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Research and Development of Gas Turbine for Next-Generation Marine Propulsion System (Super Marine Gas Turbine)

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ABSTRACT

Japan is developing a Super Marine Gas Turbine (SMGT) that will become the newest gas turbine for next generation marine propulsion. Amidst rising global concern for environmental issues, in 1997, five Japanese gas turbine engine manufacturers (Kawasaki Heavy Industries, Ishikawajima-Harima Heavy Industries, Daihatsu Diesel, Niigata Engineering, and Yanmar) joined forces to establish the Technological Research Association for Super Marine Gas Turbine (SMGT), and embarked on development of a low NOx, high efficiency gas turbine for the next generation in the maritime field. The project is being conducted on the initiative of the Ministry of Land, Infrastructure and Transport and with support from the Corporation for Advanced Transport & Technology and the Nippon Foundation.

This paper presents the results of development, including various research tests and land tests.

INTRODUCTION

Among the rising global concern for environmental issues, strict regulation against atmospheric pollution already is being carried out on land and is likely to appear in the near future in the marine arena as well. This fact was made clear when the International Maritime Organization’s (IMO) in 1997 introduced amendments concerning prevention of atmospheric pollution from sea-going vessels to the MARPOL convention.

In addition, the Japanese Government formalized its acceptance of Kyoto Protocol on June 4, 2002. Because carbon dioxide emission from coastal shipping is estimated at one fifth of that from ordinary commercial trucking, the Japanese Government set a goal to raise the percentage of transport by rail and coastal shipping.

Gas turbine technology is attractive for next-generation marine propulsion because it offers the potential to significantly reduce NOx emissions compared with conventional diesel engines.

Other advantages include smaller size and lighter weight, higher power output, reduced maintenance, and low vibration and noise, which are expected to increase profit when installed as prime mover on vessels, especially coastal vessels.

However, higher fuel consumption and higher component prices have prevented the ship-building industry from adopting gas turbine technology. Subsequently, gas turbine technology applications are limited to high-speed cruise ships and naval vessels.

In order to overcome such circumstances, in 1997, five Japanese gas turbine makers established the Technological Research Association of Super Marine Gas Turbine and started development of a low NOx, high efficiency gas turbine for the next generation in the maritime field.

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Meanwhile, in April, 2001, the National Maritime Institute of Japan started a Super Eco-Ship Project involving research and development of revolutionary coastal ships. Sponsored by the Ministry of Land, Infrastructure and Transport, it is expected to revitalize coastal shipping and encourage a shift from trucking to waterborne transport. In 2005, the final year of the project, an actual super eco-ship will be built for demonstration tests. In combination with gas turbines and a highly efficient electrical propulsion system, the super eco-ship aimed at achieving a technical breakthrough. The SMGT will be installed on the super eco-ship.

The program for the SMGT project is composed of a core research and development phase designed to confirm such performances as thermal efficiency and NOx emissions and an endurance test phase, in which reliability will be confirmed.

This paper presents the results of the core research and development phase, which has been completed.

OBJECTIVES

High reliability and operating ratios that have been verified in aircraft engines have extended the range of the applications for aero-derivative gas turbines in both naval and commercial marine applications. However, engine prices are relatively high compared with diesel engines.

On the other hand, many power plants have extended the use of industrial gas turbines developed for land use. The experience gained from the production and operations improved reliability and made prices highly competitive.

In order to increase opportunities for use of gas turbines in a variety of ship classes, the SMGT aims to develop a low NOx and high efficiency gas turbine for a next-generation marine propulsion system based on industrial gas turbine technologies, unlike most marine gas turbines.

