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MATERIALS AND DESIGN FOR ADVANCED HIGH TEMPERATURE STEAM TURBINES

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Abstract

Natural gas has long been regarded as the primary energy source for advanced power systems because of its cleanliness and highly efficient nature. Nevertheless, coal is gaining attention again as a stable energy source for power generation. In this paper, high efficiency pulverized coal power plant technology, especially materials and the design for high temperature turbine systems, is discussed. The development of materials has contributed to the high efficiency plant development, so far. The development of 12% Cr steel was key in building the state-of-the-art 600-deg C class steam turbine system. It is believed that a 700-deg C class steam turbine system will be realized with Ni-based super alloys and austenitic steels. In the near future, the system with a 700-deg C reheat temperature and 630-deg C main steam temperature is promising for the pulverized coal power plant because of the need for only moderate development work, low capital expenditure, and its high efficiency.

1. Introduction

At present, nations derive the bulk of their energy needs from high-quality fossil fuels such as oil and natural gas. However, it is forcasted that such fossil sources will be depleted within 50-60 years. Recently, we experienced a sharp rise in the price of natural gas. In addition, the population growth, and booming economies in Asia and other continents are likely to drive fossil-fuel prices even higher than current projections. On the other hand, the liberalization of the power market requires power producers to reduce the price of electricity.

These realities have intensified the need to make better use of low-quality and inexpensive fuels such as coal, residual oil, orimulsions, etc. in spite of the fact that these fuels contain more carbon than other fossil fuels. To extend the use of these fuels, it is essential that we use them efficiently and cleanly to reduce CO2 and other emissions. While the integrated gasification combined cycle (IGCC) is one of the most sophisticated technologies for power generation using these fuels, the pulverized coal power generation with super critical steam condition is expected to be the most promising technological option in the near future.

This paper presents the recent material development and study of the high temperature steam turbine system with super critical steam conditions for the pulverized coal power generation.

2. High temperature materials development

2-1 Current status of material development

In fossil-fired units, higher efficiency has been obtained mainly through the elevation of steam temperature and pressure. The change of the steam temperature in large rating units in Japan is shown in Figure 2-1.

