Recent Technology of Large Capacity Bulb Turbine-Generators

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1. Introduction

The development of ultra low head (less than 20m) hydropower energy has been the center of worldwide attention in recent years, and the number of plans for its construction is on the rise.

Conventionally, the development of hydropower energy focused more on the economically advantageous construction sites whereas low head construction sites were often overlooked. However, in terms of effective use of domestic energy, the variety of available power sources, global environmental issues, post-construction low maintenance costs, etc., the development of low head construction sites has been recently re-considered. In many cases, hydropower energies are developed using existing water passages or water passages for irrigation purposes.

Fuji Electric, since its delivery of the first large capacity bulb turbine-generators in Japan to Kansai Electric's Akao Power Plant in 1978, has the manufacturing record of more than 40 units. **Table 1** shows a recent list of large capacity bulb turbine-generators, and the rate of increase in turbine runner diameter is shown in **Fig. 1**.

As is clearly shown in **Table 1**, Tohoku Electric's Shingo No.2 Power Plant has the largest power output with 40.6MW, and in terms of size, the New Martins Ville Power Plant in West Virginia, U.S.A., has the largest runner diameter with 7.3 m.

Also, Tohoku Electric's Yamazato No.2 Power Plant (23.7MW) was recently put into commercial operation in June 1992.

Even overseas there are numerous, low head construc-

Fig. 1 Trend of bulb turbine runner diameter

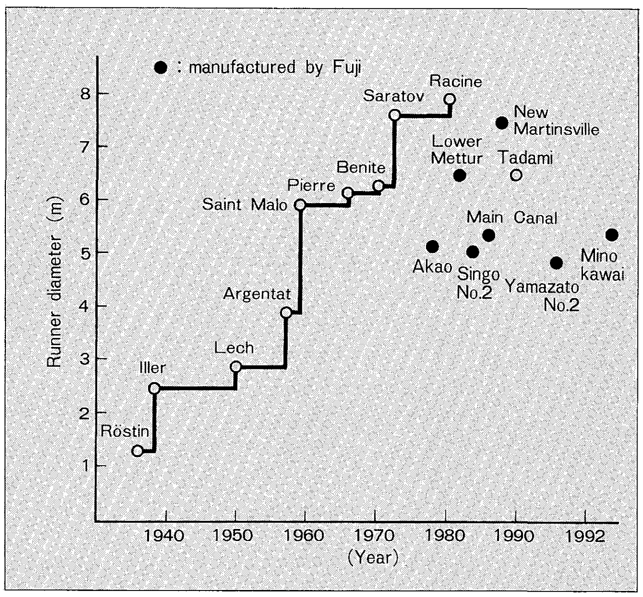


Table 1 Fuji's large capacity bulb turbines and generators

Power Station	No. of Units	Turbine					Generator			Commissioning
		Output (kW)	Head (m)	Speed (r/min)	Runner/ Diameter (mm)	No. of Runner blades	Output (kVA)	Voltage (kV)	Frequency (Hz)	
Akao (Japan)	1	34,000	17.4	128.6	5,100	5	36,000	6.6	60	1978, Oct.
Sakuma No. 2 (Japan)	2	16,800/16,600	15.5	125.0/150.0	4,485	4	17,000	6.6	50/60	1982, July
Shingo No. 2 (Japan)	1	40,600	22.45	136.0	5,000	5	40,900	6.6	50	1984, Sep.
Main Canal Headworks (USA)	1	26,800	12.8	112.5	5,350	4	27,370	6.9	60	1986, July
Lower Mettur (India)	8	17,200	7.53	75.0	6,250	4	18,333	6.6	50	1987, Nov.
New Martinsville (USA)	2	20,040	6.4	64.0	7,300	3	21,620	6.6	60	1988, Aug.
Yamazato No. 2 (Japan)	1	23,700	15.93	125.0	4,750	5	24,100	6.6	50	1992, June
Minokawai (Japan)	1	24,200	12.2	100.0	5,550	4	26,000	6.6	60	Under Manufacturing

tion sites –India, Pakistan, China, among others– in which there are large scale development plans.