The objectives of the SMGT as follows,

(1) NOx emissions below 1g/kWh
(2) Thermal efficiency of at least 38%
(3) Application of marine diesel oil

The SMGT can generate 2,500 kW of power, use marine diesel oil and reduce fuel consumption by 30% compared with existing industrial gas turbines in the same output power class. (See Fig.1) It also will reduce NOx emissions to below 1g/kWh -- one-tenth of existing marine diesel engines or one-third of existing industrial gas turbines.(See Fig.2)

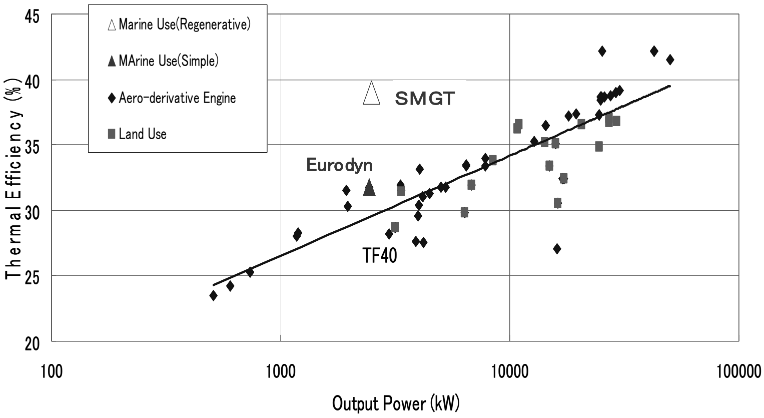


Fig.1 Thermal Efficiencies of Marine Gas Turbines

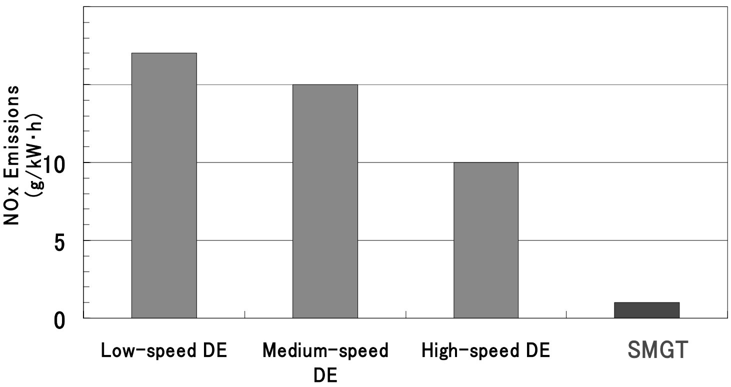


Fig.2 Comparison of NOx Emissions with Diesel Engines

TECHNICAL CONCEPT AND ENGINE FEATURES

Studies show that a simple gas turbine cycle cannot exceed a thermal efficiency of 38% even at a turbine inlet temperature of 1200℃.

The engine applied a regenerative cycle with a recuperator in the exhaust duct and is a two-split shaft gas turbine consisting of the gas generator system and the power turbine system. Fig.3 and Fig.4 show a cross sectional view and the engine cycle for the SMGT respectively. Table 1 shows design requirements.

As stated above, the SMGT's targeted performance exceeds that of conventional gas turbines. Therefore, the performance of its combustor, recuperator, compressors and turbines must also exceed the standards of conventional gas turbines.

Air is first compressed in a four-stage axial compressor and passes to a single-stage centrifugal compressor, giving a total pressure ratio of 8:1.

It passes to the recuperator to recover the energy lost in the gas turbine exhaust and achieves a higher thermal efficiency (ie., lower fuel consumption). It then enters the four can-type combustion chambers. The innovative lean pre-mixed pre-vaporized combustion technology enables the SMGT to achieve low NOx emissions for liquid fuels, such as marine diesel oil.

Hot gases from combustion flow through the gas generator turbine before reaching the independent two-stage axial power turbine running at 13,000 rpm. The gas generator consists of two-stage axial flow turbine. All nozzles and blades are cast in high temperature alloy with cooling configurations to withstand the thermal and dynamic stress at a turbine inlet temperature of 1,200℃ (about 50℃ higher than existing industrial gas turbines for the same output power class). Such a high turbine inlet temperature is one of major factors contributing to high thermal efficiency.

