

Research of Micro-gasturbine Generator

Koichi SHINMURA*

Koji YAMAGUCHI*

Sadachika TSUZUKI*

Hidemi KIMURA*

Takeshi KATO*

ABSTRACT

Research has been conducted on a micro-gasturbine generator as a compact distributed energy resource in order to improve energy usage efficiency. While aiming at a low emission level by introducing a premixed, lean-burning combustor, the engine has achieved a generation efficiency of 30.8 percent and the system achieved 26.7 percent by also adopting a recuperator and by reducing the heat and mechanical loss within its compact structure. Electricity output from the high-speed generator is converted into commercial power and supplied to the power grid. The engine, inverter and other auxiliary devices have been arranged into one compact package, achieving the highest performance and lowest noise level in the 40 kW class. Further modifications of the engine have improved the efficiency to 32.9 percent at the engine end.

1. Introduction

Most electrical power demand thus far has been supplied by large-scale thermoelectric, hydroelectric, and nuclear power plants. Higher efficiency has been pursued by increasing the scale of these facilities, but this has in turn created the issues of long construction periods, mounting equipment costs, and transmission loss over the long distances to the demand sites. Factors, such as global trends toward electric power deregulation and the increased environmental load of nuclear power plants and other facilities, have raised interest in distributed generation. Of these, micro-gasturbine generators are gathering attention due to expectations for lower costs from mass production and for reduced environmental load as a result of improvements both in generation efficiency, by adoption of a recuperator, and in low emission combustor performance^{(1), (2)}.

2. Research Aims and Themes

environmental technologies. As a part of these efforts, the company has promoted research on distributed energy to improve energy usage efficiency and to meet a part of the electrical power demand.

This research's aim is to realize a micro-gasturbine as a distributed generation (grid connect) system based on the concepts of 1) superior cost performance through high efficiency generation and long life, 2) environmentally friendlier with low emissions, and 3) a quiet and compact package. The research themes were as follows.

Themes

Engine

- A high efficiency, compact recuperator
- A compact, high-speed generator for a simple shaft configuration
- A premixed, lean-burning combustor for a low exhaust gas emission level

Electric power conversion system

- A compact and long-life inverter
- Optimum control for improving the electricity quality

Package

Honda is tackling the practical application of advanced

* Wako Research Center

- A compact package with a small installation space
- Easy maintenance
- Quiet

3. Major Specifications and Overview

Table 1 gives the major specifications of the newly developed generator system, and Fig. 1, Fig. 2 and Fig. 3 show internal and external views and the system configuration. The gasturbine engine of this system uses a recuperator to recover the energy of the exhaust gas, and has a simple, single spool structure with a high-speed generator directly coupled to the centrifugal compressor and radial inflow turbine.

The fuel used is ordinary town gas 13A which is pressurized to approximately 560 kPa by a fuel gas booster and then supplied to the gasturbine engine through a metering valve. The 1.3 kHz high frequency AC generated by the high-speed generator is converted to DC by the converter unit of the electric power control system, and then converted to commercial 3-phase AC by the inverter unit and connected to the grid.

Table 1 Major specifications of micro-gasturbine generator

Items	Specifications
Type of output	3 phase 200VAC, 50/60Hz
Rated output (kW)	42 (ISO conditions)
Thermal efficiency (engine end) (%)	30.8 (ISO conditions)
Thermal efficiency (system end) (%)	26.7 (ISO conditions)
Emissions (CO, HC, NOx) (ppm)	< 3
Fuel type	Town gas 13A
Dimensions (W × D × H) (mm)	1 506 × 942 × 1 501
Weight (kg)	950
Life (hr)	60 000
Noise level (dB(A))	65 (at 1m)

The auxiliary oil system lubricates the engine shaft bearings and cools the generator stator, and the oil cooler fan also ventilates the package interior. In addition, an air pump is used to ensure the differential pressure at the bearing oil seal.

