TUBULAR WATER TURBINE AND AC GENERATOR FOR OMATA DAM POWER STATION OF HOKURIKU ELECTRIC POWER CO., INC.

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I. PREFACE

More than 20 years have passed since the tubular water turbine was developed in Europe. Recently, researches of this kind water turbine become active again, and several trial manufacturings of the new type tubular turbine have been completed and now is a stage of actual usage. In our country, attentions are being paid to low head points as the undeveloped hydraulic power resources. The tubular turbine is now gathering remarkable attention as a water wheel utilizing economically low head hydraulic power which is disregarded because of it's high construction cost. Our Company has continued the effort for the development of this kind water turbine from the earliest time, and now we have completed a No. 1 turbine set, largest capacity in Japan, for Omata Dam Power Station. The turbine and the generator of this power station have a many excellent features.

II. SCOPE

All electrical equipment for Omata Dam Power Station, which is planned as a part of Joganji-Arimine Power Resources Development by the Hokuriku Electric Power Co., have passed our home tests with satisfactory results and already started the operation at site, and the capacity is largest in Japan as a tubular water turbine.

The Omata Dam Power Station is situated at the Omata Dam regulating pond located at the downstream of the Shin-nakachiyama Power Station, and the tail race of this station is used for the intake of another Omata Power Station. The Omata Dam Power Station is no man control power station and is remote controlled from the Shin-nakachiyama Power Station. The head race of the Omata Power Station, located at the downstream of the Omata Dam Power Station, is not to be a pressure tunnel due to geographical and geological features, but the non pressure tunnel is an only suitable system for this power station. Hence, the Omata Dam Power Station is projected to utilize the head between the intake of the Omata Power Station and regulating pondage of Omata Dam effectively as much as possible. The effective head between the Omata Dam regulating pondage and the intake of the Omata Power Station varies from max. 13 m to min. 2 m, and the water turbine must operate with huge water flows at the low head, and further the construction cost must be low as much as possible. This is a reason why the tubular movable vane propeller water turbine is adopted for the Omata Dam Power Station. On the other hand, this power station is expected to supply the ample water flow for the downstream Omata Power Station, however the water flow utilized for turbine only is insufficient for this requirement especially at the low head, therefore another water flow way providing a dispersion valve in parallel with the power station is prepared and this another water flow looses the energy by the pond and joins to the tail race and then flows into the Omata Power Station.

Equipment for the Omata Dam Power Station is designed to have special FUJI DENKI features and have considerable different points from another one manufactured in Japan. Now, the brief explanation will be given in the following on these special features.

III. ARRANGEMENT AND INSTALLATION SYSTEM OF THE MACHINES

On the power station using a tubular turbine, following two points must be considered at first.

1) Which system shall be adopted for the coupling between the water turbine and the generator, direct coupling system, or speed-increasing gear system?
2) How about a installation system of the water turbine and generator?

For the former problem, following points must be fully investigated, namely

a) Comparison between machine cost and civil engineering cost.
b) Comparison of the total efficiency, i.e., annual generated electric power between direct coupling system and speed-increasing gear system.
c) Increasing of the maintenance cost due to adopting speed-increasing gear system (lubrication for the gear etc.) and efficiency down for aging of the gear.
d) Problem of spare parts for the speed-increasing gear proper.
e) Problem of the capacity limit of the gear. (in case of the direct coupling, the capacity is hardly limitted)

According to our investigation for the Omata Dam Power Station, the direct coupling system is a little profitable on the machine cost, but the building become a little larger and the cost of building increase.

Incase of the direct coupling system, the annual generated electric power is far large because there are no loss due to gear. Considering of all these points, the direct coupling system is more profitable, and then the direct coupling system is adopted for the Omata Dam Power Station.

In case of adopting the tubular water turbine, in generally, the direct coupling system is more profitable for the head 12～13 m or above, but for the head 7～8 m or less gear system is more profitable. For the intermediate head, it must be investigated fully on each case under considering the speciality of each power station. " Tubular turbine is a machine providing the gear apparatus " is a general notion to be broken off.

Regarding installation system, in case of such a small capacity turbine and generator that can be lifted simply as one body and of using a planetary gear for the gear, bulb type system is more economical, however in case of larger capacity one, pit type system having a larger width than the width of the generator is preferable. Merits of the pit type system are that being convenient for the dismantling, reassembling, maintenance and inspection of the machines and during operator can go in and out inside of the pit as occasion demands. In foreign countries this type installation system is adopted in a many modern power stations constituting of the large capacity tubular turbine. The Omata Dam Power Station also adopted the pit type one. As shown in Fig. 1 " Model of Omata Dam P.S.", the water flow is separated left and right way at the generator part and confluxes just before guide vane again and flows into runner. Regarding the size of pit and the water passage of water inlet, model tests were conducted and we recognized there was no problem hydraulically. Further, the water channel along the generator part is available for the cooler of the generator, and this is also a merit of the pit type system.

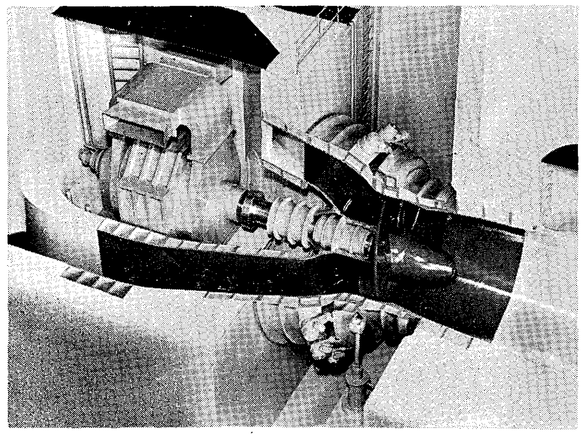


Fig. 1. Model of Omata Dam P.S.