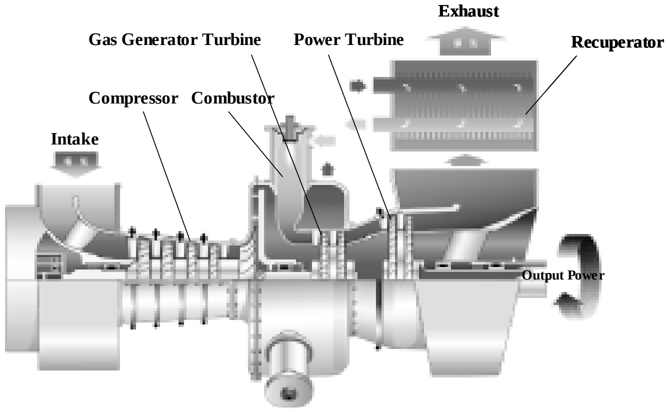


Fig.3 Cross Sectional View of SMGT

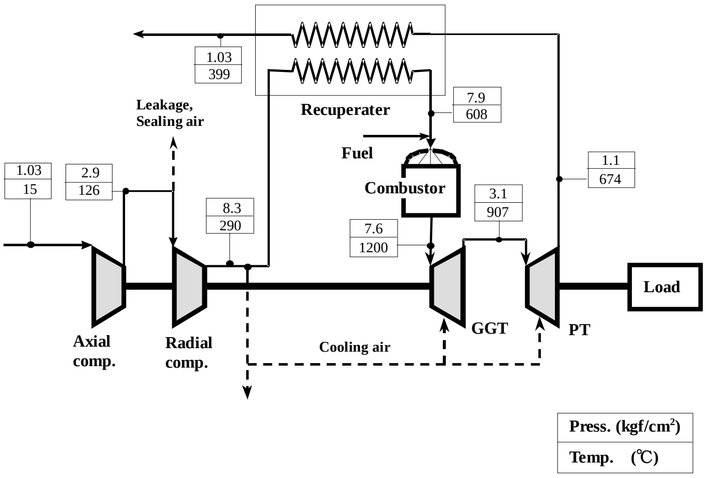


Fig.4 The Engine Cycle

Table 1 Requirements

Item		Unit	Specification
Rated Power		kW	2,590
Thermal Efficiency		%	39.1
Air Flow Rate		kg/s	9.5
Compressor	Rated Speed	rpm	21,000
	Pressure Ratio		8.0
	Adiabatic Efficiency	%	84.0
Recuperator	Temperature Effectiveness	%	83.0
Combustor	Burning Efficiency	%	99.0
Gas Generator Turbine	Rated Speed	rpm	21,000
	Inlet Temperature	℃	1,200
	Adiabatic Efficiency	%	87.5
Power Turbine	Rated Speed	rpm	13,000
	Adiabatic Efficiency	%	90.2
NOx Emission		g/kWh	1.0 ≒ 200ppm (O_2=0%)

R&D SCHEDULE

To achieve the target, main components such as the compressor, the combustor, the turbine and the recuperator require a high performance capability exceeding the existing level. Therefore in parallel with the development of an experimental unit of the SMGT, various research programs for the components were carried out step by step to ensure the achievement of the performance goal.

Finally, tests were carried out using the experimental unit to verify the overall performance of the SMGT.

The R&D schedule is shown in Fig.5. In 1997, basic overall design work for the gas turbine was completed and the above target goals for each component were specified. The component research including a variety of tests was conducted from 1998 to 2001. Land tests using the experimental unit of the SMGT started to evaluate its performance in mid-2001 and were completed early in 2003. At present, the endurance test phase for the next step of the project is underway.

