Review

Outlook on Gas Turbine

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Abstract

With the aim of preventing global warming, the Kyoto Protocol demands that Japan reduces its emissions of carbon dioxide (CO_2) to a level that is 6 % lower than 1990 levels. To this end, it is necessary to further promote energy conservation. One means of doing so is by introducing cogeneration systems. In addition, it is important to develop a technology that can make use of recyclable energy such as biomass fuel instead of fossil fuel. For Japan, moreover, it is good policy to have an optimum mix of energy sources, given that the country has meager energy resources of its own. In other words, there is a huge demand for energy-efficient and environmentally friendly technologies. The development of small-size independent distributed electricity generating systems is therefore important both technically and socially in order to promote the spread of cogeneration systems.

A gas turbine is a promising power source in that it can cleanly burn a range of fuel types and be used as the basis of a high-efficiency system. Therefore, using the technology accumulated from the development of gas turbines for automobiles, we developed a micro gas turbine for a cogeneration system that realizes an overall energy efficiency (electricity and heat) of 70 %. In this article, we will consider the past and present state of micro gas turbine technology, and consider its future prospects.

Keywords Gas turbine, Microturbine, Energy conservation, High energy efficiency, Cogeneration system, Carbon dioxide, Technical trend

1. Background and history

1.1 Introduction

The spark-ignition reciprocating engine was invented by Nicolaus A. Otto in 1876 and the compression-ignition reciprocating engine was invented by Rudolf Diesel in 1897. The principle of the gas turbine had existed for around 100 years before the invention of the reciprocating engine, however. It is said that the first person to apply for a patent was John Barber in 1791, but a practical gas turbine did not appear until the 1900s. Sir Frank Whittle devised a jet engine in 1930, which subsequently led to a flurry of research and development into gas turbines. In 1939, the first jet airplane (the Heinkel HE178) flew for the first time in Germany. In Japan, a turbojet named the "Ne-20" was developed at the end of the World War II and it was mounted on the "Kikka," which flew for the first time in 1945. A cross section of the Ne-20 is shown in **Fig. 1**. The engine consists of an eight-stage axial-type compressor, a single-stage axial-type turbine and an annular-type combustor. The Ne-20 produced a thrust of 490 kg/11,000 rpm, weighed 474 kg and had a compression ratio of 3.45. The Ne-20 was developed after repeated trial and error because only a piece of the drawing arrived in Japan from Germany. But we understand that the main structure of the gas turbine was the same as that used today. Since World War II, the performance of gas turbine engines for aviation has improved steadily. Aircraft manufacturers have aimed for faster speeds in the past and now aim for longer flight times or longer distances traveled, while carrying ever greater numbers of passengers. The inherent characteristics of the gas turbine make it extremely suitable for airplanes and these characteristics are fully exploited to develop engines with increased power.

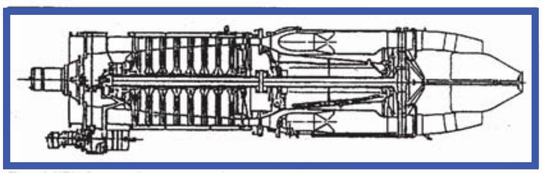


Fig. 1 "Ne-20" turbojet developed firstly in Japan in 1945.

In aviation, a gas turbine provides jet propulsion to power an airplane. In industry, on the other hand, a gas turbine generates mechanical power by spinning a shaft. For example, the gas turbine can be used to drive an electric generator, a refrigerator, and so on. BBC (Brown Boveri & Cie) developed the world's first gas turbine for electric power generation in 1939.[1] The output power was 4,000 kWe, the thermal efficiency was 17.4%, and the turbine inlet gas temperature (TIT) was 550 °C. BBC's gas turbine surpassed the performance levels of contemporary steam turbines. The gas turbine was thus maturing into an important technology for industry, also.

The performance of a simple-cycle gas turbine improves as the TIT and compression ratio increase. The latest large models of electricity generating plants have featured TIT values in excess of 1,500 °C. Each year, the TIT has risen by around 20 °C from around 500 °C in the 1930s to 1,500 °C today. This has been achieved through the development of high-temperature, heat-resistant materials and advances in turbine blade cooling technology. Through these technical advances, the specific output of a gas turbine system has risen to a point where gas turbine electricity generating systems in the 200-MWe class can be realized. The thermal efficiency of a simple-cycle gas turbine has reached around 40 %, but its performance can only be improved so far given current conditions. The highest levels of efficiency can only be obtained from combined electricity generating systems. Such combined systems consist of a gas turbine as the first stage and a steam turbine installed downstream of the gas turbine. The latest generation of such plants can output 1,000 MWe of power. They have a thermal efficiency (LHV standard) of more than 55 % and a TIT of 1,500 °C. The thermal efficiency for the electricity generating is shown in **Fig. 2**. The thermal efficiency of combined-cycle systems is more than 15 % better than that of simple-cycle gas turbines. For those classes below 10 MWe, the efficiency is actually inferior to those of a gas engine (GE) and diesel engine (DE). The maximum efficiency of a GE exceeds 45 % at 10 MWe. For gas turbines, the lowest class of output power ranges from 30 kWe to several hundred kWe. Any gas turbine with an output of 500 kWe or less is called a "micro gas turbine" (MGT). Their efficiency is around 25 % to 33 %, which is higher than that of simple-cycle gas turbines. In addition, the development of two ceramic gas turbines (CGT) in the 100-kW and 300-kW classes was undertaken as part of a New Energy and Industry Technology Development Organization (NEDO) project, and a thermal efficiency of 42 % was demonstrated for the 300-kW class CGT in 1998. Such units have yet to be commercialized, however.

