THE FIRST CLOSED-CYCLE GAS TURBINE POWER PLANT IN JAPAN

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I. INTRODUCTION

Construction of the first closed-cycle gas turbine power plant with an output of 2,000 kW was completed in the fall of 1957 and was subsequently put into trial operation. This was officially approved as the Toyotomi Power Station of Hokkaido Electric Power Co. on November 1, 1957. In spite of its small output, this plant is highly efficient and is shouldering the base load in supplying power to the Northern end of Hokkaido. Fuji Denki, with the cooperation of Hokkaido Electric Power Co., conducted special tests at the plant on control and efficiency. The results confirmed that the closed-cycle gas turbine is particularly suited for use in this area.

As this is the first gas turbine power plant, and in compliance with the request of the purchasing company, an especially large number of measuring devices have been installed in order to obtain performance results of the main and auxiliary equipment. Extensive tests such as on the operation of the governor during load interruption, performance during regular operation, and vibration were conducted.

Since operation was begun in winter and was continued throughout the cold season, the temperature at times fell below -25°C. Operation was occasionally suspended due to minor breakdowns such as freezing of the cooling water intake, and the small outdoor air pipes. Aside from these minor problems, no operational difficulties occurred, and the practicableness of the closed-cycle gas turbine was proven.

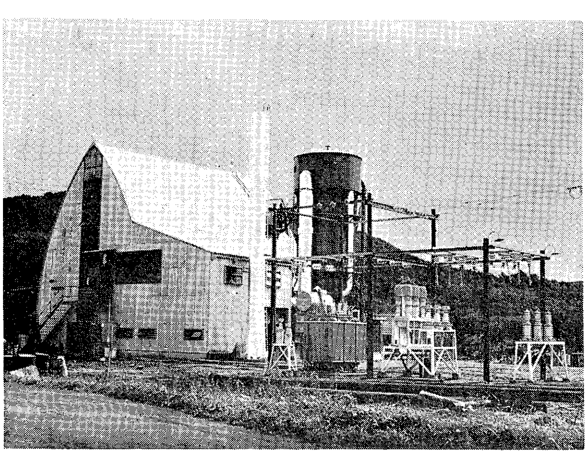


Fig. 1. General view of the Toyotomi Power Station

A general view of the Toyotomi Power Station is shown in Fig. 1. The electric power system is shown in Fig. 2.

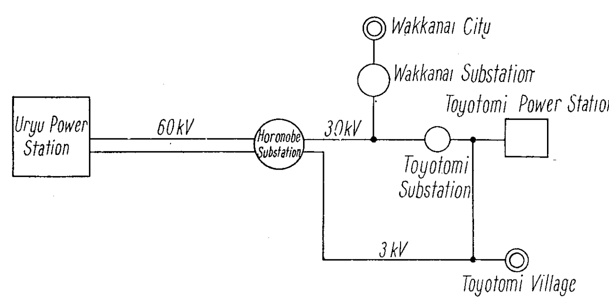


Fig. 2. System of Toyotomi Power Station

This power plant which will provide electric power to nearby areas is situated inToyotomi village near Wakkanai City on the northern tip of Hokkaido. Toyotomi village is endowed with a rich underground reserve of natural gas. This reserve is claimed to be the largest in our country. Of the two wells now emitting gas, Well No. 1 has already been in constant operation for 30 years, but the reserve is said to be almost untouched. The present average output is about 25,000 m^3/day with the major portion to be utilized by this power plant.

This gas is being used at present by a nearby small scale brick factory and a starch plant but their consumption is very small. Up until the completion of the power plant, most of the natural gas was being permitted to escape into the atmosphere.

Table 1 shows the results of an analysis of this natural gas.

The gas is chiefly methane and its composition varies slightly according to the time it is obtained. Its gushing pressure varies according to the consumption rate, reaching as high as 7 atmospheres but generally being from two to three atmospheres. Consequently a reducing valve is used to adjust the pressure to requirements.

