UDC 621. 515 : 621. 165

FUJI STANDARD STEAM TURBINE FOR MECHANICAL DRIVER

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I. INTRODUCTION

In recent years, the size of chemical plants have increased remarkably all over the world and the time required for construction has been greatly reduced through rational scheduling. In such cases, the importance of various types of compressor driving steam turbines in such plants has been increasing. Along with higher speeds and larger capacities, higher temperature and pressures as well as wider ranges of specifications are being demanded. With the international trends, it has become common to order the compressor and the steam turbine for mechanical driver to separate manufacturers, but since the levels of technology in steam turbines for mechanical driver requiring severe operating conditions are higher, steam turbines as plant components can be used just as motors in the cases of electric drive and there are no problems in the purchase form of turbine unit.

Technically, the characteristics for steam turbines for mechanical driver i.e. easy of maintenance and inspection, durability, etc. have been specified in detail in standards API 615 and 612 (American Petroleum Institute). These standards are the basis for the technical improvement of high speed turbines and also various types of improvements are being made on the basis of actual operating results.

Fuji Electric has standardized drive turbines using highly improved technical levels based on experience in design and manufacture of turbines for the last 16 years since 1956 employing the turbine technology of Siemens company, West Germany which produces about 100 high speed turbines per year with ratings from 2 to 20 MW. In the last two years, four orders have been received in Japan and 22 orders from overseas for the manufacture of such turbines.

There is a wide selection of six standard types and 30 series of turbines. The prefabrication system is used to improve quality and shorten delivery time. Large-scale production and complete after-service have been established in close relation with Siemens concerning development, design, manufacture and marketing.

This article will describe the design concepts of Fuji standard steam turbines for mechanical driver, introduce some actual results and give some future trends. It is hoped that this will serve as a reference to users for the selection of drive turbines when the planning of power plants. This article does not include the Fuji standard geared turbine for power generation to be used as a electrical power source in power plants[1].

II. STEAM TURBINES FOR MECHANICAL DRIVER

In chemical plants and in particular petrochemical plants, the power supply systems are generally planned to serve as a central power source which generates steam as the heat source, by use of compressor drive steam turbine and electric power generation steam turbine. It has been shown that steam turbines are suitable for large capacities, can be used with a wide range of speeds and can easily serve at higher speeds. Therefore, they are being used more in place of motors for mechanical driver according as the improvement of steam turbines reliability.

Turbines can be classified into various types such as the reaction and impulse types which depend on differences in design of bladings, and the back pressure, condensing, extract back pressure and extract condensing which depend on the application. Generally, condensing or extract condensing turbines of the reaction or impulse type are used for 2,000 kW or over. In other cases, the back pressure or extract back pressure types are used and for lower capacities, the reaction or impulse type back pressure or condensing types are employed. The turbine efficiency can be determined from such factors as end loss of blading, leakage loss of blading, exhaust loss and circumferential efficiency. In turbines with capacities up to 20,000 kW, the volume flow is small, and when the speed is low, the blade length becomes very small. Therefore, the first two blading losses mentioned above play a relatively important part in turbine efficiency. In order to improve the efficiency, it is a prerequisite that the speed be over a certain high value. In other words, at the higher speed, the average blade diameter becomes small and the blade length can be longer, but this can be connected with an increase in the efficiency of a small capacity turbine to the same value as that of a large capacity turbine. In turbine from 20~30 to 500 kW used to drive auxiliary apparatus, a single stage impulse type with a low speed of about 3,600 rpm matched to the characteristics of the driven apparatus is used, but low efficiency is enevitable. Which are to be driven is used, but low efficiency is inevitable. However, such turbines are used in cases where motors are undesirable in respect to explosion proofing.