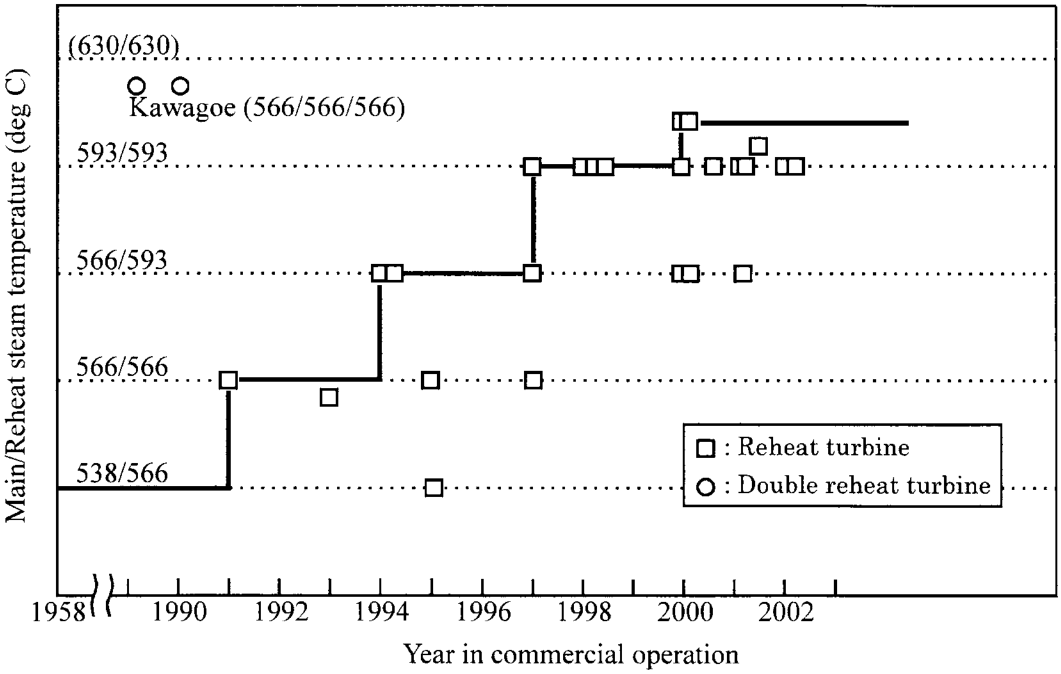


Figure 2-1 Trend of Steam Temperature in Large Rating Units in Japan

Reheat turbines with 538/566-deg C steam have been the standard for a long time. However, after the commercial operation of the Kawagoe 566/566/566-degC double reheat USC (Ultra Super Critical) turbine with a capacity of 700 MW in 1989, a marked increase in steam temperature also began in reheat turbines. The 566/566-deg C, 566/593-deg C, 593/593-deg C, and 600/610-deg C turbines successfully started commercial operation. To increase the steam temperature, one of the key issues is high-temperature materials which have a greater creep rupture strength than conventional steels. Thus, a lot of studies have been conducted on the improvement of elevated-temperature strength and on the clarification of the micro structural mechanism.

As for advanced steam turbines, we have promoted the EPDC, TEPCO (Tokyo Electric Power Company) and EPRI projects as shown in Table 2-1. In the EPDC project [1] phase-1, the operational integrity of 'Modified 12% Cr' rotor/bucket steels was verified through the rotating test at Takasago p/s for 4,818hrs at 593°C. The TEPCO project [2] was to validate the product-ability and the properties of three kinds of 'Modified 9-12% Cr' steel rotors developed in Japan. In the EPRI project [3], we were engaged in key material tasks for advanced steam turbines with 31MPa, 593/593/593-deg C in steam conditions. The properties of 'Modified 12% Cr' rotor/bucket steels and super-clean 3.5%NiCrMoV rotor forgings were verified. The EPDC project [4] phase-2 was to develop more advanced steam turbines with 630°C steam using 'New 12% Cr' rotor/bucket steels. As the result of fundamental studies and the above-mentioned projects, several heat resistant steels were developed for various steam turbine components.

Table 2-1 Participated Projects for Advanced Steam Turbines

Year	Projects	Remarks
'82 - 88	EPDC-phase-1	Turbine rotating test at 593 & 649-deg C
'82 - 84	TEPCO	Development of turbine rotor steels for 593-deg C
'86 - 90	EPRI-RP1403-15	Material development of key parts for 1100-deg F
'95 - 99	EPDC-Phase-2	Accelerated turbine rotating test at 650-deg C

Table 2-2 Typical Chemical Composition of Developed Rotor Steels (mass%)

	C	Si	Mn	Ni	Cr	Mo	V	Nb	N	W	Co	B	Fe
12% Cr (TOS101)	0.18	0.20	0.7	0.4	11.0	1.00	0.2	0.07*	0.05	-	-	-	Bal.
Mod. 12% Cr (TOS107)	0.14	0.05	0.6	0.7	10.0	1.00	0.2	0.05	0.05	1.0	-	-	Bal.
New 12% Cr (TOS110)	0.11	0.08	0.1	0.2	9.7	0.65	0.2	0.05	0.02	1.8	3.0	0.01	Bal.

