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12,000 KW GAS TURBINE POWER GENERATING UNIT FOR STEEL WORKS

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I. INTRODUCTION

The rapid development in various industries and considerable progress of rationalization of every enterprise have recently kept pace with an extreme increase of electric power consumption.

Accordingly on the one hand large power stations with a unit capacity of several hundred thousand kW have been established for power of business service and on the other hand private power stations have also been newly established or extended their output by various industries.

In these cases, it is intended not only to secure a stable power but also to raise up economy of a full plant by utilization of high efficiency followed by the progress of the modern thermal power generating equipment, whereby raising up the plant efficiency, lowering the maintenance cost, the unit power generating cost is cut down.

The closed cycle gas turbine possesses such excellent features as high efficiency, simple operation, low maintenance cost etc. as a prime mover for the private generating set.

Our Company made a technical cooperation with Escher Wyss Ltd. long since and have engaged in manufacture of the closed cycle gas turbine. As the first set, a gas turbine generator for the Toyotomi generating station, Hokkaido Power Co. was completed by us and has successfully been operated since 1957. By dint of the experience obtained meanwhile, the present gas turbine has been completed. The gas turbine has been erected closely to the existing steam turbine generator for the private generating station at the Kawasaki Steel Works, Nippon Kokan K.K. and its capacity is the largest one ever installed in Japan as a gas turbine. Taking the opportunity of completion of the gas turbine, we wish to explain the outline and details on the performance tests, exercised just after completion, for which we obtained successful results as expectation.

II. SPECIFICATIONS

As fuel for the gas turbine generator set, blast furnace gas exhausted from the blast furnace at the steel works is used, which is exhaused from the blast furnace and is fed in a condition extracted dusts through the washers and is used common with the existing steam turbine and the other purposes.

The specification for the generating equipment is as follows.

Continuous output,	
Normal:	10,000 kW
Maximum:	12,000 kW
Kind of prime mover:	Closed cycle, single-shaft, regenerative gas turbine
Turbine	
Inlet temperature:	680°C
Inlet pressure:	36 ata. (max.)
Air mass flow:	103 kgs/s (max.)
Fuel:	Blast furnace gas, besides the gas, bunker oil is capable to be used as auxiliary.
Turbine type:	Axial-reaction type blading.
No. of stage:	6
Revolution:	6,634 rpm
Air compressor,	
Type:	Axial-flow type with intercoolers.
No. of stage:	H.p. compressor 10
	M.p. compressor 5
	L.p. compressor 5
Revolution:	6,634 rpm
Speed reducing device,	
Ratio:	6,634/3,000
Air heater,	
Outlet temperature:	680°C
Air pressure:	36 ata. (max.)
No. of burner:	3
Furnace heat release:	150,000 kcal/m^{3}h (max.)
Combustion control system:	TELEPERM system, automatic combustion control
Heat exchanger,	
Form:	Tubular form with special ribs

Heat exchange rate: 90%

AC generator,

Form:	Horizontal shaft enclosed ventilated air circulation with air cooler.
Rated continuous output:	15,000 kVA
Rated voltage:	6,600 V
Frequency:	50 c/s
Power factor:	0.8
Revolution:	3,000 rpm
Excitation system:	Self-excitation by means of separately installed static exciter

Starting motor,

Type:	Horizontal shaft, enclosed ventilated type 3 phase wound rotor induction motor
Output:	400 kW
Voltage:	3,150 V
Frequency:	50 c/s
No. of pole:	2

Thermal efficiency at generator terminal:
30.2% (at normal rating)

III. OUTLINE

Fig. 1 and Fig. 2 show the interior of the machine room and the external view of outdoor type air heater for the gas turbine unit. The power station was installed at a compound of steel works, especially located at the sea-shore factory area between Kawasaki and Tsurumi, most dustly in the neighbourhood.

The blast furnace gas used as fuel also contains most dusts, however the closed cycle gas turbine is not worried about at all for any injury given owing to these circumstances, because its operation cycle is perfectly interrupted from the external air. The gas turbine possesses a cycle as shown in Fig. 3 The working medium is compressed air which is compressed by an compressor at first while it is cooled and then compressed air enters into a heat exchanger and absorbs the heat of exhaust gas from the turbine, being heated to about 380°C, and is transfered