The higher speeds of turbines often result in a major decrease in the turbine weight and the casings become thinner. Therefore, this becomes an advantage in respect to thermal stress and the flexibility is increased in respect to rapid changes in the operating and steam conditions. In such turbines, advantages results because of the high speeds, but considering the strength of the moving blades, the stress due to centrifugal force and the steam stress due to the greater flow of steam per each blade both increase. From the standpoint of shaft stability, it is necessary to be careful concerning the gear coupling, bearing metal and balancing. Other important points to consider in blading strength planning are torsional vibrations due to a string of compressor rotors, blade resonance due to speed changes and dynamic stress. There have been demands for the development of a turbine suitable for the large capacities required in driving synthetic gas compressors[2].

The characteristics required of a drive turbine including those specified in API standards 615 and 612 are given below.

(1) Reliability in respect to high load continuous operation (designed for high flexibiltity).
(2) Withstand against impulse loads during surging or rapid load changes.
  In particular, blading strength calculations must be made considering stress on the moving blades due to vibration caused by torsional vibration in a string of compressor rotors, resonance stress due to the variable speeds and dynamic stress caused by steam flow.
(3) Efficiency must be high in the wide operation output and speed ranges. There must be no decrease in efficiency with continuous operation.
(4) Bladings must be shaped for high efficiency and strength against vibrations.
(5) The standard low pressure blade series with a high capacity of steam flow must be used.
(6) The rotors must be stable in respect to vibrational balance. Simple rotor shapes made of highly reliable forgings are desirable.
(7) The journal bearings and thrust bearing must be designed well to provide damping effects. The thrust should be automatically balanced if possible.
(8) Quiet operation with no vibration and no noise at starting or in the complete operation speed range must be possible.
(9) Construction must be simple and durable. Maintenance and inspection must be easy.
(10) The number of parts in the control system must be few and the reliability high.
(11) Operation must be easy to match the plant automation level.
(12) The control devices must have high response and stability.
(13) The turbine must be compact and flexible in respect to positioning in the plant.
(14) Due to standardization, spare parts must be easy to obtain.
(15) Wide selection must be possible, the delivery period must be short and the price low.

III. FEATURES OF THE FUJI STANDARD STEAM TURBINES FOR MECHANICAL DRIVER

The Fuji standard steam turbines for mechanical driver have essence such as high durability, economy comparable to large scale industrial turbines and easy operation, maintenance and inspection as motors due to the use of reaction blading suitable for high speeds, simple rotor shapes and oil hydraulic governor.

The design is especially suited to the recent increases in capacities and higher speeds. Through the wide selection and the prefabrication system, the turbines can be delivered in a short period no matter what the specifications.

Fig. 1 shows a 12,000 kW condensing turbine for oversea under trial operation in our works. This turbine is assembled on a steel foundation. It is the standard type for export since it is designed to be loaded directly on a ship after trial operation.

These Fuji standard steam turbines for mechanical driver have the following features:

(1) Reaction type turbine
(2) High performance round headed profile and standard low pressure blades
(3) Highly stable rotor construction
(4) Oil hydraulic governor and protective devices
(5) Heat exchanger of rational design
(6) Wide selection and prefabrication system

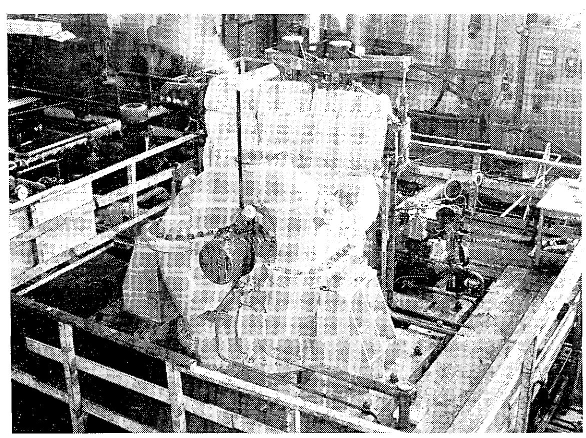


Fig. 1 12,000 kW condensing turbine

1) Reaction type turbine

Steam turbines for mechanical driver include the reaction type and the impulse type and turbine makers throughout the world have been developing both types with excellent features depending on their historical background. Those using the reaction type include Siemens and Westinghouse and those depending on the impulse type include Elliot and AEG. Gradually, it is becoming known that the reaction type can be made for higher speeds more easily than the impulse type because of the low blade stress although this was known mainly for the reaction type used previously as a geared turbine for power generation.