*: Ta or Nb

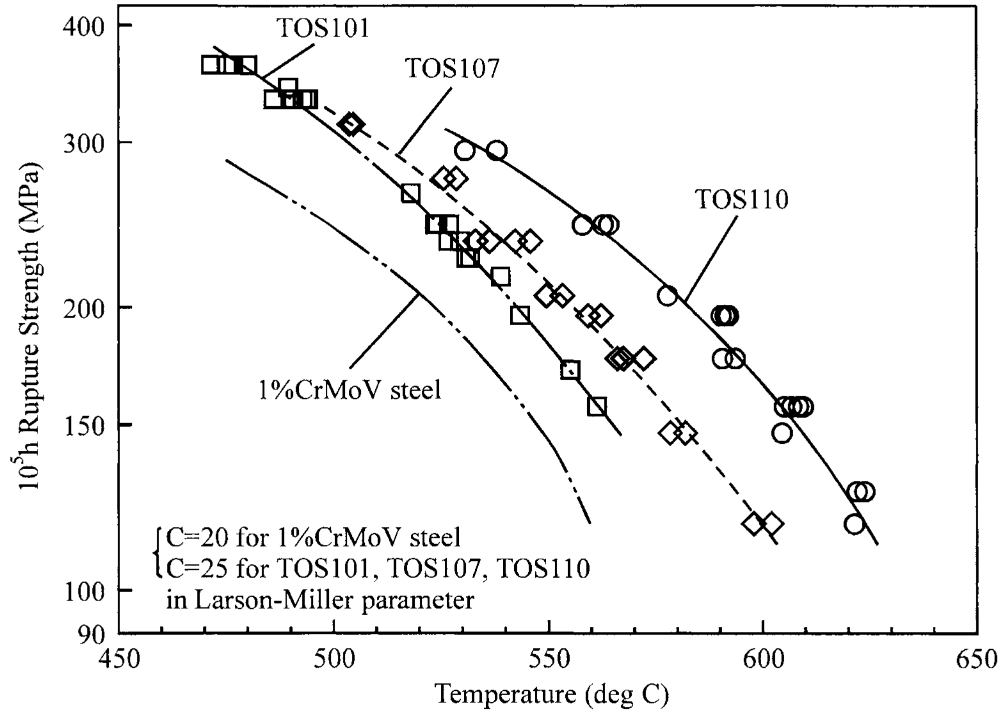


Figure 2-2 Creep Rupture Strength of Rotor Steels

Three kinds of 12% Cr rotor steels were developed for turbines with steam temperatures of 566-deg C or higher. The typical chemical composition and the creep rupture strength of the steels are shown in Table 2-2 and Figure 2-2. 12% Cr rotor steel (TOS101) was improved from H46 alloy steel for gas turbines. The steel is characterized by precipitation strengthening with Nb/Ta carbo-nitride added to $M_{23}C_6$ and VC carbides in tempered martensite. Modified 12% Cr rotor steel (TOS107) was mainly developed for rotors operating at 593-deg C in the 1980s. The most notable chemical feature is the addition of 1 mass % tungsten in TOS107. The creep rupture strength of TOS107 was improved by the solid-solution strengthening effect of tungsten in addition to precipitation strengthening with carbides. During the 1990s, there was a remarkable advance in 9-12% Cr steels in the world, represented by Fujita's materials [4, 5]. Referring to the concept behind those steels, we also developed new 12% Cr rotor steel (TOS110) with optimized alloy chemistry adding tungsten, cobalt and boron. The higher tungsten content maintains sufficient solute tungsten and increases the quantity of the intermetallic compound, such as the Laves phase, contributing to precipitation strengthening [6, 7]. Cobalt is added to prevent the formation of delta ferrite. The addition of a small quantity of boron greatly improves the creep rupture strength through the grain boundary strengthening effect.

Table 2-3 Typical Chemical Composition of Developed Bucket Steels (mass%)

	C	Si	Mn	Ni	Cr	Mo	V	Nb	N	W	Co	B	Re	Fe
12% Cr	0.17	0.40	0.6	0.4	11.0	1.00	0.2	0.4	0.05	-	-	-	-	Bal.
Mod. 12% Cr (TOS202)	0.16	0.05	0.5	0.7	11.0	1.00	0.2	0.2	0.05	1.1	-	-	-	Bal.
New 12% Cr (TOS203)	0.11	0.05	0.5	0.6	10.5	0.10	0.2	0.1	0.03	2.5	1.0	0.01	0.2	Bal.