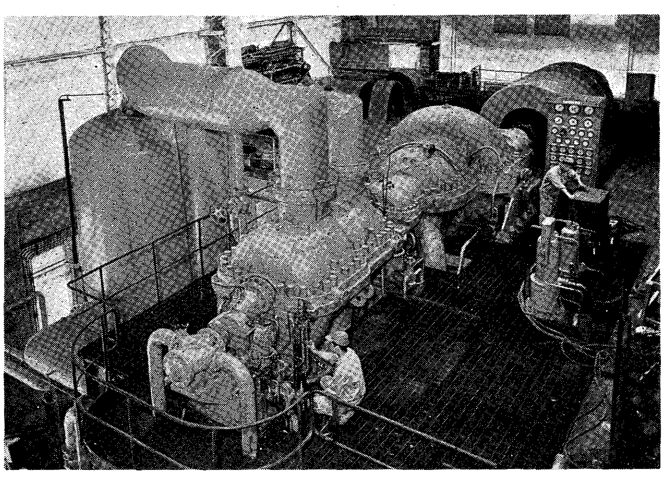


Fig. 1 Inner view of machine room for 12,000 kW gas turbine unit

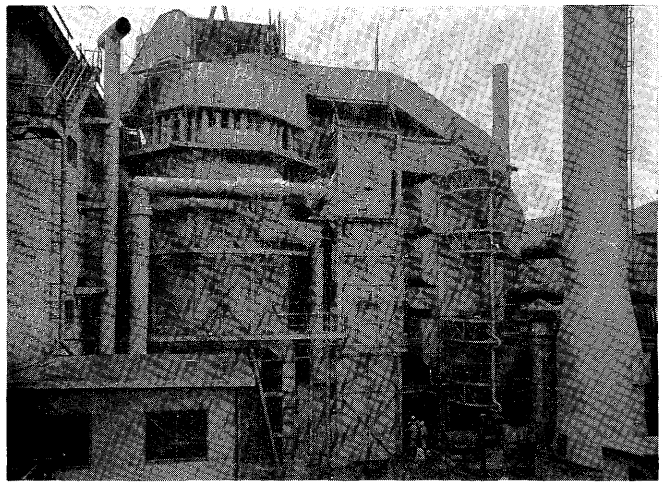
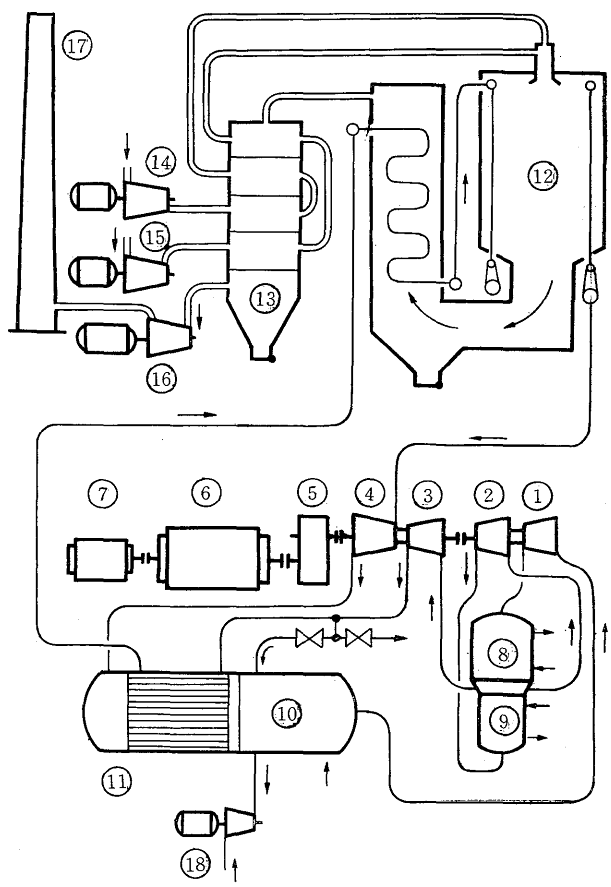


Fig. 2 Outdoor type air heater of 12,000 kW closed cycle gas turbine



① Low pressure compressor
② Middle pressure compressor
③ High pressure compressor
④ Turbine
⑤ Reduction gear
⑥ Electric generator
⑦ Starting motor
⑧ Intercooler I
⑨ Intercooler II
⑩ Precooler
⑪ Heat exchanger
⑫ Air heater
⑬ Fuel gas preheater
⑭ Fuel gas blower
⑮ Forced fan
⑯ Induced fan
⑰ Stack
⑱ Charging air compressor

Fig. 3 Cycle diagram of 12,000 kW closed cycle gas turbine to an air heater. The air heater has a radiation surface and a convection surface, the former is installed at the periphery of the combustion room and the latter is installed at the flue. The working air is heated to 680°C passing through these heat conducting tube. The heated high pressure high temperature air enters into the turbine, expanding in the turbine casing, and rotates the rotor, converting its heat energy absorbed in the air heater from fuel into a mechanical work, which drives the generator through a reduction gear and generates an electric power. The working air from the turbine enters into the heat exchanger, and being absorbed its waste heat, as described above, becomes to low temperature air and further being cooled by a precooler, it enters into the compressor again and repeats the work from the beginning.

As explained above, the same air forever circulates within the cycle and never get any damage such as soiling, corrosion etc. due to dust, rubbish, combustion gas etc.

As described above, this gas turbine is the largest in output in our country and possesses a construction with many excellent features, different from No. 1 machine manufactured by our Company. We herewith describe its brief construction.

1. Turbine Compressor Set

In a closed cycle gas turbine plant its machines and apparatus can be made compact by raising up the cycle pressure and also the efficiency of heat transfering apparatus is raised up accordingly. The sectional plan of turbine compressor set is illustrated in Fig. 4.

The drawing shows, from the left, low and middle pressure compressors, high pressure compressor and turbine, further a reduction gear to be provided, end of which AC generator to be coupled. As shown in the drawing, each two machines, being made in a lump, are put in one casing (one is for two compressors, the other for turbine and HP compressor). Consequently they are built on a common shaft, so that four machines look just as two machines.