In this report, recent bulb turbine-generator technology will be introduced, based on Fuji's substantial record and past experiences.

2. Technology of Bulb Turbines

2.1 Hydraulic performance

The size of ultra low head, large capacity turbines should be as compact as possible due to civil construction and equipment costs. To achieve these compact, high speed units, it is necessary to increase unit discharge as much as possible.

In compact, high speed units, the flow speed around the guide and runner vanes needs to be as high as possible, as the velocity head at the runner outlet may reach 50 to 100% of effective head. For this reason it is vital to use a draft tube with higher recovery efficiency of velocity head.

Since the conical shaped draft tube can be adopted for bulb turbines, the efficiency deterioration is minimal even for large discharge and the maximum unit discharge can be set approximately 30% higher than vertical shaft Kaplan turbines, which have the elbow type draft tube. However, regardless of how much the draft tube is optimized, there remains a considerable amount of unrecovered kinetic energy at the draft tube exit that becomes discharge loss.

Because of this a thorough analysis is conducted for recent large capacity bulb turbines on the configuration of tailrace downstream of the draft tube in an attempt to reduce its discharge loss.

On the other hand, when the unit discharge is increased, the flow speed of runner vanes also increases and is thus more vulnerable to cavitations. In recent years, bulb turbines, in the form of pondage type power plants, have been frequently optimized for use in power plants with high discharge and wide head variation; therefore turbines with better cavitation characteristics are in great demand.

Thus in developing the runner, the efficiency characteristics as well as the cavitation characteristics at variable discharge/variable heads are also emphasized. Fuji Electric has devised, with the application of computer analysis techniques based on the three-dimensional flow theory (which for many years Fuji has been perfecting), a runner with 3 to 5 blades enabling responce to the wide operation range of the bulb turbine.

2.2 Support structure of the bulb

Since the bulb that encloses the turbine and generator is placed in the water passage, it receives static loads such as hydraulic thrust, dead weight, buoyancy, generator torque, as well as mechanical vibrations from the rotating parts and hydraulic vibrations due to hydraulic pressure fluctuation. In addition, as the bulb itself is a large and flexible construction, the support structure (stay vane) for the bulb must have sufficient strength and stiffness.

Although there are several methods in which to support the bulb, nowadays the method using 2 stay vanes (upper and lower) as shown in **Fig. 2** is widely adopted. This method has the necessary maintenance space, minimal loss in the flow passage and requires less complicated civil