From the 1960s to the 1990s, small-size gas turbines became a focus of study and development as a power source for vehicles by European, American (GM, Ford, Chrysler, Daimler Benz, et al.) and Japanese car makers (Toyota, Nissan, Mitsubishi). A gas turbine that is to be used in an automobile must be compact in order to be installed in a typical engine compartment. Furthermore, regenerative-cycle gas turbines became the focus of R&D because low fuel consumption was required for practical applications. The component technology for automotive gas turbines is slightly different from that of gas turbines for airplanes or large-scale generating plant. That is, low weight, high compression ratios, and compactness are the technical targets for gas turbines for airplanes, which are combined with a multistage axial-flow compressor and an axial-flow turbine. Because automotive gas turbines must offer compactness and low fuel consumption, however, regenerative-cycle gas turbines are the most promising branch of the technology. In a regenerative-cycle gas turbine, a low compression ratio leads to a higher thermal efficiency. To this end, the pressure ratio of the compressor is a relatively low 3 to 4. A rotating regeneration heat exchanger, a single-stage centrifugal compressor, and a centrifugal/axial-flow turbine are commonly combined to reduce the engine size. However, no gas turbine vehicles have ever been commercialized because the challenges of fuel consumption, durability, and low cost have yet to be overcome.

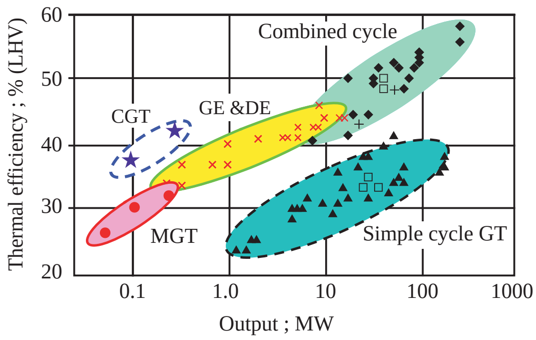


Fig. 2 Comparison of thermal efficiency with the output power.

1. 2 Features of MGT

In the latter half of the 1990s, "micro gas turbines (MGT)" appeared. These MGTs, which were based on the miniaturization technology that had been developed for automobiles, were developed for installation in distributed electricity generating systems and cogeneration systems. Capstone Engineering[6)] (USA) launched an MGT with a power output of 28 kWe and thus created a boom in the latter half of the 1990s. Their goal was to apply the MGT to various applications and to commercialize it at low cost by producing it in large quantities. The Capstone MGT is compact and smartly packaged, like a desktop computer. It's sleek and slender appearance hinted to many of the shape of things to come. Subsequently, several companies (**Table 1**; Capstone Engineering, General Electric, Ingersoll-Rand Energy Systems, Elliott Energy Systems, Bowman Power, TOYOTA Turbine and Systems, Turbec, Honewell, Honda, etc.) announced micro gas turbines ranging from a few kWe to around 300 kWe. So far, however, a few of these companies have actually commercialized their micro gas turbines.

The objective of the company's program is to develop the next generation of electricity generating systems that will propel the current generation of systems into more efficient, cost effective, and environmentally friendly systems. The MGT system is designed such that it addresses both the current and emerging distributed generation markets.

A micro gas turbine is a small-capacity gas turbine. In comparison with a conventional reciprocating engine, an MGT-powered cogeneration system offers the following advantages.

(1) Compact and low weight

(2) Low emissions and multi-fuel capability

(3) Virtually vibration free, long service life, and low operating costs
(4) Very simple design and low component count offers the promise of low mass-production costs
(5) Better part-load efficiency through variable speed operation

An MGT produces low-level NOx and CO/HC emissions without any exhaust after-treatment device, thanks to its use of continuous lean premixed combustion. The NOx emission characteristics[4] of Capstone's MGT are less than 5 ppm (O_2 = 16 %) over a power range of 18 kWe to 28 kWe. But, the NOx level in the power range below 18 kWe is very high at 30 ppm to 80 ppm (O_2 = 16 %).