As shown in Fig. 2, the generator is built in the casing having an ellipse plane section, and is connected directly to the main shaft of the turbine runner which project out from a corner of this casing. The casing is a steel plate water proof construction that is divided into several parts and reassembled at installation site. The casing is double wall except upper stream end, and the space between the double wall casing is forming the water passage.

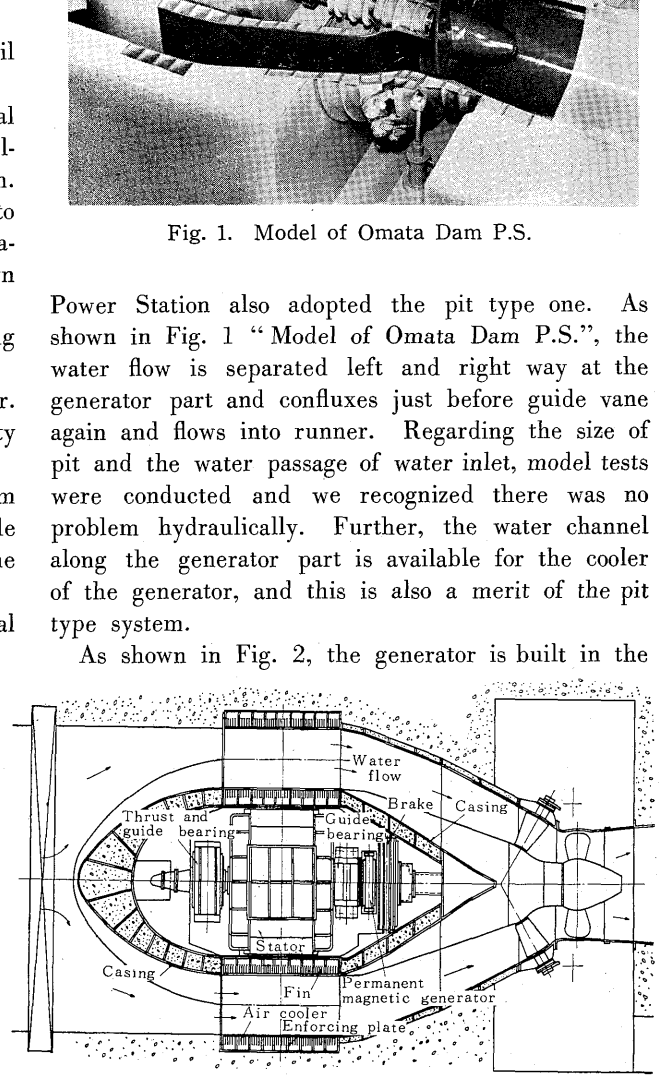


Fig. 2. Plan of generator

The casing is built in the water channel, and the outer wall of the double wall casing is connected to the foundation with the concrete. The generator is positioned upper stream side of the turbine. Because setting a large generator casing in convergent flow more minimanize the water head loss than setting in divergent flow. Upper parts of the generator pit is forming a part of the building and is covered by the air tight cover. A crane is running over the cover, hence removing the cover the generator can be lifted up.

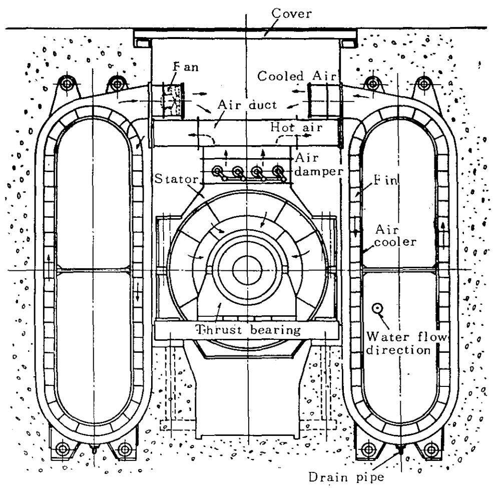


Fig. 3. Front view of generator

The generator shaft is directly coupled with the turbine shaft, and these two shaft is suported by the 3 points suspension such as from the upstream, a thrust bearing (being used also as a guide bearing), a guide bearing and a turbine bearing. At the upstream side of thrust bearing, the oil feeding the device for the runner operating is equipped. The runner servomotor is mounted in the inside of the coupling between the generator shaft and the turbine shaft. A slip ring is situated on the shaft between the thrust bearing and the generator rotor, and a permanent magnet generator is provided between the coupling and the guide bearing. As shown in Fig. 3, upper part of the stator is connected to the air cooler through a air damper and T-shaped air duct. Upper surface of the generator pit is covered with the removable air tight cover, and the ladder is prepared at the entrance of the pit.

IV. WATER TURBINE

1. General

Before manufacturing of the turbine, we developed a special runner and a guide vane for the tubular turbine, and the model tests including pres-crived water passage test were couducted. We got the excellent test results by these model tests, and then we started the manufacturing with confidence.

Specifications of the turbine are as follows :—

Type :	Horizontal shaft tubular movable vane propeller water turbine
Effective head :	13 m∼4.5 m
Quantity of water flow :	max. 30 m^3/s
Speed :	200 rpm
Run away speed :	630 rpm

Arrangement of the machines is shown in Fig. 4.