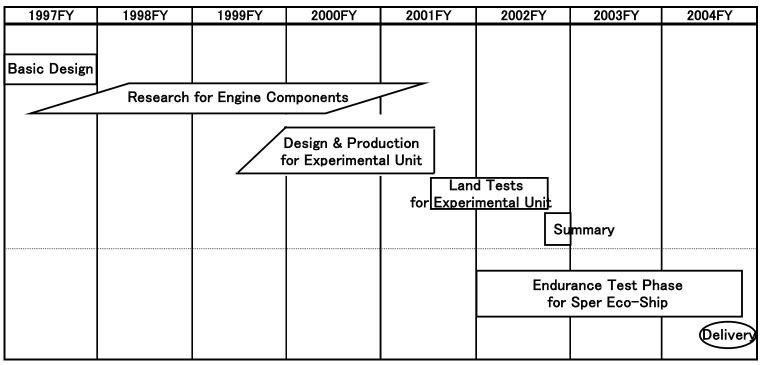


Fig.5 R&D Schedule

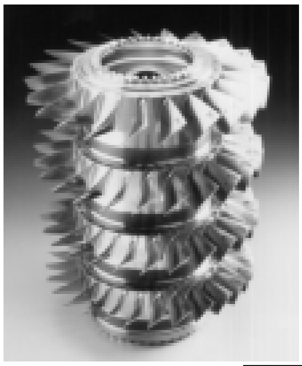
ASPECTS OF COMPONENT DESIGN AND RESEARCH PROGRAMS

The basic plan was completed in 1997 and research tests on various engine components (compressor, combustor, cooled turbine, recuperator, etc.) have been carried out from 1998 to 2000 to ensure high target performances.

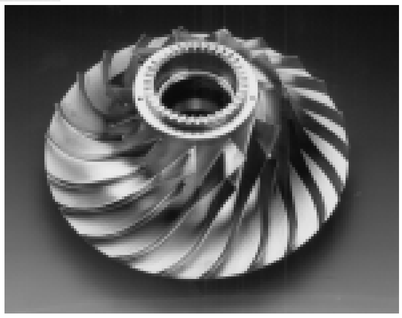
Compressor

A compressor consists of a four-stage axial compressor in the low pressure range and a single-stage centrifugal compressor in the high pressure range to achieve high efficiency. Usually it consists of a single or two-stage centrifugal compressor in the same output power class.

Aerodynamic design on both axial and centrifugal compressors was performed using the latest technology of Computational Fluid Dynamics (CFD) and the performances were confirmed through the component rig tests. This process reduced both the cost and the time needed for development. The compressor has four variable stators including a variable inlet guide vane (IGV). Fig. 6 shows the axial compressor rotors and a centrifugal compressor impeller.



(a) Axial Compressor



(b) Centrifugal Compressor Impeller

Fig.6 Compressor Rotors

The axial-compressor stage was independently tested on full scale component rigs. Expected performances on both aerodynamics and mechanical fields were demonstrated. Also the centrifugal-compressor stage was tested, and the test data verified expectations for good performances.

After these tests, component rigs incorporated with both the full-scale axial and centrifugal compressor stages were tested and useful information was obtained for the operation of the experimental unit of the SMGT.

Low NOx Combustor

Because of the shortage of fresh water on vessels, the combustor of the SMGT applies a Dry Low NOx (DLN) method. Fig.7 and 8 show the DLN combustor and the cross-sectional view.

