Since the project planning stage, Fuji Electric has participated in the development and design of a High Temperature Engineering Test Reactor (HTTR) operated by the Japan Atomic Energy Agency (JAEA) as Japan's first HTGR. During the actual construction, Fuji Electric designed the reactor core, performed safety analyses, and was in charge of the design, fabrication and construction of major equipment such as the reactor internal structure, the fuel handling and storage system, the radiation monitoring system, and so on. Based on the technical know-how acquired through this experience, Fuji Electric is moving ahead with research and development that aims to realize a HTGR on a practical scale, targeting a reactor outlet temperature of 950 °C and heat output of 600 MWt.

The US Department of Energy has launched a HTGR project, and has begun to plan research and development in order to realize this project. Fuji Electric will also participate as a member of the HTGR conceptual design team.

As part of a long-term efforts aimed at preventing global warming and supporting the upcoming hydrogen economy, in cooperation with relevant national and international agencies, Fuji Electric will continue to promote activities that aim for practical applications of HTGRs.

4. Thin-Film Amorphous Silicon Solar Cells

Circumstances surrounding solar cells have changed significantly over the past decade. Worldwide production has increased more than 20-fold. The solar cell market has also transitioned from one centered on Japanese manufacturers, to a diverse market supplied by many manufacturers from Japan, USA, Europe, and China and other Southeast Asian countries, and in addition to crystalline silicon solar cells, thin-film silicon and other types of new solar cells are now being produced in large quantities.

Turning to national policies for promoting the widespread use of thin-film amorphous solar cells, in Europe, with the adoption of a feed-in tariff (FIT) system mainly in Germany, the usage of solar cells is rapidly increasing. Even in the US where solar cell adoption rates have been sluggish, with the 2009 change in governing party, the solar cell industry is poised to gain momentum.

In Japan, thus far, widespread adoption has been promoted mainly for residential use. Additionally, as support for public and industrial uses of solar power has increased, a "new buyback program for photovoltaic power" was launched in November 2009, and surplus power is beginning to be purchased at higher prices than before. Moreover, in response to the recent change of the governing party in Japan, the "renewable energy all-quantity buyback program" cited in the manifesto of the Democratic Party is being discussed, and specific measures for expanding adoption of solar power technology are under consideration.

Fuji Electric began developing solar cells in 1978, and initially developed a-Si single and a-Si tandem solar cells that used glass substrates. Since 1993, however, Fuji's development efforts have shifted to thin-film amorphous silicon solar cells (a-Si/a-SiGe) that use inexpensive plastic film substrates. Based on the successful results of technical development, Fuji Electric completed the construction of a dedicated plant for solar cell production in Kumamoto Prefecture, Japan and began full-scale mass-production in November 2006.

Fuji Electric's solar cells (Fig. 3, Fig. 4) use plastic film as their substrate material, and as a result, exhibit the previously unobtainable characteristics of

Fig.3 Saitama Super Arena

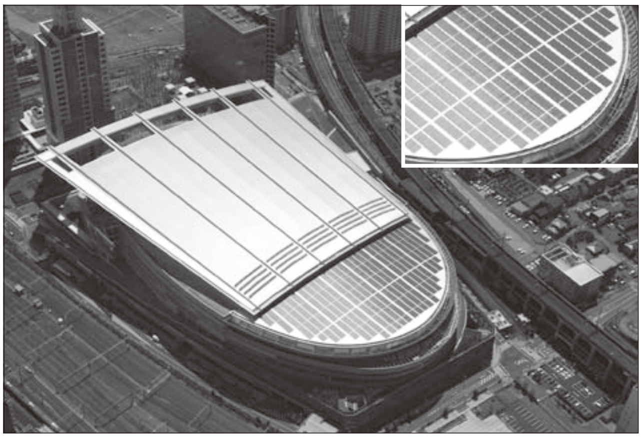


Fig.4 Academic Plaza of Kumamoto Prefectural College of Technology

being "lightweight" and "flexible", and open up a new range of applications such as to gymnasiums and factories, i.e., large roof and building wall areas, where the installation of solar cells had previously required reinforcement of the building. Also, breakage is not a concern since glass is not used as the surface material, and therefore applications requiring a high level of safety, such as highway soundproofing walls, are also being considered. Furthermore, because the module surface is covered with embossed plastic, the amount of light reflected is less than that of glass, and installations at airport facilities or the like where low glare (low reflection) is required in order to ensure the safety of operations are also being considered. In the future, to expand this business further, product development must focus on improving the output of the modules and on meeting customer needs. Through accomplishing these goals, Fuji Electric also aims to contribute positively to protecting the global environment.

5. Fuel Cells

The "FP-100i" 100 kW fuel cell power plant that Fuji Electric began selling in 2009 was awarded the "Nikkei Superior Products and Services Award" in that same year. In addition to the conventional application as co-generation equipment that uses city gas and digester gas as fuel, with the aim of expanding the market, fuel cells are being equipped with additional features for disaster response support, compatibility with byproduct gases, hydrogen supply support, and so on. Inside a power plant, a fuel cell is equipped with a reformer so as to be compatible with a variety of fuels such as city gas or digester gas. By maintaining a reserve of LP gas, operation will normally proceed with city gas being used as the fuel, but in the case of an emergency or disaster where the electricity or city gas supply is shut off, the fuel source can be changed to LP gas so that operation can continue.

In the case where the pure hydrogen byproduct from a salt electrolysis plant or the like is used as fuel, highly efficient power generation with fuel cell output efficiency of 48% can be realized, and a CO_2 emissions reduction effect of approximately 760 t annually is expected. A 100 kW fuel cell capable of using pure hydrogen fuel began operation in 2010 as a demonstration test. As a pioneer of the future hydrogen energy era, a fuel cell equipped with a hydrogen supply function is suitable for applications involving small hydrogen stations. In the case where digester gas is used as fuel, so-called green hydrogen can be produced stably without generating any CO_2. Also, digestion gas power generation fueled by digester gas generated from sewage treatment plants has been operating successfully since 2002. As carbon-neutral power, a 100 kW fuel cell is expected to provide a CO_2 reduction effect of about 800 t annually. Certified by Japan's "Green Power Certificate" system, the investment costs for these fuel cells can be recouped within a short time period.

Fuji Electric established a factory system in April 2009 for producing 20 units annually of the FP-100i, and by promoting their widespread usage through the aforementioned application development, intends to contribute to reducing CO_2 emissions.

6. Postscript

In addition to the above, in order to realize a low carbon society Fuji Electric is also pursuing various other initiatives for energy creation.

In the thermal power generation sector, Fuji Electric is advancing research and development to increase the efficiency of turbines and generators, and in the gas combined power generation sector, is collaborating with Siemens to develop high-efficiency high-performance gas combined cycle power plants.

In the hydropower sector, Fuji Electric is advancing the research and development of highly efficient hydropower facilities in collaboration with Voith Hydro, and plans to offer energy creation solutions via a global network.

Wind power is also being adopted throughout the world as a natural energy source that does not emit CO_2. In addition to onshore wind power facilities, offshore wind power generation is also actively being planned for the future, and individual turbines of larger capacity (3 MW and greater) are being produced. Building on its considerable accumulated technical expertise in power electronics, Fuji Electric is advancing the development of high performance power conditioners and permanent magnet generators. In the wind power sector, Fuji Electric's work is also centered on the most important components.

Additionally, with the introducing of large amounts of natural energy, new challenges have emerged, such as stabilization measures for the power system. Fuji Electric has already responded to this challenge by introducing a power stabilizer in a wind power plant, and has realized good results in stabilizing the power system. Furthermore, Fuji is also working on smart grid technology, a promising technology for the future, and grid solutions.

Through providing these energy solutions, Fuji Electric is determined to make positive contributions towards the goal of realizing a low carbon society.

References

(1) International Energy Agency, World Energy Outlook 2009.

(2) Global Geothermal Markets and Strategies, Emerging Energy Research.

Fuji Electric s Recent Activities and Latest Technologies for Geothermal Power Generation

Shigeto Yamada Shizuka Makimoto Hiroaki Shibata

ABSTRACT

Fuji Electric has been involved in geothermal power generation since the 1980s, and is now recognized as a leading company for supplying geothermal power plants. This paper introduces two recently completed geothermal power plants, Wayang Windu in Indonesia and Kawerau in New Zealand. The world's first practical application of a steam purity monitoring system equipped with a fault diagnosis function and an operation support function helps to improve the utilization rate of the plant. A binary power generating system, developed so that low-temperature geothermal resources can be utilized, has successfully completed a 200 kW pilot unit operation, and is slated to be introduced to the market during 2010.

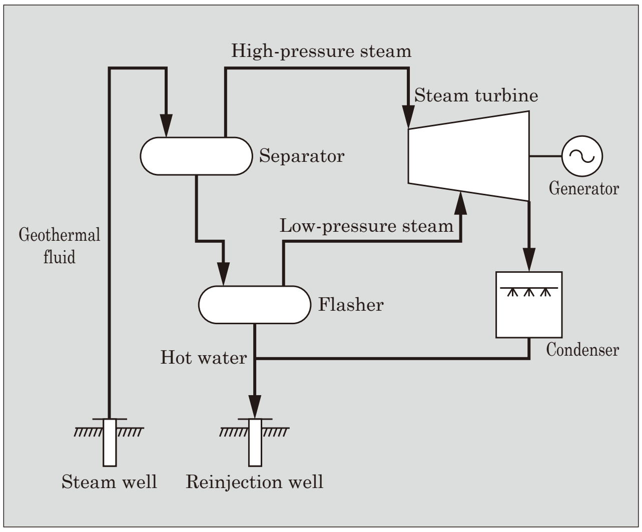
1. Introduction

Geothermal energy is a renewable energy source known for having extremely low levels of CO_2 emissions. According to calculations by the Central Research Institute of Electric Power Industry, the amount of CO_2 emissions per 1 kWh is 975 g for coal-fired power generation and 519 g for LNG combined power generation, but only 15 g for geothermal power generation(1).

Fuji Electric delivered Japan's first geothermal power facility to Hakone Kowaki-en in 1960. Then, in 1980, Fuji Electric delivered a 35 MW geothermal power facility for the Ahuachapán, El Salvadore Geothermal Power Station, and entered the geothermal power generation market in earnest. In the 1980s, Fuji Electric delivered 30 geothermal power units, totaling approximately 800 MW, to the United States and the Philippines, and came to be recognized as a leading manufacturer of geothermal power facilities. In the 1990s, Fuji Electric delivered 15 geothermal power units having a total combined capacity of approximately 700 MW. Although there appears to have been slightly fewer units delivered in the 1990s than in the 1980s, these delivery figures include three 77.5 MW units for the Philippines and one 110 MW unit for Indonesia both of which include the scope of entire geothermal power stations, and this was the time when Fuji Electric transitioned from a manufacturer of geothermal power equipment to a plant manufacturer in charge of the complete construction of a power station. Upon entering the 21st century, Fuji Electric has continued to build upon its successful track record of geothermal projects, and in early 2010, aiming for completion of a 139 MW geothermal power station, the world's largest capacity single-turbine geothermal power station, Fuji Electric initiated the onsite pilot operation.

† Energy Solution Group, Fuji Electric Systems Co., Ltd.

Fig.1 Steam flow in geothermal power generation system (double-flash cycle)



The abovementioned projects are based entirely on the flash cycle geothermal power generation. Flash cycle geothermal power generation uses geothermal steam directly to a steam turbine separated at separator from mixture of geothermal steam and hot water. Figure 1 shows a flow diagram of this process. Fuji Electric's share is approximately 40% in the world for the flash-cycle geothermal power facilities delivered over the past 10 years.

This paper discusses Fuji Electric's recent geothermal projects, and introduces a geothermal binary power generation system, newly developed in addition to the flash-cycle method, and the world's first geothermal steam purity monitoring system which has been used in practical applications.

2. Recent Geothermal Power Projects

Table 1 lists Fuji Electric's recent geothermal power projects. During the 3-year period from 2007 to 2009, Fuji Electric delivered and completed seven 398 MW geothermal power generating facilities. For 2010 and beyond, four 248 MW units are slated for shipment and completion. Among 11 projects listed in Table 1, the seven projects marked with an asterisk next to the plant name are EPC (engineering, procurement and construction) contracts in which Fuji Electric is working in collaboration with local contractors.

The Wayang Windu, Kawerau and Nga Awa Purua projects include steam separation systems composed of a separator for separating geothermal fluids from hot water and a scrubbing system for removing, as much as possible, impurities from geothermal steam.

2.1 Wayang Windu Geothermal Power Station[2]

The Wayang Windu Geothermal Power Station is located in Java, Indonesia. In 1997, Fuji Electric received an order for a geothermal power station consisting of two 110 MW units. However, plans for Unit 2 were frozen due to the Asian economic crisis, and therefore the comprehensive civil engineering and construction works completed in 1999 including the Unit 1 power generating facility and only the foundation works for Unit 2. Then in 2007, construction of Unit 2 was resumed, its capacity increased to 117 MW, and was completed in 2009. Figure 2 shows a bird's-eye view of the geothermal steam production well and the geothermal power station.

As mentioned above, at the time when Unit 1 was completed in 1999, the foundation work for Unit 2 was also completed with the same specifications as Unit 1, and equipment for Unit 2 had to be the same size as that for Unit 1. Because of this restriction, the condenser cooling system was redesigned so that the turbine exhaust pressure would be lower than that of Unit 1. As a result, although the turbines and generators of Units 1 and 2 are of the identical design, the output has been increased, from the 110 MW output of Unit 1 to 117 MW for Unit 2.

Table 1 Recent geothermal power generation projects

Country	Plant name	Capacity (MW)	Completion
Philippines	Northern Negros *	49.7	June 2007
Indonesia	Lahendong 2 *	20	June 2007
Iceland	Svartsengi 6	33	February 2008
Indonesia	Kamojang	63	February 2008
New Zealand	Kawerau *	95.7	August 2008
Indonesia	Wayang Windu *	20	February 2009
Indonesia	Lahendong 3 *	117	March 2009
Nicaragua	San Jacinto 3	38.5	February 2010
Iceland	Reykjanes 3	50	March 2010
New Zealand	Nga Awa Purua *	139	April 2010
Indonesia	Lahendong 4 *	20	September 2011 (expected)

* : EPC contract

Fig.2 Bird's-eye view of Wayang Windu Geothermal Station

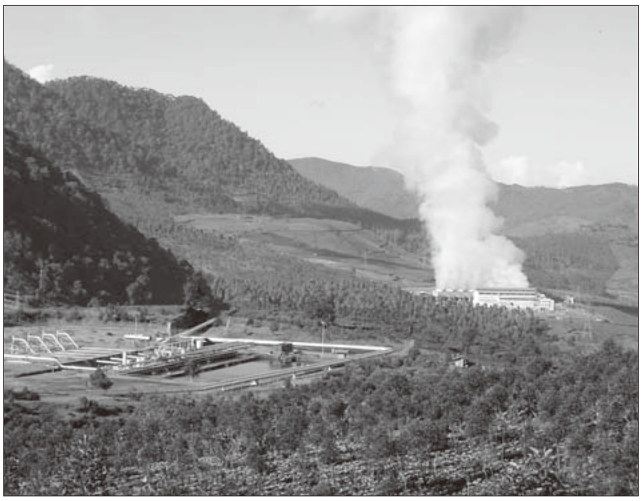


Fig.3 Bird's-eye view of Kawerau Geothermal Power Station

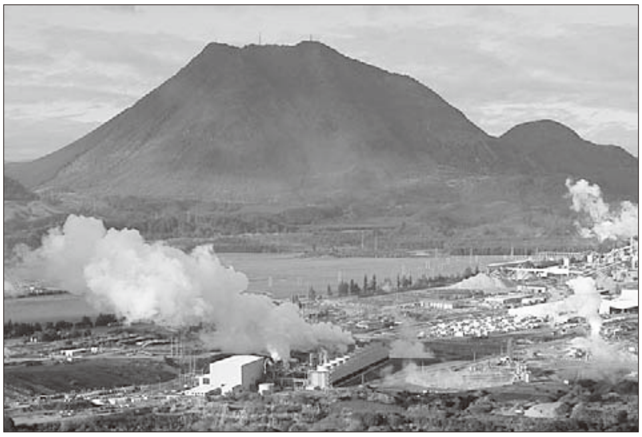


Fig.4 External view of steam separation system

2.2 Kawerau Geothermal Power Station[3]

The Kawerau Geothermal Power Station is located in the northeast region of the North Island of New Zealand. The plot of land on which the power station is built is the site of a former runway and therefore has a flat rectangular shape of 150 m (W)×350 m (L). A double-flash type steam separation system is located on the same area besides the power generating facility, which receives a two-phase flow, i.e., a mixture of geothermal steam and hot water, and supplies steam to the turbine. Figure 3 shows a bird's-eye view of the Kawerau Geothermal Power Station.

The steam separation system incorporates a design for supplying steam that is as clean as possible to the turbine. The steam separation system employs highly efficient separators, and also a scrubbing system for removing scale components such as silica that are likely to dissolve in small amounts of mist contained in the generated steam. With the scrubbing system, water is sprayed inside the steam piping, small amounts of mist are captured and discharged at drains located along the steam piping, and the scrubber ultimately removes mist and other moisture from the system. Figure 4 shows the external appearance of the steam separation system.

The Kawerau Geothermal Power Station employs a large geothermal turbine having the world's largest class last-stage blade of 798 mm, and realizes a rated output of 95.7 MW and maximum output of 113 MW. The power station was completed and handed over to the customer in August 2008, which is a short period of only 22 months from the signing of the contract in November 2006.

3. Geothermal Binary Power Generation System

As a result of rapidly rising fuel prices, measures enacted to prevent global warming, restrictions on CO_2 emissions and the like, there is increasing interest in promoting the utilization of renewable energy sources. Among renewable energy sources, geothermal power generation systems are basically not affected by weather and time of day, and are capable of stable power generation. In the flash-cycle geothermal power generation projects that Fuji Electric has been involved to date, high temperature and high pressure geothermal steam is necessary, and ensuring the geothermal resources capable of power generation had been one of the issues.

Figure 5 shows the conceptual applicability of geothermal power generating systems based on the geothermal fluid temperature and the desired output capacity. The conventional flash-cycle method is used in power generating systems where the geothermal fluid is at a high temperature and the output capacity is large, while binary power generation is used in power generating systems where the geothermal fluid temperature is low and the output capacity is small.

Geothermal binary power generation systems use geothermal fluid as a heat source to vaporize a working fluid having a lower boiling point than water, and the vaporized working fluid drives a turbine to generate power. Since a low-boiling-point working fluid is used, sufficient pressure can be obtained for power generation even when a relatively low temperature geothermal fluid is used as the heat source. Figure 6 shows a schematic diagram of a geothermal binary power generation system.