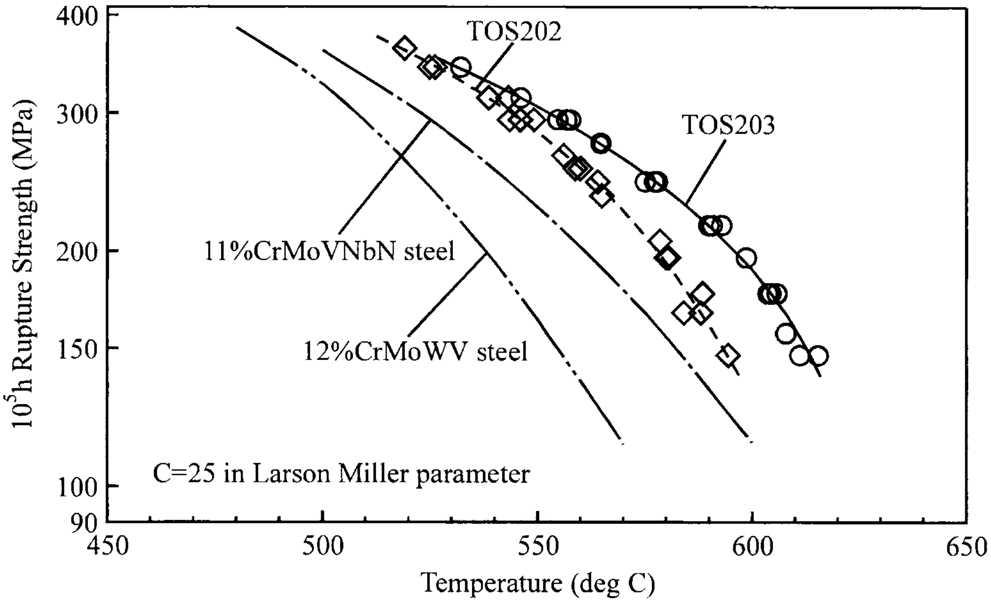


Figure 2-3 Creep Rupture Strength of Bucket Steels

Conventional bucket steels operating up to 566-deg C are 12%Cr-1%Mo-1%W-V and 11%Cr-1%Mo-V-Nb-N steels. For the same purpose, to raise the operating temperature, modified and new 12% Cr bucket steels were developed, which were based on the concept of alloy chemistry similar to that of the advanced rotor steels. The typical chemical composition and creep rupture strength are shown in Table 2-3 and Figure 2-3. Because of the much smaller product size, compared with rotors, modified 12% Cr bucket steel (TOS202) was able to be improved by a higher niobium content and a higher quench temperature. Therefore the bucket steel shows a better creep rupture strength than the modified 12% Cr rotor steel (TOS107) with a similar alloy chemistry. The characteristics of the new 12% Cr bucket steel (TOS203) [8], when compared with new 12% Cr rotor steel (TOS110), are higher tungsten, a lower molybdenum content and the addition of rhenium.

Rhenium not only acts as a solid solution element, but also has the effect of maintaining a sufficient amount of solute tungsten in matrix during creep. Thus it was presumed that the additional solid solution strengthening effects of rhenium and tungsten could/should be brought in to increase the creep rupture strength.

For high temperature casings and valve bodies, 12% Cr cast steel (TOS301), modified 12% Cr cast steel (TOS302), and new 12% Cr steel (TOS303) were developed. There were some specific requirements for castings, such as gas cutting of riser, gouging of padding, repair weld, and welding with pipes. Though these castings were developed based on the knowledge obtained from studies of rotor steels, the chemical composition was modified in consideration of the above-mentioned thermal handling, weld-ability and cast-ability.

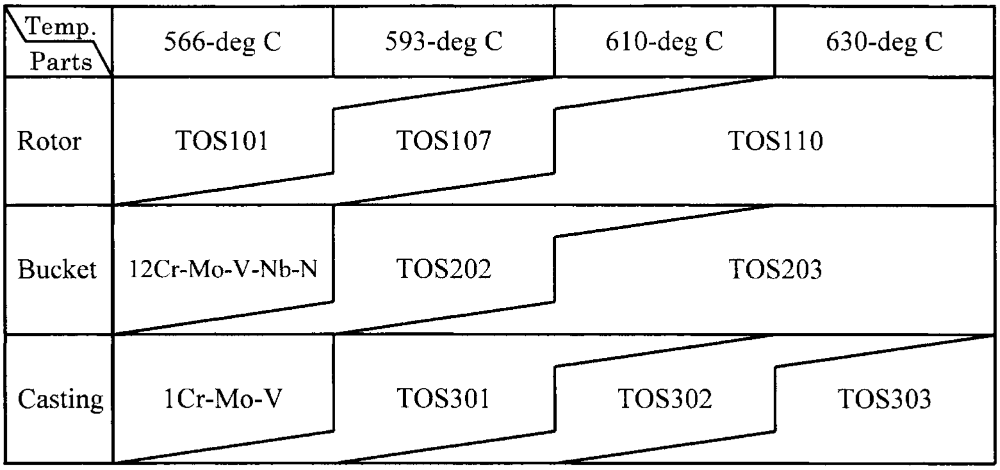
2-2 Experience of newly developed materials