Fig. 2 Bulb supporting system by two stay vanes

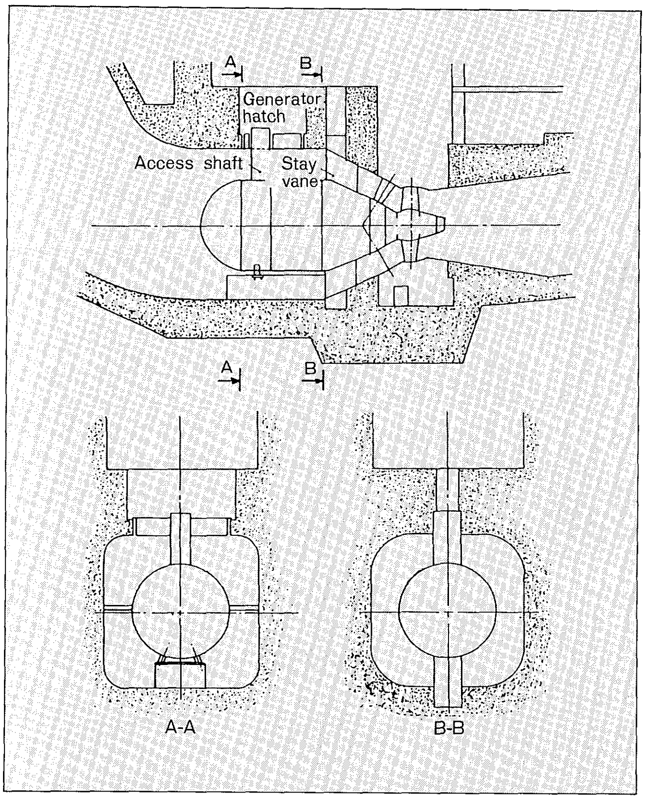
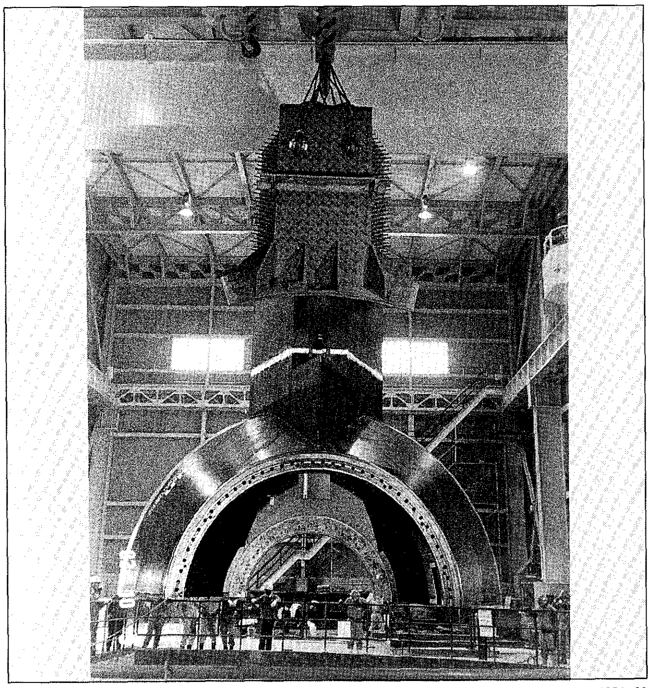


Fig. 3 Installation of upper part of stay vane at site



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work to support the load. In this method, the hydraulic thrust and generator torque are supported by upper and lower stay vanes, and the vibration-proof stays and casing support are provided as auxiliaries which aim to increase the bulb's natural vibration. **Figure 3** shows the constuction of upper stay vane viewed from the downstream side.

2.3 Construction of the bulb

The bulb is a large, flexible construction installed under water. Therefore, preventive measures against bulb leakage are of great concern. For this reason, a double packing construction is applied to the connecting flange, which is exposed to the water.

Figure 4 depicts the construction and location of the double-layer packing. The leak testing groove is provided between these packings. To check the sealing effect of the packings, water pressure is applied to the groove during assembly/installation. This groove is used not only for detecting water leaks but also as a back-up sealing device by the insertion of special packing material.

2.4 Bearing arrangement

Triple bearing and double bearing systems are adopted for high speed, large capacity bulb turbines and for lower speed, smaller capacity units respectively. The relationships of bearing arrangement, turbine power output and rotating speed are shown in **Fig. 5**.

The bearing arrangement is determined by the critical speed, distortion, maintenability, etc. of the bearing system. Whatever the bearing arrangement, a bearing support system that adapts easily to the shaft inclination (caused by a large overhanging runner) is applied.