In order to expand its product series of geothermal power generation systems, Fuji Electric plans to commercialize a geothermal binary power generation system, and carried out demonstration tests in cooperation with the Kirishima Kokusai Hotel in Kirishima City of Kagoshima Prefecture from August 2006 through October 2009. The results of the demonstrated operation showed that, the rated power of 190 kW and maximum power of 220 kW were achieved under continuous operation conditions as planned. Table 2

Fig.5 Scope of geothermal power generation system applications

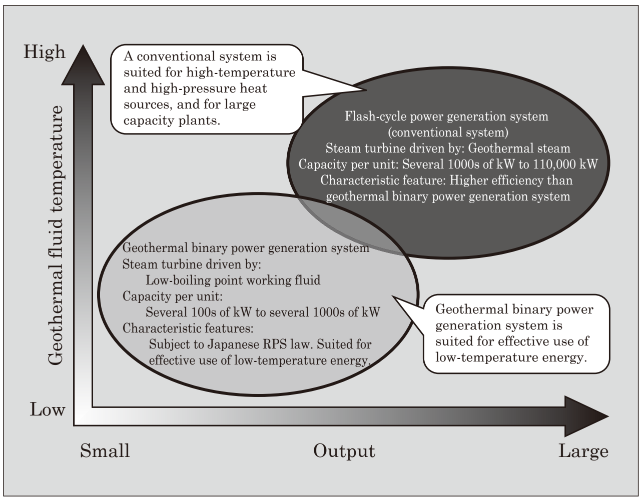


Fig.6 Conception diagram of geothermal binary power generation system

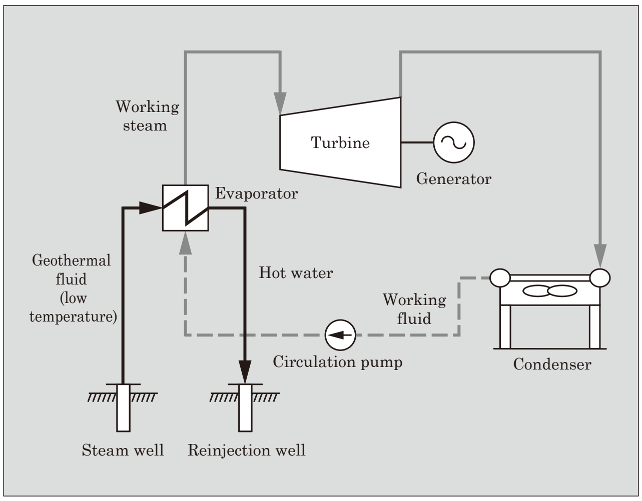
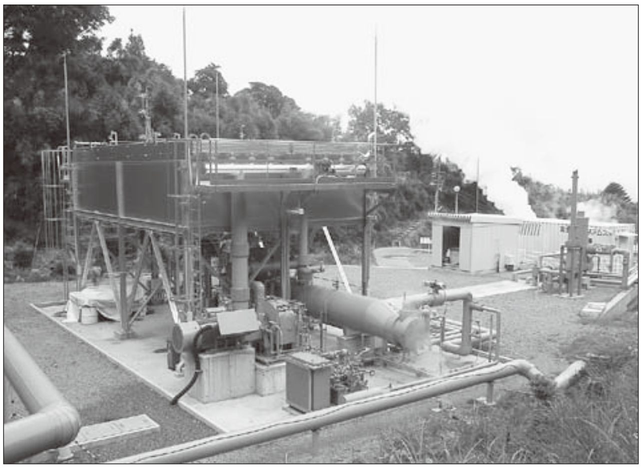


Table 2 Main specifications of geothermal binary power generation system demonstration plant

Heat source	135 °C geothermal (hot spring) steam
Output (capacity)	Rated: 190 kW (Max.: 220 kW)
Working fluid	Isopentane (C_5H_{12}, boiling point 28 °C)
Cooling method	Air-cooled

Fig.7 Geothermal binary power generation system demonstration plant



lists the specifications of the demonstration plant and Fig. 7 shows the external view of the equipment.

Based on the results of a survey of market, development for commercialization was carried out with a standard 2,000 kW as the first step. Table 3 lists the main specifications and Fig. 8 shows the external appearance.

A pentane system, which is in a liquid phase at room temperature and normal pressure, was selected as the working fluid considering easier handling during charging to and extracting from the equipment. Isopentane was used as the working fluid for the demonstration plant, however normal pentane is selected as the working fluid of the 2,000 kW commercial unit considering handling difficulties of isopentane during extremely hot period. Because it is often difficult to secure enough cooling water in geothermal sites such as the mountainous areas, the air-cooling system is used.

The first unit of this commercial geothermal binary power generation system is slated to be launched in 2010. The series with larger output is also planned for overseas markets.

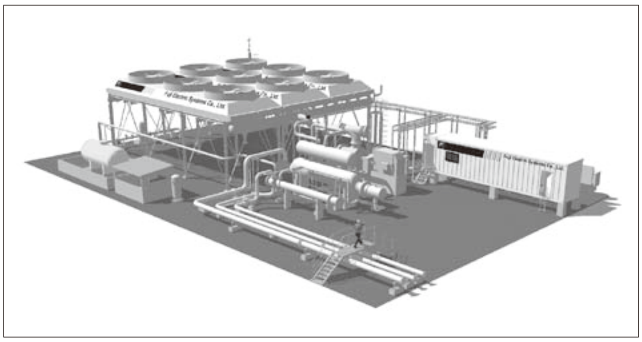
4. Steam Purity Monitoring System

Geothermal steam contains various dissolved components, such as chloride ions, silica, that originate in the hot water and are a major cause of turbine corrosion and scale deposition. Measurement of the dissolved components in geothermal steam is typically performed once every several months. Under such circumstances, the deposition of scale on the turbine is normally be in progress and often affects the tur-

Table 3 Main specifications of commercial geothermal binary power generation system

Heat source	135 °C geothermal steam and geothermal hot water
Output (capacity)	2,000 kW
Working fluid	Normal pentane (C_5H_{12}, boiling point 36 °C)
Cooling method	Air-cooled

Fig.8 External view of 2,000 kW geothermal binary power generation system



bine performance even before such scaling will be found during a overhaul period. Moreover, recently, carryover of chemicals for the production wells treatment or pH adjustment of the hot water is also considered as the cause the steam properties to deteriorate. Therefore, a system has been developed to monitor impurities and gases in geothermal steam periodically so that plant operators can know expected conditions of the turbine and possible problems in advance.

4.1 Overview of steam purity monitoring system

As shown in Fig. 9, this device is configured from a steam purity monitor and a diagnosis system, and the functions of each area described below.

(1) Steam purity monitor

The steam purity monitor enables control items pertaining to the required steam properties be measured in real-time. Figure 10 shows a schematic diagram of the steam purity monitor. The following six items can be analyzed automatically.

(a) pH
(b) Silica concentration
(c) Chloride ion concentration (calculated value)
(d) Specific conductivity
(e) Cation conductivity
(f) NCG concentration

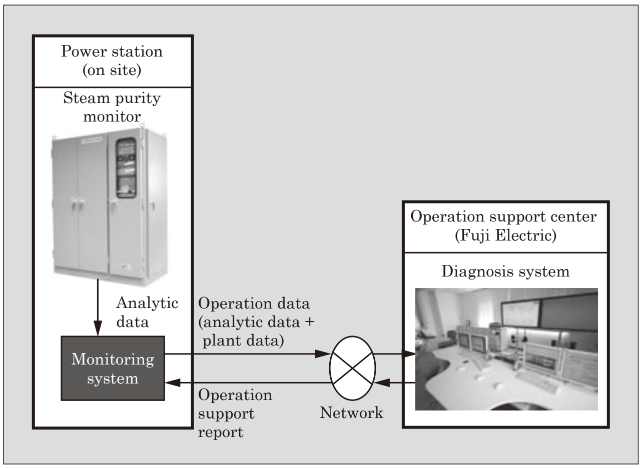
(2) Diagnostic function

The diagnostic function uses statistical techniques to diagnose geothermal steam properties, and in addition to diagnosing abnormal conditions, also performs presymptomatic diagnoses of the possibility of scale deposition. Data obtained from automated measurements is used to evaluate the properties of steam at that time.

(3) Operation support function

The operation support function provides the requi-

Fig.9 Block diagram of geothermal steam purity automatic analyzing device



site guidance for improving the steam properties and for improving operation to prevent scale deposition and corrosion inside the turbine. Based upon online measurements of the amount of gas, the operation support function also provides guidelines for the appropriate series to be operated in a gas extraction system.

4.2 Effect of steam purity automatic analyzing device

The introduction of a steam purity automatic analyzing device and the constant monitoring of scale and corrosion components are expected to produce the following effects.

(1) Improvement of plant utilization rate

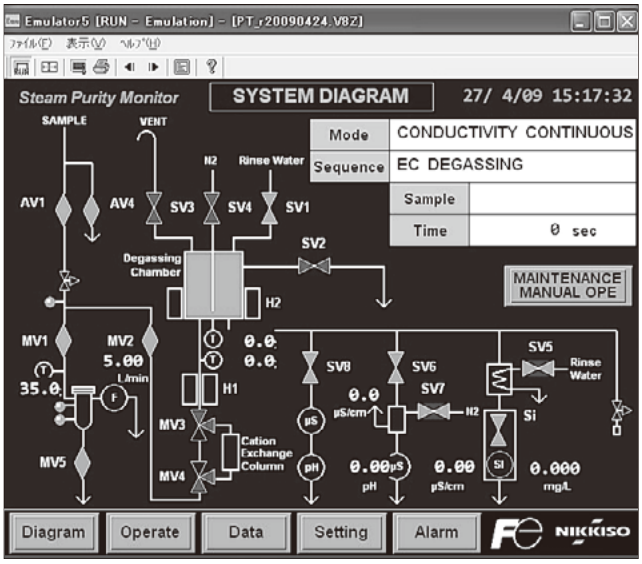
Plant operation support reports are provided so that the condition of steam generating equipment can be ascertained. Additionally, the implementation of measures to prevent scaling and the estimation of the extent of turbine scale deposition enable longer time intervals between turbine overhauls.

(2) Economic operation of gas extraction system

According to the change in quantity of gas, Fuji Electric provides the appropriate turbine series to be operated, enabling the amount of steam consumption and the amount of power consumption to be reduced.

This system, after undergoing demonstration testing for six months in a geothermal power station in Japan, has been delivered with the commercial Unit 1 to the Nga Awa Purua geothermal power station in New Zealand, and trial operation began as of January 2010. In addition, this system is also scheduled to be delivered to a geothermal power station in Iceland in 2010.

Fig.10 Schematic diagram of steam purity monitor



5. Postscript

Fuji Electric has delivered sixty units of geothermal power generation facilities with a total capacity of 2,324 MW, and has also gained market recognition as a contractor of geothermal power plants. In addition to this track record of success, Fuji Electric has also added a geothermal binary power generation system capable of using low-temperature geothermal resources to its product lineup, and is confident of being able to satisfy a wide range of customer needs.

From a global perspective, research of EGS (Enhanced Geothermal System) that generates geothermal steam artificially is proceeding in such countries as the United States, Australia and Germany in addition to power generation from the conventional geothermal resources. Fuji Electric is also monitoring industry trends in order to contribute to the utilization of power from this new geothermal resource.

Fuji Electric remains committed to expanding the utilization of power generated from geothermal resources, and will continue contributing to efforts to reduce CO_2 emissions, which are a cause of global warming.

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Recent Technologies for Steam Turbines

Kenji Nakamura Takahiro Tabei Tetsu Takano

ABSTRACT

In response to global environmental issues, higher efficiency and improved operational reliability are increasingly being requested for steam turbines, essential equipment for thermal power generation. By increasing the temperature and pressure of the steam turbine operating conditions, more efficient power generation is realized, and in order to realize a turbine applied with the higher temperature conditions of 700 ˚C for the future, Fuji Electric is participating in the METI-sponsored development of advanced ultra-supercritical power generation, and is evaluating and verifying the reliability of materials used for high-temperature valves. In addition, for geothermal steam turbines, Fuji has developed surface coatings and other technology for enhancing corrosion resistance in order to improve reliability. Fuji is also moving ahead with the development of geothermal binary power-generating turbines that utilize a low boiling point medium.

1. Introduction

In recent years, environmental measures such as for reducing CO_2 emissions have been implemented on a global scale. Demand for more efficient thermal power has also intensified than ever. Higher efficiency is also being required of steam turbines, which are a mature energy conversion technology. Improved reliability, operability and ease of maintenance are requested simultaneously in order to ensure the continued long-term supply of stable power.

To increase the inlet steam temperature and improve efficiency significantly throughout a plant, Fuji Electric is working to develop materials that have higher strength, longer life, and are capable of withstanding usage in higher temperature steam than in the past, and is also developing application technology. Meanwhile, to improve the efficiency of the steam turbine itself, Fuji Electric is also developing and commercializing new technology for the turbine blade row and steam seal areas which have a large effect on efficiency.

Fuji Electric manufactures not only conventional steam turbines, but, in the field of renewable geothermal energy, has also manufactured and delivered more than 60 geothermal turbines over a period of nearly 50 years, beginning with the construction of a practical geothermal power plant in 1960. At present, Fuji Electric is counted among the top manufacturers worldwide. This paper also introduces the technology in this field.

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2. Improved Efficiency Through Utilization of High-Temperature High-Pressure Steam Conditions

2.1 High-temperature materials technology for major components

The long-term rise in energy prices and heightened awareness of environmental issues, coupled with CO_2 emissions restrictions, are factors prompting improvement in plant thermal efficiency. New turbines tend to employ high temperature and high pressure conditions. In the large capacity turbines currently being manufactured, steam conditions of 25 MPa (abs) main steam pressure, 600 °C main steam temperature, 620 °C reheat steam temperature have become mainstream.

Figure 1 shows the high-temperature materials technologies used in the major components of a large capacity steam turbine, and these items are described in detail below.

(1) Development of materials for high-temperature turbines

In the pursuit of higher temperatures, high reliability can be ensured by using advanced materials having excellent high temperature creep characteristics, without changing the basic turbine structure. In particular, in a 600 to 620 °C class steam power plant, advanced 12% Cr steel is used in the rotor (Fig. 2), a main component, and as the casing material (Fig. 3).

(2) Overlay welding

Rotors made from 12% Cr steel are used in the high-pressure and intermediate-pressure rotors that require high-temperature strength. For the following reasons, however, these rotors have poor friction characteristics compared to low-Cr steel rotors.

(a) Thermal conductivity is low.

(b) Oxide film is difficult to form on the surface.

Fig.1 High-temperature materials technology for large-capacity steam turbines

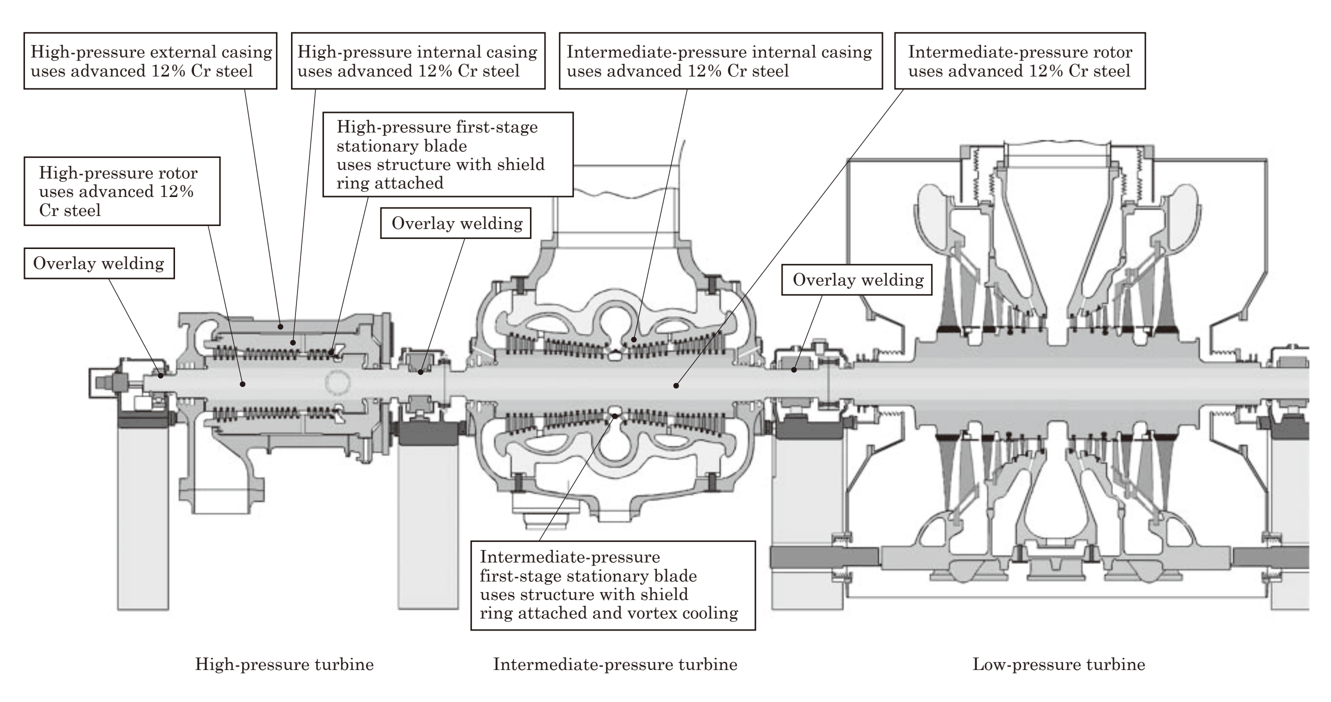


Fig.2 Rotor prototype under construction

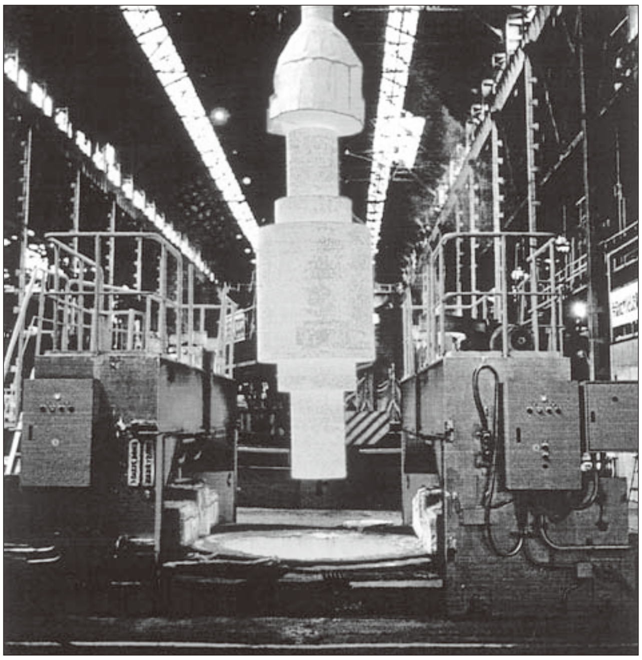
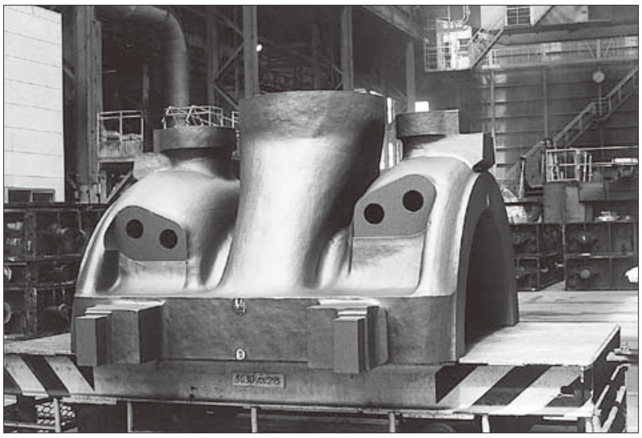


Fig.3 Intermediate-pressure internal casing under construction



(c) Carbonized compounds are formed easily from the carbon in the lubricating oil and Cr.