Some MGTs adopt a self-acting air-lubricated bearing that needs neither oil nor an oil supply device. For instance, Capstone's MGT employs a foil-type air bearing, shown in **Fig. 3**. The structure of the bearing helps to prevent contact between surfaces in the event of unstable operation of the bearing axis as a result of axial vibration, because the thin foil can deform easily. This reduces both initial costs and running costs. Small mechanical losses are incurred as a result of adopting a high-speed direct drive alternator and a high-frequency inverter, and the thermal efficiency of the partial load is relatively high. The electric generation efficiency of the first generation of MGTs is almost 25 % to 30 % (Table 1), and is expected to reach 35 % to 40 % with the appearance of the second generation.

The MGT offers other advantages in that no coolant is necessary, and the exhaust heat energy is easy to use because the exhaust temperature is relatively high. The MGT is suitable for application

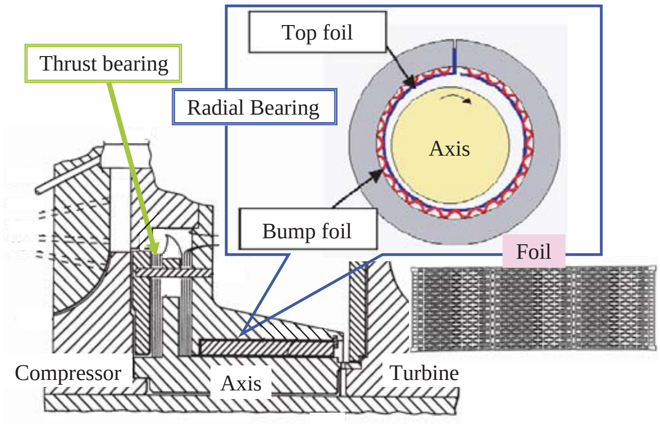


Fig. 3 Foil bearings incorporated in Capstone microturbine.[5-9]

Table 1 List of MGTs made by main companies.[2-6]

	Capstone C30	Capstone C60	Ingersoll-Rand's PowerWorks 250	TOYOTA Turbine & Systems TPC50RA	TOYOTA Turbine & Systems TPC300A	General Electric	Bowman Turbogen™ TG80RC-G
Electrical efficient (%)	26	28	32 (Target)	26	18	35 (Target)	28
Output power (kWe)	30	60	250	50	295	175	80
Mass flow rate (kg/s)	0.31	0.49	1.84	0.48	2.0		
Pressure ratio	3.5		4.1	3.5	6.7		4
Axial speed (rpm)	96,000	96,000	45,000	80,000	49,000/35,000		68,000
TIT (°C)	840		927	940	940		
Exhaust temp. (°C)	275	370		271	580		238
Exhaust energy (kW)	85	150		101 (Hot water)	1074 (Steam)		136
NOx (ppmv)	< 9 (15%O_2) (Natural gas)	< 9 (15%O_2) (Natural gas)	< 9 (15%O_2) (Natural gas)	< 15 (16%O_2) (Town gas 13A)	< 19 (16%O_2) (Town gas 13A)	≤ 10 (15%O_2)	< 25 (15%O_2)
Fuel	Gaseous propane or Natural gas	Natural gas	Natural gas	Town gas 13A, LPG, Kerosene	Town gas 13A, LPG, Kerosene	Natural gas	Natural gas, LPG, Propane, Butane
Maintenance interval (h)	8,000			12,000	12,000	11,000	
Life time (h)				48,000	48,000	45,000	
Sound level (Package)	65 dBA @ 10 m	70 dBA @ 10 m	72 dBA @ 1m	65 dBA @ 1 m	70 dBA @ 1 m		70dBA @ 1 m
Unit cost ($/kW)						≤ $500/kW (Target)	

to cogeneration systems that are used to supply electric power and steam at the same time. Furthermore, an MGT with an electricity generating efficiency of more than 40 % has been developed by adopting heat-resistant ceramics. If a CGT were to be put to practical use, the total thermal efficiency could be improved to exceed 80 %. We expect to see MGTs featuring in the construction of environmentally friendly distributed energy supply systems more and more in the future.

A hybrid electricity generating system incorporating a high-temperature fuel cell and a gas turbine has been suggested as another future technology, and is promising in that the efficiency of the electricity generating system will probably exceed 70 %. For example, there is one hybrid system with a high-temperature fuel cell (SOFC, MCFC) and an MGT. An MCFC/MGT hybrid system (with a rated rating output power of 300 kWe), aimed at achieving an electricity generating efficiency of 55 % has been developed, and this system was demonstrated at the Aichi World Exposition held in 2005 (March to September). This system uses town gas and/or biogas (generated from waste) as its fuel, making it well suited to the pursuit of a recycling society.