2.5 Welded guide vanes

Guide vanes constructed by welding are frequently

Fig. 4 Double-layer packing

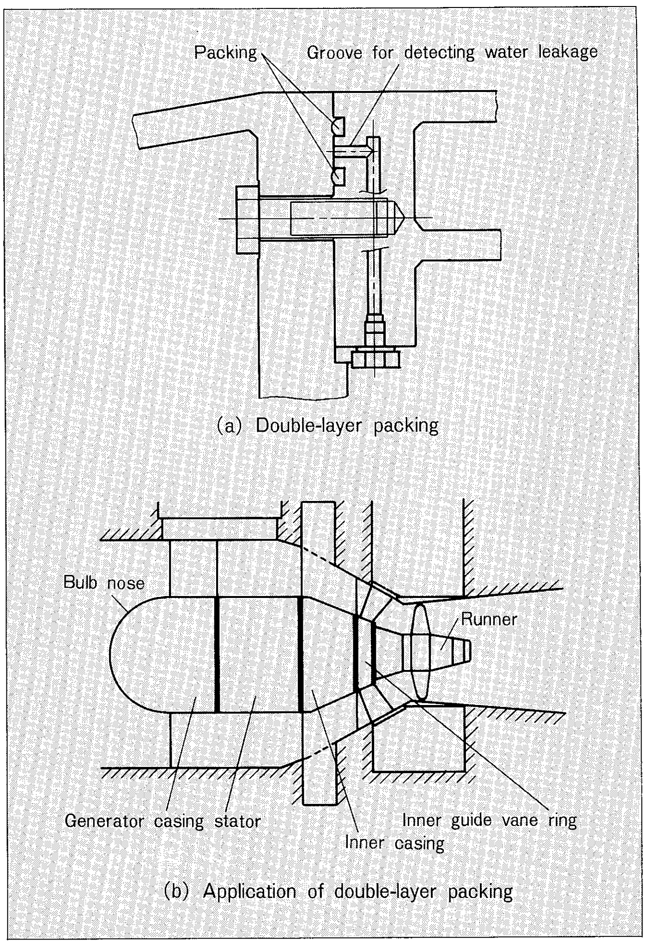


Fig. 5 Bearing arrangement of bulb

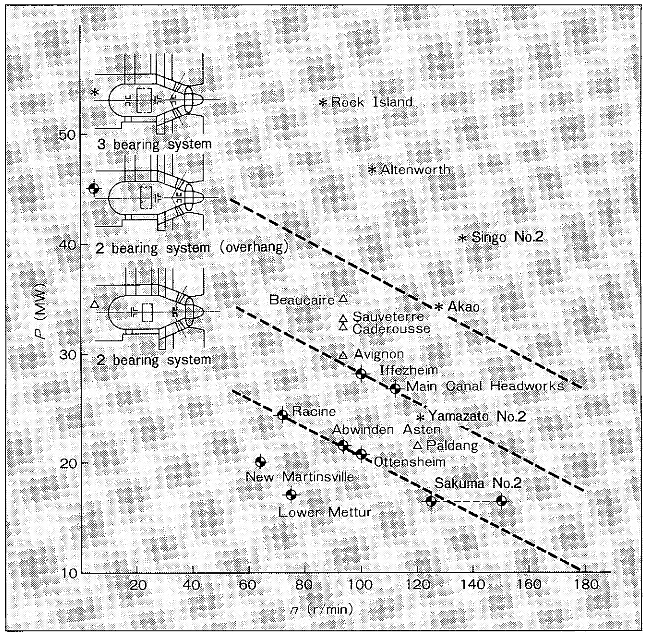
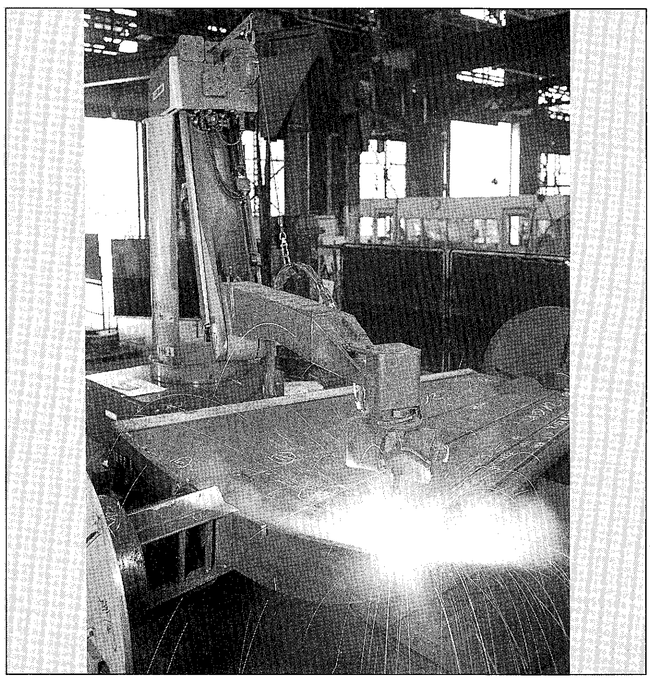