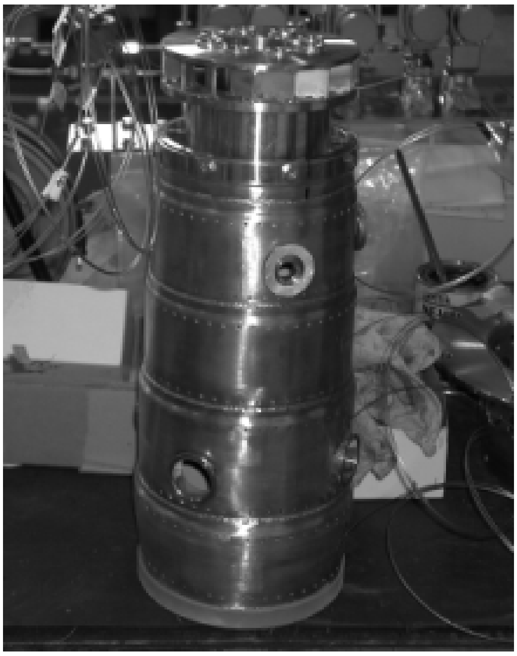


Fig.7 DLN Combustor

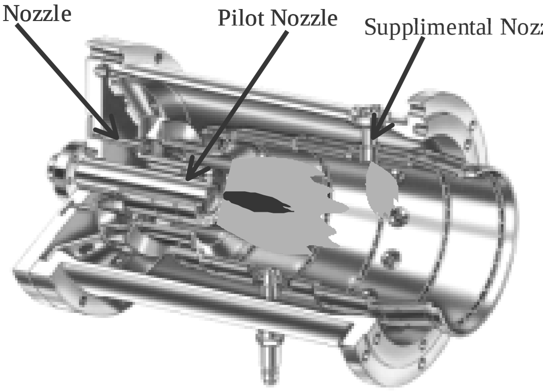


Fig.8 Cross-sectional View

The can-type combustor is selected for easy installation and removal. The combustor consists of four combustion chambers to realize relatively moderate circumferential temperature distribution at the turbine inlet, which reduces vane cooling requirements.

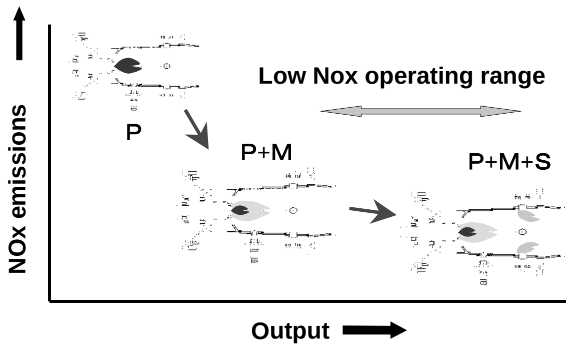


Fig.9 Burning Control Method

In order to achieve the required NOx emission level burning marine diesel oil, the SMGT applies the lean pre-mixed pre-vaporized combustion concept for the low NOx combustor. The adoption of the staged combustion method, using three burning zones with three different types of fuel nozzles inside the combustor, enables steady burning over a whole operating range.

A pilot fuel nozzle is used for lighting and low power operation and also to support flame stability over the whole operating range. A main nozzle provides lean pre-mixed pre-vaporized combustion and a supplemental fuel nozzle supplies fuel behind the main burning area in high power operation. (See Fig.9)

Component tests verified the achievement of the target NOx emission level enabled selection of the configuration of the combustor for the experimental unit.

Gas Generator Turbine

The gas generator turbine is two-stage axial turbine and all the blades are shroudless. A blade speed of 400m/s was selected at the average radius for both stages as high as possible within a permissible level for the design life requirement of the blades. Furthermore the centrifugal stress level on the discs at this blade speed allows the selection of practical metal materials.

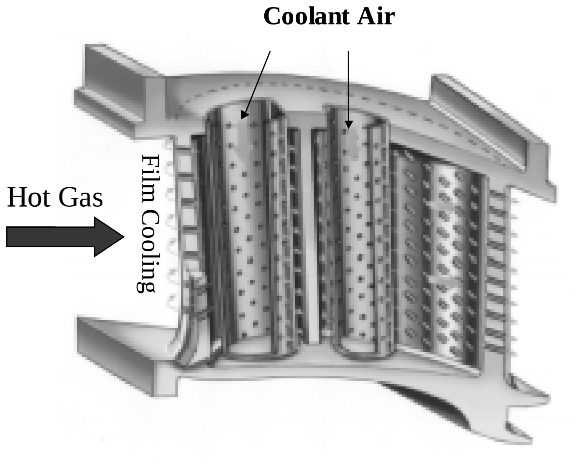
The combination of two-stage configuration and this blade speed results in moderate aerodynamic loading, leading to higher turbine efficiency.

The gas generator turbine is operated under a turbine inlet temperature of 1200℃ and all nozzles and blades are air-cooled. This gas temperature exceeds that of existing industrial gas turbine in the same output class as the SMGT.