2. Model test

The water turbine is the machine having the largest capacity as tubular turbine in Japan and is the first one adopting the pit type, and the model tests of the turbine was conducted with prudence on the efficiency, the cavitation and the runaway speed. In order to give a suitable rotating flow to the water rushing into the runner, the guide vane is twisted three dimentional vane. Operating force which is

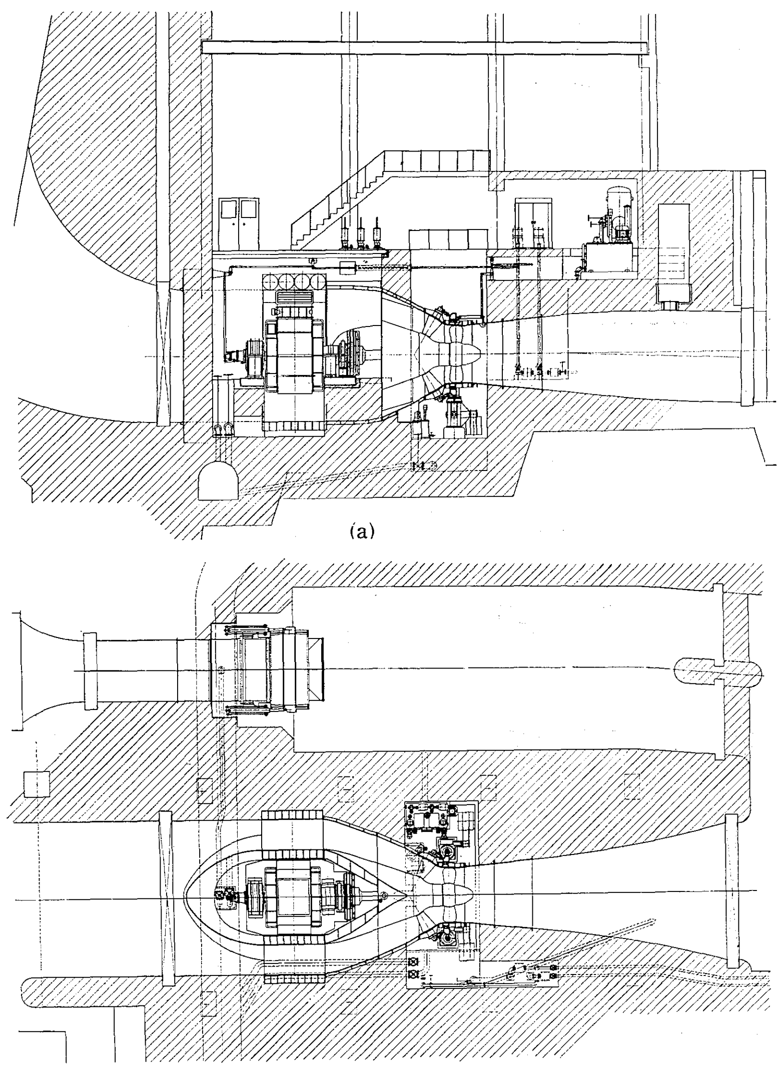


Fig. 4. Machine arrangement

necessary to decide the capacity of guide vane servomotor was also tested.

Efficiency test was conducted at 250 mm diameter runner and 3 m effective head. Maximum efficiency of the model was 89.5% and in actual case this efficiency is modified to be 93.2% by the Moody 1/5 power formula. Fig. 5 shows modified efficiency curves. The cavitation test was conducted by the same model having 250 mmϕ runner diameter. For the calculation of the σ value, draft height at the upper end of the runner is applied, so the experiment sticks to the actual one. Fig. 6 shows the model used for the cavitation test, and the outer view of the model under testing are shown in the Fig. 7. The test results show non-cavitation status at the σ value, and this observation photograph is shown in Fig. 8 (a). As well known, runaway speed depends on the σ-value so much, further setting angle of the vane also effects to the runaway speed. In case of unevenness of the setting angle of the vane, especialy one of the vanes having special smaller setting angle, the effects are very remarkable. Therefore, of course the model must be precise, but we are checking strictly the setting angle of the vane.

