THE 2,000 kW GAS-TURBINE PLANT

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I. INTRODUCTION

The first unit of gas-turbine has been completed at the Kawasaki works of Fuji Electric Mfg. Co., Ltd. This set is intended for installation, coupled with a turbine generator of 2,000 kW rating, at Toyotomi Power Station of the Hokkaido Electric Power Co. Two centuries have passed since the gas-turbine began to look like what it is at present. It took such a long time and efforts to make the gas-turbine practicable ; there is no invention is said to have exacted such amount of hard work from engineers for completion as it did.

Thanks to spectacular improvement of compressor and turbine performance and to advancement in the technique of heat resisting steel production, nowadays the gas-turbine is undeniably one of the most promising prime movers. In Japan also, there is a growing tendency to use it for power generation or for ship propulsion. The first set recently produced by our Company is going to be the forerunner of commercial gas-turbine power station in Japan. Naturally this is the first experience for our Company and various research efforts were made prior to the production.

On the occasion of completion of this unit, a brief information will be given as follows. Fig. 1 shows the general appearance of its main machinery group as it is undergoing a trial run at the works. The gas turbine built by our Company is a closed-cycle type which has excellent characteristics as stationary power station unit. For completion of this new prime mover, our company introduced technics from Escher Wyss Co. which boasts of long experience in turbine production.

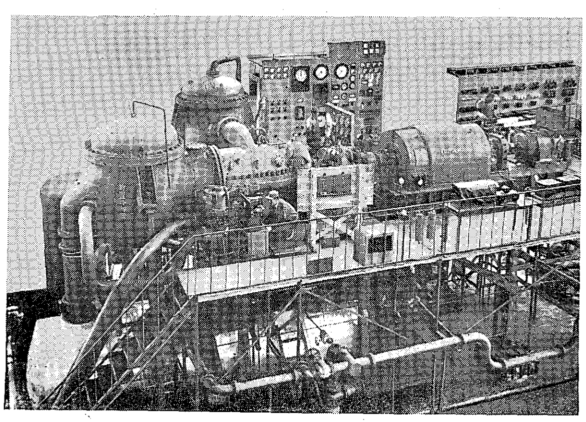

Fig. 1. Main machine parts of the 2,000 kW gas turbine set at Fuji Denki Kawasaki Works

II. FEATURES

Another name of a closed-cycle gas-turbine is hot air turbine. It means that nothing but the compressed air circulates the working air circuit and no fuel nor combustion gases are permitted to enter it.

As is well-known, the working principle is the same as in the open-cycle gas-turbine. That is,

i Compression by the compressor.

ii Equi-pressure heating by the heat exchanger and air heater.

iii Expansion by the turbine.

iv Cooling by the heat exchanger and precooler.

These four stages are involved. The compressed air, while passing through the piping system of air heater, is imparted with the combustion heat of fuel ; then enters the turbine to expand there. After that, it returns to the compressor, passing through the heat exchanger and precooler. Accordingly, the working air in the cycle is kept clean all the time. As the closed cycle is isolated from the atmosphere, the pressure at the compressor entrance or turbine exit can be selected without regard to the atmosphere.

By virtue of these features, this type has the following advantages over the open-cycle type :

i) The output can be adjusted through raising or lowering of level pressure. In other words, the weight of working gas passing through the cycle in unit time can be varied by mere adjustment of level pressure, without changing the temperature at each point of cycle. Therefore, the rate of flow is maintained constant so that a very high efficiency is available even under partial load.

ii) Heating of compressed air is done indirectly through the pipe wall in the air heater ; this renders it possible to utilize any kind of fuel good for the conventional steam boiler, be it bituminous coal or lignite or peat.

iii) For higher working gas pressure can be used than that of the open-cycle type. As a result, it can be built compact and, if need be, can be produced with an output of higher order. But, it will not always be lighter than the open-cycle one, for it is provided with an air heater of relatively heavy weight.

