DEVELOPMENT OF A HIGH-EFFICIENCY 50KW MICRO GAS TURBINE COGENERATION SYSTEM

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Introduction

The use of cogeneration systems has been increasing in Japan since the end of the 1980's, when engineering guidelines for grid connection were first established.

In comparing the gas turbine cogeneration system with the reciprocating engine-type cogeneration system that has the same power generation capacity, it is apparent that the gas turbine cogeneration system is smaller in size, lighter in weight, and easier to maintain, since it has fewer parts and does not require any water cooling apparatus. Moreover, because the exhaust gas from this turbine has a relatively high temperature, it is suitable for a cogeneration system and facilitates the design of the system. However, until now, production focused mainly on large models with a rating of 1,000kW or greater, and gas turbine cogeneration system was available to industrial customers, who required a large amount of electricity and steam.

"Micro gas turbines", defined in Japan as having a rating of 300kW or lower, have been attracting attention since the 1990's in the United States, Europe, Japan, etc. as high-efficiency, low-cost, and small distributed power-generation equipment. The development of micro gas turbines is now well underway, and some type of micro gas turbines have produced for commercial operations.

Toyota Motor Corporation has devoted attention to gas turbines because of their light weight, small size, and low emissions, and has been developing gas turbines mainly for various automobile applications since the early 1960's.

Toyota Turbine and Systems Inc., established in 1998, is a subsidiary of the Toyota Motor Corporation, which develops and implements markets for micro gas turbine cogeneration systems using the knowledge and experience it has acquired in the development of gas turbines.

Japan's leading city gas companies have been developing and engineering systems relating to cogeneration systems to expand the sale of gas. Toho Gas Co., Ltd, Tokyo Gas Co., Ltd, and Osaka Gas Co., Ltd have all collaborated with Toyota Turbine and Systems Inc., and have jointly developed a 290kW simple-cycle unit and a 50kW simple-cycle unit, evaluated its performance and durability, modified its operational issues, and completed the lineup of these products between 1999 and 2001.

Following these developments, Toyota Turbine and Systems Inc. developed a higher-efficiency regenerative cycle unit (TPC-50R). Toho Gas Co., Ltd. has been evaluating its performance and durability, modifying its operational issues, and expanding the lineup of Toyota Turbine and Systems' products since January 2002.

This paper describes the design, development, specifications, evaluation, and operational experience of the TPC-50R. The TPC-50R has two types of equipment for the utilization of the heat recovered from exhaust gases. One is a heat source for hot water, and the other is for air conditioning. Toho Gas Co., Ltd. has evaluated both systems.

System Design

Description

TPC-50R is a single-shaft configuration, yielding a regenerative-cycle electrical efficiency of 25.5%. It integrates all components into the package, such as the micro gas turbine, high-speed generator, gas compressor, inverter, inlet-air filter, and control equipment. For power generation applications, full power is produced at a power turbine speed of 80,000 rpm for both the 50 and 60Hz configurations. At full power, the exhaust flow is 1,444m3/hour at approximately 250 degrees C. Although flow and exhaust temperature are lower than in the simple-cycle system, relatively high electrical efficiency delivers an overall efficiency of around 70 to 80%.As the heat source for hot water, TPC-50R produces 14 tons/hour of hot water at 88 degrees C. In its air conditioning application, as a heat absorption type chiller/heater with direct injection of exhaust gas, 77kW(22USRT) can be recovered.

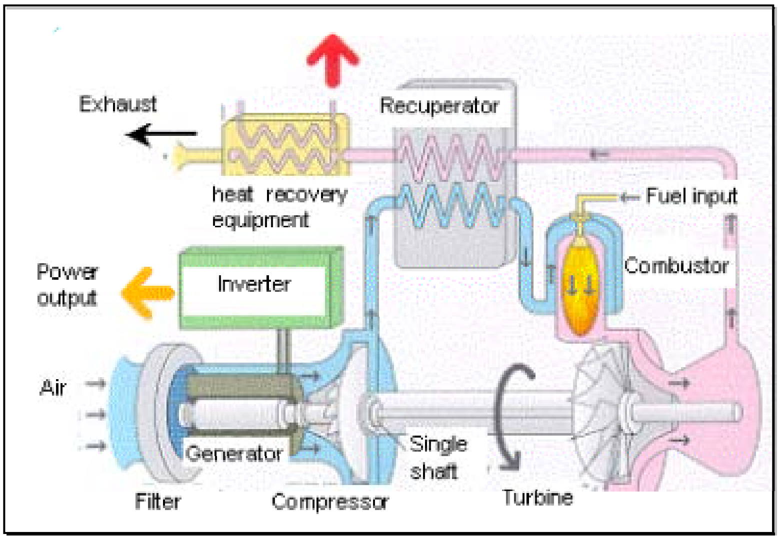

Figure1 System Description

Core Engine

The core engine of the TPC-50R(TG-051) builds on the wealth of knowledge and experience gained through the development and operation of the Toyota Motor Corporation's gas turbine, and utilizes the single-shaft turbine based on that of the simple-cycle unit.

Generator Unit

A high-speed generator driven by power turbine output produces high-frequency(2.667kHz) electricity output. An inverter regulates the output to the grid voltage 200/210/220V and a frequency of 50/60Hz.