Table 1. Analysed result of fuel gases

Date	GO_2	C_nH_m	O_2	CO	H_2	C_nH_{2n+2}	N_2
1957-11- 7	3.45	1.7	1.1	—	—	91.8	1.88
11- 8, No. 1	0.4	1.5	2.45	1.4	1.0	93.25	—
〃 2	1.4	—	1.9	0.6	—	96.05	—
〃 3	1.45	—	0.6	0.2	2.0	93.2	2.55
11- 9, 〃 1	2.4	—	0.45	0.35	2.5	91.9	2.4
〃 2	2.16	—	0.55	0.8	—	96.49	—
11-10, 〃 1	1.85	—	0.35	—	—	97.8	—
〃 2	1.67	—	0.61	0.1	—	97.62	—

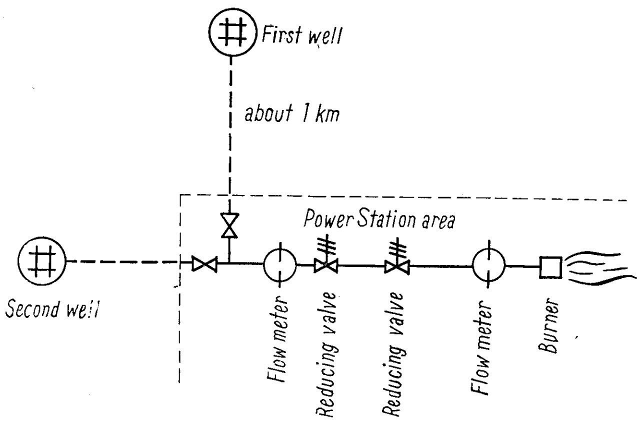
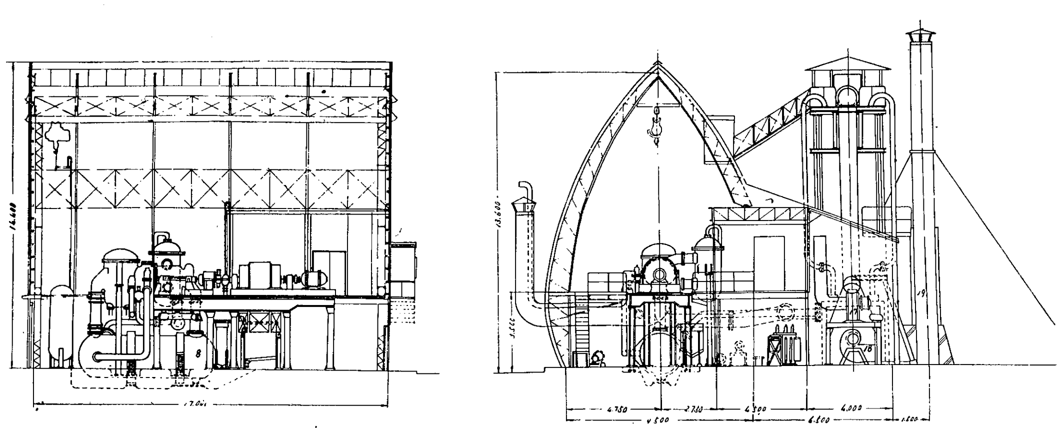


Fig. 3. Plan of fuel gas system

Fig. 3 shows the gas feed situation. After the fuel gas is brought to the power plant compound, it is combined with the gas from the two wells and flows through the first stage reducing valve after passing through a flow meter. This regulates the pressure to about 300 mm WC and a second stage reducing valve further reduces it to about 50 mm WC. The gas then passes through the flow regulating damper and is emitted from the combustor into the air heater where it is burned.

II. SPECIFICATIONS

The plant layout is shown in Fig. 4. As mentioned previously, motive power for the plant is



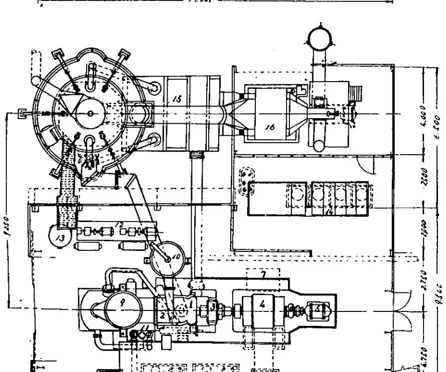


Fig. 4. Plan of Toyotomi Power Station

supplied by the closed-cycle gas turbine. The closed-cycle gas turbine is a new prime mover invented and developed by the "Escher Wyss" Company of Switzerland. Completion of the Toyotomi power station is the result of a technical tie-up between our Company and the Escher Wyss Company.