III. STRUCTURE OF 2,000 kW GAS-TURBINE

Fig. 2 is the working diagram of the main machinery group of gas-turbine. The main machines are installed on a steel foundation, arranged in a straight line: from left to right, the precooler, compressor turbine, reduction gear, generator, exciter, and starting motor; with the intermediate cooler at the back of the compressor turbine. Just below the steel foundation upon which the main machinery group stands is the heat exchanger. The appearance of this group is shown in Fig. 1. All the main machines are laid together on the upper floor and

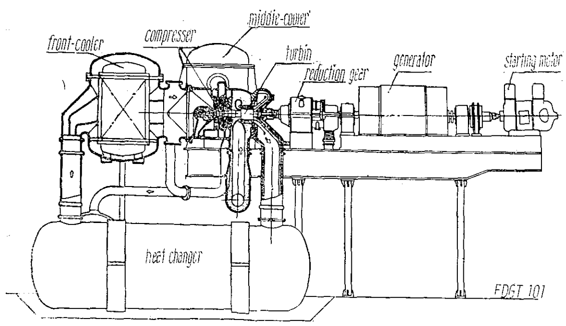

Fig. 2. Diagram of the layout of the main machine parts

they are fully controlled in the switchboard room on the same floor. This plant operates at 27 atm. maximum; 660°C turbine entrance temperature; and 7 atm. compressor entrance pressure.

As seen from Fig. 2, the 7 atm. working air is compressed by the three-stage centrifugal compressor of TUCO machine adjoining the precooler. The compressed air is then heated in the heat exchanger and air heater (not shown in the figure) by the exhaust heat from the turbine and the combustion heat of fuel. Thus heated up to 660°C, it comes into the turbine of TUCO machine mentioned above and rotates it. Next, it is cooled by the heat exchanger and precooler; thereby completing a cycle, it goes back to the compressor for another cycle. The work given to the turbine is transmitted over the reduction gear to the two-pole a-c generator to produce 2,000 kW power.

Table 1 summarizes the main specifications of a 2,000 kW gas-turbine power plant. The following are the details of each component.

Table 1. Major specifications of 2,000 kW gas turbine

Rated output		2,000 kW
Driving system		closed-cycle gas turbine drive
Turbine	Type	axial-flow
	Stage	5
	Entrance temperature	655°C
	Entrance pressure	26.5 atm. absolute (under rated output)
Compressor	Type	centrifugal
	Stage	3
	Entrance pressure	8 atm. absolute (under rated output)
	Pressure ratio	3.5
	Revolution	13,000 rpm
Revolution number		13,000 rpm
Reduction gear		Epicyclic gear concentric shaft
Reduction ratio		13,000: 3,000
Heat Exchanger	Type	special-rimmed tube
	System	counter-flow type
	Effectiveness	89%
	Heating Surface area	1,390 m²
Air Heater	Type	forced circulation radiation heat type for outdoor installation
	Draft	balanced draft
	Fuel	heavy oil or natural gas
	Combustion	Self-controlled combustion
	Air temperature	660°C (maximum)
	Air pressure	31 atm.
Generator and Exciter	Kind	3-phase a-c synchronous generator
	Type	closed hood ventilation type, revolving-field type
	Output, power factor	2,500 kVA, 0.8
	Number of Poles	2
	Voltage, current	3,300 V, 437 A
	Frequency	50~
	Revolution	3,000 rpm
	Exciting voltage	65 V
	Exciter capacity	18 kW
Starting motor	Type	Closed ventilated, 3-phase wound rotor type induction motor
	Output	100 HP
	Voltage	3,300 V
	Revolution	3,000 rpm
	Number of poles	2