Fig. 6 Welding of guide vane



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employed because the resulting reduction in weight becomes more economical and reduces the capacity requirements of travel cranes. **Figure 6** illustrates a welded guide vane being fabricated. Normally, the outer plate and rib are made of a general purpose steel plate, and the trailing edge and shutter are made of stainless steel, fabricated to precise specifications with tools and jigs exclusively for this purpose. Consequently, compared to the existing cast steel guide vanes, quality control is facilitated and the quality itself is improved.

Also, welded guide vanes enable an approximate 40% weight reduction in comparison with cast steel guide vanes.

3. Technology for Bulb Turbine-Generators

The bulb turbine-generator is installed in the water passage; therefore, its shape and construction differ from standard hydraulic turbine-generators in the following ways:

(1) The stator core is longer because of limited bulb diameter due to hydraulic requirements,

(2) The generator's outer surface is directly exposed to river water.

As a result, the ventilation/cooling methods particular to bulb turbine-generators are adopted:

(1) A forced air cooling method using an electric motor driven fan,

(2) A cooling method using the river water which flows outside the bulb.

The following describes recent trends of the ventilation/cooling of bulb turbine-generators.

3.1 Fin cooling method

The fin cooling method is, as shown in **Fig. 7**, the method where copper cooling fins are welded on the inner surface of the bulb's top nose, where heat is dissipated to river water. Since the generator can be cooled without using any air-water heat exchangers, the cooling water, which often caused maintenance problems, can be eliminated.

Shown in **Table 2** is a record of Fuji's bulb turbine generators using the fin cooling method. In this method, since heat loss increases with generator capacity, the area for dissipating heat loss must also be increased. This phenomenon gives rise to a limit on generator capacity.

This water-less cooling method has been in recent years increasingly in demand for the maintenance-free powerplant. Fuji Electric has been investigating and developing this method, examining the possibility of broadening its application range. At present, it is being confirmed that the fin cooling method is applicable to generators of 26MVA, 100r/min.

3.2 Outer surface direct cooling method

Outer surface direct cooling is a method in which the stator core is directly stacked on the stator frame (the bulb's outer case), and stator heat is dissipated to the river water without the use of cooling air. In the case of a small capacity induction generator, the rotor is a cage type having no temperature limitation; therefore, the aforementioned cooling of only the stator will be sufficient.

For the synchronous generator, the rise in temperature of the field windings must be limited. Therefore, the field windings must be cooled by air, necessitating an air/water heat exchanger for I^2 R loss of field windings and windage loss. However, using the outer surface direct cooling method, the heat loss to be exchanged will be approximately 60% of that in the conventional cooling method. Therefore, a considerable reduction of the air/water heat exchanger and