The regulated output connects to the utility grid. The inverter also detects the fault conditions that are necessary for grid connection safety, as stipulated under the Japanese guidelines. In conjunction with a reduction in the materials, such as the synchronizer, circuit breaker, and protection relays, compact unitization has been achieved.

Combustion

It is not necessary for the TPC-50R to install the NOx reduction equipment such as steam and ammonium. The combustion system for the TPC-50R is the Dry Low Emissions (DLE) combustion system based on the lean-burn pre-mix arrangement, and operates with a wide range of gaseous fuels. The NOx reduction by this system amounted to less than 9 ppm (at O2=16%). Furthermore, its good "turndown" capability makes it possible to operate the TPC-50R in conjunction with the heat demand, for example, in conjunction with a heat absorption-type chiller/heater with direct injection of exhaust gas. Toho Gas evaluated the first version of the TPC-50R to be launched, which utilized the DLE combustion system.

Recuperator

A recuperator is a type of heat exchanger from waste heat to compressed air, which utilizes a recuperated cycle. The recuperator for the TPC-50R is a plate fin-type heat exchanger. By this heat conduction, waste heat is cooled from approximately 650 degrees C to 250 degrees C, and compressed air, i.e. combustion air, is preheated. This preheating almost doubles the electrical efficiency, from 13% to 25.5%.

Waste Heat Recovery Equipment

Because of the large investment, it would be difficult to justify the use of micro gas turbines for electrical power generation alone without utilizing the thermal energy represented by the excess waste heat. The efficient utilization of this waste heat is necessary for micro gas turbines to deliver a high overall efficiency. In order to introduce and utilize a micro gas turbine, it is necessary to construct a system that utilizes the heat recovered from the exhaust gases for various applications as a "cogeneration system". Many applications should be considered such as heating water, air conditioning, refrigeration, etc., because they can benefit from utilizing this wasted thermal energy. Toyota Turbine and Systems possesses the following 50kW micro gas turbine cogeneration lineups, compared to the simple-cycle unit(TPC-50).

(1) heat source for hot water

Applications requiring hot water include heated pools, public baths, hotels, and restaurants.

Table1 shows the performance of TPC-50 and TPC-50R, and figure 2 shows the system flow of TPC-50R.

With large heat requirements, simple-cycle gas turbines are appropriate. The TPC-50, Toyota Turbine and Systems' simple-cycle unit, produces 26 tons/hour of hot water (304.6kW), and delivers an overall efficiency of 88%.

On the other hand, when such a large amount of hot water is not required, the simple cycle TPC-50 is not suitable, because its electrical efficiency is lower(13%) than that of the regenerative-cycle unit (25.5%).The TPC-50R, Toyota Turbine and Systems' regenerative-cycle unit, with an electrical efficiency of 25.5%, produces 14 tons/hour of hot water (89.5kW), delivering an overall efficiency of around 70% to 80%.The use of -regenerative- gas turbines is advantageous for applications with low heat requirements, because of their high power generation efficiency.

Gas turbine cycle	Regenerative (TPC-50R)	Simple (TPC-50)
Electrical output	50kW	50kW
Hot-water output	89.5kW (at 60 degrees C)	304.6kW (at 60 degrees C)
Electrical efficiency	25.5%	12.6%
Waste heat recovery	45.7%	76.8%
Overall efficiency	71.2%	89.4%

Table1 System Performance of hot-water heat recovery systems

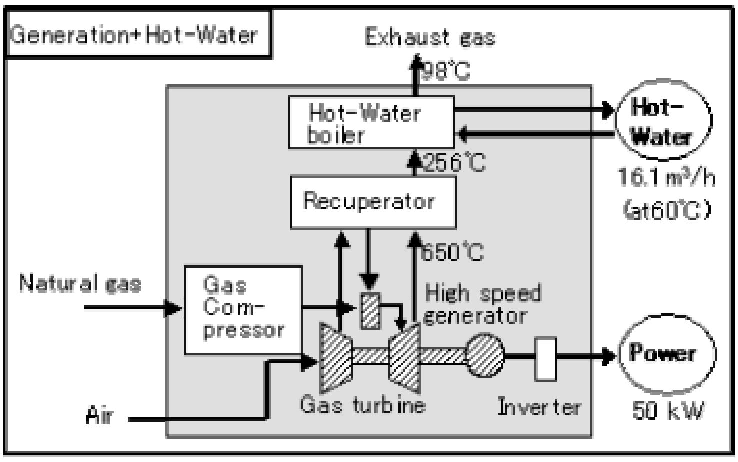

Figure2 System Flow of Hot Water Recovery

(2)heat source for gas absorption chiller / heater

The gas absorption chiller / heater for TPC-50 and TPC-50R is based on a direct-fired double-effect chiller / heater, that utilizes a high-efficiency two-stage lithium bromide(LiBr) generator and water absorption cycle free of ozone-depleting CFCs and HCFCs. To construct a cogeneration system requires the implementation of a rather complex structure. The exhaust-driven gas absorption chiller / heater contains two high-stage generators. Micro gas turbine waste heat is fed to into one of the high-stage generators to concentrate LiBr. The exhaust of the auxiliary forced-draft burner, installed in the gas absorption chiller / heater, is fed into the other high-stage generator. These two high-stage generators make it easier to control each heat source.