Fuji Electric employed standard geared turbine for power generation turbines of up to 20 MW and has played a leading role in technological improvement of geared turbines due to our establishment of design and production methods for highly reliable reduction gear[3] and the development of high speed turbine for mechanical driver.

The main difference between the reaction and impulse types is that in the former, the effective heat drop of the steam is expanded into the stationary and moving blades. In orther words, there is a reaction degree of about 50% in the moving blade, the steam speed in the blades is kept comparatively low, and also there is a constant expanded flow, so that no steam exfoliation occur which cause a efficiency drop in the stream.

In the impulse type, the effective heat drop is all expanded by a nozzle, this high speed steam flow is blown against the moving blade and the impulse power is utilized. Therefore, the impulse type is generally designed with a high steam speed and few blade stages, in comparison with the reaction type. In recent years, the speeds of compressors have been increasing but the exhaust loss has become large because of the small number of blade stages due to the high speeds. However, the reaction type has more stages than the impulse type so that the amount of exhaust loss is small in respect to the turbine efficiency.

Fuji Electric turbines utilize the impulse type generally only for the first governing stage. This is for partial admission nozzle cut-off governing and in this stage, the heat drop used is as slight as possible. After this stage, the heat drop is large in the reaction stages, a high efficiency is maintained and the impulse blade stress level is reduced.

In the reaction type, the steam exhaust angle is large, and it is possible to make the axial clearance on either side of the moving blade large without decreasing efficency. There are no limitations on operation due to differences in axial ex- pansion at the time of rapid load changes or changes in extraction amounts which are often found in turbines for mechanical driver. Since the blade end and leakage losses are small, the radial clearance can be sufficiently large and there are no drops in efficiency due to continuous operation like those found in a turbine with a small radial clearance which is a precondition for contact of the blade ends. The thrust due to the steam pressure occurring in a series of reaction blades is automatically balanced under any operating conditions by means of the use of a so-called balance piston and the rest thrust force is sufficiently small. Even in cases when silica is attached to the blades, automatic balancing is ensured and this means greater safety. In extract turbines, the thrust in the blade section changes due to both load changes and changes in the amounts extracted but a system which automatically changes the steam line to which the balance piston is attached on one end has been developed and patented by Fuji Electric.

2) High performance round headed profile and standard low pressure blades

These turbines use a round headed profile in the high and middle pressure parts in both the stationary and moving blades which resemble the blades used in large capacity turbines of the 350 MW class. It was confirmed by the shallow water flow analog test and the high speed blade test that this profile has a very high performance with no steam break away over a wide range of changes in the flow-in angle. There is also no decrease in efficiency at partial loads or changes in the rotating speed. In respect to the requirements recently for higher speeds and greater capacities, a new profile for higher axial speeds has been developed and put into use. Both of the above two profiles are durable with a large modulus of section in respect to vibrational strength and a low stress concentration. In addition, integral shrouds have been provided for all the moving blades so that the blade end loss is reduced and a vibration damping effect is produced. A rivetted type shroud is standard with the stationary blades.

For the low pressure blades in condensing turbines, 22 types of low pressure blades in three design series have been standardized and the correct blades can be chosen to match the condenser vacuum, the amount of condensation and the speed. As can be seen from *Table 1*, the maximum speed is 20,000 rpm and the maximum blade length is 422 mm.