2. Activity at TOYOTA

2. 1 Progress within the TOYOTA Group

Research into gas turbines by the TOYOTA Motor Corp. (TMC) began in the 1960s, with automotive gas turbine development running from the mid-1970s until the mid-1990s. R&D related to automobile gas turbines at the TOYOTA Central Res. & Develop. Labs., Inc. (TOYOTA CRDL) began in the mid-1980s. TMC had been developing gas turbines for passenger cars or buses. **Figure 4** shows a TOYOTA GTV gas turbine passenger car which was powered by a GT41 gas turbine engine (**Fig. 5**). TOYOTA CRDL was mainly in charge of the compressors and combustors, which are the main components of an MGT. In the 1990s, TOYOTA CRDL participated in R&D related to a 100-kW class ceramic gas turbine (CGT) for use in automobiles. This was part of a project (April 1990-March 1997) sponsored by the Ministry of International Trade and Industry (MITI). In this project, we developed radial compressors, combustors and gas generators for the ceramic gas turbine. The CGT engine shown in **Fig. 6** was tested

Fig. 4 TOYOTA GTV passenger car powered by a GT41 gas turbine.

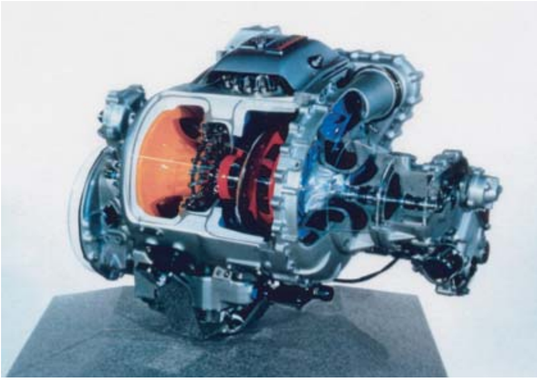


Fig. 5 TOYOTA GT41 gas turbine (output power of 110 kW).

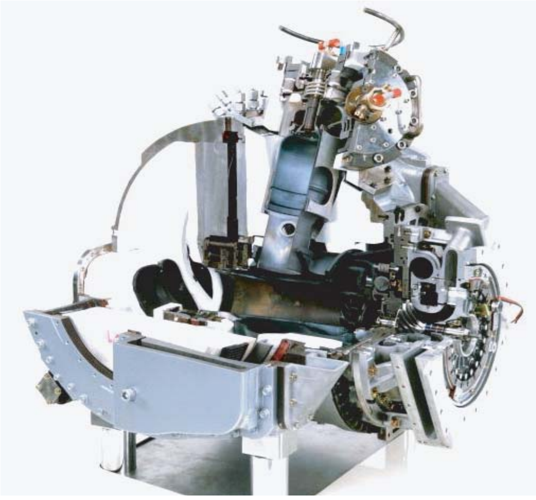


Fig. 6 Automotive 100-kW class ceramic gas turbine.

at a turbine inlet temperature of 1,350 °C. A power output of 95.3 kW and a best thermal efficiency of 35.6 % were achieved in the final engine tests at the end of the project.

When TMC started a project to develop micro gas turbines for cogeneration systems in the autumn of 1996, TOYOTA CRDL also participated. TOYOTA Turbine and Systems (TT&S) was established in 1998 and commercialized its first cogeneration systems using micro gas turbines. TOYOTA CRDL developed low-NOx combustors, high-compression ratio radial compressors, and component technologies based on oil-less, self-acting air-lubricated bearings for the 50-kWe class MGT.

TT&S developed and commercialized a 50-kWe class and a 300-kWe class MGT.[11-12] The 50-kWe MGT is available as a simple-cycle (**Fig. 7**) and recuperated-cycle (**Fig. 8**) unit with a single shaft that directly powers a high-speed electric generator running at a maximum of 80,000 rpm. The characteristics of cogeneration systems differ, so the two types of unit are offered. The simple-cycle MGT generates 50 kWe of power and 230 kW (heat value) of steam. The total thermal efficiency is around 72 % in a simple-cycle MGT cogeneration system. This unit is suitable for those users needing large amounts of steam. The recuperated-cycle MGT generates 50 kWe of power and 100 kW (heat value) of hot water. The total thermal efficiency is around 76 % in the recuperated-cycle MGT cogeneration system. This engine offers an advantage in that its electricity generating efficiency is good under partial loads, as indicated in **Fig. 9**. Unfortunately, this recuperated-cycle engine is comparatively large because it is combined with a heat exchanger. The appearance of this unit is shown in **Fig. 10**. It is also incorporated into a single-package cogeneration system. This cogeneration package is shown in **Fig. 11**. The cogeneration package with the recuperated-cycle gas turbine is offered as a single package that

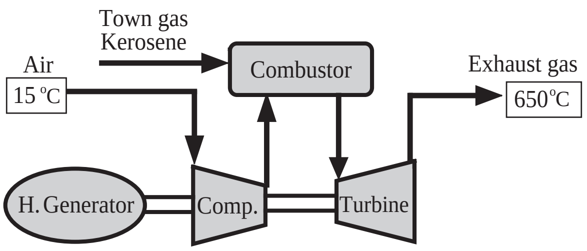


Fig. 7 50-kWe simple-cycle MGT.