Fig. 7 Fin cooling method

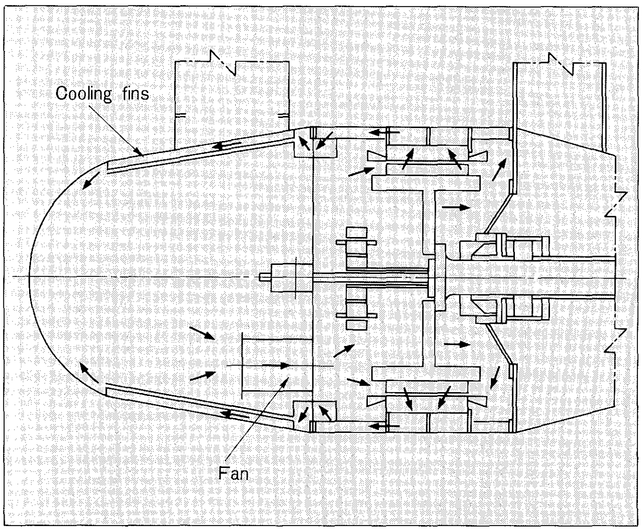

Table 2 Bulb turbine generators with cooling fin

Customer	Power Station	Unit	Output (kVA)	Voltage (kV)	Speed (r/min)	Cooling Air temp. at outlet of cooling fin	Remarks
EPDC, Japan	Sakuma No. 2	2	17,000	6.6	125/150	50	Pressurized by 1.0 atg
T.I.D., USA	Merced Main Canal	1	2,830	4.16	180	45	
T.I.D., USA	Dawson	1	4,660	4.16	120	50	
Akita Pref., Japan	Itado	1	2,040kW	6.6	375	60	Induction generator
Kyushu Electric Power Co., Inc., Japan	Yuda	1	5,750	6.6	150	50	
Fukushima Pref., Japan	Oya	1	3,470	6.6	214	52	
Hokkai Suiryoku Co., Ltd. Japan	Nibutani	1	3,060	6.6	250	50	
The Kansai Electric Power Co., Inc., Japan	Minokawai	1	26,000	6.6	100	50	

Fig. 8 Piping diagram of outer surface cooling method

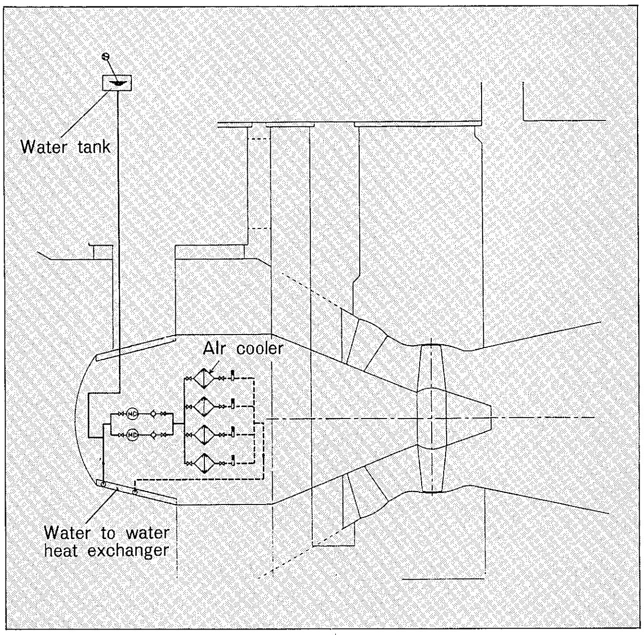

Fig. 9 Relationship between fan rotating speed and generator output

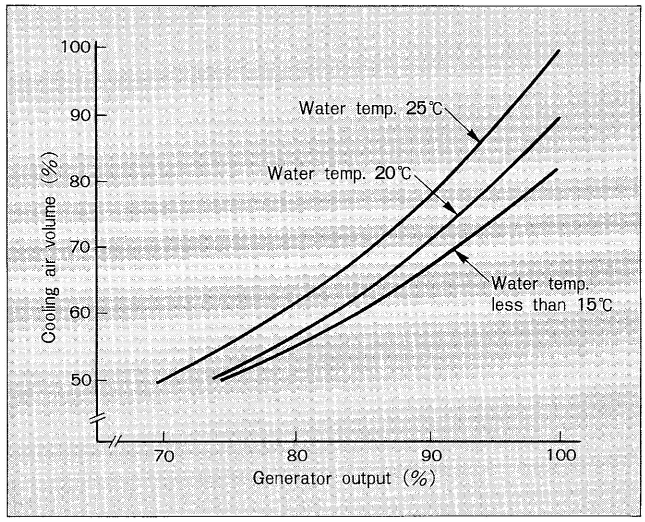

Table 3 Load test results at Yamazato No. 2 project

Operating Conditions			Temperature Rise at Stator Coil (°C)		Cooling Air Temp. (Outlet of Air Cooler) (°C)	
Output (%)	Air Volume (%)	Water Temp. (°C)	Design Value	Actual Value	Design Value	Actual Value
95.9	80.0	15.6	70.5	72.8	26.5	26.9
80.6	70.0	15.0	58.5	59.0	23.5	24.0
67.7	60.0	15.2	52.0	52.7	22.2	22.9

the amount of cooling air flow rate will be achieved. For high speed bulb turbine-generators, this leads to the possibility of the adoption of self-ventilation, applied to standard generators.