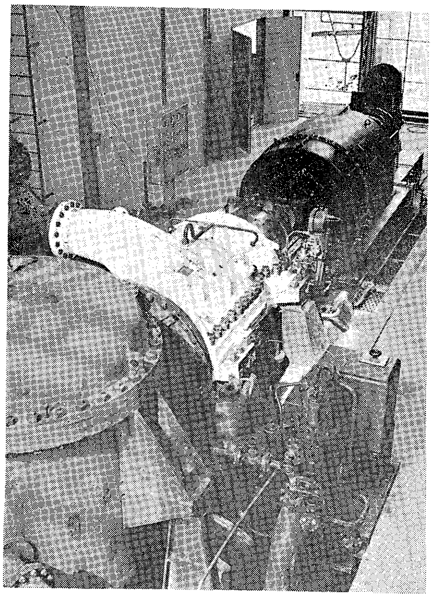


Fig. 5. Turbomachine set

As shown in Fig. 5 the main equipment is comparatively small. Because of the small number of auxiliary equipment, the turbine room is compact.

The principal specifications of the Toyotomi power station are shown in Table 2.

Table 2. Major specifications of 2000 kW gas turbine

Rated output	2000 kW
Type of gas turbine	closed cycle, tandem type
Type of compressor	radial flow type, with one inter cooler
Inlet temperature	25°C
Inlet pressure	8 ata
Type of turbine	axial flow type
Inlet temperature	660°C
Inlet pressure	27 ata
Revolution	13,000 rpm
Type of recuperator	shell and special-ribbed tube type
Effectiveness	90%
Generator capacity	2,500 kVA
Revolution	3,000 rpm
Total efficiency of the plant	26%

III. SPECIAL FEATURES OF CONSTRUCTION

This power generating facility has many special features as mentioned previously. Only the principal features will be explained hereunder.

1. Turbine-compressor unit

As the name indicates, in the closed-cycle gas turbine the cycle is isolated from the surrounding atmosphere and the pressure within the cycle can be selected at any level. An attempt is therefore being made to reduce the size of the equipment by generally using high pressure. As will be mentioned later, this will make it possible to easily and safely regulate output.