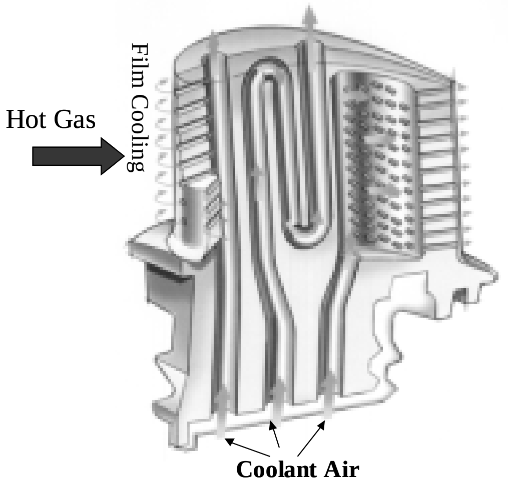
The first nozzles and blades are exposed under the most severe conditions. Their performance and reliability greatly influence those of the SMGT. To ensure the achievement of the target cooling performance, various rig tests for heat transfer characteristics were carried out. The design of the first nozzles and blades for the experimental unit were based on experimental data and analysis using the latest technologies of the CFD. Fig.10 shows the cooling configuration of the first nozzle and the blade for the experimental unit.

The first nozzle has two cavities with cross-flow impingement cooling augmented by film external cooling at the leading edge, suction surface and pressure surface. Pedestals in the internal trailing edge region are supplied with coolant air from the aft cavity and spent air is exhausted from the trailing edge. Both forward and aft cavities are fed from the outer side.

For the first blade, the inner wall is cooled by a cooling air-flow serpentine passage with turbulence promoters or pedestals and the outer surface is film-cooled at the leading edge, suction surface and pressure surface.



1st Nozzle



1st Blade

Fig.10 Cooling Configuration for Gas Generator Turbine

Power Turbine

The power turbine is a two-stage axial turbine and all the blades are shrouded. Also all the nozzles and blades are uncooled.

Aerodynamic design concepts used in the gas generator turbine were applied in the power turbine to achieve higher efficiency.

However the blade speed at the average radius is 320m/s lower than that on the gas generator turbine. The blade strength level at this speed allows attachment of tip-shrouds on the top of the blades for both stages. It contributes to achieving more efficient performance.

Recuperator

The simple cycle gas turbine loses about 70 percent of the heat energy produced with fuel burn from the exhaust gas. That is the main reason why fuel consumption in gas turbines is higher than in diesel engines. A regenerative cycle offers a solution to the problem of improving gas turbine fuel consumption.

The recuperator is used to recover heat from the exhaust and pre-heat the compressor delivery air prior to combustion. The heated air through recuperation requires less increase in temperature within the combustion process to achieve the required turbine entry temperature. As a result, less fuel is burned.

The recuperator is mounted on the enclosure downstream of the exhaust collector. Fig.11 shows the recuperator. A plate-fin construction is selected as the optimum heat exchanger solution providing high levels of effectiveness, compactness and robustness.

Fig.12 shows a configuration of the core for the plate-fin recuperator. A partition is arranged with many several-milimeter high fins on one side and forms a flat plane on the other side. When a number of partitions are stacked, narrow flow passages are formed among neighboring partitions. When hot exhaust gas and compressor delivery air flow alternatively in such fine passages, numerous fins arranged between two partitions make full turbulent flow and heat exchange is stimulated among flows through neighboring partitions.

Component test results verified achievement of the target heat transfer level, and the configuration of the recuperator was selected for the experimental unit. More than 100 partitions are piled up for the experimental unit.