Table 2-4 shows the first use of and the achieved highest temperature of developed materials for advanced steam turbines.

Table 2-4 First Use and Achieved Highest Temperature of Developed Materials

Steel	Steam temperature (deg C)	Main steam pressure (MPa)	Output of turbine (MW)	Applied parts	Year in service	Achieved highest temperature (deg C)
Mod. 12% Cr rotor (TOS107)	566/566	24.1	500	HP-IP rotor	1991	610
New 12% Cr rotor (TOS110)	593/593	24.1	700	HP-IP rotor	2000	593
Mod. 12% Cr bucket (TOS202)	566/566	24.1	500	Buckets & Bolt	1991	593
New 12% Cr bucket (TOS203)	593/593	24.1	700	Buckets	1998	610
Mod. 12% Cr casting (TOS302)	566/593	24.1	1000	IP inner casing	1997	593
New 12% Cr casting (TOS303)	600/610	25.0	1100	CRV body	2000	610

Modified 12% Cr rotor steel (TOS107) was first applied to Tsuruga #1 with a steam temperature of 566-deg C in 1991. Since then, many TOS107 rotors have been applied to advanced steam turbines with steam temperatures of up to 610-deg C. The new 12% Cr rotor steel (TOS110) was first applied in 2000. In addition to the excellent experiences with the rotors, all developed materials have already been in actual use and have been operated successfully.



Temp. \ Parts	566-deg C	593-deg C	610-deg C	630-deg C
Rotor	TOS101	TOS107	TOS110	
Bucket	12Cr-Mo-V-Nb-N	TOS202	TOS203	
Casting	1Cr-Mo-V	TOS301	TOS302	TOS303

Figure 2-4 Estimated Temperature Range and Developed Materials

The estimated temperature range in which the developed materials could be of practical use is shown in Figure 2-4. It is believed that a turbine with a steam temperature of up to 630-deg C could be constructed using these materials.

3. High temperature steam turbine system

3-1 System Design

Between 1981-2000, a Japanese National Research and Development Project showed that a steam turbine system with a main steam temperature of 630-deg C and a reheat steam temperature of 630-deg C could be built using 12% Cr ferritic steel. After that a steam turbine system with a main steam temperature of 600-deg C and a reheat steam temperature of 610 deg C was successfully built at EPDC Tachibanawan #1. We anticipate that a main steam temperature of 630-deg C and a reheat steam temperature of 630-deg C will be realized in the near future, and the progress of the steam turbine system will not stop there.

Figure 3-1 shows the thermal efficiency of steam turbine systems with steam temperatures above 600-deg C. If the main steam temperature is raised to 700-deg C, the thermal efficiency goes up 5% from that of a 600-deg C steam temperature at the same main steam pressure. Some advanced materials are being investigated for use at higher temperatures. Ferritic steels like CrMoV and 12% Cr steel are currently used for steam turbines and are being improved for higher steam temperatures. In addition, austenitic steels and Ni-based super alloys are being considered for use at a 700-deg C steam temperature. It is necessary to employ high temperature materials like Ni-based super alloy to achieve 700-deg C especially for a high-pressure turbine (HPT) where the steam pressure is also high. Because parts like casings and the rotors of turbines are much larger than the parts that are currently being made of Ni-based super alloys today, a lot of research and development work is required to establish and verify the manufacturing technology for the larger parts. Other components of power plants like boilers and pipes have a similar problem.