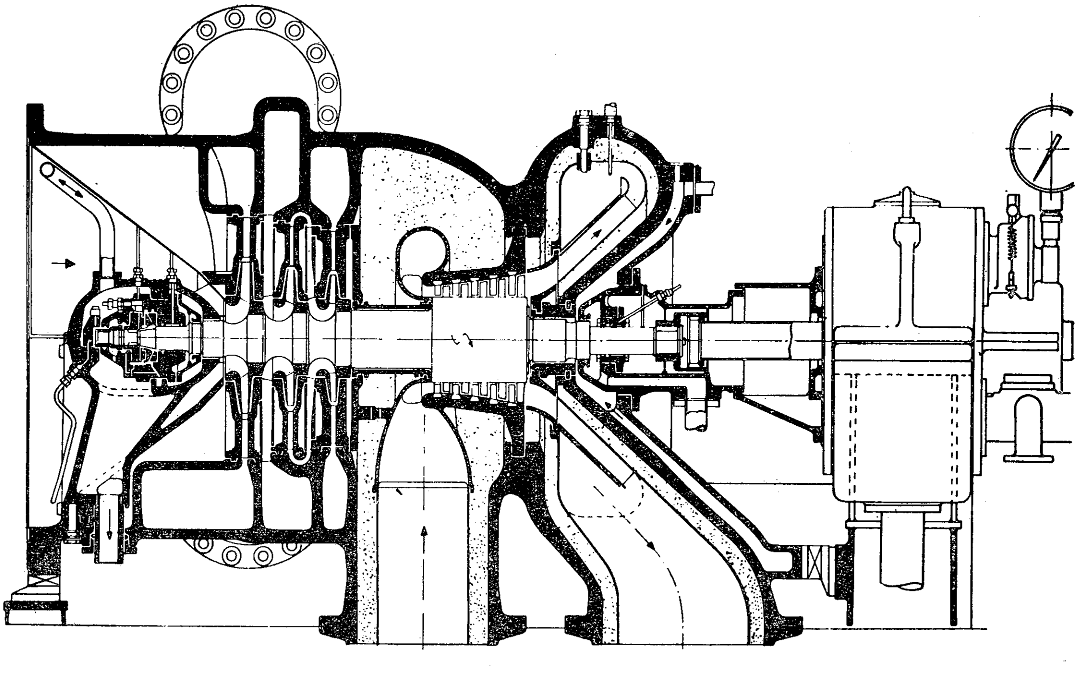


Fig. 6. Turbine-compressor unit

Fig. 6 is a sectional view of the turbine-compressor unit.

The turbine and compressor are of integral construction with the same shaft and casing. Its entire length is no more than about 1.5 m and there is absolutely no need to support the shaft under high temperature and pressure. Therefore the need for cooling or leakage prevention does not exist.

The fact that the 2,000 kW gas turbine requires a rotor which is less than 0.5 m in diameter and less than 1.5 m in length cannot be seen in any other prime mover. The rotor is one of the most important components of the gas turbine and is subject to frequent difficulties. Its compactness, however, has simplified close examination, forging and heat treatment of the main shaft. No breakdowns occurred all during the actual operation. As shown in Fig. 6, the shaft drives the generator through the reduction gear. The turbine has an inner casing and the space between it and the outer casing is heat insulated. This minimizes the heat capacity of the inner casing and makes adjustments for the temperature variations of the fluid. It is so designed that temperature difference will not cause brushing with the turbine blades during rapid heating and cooling (quick starting and stopping). Also, heating of the outer casing is prevented and changing of the shape of the machinery during operation, particularly divergence from the center line due to thermal expansion and distortion, is checked. Since the shaft does not project beyond the compressor outlet and turbine inlet, the problem of high-pressure air leakage does not exist. Furthermore, there is no need for a bearing at the high temperature zone so that all drawbacks have been ingeniously overcome.

2. Shaft sealing system

The main rotor shaft is supported near both its ends. Leakage of lubricating oil and its vapour from the bearing into the closed-cycle contaminates the circuit, particularly the blades of the turbine and compressor and the heating surface, resulting in a drastic drop in efficiency. A fire hazard is also created. Prevention of this flow is, therefore, a serious problem. Due to the vibration of the shaft, the bearing distance has been shortened as much as possible. The bearing is therefore installed immediately in front of the compressor inlet or behind the turbine outlet. The pressure here varies widely from atmospheric pressure to 7 atmospheres according to the output. The lubricating oil pressure too changes in accordance with the output. Since this pressure change must sometimes be conducted suddenly as in the case of a rapid stop, a only mechanical sealing system such as a labyrinth seal is inadequate. Consequently a sealing air system is employed. In other words, a constant flow of air with a pressure slightly higher than that at the compressor inlet and turbine outlet is inserted between the bearing and its inlet or outlet. This air checks the leakage of cycle air and the flow of the lubricating oil. As a result, the journal box is of double layer construction and the bearing is contained within the sealing air chamber.

3. Recuperator (Heat exchanger)

Since the entire working cycle is under high pressure, the volume flow of the working medium flowing through the recuperator is reduced. Through the adoption of a large Reynolds Number, thermal conductivity has been increased so that the size of this small recuperator is further reduced. The shell of the recuperator consists of a two meter in diameter and six meter long and is filled with a large number of specially ribbed two layer tubes as shown in Fig. 7. The heat exchanging rate of this recuperator is greater than 90 per cent and the pressure loss is low. Such a high efficiency cannot be obtained in an open-cycle gas turbine and is one of the advantages of the closed-cycle gas turbine.