For the compressor blade form, an axial-outlet form with a degree of reaction more than 100% is adopted, which is a peculiar technique of Escher Wyss. The compressor of this form has a high compression ratio per stage and high efficiency at a comparative low peripherical speed, and the performance of multi-stage compressor being as good as single-stage compressor, it has a wide and stable operating range.[1] The turbine is built in the same casing as the HP compressor. A form in which turbine and compressor are built together is called TUCO type and is widely adopted for the modern closed cycle gas turbine, whereby not only a whole arrangement is made easily by decrease of numbers of casing, but also by means of pressure balance made well between high pressure at compressor outlet and high temperature high pressure at turbine inlet, leakage of the working air is prevented and a bearing at high temperature high pressure part can be eliminated.

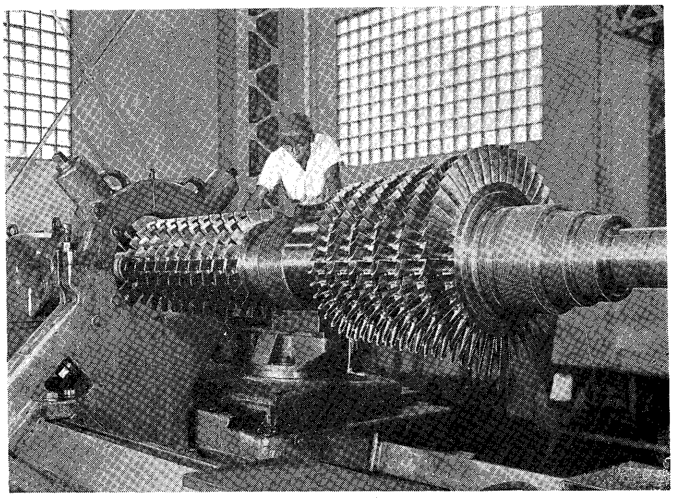


Fig. 5 Turbine shaft under the final finishing

The moving blades of compressor and turbine are set in the slits cut on the shaft and the stationary blades are set in the slits on the periphery of inner casing to form a stationary blade holder. The turbine rotor is rotated at a high speed of 6,600 rpm, moreover temperature around turbine inlet being attained to such high temperature as about 650°C, therefore it was manufactured with utmost care. Especially as to the shaft material, a heat stability process was repeatedly carried out and dynamic balancing test and over speed test were also exercised quite strictly and sufficiently. Fig. 5 shows the turbine shaft under the final finishing.

The end of the stationary blade is inserted into the ring, which faces Labyrinth embedded on the shaft and protects air leakage between stages.

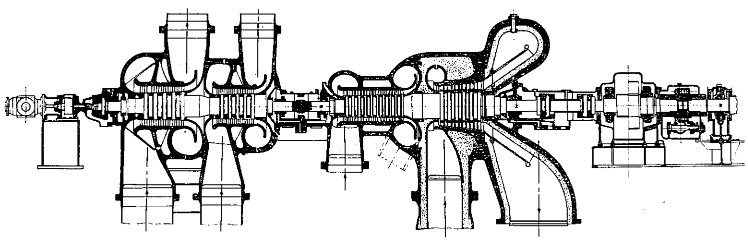


Fig. 4 Sectional plan of turbine compressor set

Moreover the cycle pressure is maintained by means of a pressure tight construction made for respective casting. Further in case of turbine, rock wool is inserted as a heat resisting material between inner and outer casings, whereby heat of the high temperature air passing through the turbine is interrupted against the external parts, i.e. heating insulation is performed inside the pressure tight casing. The inner casing is exposed in a high temperature of 680°C, however the internal pressure being balanced with the external pressure, it exists as a wall of fluid pass having a comparatively thin thickness and a small heat capacity, and the outer casing is strong enough only to withstand against a internal pressure as a pressure tight vessel at room temperature, for which there is no fear against thermal stress and thermal deformation. This is the fact that the response character against variation of condition of a gas turbine is raised up.

2. Air Heater

The closed cycle gas turbine is an external combustion system in which air is used as a working medium and calorific energy of fuel is heated indirectly through the heater pipe wall. Accordingly, quite differently from an internal heating system, the air heater to transmit heat quantities of fuel becomes a very important element of the constitution. Fig. 6 shows its construction.

The cylinder part of eight angle section at the left side in the drawing shows the combustion chamber, on which top burners are installed in a downward direction and fuel is jeted from these burners and burns. The heat quantities produced by combustion