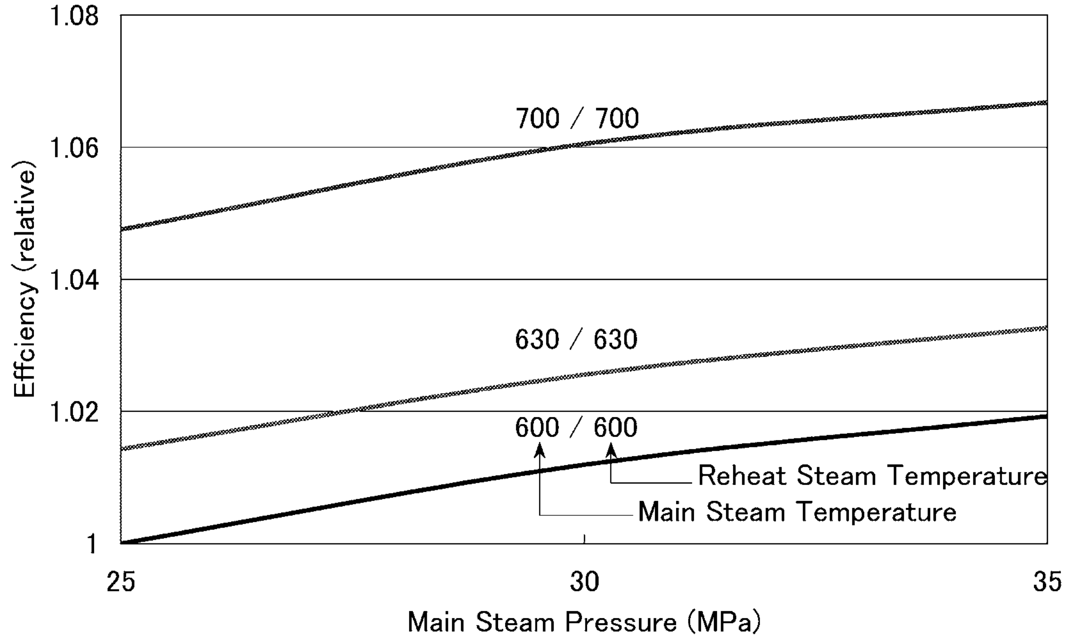


Figure 3-1 Thermal Efficiency of High Temperature Steam turbine

On the other hand, we can look at a 700-deg C intermediate-pressure reheat turbine (IPT) from a different view. The inlet pressure of the IPT is around 5Mpa, which is similar to the pressure of recent gas turbine models that have a turbine inlet temperature of over 1300 deg C. The temperature of the IPT is much lower than the gas turbines. Therefore, we expect that the design of the 700-deg C IPT will be made easier by taking into account the design of the gas turbine and the 700-deg C IPT will be accomplished with much less technological development and verification than the 700-deg C HPT.

Table 3-1 shows the comparison of some options of steam temperatures. The condition in Case 1 is a 600/600-deg C and based on the current technology. Case 2 has a 630/700-deg C steam condition. Case 3 has 700-deg C temperatures for both the main and reheat steams. Figure 3-2 shows the simplified flow diagrams of these cases.

Case 3 has the highest thermal efficiency because of the 700-deg C main and reheat steam temperatures. Ni-based super alloy is employed for the material of the large parts: the super heater of the boiler, the main steam pipe, the main steam valve and the HPT. The technological development of large Ni-based super alloy parts requires much time and financial expenditure.