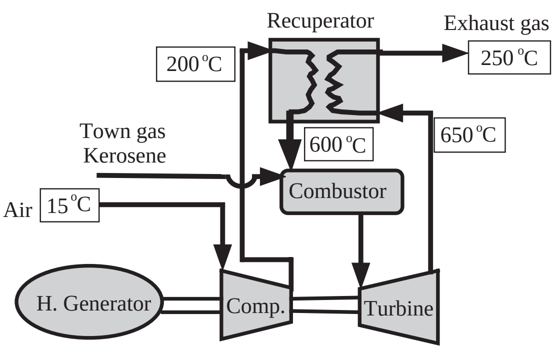


Fig. 8 50-kWe recuperated-cycle MGT.

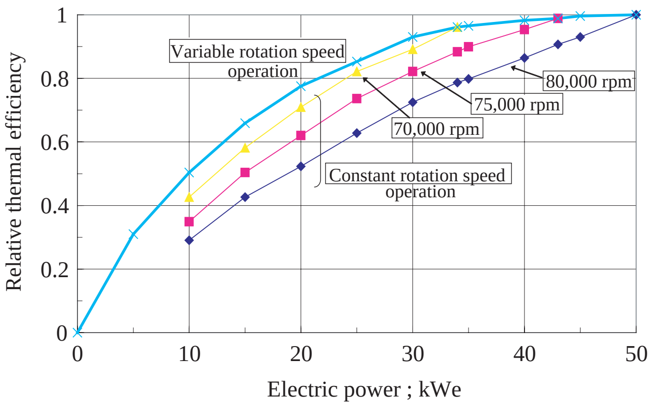


Fig. 9 Relative thermal efficiency of partial loads for the 50-kWe recuperated-cycle MGT.

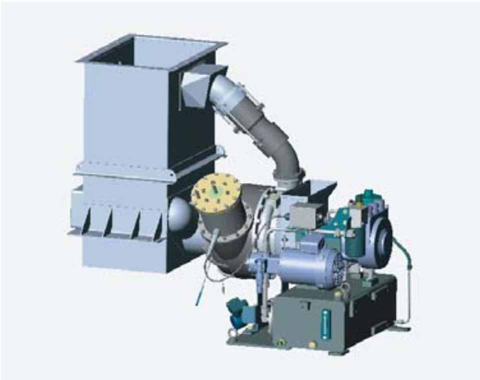


Fig. 10 50-kWe recuperated-cycle micro gas turbine engine (TT&S).

incorporates a gas compressor, an exhaust gas hot water boiler, an exhaust gas dump and protection facilities for grid-connected operation. The gas compressor is necessary to enable the use of town gas as a fuel, and is incorporated into a single-unit package.

The 300-kWe class MGT (**Fig. 12**) is a simple-cycle MGT. The simple-cycle MGT generates 295 kWe of power and 1,074 kW (heat value) of steam. The total thermal efficiency is around 83 % in a simple-cycle MGT cogeneration system. On the other hand, TT&S did not develop a 300-kWe class recuperated-cycle MGT because the heat exchanger for the 300-kWe class engine would have been larger and more costly than that for the 50-kWe class, so there would have been no cost merits. Originally, this class of unit was offered with two shafts, but is now offered with only one shaft so as to reduce the initial costs even further. Also, because there is no high-speed generator for this 300-kWe class unit, it employs a reduction gearbox that reduces the axis speed in order to drive a conventional generator. The engine cannot change its rotational speed because a conventional generator must rotate at a speed that matches the frequency of the grid to which it is connected. Therefore, the single-shaft 300-kWe class MGT runs at a constant speed. In comparison with the 50-kWe class MGT that is directly connected to a high-speed generator, and which varies its rotational speed, the control method is different. The 300-kWe class MGT does not include a lot of new technology, and can use conventional mass production technology. As a result, the unit price of a generation system using the 300-kWe class MGT can be reduced in comparison with that of the 50-kWe class MGT.