As a countermeasure, low Cr steel is overlay-welded onto rotor surfaces in the journal area, the thrust collar area and the pass-through areas of the bearing pedestals, and Cr content in the rotor surface layer is set to an amount equivalent to that of 1% Cr steel to prevent damage to the axle from burn-in or scraping.

(3) Stationary blade with shield ring (Fig. 4)

In the first stage of high-pressure and intermediate-pressure turbines, a stationary blade with a shield ring is employed so the high temperature inlet steam does not make direct contact with the rotor surface. Low temperature steam, after having passed by the initial-stage stationary blade, flows toward the rotor surface so that the rotor surface is maintained at a low temperature and the increase in creep life consumption is suppressed.

(4) Vortex cooling (Fig. 4)

In the first stage of a double-flow type intermediate-pressure turbine, a portion of the reheat steam from the tangential steam flow inlet open to the shield ring forms a swirling flow and is discharged, and vortex cooling is used to cool the rotor surface. In intermediate-pressure turbines, vortex cooling combined with the aforementioned shield ring prevents the rotor surface from reaching a high temperature and suppresses an increase in creep life consumption.

2.2 Elemental technical development for 700 °C class high-temperature valves

For the practical application of advanced-ultra supercritical (A-USC) pressure thermal power generation technology, with which thermal efficiency is expected to be dramatically higher than conventional coal-fired power generation, a large capacity boiler turbine system for use in the power industry and capable of withstanding steam conditions of a steam temperature of 700 °C or higher and steam pressure of 24.1 MPa or higher must be developed. To develop this elemental technology, in 2008, the Japanese Ministry of Economy, Trade and Industry began funding project grants related to the development of practical elemental technology for A-USC thermal power generation. Fuji Electric is working to develop high-temperature valve elemental technology, one of the items for technical development in this grant-aided project.

(1) Overview of elemental technical development

A high-temperature valve is installed at the inlet to a steam turbine, and plays an important role in operations related to the safe running and stopping of the steam turbine, i.e., steam flow control and emergency shutdown when a protection device has been activated, and is required to be highly reliable at all times. Because it is exposed to high temperature steam, the sliding part is processed with a surface hardening

Fig.4 Stationary blade with shield ring and vortex cooling at intermediate-pressure turbine inlet

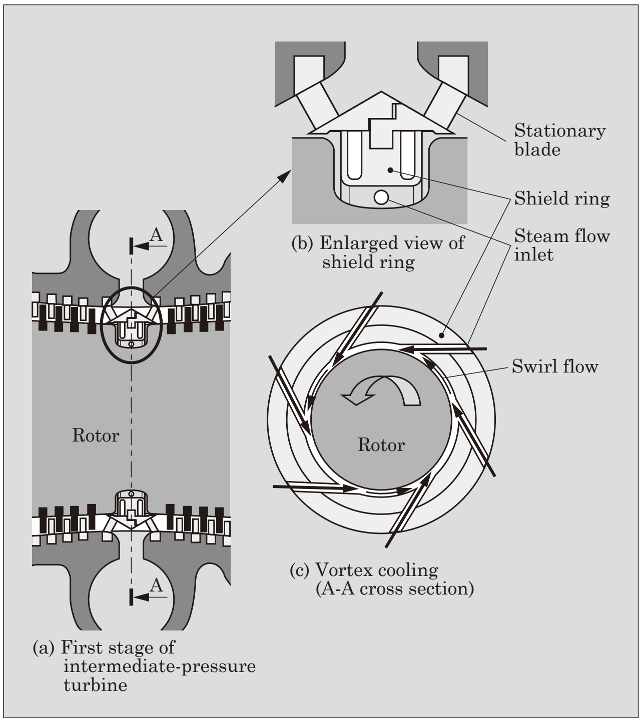


Fig.5 High-temperature wear tester

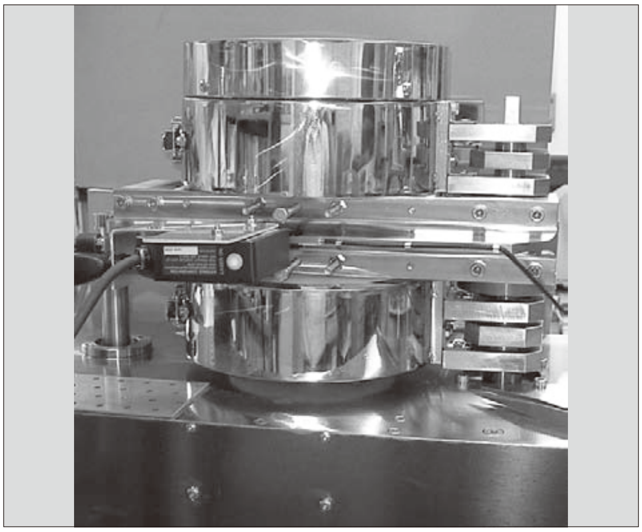
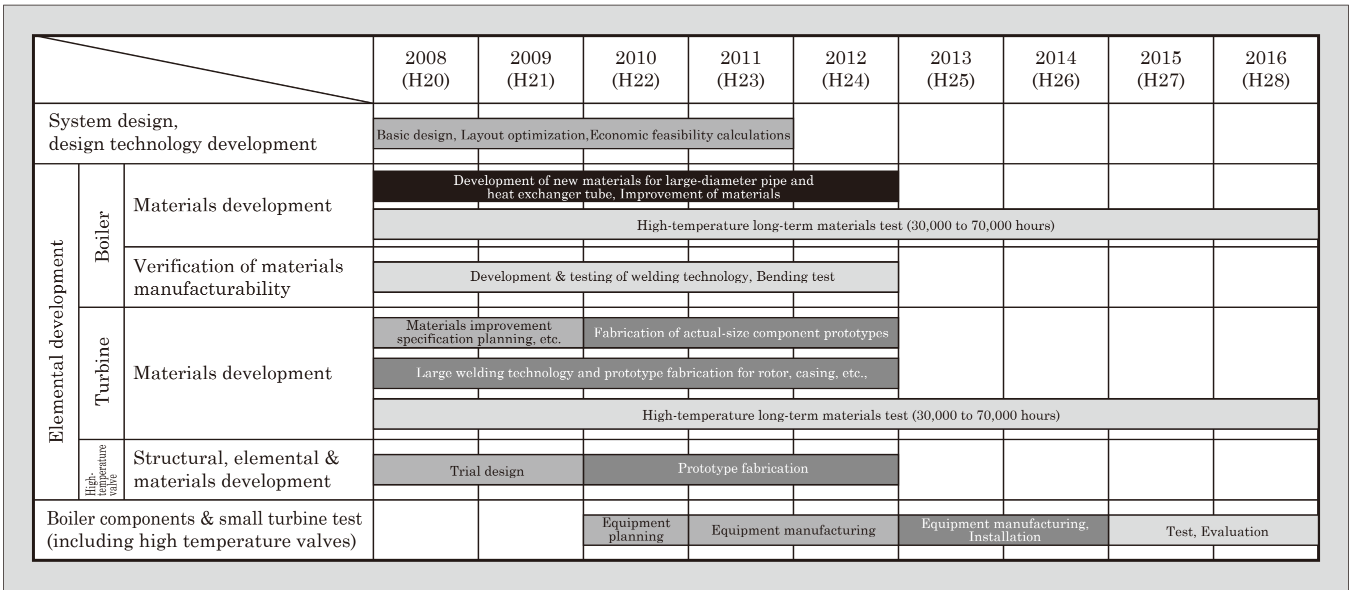


Fig.6 A-USC development schedule



treatment that results in excellent oxidized scale resistance, wear resistance, seizing resistance and sliding resistance. In a high-temperature A-USC plant environment where the steam temperature is 700 °C or higher, in consideration of material strength, nickel-based alloys must be used as the main material. The friction characteristics and high-temperature oxidation characteristics of nickel-based alloys and surface-hardened conventional materials have not yet been clarified.

Fuji Electric has built a high-temperature wear tester (Fig. 5), and by measuring the amount of wear, has verified wear resistance and evaluated friction characteristics. Additionally, steam oxidation testing is being considered for evaluating the resistance to oxidized scale.

Based on the results of each verification test, materials are selected for the sliding parts and airtight parts, and this step leads to the design of the gap (clearance) in each sliding part.

(2) Development schedule

In this development, as a Japanese national grant-aided project, domestic Japanese turbine and boiler manufacturers joined forces with research institutions and began in fiscal year 2008 to advance elemental technologies development, materials development and system design according to the schedule shown in Fig. 6. Fuji Electric is in charge of consolidating development of high-temperature valves and plans to construct a full-size inlet valve and, beginning in 2013, to verify its functionality under steam conditions that are the same as actual conditions by performing boiler components and small turbine test.

3. Improved Efficiency Through Development of Elemental Technologies

3.1 Advanced small LP blades

By applying the design techniques for advanced low pressure (LP) blades developed for general-purpose large-size steam turbines to the design of LP blades of length of 560 mm or less, a series of high-efficiency small LP blades that aim to improve performance significantly has been developed (Table 1).

The main features of Fuji Electric's series of advanced small LP blades are as follows.

(a) Higher efficiency from a design that utilizes the latest CFD (computational fluid dynamics) technology

(b) Realization of a more compact size by increasing the load on each stage of the LP blades, and reducing the total number of stages of turbine blades

(c) High reliability based on extensive operating experience with prior-generation blades

Moreover, the application of this series of advanced small LP blades to geothermal turbines was considered during the planning stage, and in addition to the abovementioned characteristics, the following characteristics are also provided.

(a) High reliability as a result of materials selection and strength design for a corrosive environment

(b) Use of simple inverted T-shaped root at all stages to prevent deterioration of strength and reliability due to stress concentration

(c) Higher efficiency by attaching a shroud to all stages to reduce leakage loss at the blade tip

Figure 7 shows a rotor using a 555 mm blade, which is the largest size blade in the series.

Table 1 High-efficiency small LP blade series

50 Hz-use (nominal circular area)	60 Hz-use (nominal circular area)
555 mm blade (3.2 m^2)	462 mm blade (2.2 m^2)
487 mm blade (2.5 m^2)	406 mm blade (1.7 m^2)
348 mm blade (1.6 m^2)	290 mm blade (1.1 m^2)

3.2 Seal technology

To improve the performance of steam turbines, in addition to the aforementioned turbine blade development, technical development for improving efficiency is also needed.

Fig.7 Rotor using 555 mm blade (during implementation of rotational vibration test)

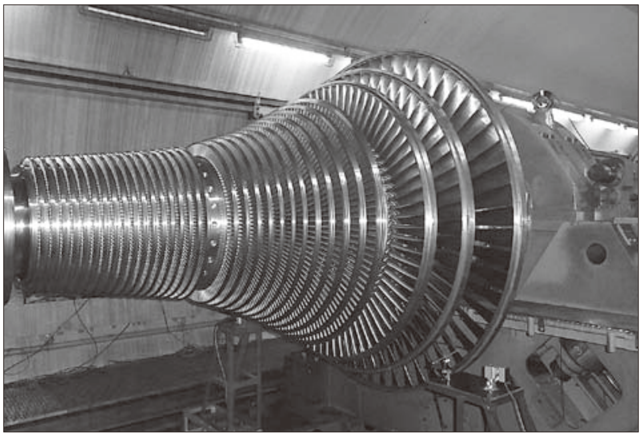
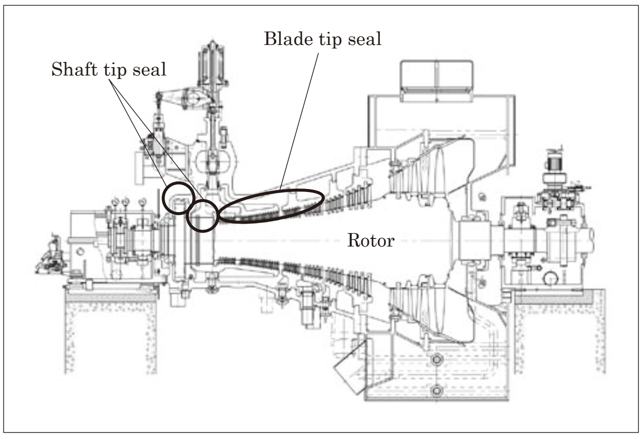


Fig.8 Locations where seal technology is applied



A clearance must be provided between the rotating body and stationary body in a steam turbine so that, throughout all operation zones, i.e., startup, normal operation and stopping, the rotating and stationary bodies will not contact each other. Consequently, the clearance must be larger than that required for normal operation, and this had become a limiting factor for improving efficiency. By applying the following seal technologies, the amount of steam leakage at the steam turbine blade tip and at the shaft end seal is reduced, efficiency is improved and reliability during operation is ensured as shown in Fig. 8.

(1) Brush seal

A brush seal is an aggregation of wear-resistant wires installed on the stationary side of the seal area. Figure 9 shows a verified example in which a portion of the seal fin of the shaft tip seal area has been replaced with a brush seal. With the wires of a brush seal, the effect from contact with a rotating body is much smaller than in the case of a conventional seal fin, and a minimum clearance can be maintained during operation.

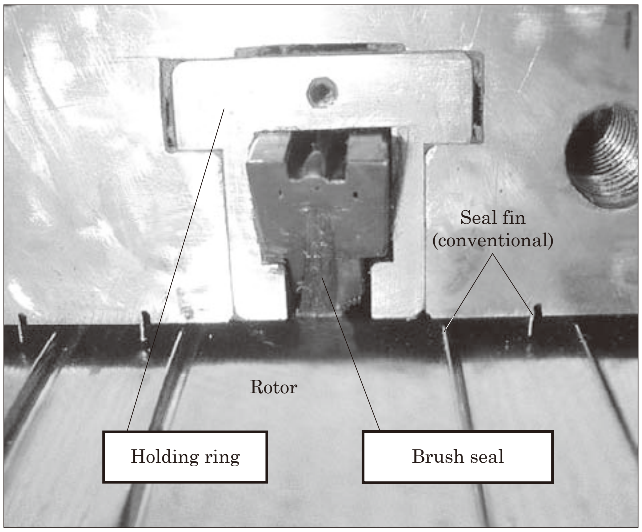
Assembly verification tests, the wear resistance tests and leakage characteristic tests have been completed, and brush seals are beginning to be used in steam turbines at power plants in Japan.

(2) Abradable coating

Abradable coating is a coating applied to free machining metal on the stationary-side inner surfaces that face the seal fin of the rotating side of the blade tip and shaft tip seal areas. Figure 10 shows a schematic diagram of a packing gland to which an abradable coating has been applied. The abradable coating reduces the effect of contact with the seal fin during operation of the steam turbine. Moreover, because the seal fin cuts into to the coating material on contact, the optimal and minimum clearance can be formed during operation.

The wear characteristics resulting from a contact test between the coating material and the seal fin have been verified, and abradable coating will be used in practical applications as of 2010.

Fig.9 Brush seal



4. Utilization of Renewable Energy

Geothermal energy is a renewable clean energy source, and its utilization is expected to increase in the future to help prevention of global warming.

4.1 Geothermal turbines

Geothermal steam contains various corrosive chemical substances such as chlorides, sulfates, hydrogen sulfide and carbon dioxide. Even after geothermal steam is processed with a separator (steam separator) and flasher (vacuum evaporator) to remove those substances, the amount of corrosive components contained in the steam entering the turbine is 100 to 1,000 times that of a conventional steam turbine. Technology to improve resistance to such types of corrosion as whole surface corrosion of components, stress corrosion cracking (SCC), corrosion fatigue, erosion-corrosion and the

Fig.10 Abradable coating

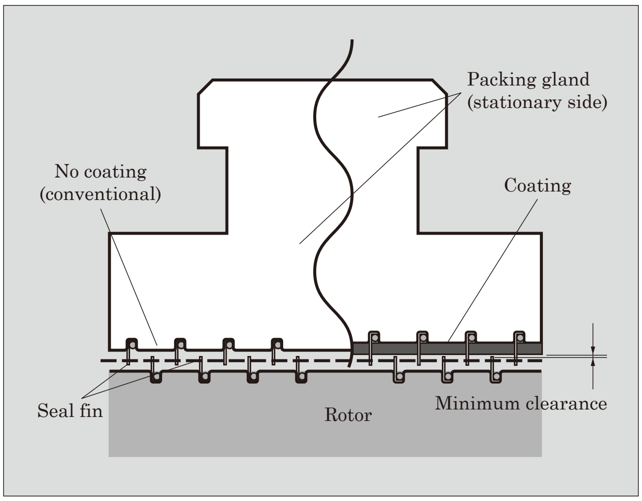


Fig.11 Application of thermal spray coating to rotor

like is needed. As the main techniques for addressing these issues, coating and shot peening techniques have been developed.

(1) Coating technology

Coating is a technique in which a thermal spray coating is applied to the surface of components in order to limit the whole surface corrosion and erosion-corrosion of components, such as the rotor and stationary blade holder, which are exposed to a highly corrosive geothermal steam flow (Fig. 11).

Basic testing at laboratories and corrosion testing at geothermal sites have been carried out, and coating technology for applying WC-CoCr-based thermal spray material with a HVOF (High Velocity Oxy-Fuel) thermal spray has been established and is being applied to actual turbines as a technique providing excellent corrosion resistance and erosion-corrosion resistance.