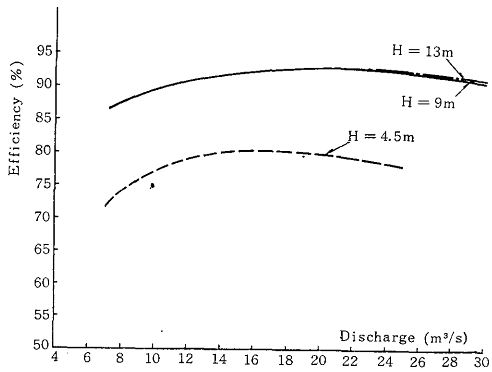


Fig. 5. Efficiency curve of turbine

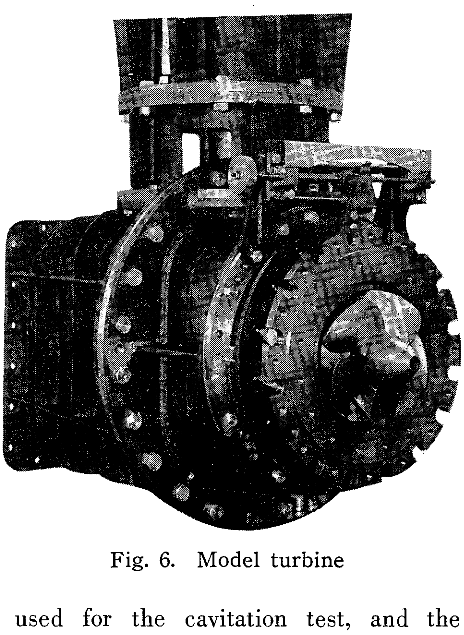


Fig. 6. Model turbine

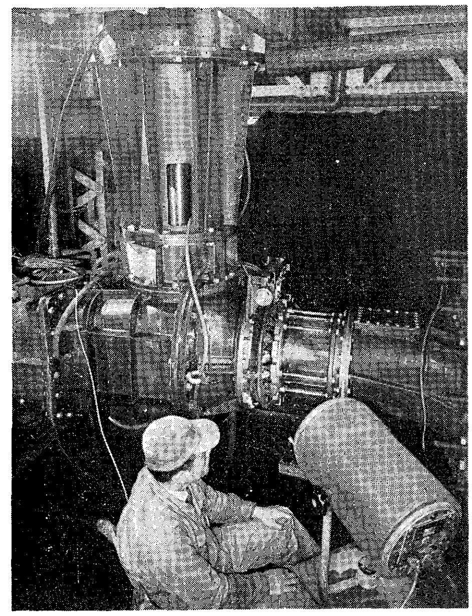
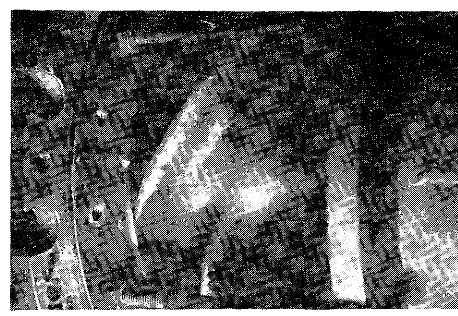


Fig. 7. Model test


(a) Under the condition of plant σ

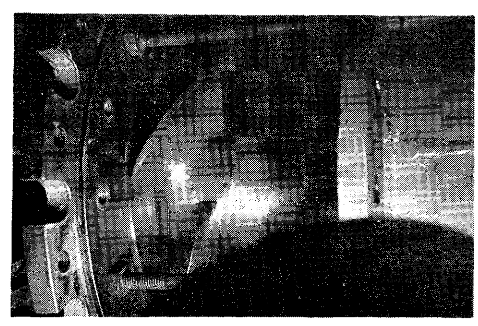

(b) Under the condition of σ break

Fig. 8. Cavitation

Fig. 9 shows the variation of runaway speed due to the σ-value and Fig. 10 shows the photograph of the status at the maximum runaway speed.

3. Construction

As the direct coupling system is adopted for this turbine, the construction is just like a vertical shaft Kaplan turbine laid in the horizontal plane as it is. Therefore we have merits to be able to utilize our rich experiences in vertical shaft Kaplan turbines.

Almost of the main parts, such as casing and guide vane ring etc. are of welded construction, and

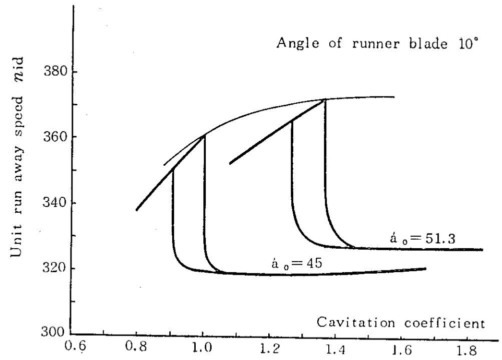


Fig. 9. σ–n_{id} character

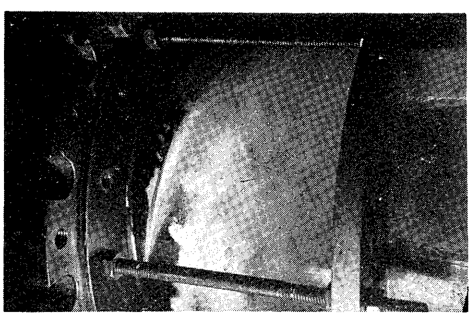


Fig. 10. Cavitation at runaway speed

the grease lubricating system is adopted for the turbine bearing. Water sealing for the bearing employs carbon packings. In the coupling between the generator shaft and the turbine shaft, the runner servomotor is provided, and operating oil for the servomotor is supplied from the pressed oil feeding device being mounted on the upstream of the generator. A runner blade is made of 13% Cr steel and is designed to be sufficient safe against vertical deflection of the shaft and to reduce the overhung weight by adopting the grease lubricating turbine bearing. The guide vane is, as prescrived, three dimentional vane and is arranged in oblique angle to the turbine shaft, and special considerations are paid on the design to be able to shut off the water completely at the time of entirely closing. The guide vane servomotor provides the counter weights, and at the time of oil pressure loose the counter weight closes the guide vane automatically upto no load opening so that the speed does not rise up to the runaway speed. Fig. 11 shows the turbine proper just finished of the assembling in the manufacturing shop. Inner and outer guide vane rings of which is contacting with guide vane are treated to have coaxial spherical surface, and in spite of being oblique guide vane the gaps between the guide vane and the ring are very small. By employing of special assembling jigs, the guide vane completed with outer ring can be removed horizontaly to the runner side. Fig. 12 shows the status of the guide vane which is provided on the outer ring. The runner ring is having a halved construction and the runner can be removed from the turbine pit separately from the turbine shaft. A mechanical standard type governor is adopted and is cooperating with electrical level regulator provided on the tail race, so that the constant water quantity operation, being no relation with head, is possible. In case of the water quantity from the turbine only being unsufficient due to lowering of Dam level, the dispersion valve starts to open at the time of limit opening of the turbine and is adjusted so that the summary water quantity is to be sufficient. The opening limit of the turbine is limited by the head.