The package design was divided into upper and lower

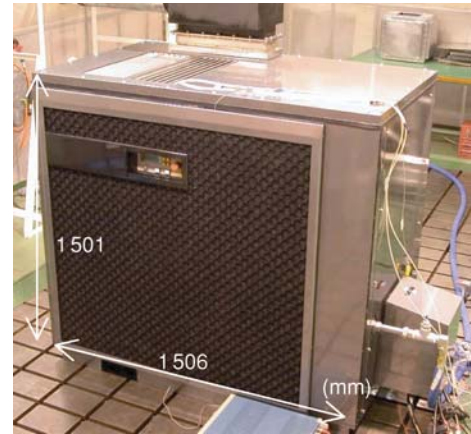


Fig. 1 External view of micro-gasturbine generator

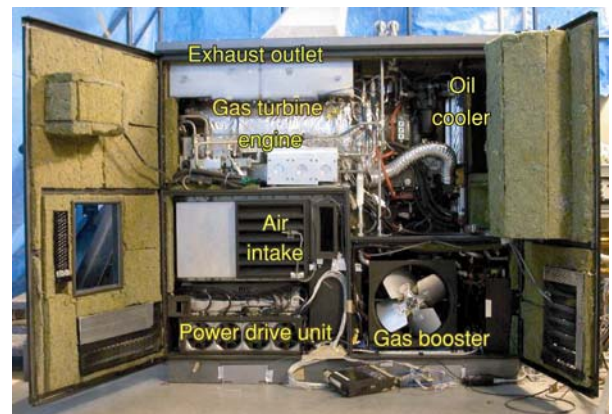


Fig. 2 Internal view of micro-gasturbine generator

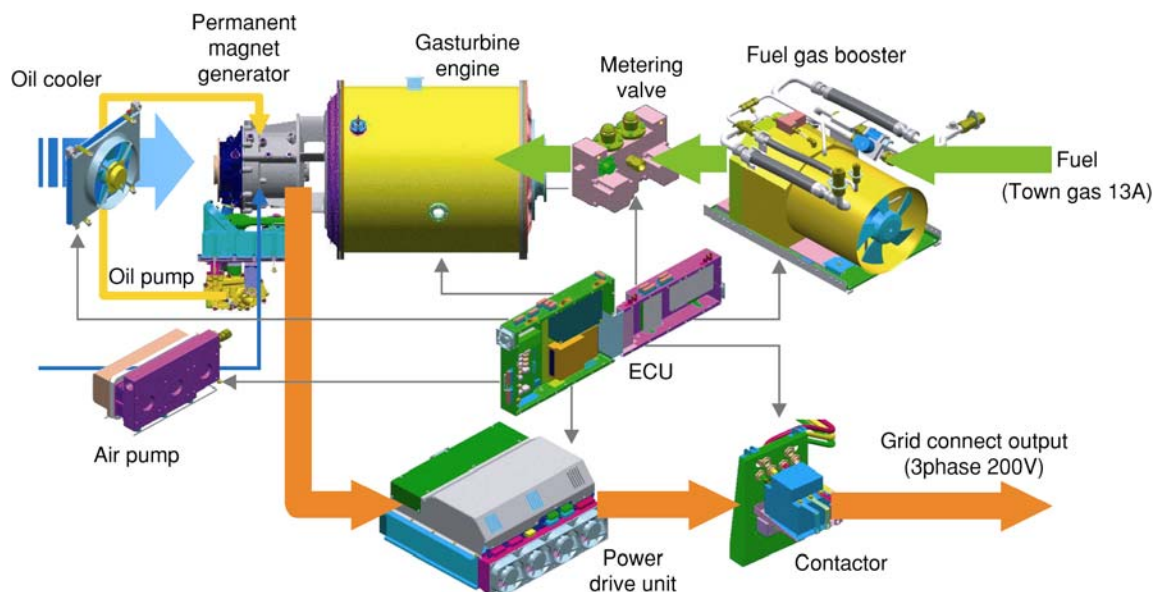


Fig. 3 System diagram of micro-gasturbine generator

sections as shown in Fig. 2 to allow efficient ventilation of the package interior. The engine and other heat sources are located in the upper section, and the engine air intake duct, electric power conversion system, electrical fittings and other components with low heat tolerance are located in the lower section. The required maintenance space was also reduced by adopting a layout that allows all components to be inspected and replaced from the front during periodic maintenance. The size is the smallest in the 40 kW generator class.

The dominant noise is the noise leak from the ducts. To reduce this noise, a 3-vent structure with sound absorbing material was adopted for each duct. This reduced the noise level to 65 dB (A)/1 m (a level that allows daytime operation in a commercial district).

Figure 4 shows the engine and system performance. A generation efficiency of 30.8% at the engine end and 26.7% at the system end was achieved under standard atmospheric conditions. This is the highest performance level in the 40 kW class (Fig. 5). In addition, gasturbine performance generally drops as the air temperature rises, but these effects were suppressed by varying the engine speed.

The engine combustor adopted the premixed, lean-burning method⁽³⁾ using a multi-venturi mixer that generates a homogenous air-fuel mixture. This method allows stable combustion while suppressing the flame