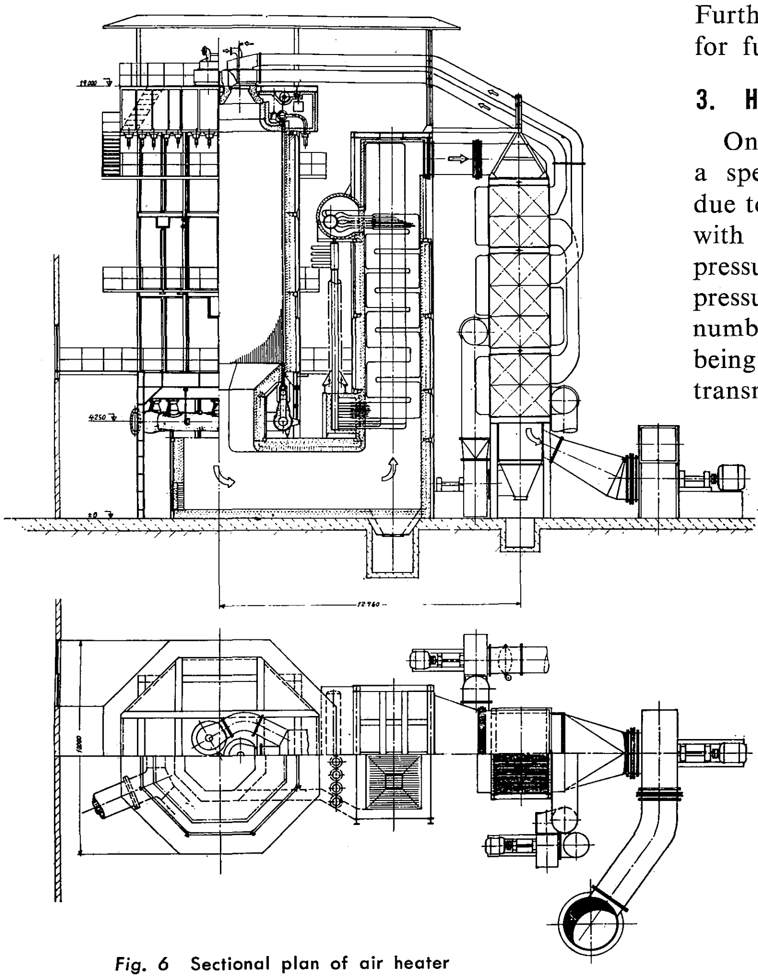


Fig. 6 Sectional plan of air heater

Fig. 7 Inner view of combustion chamber under construction

pass through heating tubes arranged vertically in the periphery of the combustion chamber and heat the air passing through the tubes. The temperature of the air attains here to 680°C. Accordingly this part of the heating tubes attains to the highest temperature during a cycle, so utmost care must be paid for its material. Fig. 7 shows the heating tubes assembled at site. As the fuel is such calorific gas as about 800 kcal/m^3, a plate form heat exchanger is arranged for preheating, which is illustrated at the right side. Further a soot blower is prepared at a suitable place for fuel gas contained many dusts.

3. Heat Exchanger and Cooler

One of causes for high thermal efficiency, that is a special feature of a closed cycle gas turbine, is due to the reason that a heat exchanger and a cooler with extremely high rate of heat exchange and low pressure loss are able to utilize. By raising the pressure of working air, not only the Reynolds numbers become a higher order, thermal conductivity being made better and large heat quantities can be transmitted with a small area, but also high density of air decreases volume flow and as it is sufficient with a small space, a high efficiency heat exchanger can be used with a size of practical use. The rate of heat exchange for

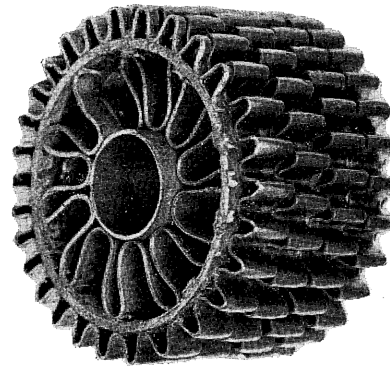
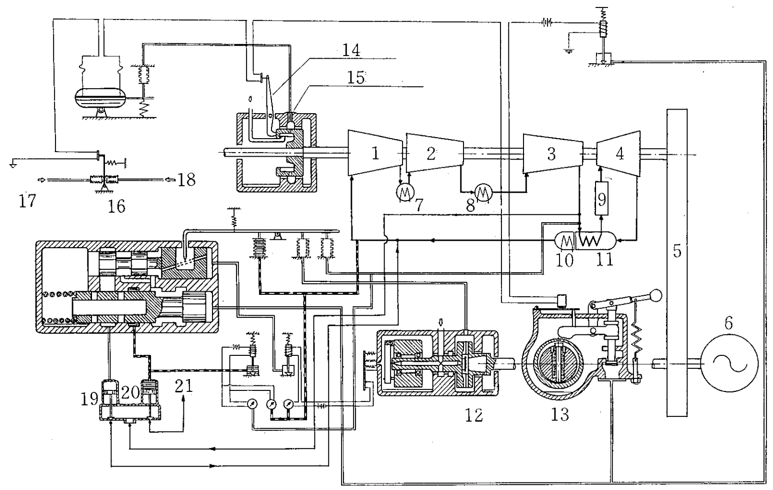


Fig. 8 Heat exchange tube equipped with wave form rib on external and internal sides

the heat exchanger used in the present gas turbine exceed 90% and temperature difference of cooler outlet is only 5°C. In order to utilize such merits, for the heat exchanger, double tubes attached with special ribs manufactured with our peculiar technique on the outside and inside of the tube has been used as shown in Fig. 8 and for the cooler, tubes with fins having the most effective size confirmed by our test have specially been manufactured and used.

Further the heat exchanger was erected just under the turbine, being made in one body with the precooler, whereby the pipings between these were eliminated.

There are two intermediate coolers for low pressure and middle pressure, but these, being in a lump, were made of one casing and erected vertically, standing at the side of the compressor.



① Low pressure compressor	⑫ Speed governor
② Middle pressure compressor	⑬ Mechanical overspeed trip
③ High pressure compressor	⑭ Safety device for thrust bearing
④ Turbine	⑮ Hydraulic overspeed trip
⑤ Reduction gear	⑯ Lubricating oil pressure trip
⑥ Generator	⑰ Pressure in sealing oil tank
⑦ Intercooler I	⑱ Lubricating oil pressure
⑧ Intercooler II	⑲ Bypath valve
⑨ Air heater	⑳ Blow off valve
⑩ Precooler	㉑ To atmospher
⑪ Heat exchanger	

Fig. 10 Schema of speed regulating device

4. Control Equipment

The control equipment of the gas turbine consists of a speed controlling device of gas turbine, an output settling device, various kinds of protective relays, an automatic combustion control device and other electrical controlling systems.