The absorption chiller / heater is available in a rating of 77kW of cooling and heating using a micro gas turbine exhaust, and with the use of both a micro gas turbine exhaust and an auxiliary burner, 140.7kW of cooling and 115.8kW heating are available.

Though the overall efficiency is lower than for hot water recovery, it is important for popularizing micro gas turbine cogeneration systems to utilize waste heat as the heat source for heating and air conditioning. The advantage of the TPC-50R is its higher electrical efficiency, especially when the electricity demand is relatively larger than the heat demand. The TPC-50R can recover waste heat by use of a heat absorption chiller / heater. It recovers 77kW of waste heat for air cooling and heating. On the other hand, the simple-cycle unit can also recover a larger amount of heat by the use of a heat absorption type chiller/heater than the regenerative-cycle unit, which makes direct use of exhaust gases in the heat source for generating cold and hot water.TPC-50-air conditioning system recovers 299kW of waste heat as an air cooler, and recovers 267kW of waste heat as an air heater. This difference in the air conditioning output of TPC-50R and TPC-50 is caused by the difference in their waste heat amount. A comparison between the two is described in Table2, and system flow of TPC-50R is described in figure3.

Gas turbine cycle	regenerative(TPC-50R)	simple(TPC-50)
Electrical output	50kW	50kW
Cooling output (water at 7 degrees C)	77kW	299kW
Heating output (water at 60 degrees C)	77kW	294kW
Electrical efficiency	25.5%	12.6%
Waste heat recovery	39.3%	74.1%
Overall efficiency	64.8%	86.7%

Table2 System Performance of the absorption chiller / heater heat recovery system

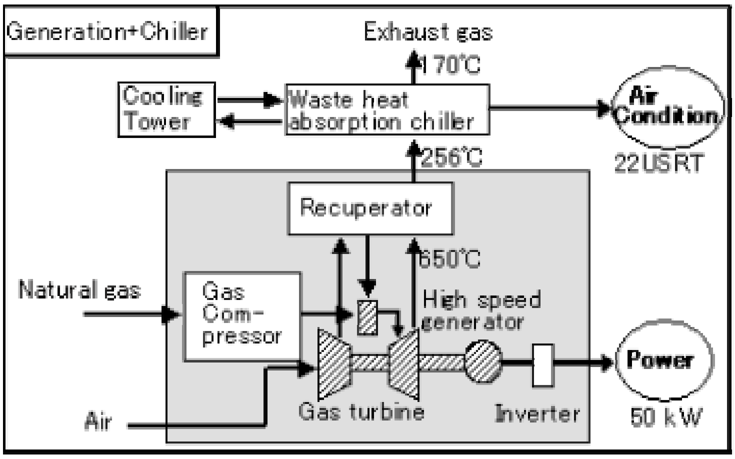

Figure3 System Flow of Absorption Chiller

(3)Heat source for steam

Steam is not available from the heat recovery of TPC-50R.Because its waste heat temperature is low, steam is not available when using the TPC-50R's waste heat effectively.

(4)Controller

The TPC-50R may be controlled in three ways, according to the heat demand, the electrical demand, and the optional command.

Control in conjunction with the heat demand results in overall superior efficiency.

The controller for the hot water heat recovery system calculates the heat demand by measuring the hot water temperature. Although the electrical demand is sufficient, the controller decreases the micro gas turbine output when the calculated heat demand is small. This prevents the production of "waste" hot water, and increases overall efficiency.

The controller for the gas absorption chiller / heater calculates the heat demand by measuring the cooling or heating water temperature. Depending on the calculated heat demand, the controller drives the micro gas turbine and auxiliary burner effectively, as described in table3.

When the heat demand is smaller than the minimum output of the auxiliary burner (State(A)), the absorption chiller / heater is not available.

When the heat demand is smaller than the exhaust of turbine idling(State(B)), the absorption chiller / heater cannot be controlled by the micro gas turbine output. The micro gas turbine is therefore turned off, and the absorption chiller / heater is controlled by means of its auxiliary burner only.

When the heat demand is within the range of the micro gas turbine output (State(C)), the absorption chiller / heater is controlled only by the micro gas turbine output.

When the heat demand is beyond the range of the turbine output(State(D)), the micro gas turbine is driven at its rated output, and the absorption chiller is controlled by means of the auxiliary burner output.

Additionally, when the micro gas turbine is not available, such as during overhauls or breakdowns, the absorption chiller / heater runs using its auxiliary burner with sufficient capacity for full power.

Heat Demand	None (A)	Smaller than exhaust of turbine idling (B)	Within the range of turbine output (C)	Beyond the range of turbine output (D)
Turbine	Stop	Stop	Controlled	Rated output
Burner	Stop	Controlled	Stop	Controlled

Table3 Control method of the absorption chiller / heater for TPC-50R

Control in conjunction with the electrical demand also results in improved overall efficiency, and can minimize operational costs.