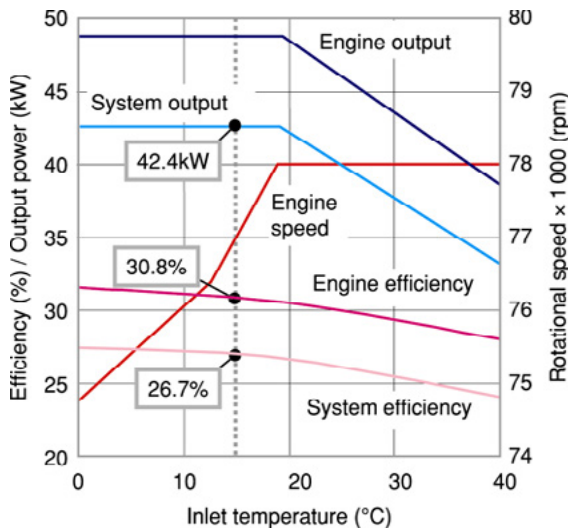


Fig. 4 System and engine performance characteristics

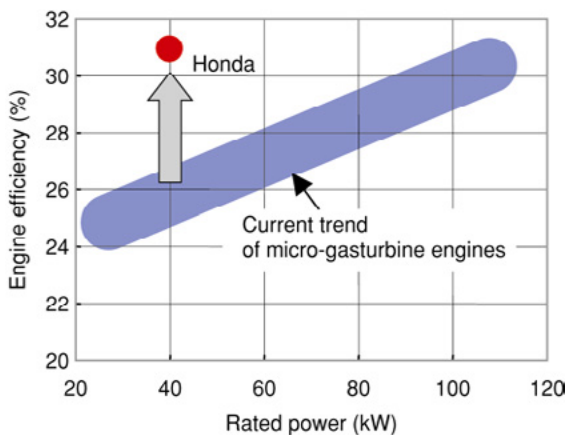


Fig. 5 Honda engine compared with current trend

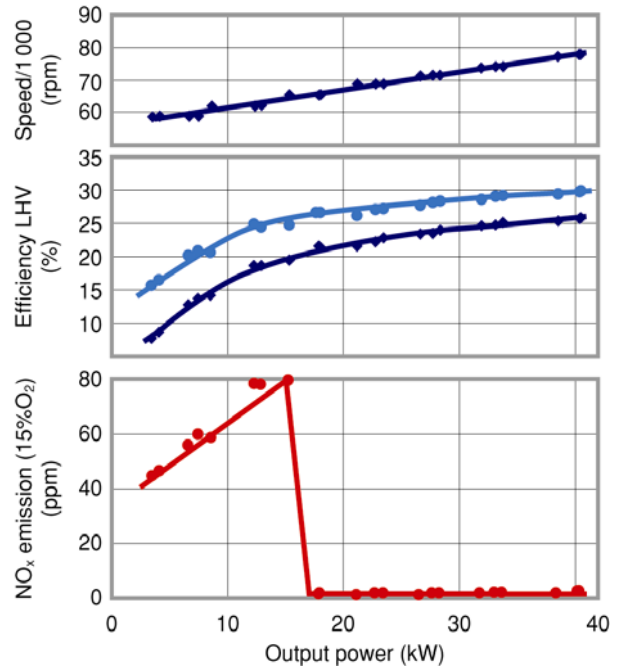


Fig. 6 System emissions and efficiency (at inlet temp. 24 °C)

temperature, and achieved an emission level of 3 ppm or less (NO_x , CO, HC at 15% O_2) over the wide operating range from 50% to 100% engine load (Fig. 6). This is lower than the average value for all power plants including nuclear power plants⁽⁴⁾.

4. Engine

The gasturbine engine efficiency generally tends to drop together with the size. This is caused by 1) increased loss due to a relative increase in the rotor tip clearance, 2) limitations on raising the turbine inlet temperature (difficulty in incorporating a complex cooling structure), and 3) a relative increase in the bearing and other mechanical losses.

The efficiency of the newly developed engine was improved by adopting a regenerative cycle using a recuperator which recovers the heat of the exhaust gas (Fig. 7). In addition, the recuperator has a multi-tube structure with an annular shape. This made it possible to locate high temperature parts on the inside and to cover the outer circumference of the engine with low temperature air from the compressor, thus greatly reducing the radiation loss to the outside from the turbine exit passage, the recuperator,

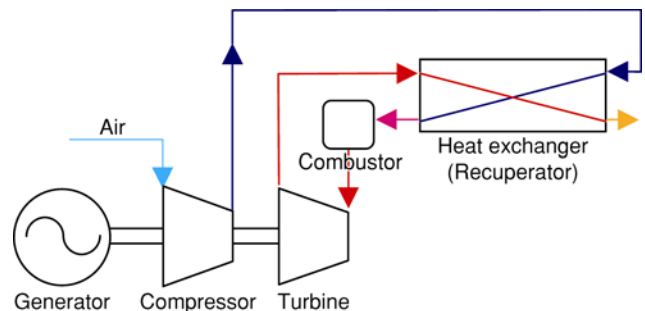


Fig. 7 Flow chart of recuperated gasturbine cycle

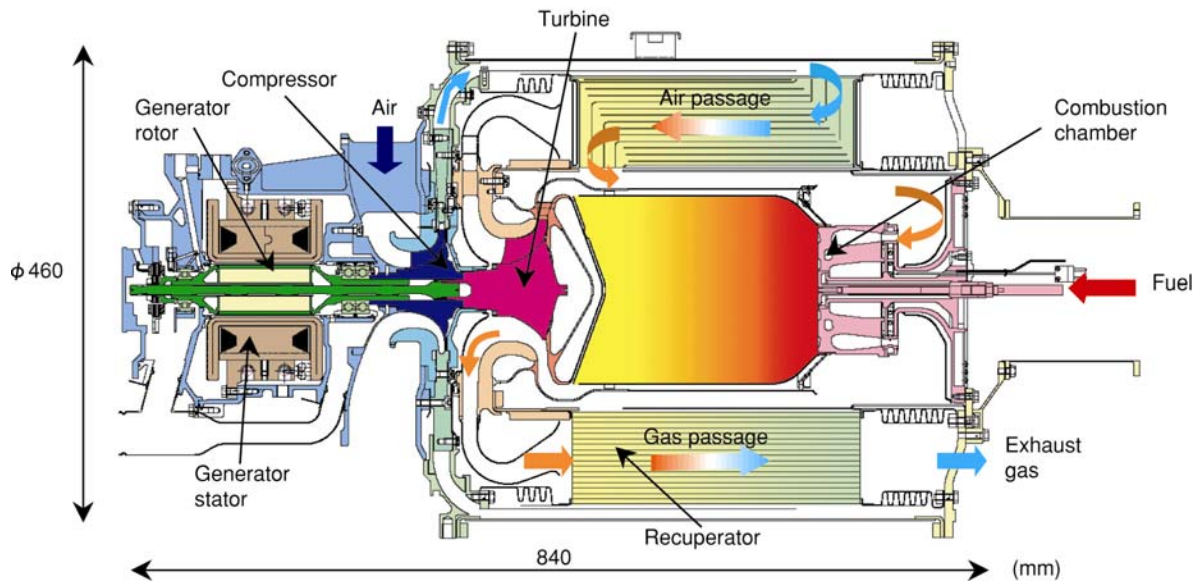


Fig. 8 Cross-sectional view of micro-gasturbine engine

etc. Mechanical loss was reduced by adopting a single spool structure with the high-speed generator directly coupled to the centrifugal compressor and radial inflow turbine, thus eliminating the need for reduction gears. Figure 8 shows the engine structural drawing. This structure is axially symmetric, which reduces the stress on high temperature parts with a large temperature gradient.