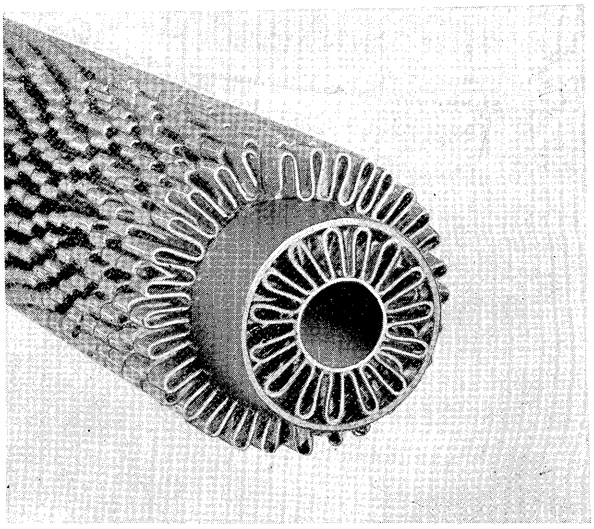


Fig. 7. Heat exchanger tube

4. Steel foundation

The gas turbine, generator and other accessory equipments are placed about 3.5 meters above the ground. Moreover, its rpm is very high, being 13,000.

In such a high speed the occupied space of the foundation would be appreciably increased if a rigid foundation is wanted. We therefore decided to obtain an extremely low natural frequency of vibration.

The bed on which the gas turbine generator is placed is of all steel construction as shown in Fig. 8.

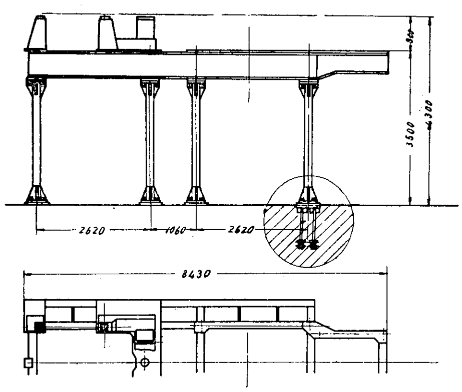


Fig. 8. Common bed for machine group

It is supported by very narrow girders and the designed horizontal natural frequency does not exceed a few cps. This is less than one several tenths of the rated turbine speed and also lower than the slow running speed of the gas turbine in starting. The turbine is therefore always rotating above the primary critical speed of the bed and is being operated between the high order resonance frequencies.

If such a flexible bed for rotating machines is designed carefully, not only will all dangers be eliminated but it was proven that this would be a superior equipment as its space utilization grade would be greatly enhanced.

5. Air heater

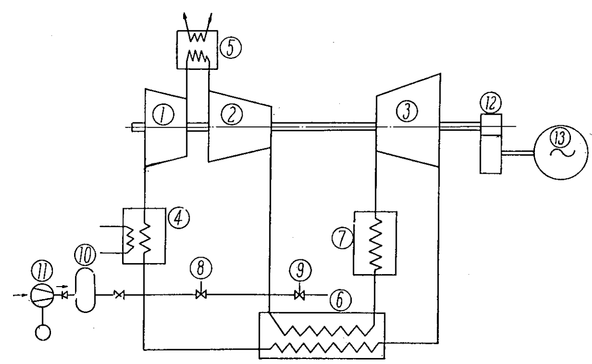
Since the outdoor type is used it remains completely covered by snow as the temperature drops below −25°C in winter. The hazards of freezing are therefore forever present. Turbine stoppages occurred at the outset due to freezing of the outdoor small tube for the control air system. The air heater differs from a steam boiler in that it contains no water content. Therefore, in spite of the severe cold of this area the equipment functions outdoors without difficulty. Another specialty of the air heater is the fact that it uses only natural gas as fuel. Since our Country possesses only a few rich gas fields, no large capacity natural gas combustors have been manufactured. Following a long period of model tests, we have succeeded in making a special gas combustor. This has made it possible to regulate combustion from full load to no load by means of a single combustor.