The controller for the electrical demand measures the receiving electricity. The TPC-50R is controlled so as to minimize the receiving electricity, and to prevent a reverse flow simultaneously. Minimizing the receiving electricity also minimizes the operating costs. On the other hand, preventing a reverse flow makes designing the grid protection easier, and reduces facility costs such as protection relays.

Optional commands are also available. The TPC-50R produces an output of 0 to 50kW in conjunction with an optional command using a 4 to 20mA signal.

Specifications

The tables detail the specifications of the TPC-50R and its heat recovery equipment.

(1)TPC-50R

Table4 details the specifications of the TPC-50R package with city gas. Toyota Turbine and Systems Inc. also has other lineups, such as LPG and kerosene.

(2)Hot water heat recovery system

Table5 details the hot water heat recovery system of TPC-50R. The capacity 89.5kW is achieved on these conditions. If necessary, 88degreeC hot water is also available.

(3)Absorption chiller / heater

Table6 details the absorption chiller / heater of the TPC-50R.The auxiliary burner is detailed in "System Design".

Fuel		City gas
Electrical Output		50kW (15 degrees C)
Voltage		200/210/220V
Frequency		50/60Hz
Gas Turbine	Model	TG-051
	Type	Single-shaft Regenerative Cycle
	Combustion System	Dry Low Emission(DLE) Lean-burn pre-mix arrangement
	Shaft Output	57kW (15 degrees C)
	Speed Range	80,000min^{-1} (full load)
	Fuel Consumption	197kW(LHV)
	NOx	9ppm(16% O_2)
Generator	Type	Permanent Magnetic Generator
	Phases	3
	Poles	4
	Output	55.3kVA
	Voltage	AC370V
	Frequency	2.667kHz
	Power Factor	0.95LAG
	Speed Range	80,000min-1
Inverter	Input	Available to the generator above
	Output	50kW
	Voltage	200/210/220V
	Frequency	50/60Hz
	Phases	3
	Power Factor	0.98LAG to 1
	Efficiency	>93%
	Grid Fault Detection	Over voltage, Under voltage, Over frequency, Under frequency, Local island (both active and passive)
Gas Compressor	Input	1.47 to 2.45kPa
	Output	638kPa
Enclosure	Sound Level	70dB@1m
Size		W2,100mm x L1,000mm x H1,850 to 2,430mm
Mass(in operation)		2,000kg

Table4 Specifications of TPC-50R

Capacity	89.5kW
Hot Water Output	15.4m^3/hour
Water Temperature	input 55 degrees C output 60 degrees C(maximum 88 degrees C)
Exhaust Temperature	98 degrees C

Table5 Specifications of the hot water heat recovery system

Fuel		City gas
Refrigerant		Water
Cooling	Capacity	140.7kW (Auxiliary Burner and Exhaust) 77kW (Exhaust Only)
	Water Temperature	Input 12 degrees C, output 7 degrees C
	Flow Rate	22.0m^3/hour
	Fuel Consumption for Auxiliary Burner	63.6kW (Cogeneration) 125kW (without Exhaust)
	Exhaust Temperature	170 degrees C (Turbine Exhaust) 190 degrees C (Auxiliary Burner)
Heating	Capacity	115.8kW
	Water Temperature	Input 55 degrees C, output 60 degrees C
	Flow Rate	22.0m^3/hour
	Fuel Consumption for Auxiliary Burner	41.7kW (Cogeneration) 125kW (without Exhaust)
	Exhaust Temperature	130 degrees C (Turbine Exhaust) 190 degrees C (Auxiliary Burner)
Sound Level		70dB
Size		W2,100mm x L1,880mm x H2,270mm
Mass(in operation)		3,070kg
Cooling Tower	Cooling Water Temperature	input 37.5 degrees C, output 32.5 degrees C (at wet bulb temperature of 27degrees C)
	Flow Rate	40m^3/h
	Size	W1,850mm x L1,850mm x H2,743mm
	Mass	415kg (without water) 825kg (in operation)

Table6 Specifications of absorption chiller / heater

Test Results 1. TPC-50R with hot water heat recovery system

(1)Durability and Operating Experience

To evaluate the performance of the TPC-50R and to confirm its reliability and durability, a durability test was conducted in the Toho Gas Co., Ltd. Technical Research Institute for one year, comprising almost 6,000 hours and 300 starts/stops. Photo1 shows the tested TPC-50R.