1. Compressor turbine set (TUCO machine)

Fig. 3 is a view of this set with the upper half

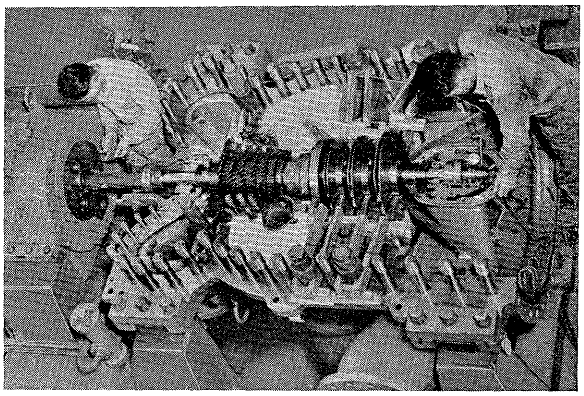

Fig. 3. Compressor-turbine set

cut away. As can be seen, it is of very simple design ; both the turbine and the compressor are housed in a common casing. They are arranged. on one common shaft supported by two bearings The compressor and the high pressure parts of the turbine are facing each other. It is only on the low pressure side that the shaft runs through the casing which makes the sealing easy. The rotor is composed of the compressor part with three stages of centrifugal rotating discs and the turbine part with five steps of axial-flow blades. You can see how relatively small it is, as contrasted with a worker standing by ; accordingly the whole units of machine too. The compressor rotor discs are fitted into the shaft, while the turbine blades are directly fitted to the common shaft ; as Fig. 4 shows, they are set in the groove cut in the axial direction at the part of shaft specifically made heavy. The stator blades of turbine are set in the turbine casing, which is made of heat resisting steel and is separate from the common casing. It is thermally insulated from the common casing, with small holes so that inner and outer pressures may balance each other. Accordingly, even though a pressure as high as 27 atm. is reached, the pressure vessel is built of ordinary steel, because the outer casing, thermally insulated and kept cool, can withstand the pressure. This construction of double casing can save the consumption of heat resisting steel, leading to economy in special materials and reduction of building cost of machinery. Since the gas flowing inside the system is the compressed clean air cut off from the atmosphere, there is no fear of corrosion, contamination, or efficiency decline and no need for frequent cleaning. Moreover, simplicity of design is largely contributing to increased raliability and lower maintenance cost.

The heat resisting steel used in the main machinery is durable enough for 100,000 hours service under a full load ; if operation includes partial load period, the average load will fall and the life will be prolonged that much.

The compressor turbine rotor rotates at 13,000 rpm., which is reduced to 3,000 rpm. to drive the generator. The reducing device is a very small epicylic gear type with the driving and the driven shafts arranged on a straight line. It is equipped with a main oil pump, governor and emergency governor ; and is coupled with a turning device.

2. Heat exchanger

In the gas-turbine cycle the heat exchanger also plays an important role. Fig. 5 shows its appearance. The raised pressure of air flowing through the circuit helps the improvement of heat exchange rate and reduction of heat exchange surfaces. Further, cleaness of working air obviates the deposit of combustion products and dust or corrosion, and permits the use of heat exchange tube of any shape. This exchanger employs a special heat exchange tubing with numerous number of ribs attached to the inner and outer wall, and gives 90% efficiency in spite of relatively small volume. The high-compressed air leaving the compressor flows into this multi-ribbed tube, while the low-pressure, high-temperature air from the turbine fills the drum and flows around the tube in opposite direction, thereby effecting heat exchange.

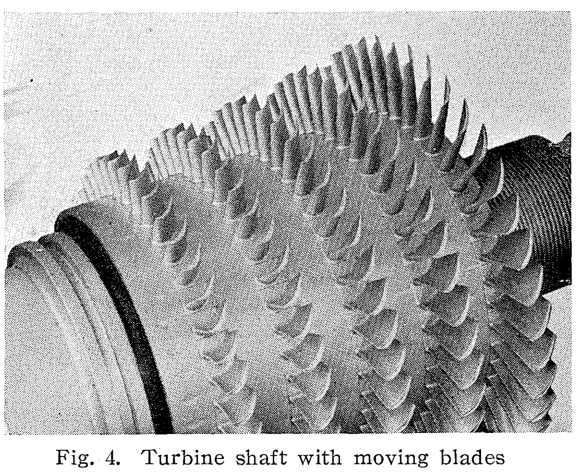

Fig. 4. Turbine shaft with moving blades

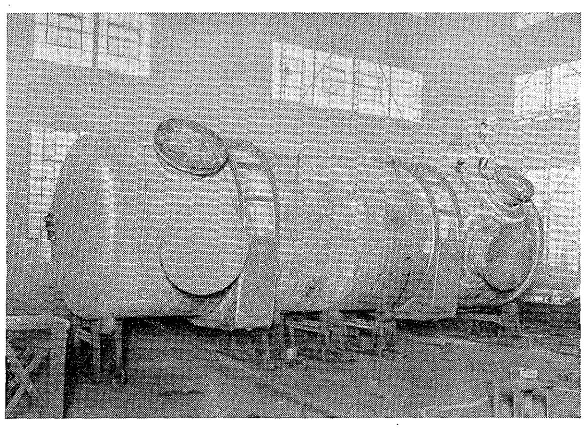

Fig. 5. Heat exchanger

3. Air heater

It resembles a radial type steam boiler in construction. Its dimensions are also nearly identical to those of a steam boiler with similar capacity. Combustion heat of fuel is transferred to the working air in the air heater for the most part through radiation and the rest through conduction. Fig. 6 is the sectional view of air heater. The combustion chamber is a vertical cylinder with a row of heating tubes arranged close to the inner wall. The working air, while passing through these tubes, is heated to 660°C. As the temperature is considerably high and the fluid passing through the heating tube is com-