Generally in turbines used for mechanical driver, low vacuum is used so that the blade load is large in comparison with the volume of steam flow. In turbines for power generation, the speed is 3,000 or 3,600 rpm in the case of direct coupling and can be selected optionary in the case of geared turbines. Therefore, the thermodynamic calculations for the blades need only consider the volume flow as a variable. However, in the turbines used for mechanical driver, the speeds change and since the speeds are also a determining factor, it is very important to use blade profiles which will not cause a drop in efficiency in respect to the operating speed range. Naturally, there are limitations for this reason

Table 1 **Standad low pressure blade**

Symbol	Final stage blade base diameter (mm)	Blade length (mm)	Area of blade outlet (m^2)	Max. speed (rpm)	Blade foot's type
SK22	230	106	0.125	20,000	
SK28	287	132	0.195	16,000	
SK36	367	169	0.319	12,500	
SK45	459	211	0.499	10,000	
SK56	574	264	0.779	8,000	Fork
SK63	642	295	1.018	7,150	
SK71	729	335	1.257	6,300	
SK80	813	374	1.626	5,650	
SK90	919	422	1.994	5,000	
HK22	230	99	0.112	16,000	
HK28	287	124	0.175	12,500	
HK36	367	159	0.287	10,000	
HK45	459	198	0.448	8,000	
HK56	574	248	0.700	6,300	T
HK63	642	278	0.914	5,650	
HK71	729	315	1.129	5,000	
HK80	813	351	1.46	4,500	
HK90	919	397	1.791	4,000	
K 600	280	100	0.119	12,000	
K 800	360	150	0.240	9,000	T
K1100	460	200	0.414	7,000	
K1400	586	254	0.671	5,000	

and it is necessary to have a standard series of low pressure blades of many types to match the operating speed range. A large FACOM 230–50 computer was used in developing the low pressure blades. Blade profiles were determined for 10 sections in the radial direction of the blade by means of the NACA profile and camber line. Then fluid calculations were made for noncompressible flow and investigations were made to determine if there would be any exfoliation in the steam flow and load for various combinations of speeds, condenser vacuum and volume flow. A stress and vibration analysis was also made for the blade part and the foot part. These calculations were repeated and the final blade profiles were determined in consideration of processing. Then a model blade was constructed and subjected to strength vibration tests and fluid tests.

One of the main problems in increasing the speed is the strength of the foot parts of the moving blades

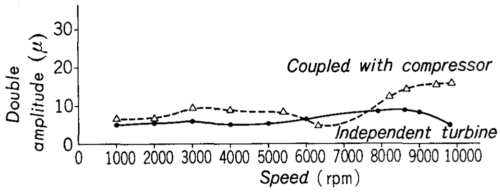


Fig. 2 **Rotor vibration spectram of 7,418 kW condensing turbine**

of the first and final stages. Fuji Electric employs the fork system which is the same as that used in large capacity turbines. Compared with the former T-type foot, 25% higher speeds are possible and a higher damping effect can be obtained in respect to vibration stress. In long, low pressure moving blades, damping wires made of 12% CrMo steel or titanium are used to reduce the stress which occurs due to torsional vibrations in strings of compressor rotors and speed resonance.

Refer to references (4) and (5) respectively for the development of the low pressure blades and blade strength.

3) Highly stable rotor system

In impulse type turbines, it is generally necessary to decrease considerably the steam leakage loss due to the large pressure differences between the inlet and outlet of the nozzle. Therefore, a carrier ring is provided and the rotor shape is of a pierced disk to provide steam tightness around center of the rotor. The rotors of the reaction type, however, are of a simple cylindrical type made of highly reliable forgings which are stable to vibrations. In the standard API 615 and 612, the rotor design is given such that critical speeds are 121% above or 60% below the rated speeds. Rather severe permissible rotor vibration amplitudes have been specified. The rotor vibrations are torsional and bending vibrations but for the former it is necessary to consider the gear couplings between the compressor and the turbine (supplied by the compressor manufacturer) and for the latter, the spring constants of the bearing oil film and the bearing part, as well as the damping characteristics. In the Fuji turbines, the number of rotor torsional vibrations is much greater than the rated speed.

The critical speed of the rotor system (bending vibration) is greatly effected by the type of bearing metal used. In Fuji turbines, double and quadruple arc bearing metals are standard for the journal bearings. When the double arc metal is used, the rotor is usually rigid with a critical speed of more than 121% above the rated speed. The quadruple arc metal is used in high speed bearings, since it has particulary high damping effects. The spring constant of the oil film of this type of bearing metal is small and the critical speed of the rotor system is less than 60% of the rated speed.