4. Dispersion valve

The dispersion valve is provided in parallel with the turbine generator, and the dispersed water looses the energy by the pond and joins to the tail race of the turbine. The type of the valve is Howell-

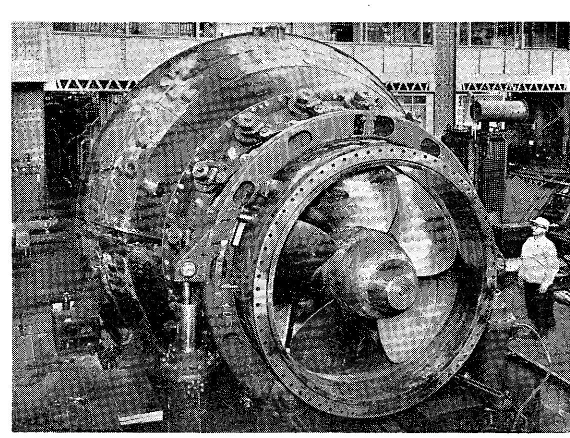


Fig. 11. Assembled turbine

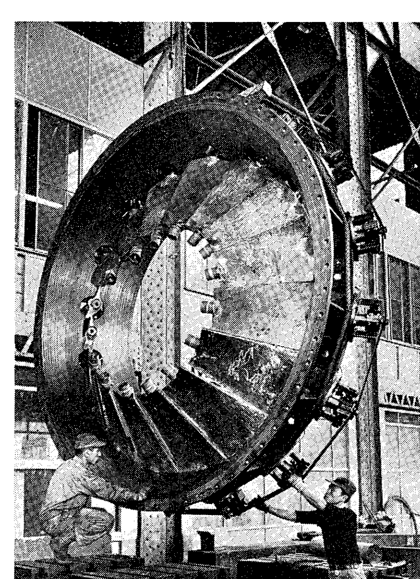


Fig. 12. Guide vane and ring

Bunger valve, and it's dispersion quantity, almost of which is dispersed into water, is as follows :—

Head	6.2 m	3 m	2 m
Dispersion	30 m^3/s	20 m^3/s	15 m^3/s

The dispersion of the dam, in many cases, is executed into the air, and into water is very rare case. The velocity head of the water which is dispersed into water can be extinguished thoroughly by increasing the capacity of the pond. In case of the configulation of the Omata Dam Power Station, the dispersion outlet is being the inclined surface of water instantaneously, and is connected to the non-pressure water channel directly, hence the capacity is limited so much. As the dispersion water joins the tail race of the turbine, there is a possibility that the disordered water gives bad influences on the turbine generator, namely variation or commotion of the discharge water level of the turbine. Then, we made a model of a reduced scale 1 : 20 of the actual size and conducted the hydraulic test in order to find out suitable form of the valve. Fig. 13 shows the testing apparatus for the dispersion valve.

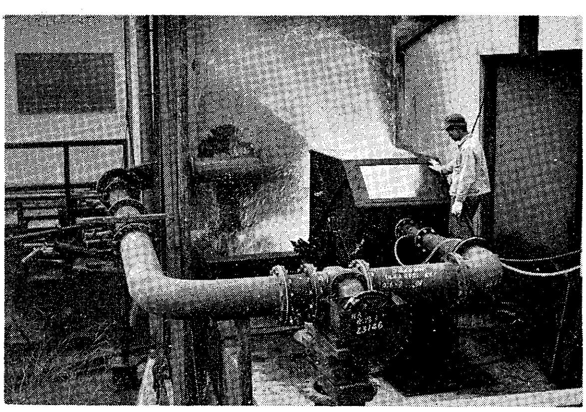
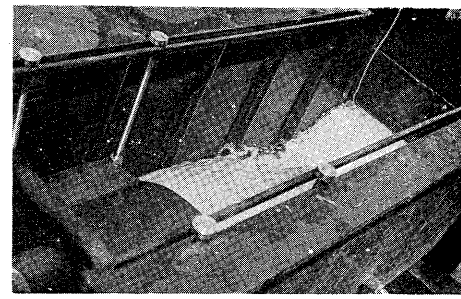


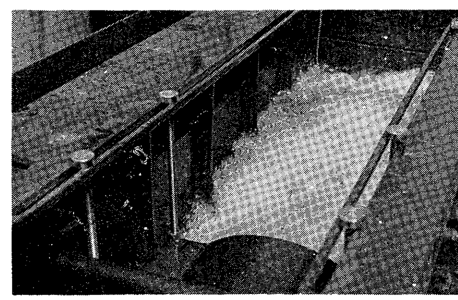
Fig. 13. Testing apparatus for dispersion valve

At first, dispersion characteristics of three cases, such as in the air, in the air and water and in the water were tested, and after a many tests of how to deenergize of the water, we found out that providing a proper diffusion room at the outlet of the valve, mixing another static water into the dispersion water in this diffusion room, and then flowing out the water, by this method calm and stable water was flowed into the tail race. Fig. 14 shows the hydraulic test of each dispersion (a) into air, (b) into water and air, (c) into water by using the similar ponds. In these tests, the wave height in the pond was kept, in actual scale, under about 300 mm.