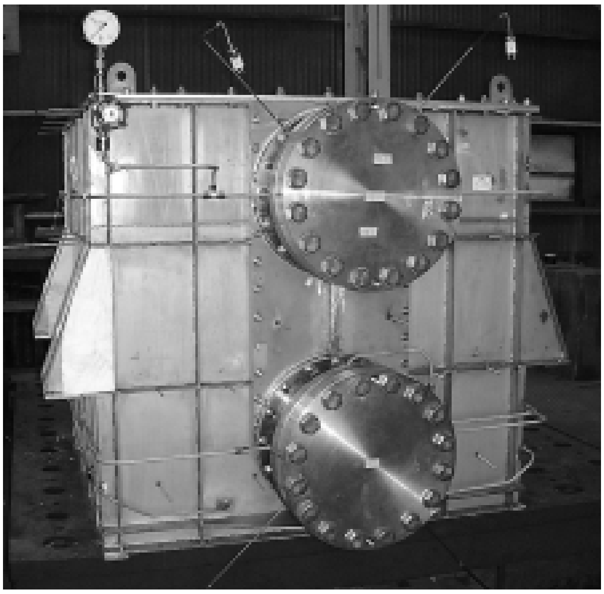


Fig.11 Recuperator

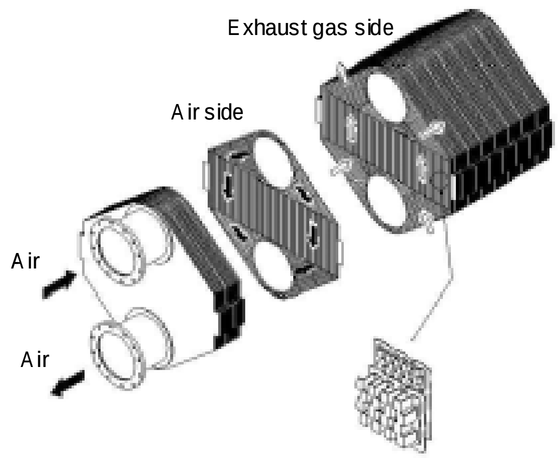


Fig.12 Configuration of Core for Plate-fin Recuperator

Research for Problems in Marine Applications

Research for problems associated with marine gas turbines also was carried out.

The various components will be subject to corrosion from the chloride in ocean water, and the turbine blades and other high-temperature components may be corroded by sulfur in the fuel. To select suitable materials and anti-corrosion coatings, salt-water spray tests and high-temperature corrosion tests were carried out, and the results are being evaluated.

In addition, when regenerative double-shaft gas turbines are used in ships, transient response to sudden load changes is important. Simulation models of the SMGT and propulsion systems have been made, and transient response characteristics under various conditions were studied.

Other research included analyses of the SMGT's operating support systems and self-adjusting systems.

LAND TESTS

Based on findings and technological experiences gained during the research stage, a 2,500kW experimental unit has been built in 2001. Land tests started the same year.

Fig.13 shows the experimental unit without the recuperator. Fig.14 shows the drawing of the experimental unit installed with the recuperator. Fig.15 shows the test facility and the experimental unit of the SMGT installed inside the enclosure.

In 2003 the SMGT completed its performance testing. About 140 hours of testing and 150 start-ups were carried out since 2001 at Kawasaki's Akashi plant (near Kobe).

Land tests confirmed that the SMGT has met all target goals. Fig.16 and fig.17 show the engine performance and NOx emissions measured in the land tests.

After completing the tests, the parts of the experimental unit were inspected and mechanical integrity was confirmed.