The closed cycle gas turbine is always operated under a constant temperature condition, i.e. the air temperature entering into the turbine is always maintained constant at 680°C even at a full load or a partial load. The output is controlled by the air pressure. Moreover as the pressure ratio of each part is constantly irrespective of load, for instant if air volume in the cycle is made half, the pressure of each part becomes half and even the volume flow of air passing through the turbine is constant, its mass flow becomes half. Thus there exists a linear relation between output and pressure, accordingly the setting of output is not different from the setting of pressure, moreover as the thermal efficiency is lowered very little even at a half load, the fuel quantity supplied to the air heater may also be fed proportionally to the pressure.

The light board equipped with these control devices has been erected in the existing switch board room.

The light coloured and new looking parts in Fig. 9 show the switch board for the extension and those for feeding to the existing lines. The operation can be carried out quite easily and scarcely necessitates hands, but it is quite enough with only one operator. Fig. 10 shows the speed control system and Fig. 11 shows the protective device. The speed control is carried out mainly by means of a bypass control. When a output of the turbine becomes larger than an actual load and its speed begins to raise up, the

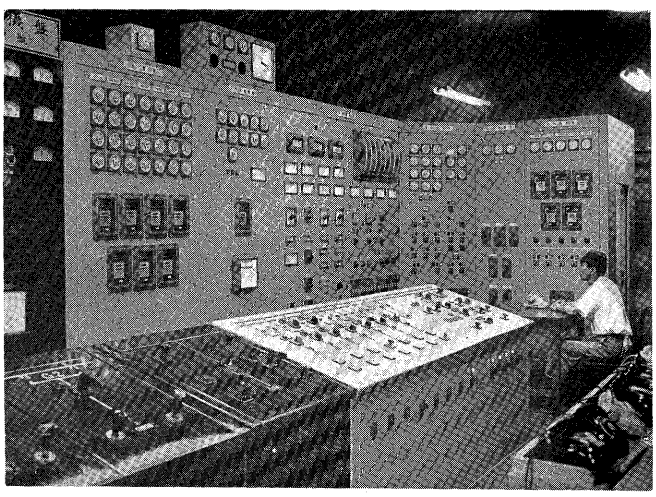


Fig. 9 Control board of 12,000 kW gas turbine

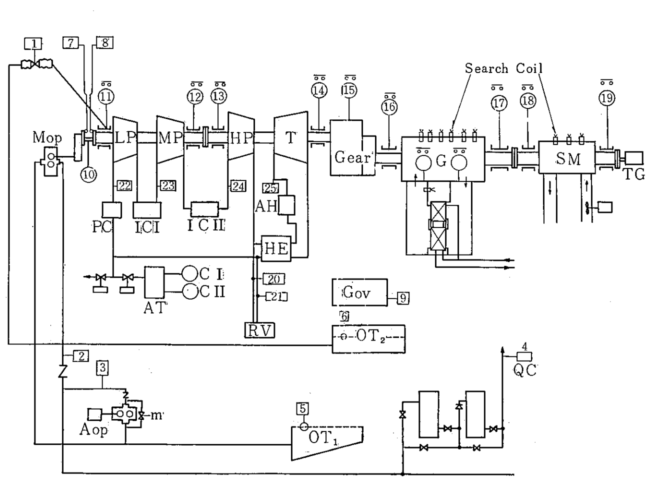


Fig. 11 Safety device for gas turbine

oil pressure type speed governor actuates and opens the bypass valve.

The bypass valve is put in the piping which short-circuits the operating air circuits of compressor outlet and compressor inlet, and when the bypass valve opens, one part of air compressed by the compressor does not come to the turbine but flows directly to the low tension side, so that the turbine output decreases by this amount and its speed is made to go down, balancing with the load, and in the reverse case it is made to close the opened valve and the speed is made to go up. This is an extremely effective control system because bypass quantity is comparatively small, operation is very simple, quick response and moreover the valve is not existing in the main flow of the cycle, so that there is no anxiety for either losses to be given usually or faults to be happened as it is equipped on the low temperature side.

The governor is equipped with an accelerating regulator besides, which in case of a sudden speed change, for instant in case of a full load interruption, is actuated earlier than the governor and protects the shaft against over speed. Further, as in the case of a steam turbine, an over speed regulator is equipped with and stops the turbine when over speed occurred owing to some accidents, however the present gas turbine is equipped with an oil pressure type emergency governor on the shaft end besides a mechanical emergency governor usually used to intend the double safe operation.

This principle is same as an oil pressure type governor, which by detecting an oil pressure produced due to over speed revolution, actuates the protective relay, whereby the safety circuit is operated.

Besides the above, there are provided with such protective devices that lubricating oil pressure, temperature of bearing metals, bearing position, oil level, air pressure of cycle etc., being detected out, are arranged to be connected to the circuits for turbine rapid stopping or alarming respectively in case of their abnormal conditions.