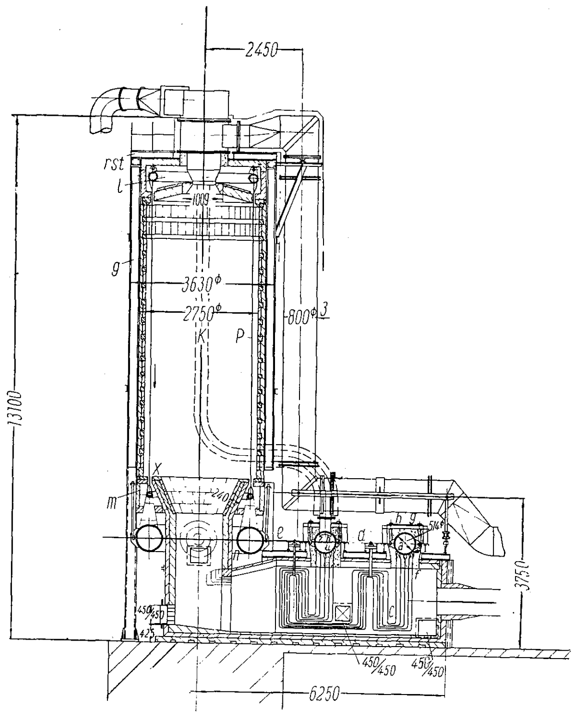

Fig. 6. Diagram of the air heater

pressed air, care must be exercised not to overheat the tube. On the other hand, furnace efficiency should be improved, for the efficiency of air heater has a direct bearing on the plant efficiency. Design and structure of furnace and burner have been selected so as to ensure safe, efficient operation over a long period. For the heating tube of high-temperature part, drawn tubes of special austenite steel are employed.

Fig. 7 is the chimney-side view of the air heater. Unlike the steam boiler, it needs no water, so there is no trouble of freezing. For this reason, it is a perfect outdoor type. Another feature is that it can readily be converted to outdoor type under any climate. It is adapted for such fuel as crude oil or natural gas ; this is decided on the ground that the site of the power station has an abundant source of natural gas. Indirect heating by means of heating tubes imposes little restriction on the kind of fuel used. Series of experiments on combustion with heavy oil, natural gas and coal are being made and the results have confirmed that they are well fit for the closed-cycle gas-turbine.

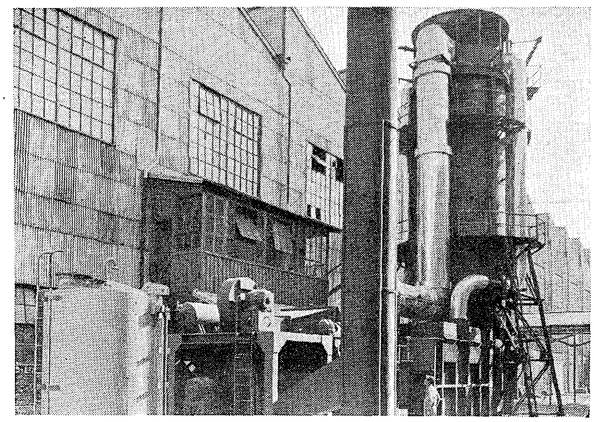

Fig. 7. General view of the air heater

4. Generator and starting motor

a. Arrangement

General appearance is given in Fig. 8. The generator, exciter and starting motor are arranged on a single axis, with the exciter overhung on the generator shaft.