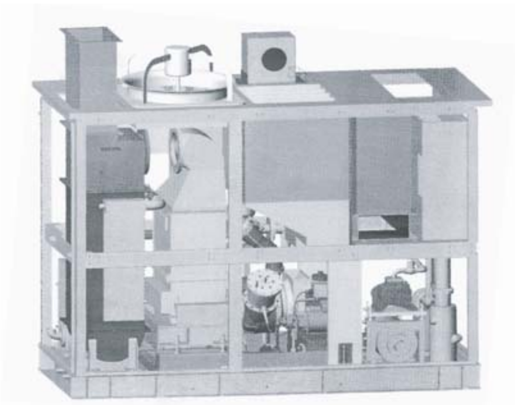


Fig. 11 Package of a 50-kWe MGT cogeneration (TT&S).

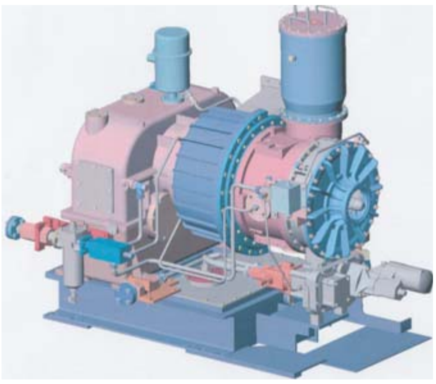


Fig. 12 300-kWe class simple-cycle and two shafts MGT (TT&S).

2. 2 Objectives of TOYOTA CRDL

Part of the research and development activities related to an MGT for cogeneration systems, undertaken by TOYOTA CRDL[12-18] after the latter half of 1990, the following three technologies are described in this special issue.

(1) Low-NOx combustor for gaseous and liquid fuels

(2) Investigation of self-acting air-lubricated bearing without oil lubrication

(3) R&D and demonstration of MCFC/MGT hybrid generation system

Low-NOx combustion technology, which is based on lean premixed combustion, limits the production of thermal NOx relative to diffusion combustion. This low-NOx combustion technology can be applied to both gaseous and liquid fuels. However, some means of atomizing and evaporating are needed for the liquid fuel, in contrast to gaseous fuel. Gaseous fuel (town gas type 13A) offers an advantage in that the NOx exhaust emission is lower than that of liquid fuel (kerosene). However, a fuel storage tank is necessary for kerosene, whereas the connection and piping for town gas is convenient and simple.

Fuel costs are fluctuating. Comparing town gas costs (per heat value) with those of kerosene, the both is currently almost equal. However, a gas compressor is needed to ensure that the gas is injected into the combustor at high pressure. The power needed to drive the gas compressor accounts for around 6 % of the rated output power. We developed a lean premixed combustor for gaseous fuel and a lean premixed prevaporized combustor for kerosene, both for application to the 50-kWe MGT. The details will be described in the following article.

Capstone's MGT adopted a foil-type air bearing instead of oil lubrication. However, foil bearing surfaces are reputed to have a low hardness and a small load capacity in a dynamic pressure type air bearing. For an MGT, we have to overcome the problem of the thrust performance being notably poorer than the radial performance. A high level of performance exceeding the design level at the rated load is necessary for application to the shaft of the MGT, although the bearing load of a foil type is largest in a conventional dynamic pressure type air bearing, as shown in **Fig. 13**. We investigated dynamic air pressure bearings that could exceed the performance of a conventional foil bearing. As a result, we devised a thrust air bearing with a sheet spring. The structure of the shaft is shown in **Fig. 14**. We carried out tests on the air bearing and confirmed that the bearing loss was two places lower than it would be with oil lubrication.

A hybrid electricity generating system with a high temperature type fuel cell and a gas turbine offers considerable promise as a high-efficiency future technology. It is expected that electricity generating efficiencies will exceed 70 % in the future. A 300-kWe class MCFC/MGT hybrid system was developed and demonstrated in a test running for more than 5,200 hours at the Aichi World Exposition held in 2005 (March to September). The electricity generating efficiency of this system was 52 % at maximum power, the highest currently achieved by such a hybrid system. This hybrid system uses biogas, which is generated from a waste, as its fuel, making it an ideal technology for a recycling society. The fuel cell is a complicated system. The control of its output power is delicate and difficult. We investigated and established that the controllability of the hybrid system could be improved by employing a new algorithm for the MGT operation. Details are given in another article.