The Fuji rotors are generally of the rigid type and this has a great influence on lowering the critical speed of the rotor system due to the spring constants of the oil film in the bearing part. Since the damping effect in the bearing part is effective, it is impossible to confirm in an actual turbine the critical speed of the rotor system under the good balancing condition. *Fig. 2* shows the rotor vibration characteristic of a 7,418 kW condensing turbine using the quadruple arc bearing metal. The amplitude can be seen to be almost constant from the runner-out up

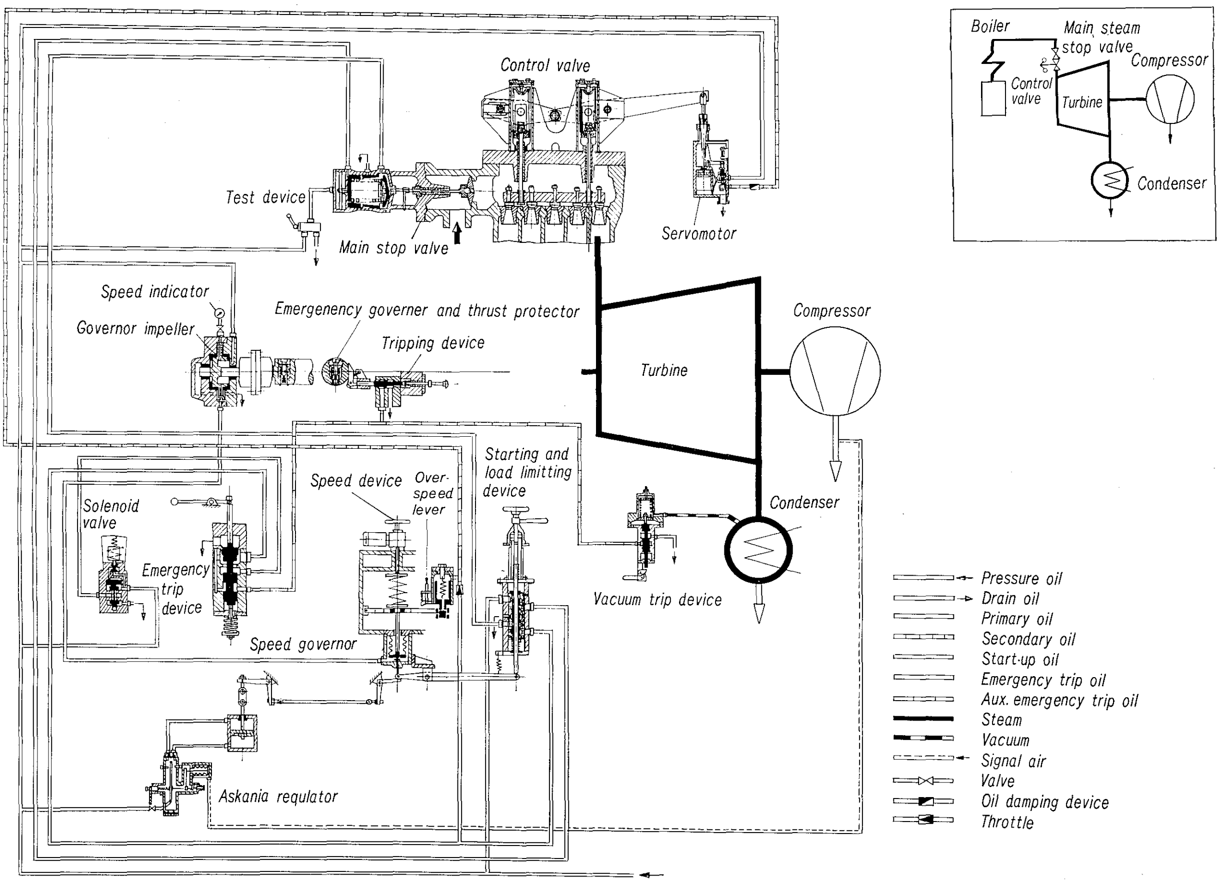


Fig. 3 **Control and safety system diagram**

to the maximum speed. A report will be given later concerning the rotor vibration characteristics and the bearing metal.