(2) Shot peening technology

Shoot peening technology has been developed and applied to actual turbines. With shot peening, high stress areas of the rotor are struck with a steel ball, generating compressive residual stress on the component surface and improving the resistance to SCC and corrosion fatigue.

The results of SCC tests and corrosion fatigue tests on blade materials and rotor materials treated with shot peening revealed significantly improved resistance.

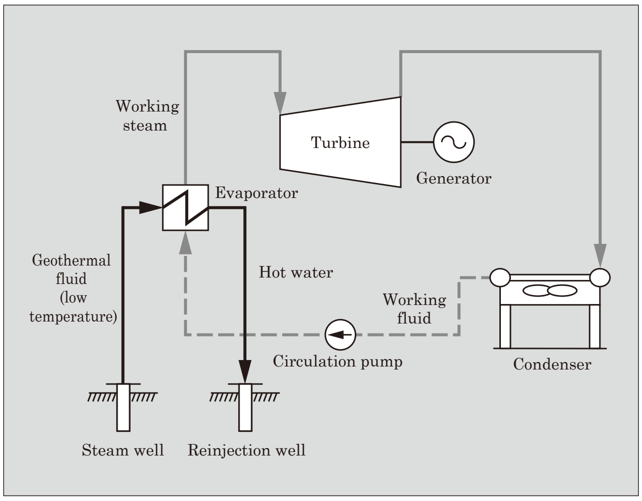
4.2 Turbine for geothermal binary power generation

In recent years, binary power generation systems, capable of recovering power from not only high-temperature geothermal wells but also from low-temperature geothermal energy sources that had not been utilized previously because of the difficulty of extracting energy, have been attracting attention due to the large number of available locations (Fig. 12).

Because low-temperature thermal energy has a low heat drop and is difficult to extract, it is often discarded without being used. In order to recover energy from low-temperature thermal energy, a medium having a lower boiling point than conventional steam vapor must be used. To commercialize power generation that uses low-temperature thermal energy, the technical challenges specific to low-boiling point media must be identified. That is, methods for analyzing and evaluating their (1) energy characteristics, (2) fluid characteristics, (3) strength characteristics, (4) seal characteristics and the like, must be developed.

In binary power generation, the main machinery is a steam turbine, and a low-boiling point medium is used as the working fluid. Accordingly, development is moving forward to meet the following two technical challenges.

Fig.12 Geothermal binary power generation system conception diagram



(1) Design of optimal flow path and blade row that uses a low-boiling point medium

To optimize the flow path shape, including the blade, the design methodology must be re-established and re-verified. For low-boiling point media that is completely different from steam vapor, design tools optimized for characteristics based on thermal dynamics, fluid dynamics and strength of materials analyses will be developed, and design techniques for the flow path shape and blade row design will be established.

(2) Development of seal technology

Because the low-boiling point medium used is flammable, there must be no leakage to the outside. Typically, however, the seal structure used in steam turbines is susceptible to leaks. Therefore, new seal structures capable of completely preventing the leakage of internal fluids are being developed and the technology is being established and verified.

5. Postscript

Fuji Electric has improved the reliability and performance of steam turbines, including geothermal turbines.

Fuji Electric is committed to development in order to continue to provide high-performance, highly-efficient and easy-to-use steam turbines.

Recent Technologies for Rotating Machines

Akihide Mashimo Akinobu Nakayama Hiromichi Hiwasa

ABSTRACT

For mid-sized thermal power plants, Fuji Electric has completely developed and shipped 300 MVA type rating air-cooled turbine generators, which are the world's largest capacity class. In order to realize a large-capacity air-cooled generator, the ventilation behavior inside the generator must be understood in detail. Therefore, computational fluid calculations of ventilation flow analysis were performed for important regions, and the cooling effect was sufficiently improved with the optimized entire ventilation based on ventilation network calculations that reflected those results. Also, for the 3,000 kW-class of direct-drive permanent magnet generators for wind power generation, the method for cooling the interior of the generator at locations closer to heat-generating parts and the arrangement of magnets on the rotor to reduce cogging torque were designed.

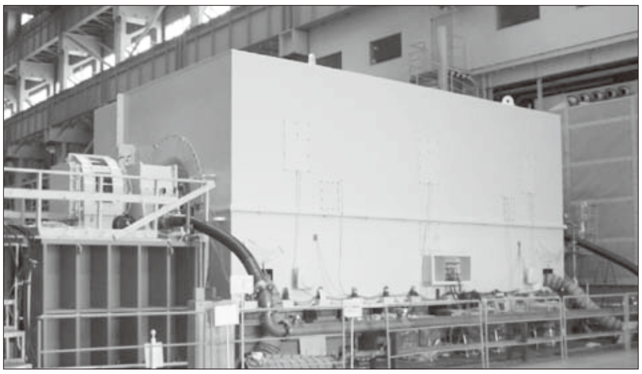
1. Introduction

Rotating machines are devices that convert electrical energy into mechanical energy, or conversely, mechanical energy into electrical energy. The operating principles of such machines were discovered in the mid-19th century, and although this is a mature machine technology, improvements in the materials, design technology and manufacturing methods of rotating machines are still being implemented in order to satisfy various needs in the market.

Recently, in the thermal power sector, there is increased market need for power generating facilities with improved economic efficiency, ease of maintenance, operability and the like for medium-scale thermal power and combined-cycle geothermal power generation facilities. Fuji Electric has a history of working to increase the capacity of air-cooled turbine generators that have excellent maintainability, and, in contrast to hydrogen-cooled turbine generators, do not require a hydrogen gas supply system or a hydrogen gas seal system. Recently, a 300 MVA-rated air-cooled turbine generator, the largest capacity class in the world, was designed, manufactured, subjected to factory tests and then shipped, and this paper introduces the latest technologies deployed in the generator.

In addition, natural energy is also attracting attention for its potential to reduce greenhouse gas emissions. So that wind power can contribute positively to this goal, a permanent magnet generator for wind power is being developed, and details of a prototype expected to be completed during 2010 are also presented herein.

Fig.1 Appearance of 300 MVA air-cooled turbine generator



† Energy Solution Group, Fuji Electric Systems Co., Ltd.

2. Large-Capacity Air-Cooled Turbine Generator

2.1 Specifications and design

Figure 1 shows the appearance of a 300 MVA-rated air-cooled turbine generator, and Table 1 lists its main specifications.

The design of this turbine is based on the reliable technology of Fuji Electric's standard series of air-cooled turbine generators, with the addition of new technologies in order to increase the capacity.

(1) Generator construction

Table 1 300 MVA air-cooled turbine generator ratings

Output		300 MVA
Voltage		16 kV
Power factor		0.85
Rotating speed		3,000 r/min
Frequency		50 Hz
Temperature rise		B-class (IEC 60034-1)
Coolant temperature		40 °C
Method of cooling	Stator	Indirectly air-cooled
	Rotor	Directly air-cooled in radial direction

As shown in Fig. 2, a generator is constructed from a rotor that rotates and is supported on the both sides by bearings, a stator and a stator frame. The turbine generator rotates at high speed and, in order to withstand the accompanying centrifugal forces, has a construction that is longer in the axial direction.

(2) Stator construction

The stator is a structure that elastically supports the stator core via a support plate in the stator frame and regulates the transmission of magnetic vibrations of the core toward the stator frame or foundation. Because larger capacities require a longer core length, the design is optimized for the number of support plates, support locations and the like.

(3) Rotor construction

Both the outer diameter and axial length dimensions of the rotor are close to the maximum size with which Fuji Electric has a proven track record, including applications of hydrogen-cooling. The bearing stand is designed to put an importance on minimal maintenance. Because of the long bearing span, evaluations of the critical speed and vibration were checked carefully, and the results were reflected in the design. As shaft lengths increase, a problem arises in which double frequency vibration occurs due to shaft deflection during processing, but by using the same machining processes as for large-scale hydrogen-cooled generators and the like, the double frequency component vibration is designed to reduce.

2.2 Ventilation and cooling

Indirect cooling is used for the stator winding, while direct radial cooling, in which a ventilation path is established in the radial direction of the conductor, is used for the rotor winding.

As shown in Fig. 2, the ventilation circuit is configured such that cooling air is fed from the axial fans at both ends of the rotor to each part, and at the middle portion of the stator core, cooling air flows from the outer diameter to the inner diameter of the stator core, while at the ends of the stator core, cooling air flows from the inner diameter to the outer diameter.

These ventilation and cooling designs reflect data obtained from Fuji Electric's prototype and actual air-cooled turbine generators as well as recent validation results of flow analyses. Several examples are discussed below.

(1) Optimization of stator ventilation

The stator ventilation circuit shown in Fig. 2 suppresses temperature rise at the middle portion of the stator core due to the increased axial dimension of the stator, and makes the temperature distribution uniform in the axial direction. So that the temperature distribution is made uniform, the allocation of zones in which cooling air flows from the outer diameter and zones in which the cooling air flows from the inner diameter, as well as the volume and speed of airflow, must be optimized. A solution to these problems requires not only the installation of a cooling duct, but also an understanding of the various parameters affecting the allocation of cooling airflows. One factor of them to consider is the dimensions and shape of the air gap inlet between the stator and rotor (Fig. 2). This air gap inlet, through which approximately half of the total airflow volume in the turbine passes, has a relatively large effect on the cooling air distribution, and the amount of pressure drop will vary according to its dimensions and shape. On the other hand, the

Fig.2 Generator cross-section and ventilation circulation

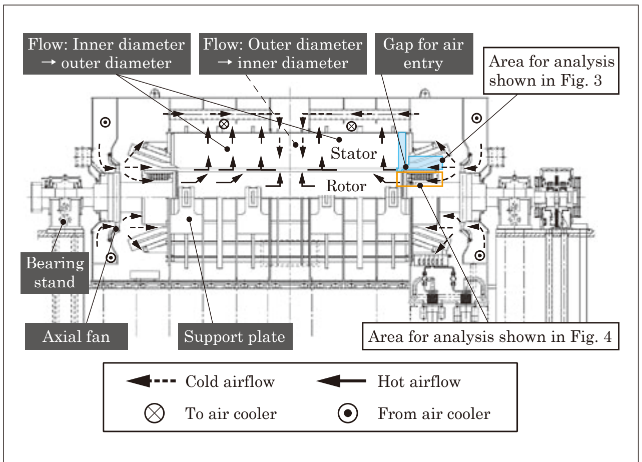


Fig.3 CFD analysis of gap for air entry

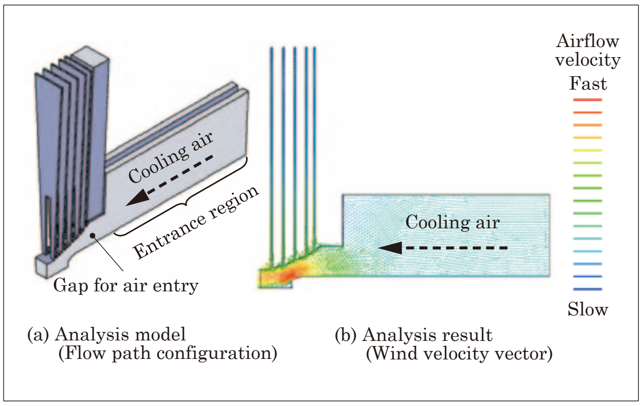
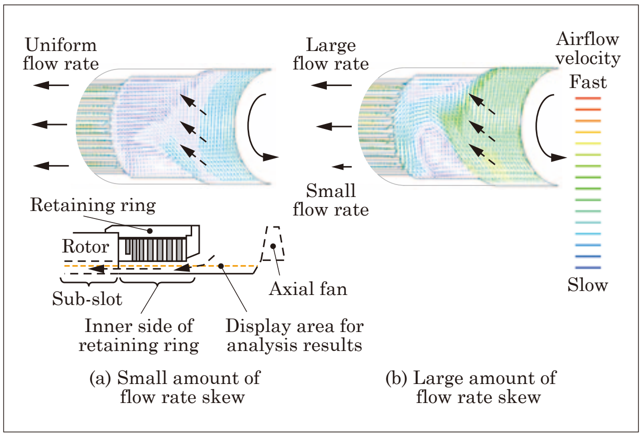


Fig.4 CFD analysis for inner side of retaining ring



parameters of air gap distance and inlet shape are determined based on such considerations as the electrical specifications, the reduction of flux concentration at the ends of the core, and the retaining ring dimensions necessary to realize sufficient strength, and a design that optimizes both the electrical specifications and the ventilation is needed.

Thus, the computational fluid dynamics (CFD) analysis shown in Fig. 3 was applied to understand the relation between the air gap inlet dimensions and shape and the pressure drop, and the results were incorporated into the ventilation network calculation to evaluate and optimize the total ventilation distribution. The validity of this network calculation was confirmed based on comparison to prior measurement data of the cooling airflow distribution.

(2) Optimization of circumferential cooling air distribution of rotor

The cooling air, after flowing from the axial fan through the space on the inner side of the rotor winding overhang and into a sub-slot, which is an axial-oriented ventilation path provided at the bottom of the slot, cools the rotor while flowing in the radial direction in each conductor, and is then exhausted to the outer diameter of the rotor. The rotation of the rotor and the blade angle of the axial fan cause the cooling air from the axial fan to flow in an oblique circumferential direction toward the inner side of the rotor end winding, and interference with structural objects on the inner side of the end winding may cause a skewed airflow distribution in some cases[1]. If the airflow skew is large, the flow rate of cooling air to the rotor conductor becomes non-uniform in the circumferential direction, and the distribution of conductor temperature will also become non-uniform. For this problem, CFD analysis was used to verify the relationship between airflow skew and such factors as the dimensions of the air gap at the inner side of the rotor end winding, the fan blade angle and the incoming flow rate, and to optimize the design.

As an example of such verification analysis, Fig. 4 shows the analysis results for models of having small amounts of flow rate skew (good example) and large amounts of flow rate skew (bad example). From the figure, it can be seen that the flow rate skew differs for the different conditions. Since the rotor ventilation is difficult to measure, optimization is realized based on verification using this type of flow analysis.

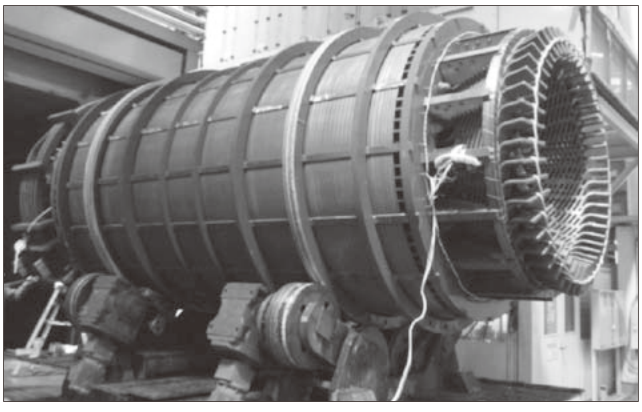


Fig.5 Appearance of stator

2.3 Application of global vacuum pressure impregnated insulation for stator windings

The global vacuum pressure impregnated (Global VPI) insulation technique is used for the stator winding insulation. With the Global VPI insulation technique, the stator winding and core are formed integrally and are impregnated with insulating resin, so that the resin can fill gaps between the core, winding and wedge. Since the application of this technique prevents the wedge and winding from becoming loose, maintenance to prevent loosening can be reduced. Also, as mentioned above, since there are no air gaps between the winding and core, the thermal transmission from the winding to the core improves, and benefits such as better cooling performance than in the case of single bar VPI can be realized.

In a turbine generator global VPI system, the following insulation technologies are used to ensure reliability.

(a) Highly heat-resistant epoxy resin
(b) Highly pregnable mica paper tape
(c) Internal electric field relaxation layer providing high voltage endurance and a long service life
(d) Thermal stress relaxation layer providing high cycle resistance

In the Global VPI process, factors such as resin viscosity and the ratio of curing agent used are strictly controlled and the status of the resin impregnation is constantly monitored and controlled with a monitoring system that monitors temperature, degree of vacuum, pressure when pressurized, and capacitance. Figure 5 shows the appearance of a stator after the Global VPI

Fig.6 Measuring results of airflow velocity in stator core ducts

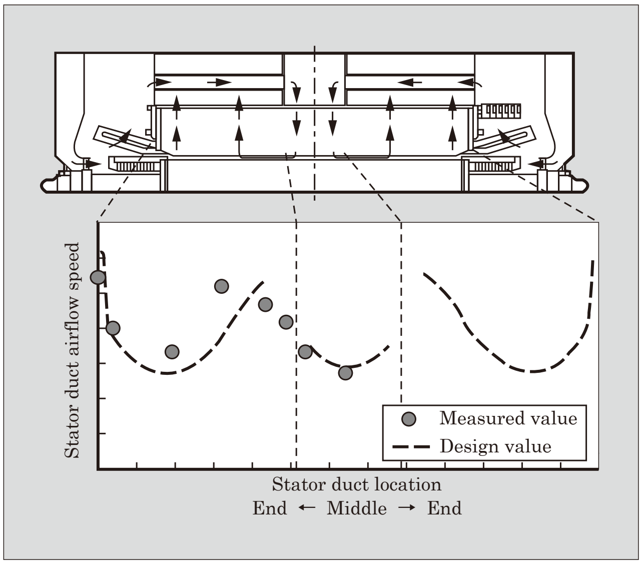
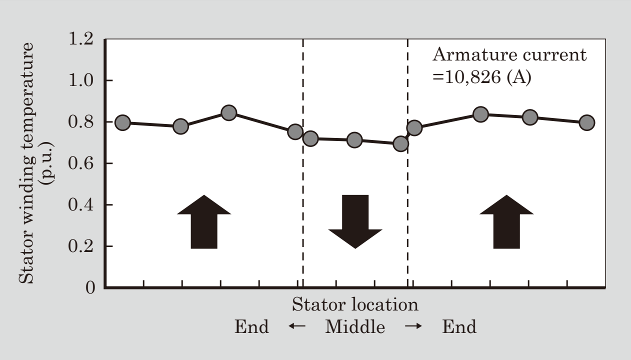


Fig.7 Stator winding temperature measurement results (short-circuit temperature rise test)



process at a factory.

2.4 Factory test results

In the factory test of this generator, performance characteristics for winding temperature rise, short-circuit ratio, reactance and the like were all satisfied, and at the ratings shown in Table 1, the favorable result of a 98.60% conventional efficiency was obtained.

Figure 6 shows the distribution of the stator core duct airflow speed measured with a small anemometer placed in the duct. Results nearly identical to the design values were obtained. Figure 7 shows the stator winding temperature measurement results in a short-circuit temperature rise test. The temperature distribution in the axial direction is uniform, and the realization of the aforementioned ventilation and cooling can also be verified from the winding temperature distribution.