In the above, outline of the constitution are described. Fig. 12 shows the arrangement of components of the constitution. But the air heater is installed outdoor and is not shown here. As shown in the figure, main machine group such as turbine, compressor, generator, starting motor etc. are mounted upon the steel fabricated bed and set on the height of the 2 nd floor and the heat exchanger is erected just bellow these machines. The steel bed mounted with machine group are supported with thin I-bars and is formed a so-called elastically supported foundation.

The natural frequency of the bed is under operating revolution of the machines for both vertical and horizontal directions. This is the fact that the space under the bed becomes large, thus utility factor of the space is raised up.

This kind of bed has not been experienced in our country. However as it was very much successful when the same bed was applied for No. 1 gas turbine, we have adopted it in the present gas turbine.

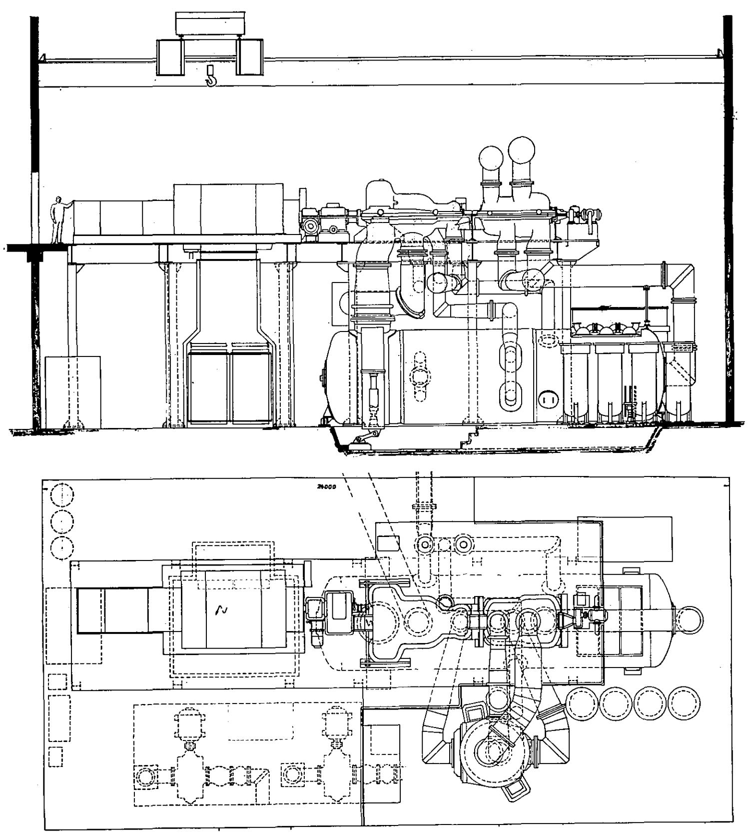


Fig. 12 Disposition in machine room

IV. PERFORMANCE TEST

The equipment for the power station has completely been finished after completion of manufacture, its erection at site, trial operation finished and the final adjustment of governor and other equipment, and a detailed performance test has been carried out after completion of the plant under agreement of our customer. Fig. 13 shows the machine room under performance test. A machine group such as starting motor, generator, reduction gear, turbine and compressor is shown from the front to the obliquely back side in the figure just shown from the opposite side of Fig. 1. At the right end in the figure, one part of the intermediate cooler is visible. In this figure these are a testing table and a meter board specially installed for this performance test that are seen at the frontb etween turbine and intermediate cooler and a black part in the back side along generator and turbine. The measurement was carried out, by using

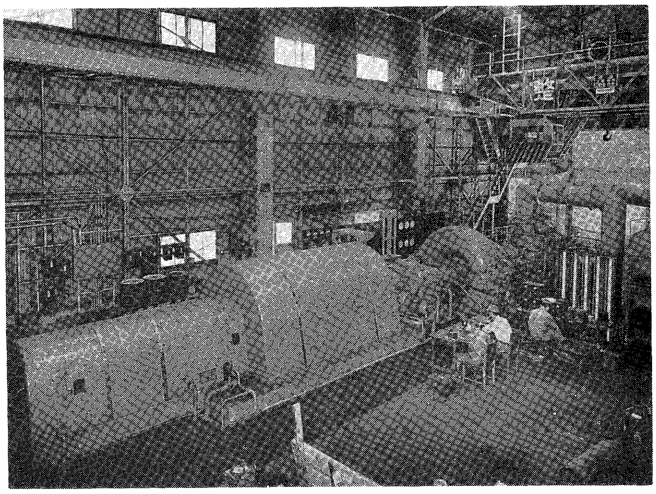


Fig. 13 12,000 kW gas turbine in performance test

a lot of accurate instruments such as precise pressure indicator with 1,000 divided scale, mercury column, precise differential pressure indicator, automatic temperature recorder, magnetic oscillograph etc. besides ordinary pressure gauges and thermometers.

In case of performance test of gas turbine, the relation between the elements in the cycle is in a closed connection respectively, so one of the constituted components, getting out of order, will give a considerable effect on the whole performances, moreover it is extremely difficult to decide where the cause exists and it may be said that the measurement of performances is of no use unless temperatures, pressures etc. to be measured are tested as accurately as possible. For this purpose we paid a great care in order to achieve the measurement of a lot of places concentrically, repeating discussions fully as well as raising the accuracy of the measuring instruments themselves, utlizing the most of our experience in the preceeding Toyotomi Power Station.

The performance tests were carried out in order of emergency speed regulator test, governor test, output and load tests under a condition after completion.