For rotor turning Fuji standard motor operated type manual closing, automatic separation devices can be provided in the rear bearing pedestal when required.

4) Oil hydraulic governor and protective devices

Fuji Electric employs two types of governors for steam turbines: the electro-hydraulic and the oil hydraulic governors but in the steam turbines for mechanical driver, the oil hydraulic type is generally used at present. The electro-hydraulic type is used when there is complex control such as three- stages extraction pressure control. The oil hydraulic type governors are standard including application in the standard Fuji geared turbines for power generation. All parts are interchangeable and reliability is high.

Compared with mechanical type, the oil hydraulic type has fewer parts, like link mechanisms and sliding parts, so that response is rapid and maintenance and inspection are easy. Speed detection by means of the governor impeller is not adversely influenced by the original oil pressure and temperature. Since transmission of signals is performed by oil pressure, it is easy to combine external control values such as the compressor exhaust pressure, flow, suction pressure control and extraction pressure control in the control system which is in keeping with the plant automation trends. It is also possible to provide a Woodward type governor if the cusotmer desires.

In the case of turbines for power generation, there is load shedding condition but in turbines used for mechanical driver, there is no such condition and few problems related to the higher turbine speeds.

The protective devices include emergency governor for emergency turbine stops, thrust failure protection device, stripping device, main stop valve, solenoid valve and lubricating oil low pressure switches. All of those devices specified in the API standards are provided. The main stop valve testing device is standard and an emergency governor testing device can be provided if the customer so requests. *Fig. 3* shows the control and safety system of a condensing turbine.

For sealing steam pressure control, an air-pressure controlled relief valve or an automatic pressure control valve are used.

5) Rationally designed heat exchanger

Fuji Electric employs two types of condensers: the surface type and the mixing type. As shown in *Fig. 4,* the surface type uses a thin cylindrical plate welded rigid support system. A bellows is provided for connection to the turbine exhaust part. For flexibility in positioning, series have been arranged with various combinations of cylinder diameter, cooling pipe length and the number of cooling water passes. The design is completely rational with no heat unbalances since all calculations including cooling pipe arrangements were made using a FACOM 230–50 computer.

In the mixing type, no cooling pipes are used and cooling water sprayed through nozzles for condensing. It is suitable for plants for drive power and supply of hot water.

The heat exchangers also include steam ejector coolers, gland steam condensers and oil coolers. All of these are standardized.

6) Wide selection and prefabrication system

Refer to sections IV and V.

IV. RANGE OF APPLICATION AND TYPES OF FUJI STANDARD STEAM TURBINES FOR MECHANICAL DRIVER

One of the most remarkable trends recently has been the reduced utilization of waste heat in accordance with improved process technology. As the scale of power plants increases, there are greater demands for higher reliability and more heat economy. The wide selection system is employed to meet the demands of industry so that a turbine can be selected to fit any specifications. This provides for greater efficiency not only in the design and manufacture but also in the planning of the power plant. *Table 2* shows the types of Fuji standard turbines and *Table 3* and shows the application ranges.

The G and HG series are both back pressure turbines and the HG series in particular are high pressure and temperature turbines which can be used with inlet steam condition up to 140 kg/cm^2·g, 535°C. The HG series will be reported in a later article. By selecting the best turbine, it is possible to design a plant with high efficiency. The K(00), K(01) and WK series are all condensing turbines but the K(01) models are low pressure turbines with maximum