3. Future trends for micro gas turbines

3. 1 MGT for cogeneration system

The advanced microturbine (as it is called in the USA) program is an ongoing 6-year study by the DOE in the USA, running through fiscal years 2000-2006, with government investment of more than $60 million. The American government is promoting the spread of dispersed power supply systems for several reasons. Existing electric power systems are heavily loaded. Distributed electricity generation could relieve this load. Lower installation and maintenance costs are a prerequisite to the widespread take-up of such systems. Future

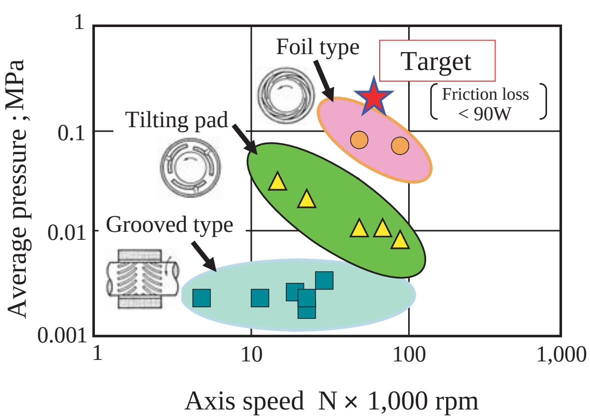


Fig. 13 Comparison between three types of dynamic air pressure bearings.

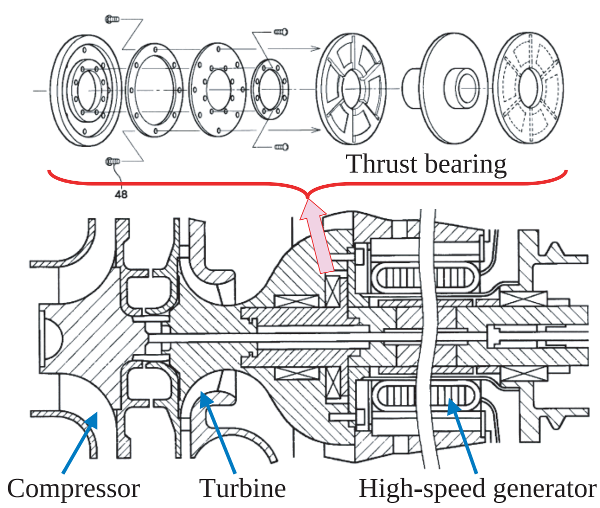


Fig. 14 Self-acting air lubricated thrust bearing with a sheet spring.

installations will see improvements in the areas of packaging and smaller footprints. R&D should continue to support complimentary technologies such as absorption chilling.

Although the Japanese market would appear to be very similar to the USA, it is important to remember that future market developments will be driven by economics. Regarding the spread of MGTs, "affordability" (obtained by dividing the system performance or function by the system cost) is a key word. The initial cost of existing systems is more expensive than ¥300,000/kW, but rapid adoption is expected when a price-point of ¥50,000 to ¥150,000/kW is realized in the future.

In addition, the following functions must be provided if electric generation systems are to be a success in the Japanese market.

(1) Controllability of variable output power (controlled number of MGTs)

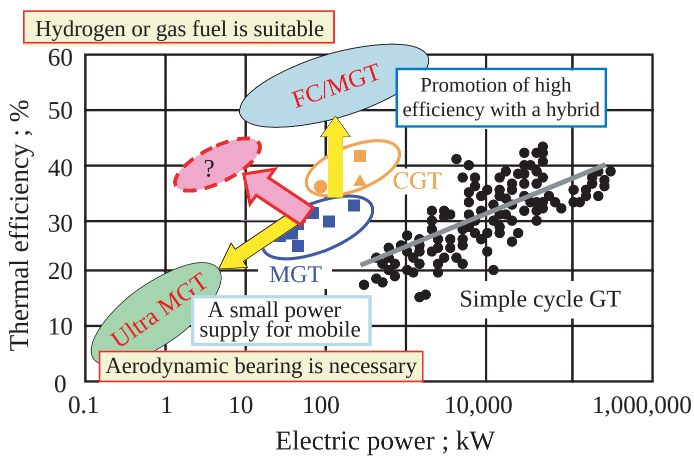


Fig. 15 Future prospects on gas turbine systems.

Fig. 16 300-kWe class MCFC/MGT hybrid system.[19)]

(2) Independent operation without system interconnection.

(3) Simple maintenance and reduced cost

(4) Low NOx and low CO exhaust emissions

3. 2 New technologies in gas turbines

At the frontier of electric generation technology, I think that R&D will go in two directions, as shown in **Fig. 15**. One is R&D related to hybrid generating systems that will offer high efficiencies of more than 60 %, while the other is R&D related to ultra micro gas turbines (UMGT), which should be able to provide portable power supplies, although at very low energy-conversion efficiencies.

3. 2. 1 Hybrid systems combining fuel cells and micro gas turbines

Table 2 lists four types of fuel cells. The MCFC and SOFC are high-temperature fuel cells. A hybrid power generating system combining a high-temperature fuel cell and an MGT is promising as a high-efficiency, next-generation system. A pressurized MCFC and MGT hybrid system (**Fig. 16**) was developed to demonstrate high power generation efficiency (target of 55 %) at the Aichi World Exposition, Japan. These high-temperature fuel cells have the ability to generate electricity more efficiently and benignly from hydrocarbon fuel. In particular, an SOFC/MGT, as shown in **Fig. 17**, offers considerable promise. Furthermore, operation that can satisfy changing demand may be possible because the performance of an FC is such that the efficiency at a partial load remains high compared with heat engines. However, improving

Table 2 List of four types of fuel cell.