For both stator and rotor windings, the value of winding temperature rise in an equivalent load temperature rise test sufficiently satisfied the limits specified by the IEC 60034-1 standard.

3. Development of Large Capacity Permanent Magnet Generator for Wind Turbine

3.1 Development specifications

At present, the mainstream wind power generation systems are speed-up gears for accelerating the rotating speed of wind turbines, and doubly-fed systems comprised of a wound-rotor induction generator and a power converter that supports the excitation capacity (see Fig. 8(a)). This method, although advantageous in terms of price due to miniaturization of the generator and converter, increases the number of parts such as speed-up gears and generator brushes that require maintenance. On the other hand, a direct drive system that does not involve speed-up gears is configured from a low-speed permanent magnet generator and a power converter (full converter) that supports the generating capacity (see Fig. 8(b)). With this method, rather than increase the system size, the ease of maintenance is improved and a wide variable speed range

Fig.8 Example of wind power generation system

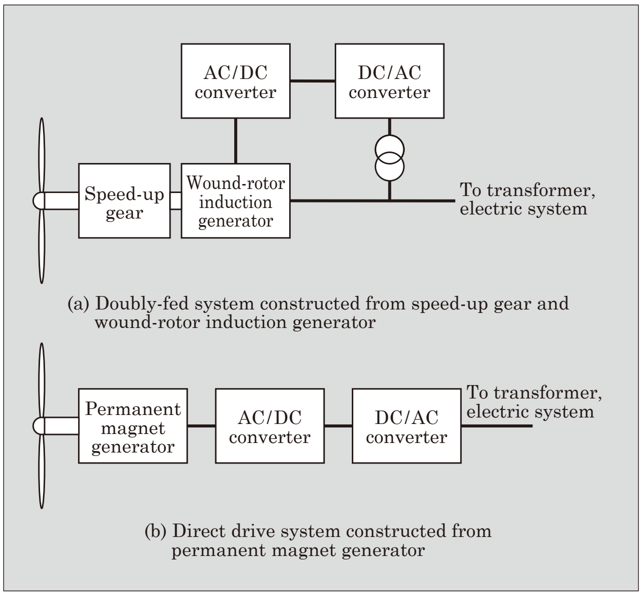
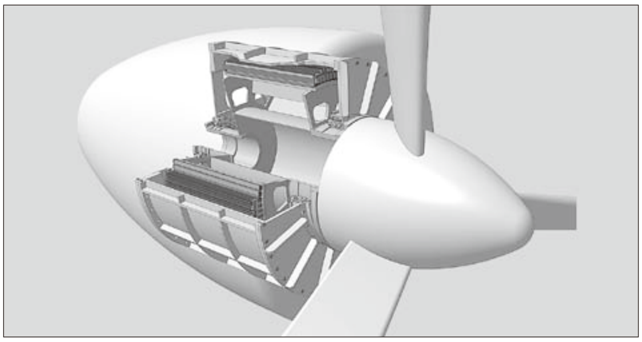


Table 2 Specifications of low-speed high-capacity permanent magnet generator for wind power use

Output	3,000 kW
Voltage	690 V
Efficiency	95%
Rpm	15 r/min
Temperature rise	F-class (IEC 60034-1)
Cooling method	Interior forced-air cooling

Fig.9 Generator cross-section (drawing of installation in a wind turbine)



can be handled with the full converter. There are also many operational benefits, such as, in particular, the improvement in power generating efficiency at areas of low wind speed(2). Additionally, to emphasize efficiency while avoiding an increasing in the size of the equipment, some permanent magnet power generating systems are also equipped with speed-up gears.

A low-speed high-capacity permanent magnet generator that uses a direct drive system under development by Fuji Electric has a 3,000 kW class output, which is the largest class for land-based wind power installations. The main development specifications are as shown in Table 2. Figure 9 is a three-dimensional

Fig.10 Schematic diagram of ventilation path inside generator

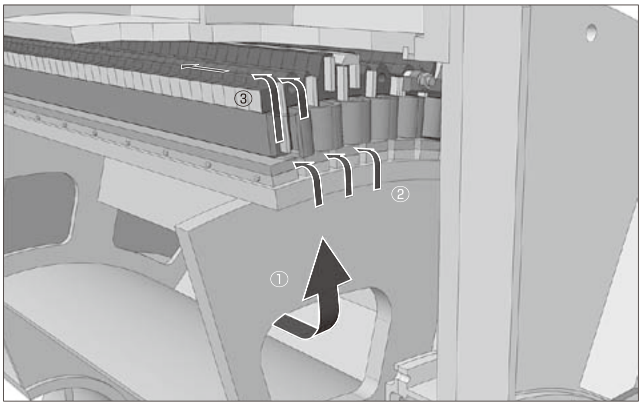
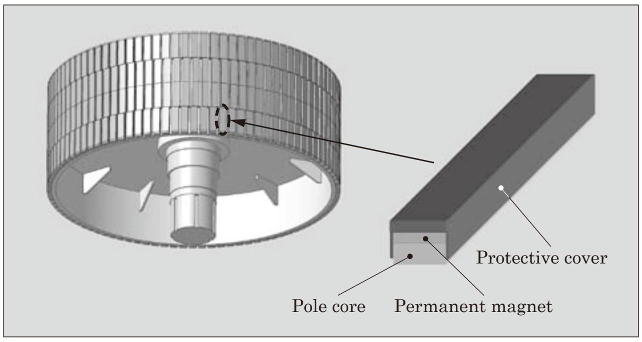


Fig.11 Rotor magnet arrangement



cross-sectional diagram of the generator.

3.2 Ventilation and cooling

One challenge for direct-drive generators is how to reduce their mass. The maximum allowable mass is determined by crane limitations during transport and lifting. Improving the cooling performance of the generator is an important factor in enabling the realization of smaller size and lighter weight.

Figure 10 shows the cooling air ventilation path inside a generator. The arrows indicate the flow path of the cooling air. With a permanent magnet generator, because the magnet is aligned continuously in the axial direction of the rotor, a cooling duct for the rotor cannot be provided easily. In this case, the gap between the rotor and stator is the only flow path for the cooling air, and the cooling effect will be low. Thus, a frame surface cooling method in which a fin is mounted on the frame and cooled with outside air is utilized often.

In this example, a space between the stator core and frame through which air can flow to cool the outer periphery of the stator core is provided (see the flow path ③ in Fig. 10). For cooling areas closer to heat-generating parts, a 30 to 40% improvement in cooling performance compared to frame surface cooling was confirmed theoretically.

3.3 Structure

A portion of the characteristic structure of a direct drive generator is described below.

(1) Winding structure

A concentrated winding structure is frequently used with small permanent magnet motors. Compared to the usual winding structure, a concentrated winding structure enables the coil ends to be shortened, contributing to lower winding loss and lower mass due to the shorter length.

(2) Rotor shape

The number of magnets arranged on a rotor is great many in the case of a large generator. Accordingly, the process of attaching the magnetized magnets one-by-one requires a tremendous amount of time.

To improve the assembly process, the magnets are attached in their non-magnetized state first, and are then magnetized at each magnetic pole location. Several of these split-pole magnets are then aligned in the axial direction so as to form a single pole. Arranging the magnetic poles in tiers results in a skew arrangement that is effective in reducing cogging torque as well as vibration and noise. Figure 11 shows an example skew arrangement with 4 tiers of split poles.

(3) Shaft structure

A hollow shaft is used, and workers have to cross over to the wind turbine side when performing maintenance on the shaft. Figure 9 shows the structure of a rotating shaft, and methods for fixing the shaft to the nacelle are also being studied.

4. Postscript

As the latest technologies for rotating machines, technologies used for increasing the capacity of existing air-cooled turbine generators and technologies used for developing new wind power permanent magnet generators have been described. Although rotating machine technology is said to be a mature technology, Fuji Electric intends to continue to develop and apply new technologies to new models as well as to existing models, and to manufacture rotating machines that meet market needs.

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Modular High-temperature Gas-cooled Reactor for Expanding Nuclear Heat Utilization

Futoshi Okamoto **Kazutaka Ohashi**

ABSTRACT

The modular High Temperature Gas-cooled Reactor (HTGR) is a new generation type of the reactor with the inherent safety. The HTGR can supply heat of very high temperature of approximately 950 degrees C compared to that of the Light Water Reactor. Its development has started in many countries as it has a potential to expand the nuclear heat utilization to reduce CO_2 emission. Fuji Electric is focusing on the R&D towards the practical use of the modular HTGR based on the technologies gained during the development of Japan's first HTGR, HTTR. Major activities of our R&D work are development of the heat resistant core restraint mechanism to maximize the effective core coolant flow rate, development of the core design method to improve its safety characteristics during an accident, and improvement of the evaluation method of the decay heat removal from the core only by the natural phenomena, such as natural convection, core conduction and radiation.

1. Introduction

The modular high temperature gas-cooled reactor (HTGR) has excellent inherent safety characteristics. The modular HTGR is also a next-generation reactor capable of utilizing high temperature heat (up to 950 °C), which is significantly higher than the 300 °C temperature that can be used with light water reactors (LWRs). This reactor can be used for high efficiency power production with a direct gas-turbine using high temperature heat, hydrogen production from water using a thermo-chemical process, or as a process heat supply using high temperature steam for chemical plants. Modular HTGRs are being developed in Japan and overseas and have the potential to expand the range of nuclear heat utilization, which previously had been limited to power generation, and as a primary energy source that also is an alternative to fossil fuels, to bring about a large reduction in the amount of CO_2 emissions.

This paper discusses the design concepts and features of HTGRs, domestic and international development trends, and Fuji Electric's involvement in HTGR development.

2. HTGR Characteristics

2.1 Comparison of HTGR and LWR structures

Figure 1 shows a nuclear reactor concept of a HTGR.

An LWR uses metal-clad fuel. An HTGR, however, uses ceramic-coated fuel particles that have a diameter of approximately 1 mm. This coating serves to contain the radioactive material generated by nuclear fission. The coated fuel particles have excellent heat resistance characteristics. Even after long-term operation at high temperatures exceeding 1,000 °C, or at the super-high temperature limit of 1,600 °C under accident conditions, the radioactive material will be contained reliably inside the fuel, without damage to the integrity of the fuel coatings.

Heat generated within the fuel is extracted from the nuclear reactor using chemically inert helium gas as a coolant. Even at high temperatures, helium does not react chemically with fuel or structural materials.

To maintain nuclear fission reactions inside a nuclear reactor effectively, the fast neutrons generated by nuclear fission must be moderated. In a LWR, the light water, which is also a coolant, is used as a moderator. In a HTGR, graphite, having the characteristics of low neutron absorption, strong resistance to radiation, excellent heat resistance and good thermal conductivity, is used as a moderator. The graphite also functions as structural material of the core. Furthermore owing to its high thermal capacity, graphite also serves to mitigate rapid temperature increases during an accident.

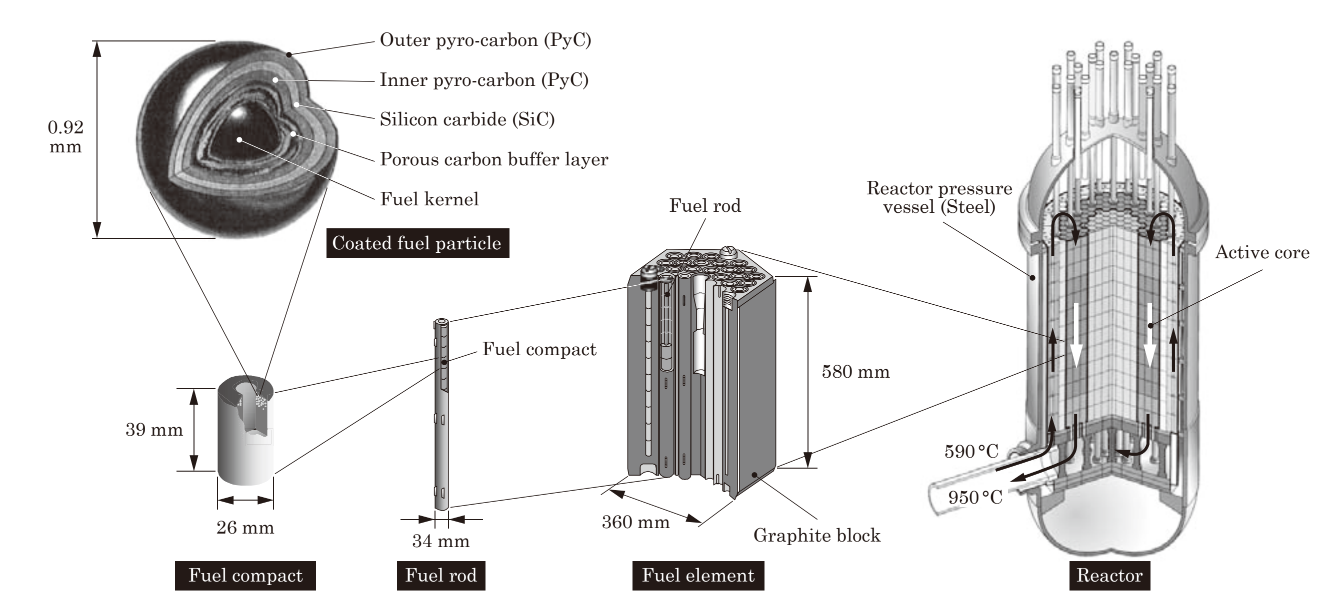
2.2 Modular HTGR

HTGRs use coated fuel particles that are highly resistant to heat. Graphite, used as a moderator, has a large thermal capacity and becomes a large heat sink during accidents. This feature, coupled with the negative temperature feedback characteristics of the core, mitigate abnormal power increase and slows temperature rises during accidents, resulting in excellent safety characteristics.

By limiting the thermal output of a reactor to below a certain level, these safety characteristics can be utilized to their full extent. A reactor can be con-

† Energy Solution Group, Fuji Electric Systems Co., Ltd.
‡ Technology Development Group, Fuji Electric Holdings Co., Ltd.

Fig.1 Reactor concept of HTGR



structed so that in the event of an accident, the reactor shuts down naturally, decay heat is removed naturally, and there is no risk of releasing large amounts of radioactive material that would necessitate the evacuation of the surrounding public of the site. The reactor with these features is the modular HTGR, which has a maximum thermal output on the order of 600 MWt (approximately 300 MWe of electric power). This safety characteristics makes a clear distinction with LWRs, which is aiming for improved economic efficiency through economies of scale, and have recently reached the 1,700 MWe level and scaling-up to larger sizes is planned. By increasing the safety of nuclear reactors and simplifying the safety systems needed in case of accidents, economic viability of the modular HTGR can be ensured even if the reactor power is reduced.

Modular HTGRs have the following safety features.

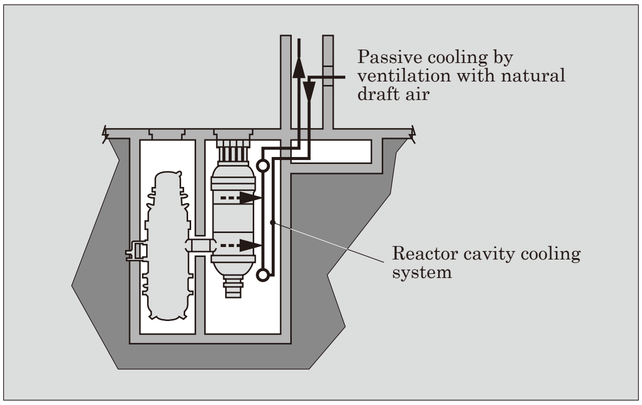
(1) Natural cooling during an accident

As mentioned above, a modular HTGR has a smaller sized reactor so that the decay heat of the reactor can be removed adequately by natural cooling, even during an accident. For example, even in the case of the loss of helium coolant due to rupture of the main cooling pipe (a Loss of Coolant Accident), heat will be removed from the reactor building naturally through the soil and atmosphere, so that the reactor can be cooled adequately, and the fuel temperature kept below the limiting temperature at which fuel integrity can be maintained (see Fig. 2).

(2) Passive shutdown of reactor at the time of an accident

In general, a reactor using low enriched uranium fuel has a characteristic whereby, as the temperature of the core rises, negative reactivity feedback acts so as to mitigate nuclear reactions naturally. The fuel temperature of a HTGR during normal operation has sufficient margin to the limiting temperature under accident conditions, and therefore, at the time of an accident, even without an emergency shutdown action of the control rod, the reactor will be shut down passively due to the negative reactivity feedback.

Fig.2 Natural cooling of the reactor by the reactor cavity cooling system



(3) Radioactive materials are retained in fuel particles after an accident

As mentioned above, if an accident occurs, even if the operator takes no actions or if the safety system does not work, the integrity of the fuel will be maintained solely by natural physical phenomena. Accordingly, radioactive materials accumulated in the core will be reliably contained in the fuel, and there is no need for a pressure and leak-proof containment vessel as in the LWR.

2.3 Use of high-temperature heat

LWRs have become the mainstream type of nuclear power generation at present, but because of their useable upper limit temperature of about 300 °C, applications other than power generation by steam turbines are extremely limited. In contrast, an HTGR can utilize heat in the range of 700 to 950 °C, and thus can be utilized for direct gas turbine power generation with an efficiency of nearly 50% as a power plant. Additionally, without any power conversion stage, the heat obtained from the reactor can be utilized directly for the production of hydrogen from water by a thermochemical process, or as high temperature steam as the process heat source at a chemical plant. Moreover, when connected to a steam turbine cycle, an HTGR can be used as a cogeneration plant that supplies electric power and process steam for use in a chemical complex. Thus, HTGRs can significantly expand the range of utilization of nuclear power, which had previously been limited to power generation, and can substitute for fossil fuels as a primary energy source and contribute to reduce CO_2 emissions dramatically.

3. Current Status and Fuji Electric's Efforts in HTGR Development

3.1 History of HTGR development and Fuji Electric's achievements

(1) History of HTGR development

The development of the HTGR started with the construction of an experimental reactor in the UK with the Dragon Project launched by the OECD (Organization for Economic Cooperation and Development) in 1959. Later, during the 1960s and 1970s, experimental and prototype reactors were constructed and operated in the United States and Germany (then West Germany). The prototype reactor had an electric output of approximately 300 MWe, and performance demonstrations as power plants using a steam turbine were carried out for both reactors.

Through the 1970s, the development of HTGRs, as well as LWRs and other reactors, was advanced in the United States and Germany with a fundamental orientation toward large-size reactors. However, the Three-Mile Island and Chernobyl accidents led to worldwide interest in the concept of inherently safe reactors that ensure safety without relying on active components, and the direction of development shifted dramatically from large-size reactors to modular HTGRs. Thereafter, the focus of HTGR development in both the United States and Germany shifted to small-size modular HTGRs that use steam turbines for power generation.