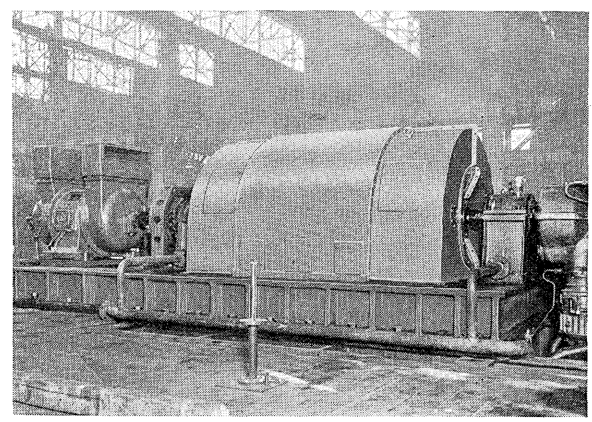

Fig. 8. General view of main electrical machines

b. Features

This generator is of the same construction as a heavy type turbo-generator. With respect to mechanical construction as well as electrical characteristics, it is identical to a heavy type two-pole turbo-generator. To withstand the mechanical impact and thermal stress under short-circuiting, the stator windings use a stranded wire ; and the mechanical supporting of coil end is secured by clever crossing of three-turn and four-turn coils. The stator and rotor have a large number of holes and grooves to ensure cooling. The generator characteristics as determined through tests are given in Table 2.

Figs. 9 and 10 respectively show the stator of this generator and the rotor under construction. The general layout of these machines at Toyotomi Power Station is given in Fig. 11. Except one part of it, the air heater is placed outdoors; the machine group including a gas turbine, generator, heat exchanger, is separately housed indoors; and the control room with the switchboard is set apart.

Table 2. Test results

Short-circuit ratio	0.6
Efficiency (power factor 0.8)	96.3%
Distortion factor	1,9%
Xd	120%
Xq	102%
Xd′	33%
Xd″	7%
Xq″	5.5%
Td'_0	3.4 sec.
Td′	0.4 sec.