	PEFC	PAFC	MCFC	SOFC
Electrolyte	Polymer membrane	Phosphoric acid	Molten carbonate	Ceramic
Movement ion	H^+	H^+	CO_3^{2-}	O^{2-}
Temperature (℃)	60∼100	150∼200	550∼650	800∼1000
Efficiency (%)	∼45	∼45	∼50	∼50
Hybrid system	—	—	50∼65	55∼70

<Note>
PEFC : Polymer Electrolyte Fuel Cell
PAFC : Phosphoric Acid Fuel Cell
MCFC : Molten Carbonate Fuel Cell
SOFC : Solid Oxide Fuel Cell

the controllability for generating electricity is an actual subject because an FC is a complicated system with a delicate balance of heat and mass flow rate. Although a hybrid system enables the easy control of heat and mass flow rate by combining the FC with an MGT, the development of hybrid systems is still in the early stages. We will be watching these development trends with interest.

3. 2. 2 Ultra micro gas turbine

A new technology called "micro electro mechanical systems" (MEMS) which employs a silicon-based micro-processing technique can be used to fabricate a wide range of micro mechanisms. For example, an ultra micro gas turbine (UMGT: from a few W to several kW, an output that this several degrees lower than that of an MGT) was studied and developed at MIT[20-23] in the latter half of the 1990s. After this, UMGT development has focused on the creation of a small-size but high-density substitute for portable batteries. The size of the UMGT is very similar to that of a dry cell, as shown in **Fig. 18**. This system has the advantage of being able to generate electricity for as long as fuel is supplied. There are some practical applications where this would be useful, even if we assume that the energy conversion efficiency would be around 3 %. If this portable UMGT were to be commercialized, we could expect to a many different applications.

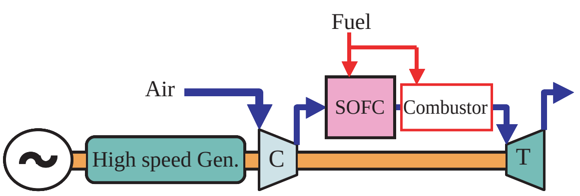
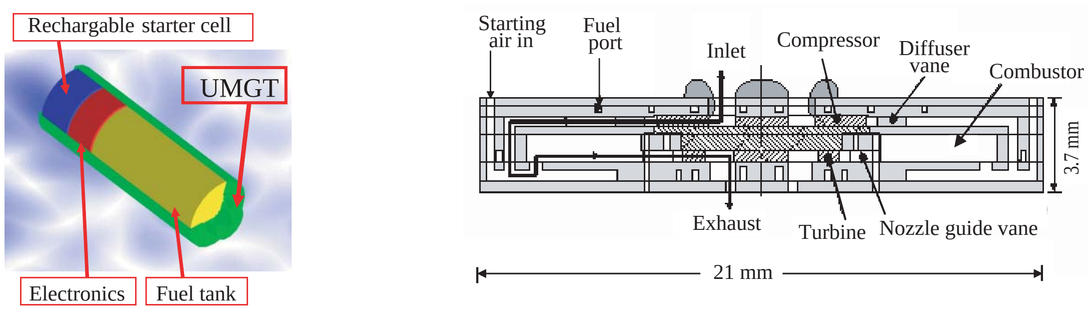


Fig. 17 Schematic of a SOFC/MGT hybrid generation system.

4. Afterword

This year (2005), it is 75 years since 1930 when Sir F. Whittle applied for his patent on the jet engine. In other words, three quarters of a century have passed. During this time, gas turbines have grown to produce ever greater power outputs, and the electricity generating efficiency now exceeds 55 % in the case of combined systems incorporating a steam turbine or a fuel cell. For small power systems, an ultra-micro gas turbine is being studied and developed as a portable power supply, and it is expected to become the next-generation mobile power supply.

In this way, I regard the gas turbine as being a representative invention of the 20th century, but what aspects of gas turbine technology will be transformed in the 21st century? Considering the technologies that have supported the development of gas turbines, we see innovations in material technology and massive progress in design technology. Furthermore, I think that the biggest driving force, which transcends the technology, is the dreams of researchers and engineers and their admiration and respect for the technology. That is, we have to wonder which dreams the researchers and engineers want to realize in the future.



(a) Dry cell system

(b) Schematic of a UMGT

Fig. 18 Dry cell and UMGT investigated at MIT.[20-24]

More than anything, I hope that gas turbine technology will make a major contribution to preserving the environment and creating a society that can coexist with nature.

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