IV. REGULATING AND SAFETY EQUIPMENT

The regulating method of the closed-cycle gas turbine is twofold. The primary control is to regulate output by changing the mass flow without changing the volume flow by varying air density through raising or lowering the pressure level within the cycle. The other is by-pass control wherein some of the high pressure air from the compressor outlet is forced to return directly to the compressor inlet without passing through the turbine.

1. Primary control

For this Control, an air tank and air charging compressors to provide air to the cycle and a discharge valve to discharge air from the cycle have been installed. Thus, in this way, the required cycle pressure is constantly maintained. When output requirement increases, a large amount of compressed air is immediately fed from the tank. Or if there is a sudden reduction in load, the discharge valve is opened and the air rejected. The arrangement of these valves and the air tank is shown in Fig. 9.



① Compressor I ② Compressor II ③ Turbine
④ Precooler ⑤ Intercooler ⑥ Regenerator
⑦ Air heater ⑧ By-pass valve ⑨ Discharge valve
⑩ Air tank ⑪ Changing compressor
⑫ Reduction gear ⑬ Generator

Fig. 9. Schematic plan of closed-cycle gas turbine

The feature of this regulating method is that the temperature at each point of the cycle remains constant regardless of the load and its relationship with the pressure remains unchanged. Consequently, the flow within the turbine and compressor remains unchanged and efficiency is not lowered. High efficiency can therefore be maintained at partial load, too.

2. By-pass control

Whereas the aforementioned primary control is performed at a steady state, in by-pass control, the purpose is to conduct transient control. In this method, the gas turbine output can be drastically changed at an instant. For example, instantaneous changes can be made from full load to no load and vice versa. As shown in the diagram, the by-pass valve has been installed for this purpose.

3. Safety devices

Just as in the case of steam turbines, this gas turbine unit is equipped with all types of safety equipment so that the turbine may be safely stopped in any emergency.

The following main safety devices have been installed :

1) Overspeed safety (governor)
2) Thrust bearing safety
3) Lubricating oil safety
4) Excess pressure safety
5) Blowoff warning device for flame.

These safety devices automatically shutoff the machines as soon as a breakdown occurs.

V. RESULTS OF PERFORMANCE TEST

As soon as the Toyotomi Power Station was completed, tests were conducted to confirm the capability of the power station. The testing period lasted from September 12 to November 26, 1957. The following tests were conducted in cooperation with Hokkaido Electric Power Co.

1) Governor test
2) Load test
3) Electrical tests

Due to a delay in the drilling operations at Well No. 2 for the natural gas to be used as fuel, this source could not be used during the trial operations. As a result supply of fuel for full load operation was inadequate. As an alternative, propane gas was mixed and burned, particularly during the performance test. The mixture ratio was about 1 : 3.

On using propane gas, 150 × 50 kg-bombes were readied and the gas was burned steadily with the use of a vaporizer and regulating tank.

1. Results of overspeed safety device test

This test is usually the first to be conducted in a turbomachine. Since high-speed turbomachines do not operate safely at excessive speed, an overspeed safety device must control any unusual rise in rotative speed. The purpose of this test was to confirm this action. Four tests were conducted with the safety device functioning properly each valve. It was shown that this safety operates at 110 per cent of the rated rpm. Fig. 10 is an oscillogram showing the test results.

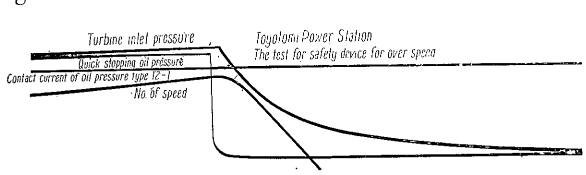


Fig. 10. Oscillogram of the test for safety device for over speed

2. Results of governor test

Table 3 shows the results of this test. This test was conducted to find the minimum and maximum range of speed regulation through manual operation at no load. It also tested the action of the governor when the load was suddenly interrupted while the turbine was operating at the rated speed or thereabouts carrying a load. Table 2 shows the range of manual speed regulation to be exactly the same as that for the steam turbine. The maximum instantaneous speed at load interruption did not always attain the prescribed maximum value or 110 per cent of the normal rpm. The lasting speed at full load showed a 3.5 per cent increase over the normal rpm and was within the 3 to 4 per cent range. Fig. 11 is an illustration of an oscillogram for a 1,500 kW load interruption conducted on November 8, 1957.