Table 2 gives the engine specifications, and Fig. 9 shows a comparison of estimated and experimental results of the

improved engine efficiency through exhaust heat recovery by the recuperator. The Version 1 engine mounted in the system had a recuperator temperature efficiency of 87.6% and a generation efficiency at the engine end of 30.8%. In contrast, the Version 2 engine was further modified to reduce friction and improve the recuperator temperature efficiency to 90.6%, thus achieving a generation efficiency of 32.9% at the engine end⁽⁵⁾.

The gasturbine engine efficiency can be improved by increasing the turbine inlet temperature (TIT), but this has a large effect on the life span of high temperature parts. The newly developed engine set the TIT at 900 °C in consideration of this life, and the results of FEM analysis with the accuracy confirmed by high temperature spin tests and measurements of turbine component temperatures during operation provided prospects for a turbine life span of 60 000 hours.

In addition, engine overspeed burst tests were conducted to verify that fragments did not fly out of the engine even in the event of rotor burst, and the safety was confirmed.

The recuperator and the high-speed generator, which are the major components, are described below.

4.1. Recuperator

Table 3 and Fig. 10 show the major specifications and the external view, respectively. The annular shaped recuperator has compact and highly efficient counterflow passages.

Table 2 Engine specifications at ISO conditions

Items	Specifications	
	Version 1	Version 2
Engine speed (rpm)	77 000	
Turbine inlet temperature (°C)	900	
Max. electrical output (kW)	47.8	51.7
Engine efficiency (%LHV)	30.8	32.9
Recuperator temperature efficiency (%)	87.6	90.6
Dimensions (mm)	φ460 × L840	
Weight (kg)	145	

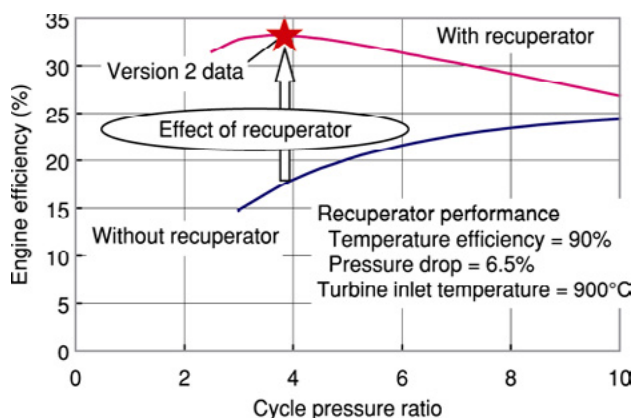


Fig. 9 Relationship between cycle pressure ratio and engine efficiency

Table 3 Recuperator specifications

Items	Specifications
Core size (mm)	φ430 × L289
Core weight (kg)	45
Material	SUS304
Plate thickness (mm)	0.1
Flow rate (kg/s)	0.4
Temperature efficiency (%)	90.6
Pressure drop (%)	6.4

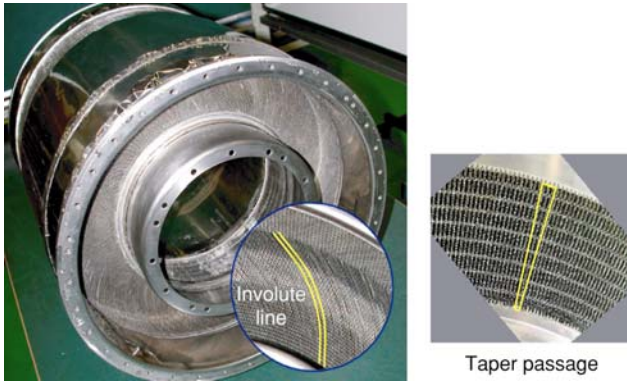


Fig. 10 Front view of recuperator with two different passage types

The main factor lowering the recuperator temperature efficiency is generally an uneven air and exhaust gas flow profile. Figure 11 shows the results of estimating the drop in temperature efficiency due to the flow profile. Line A shows the case when the exhaust gas and air flow profiles match, and line B shows the case when these do not match. According to these estimation results, the target flow profile value needed to achieve the target efficiency of 90% has a standard deviation of 0.07 or less (area Q in Fig. 11).

When the heat exchange plates are arranged radially in an annular shaped recuperator, the passages become tapered with a narrower passage width on the inside and a wider passage width on the outside (Fig. 10). This produces a distorted flow which causes the efficiency to drop (point P in Fig. 11). To prevent this distorted flow, an involute shape was adopted which has a constant passage width at any cross section. In addition, the air passage turns the flow, so the flow profile easily becomes slanted towards the inside. Therefore, the flow profile was equalized by placing ribs in the turn