Table 3-1 Turbine Systems

			Case 1	Case 2	Case 3
Steam Temperature					
	Main	deg C	600	630	700
	Reheat	deg C	600	700	700
Steam Pressure					
	Main	MPa	25	25	25
	Reheat	MPa	5	5.5	5.5
Thermal Efficiency		---	Base	1.03	1.047
Material (Typical)					
	HPT	---	12Cr	12Cr	Ni base
	IPT	---	12Cr	12Cr, 25Cr	12Cr, 25Cr
	Valve	---	12Cr	12Cr, Ni base	Ni base
Development Priod		---	Done	Short	Long
Development Cost		---	Base	Low	High
Operability		---	Base	Same	Low

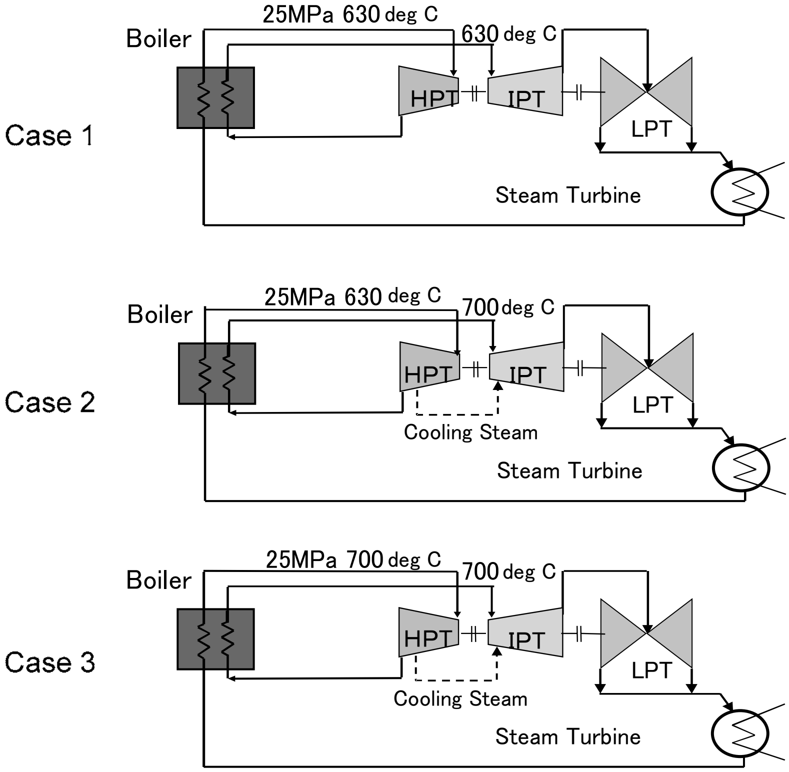


Figure 3-2 Flow Diagrams

Because relatively high thermal expansion and low thermal conductivity of the Ni-based alloy cause higher thermal stress than the ferritic material during plant start up and shut down, the operability of the Case 3 system is lower than the others. The capital cost of Case 3 will be considerably higher than Case 1. The thermal efficiency of Case 2 is lower than that of Case 3, but close to it. Conventional ferritic materials like 12% Cr steel and CrMoV steel can be used for the high pressure parts of Case 2, such as the super heater of the boiler, the main steam pipe, the main steam valve and the HPT because of the 630-deg C main steam temperature. The components that constitute the 700-deg C reheat system require Ni-based super alloys. These are the reheater, the reheat pipe, reheat valve, and the IPT. We can, however, reduce the number of Ni parts using the cooling technology that has been developed in the gas turbine industry. The details of the design will be discussed in the next section. Consequently, the development time and cost will be much lower than in Case 3. The operability and capital cost is almost the same as in Case 1. Considering these points, we found that Case 2 has good potential to be the next generation system although the most efficient Case 3 with the 700-deg C main steam temperature should be a long-term development target for the future.

3-2 Turbine design

We studied Case 2 further to check the technological feasibility for the near future. The 700-deg C reheat system and the components are conceptually designed. Figure 3-3 shows the mass and heat balance for the Case 2 system.