Table 3. Test results of speed governor

Test load (kW)	500	1000	1500	2000
Initial speed (rpm)	2990	2995	3000	2995
Max. speed (rpm)	3215	3170	3250	3275
〃 rate (%)	7.5	5.8	8.3	9.3
Lasting speed (rpm)	3020	3070	3080	3105
〃 rate (%)	1.0	2.5	2.7	3.5
Time, to max. speed	4.0	1.1	1.0	0.8
〃 to lasting speed	22.5	7.5	12.1	17.8

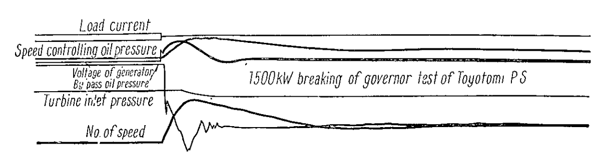


Fig. 11. Oscillogram of governor test

3. Results of load test

This test was conducted from November 7 to 26, 1957. Tests were conducted for loads of 500 kW, 1,000 kW, 1,500 kW and 2,000 kW. The temperature was maintained as close as possible to normal for a long period and the temperature and pressure at many points of the cycle and the operating air flow were measured. Generator output and fuel consumption were also measured. Simultaneously, fuel gas specimens were obtained and analyzed. Table 1 previously mentioned, includes the values for this analysis.

As mentioned before, control of turbine output transforms the pressure of the cycle, regulates mass flow and maintains a fixed temperature. Therefore, generator output and cycle pressure are closely related. Fig. 12 shows the relationship curve obtained through the load test. The diagram shows that definite linear relationship exists. This shows that the closed-cycle gas turbine output can be easily controlled by regulating the cycle pressure.

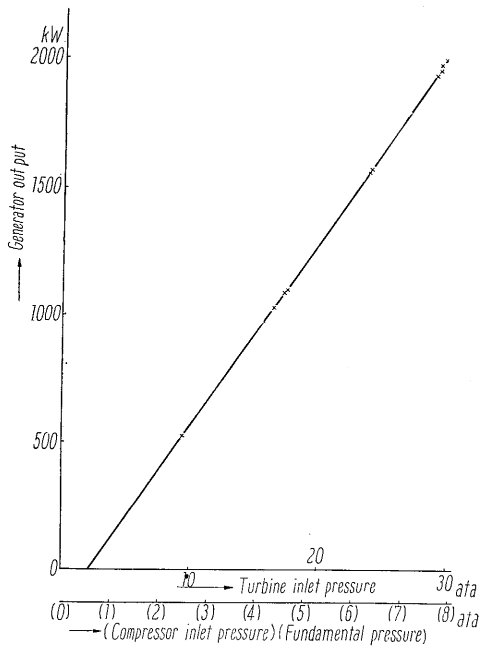


Fig. 12. Relation between cycle pressure and generator output

Fig. 13 represents an efficiency curve obtained from direct calculation of generator output and fuel consumed. The generator is connected to the gas turbine through the reduction gear. It is also connected directly to the starting motor, exciter and main oil pump. Generator output is, therefore, the