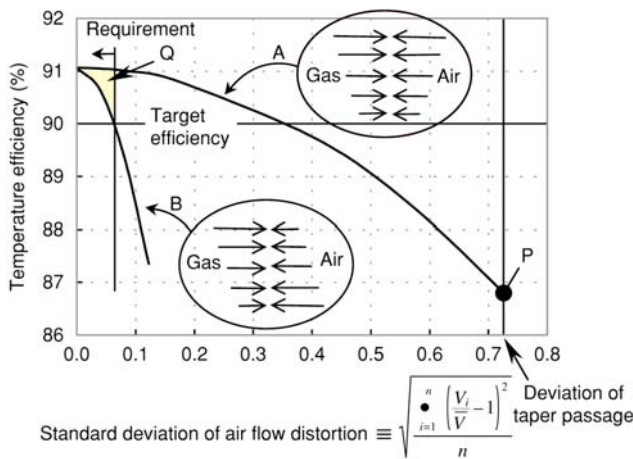


Fig. 11 Calculated effect of flow distortion

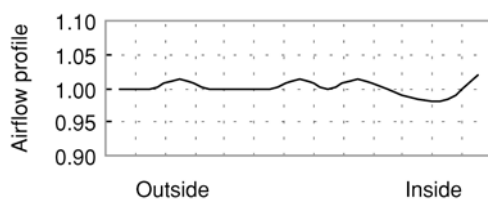


Fig. 12 Air flow profile at 100%N

sections to control the flow (Fig. 12). Temperatures inside the recuperator were measured to confirm the effect. The results are shown in Fig. 15. The temperature drops at a constant gradient from the inlet to the outlet, indicating that heat transfer is performed evenly throughout the entire recuperator.

The heat exchange plates have a primary surface structure that does not use fins or other separate parts. The stainless steel plates that form the exhaust gas passages are corrugated plates shaped into fins. These are matched with rib-pressed stainless steel plates that form the air passages, and both are laser welded along the sides to form a pair (Fig. 13, Fig. 14). 510 of these plates are then brazed into an integrated annular shape to create air and exhaust gas seals. The size and weight

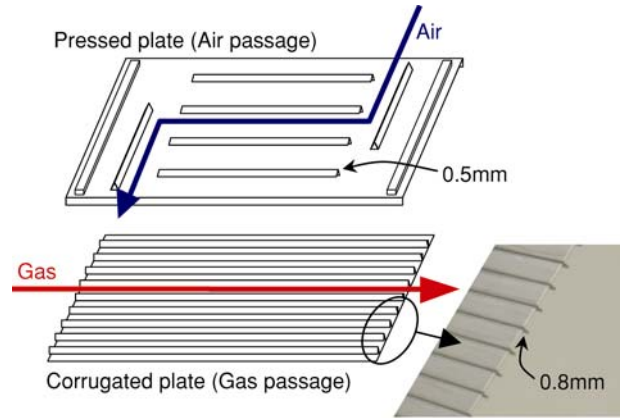


Fig. 13 Plate model of passage

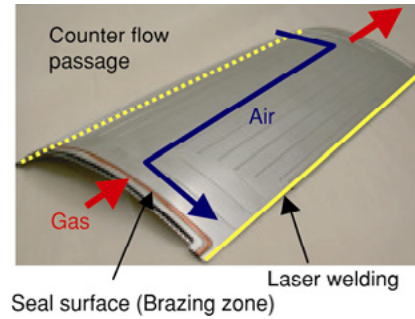


Fig. 14 Laser welded cell (Involute shaped)

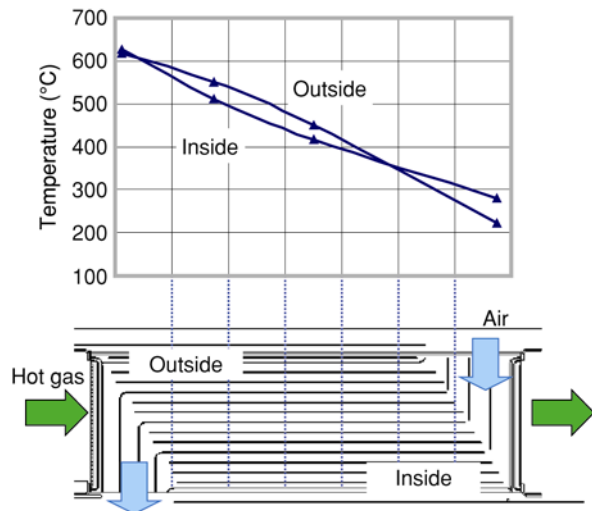


Fig. 15 Measured temperature of recuperator

were reduced by using small air and exhaust gas passage heights of 0.5 and 0.8 mm, respectively, and raising the coefficient of heat transfer. The total seal length for all 510 heat exchange plates is 306 m for the laser welded portions and 122 m for the brazed portions, but the leak amount was kept to 1% or less (equivalent to a non-sealed area of $\phi 2.7$ mm).

Preventing flow distortion and developing a brazing method for a leakless recuperator fulfilled the recuperator efficiency target of 90% or more.

4.2. High-Speed Generator

The high-speed generator is a permanent magnet type and is directly coupled to the engine. Table 4 gives the major specifications, and Fig. 16 shows a structural drawing of the rotor. Using an integrated shaft reduces the number of bearings which in turn reduces mechanical loss; however, the shaft length must be shortened to avoid shaft bending resonance, and the structure must be capable of supporting a low strength magnet at high revolutions. In addition, a sufficient amount of magnetic flux must be ensured with this limited size, and rotor eddy current loss and stator loss must also be reduced.

To ensure the amount of magnetic flux needed for the required output, the generator rotor uses a permanent magnet (Nd Fe B) with a high magnetic flux density. This magnet was shrink fitted onto a high strength nickel-chrome alloy tube to create a structure with a compressive load even at high revolutions.

Rotor eddy current loss not only lowers the efficiency, but also heats the ring, resulting in demagnetization of the magnet due to the temperature rise and a lower magnet compressive load due to thermal expansion of the ring, ultimately impairing basic functions. The teeth in a slot type stator have low reluctance so magnetic flux passes easily through the teeth, causing fluctuation of the magnetic flux which can easily produce eddy currents on the rotor surface. As a countermeasure for preventing this eddy current loss, a slotless type stator was adopted in which the coil is arranged in a cylindrical shape on the inside of a toothless core (Fig. 17). The coil is formed by heat pressing self-bonding wires (Fig. 18).