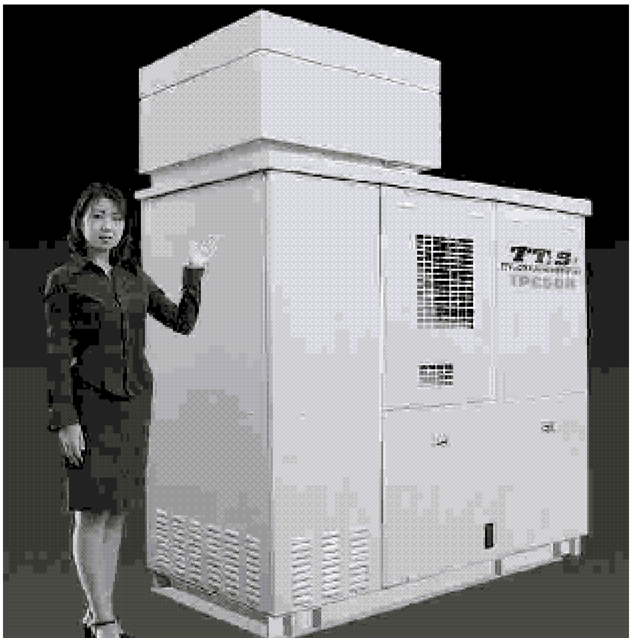

Photo1 TPC-50R with hot water heat recovery system

The performance fluctuation throughout the test is shown in figure4. The electrical efficiency is a little smaller than the specified value. This is due to the air inlet temperature. Generally, the higher the air inlet temperature becomes, the smaller the turbine output, and the shaft efficiency decreases. Figure5 shows the power output results through the test versus the inlet air temperature. Almost all the results of the air inlet temperature were higher than the specified value(15 degrees C), which resulted in a power output smaller than 50kW. However, almost all of the results for the power output exceed the specified value beyond 15 degrees C, as shown in figure5.

On the other hand, sufficient heat recovery efficiency is confirmed through the test. It also showed the overall efficiency of the TPC-50R to be sufficient.