In the 2000s, from the perspective of protecting the environment and preventing global warming, in the United States, the development of a modular HTGR aiming for a reactor outlet temperature of at least 950 °C, and a hydrogen production system that connects to the modular HTGR, was initiated as a NGNP (Next Generation Nuclear Plant) project with funding from the US Department of Energy.

In Germany, development of modular HTGRs started in the 1980s, and research was carried out vigorously. With the subsequent change in Federal government policy to suspend all nuclear power development, this development work was halted in the early 1990s. However, German HTGR technology has been come into China and South Africa, and both countries are moving ahead with plans to build HTGR demonstration reactors.

Recently, throughout the world, there has been heightened interest in HTGRs for hydrogen production and for use as a process heat source, and even in the Generation IV International Forum (GIF), which is a framework for cooperative international research and development that began as a proposal from the United States, HTGRs have been selected as one of the candidate plants, and international cooperation is also underway.

In Japan, the research and development of HTGRs for multi-purpose utilization other than power generation started in the late 1960s at the former Japan Atomic Energy Research Institute (currently the Japan Atomic Energy Agency (JAEA)). Thereafter, the construction of Japan's first HTGR, the High Temperature Engineering Test Reactor (HTTR), began in 1990. In 2001, this reactor achieved its rated power operation, and in 2004, 950 °C high-temperature helium gas was successfully produced by the HTTR[(1)].

(2) Fuji Electric's achievements

Fuji Electric has participated in cooperative HTTR design, research and development since the beginning of JAEA's research and development initiative. In tests of high temperature components, i.e., strength tests of the reactor internal structures, seismic tests of the core, performance tests of seals between blocks, thermal property tests of materials and so on, elemental technologies necessary for design and manufacturing have been developed. Fuji Electric installed an in-house high-temperature high-pressure helium loop, and performed demonstration testing on structures, reliability of components. With the Helium Engineering Demonstration Loop (HENDEL) for carrying out demonstration testing of the various HTTR high-temperature components, Fuji Electric has played a leading role in the construction. At the same time, Fuji designed, fabricated and installed a "Single Channel Fuel Stack Test Section" (HENDEL-T1) for evaluating the heat transfer and flow characteristics of coolant in the core and an "In Core Structure Test Section" (HENDEL-T2) (Fig. 3) for evaluating the integrity of core support structures, and supported research and development for demonstrating the performance and integrity of large-size components[(2),(3)]. For the core bottom structures, Fuji Electric has manufactured, installed and tested 1/5th scale and 1/3rd scale seismic testing equipment for the purpose of acquiring basic response data and for demonstrating integrity at the time of an earthquake[(4)].

In the construction of the HTTR plant, Fuji Electric, as a deputy administrative role, coordinated reactor construction, cooperated with JAEA regarding the design of the reactor core and in conducting safety analyses for the reactor system design, and was responsible for the design, manufacture and construction of major components such as the reactor internals, a fuel handling and storage system, and a radiation monitoring system. Figure 4 shows the appearance of the reactor internals as seen from the top layer of the reactor core. Figure 5 shows a fuel handling machine, a major component of the fuel handling system.

After construction of the HTTR was completed, Fuji Electric was responsible for constructing a spent fuel storage facility, which is a dry storage system for the long-term onsite storage of spent fuel, after having been stored in the reactor building and cooled, and for designing and manufacturing an irradiation creep test device for conducting creep testing inside the HTTR core[5].

Fig.3 Reactor internal structure demonstration test section (HENDEL-T2)

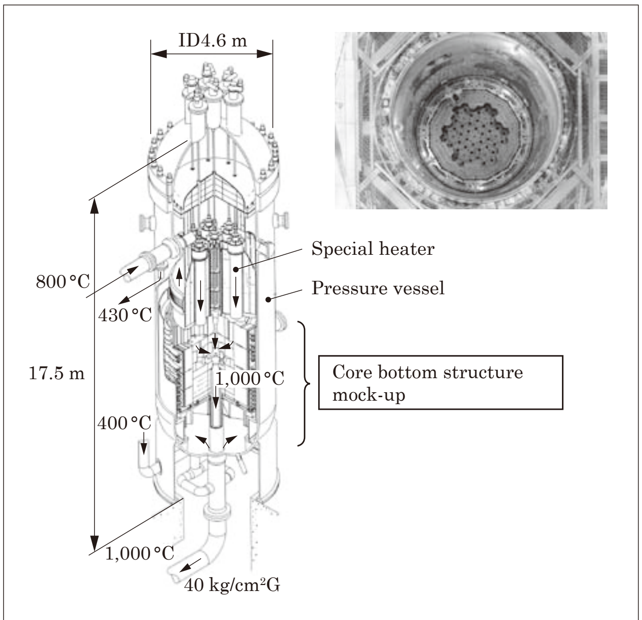
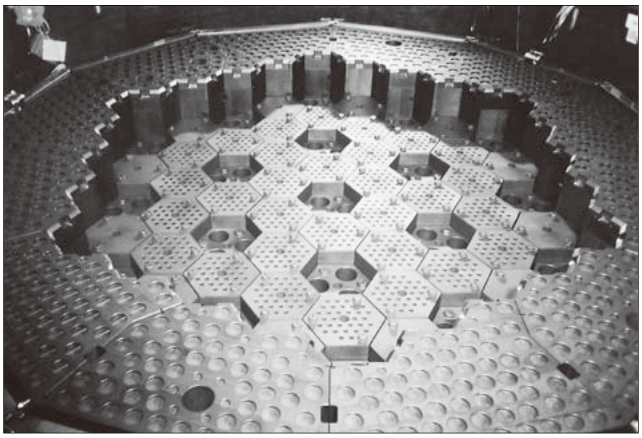


Fig.4 Top layer of High Temperature Engineering Test Reactor (HTTR) core



3.2 HTGR development efforts

In order to realize hydrogen production with an HTGR, a higher reactor outlet temperature of at least 950 °C is needed. Previously, HTTRs and other small test reactors have achieved this level of performance, but many challenges remain before they can be used in practical applications. In the case of practical application of a modular HTGR of 600 MWt power, its power level must be increased to 20 times of the 30 MWt HTTR. To ensure the inherent safety of this output power, the fuel temperature limits must be satisfied during normal operation and during accidents. During normal operation technical, measures are needed to ensure the effective core coolant flow rate. On the other hand, the power distribution shape must be optimized to meet the limiting fuel temperature under accident conditions and also to maintain higher plant availability due to a longer fuel burn-up period. Additionally, to reach the highest power level while maintaining the inherent safety, design margin in the evaluation of the decay heat removal capacity by natural cooling from the reactor vessel, it is also important to utilize this cooling capability as much as possible.

Based on the aforementioned technical issues, Fuji Electric is advancing research and development with

Fig.5 High Temperature Engineering Test Reactor (HTTR) fuel handling machine

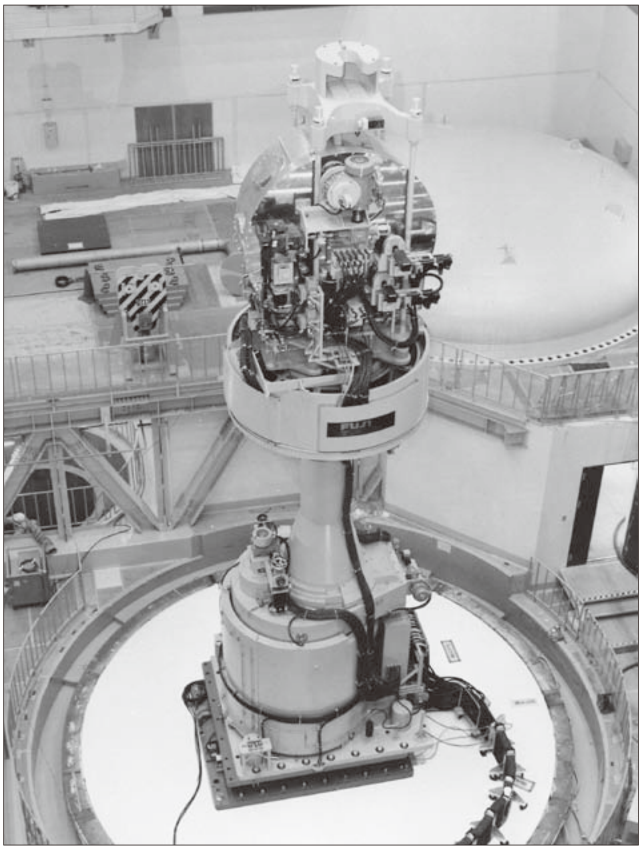
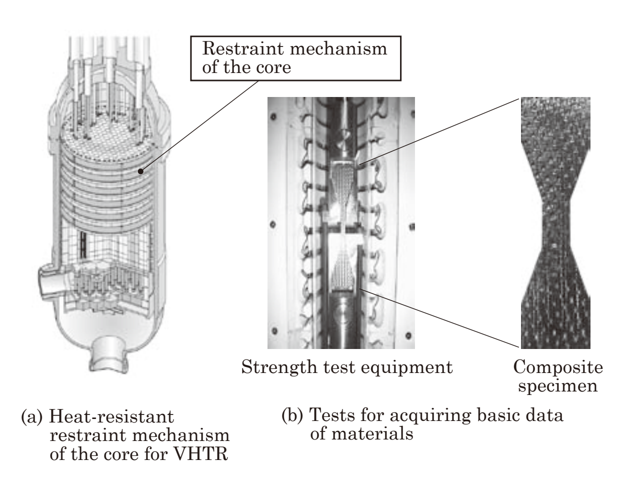


Fig.6 Heat-resistant restraint mechanism of the core for very high temperature gas reactor (VHTR)



the goal of achieving the practical application of a modular HTGR on a commercial scale aimed at realizing thermal power of 600 MWt and an outlet temperature of 950 °C. The major research and development items are introduced below.

(1) Heat-resistant restraint mechanism of the core

So that the fuel temperature does not rise excessively even if the reactor output temperature is increased to 950 °C, reactor internals of stacked graphite blocks must be tightened from the outside and the bypass flow through gaps between the blocks must be minimized so as to ensure the effective coolant flow rate of the fuel coolant channel. In the case of the HTTR, since the reactor inlet temperature is around 400 °C, a restraint mechanism was established using metal materials. In the case of a HTGR for hydrogen production, however, in order to ensure the plant thermal efficiency, a reactor inlet temperature of approximately 500 to 600 °C is required. For this purpose, composite ceramic materials having excellent heat-resistant properties are used instead of metal materials, and structural concepts, tests for acquiring basic data of the materials, development of a strength evaluation method are being performed (Fig. 6).

(2) Core design study with axially flattened power distribution shape

To ensure the inherent safety of a modular HTGR, the fuel temperature during an accident must not exceed the limit value. Since the decay heat during an accident is removed radially from the reactor vessel by natural cooling, the maximum fuel temperature will be in the vicinity of the maximum power point in the axial direction. Therefore, to reduce the fuel temperature during an accident, the axial power distribution of the core must be flattened. Fuji Electric is developing the methodology for designing the flattened power distribution shape core concept to meet the limit temperature of 1,600 °C during a depressurization accident, as shown in Fig. 7, with a reactor thermal output of

Fig.7 Concept of flattened power distribution shape core

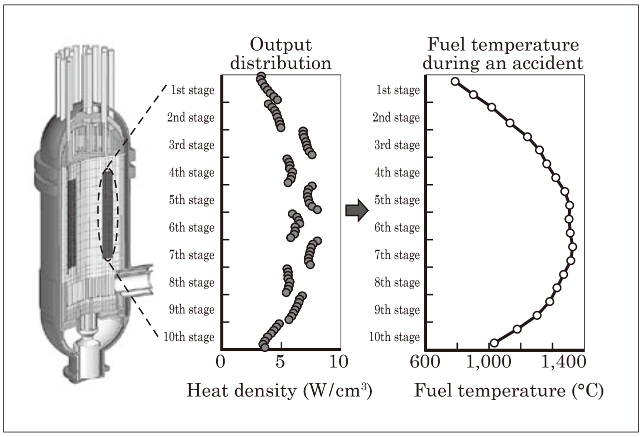
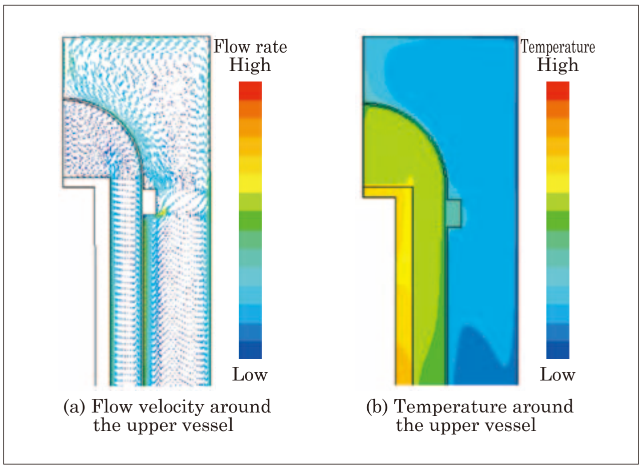


Fig.8 Example of analysis result of heat removal from reactor by natural cooling



600 MWt, a reactor inlet temperature of 590 °C and output temperature of 950 °C as basic conditions, and a design target of 550 days × 2 batches as the refueling cycle and number of batches.

(3) Evaluation of decay heat removal characteristics from the reactor by natural cooling

Cooling of the reactor pressure vessel during normal operation and during an accident is carried out by two heat transfer phenomena, radiation and natural convection. Accordingly, if the decay heat removal capability of these phenomena can be precisely evaluated, the design margin could be reduced reasonably and cheaper materials for the reactor pressure vessel could be used. Thus, in order to enhance the accuracy of the evaluation of heat removal by natural cooling, experimental data[6] of scale model tests previously implemented by the JAEA is utilized effectively, and the validation of the evaluation method is being performed. An example of thermal hydraulic analysis results for a reactor vessel mock-up test facility is shown in Fig. 8.

4. Postscript

Modular HTGRs are the next-generation of nuclear reactors, and in addition to having excellent inherent safety characteristics, also have the potential to bring about a significant reduction in CO_2 emissions through expanding their application other than power generation, such as hydrogen production or the process heat supply for chemical plants. Fuji Electric will continue to cooperate with related organizations in Japan and overseas, and intends to apply its full resources to advance the commercialization of HTGRs.

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Development of the FP-100i Phosphoric Acid Fuel Cell

Masakazu Hasegawa   Yoshimi Horiuchi

ABSTRACT

Since 1998, Fuji Electric has delivered twenty-five 100 kW phosphoric acid fuel cell units. The cumulative operation time of these fuel cells has exceeded the lifespan targeted by the original development (40,000 hours), and their reliability and durability have been proven. In 2009, Fuji Electric began selling the “FP-100i,” a newly developed low-cost phosphoric acid fuel cell. Integrated with peripheral devices, the FP-100i features improved ease-of-use and is able to support installation in a wider range of environments. As part of future efforts to popularize and expand usage of the FP-100i, application development will be promoted for fuel cells equipped with disaster response capability, fuel cells that use pure hydrogen or by-product hydrogen, fuel cells equipped with hydrogen supply capability for supplying hydrogen stations for electric vehicles, and so on.

1. Introduction

Fuel cells are power-generating systems that generate electricity directly from a reaction between hydrogen and oxygen, and for which there are great expectations as a next-generation energy source.

Because they are able to extract electricity directly by causing a chemical reaction of their fuel, fuel cells have advantages over conventional internal combustion engines, such as car engines and gas turbines that cause a combustion reaction of the fuel and extract electricity via a generator, of lower loss and higher electrical efficiency. Additionally, in contrast to large-scale centralized power plants, consumers are able to use fuels cells in their vicinity as dispersed local power sources so that the energy loss is low and waste heat can be utilized. Utilizing city gas or the like, a fuel cell internally reforms (converts) that gas into hydrogen, and then uses the hydrogen as fuel to generate electricity. In other words, electricity can be generated as long as hydrogen is present, and since a wide variety of fuels can be reformed into hydrogen, the capability to function as a multi-source energy system is another advantage of fuel cells. For these reasons, fuel cells are attracting heightened interest worldwide for the prevention of global warming and are a promising tool for use in reducing greenhouse gas emissions, and efforts are actively underway to develop and commercialize fuel cell technology.

Fuji Electric has been selling a 100 kW phosphoric acid fuel cell. Aiming to expand sales, Fuji Electric developed a new phosphoric acid fuel cell known as the “FP-100i”, and launched this model in 2009. This paper discusses the current status of phosphoric acid fuel cells that have been delivered by Fuji Electric, features of the new FP-100i, and the future outlook for phosphoric acid fuel cells.

2. Current Status of Phosphoric Acid Fuel Cells

Fuji Electric began developing phosphoric acid fuel cells in 1973, and has developed 50 kW, 100 kW and 500 kW models for use in onsite applications, and in cooperation with gas companies and electric power companies, has field-tested more than 100 units. This accumulated experience and know-how was incorporated into a 100 kW commercial model that was launched in 1998, and 25 units of this model have been shipped to date.

Table 1 shows the delivery history, the cumulative operating time and the operating status of this 100 kW commercial model. The main operating sites are hospitals, hotels, office buildings, sewage treatment plants and the like. The delivered units are used as co-generation systems that supply electricity and hot water.

This commercial model, when first brought to market, had an overhaul cycle (lifetime of main equipment such as the fuel cell stack and reformer) of 40,000 hours, and has achieved this goal of 40,000 hours at all sites where this model is currently in operation. In particular, a system delivered to a hotel was overhauled after 91,568 hours of cumulative operation, which is longest time record for Fuji Electric.

Since 2006, Fuji Electric has been selling models that support overhaul cycles of 60,000 hours. In addition, with the revision of Japan’s “Fire Service Act” in 2006, fuel cells came to be regarded as emergency power sources. In 2008, Fuji Electric’s commercial 100 kW model was the first fuel cell to be certified in compliance with the Fire Service Act. During normal operation, this model operates as a co-generation system, but in the event of an emergency, is designed to con-

† Energy Solution Group, Fuji Electric Systems Co., Ltd.