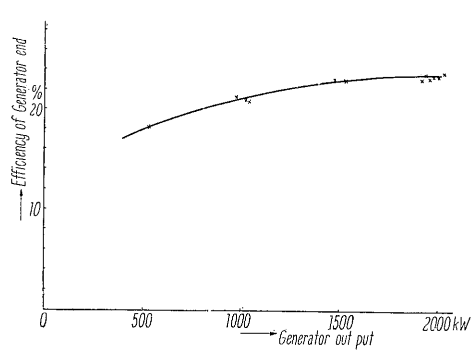


Fig. 13. Efficiency curve of Toyotomi Power Station

net output excluding the mechanical losses of these equipment. Consequently this is expressed as the thermal efficiency value for the generator output, as represented in the diagram, efficiency at full load is indicated as 24 per cent which is 2 per cent less than the designed value. The chief reason the compressor efficiency was slightly less than the designed value was because, this being a prototype, complete matching of the turbine and compressor could not be achieved. This value, however, is not by any means inferior in comparison to the thermal efficiency of other gas turbines in actual use or of most of the steam generating plants. The diagram also shows that the efficiency curve is extremely flat and the lowering of efficiency at partial load to be barely noticeable. For example, the value at one-half load is about 89 per cent of that at full-load and even at one-fourth load the value is 75 per cent of that at full load. This is one of the features not available in other prime movers.

4. Results of other tests

1) Measurement of vibration

Because of the extremely high rotative speed of the main equipment and the adoption of a flexible supporting foundation of steel construction, exact measurements were made of vibration in the various units and the bed. Part of the results is shown in Table 4. Although a tendency to increase in proportion to an increase in load was indicated, the vibration was slight. With the exception of the horizontal direction of the reduction gear mechanism, however, this was less than 5μ and operation was remarkably quiet. The Reutlinger measuring device was used to measure vibration. The points measured are shown in Fig. 14. Odd numbers represent vertical vibration measurements and even numbers represent horizontal vibration measurements.

Table 4. Measured results of vibration

Load (kW)	Measuring point (unit 0.001 mm)									
	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩
500	1.4	1.5	1.1	2.2	3.6	6.2	4.5	5.5	3.7	2.2
1000	1.2	2.7	1.4	2.9	5.5	7.5	4.0	4.5	4.8	2.7
1500	1.7	3.2	1.8	4.0	5.5	10.0	5.5	5.0	6.0	3.5
2000	2.0	3.2	2.2	4.0	3.9	9.7	5.5	4.5	5.0	3.0

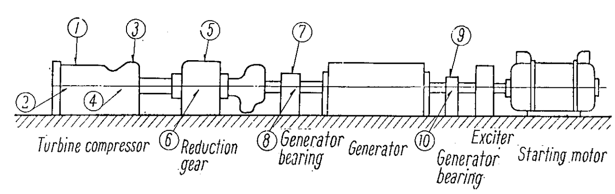


Fig. 14. Measuring point of vibration

2) Results of air heater test

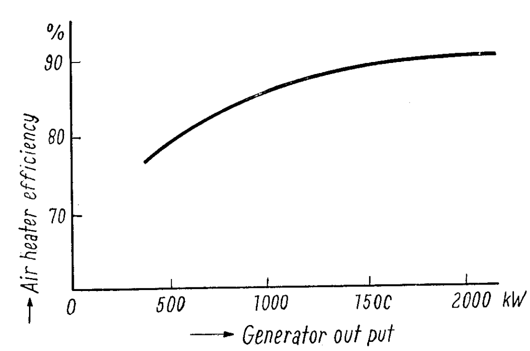


Fig. 15. Air heater efficiency

The air heater efficiency for various loads is shown in Fig. 15. The fuel fed to the air heater was automatically regulated by the cycle pressure and the temperature at the turbine inlet. Thorough tests were first conducted on a model of a natural gas combustor and the results used to determine the actual model. Favorable combustion occurred during actual operation and a high combustion efficiency was indicated without any signs of abnormal combustion such as backfire and blow off.

VI. CONCLUSION

The Toyotomi Power Station not only utilizes a new type prime mover but it also has incorporated other new type equipment. In attaining our objective we conducted long and earnest tests on performance dependability as well as on durability. The results have generally satisfied the designed specifications, although the overall efficiency value is about 2 per cent less than the designed value of 26 per cent, it probably can be said that this efficiency is not inferior to that of any gas turbine now in use or that of most steam power plants now in operation.

On the basis of these results, we are planning further improvements in performance as well as larger capacity equipment in our efforts to promote the widespread use of gas turbines in the field of thermal generation.

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