Table 4 Generator specifications

Items	Specifications
Generator type	Permanent magnet
Rotor size (mm)	$\phi 48.8 \times L90$
Magnet material	Nd Fe B
Stator type	Slotless
Electromagnetic conversion efficiency (%)	97

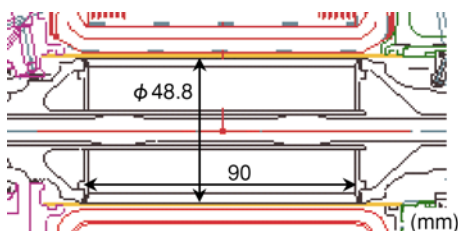


Fig. 16 Cross-sectional view of generator rotor

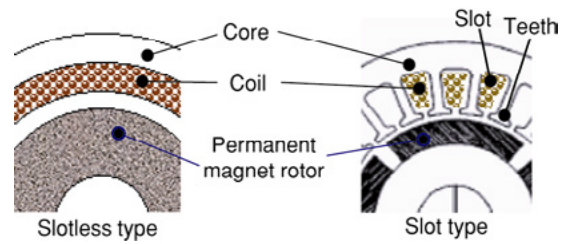


Fig. 17 Structures for slotless and slot stator

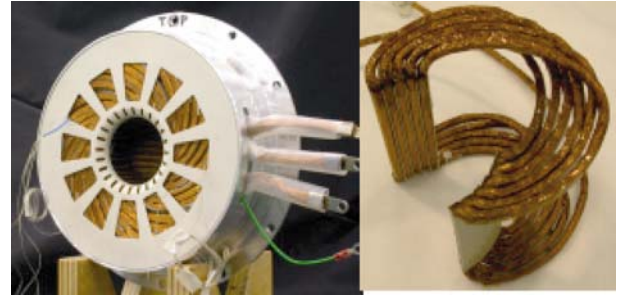


Fig. 18 External view of stator coil

In addition to copper loss caused by the resistance inside the coil, stator loss also includes eddy current loss which occurs inside the strands due to magnetic flux fluctuations and circulating current loss which is caused by the phase difference between each strand in an in-phase bundle. Both of these losses can be reduced by using fine strands ($\phi 0.3$), and by adopting Litz wire twisted together with strand bundles.

Ensuring a sufficient amount of magnetic flux and reducing both rotor eddy current loss and stator loss in this manner resulted in a generator efficiency of 97%.

5. Electric Power Conversion System

The electric power conversion system must ensure an output electric power quality that conforms to the grid connect guidelines and other regulations^{(6), (7), (8)}, and must also be highly efficient and compact.

Table 5 gives the achieved values and the major specifications. The electricity quality as measured on an actual grid shows a power factor of 0.99 and a total harmonic distortion (THD) of 3.5%, both of which easily clear the respective standard values of 0.95 or more and 5% or less as prescribed by the grid connect guidelines and other regulations. With this high power factor and measures, such as reducing the DC filter loss, the efficiency achieved was 95.1% at rated power.

Table 5 Electric power control unit specifications

Items	Specifications
Type of control	3 phase PWM control
Output power (kW)	42
Efficiency (%)	95.1
Total harmonic distortion (%)	3.5
Power factor	0.99
Volume (litter)	87
Weight (kg)	98

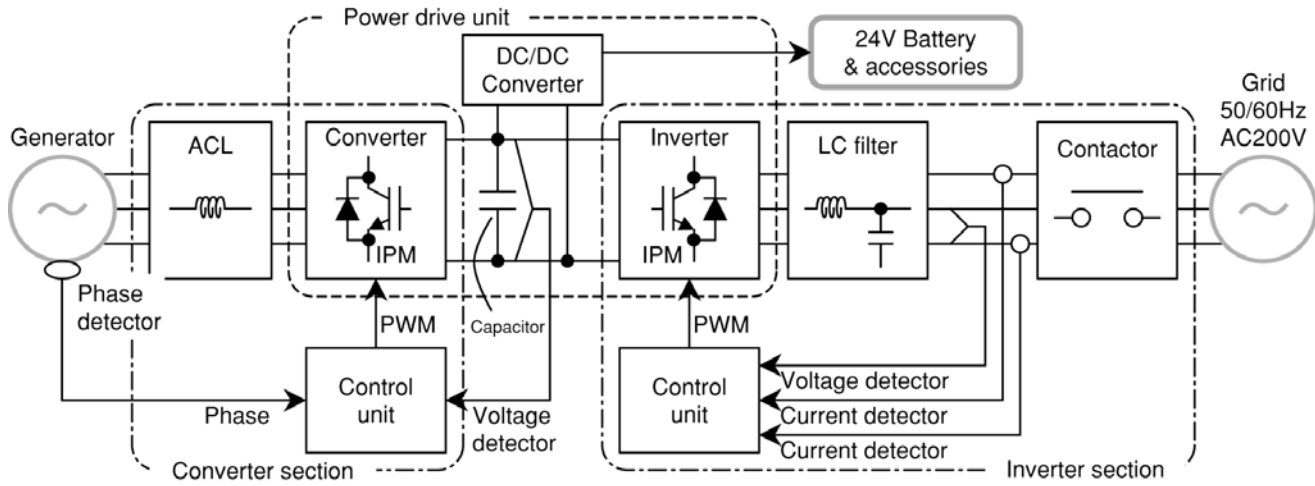


Fig. 19 Block diagram of electric power control system

Figure 19 shows the block diagram. This electric power control system is comprised of a converter unit that commutates the high frequency AC from the high-speed generator into DC, a DC filter capacitor group, an inverter unit that converts the DC into commercial 3-phase AC and connects it to the grid, and a DC/DC converter for the auxiliary power supply.