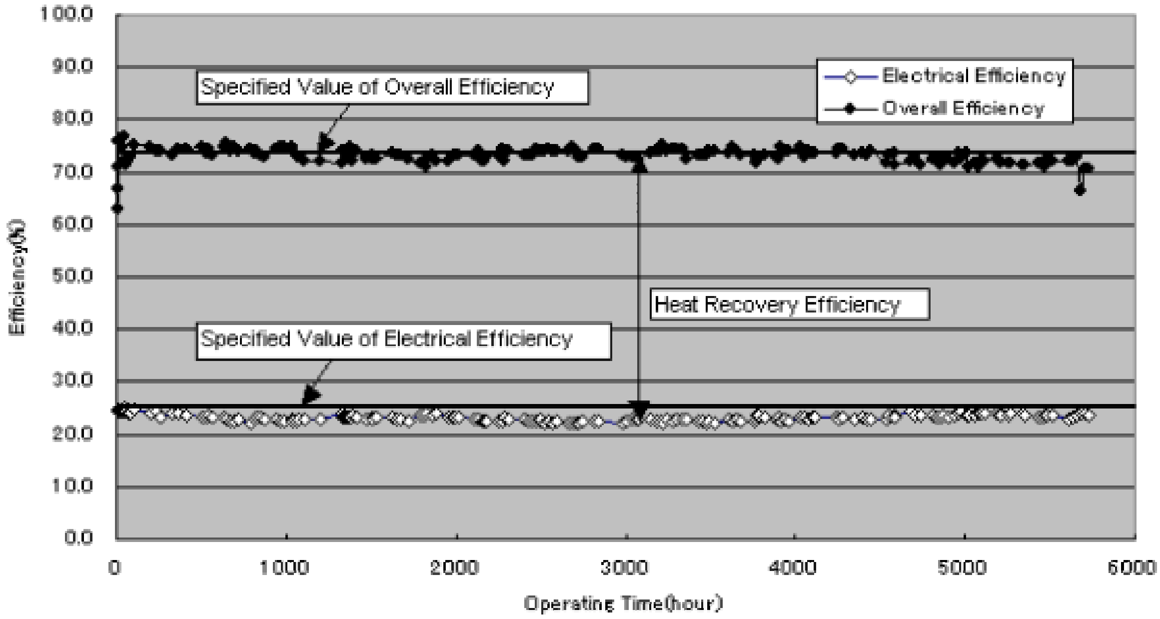

Figure4 The performance of the TPC-50R with hot water recovery system

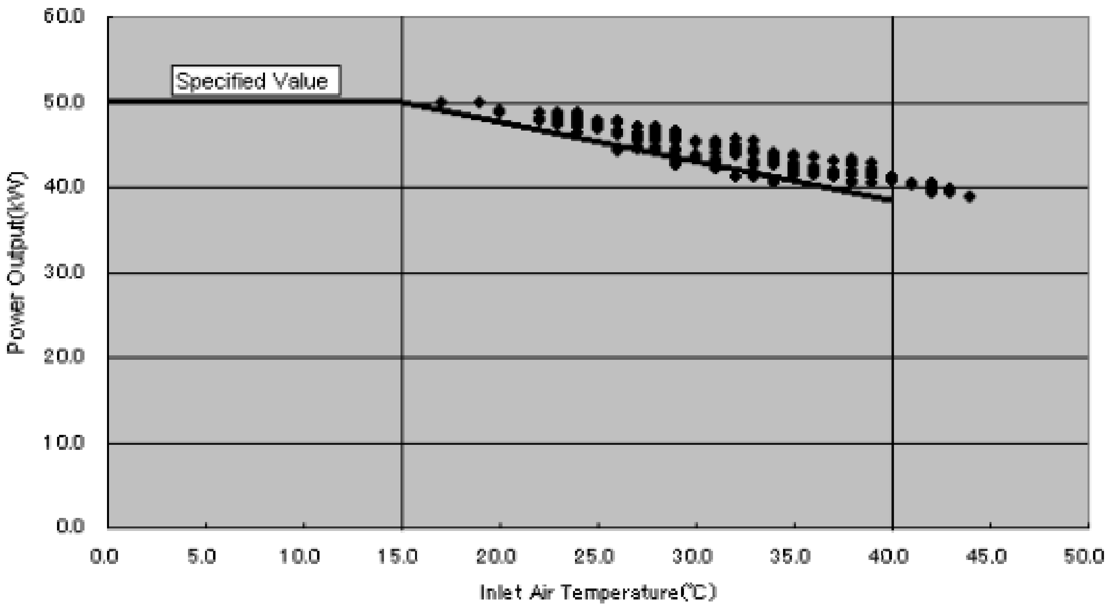

Figure5 The power output versus the inlet air temperature

(2)Emissions

Figure6 shows the NOx emission levels at each load. At the 50%, 75%, and 100% load levels, the NOx emission levels are lower than specified value, approximately 37ppm @ O2 = 0% (9 ppm @ O2 = 16%, described in the specification, is equivalent). At the 0%, 25% loads, the NOx emission levels are extremely large. This is caused by the Dry Low Emission combustion system control of the TPC-50R. The TPC-50R combustor is able to operate under both dry low emission (pre mix lean-burn arrangement) combustion and diffusion combustion. At load of 50% and above, dry low emission combustion is primarily effective and at less than 50%, diffusion combustion is effective to prevent misfires. This diffusion combustion produces a larger amount of NOx, and makes the NOx level higher at lower loads. However, diffusion combustion makes a small contribution even at the rated load. It is necessary to prevent diffusion combustion nozzles from overheating. (see (4) Trouble shooting)

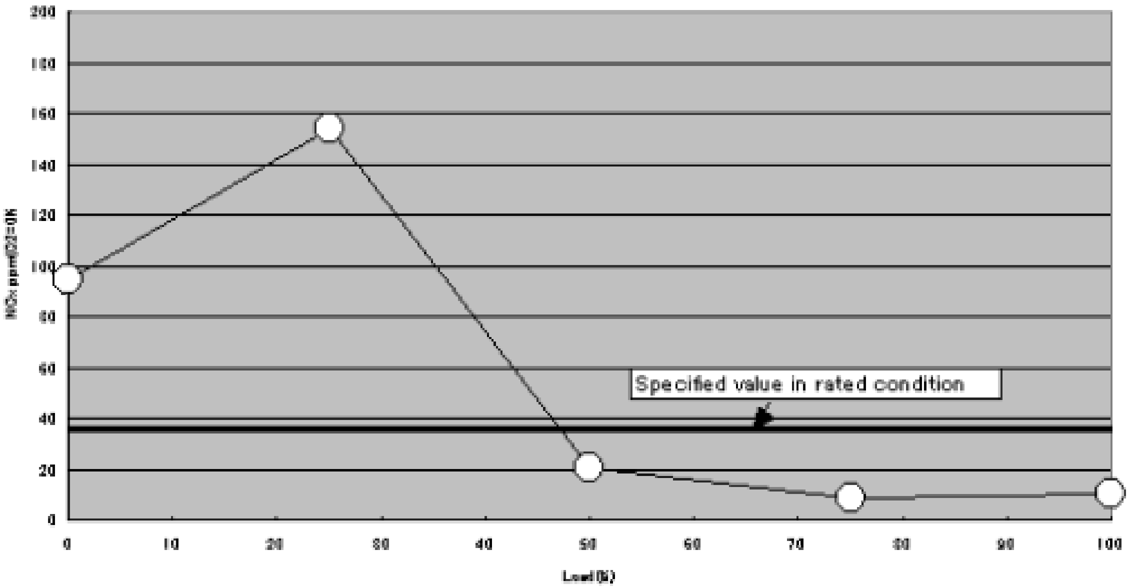

Figure6 NOx emission levels of TPC-50R

(3)Gas Pressure Fluctuation caused by the Gas Compressor

The gas compressor is necessary for the TPC-50R to be available at city-gas pressure (1.96kPa). As it absorbs fuel gas forcibly and intermittently, gas pressure fluctuations sometimes occur. These fluctuations may affect other gas equipment and the meter indication, thus it is important to evaluate the fluctuations caused by the gas compressor.

Toho Gas Co., Ltd. and Toyota Turbine and Systems Inc. measured gas pressure fluctuations under certain conditions. The results are shown in table7.

The results at Startup indicate the maximum instantaneous value. The results under Maximum in Operation indicate the maximum value in load control operation. The results at Rated Load indicate the fluctuation in a steady state. On the other hand, fluctuations at the gas meter inlet predict the extent to which the other gas users' equipment is affected. "Gas Meter Outlet" predicts the extent to which the same user is affected. "Package Inlet" indicates the maximum value among the measuring points.