Table 1 Delivery history and operating status* of Fuji Electric's commercial-model 100 kW phosphoric acid fuel cell

<table>
<tr><th>Operating site</th><th>Fuel</th><th>Overhaul cycle time (h)</th><th>Date of delivery</th><th>Cumulative operating time (h)</th><th>Operating status</th><th>Overhaul imple-mentation status</th></tr>
<tr><td>Hospital</td><td rowspan="7">City gas (13 A)</td><td rowspan="16">40,000</td><td>August 1998</td><td>44,265</td><td rowspan="5">Terminated</td><td></td></tr>
<tr><td>Hotel</td><td>March 1999</td><td>91,568</td><td>Implemented</td></tr>
<tr><td>University</td><td>April 2000</td><td>41,735</td><td></td></tr>
<tr><td rowspan="4">Office building</td><td>March 2001</td><td>42,666</td><td></td></tr>
<tr><td>March 2001</td><td>48,734</td><td></td></tr>
<tr><td>July 2000</td><td>64,117</td><td rowspan="2">In operation</td><td>Implemented</td></tr>
<tr><td>July 2000</td><td>48,269</td><td></td></tr>
<tr><td>Demonstration facility</td><td>Biomass gas</td><td>July 2001</td><td>10,952</td><td>Terminated</td><td></td></tr>
<tr><td>Training facility</td><td>City gas (13 A)</td><td>December 2001</td><td>66,442</td><td rowspan="17">In operation</td><td rowspan="7">Implemented</td></tr>
<tr><td rowspan="2">Sewage treatment plant</td><td rowspan="2">Digester gas</td><td>March 2002</td><td>68,157</td></tr>
<tr><td>March 2002</td><td>68,391</td></tr>
<tr><td>Hospital</td><td rowspan="8">City gas (13 A)</td><td>July 2003</td><td>58,160</td></tr>
<tr><td>University</td><td>October 2003</td><td>49,731</td></tr>
<tr><td>Exhibition facility</td><td>November 2003</td><td>53,199</td></tr>
<tr><td>Office building</td><td>January 2004</td><td>51,486</td></tr>
<tr><td>Hospital</td><td>March 2004</td><td>48,825</td><td></td></tr>
<tr><td>Exhibition facility</td><td rowspan="9">60,000</td><td>March 2006</td><td>34,646</td><td></td></tr>
<tr><td>Hospital</td><td>March 2006</td><td>32,155</td><td></td></tr>
<tr><td>Hospital</td><td>March 2006</td><td>32,377</td><td></td></tr>
<tr><td rowspan="4">Sewage treatment plant</td><td rowspan="4">Digester gas</td><td>December 2006</td><td>29,680</td><td></td></tr>
<tr><td>December 2006</td><td>29,181</td><td></td></tr>
<tr><td>December 2006</td><td>29,068</td><td></td></tr>
<tr><td>December 2006</td><td>29,198</td><td></td></tr>
<tr><td>Government building</td><td rowspan="2">City gas (13 A)</td><td>September 2007</td><td>20,633</td><td></td></tr>
<tr><td>Office building</td><td>January 2009</td><td>10,700</td><td></td></tr>
</table>

* : Operating status as of April 1, 2010

tinuously supply emergency power to a specified load. In the certification examination, this model passed a difficult jet-proof type waterproof test in which water is sprayed from all directions to see whether a failure would occur. In 2009, the FP-100i was awarded a "Nikkei Superior Products and Services Award" that honors outstanding new products and services sold in Japan.

Thus, the reliability and durability of Fuji Electric's phosphoric acid fuel cells have been demonstrated in actual onsite applications.

3. Characteristics of Phosphoric Acid Fuel Cells

Fuel cells are categorized as alkali fuel cells, polymer electrolyte fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells or solid oxide fuel cells, according to the type of electrolyte used, and their operating temperatures, sizes and usages differ. Among these different types, the phosphoric acid fuel cell was the earliest to be commercialized. The main features of Fuji Electric's commercial-model 100 kW phosphoric acid fuel cell are listed below.

(1) High electrical efficiency, from low output to high output

As shown in Fig. 1, high electrical efficiency can be maintained even at partial loads, and load-following operation can be realized. Pattern operation is also possible, whereby the fuel cell runs at its 100 kW rated operation during the day, but at night, runs at partial-loaded operation with a lower output when the usage of electricity is less.

(2) Capable of utilizing multiple sources of fuel

Phosphoric acid fuel cells can accommodate various types of fuel gases with different colorific power, such as LP gas, city gas, digester gas, and hydrogen gas. This capability allows fuel to be switched, and therefore even if a lifeline to city gas or the like is suspended during an emergency, operation can be continued by changing over to a reserve of LP gas or the like.

(3) Excellent environmental characteristics

As can be seen in Fig. 2, the gas emitted from the fuel cell system has extremely low NO_x and SO_x content compared to other types of electric power generators. Moreover, there are no rotating parts since power is generated by a chemical reaction, and the layout inside the fuel cell package and the panel structure are devised such that noise at a distance of 1 m from the fuel cell is less than 65 dB (A). This low noise characteristic facilitates installation at hospitals, hotels or other facilities where quiet operation is required.

Fig.1 Phosphoric acid fuel cell electrical efficiency and image of power load and output power

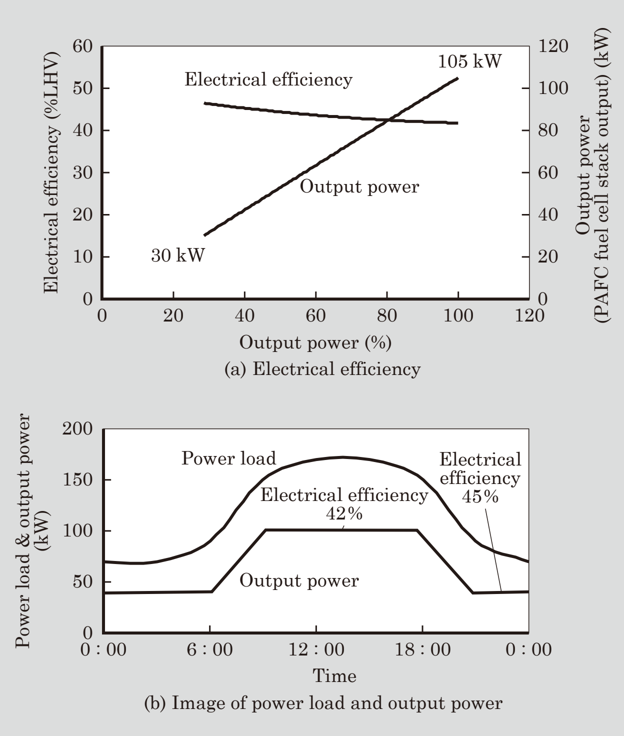
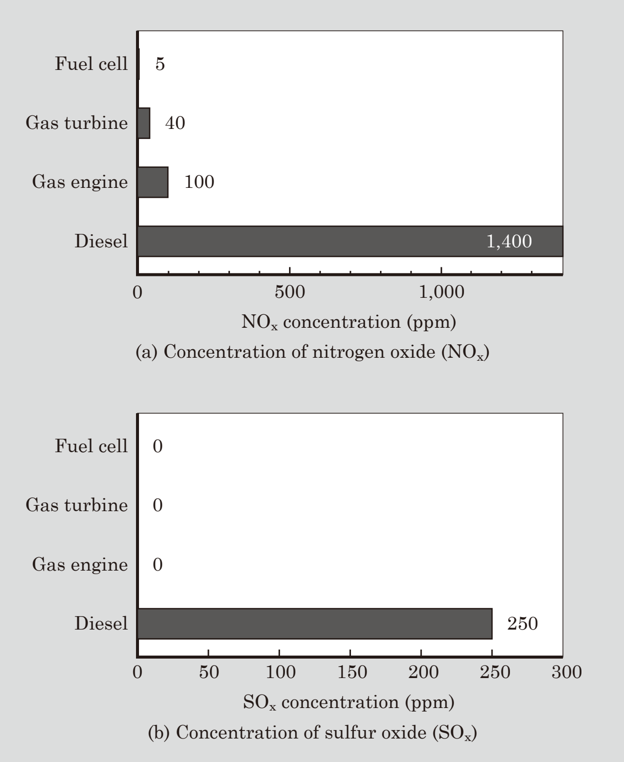


Fig.2 Analysis of exhaust gas from various types of generators



(4) Capable of year-round continuous operation

So that operation can continue stably, the fuel cell operation is halted once per year for an annual inspection. Fuel cells, however, are designed so that periodic maintenance such as filter replacement can be performed while operating, and therefore can be operated continuously for one full year.

4. Development of the "FP-100i" Popular-Type Phosphoric Acid Fuel Cell

To expand the usage of phosphoric acid fuel cells, there was a need to improve user convenience and to expand the range of environmental conditions under which installation was possible. Table 2 lists the specifications of the FP-100i. Aiming for a PR boost resulting from the positive environmental contribution and enhanced corporate social responsibility (CSR) associated with the installation of a fuel cell, so that the fuel cell may be installed at a site viewable by the general public, the entire system is finished with an in-line design whereby the inlet and exhaust ducts on the outer perimeter of the system are neither concave nor convex, and roof-mounted equipment is surrounded by fencing. Unlike the rigid image of a conventional power plant, a two-tone color palette of browns and whites provides a gentle image in harmony with the surrounding buildings and nature. The appearance of the FP-100i is shown in Fig. 3, and its features are described below.

4.1 Reduction of installation footprint and streamlining of onsite construction work

Fuel cells require the following types of peripheral equipment: waste heat treatment equipment, nitrogen

Table 2 FP-100i specifications

Rated output power	100 kW AC
Output voltage	3 ϕ 3 W, 210 V/220 V
Output frequency	50 Hz/60 Hz
Electrical efficiency	42% (LHV) *Generating-end (Digester gas: 40%)
Thermal output (Either (1) or (2) can be selected from the column at right)	(1) High-temperature recovery type 50 kW (90 °C) Total efficiency: 62% (LHV)*
	(2) Medium-temperature recovery type 123 kW (60 °C) Total efficiency: 92% (LHV)*
Exhaust gas	NOx: 5 ppm or less (O_2: 0%) SOx, dust: Below detectable limit
Fuel consumption	City gas: 22 m^3 (Normal)/h (Digester gas: 44 m^3 (Normal)/h)
Operating method	Fully automated, grid-connected, independent operation
Dimensions	W2.2 × L5.6 × H3.4 (m)
Weight	City gas-fed type: 15 t (Digester gas-fed type: 16 t)

* LHV: Lower Heating Value. (Refer to Supplemental Explanation on page 240)

gas supply equipment, water treatment equipment, heat recovery equipment, an electric facility and a neutralizer. Previously, construction work for the installation, piping and wiring connections for this peripheral equipment was carried out onsite. With the FP-100i, however, this equipment has been integrally formed to reduce the size of the installation footprint and streamline onsite construction work. The size of the required installation footprint, including space for maintenance, has been reduced from 75 m^2 to 43 m^2 (Fig. 4). Further, although the waste heat treatment equipment to be mounted on the roof of the system is assembled onsite due to transportation restrictions, connectors are used for the wiring connections and the pipe laying work has been reduced to two lines in order to streamline the onsite construction work. In addition, because the peripheral equipment is mounted on the system, the size and weight of each device has been reduced. The main details are described below.

(1) Lighter-weight waste heat treatment equipment

Previously, the cooling water of the waste heat treatment equipment's condenser was the same as the cooling water that circulated inside the fuel cell package and that contained a small amount of phosphoric acid. By providing a heat exchanger in the circulation loop and separating the cooling water of the waste heat equipment from the cooling water inside the fuel cell package, corrosion due to the cooling water is prevented. As a result, the tube material used in the condenser could be changed from stainless steel to copper, and the thermal conductivity was improved. Additionally, the cooling fin pitch was reduced, a thin metal plate structure was used for the main body (casing) structure, and the condenser weight was reduced by about a factor of about two, from 1,350 kg to 600 kg. The lighter weight enables the condenser to be mounted on the roof, and realize an integrated structure.

(2) Reduction of nitrogen gas cylinders

Fig.3 Appearance of FP-100i

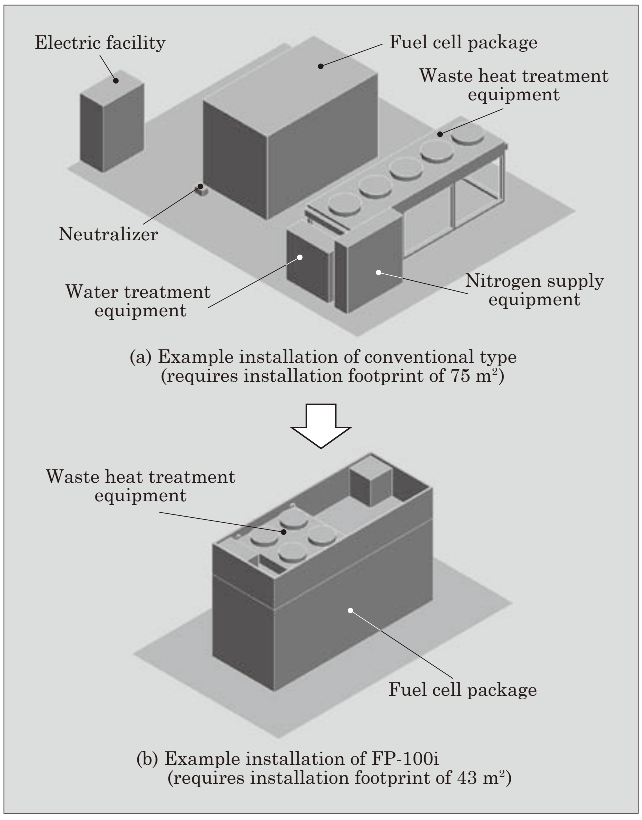
Fuel cells are provided with nitrogen equipment because, for safety reasons when the system is stopped, the flammable gas inside piping and devices must be replaced with nitrogen gas. Nitrogen gas cylinders (7 m^3/cylinder) were previously provided as 2 systems having a total of 6 cylinders (3 cylinders per system), but by optimizing the time for the flammable gas replacement, this has been reduced to 2 systems having a total of 4 cylinders (2 cylinders per system), and integrated. To verify operation after the reduction of nitrogen gas cylinders, demonstration tests were conducted using actual equipment, and it was verified that the gas inside the piping and devices had been replaced with nitrogen gas and that the gas concentration was reduced to sufficiently safe levels.

4.2 Support of low-temperature operation

An ambient temperature in the range of −5 °C to +40 °C had previously been required for installation of a fuel cell system, but with the FP-100i, the method of ventilation and device layout inside the fuel cell package have been redesigned to support ambient temperatures in the range of −20 °C to +40 °C. As a result, outdoors installation in cold climates is possible.

Based on thermal fluid analysis, the ventilation flow and the temperature distribution inside the fuel cell package were analyzed, and the ventilation air flow and device layout optimized. Actual equipment was used to verify the capability of the fuel cell system

Fig.4 Reduction of installation footprint and streamlining of onsite construction work



to operate continuously, without any trouble, in the temperature range from −20 °C to +40 °C. Specifically, as shown in Fig. 5, the fuel cell package is partitioned into a sub-component area provided with an inverter, pump, water treatment equipment, tank and the like, and a main component area provided with the cell tank and reforming system. Moreover, because the temperature is low during winter, an electric heater is provided at the inlet to the sub-component area to protect electric equipment and prevent the freezing of equipment that handles water.

4.3 Improved Transportability

Because marine transport would be necessary in order to popularize the usage of fuel cells abroad, Fuji Electric developed the following two technologies for improved transportability.

(1) Elimination of power supply for warming during transit

In a phosphoric acid fuel cell, phosphoric acid is used as the electrolyte in the cell stack. Because a high concentration of phosphoric acid will freeze at room temperature, in the past, a generator or the like was used to supply electricity to an electric heater that kept the phosphoric acid warm during transit. However, because of the difficulty of retaining heat during transportation by ship, there was a desire to eliminate the need for keeping the phosphoric acid warm. Thus, Fuji Electric developed a method for preventing freezing by lowering the concentration of phosphoric acid during transit. This method was demonstrated on actual equipment and makes possible transportation without the need for warming.

(2) Development of protective material (shock absorber)

Fuel cell systems are designed to be able to withstand vibrations of up to 1 G during transportation. However, when being loaded onto a ship in port, mechanical shocks in excess of 1 G may be applied. Therefore, protective material (a shock absorber) is attached to the bottom of the fuel cell system so as to be able to withstand impacts of up to 3 G.

4.4 Improved earthquake resistance

In order to improve earthquake resistance, the strengths of the fuel cell system stand and stack were analyzed during the planning stage, and those results were reflected in the design. Then, a vibration test was performed in which actual equipment was mounted on a vibration tester whereby the waveform of the vibrations was equivalent to the actual seismic vibrations of the Niigata Chuetsu Earthquake, and after the vibration test, the fuel cell system was confirmed to be capable of generating power without problem.

5. Future Outlook

By leveraging their characteristic feature of a hydrogen fuel source, Fuji Electric's phosphoric fuel cells help to advance development for new applications which, in the past, had mostly been implemented as co-generation applications fueled by city gas. Figure 6 is an explanatory diagram showing new applications for phosphoric fuel cells, the main details of which are described below.