In order to avoide the effects of the surface wave of the pond to the tail race directly, submerged dam is built before the conflex point to the tail race. The operation of the valve depends on the level of the tail race, and the valve starts only at the time



(a)



(b)

(c)

Fig. 14. Dispersion test

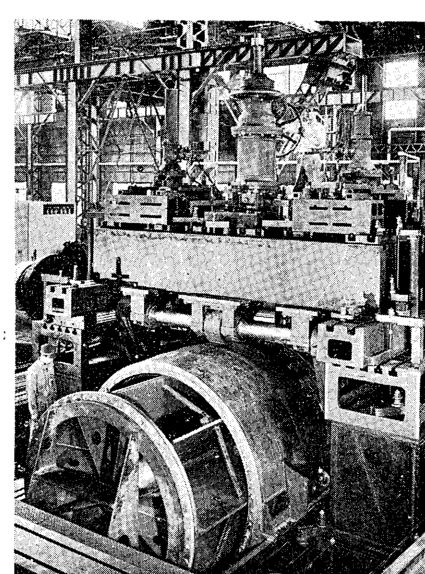


Fig. 15. Dispersion valve

of turbine stop or level by the turbine only being unsufficient, i.e., at the time of that the water to be supplied to the downstream is unsufficient. For the opening regulation of the dispersion valve, the oil servomotor is applied, and the valve is to be co-operated with the level regulator of the turbine, and special considerations are paid so that the water shall not leak at the closing time. Fig. 15 shows the photograph of the dispersion valve assembled in the shop.

V. GENERATOR

1. Rating

Output	:	3,600 kVA
Voltage	:	3,300 V
Frequency	:	60 c/s
Speed	:	200 rpm
Power factor	:	lagging 0.9
Exciting voltage	:	220 V

2. Construction

A generator coupled with a tubular turbine is strictly limited on the dimensions by the request from the hydraulics. Especially the diameter must be small as much as possible. In general, for the decision of diameter of the generator, the most economical value among the range of GD^2 value which is stipulated by the allowance of the speed regulation and the penstock condition is considered. In case of the tubular turbine, the maximum diameter is limited, then the most economical diameter must be selected under this limitation. Then, surely the GD^2 value is to be small and the speed regulation is to be large. As the diameter of the rotor is small, even if the speed regulation is large, mechanical stress is not considerable, and considering the cooling air pathes of the slender machine, manufacturing of the high efficiency generator is possible. In case of adopting the induction generator, the power factor and efficiency will be worse. However in case of synchronous generator, as this time, there are no fear of reducing the power factor and efficiency, and if the abnormal voltage up due to increase of the speed regulation is suppressed, there are no problem on the characteristics and the manufacturing. In comparison with the gear system having the some limit of capacity, the direct coupling system have little limit of capacity technically. In the following sections, special features of this generator is to be explained.

3. Air cooler

A co-axial section of the generator casing shows the ellipse shaped double layer wall as shown in Fig. 3. The outer wall of this double wall is contacting to the concrete foundation firmly and the inner one is forming the water passage for the turbine. Spaces between outer and inner walls are partitioned co-axially with the shafts by the enforcing plates to be air hollows. Inner wall being contacting mass water flows continuously, air in the hollow can be cooled. Cooling air, which is rised in temperature in order to cool the generator, is led through air tunel into this air hollow, and during this circulation air is cooled, then the casing is to be the air cooler.

In order to increase the cooling effect, many iron rectangular small plates are welded vertically and zigzag on the inner wall as cooling fins. Cooled air is ejected into the pit and is inhaled into the both ends of the generator to cool again.

As descrived in the above, the casing, i.e., water passage of the turbine is utilized to be air cooler for the generator at the same time, and the generator proper is completely separated from this air cooler. This is an unprecedented feature of this machine and it's merits are as follows :—

1) No necessary of special cooling water but main water flow for the turbine is to be cooling water as it is.
2) As the casing for the water passage of the turbine is utilized as cooler, the space can be minimanized.
3) As the water contacting surface of the cooler is smoothed surface plate, there is no fear to catch anything.
4) As increasing of cooling area is easy, cooling for the large capacity tubular water turbine generator is simplified very much.

When the warmed air is cooled, it can be considerable that the water drip is condensed on the inner surface of the cooler, hence the drain pipe connected to the drain pit is provided on the lowest part of the cooler. Air contacting surface of inner walls, cooling fins, enforcing plates and backside of outer walls are treated to be anticorrosive. Fig. 16 shows a complete air cooler.

Fig. 16. Air cooler

On the completed air cooler, 2.8 atg pressure test and cooling ability test was performed at the factory.

Further, in order to check the cooling effect, the test was conducted by using the testing apparatus constituted with a blower, a heater and a cooler, and a coefficient of overall heat transmission was calculated. That is to say, the cooler was laid and filled with water, and the water was supplied from the pipe to make the water flow in the cooler. Air inlet temperature was adjusted by using 80 kW heater, and the blower, the heater and the cooler was forming a closed circuit for the test.

The surface heat transfer rate α calculated from the test results are shown in the Fig. 17. The

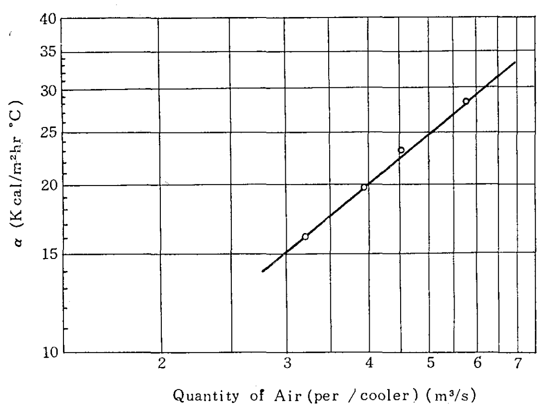


Fig. 17. Surface heat transfer rate of air cooler

cooler outlet air temperature at water temperature 25°C calculated from this α is 40°C or lower. And we found out the necessary pressure head for the necessary air flow is small and we recognized good performace of the cooler also.