Figure 20 shows the power drive unit (PDU) which is the major portion of the electric power conversion system. The hot switching devices (converter and inverter) and the DC/DC converter are concentrated in a single area over a heat sink to increase the cooling efficiency and reduce the size. In addition, the converter and inverter have been combined into an integrated structure and the output control responsiveness has also been improved. This made it possible to reduce the DC filter capacitor charge/discharge loss, and achieved high efficiency with a small volume while ensuring the required long life span of 60 000 hours.

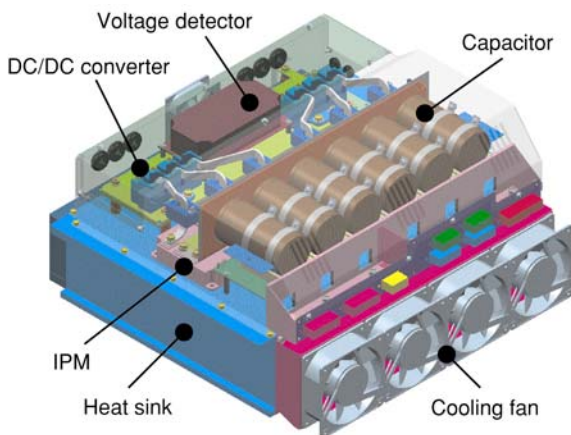


Fig. 20 Detail of power drive unit

5.1. Converter Unit

When converting the AC voltage of the high-speed generator to DC, systems that use ordinary diode commutation only can provide a low DC voltage at low engine speeds and cannot supply electric power to the grid. In addition, there is also the disadvantage that an inverter must

be installed separately to power the generator as a motor during engine startup.

On the other hand, the pulse width modulation (PWM) system can generate the desired DC voltage at any engine speed, making it possible to supply electric power to the grid over a wide range from low speed to high speed. Furthermore, starter functions can be obtained by simulating inverter action with the PWM, which helps to reduce the size. For these reasons, the PWM system was adopted for the converter unit, and by performing vector control for each phase current enabled high efficiency and stable operation over a wide operating range.

5.2. Inverter Unit

The inverter must ensure an electricity quality (power factor, harmonic distortion, etc.) that conforms to the above-mentioned grid connect guidelines and other regulations, and must also possess functions to protect the grid when trouble occurs, such as when isolated operation is detected. In order to satisfy the required electricity quality, high accuracy grid voltage phase detection and high-speed current waveform shaping control were adopted. As a result, the low-order harmonics were reduced and the LC filter in the output stage only needed to eliminate the switching harmonics, which helped to reduce the size. In addition, the various processing needed for the grid connect protection functions was performed by software, making it possible to satisfy the required functions without adding new dedicated circuits or other components.

6. Engine Control

The generator must not only provide the rated power, but must also be capable of continuous generation at partial power (rated or less). There are two methods for controlling the output with a single spool gasturbine engine such as this system. The first is to fix the engine speed and lower the turbine inlet temperature (TIT) and the turbine exhaust temperature (TET) as shown in Fig. 21, and the second is to lower the engine speed and operate near the temperature upper limit. In consideration of the engine characteristics, the latter method which has less of a drop in engine thermal efficiency was adopted.

On the other hand, the gasturbine engine speed changes

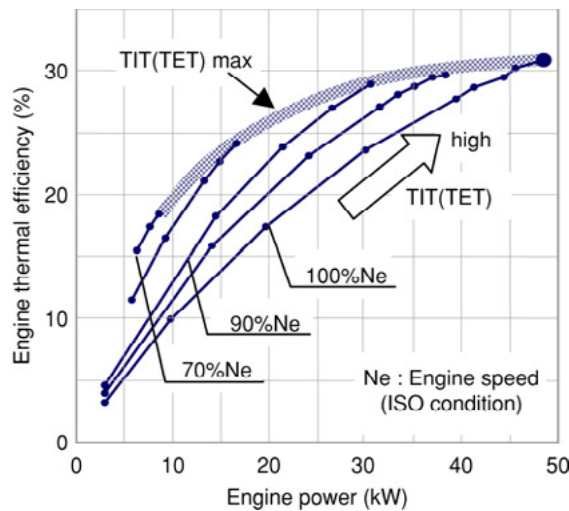


Fig. 21 Engine performance

when TIT or TET reaches the upper limit depending on the air temperature (T1) and air pressure (P1), so control that allows operation which traces an efficient line under any atmospheric conditions is required. When a method that directly feeds back the TET and other temperatures is used, the transient characteristics prevent the control period from being shortened, which means that stable control and a fast transient response cannot be obtained. For these reasons, the stability was improved by adopting an engine speed control method that uses engine performance map data.

Figure 22 shows this engine control block diagram. The TIT and TET characteristics relative to the engine speed and output are converted to map data, and the appropriate operation line at that time is derived from that map and the sensed T1 and P1 (upper block). The target engine speed is then obtained and engine control is performed based on this

operation line and the required output value (lower block). T1 and P1 are not subject to sudden changes, so the operation line update interval can be made sufficiently longer than the engine speed control period, thus reducing the processing load. This control method succeeded in reducing the engine speed fluctuation at rated power to ± 100 rpm or less.