1. Emergency Speed Regulator Test

The revolution of turbine was raised, while raising a setting value of revolution setting mechanism, and working revolution of emergency speed regulator was confirmed.

This working revolution must function accurately at 110% ± 1% of the regular revolution.

Moreover the test was exercised more than 2 times and in either case the operation speed must be almost constant. The test results were successful to pass this regulation truely.

Table 1 **Result of load interruption**

	Testing load (kW)	12,000	9,000	6,000	3,000
Speed	During loading (rpm)	3,010	3,010	3,010	3,010
	Momentary max. speed (rpm)	3,250	3,250	3,220	3,230
	Rising rate (%)	8.0	8.0	7.0	7.3
	After settled (rpm)	3,140	3,120	3,100	3,080
	Rising rate (%)	4.3	3.7	3.0	2.3
Time required	To max. speed (s)	0.9	1.2	2.7	2.9
	To settled speed (s)	37	25	61	62

2. Governor Test

Continued to the emergency speed regulator test, a checking test for speed regulating range by means of governor and a load interruption test at full load and partial loads were carried out.

By the load interruption, generally the generator is disconnected from the net work and the revolution of turbine temporarily increases, soon after it is to be settled, however the governor shall not allow to attain to a working speed of emergency speed regulator even temporarily at the time of load interruption by speed controlling, moreover it must im mediately attain to a stable settling state and the settled speed must be within 5% even in case of full load. To confirm such performance of control device, a load interruption test was carried out. This test result is shown in Table 1 and one of oscillograms at that time is shown in Fig. 14. Fig. 14 illustrates time (0.5 sec./one division), load current, revolution of generator, lift of control valve, air pressure of cycle and oil pressure of governor from below. As shown in the figure, instantaneous maximum speed was 3,240 rpm. In general, a closed cycle gas turbine enables its size of machine very

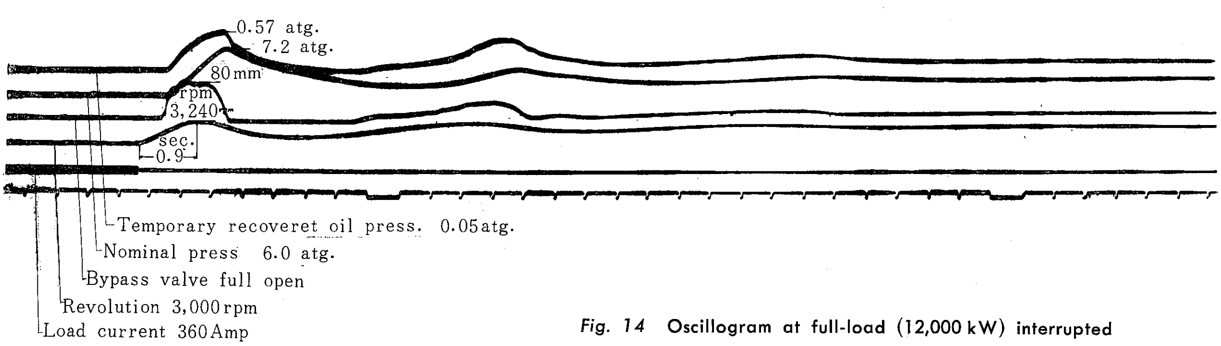


Fig. 14 Oscillogram at full-load (12,000 kW) interrupted

compact but which results in making an inertia of its rotating body very small. Accordingly in case of load interruption it is likely to run in excess speed, however as shown in both figures the rising rate of instantaneous maximum speed was settled within a quite safe range and showed a very small change due to load. This is owing to the effect of accelerating regulator, including which we are sure the governor showed an excellent performance.

3. Output Test and Load Test

These were tests by which power station equipment such as turbine, generator, air heater, fuel supplier etc. were checked if it would generate its approved output or not and as a load test, temperature rise test for each machine and apparatus was commonly carried out according to the regulation. And the conditions for each bearing, thermal expansion of machines and apparatus, vibration, operation of governor, temperature and pressure of lubricating oil, firing condition etc. were carefully observed.

Fig. 15 shows an operation record at the time of government test exercised on Dec. 12 th 1961. The emgrgency speed regulator test was carried out on the day before this operation test. Abscissa of the figure illustrates hours elapsed and time is described in the center of the record paper. The right line of the recorded curve illustrates temperature of working air into turbine and the left line illustrates air pressure into turbine. As in a closed gas turbine there is a relation of linear line as shown below between an effective output at generator terminal and turbine inlet pressure, this pressure curve can be considered equivalent to the generator output. As shown in the figure, after checking a test of 3,000 kW output, its load interruption test was carried out at 9–30 in the morning and just after restored, output being raised to 6,000 kW its load interruption test was carried out. Restored immediately, output being raised to 9,000 kW, the same test was carried out, moreover at the full load, 12,000 kW load interruption test was carried out at 12 o'clock and in succession full load operation was carried out during more than 6 hours, whereby the government test was finished.

As understood by the figure, air temperature into the turbine was kept a constant value (680°C) irrespective of the load and got very small change even at the time of load interruption. For the fuel supplied to the air heater, our TELEPERM system automatic combustion control device has been applied, by means of which it is easily understood that there exist entirely no such dangers as breakage etc. to give the turbine in the high temperature rotating part due to thermal shock. Further it has been proved that it instantaneously restored even in case of output becoming zero by load interruption or becoming suddenly from no load to original load, for instant, to full load.