4. Thrust bearing

The thrust bearing have to be loaded max. 52 t of thrusts and max. 38 t inverse thrusts. As the horizontal machine, these thrusts are so much large. The thrust bearing is consisting of 10 pc's segments which are mounted in spherical supporting bushes. The quantity of segments for the inverse thrust bearing is just the same. White metal is casted on the sliding surface of the segment, and the opposit surface is constructed as to transfer the thrusts through sphere surface to the small soft metal plate. The bushes, which is spherically supported, follow up the incline of the shaft automatically, and the sliding direction of the segment is suitable for the oil film theory. Then satisfactory lubrication can be gain. As cooling system for the lubricating oil, oil circulating system is adopted.

5. Brake

As shown in Fig. 19, 3 pc's of cylinder type air brake are mounted on the frame as star figure, and is arranged on the outer periphery of the coupling

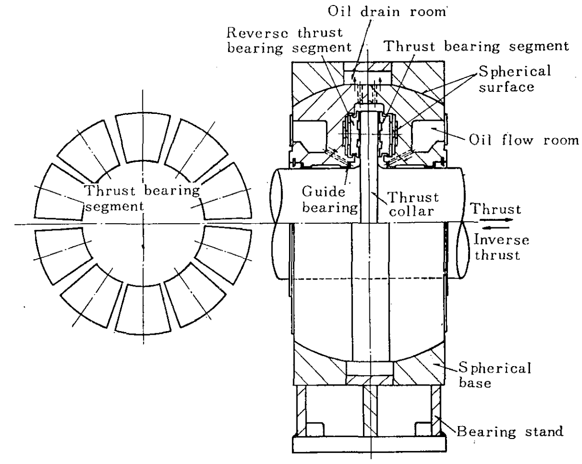


Fig. 18. Thrust bearing

frange between the turbine and the generator. On the outer periphery of the coupling flange, a brake segment is splitted into 6 parts and is bolted. When the brake cylinder is filled with compressed air, a piston in the cylinder is going upwards, and the strong sliding between the top brake shoes and brake segments gives the brake power to the rotating shaft. As the brake is arranged in star positions on the periphery of the coupling, unfavourable stress for the bearing will not arise. The brake shall be started at 30% of the rated speed when the generator is going to stop.

6. Dismantling

From a hydraulic point of view, the casing of the generator is to be small as much as possible. Therefore, the gap between the casing, i.e., the air cooler and the generator stator is minimanized. Meanwhile, removing the rotor from the stator inside the pit will need surplus axial direction length of the pit, this is unprofitable. And after lifting out the stator and rotor, removing the rotor from the stator will result to increase the crane capacity, then this is also uneconomical.

Then, for this generator, the stator is splitted into

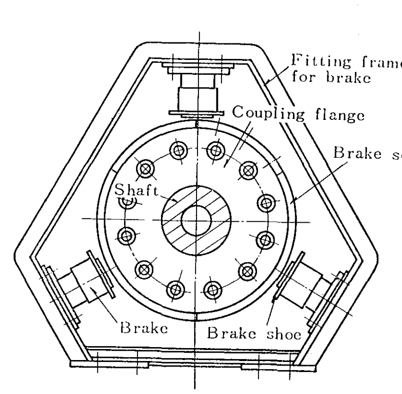


Fig. 19. Air break

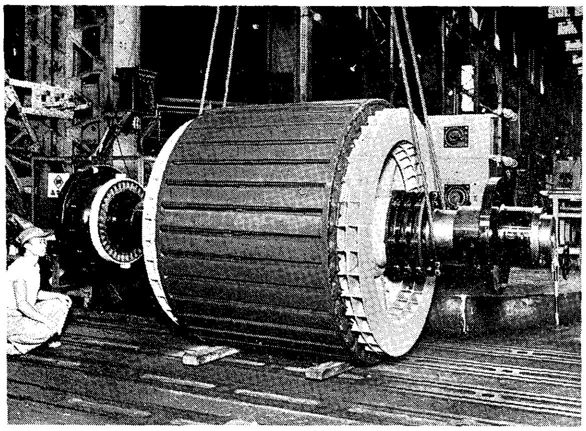


Fig. 20. Rotor

2 parts, upper and lower one, and after removing the upper part of stator the rotor is lifited up and then the lower part of stator is lifted. As the stator is splitted into 2 parts under mounting of the rotor, two parts of the stator is symmetrical electrically, and intermediate coil between two parts is not provided. By this construction, the stator can be splitted only by cutting the connecting cable two parts. On the tacho-generator, same considerations are paid. During the generator stopping and/or dismantling, coils are placed in the high hummidity, then the moisture proof device is important for the coils. However, for this generator, F-resin insulation is used for all of coils, a stator coil and a field coil, hence there are no necessary of considering the moisture proof device. F-resin coil has a high moisture proof and needs no special moisture proof device, and further in case of dismantling and reassembling, drying operation is not necessary. Regarding F-resin coil, we have experiences that in spite of leaving the coil in the high humidity for 2 or 3 months, we did not find out the any insulation resistance down but several hundreds meg ohm resistance was kept.

As the runner operating rod is mounted in the rotor shaft, in case of lifting of the rotor it is necessary that removing the coupling bolt for turbine shaft, shifting the rotor horizontally a little in order to make a suitable gap between the both surfaces of coupling flange and removing the connecting bolt of the rod. The crane capacity depends on the rotor weight and is 18 t.