In addition, the engine characteristics may change gradually when operated for long periods, but these time-based changes are supported by sensing the TET and periodically correcting the initially set map based on the difference from the TET assumed from the map.

7. Conclusions

Research on a micro-gasturbine generator as a compact distributed energy resource was conducted in order to improve the energy use efficiency, and the following results were obtained.

- (1) A generator system equipped with a high efficiency regenerative cycle engine was developed which satisfied the life span and safety requirements. This system achieved a generation efficiency of 30.8% and 26.7% at the engine and system ends, respectively. These are currently the highest reported values in the world for the 40 kW class. In addition, further improvements to the engine unit resulted in a generation efficiency of 32.9% at the engine end.
- (2) An emission level of 3 ppm or less was achieved over the wide output range from 50% to 100% by a premixed lean burning combustor that uses a multi venturi mixer. This is lower than the average value for all types of power plants including nuclear power plants.
- (3) The engine, inverter and other components were arranged into a compact package in consideration of heat and ease of maintenance, and the low noise level of 65 dB (A)/1 m was achieved.

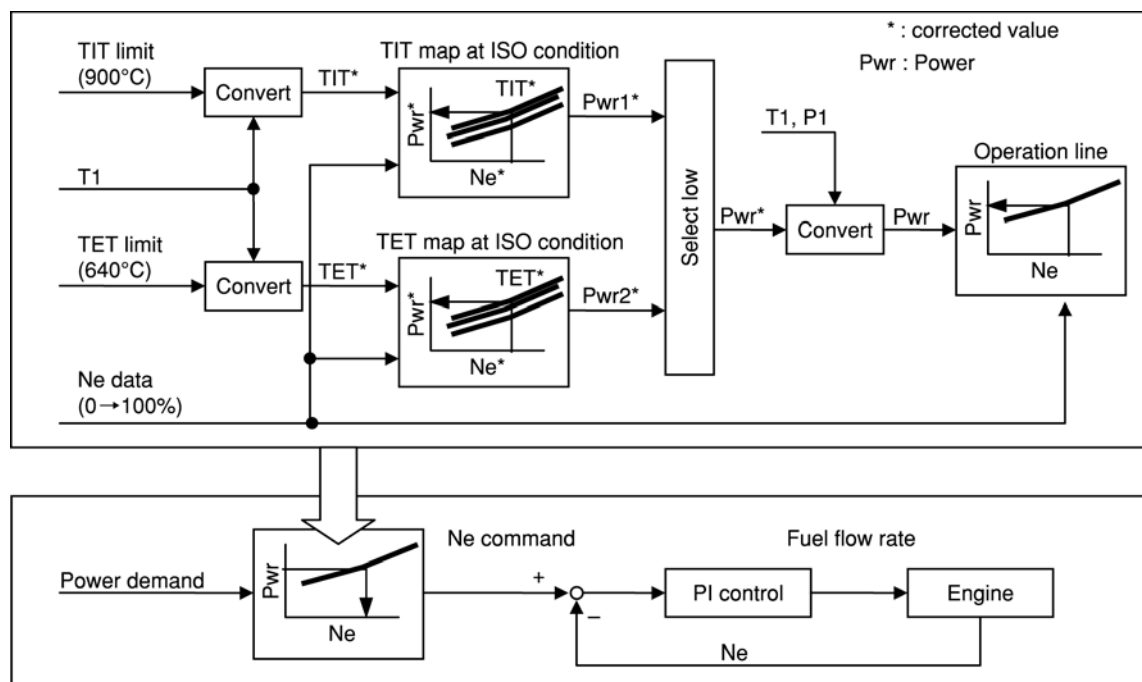
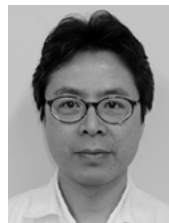


Fig. 22 Engine control block diagram

References

- (1) Yoshiki, H.: Development and Problems of Micro Gas Turbines, Journal of the Gas Turbine Society of Japan, Vol. 29, No. 3, p. 123-128 (2001)
- (2) Miura, S.: Development Status of Small Distributed Power Generation Technologies Micro Gas Turbine Technologies, Journal of the Gas Turbine Society of Japan, Vol. 29, No. 3, p. 134-140 (2001)
- (3) Yamazaki, A., Kurokawa, M., Inoue, T., Murakami, H.: Research of Natural Gas Low Emission Combustor, HONDA R&D Technical Review, Vol. 15, No. 2, p. 85-92 (2003)
- (4) The Tokyo Electric Power Company, Inc.: TEPCO Environmental Action Report 2002, p. 113 (2002)
- (5) Shinmura, K.: Microturbine Research at Honda, Presented in 2003 ASME TURBO EXPO Panel session (2003)
- (6) Agency for Natural Resources and Energy: Guideline for islanding protection technique of dispersed generator '98 (1998)
- (7) Japan Electric Association: Technical Guidelines for the Grid Connection of Dispersed Energy Sources, JEAG9701 (2001)
- (8) Japan Electrical Safety & Environment Technology Laboratories: Test Methods for Compact Solar Cell Generation System Grid Connect Protection Devices (1993)

■ Authors ■



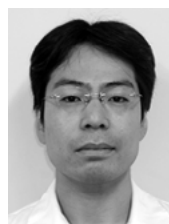
Koichi SHINMURA



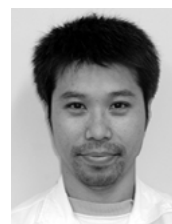
Koji YAMAGUCHI



Sadachika TSUZUKI



Hidemi KIMURA



Takeshi KATO