It is possible that the maintenance for the cooling water system will be significantly reduced by concurrently adopting either the closed water-circulating system with separately installed water-water heat exchangers, or the fin cooling method.

The water-water heat exchanger is generally installed in the tailrace for standard turbine-generators. However, for bulb turbine-generators it is preferable to install a water-water heat exchanger in the top nose because it is difficult to install a heat exchanger in the tailrace (as in bulb turbines) and also because the bulb's outer surface is exposed to river water.

At the present time, Fuji Electric is developing bulb turbine-generators equipped with both the outer surface direct cooling method and the water-water heat exchanger mounted in its top nose. **Figure 8** shows a diagram of its piping system.

3.3 Speed control of the motor driven fan

For the bulb turbine-generators, forced ventilation by means of motor driven fans is adopted. The rating of motor driven fans is selected so that when the generator is at the rated output and the cooling water is at its maximum temperature, the winding temperatures will be less that specified by each insulation class. Since in actual operation the generator output and the cooling water temperature will vary, the cooling air flow rate can be reduced depending on generator output and cooling water temperature.

The input of motor driven fans W is given by the following formula:

$$W = (P \times Q \times 9.8) \times 10^{-3} / \eta \ (\text{kW})$$

Where, P: Pressure drop inside the unit (mmAq)
Q: Cooling air flow rate (m^3/s)
: Fan efficiency

Meanwhile, when the cooling air flow rate is expressed by Q, the pressure drop P inside the unit is:

$$P \propto Q^2$$

Therefore, $W \propto Q^3$

In other words, by reducing the cooling air flow rate, the input of motor driven fans can be reduced proportionally to the third power of the cooling air flow rate.

Normally, the input of the motor driven fan is equivalent to 0.2 to 0.5% of the generator's rated output. Therefore, if the cooling air flow rate can be reduced by 50%, then the input of the motor driven fans will be 0.025 to 0.0625% of the generator's rated output. This effect is equivalent to an improvement in generator efficiency of 0.175 to 0.4375%.

Fuji Electric has applied a speed control system to the motor driven fans for the bulb turbine-generator at Tohoku Electric's Yamazato No. 2 Powerplant. The ratings of this turbine-generator are shown in **Table 1**.

For selecting the control method of air flow rate, the following points were taken into account:

(1) This generator belongs to the F class of insulation and the winding temperature rise is B class. Therefore, the winding temperature is less than the temperature limit (120°C) of the B class, even if the cooling air flow rate is reduced.

(2) Taking into consideration the effect of the heat cycle on the insulation material, the winding temperature rise is limited to the B class plus 10°C, or, less than 90°C.

(3) The temperature of the hot air is kept equivalent to or less than the air temperature during rated operation, taking into account the difference of thermal expansion between the stator frame and stator core.

The calculated control curve of the cooling air flow rate, based on the conditions above, is shown in **Fig. 9**.

The control of the cooling air flow rate was carried out by changing motor speed with the VVF control. Also, the 7-step speed control (not continuous control) was selected using a programmable controller. The delay circuit is provided inside of the programmable controller because when the motor is operating at the boundary of changing speed, the rotating speed may become vulnerable to huntings and the winding temperature may also vary at certain intervals.

As shown in **Table 3**, the measured values closely approximate the design values, verifying the effectiveness of this method.

4. Conclusion

In this report recent bulb turbine-generator technology is described. It is assumed that further development of large capacity bulb turbine-generators will continue, and the authors would be pleased if this report is of any assistance to such future developmental work.