5.1 Fuel cells that utilize pure hydrogen and by-product hydrogen (refineries, chemical plant by-product gas)

Fuel cells that utilize pure hydrogen or by-product hydrogen do not require that the fuel be reformed, and are supplied directly with hydrogen fuel to generate electrical power. By using pure hydrogen (99.9% high concentration hydrogen) generated from a caustic soda factory or the like as fuel, a system with even higher electric efficiency can be constructed. This is because the waste hydrogen emitted from the fuel cell is not exhausted directly, but instead, is returned to the fuel cell stack inlet and recycled so that a high rate of hy-

Fig.5 Layout and ventilation flow inside fuel cell package

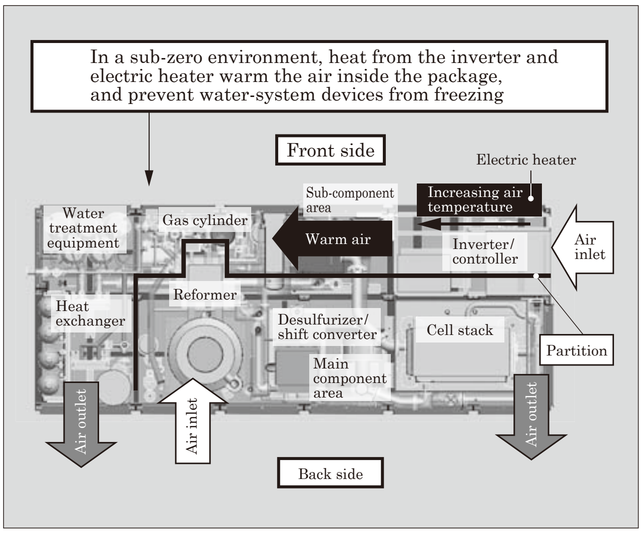


Fig.6 New applications for phosphoric acid fuel cells

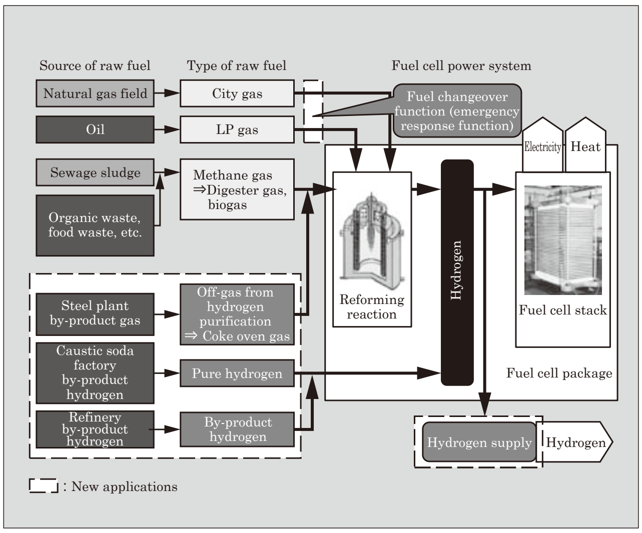
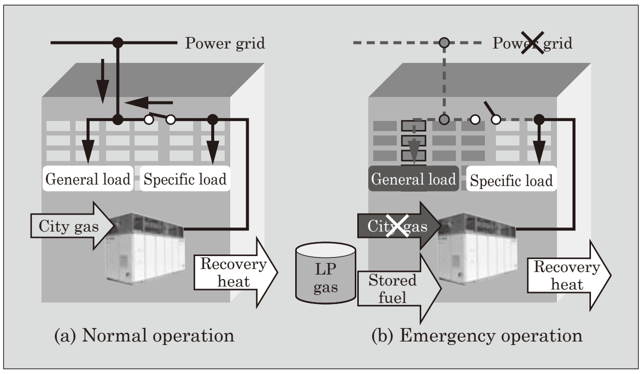


Fig.7 Power supply methods for normal operation and emergency operation



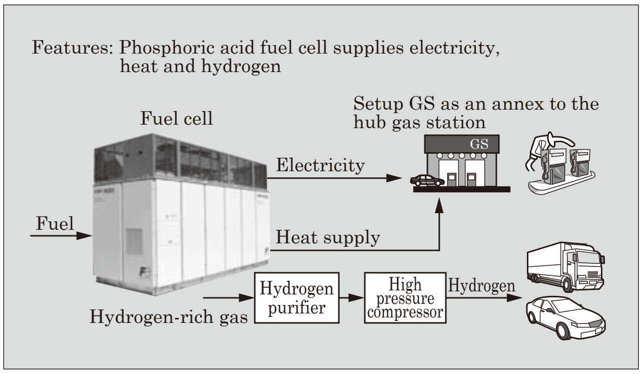
drogen utilization can be realized. A system with high electric efficiency of up to 48% (at the fuel cell stack output) can be constructed, and compared to the case in which a boiler is used, the use of pure hydrogen results in a CO_2 reduction effect that is 1.6 times larger.

5.2 Fuel cell equipped with emergency response function

In the event of an emergency or the like where the electricity or city gas is shut off, power is typically supplied by an emergency power generator. By installing fuel cells equipped with an emergency response function at disaster prevention centers and the like, power and heat will be supplied normally, and during an emergency, the fuel can be switched from city gas to stored LP gas so that power generation can continue and power and heat can be supplied.

The heating value of LP gas is approximately twice that of the city gas and therefore the reforming conditions for making hydrogen are different. Nevertheless, the fuel cell generates power once fuel has been reformed into hydrogen by the fuel reforming system, and power generation can continue without stopping. Moreover, when operating with LP gas as the fuel, the output is 70 kW, and a 50 kg gas cylinder will be enable electricity to be supplied for approximately three hours. Figure 7 shows the methods of power supply during normal operation and emergency operation.

Fig.8 Fuel cell equipped with hydrogen supply function



5.3 Fuel cell equipped with hydrogen supply function

Fuel cells equipped with a hydrogen supply function are tri-generation systems capable of supplying not only electricity and heat, but also hydrogen. During the daytime, electricity and heat from co-generation are utilized, and during the nighttime when the load is less, the power output is decreased and excess hydrogen production capacity is harnessed to extract and supply hydrogen gas. These types of fuel cells are suited for usage at hydrogen stations necessary for fuel cell-powered vehicles, business offices that require small amounts of hydrogen, and so on. Figure 8 shows a schematic representation of these applications.

6. Postscript

Because fuel cells are systems that contribute to curbing global warming and protection of the global environment, efforts to promote their popularization and widespread usage will have a positive impact on society. To promote the usage of fuel cells, Fuji Electric intends to expand the range of applications further and to improve user benefits.

The authors express thanks to the relevant organizations and users for their guidance and cooperation thus far, and ask for increased understanding and support in the future.

Film Type Amorphous Silicon Photovoltaic Module and its Application Technology

Tetsuro Nakamura Hisanobu Yokoyama Hironori Yanase

ABSTRACT

Fuji Electric's photovoltaic modules are formed by encapsulating solar cells fabricated on a plastic substrate without using glass. These modules are lightweight, flexible, thin and unbreakable, and can be installed on a building without requiring that the building structure be reinforced. Laminating these modules to various materials such as a curved steel plate enables the modules to be integrally formed with advanced building materials such as roofing materials or wall materials. Also, integrating with non-building materials, such as a waterproof sheet, and improving the installation method will expand the range of possible installation sites and usage methods as well as increase the added value. The cells are formed with a series-connection structure that enables modularization of the cells with only simple wiring and facilitates the fabrication of larger cells areas.

1. Introduction

The production of photovoltaic power has increased rapidly over the past 10 years, with product output growing at a rate of 30 to 40% annually, and is driving force behind the environmental and energy policies of countries throughout the world. A backdrop to this rapid growth is the global challenge of reducing greenhouse gas emissions. As one response to this challenge, Fuji Electric is working to manufacture, sell and promote the widespread usage of solar cells.

There are various types of solar cells, and these different types are made from different materials. Fuji Electric has been researching and developing amorphous silicon solar cells since 1978. Amorphous silicon solar cells have a large optical absorption coefficient in the visible light range, and can be fabricated as a thin film having a thickness as small as 1 mm. The nominal output of a solar cell is defined as the output value at the reference temperature of 25 °C. Actual operating temperatures for outdoor use are often higher than 25 °C. Because amorphous silicon has a larger energy band gap than liquid crystal silicon and resists degradation of its power output even at high temperatures, amorphous silicon solar cells are said to be highly practical. Since October 2004, amorphous silicon fabricated on a flexible plastic film substrate and encapsulated by a polymer has been sold as lightweight, flexible and unbreakable film modules.

2. Photovoltaic Modules

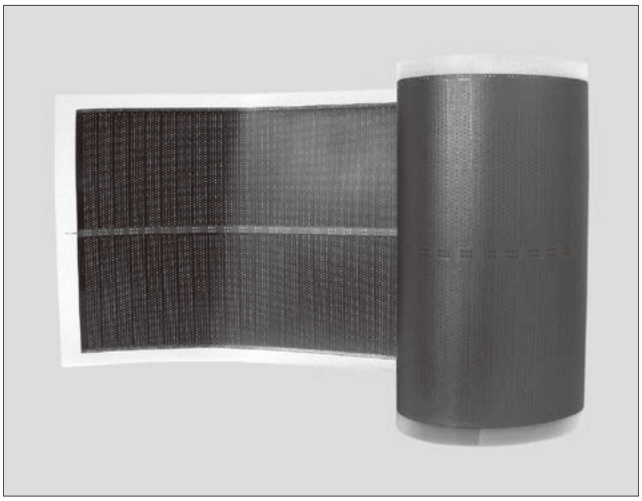
Fuji Electric's photovoltaic modules shown in Fig. 1 have the following characteristics. The modules are categorized roughly into BIPV (building-integrated photovoltaic module) and BAPV (building-applied photovoltaic module) types.

(a) An integrated series-connected structure has been incorporated at the production stage. Consequently, large dimensions can be realized easily with modularization and simple wiring, making it possible to cover an entire roof or side wall.

(b) By eliminating the glass on the light receiving side, the securing frame and so on, and by covering that surface with a weather-resistant polymer, lightweight, flexible and unbreakable modules that did not exist previously can be fabricated.

(c) In addition to the conventional stationary-type modules, photovoltaic modules that are glued together with various materials and integrally formed with building materials, such as roofing materials or wall materials, and that achieve

Fig.1 Flexible photovoltaic module



† Energy Solution Group, Fuji Electric Systems Co., Ltd.

harmony with their surroundings, can be realized.

2.1 BIPV

The BIPV modules sold so far have mainly been the glass covered type. Glass-covered modules have a heavy weight per unit area. Accordingly, their use requires roof reinforcement and their size has been limited. Targeting application to the roofs of buildings, especially large public or industrial buildings, Fuji Electric has been supplying lightweight BIPV modules made from a film-type photovoltaic module laminated directly to a steel plate. These BIPV modules can be applied in the same way as an ordinary steel roof, enabling the realization of a steel roof equipped with low-cost and well-designed solar cell functionality. In addition, because they are flexible, the steel plates can be bent and installed on curved surfaces as shown in Fig. 2, resulting in excellent design characteristics when installed on a dome-shaped roof or at locations where a refined design sense is desired. Also, in the field of construction waterproofing, a technique that uses waterproof sheets has been used increasingly due to its short construction period and low cost, and even higher added value can be obtained by integrating these waterproof sheets with sheet-like solar cells (Fig. 3).

Fig.2 Minato Mirai in Yokohama, Japan

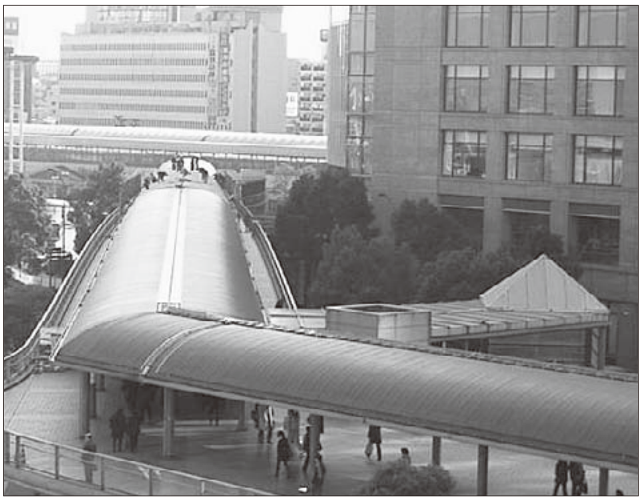
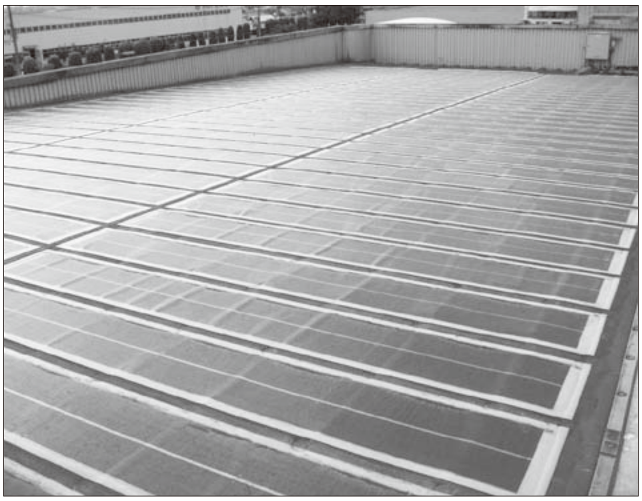


Fig.3 Waterproof sheet type



2.2 BAPV

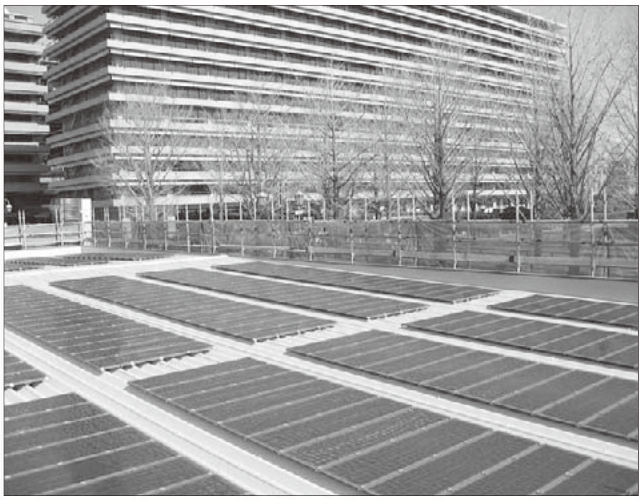
BAPV modules are typically encapsulated by a fluorinated polymer having excellent weather resistance specifications. These photovoltaic modules exhibit excellent durability without sacrificing flexibility. Installation methods and methods for attaching mounting pins have been proposed according to the needs of the user. The potential for various other uses also exists, and applications in a wide variety of fields, such as to vending machines, covers for water treatment plants, energy-saving devices (such as household electric appliances), soundproof walls along a highway, and waterproof sheets, are being considered (Fig. 4).

Steel plate folding-type modules are also being sold for use on existing roofs.

When installing a solar cell on an existing building, the weight of the solar cell installation must not exceed the load capacity of the building. In the case of

Fig.4 Solar raft type

Fig.5 Solar cell on roof of bicycle parking lot, Kumamoto prefectural government



a building having a small load capacity, reinforcement is necessary. Fuji Electric's steel plate folding-type modules have a weight, including the steel plate itself, of approximately 4 to 8 kg/m^2 which is about half that of stationary type modules made by other companies, and therefore reinforcement of the building is not required (Fig. 5).

3. Module Installation Techniques

Solar cells are typically installed on the roof of a building or on a custom frame pedestal. Due to space constraints, however, these cells have only achieved a limited increase in popularity. As a solution, modules that are easier to install are being developed and installation demonstration tests are being conducted. Because film-type modules are fabricated exclusively from polymers, they are not suited for installations where the modules are only partially attached, and instead have had to be attached to the surface of structural objects such as steel plates. However, by embedding metal in a module and providing anchoring holes formed in this metal, the module can easily be attached a structural object. Moreover, the module has a weight of approximately 2 kg/m^2, which is extremely light.

Fig.6 Entrance to Fuji Electric's Tokyo Plant

Fig.7 Photovoltaic modules undergoing validation testing

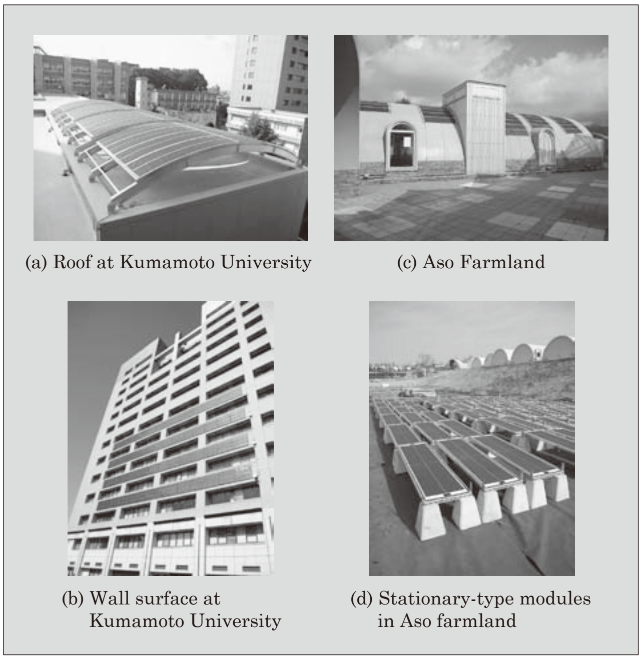


Figure 6 shows an example installation at the entrance to Fuji Electric's Tokyo plant. The modules are lightweight and thin and can be integrated with the walls, resulting in a natural appearance that is in harmony with the surroundings.

Following the experimental installation at the Tokyo plant, as a Japanese national project, the installation is being validated in collaboration with the Kumamoto Technology and Industry Foundation and Kumamoto University (Fig. 7).

Temporary and easy installations, whereby land for which there is no planned usage, such as unused farmland and other idle land, is utilized effectively by installing modules secured with wire or rocks so that they may be moved if the land subsequently is allocated to other applications, are also under consideration, and these installations are being validated.

Film-type modules fabricated exclusively with polymers are products that target mostly overseas applications with system integrators. Using a fluorinated polymer having excellent weather resistance as their surface material, these modules exhibit superior long-term reliability. Fuji Electric has accumulated expertise in adhesives, and this knowledge is included in the installation manual provided to customers so that the photovoltaic modules can be affixed securely to the desired adherend.

4. Postscript

This paper has introduced film-type amorphous photovoltaic modules and their application techniques. Through leveraging the advantages of lightweight, flexible and unbreakable film-type amorphous solar cells, Fuji Electric is determined to develop products that meet customer needs, to promote the usage of solar cells further through proposing various installation techniques, and to contribute to efforts to prevent global warming.

Supplemental Explanation

Heating values (HHV: Higher Heating Value, LHV: Lower Heating Value)

The “heating value” is the amount of heat released when combustion gas, resulting from the adiabatic and complete combustion of a unit quantity of fuel in a certain state, cools to its original temperature. The heating value can be expressed as either the higher heating value (HHV) or the lower heating value (LHV).

During the combustion process, the latent heat of vaporization of hydrogen gas, generated from the reaction between hydrogen and oxygen and also generated from the vaporization of moisture contained in the fuel, and the latent heat of condensation, obtained when the generated water vapor in the combustion gas condenses, are released. The latent heat of vaporization and the latent heat of condensation are included in the quantity known as the “higher heating value (higher heating value or gross heating value)”, but are not included in the quantity known as the “lower heating value (lower heating value or net heating value)”.

The standard heating values used in heating value calculations differ according to the country, type of statistics and equipment, and therefore care must be exercised when using these calculated heating values.

Higher heating values are used mainly in the following items.

(a) Comprehensive energy statistics and other similar types of statistics
(b) Power generating efficiency of thermal power plants in Japan
(c) Heating values used in the “Law Concerning the Rational Use of Energy” (Japanese Energy Act)
(d) Heating values used for calculating CO_2 emissions in Japan

Lower heating values are used mainly in the following items.

(a) Thermal efficiency of boilers
(b) Thermal efficiency of power engines such as diesel engines, gas engines and gas turbines
(c) Indication of co-generation performance
(d) Heating values used for calculating CO_2 emissions for IPCC (Intergovernmental Panel on Climate Change)

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