In the above sections special features of this machine have been descrived in a brief, and Fig. 21 shows general outer view of the generator.

VI. OPERATION CONTROL

Simplicity and stability are the first requirement for the operation control of the tubular water turbine generator. In other words, as many of this type generator are medium or small capacity one, the system complicated operating controls, such as reactive power control and voltage control etc., are not necessary, and then the lowest installation cost and the simple control system are preferable.

For synchronization of generators, many methods are available. In case generator having large capacity and the disturbance by the rush current being large, most prudent synchronizing system is adopted and the synchronizing apparatus is provided to synchronize the phase of speed and voltage, then the synchronization without shocks is possible. In other way the most simple starting, as induction generator, is that the synchronization of non-excited generator is done at spontaneous speed without detecting speed. In this case, the current flows as an induction machine corresponding with their slips, and the speed gradually approach to the synchronized speed by induction torque and at the time of excitation, the synchronization is finished and the current is reduced at once. The amplitude of the rush current and the time of the synchronization depend on the speed (slip) at the time of closing. In case of closing of the already excited generator, if the speed and phase does not match, larger rush current flows than non-excited one and large shock is given to the power system.

Omata Dam generator is rather large capacity one as a tubular water turbine generator, and the influence to the power system is not avoidable. Hence the non-excited synchronizing start under matching of the speed only is adopted.

When the revolution speed rise up more than 80～90% of the rated speed, the speed matching device starts to approach the speed to the system frequency. Difference with the system frequency being within some set values of 0.5～1.5%, the slip relay operate to start under non-excitation. In some cases of non-excitation synchronization, the synchronization can be gained due to reaction torque of the salient pole machine, but if on poles of opposit porality synchro-

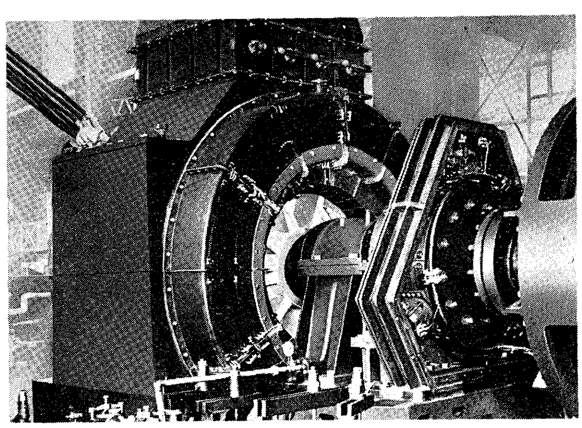


Fig. 21. Generator

nization at the time of applying of the exciting current one pole slips and resynchronizing is necessary, then some huntings are not avoidable. For this generator, special considerations are paid so that synchronization may not be conducted on the pole of opposite porality even the case of synchronizing by the reaction torque. Pull in torque of the generator is more than 45%.

For this kind generator having an abnormal small GD^2 value and high efficiency, as prescrived, with this degree of the torque the auto-synchronization can be gained simply under some slips. Simple and safety are to be considered at first for the excitation system, and the self exciting system without compound characteristics is adopted. Exciting current is supplied through transformer from the generator terminals. The secondary side of the transformer is consisting of two independent windings, during light load the power is supplied from one winding only. In case of full load, by a power relay output of another winding is applied in series automatically at the DC side, and exciting voltage is to be twice, thus two stage changeover constant exciting system is adopted. In case of increasing of the generator speed, for instance, the case of breaking full load of a generator, the generator terminal voltage will arise in proportion with the speed because of constant excitation. However for this generator, the over voltage protection is prepared by cutting the exciting current at the time of operation of a circuit breaker. Adjusting of the setting value of the exciting current can be conducted by tap changing of the power source transformer. Under constant excitation, the variation of the load will result the variations of power-factors and currents as shown in Fig. 22. Namely, at the point of full load the power-factor is rated value, but at the point of light load, reduction of the load current is small and supplying of reactive current increase as to be reactive power supply source.

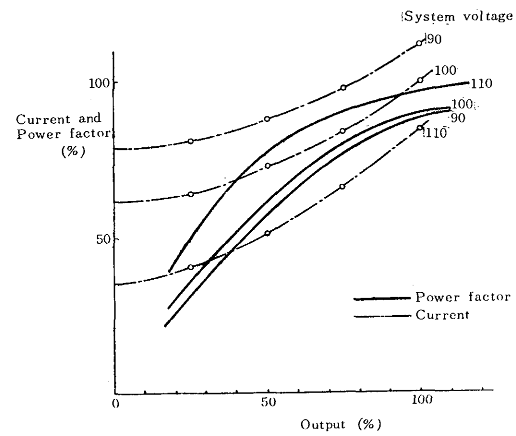


Fig. 22. Load characteristics

Especially in case of system voltage being low, supplying of reactive current increase and discharge functions of recovering of the system voltage. Under full load operation, system voltage is apt to down, in this case the load current will excess over the rated value slightly, however the exciting current can be adjusted under rated value by tap changing of the transformer. The exciting control apparatus of this generator is simplified at most, and complification of the control circuits due to the exciting apparatus is avoided as possible in comparison with induction generator, and the generator is aimed to display the functions as the reactive power source sufficiently.

VII. POSTSCRIPT

In the above chapters, outline of the tubular water turbine and the generator for the Omata Dam Power Station was illustrated, and we hope this brief illustration will serve to you for your planning of this kind power station.