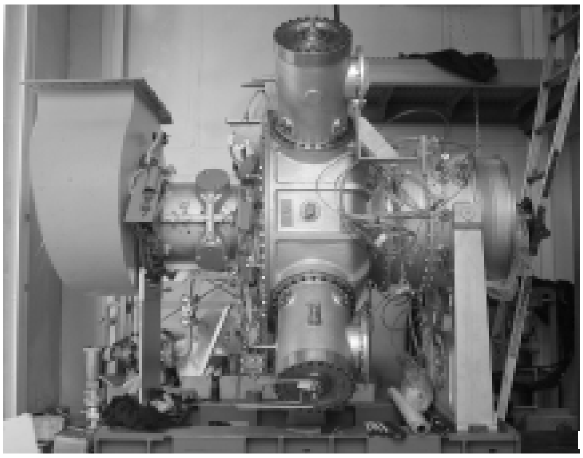


Fig.13 Experimental Unit without Recuperator

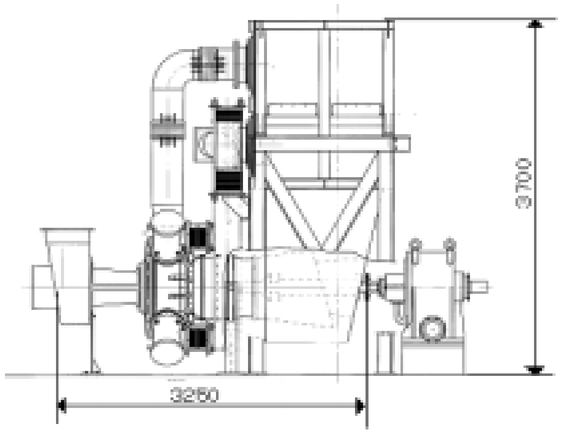
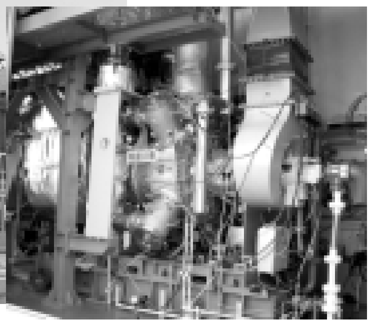


Fig.14 Drawing of Experimental Unit

(a) Enclosure

(b) Recuperator



(c) Power Section

Fig.15 Test Facility

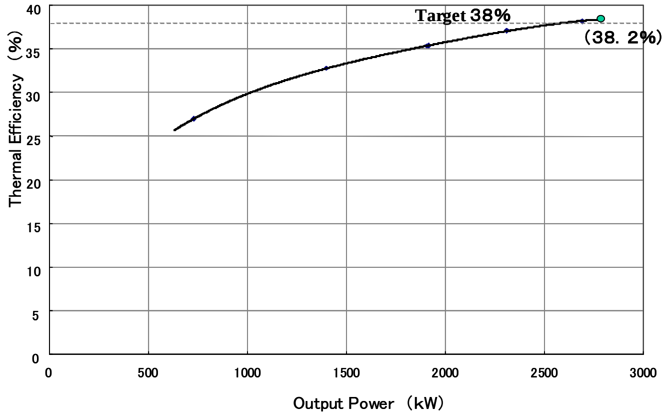


Fig. 16 Results of Thermal Efficiency

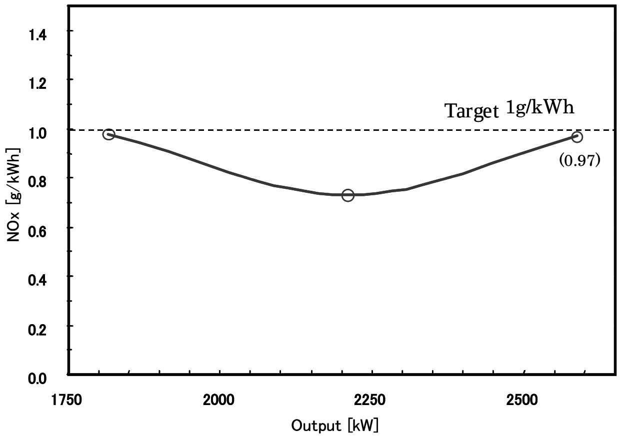


Fig.17 Results of NOx Emissions

CONCLUSION

The land tests ended early in 2003 and the core research and development phase of the project was completed at the end of March 2003.

This paper shows that excellent results were achieved for the core research and development phase.

In the next phase of the project, endurance tests will be carried out with the aim of achieving practical use in an experimental vessel for the Super Eco-Ship in the near future. Success in these tests would lead to production of a gas turbine propulsion system for installation on the experimental vessel in the Super Eco-Ship Project.

SMGT technology is expected to bring about the following practical benefits:

1. Contributing to a cleaner environment by reducing NOx emissions.
2. Improved cost-effectiveness compared to existing gas-turbine technologies. Better fuel consumption will also help reduce CO_2 output.
3. Increased freedom of ship-design brought about by compact size and light weight of the main unit. Also, increased onboard cargo capacity and higher vessel speeds.
4. Labor-saving effected by simplified engine installation and repair/maintenance procedures.
5. Reductions in ship vibration and noise pollution.

ACKNOWLEDGMENT

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The authors would like to express their gratitude to all persons involved.

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