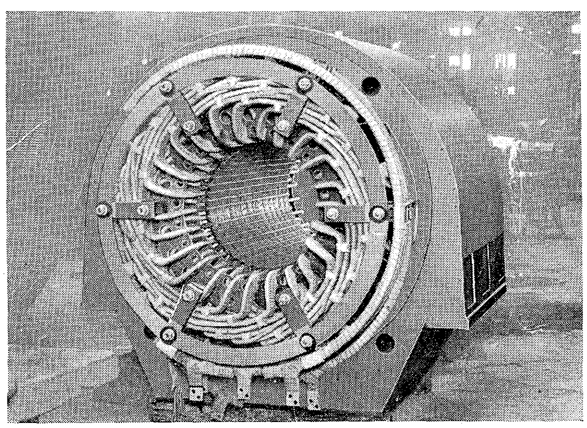

Fig. 9. Stator of the generator

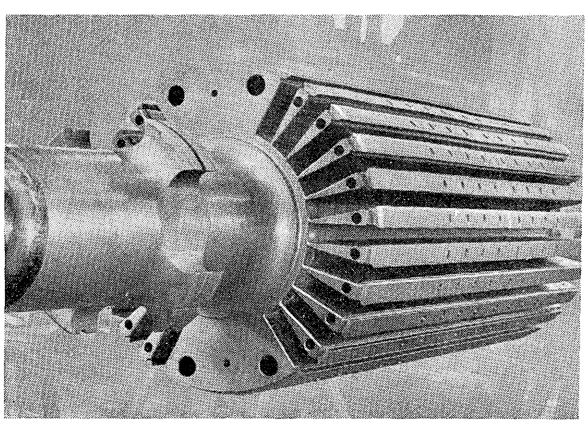

Fig. 10. Shaft of generator, ready for winding

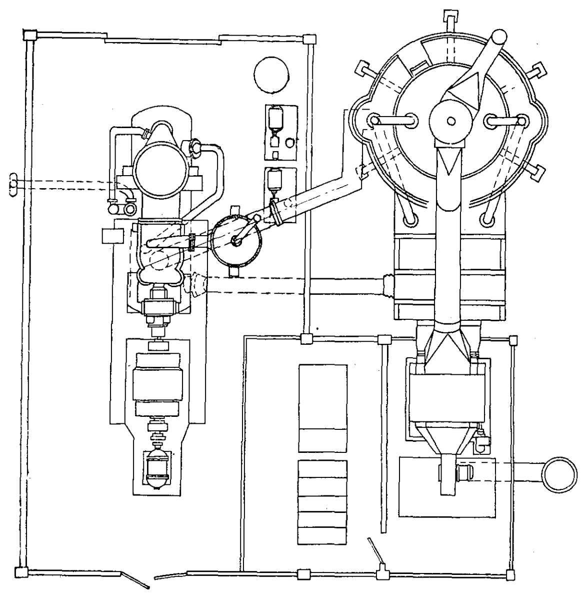

Fig. 11. Layout diagram of 2,000 kW gas turbine power plant

IV. CONTROL AND SAFETY DEVICES

The regulation of load and speed of closed-cycle gas-turbine can be secured with a relatively simple device. The temperature at turbine entrance is maintained constant except under no-load or similar conditions; either by merely adjusting the pressure level of circuit or by by-passing a portion of high-compressed air to low pressure side, load or speed can be readily regulated. As the air heater has a comparatively large thermal capacity, there is no need for fine adjustment of fuel volume in response to load and the temperature control is relatively easy. Fig. 12 is an explanatory diagram of the control system of this turbine plant. The control system adopted is oil-pressure type. The governor is of centrifugal pump type coupled to the reduction gear, which produces oil pressure depending linearly upon the revolution number of main motor and rotates the lever of controller. The upper piston of the controller is displaced by the amount of movement corresponding to the rotation of the lever. Then the valve by-passing the compressor entrance, that is, high-pressure side and the compressor exit, that is, low-pressure side, is opened to the extent corresponding to the displacement of the piston. For instance, when the speed exceeds the prescribed limit, oil pressure rises, making the lever turn counterclockwise, the controlling valve move to the right to operate the by-pass valve to open. As a result, a portion of high-compressed air coming from the compressor directly passes to the low-pressure side. Consequently the volume of working air passing through the turbine decreases, lowering the turbine output. On the contrary, the air volume flowing through the compressor increases by

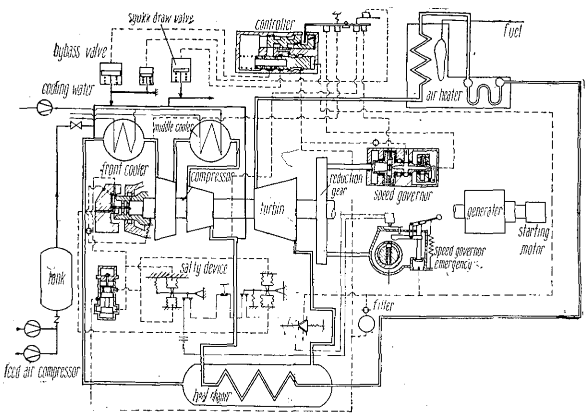

Fig. 12. Cycle diagram of governor system

by-passing. Therefore, the necessary power for the compressor increases. This double action works to lower the rotating speed and maintain the prescribed value. This is also perfectly true with the case of reduced load. Even in the extreme case when the load is abruptly cut off while under full-load operation, the action takes place with equal reliability.

Conversely, when the load increases or the revolution number is about to drop, it works to close the by-pass valve.

Thus, immediately after the sudden shut-down of the load, the output can be instantaneously restored to the original value. For example, when no self-regulation of speed is required as when the turbine is included in a large electric network, the by-pass value may be closed for operation ; to increase the output in this case the only step to be taken is to increase the pressure level of circuit by means of an air-supply compressor separately installed. The control procedure is simple as described above, the output is approximately proportional to standard pressure, and the air heater efficiency is nearly constant. Therefore, once the fuel consumption is preliminarily set up to be proportional to the standard pressure, the combustion can be automatically controlled by the adjustment of temperature at turbine entrance.

The control system includes a safety device, too. When the revolution number reaches 110% of prescribed limit, the emergency governor of eccentric disc type operates an emergency stop. Besides, there is an oil-pressure type safety device attached in parallel to the shaft end to guard against over-speed. Other safety devices are added to bring the machine to an immediate stop in such emergencies as oil-pressure drop and faults on the bearings, etc. Every precaution is given in the design to ensure safe operation as a practicable operation.

V. CONCLUSION

This is the first production by our Company of a gas-turbine which is acceptedly a new-comer in the field of prime movers, even speaking by world standards. Naturally, it is entirely different from the company's conventional production. For this reason, the successful production of this novel machine has been preceded by a number of basic tests and experiments. Even now a trial run is being continued at Kawasaki works on it, already generating output in the order of 10,000 kWh. The results of various tests will soon be ready for publication. It has many recognized features : simple construction, easy control, long service life and high efficiency for a wide range of load.