It is considered that such small fluctuations may not affect other gas equipment significantly. Even if such fluctuations do affect other gas equipment, simply setting up a second gas meter is effective in reducing the fluctuations.

	at Startup	Maximum in Operation	at Rated Load
Gas Meter Inlet	0.22 / 0.11	0.10 / 0.09	0.08 / 0.07
Gas Meter Outlet	0.37 / 0.58	0.30 / 0.30	0.18 / 0.18
Package Inlet	0.50 / 0.78	0.38 / 0.38	0.20 / 0.20

Table7 Results of Gas Pressure Fluctuations kPa (Peak to Peak), 1st/2nd measurement

(4)Trouble shooting

a. Damage to the recuperator

Some decrease in the power output and efficiency from the specified value appeared during the durability test. Toyota Turbine and Systems improved the durability of the connecting equipment between the recuperator and turbine outlet, and recovered the output and efficiency. A recuperator works as a heat exchanger that conducts the turbine's exhaust heat to the compressed air from the turbine compressor. As the result, it is supposed that compressed air leaked into the flue of the recuperator, and that the damage to the connecting equipment causes a decrease in the power output and shaft efficiency.

b. Load Control Failure

In the load control, an incorrect speed was detected as the commanded value. This indicates that the difference was too large. Toyota Turbine and Systems Inc. improved the proportional valve, and modified the load control program. No such incorrect speed has been detected since then. As a result, the incorrect speed was caused by the proportional valve failure and / or too rapid speed control.

c. Improvement of the combustor

Because of the misfire fault, it appeared that the diffusion combustion nozzle was damaged. The damage was caused by the overheating of the DLE combustion flame. It is necessary to prevent diffusion combustion nozzles from overheating. Toyota Turbine and System improved the combustor and its control, so as to make a small contribution even at the rated load. This can prevent the overheating of the diffusion combustion nozzles, because they are cooled by a small amount of air and gas.

Test Results 2. TPC-50R with absorption chiller / heater

(1)Durability and Operating Experience

Toho Gas Co., Ltd. installed the first TPC-50R with an absorption chiller / heater at Howa Sports Land, as shown in Photo2. Howa Sports Land is a sports facility with an ice-skating rink, heated swimming pool, and gymnasium. It also has a training institute. The TPC-50R power output is connected to the grid and utilized all over Howa Sports Land. The TPC-50R chiller / heater output is utilized for air conditioning at the training institute.

The TPC-50R was installed in April 2002, and has been in operation since then, for approximately 5,000 hours, with 200 starts / stops. For the first 3,000 hours TPC-50R air conditioner was operated as a cooler and, for the remaining hours, as a heater. It is operated in conjunction with the heat demand at the Howa Sports Land training institute.

Photo2 TPC-50R with absorption chiller / heater installed Howa Sports Land

Performance fluctuations throughout the test are shown in figure7 and figure8 .While the air conditioner of the TPC-50R is operated as a cooler, the electrical efficiency is somewhat lower than the specified value, and while it is operated as a heater, it almost reaches the specified value because of its air inlet temperature and load condition. On the other hand, the overall heat recovery efficiency is much higher than that described in the specification. This is because the overall efficiency in figure7 indicates the 'overall' efficiency including the auxiliary burner fuel input and the output heat derived. The absorption chiller / heater heat efficiency with the auxiliary burner is higher than that with the turbine exhaust.

The amount of heat recovery almost reached the specified value when cooling, and exceeded the specified value when heating. Excess heating output is caused by the auxiliary burner. Its rated fuel input is regulated somewhat higher than initially specified. While operated as a cooler, The TPC-50R was not often operated at the rated load even in the middle of summer. This is indicated by an operational issue, i.e. other existing absorption chillers / heaters were operated in summertime, though the TPC-50R was not operated at its rated load.