It is also well understood that the response character against load variation in a closed cycle gas turbine is extremely excellent.

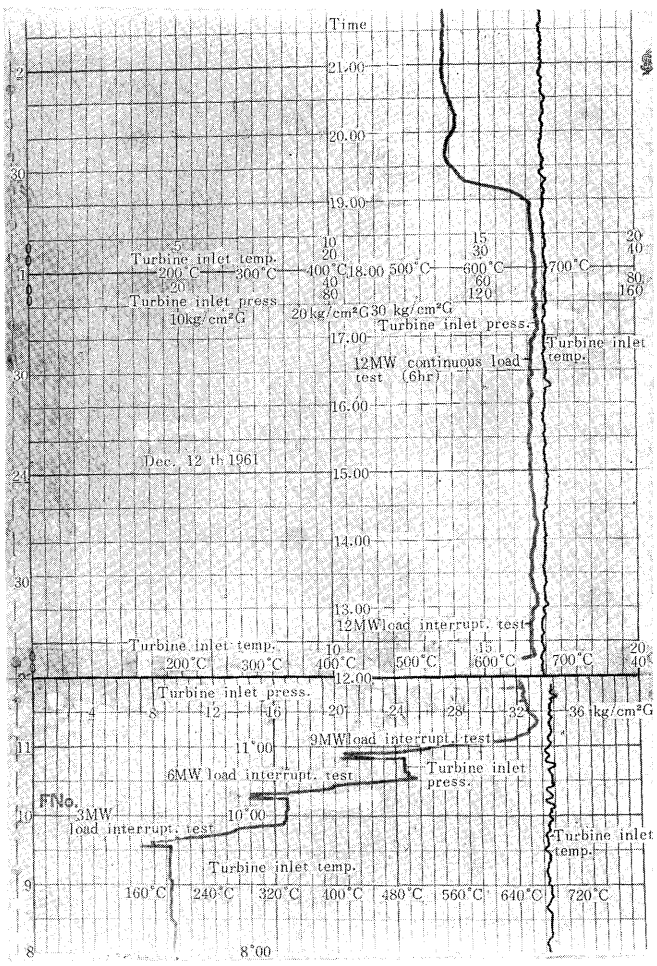


Fig. 15 Test operation record

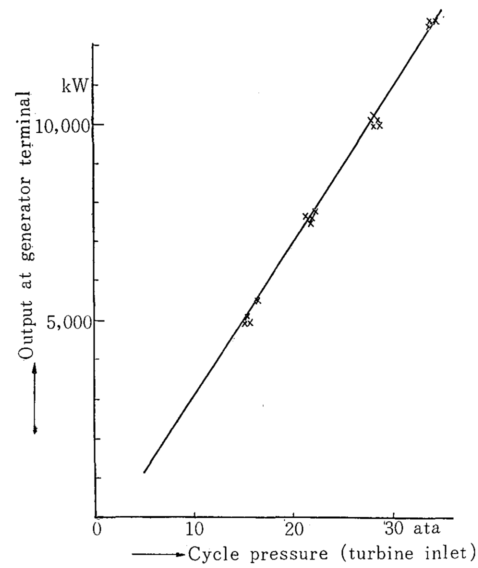


Fig. 16 Output—pressure curve

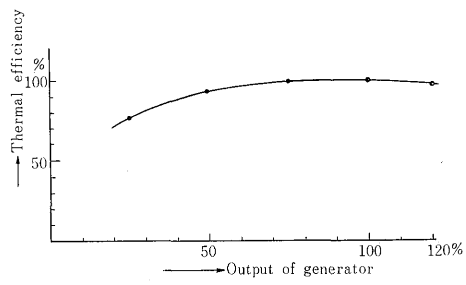


Fig. 17 Partial load efficiency

Fig. 16 illustrates a relation between generator output and cycle pressure, which well shows a linear relation and is understood it coincides with our design figures.

Fig. 17 illustrates a relation between generator output and thermal efficiency obtained from calorific value of fuel and generator output.

It is well understood that the efficiency at partial loads is lowered very little compared with that at full load, i.e. the partial load character is quite superior. Design figure of thermal efficiency at the rated load is 30.2% and actual efficiency tested has almost satisfied the design value.

4. Other Test Results

With regards to vibration of turbine, compressor and other machines and apparatus under loading, measurement on each bearing and other parts were exercised. This measuring device was arranged on the steel fabricated bed supported elastically, but amplitude of vibration of these machines was small, for instant, that of the main of the machine was only 2–5 microne at the time of full load.

Further the detail test performance for air heater, turbine, air compressor and others data for each component are now under preparation, which we wish to publish by next chance. But it has already been confirmed that these performances obtained are almost equal to our original design.

V. CONCLUSION

The present plant equipment was officially approved as a new thermal power station with output 12,000 kW after completion of the government tests exercised for two days on 11 th & 12 th Dec. 1961.

This output is a record making capacity, considerably large beyond the conventional power plants actually operated in our country as not only a closed cycle gas turbine but a open cycle gas turbine.

Further its performances and reliability have also sufficiently been confirmed. Our Company is now endeavouring for development of gas turbines with more superior functions as well as larger outputs, utilizing the above good results as a basic research and also for more extension of its utilization to the field of thermal power plant and other industrial plants.

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