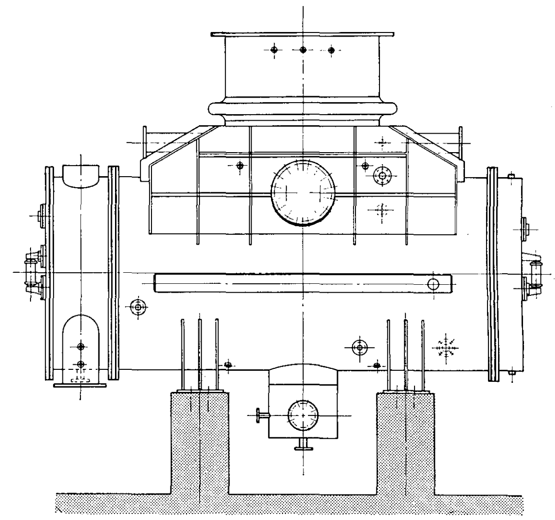


Fig. 4 Outerview of condenser

Table 2 Fuji standard steam turbine types

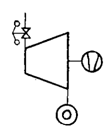
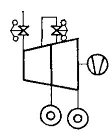
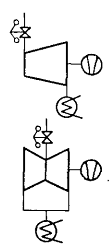
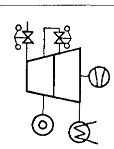
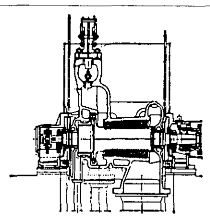
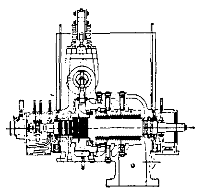
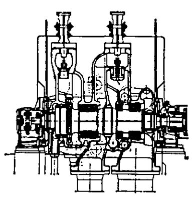
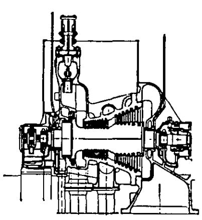
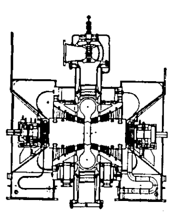
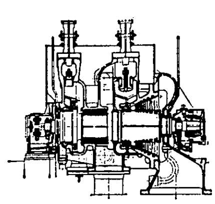
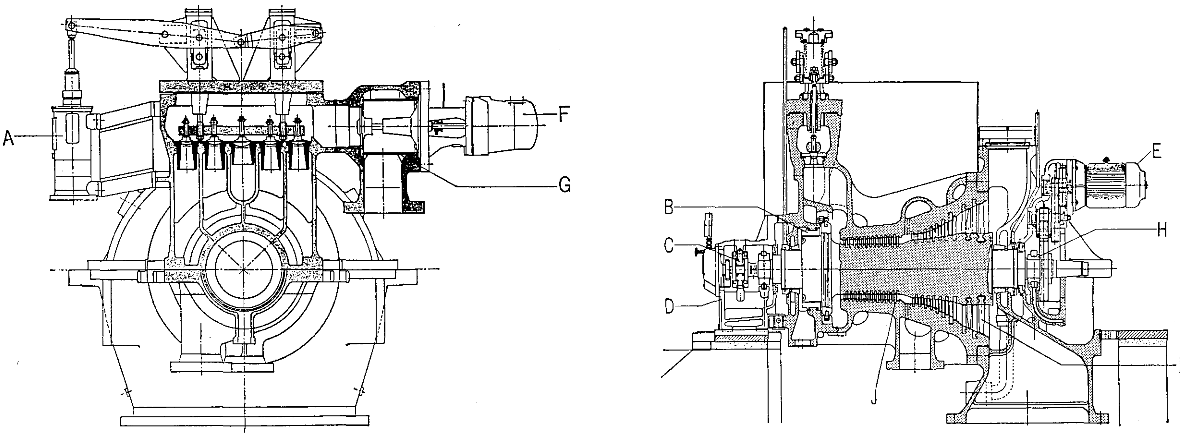
Type	Series symbol	Explanation
Back pressure turbine	G HG	 The steam leaving the turbine is utilized for process heating, etc. in the plant at the required pressure (back pressure) and temperature. The HG type is employed for especially high temperature and pressure steam.
Extract back pressure turbine	EG	 A back pressure turbine in which steam with a certain pressure and temperature is extracted from the middle stage of the turbine used for process heating, etc. in the plant.
Condensing turbine	K WK	 The steam from the turbine is lead to a condenser where it is expanded to a vacuum and converted into effective work. The WK type is especially suitable when large amounts of steam are required.
Extract condensing turbine	EK	 A condensing turbine in which steam with a certain pressure and temperature is extracted from the middle stage of the turbine and used for process heating, etc. in the plant.