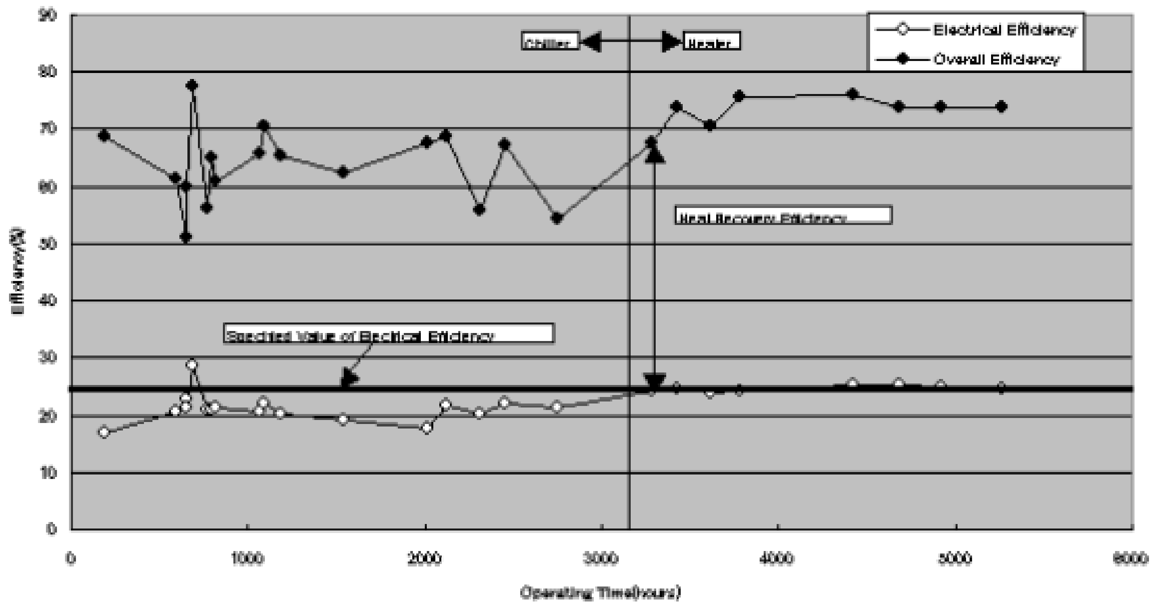

Figure7 Efficiency of TPC-50R with absorption chiller / heater

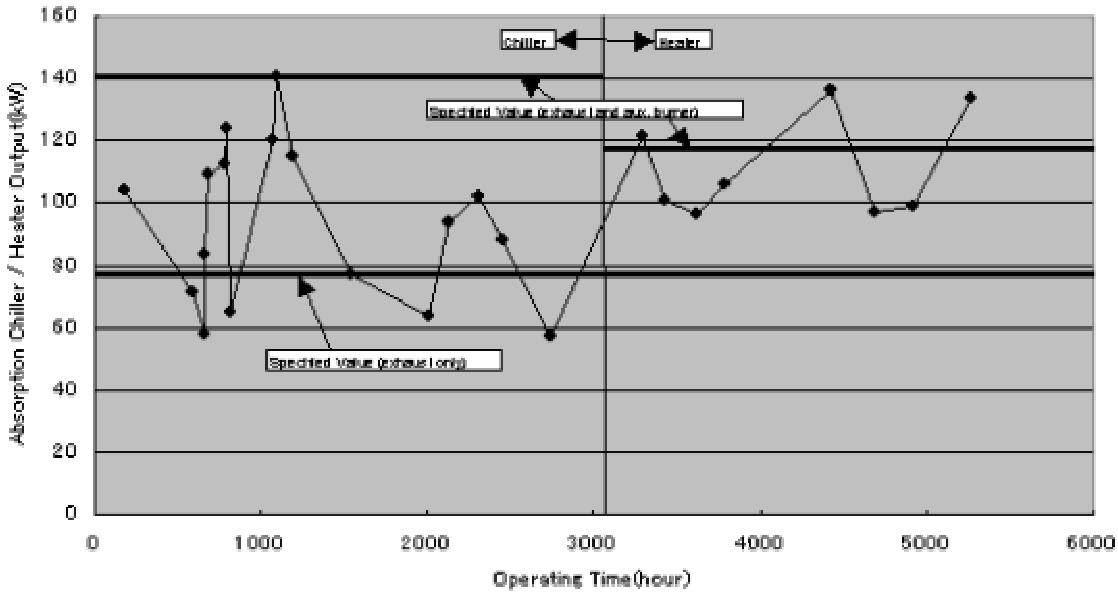

Figure8 Output of absorption chiller / heater

(2)Trouble shooting

a. High-Stage Generator Failure.

The absorption chiller failed to work as a result of its high-stage generator failure. This occurred because of the imbalance between the heat input and load, i.e. the output range of the auxiliary burner was not sufficient, and/or the controller did not work well in conjunction with the heat demand. As a result, in a certain(possibly transient) condition, excess exhaust was conducted to the high-stage generators, the LiBr-water solution became excessively concentrated and its temperature superelevated. Sanyo Electric Air Conditioning Co., Ltd. , the manufacturer of the TPC-50R absorption chiller / heater and a subsidiary of Sanyo Electric Co., Ltd. , regulated the auxiliary burner input and modified the control program so as to prevent the high-stage generator from conducting the excess heat.

b. Improvement of the combustor

The gas-turbine combustor was improved to prevent damage to the diffusion combustion nozzles such as described in Test Results 1 above.

Conclusions

- Toho Gas Co., Ltd. and Toyota Turbine and Systems Inc have succeeded in developing the micro gas turbine TPC-50R as a cogeneration system. Toho Gas Ltd. evaluated its durability and operational experience and implemented some improvements in collaboration with Toyota Turbine and Systems.
- Waste heat recovery equipment was also developed such as a hot-water heat recovery system and an absorption chiller / heater.
- Toho Gas Co., Ltd. evaluated the TPC-50R with a hot-water heat recovery system at its Technical Research Institute. The TPC-50R achieved almost 6,000 hours of operation.
- Toho Gas Co., Ltd. evaluated the TPC-50R with an absorption chiller / heater at Howa Sports Land. The TPC-50R achieved almost 5,000 hours of operation. Some operational issues became apparent, such as the operating sequence among the TPC-50R and other installed absorption chillers / heaters. Toho Gas Co., Ltd., Toyota Turbine and Systems Inc., and Howa Sports Land are now try optimizing their load control together to save much more energy.

References

Kenjiro Takase et al., "A PRELIMINARY STUDY OF AN INTER-COOLED AND RECUPERATIVE MICROGASTURBINE BELOW 300KW", ASME TURBO EXPO 2002, GT-2002-30403.

Koji Ishibashi et al., DEVELOPMENT OF 50KW MICRO-GAS TURBINE COGENERATION SYSTEM, GASEX2002, B3.3.