Table 3 Fuji standard steam turbine series

Series	Sectional view of turbine	Symbol	Maximum speed (rpm)	Maximum output (kW)	Maximum inlet steam conditions	
					Pressure (kg/cm^2·g)	Temperature (°C)
G		G 250	16,000	4,000	70	500
		G 300	12,500	7,000	70	500
		G 400	10,000	11,500	70	500
		G 500	8,000	16,000	70	500
HG		HG 25/16	16,000	5,000	140	535
		HG 32/20	12,500	8,000	140	535
		HG 40/25	10,000	12,500	140	535
EG		EG 250	16,000	4,500	70	500
		EG 300	12,500	8,000	70	500
		EG 400	10,000	13,000	70	500
		EG 500	8,000	18,000	70	500
K		K 600	16,000	4,000	70	500
		K 800	12,500	8,000	70	500
		K 1000	10,000	10,000	70	500
		K 1100	8,000	14,000	70	500
		K 1400	6,300	22,000	70	500
		K 601	16,000	4,000	40	400
		K 801	12,500	8,000	40	400
		K 1001	10,000	10,000	40	400
		K 1101	8,000	13,000	40	400
		K 1401	6,300	20,000	40	400
WK		WK 28	16,000	5,000	25	400
		WK 36	12,500	8,000	25	400
		WK 45	10,000	12,000	25	400
		WK 56	8,000	20,000	25	400
EK		EK 600	16,000	4,000	70	500
		EK 800	12,500	8,000	70	500
		EK 1000	10,000	10,000	70	500
		EK 1100	8,000	15,000	70	500
		EK 1400	6,300	22,000	70	500



(A) Servomotor
(B) Labyrinth ring
(C) Thrust bearing
(D) Bearing pedestal
(E) Electric turning gear
(F) Emergency valve
(G) Strainer
(H) Journal bearing
(I) Standard low pressure blade
(J) Reaction stage

Fig. 5 Prefabrication system (K series)

inlet steam conditions of 40 kg/cm²·g, 400°C. The WK series is of the double flow type which matches to a large steam valume flow. The maximum steam inlet conditions are 25 kg/cm²·g, 400°C. The EG and EK series are extract back pressure and extract condensing turbines respectively. Except for the HG, K(01) and WK series, all series have maximum steam inlet conditions of 70 kg/cm²·g, 500°C. The output for each series is given as the maximum value per the single cylinder. In practice, it is possible to couple turbines of the HG and WK series in tandem to form a HG-WK series.

With the block design system now being planned, each series will be divided into high, medium and low perssure parts and in this way it will be possible to design and manufacture a single cylinder turbine fulfilling the desired specifications by welding these parts together. This idea has already been partially put into practice. The block design system and its development will be explained in a later article.

V. PREFABRICATION SYSTEM

Fuji Electric steam turbines are machined, assembled, inspected and tested in the turbine works located in Kawasaki. In order to improve the scale of production both qualitatively and quantitatively, a prefabrication system has been developed for planned production and delivery quality control. This system has made a wide selection possible. *Fig. 5* gives an explanation of the prefabrication system for the K series. The turbine is divided into four parts: ① the control valves and blades related to turbine efficiency, ② the large heavy parts likely casing and rotor for which the material delivery period is long, ③ the standard series of final low pressure blades which present a problem in respect to vibration strength, bearings, protective devices, etc. and ④ the steel foundation and pipes for around the turbine. Parts ① and ④ are designed in accordance with individual specifications and the design calculation for all control valves and blades are programmed on a FACOM 230–50 computer. The steel foundation and the pipes around the turbine are also semi-standardized.

VI. CONCLUSION

This article has described the technical features, wide selection and prefabrication system of the increasingly popular Fuji standard steam turbines for mechanical driver from the manufacturer's design side. The author hopes that it will serve as a reference for users in the selection of equipment when designing power plants and for compressor manufacturers when making estimates for turbines.

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