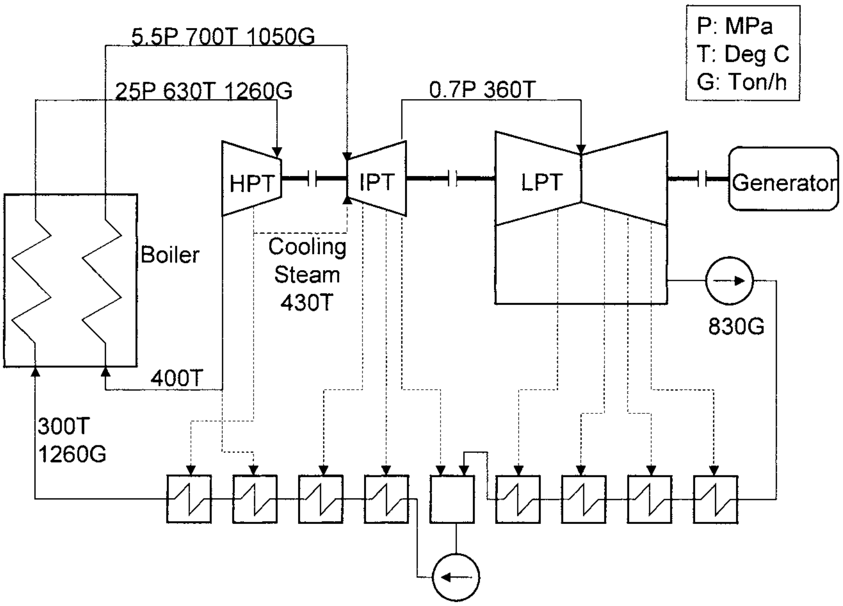


Figure 3-3 Mass and Heat Balance of Case 2

We set the power output 500MW as a typical design condition. The main steam pressure and temperature are 25Mpa and 630-deg C. The reheat steam pressure and temperature are 5.5Mpa and 700-deg C. There is a cooling steam line from the HPT to the IPT. Cold reheat steam was not used for the cooling to avoid the thermal stress caused by the large temperature differences between the hot reheat steam and the cooling steam.

Table 3-2 Gas Turbine and IPT

		Gas Turbine	IPT
Turbine Inlet Temperature	deg C	1000-1300	700
Turbine Inlet Pressure	Mpa	1.5-3.5	5
Rotor Temperature	deg C	400-500	400-600
Casing Temperature	deg C	200-400	400-600
Blade Material Temperature	deg C	600-900	650
Nozzle Material Tempreture	deg C	600-900	700

We introduced some ideas from the gas turbine design to the IPT design as gas turbines have a lot of experience with high temperature technology. The comparison between the gas turbine and the IPT is listed in Table 3-2. The major differences between them are the turbine inlet temperatures and the ways of providing the working medium. The turbine inlet pressure of gas turbines is similar to that of the IPT though the turbine inlet temperature of gas turbines is much higher than that of the IPT. This means that heat transfer coefficients between the working medium and turbine materials, such as the rotor, are at similar levels in both the gas turbines and the IPT, therefore we can use the gas turbine's cooling technology for the IPT design. In gas turbines, the working medium of the turbines, high temperature gas, is provided directly from upstream combustors. In contrast, the working medium of the IPT, steam, is provided through pipes from a boiler. So it is necessary to consider a structure that is peculiar for the steam inlet part of the IPT.

The idea that we borrowed first from gas turbines was the blade shank to isolate the IPT rotor thermally from the high temperature steam. Secondly, we used the inner casing cooling concept to reduce the casing temperature.

The cross section of the IPT is shown in Figure 3-4. 700-deg C steam flows into the IPT through pipes located on the upper side of the IPT. A double piping structure was used for the inlet pipes to accommodate the 700-deg C steam. Inner pipes that are made of austenitic material, contain the 700-deg C steam, and are connected to the first stage nozzle casing that is also made of austenitic material. Thus, the 700-deg C steam is isolated from the other parts before arriving at the inlet of the first stage blades. The blades in stages 1-3 are made of Ni-based super alloy and have lightly cooled shanks to prevent heat flow from the high temperature steam hitting the rotor. This configuration allowed us to select conventional ferritic material, 12% Cr steel, for the rotor. The cooling steam fills the chamber between the inner casing and the nozzle casing. The space between the inlet steam pipe and the casing is filled with the cooling steam, as well. Therefore the inner casing and the outer casing are thoroughly isolated from the high temperature steam to avoid using austenitic or Ni-based materials. We selected conventional 12% Cr steel for the inner casing and CrMoV steel for the outer casing.

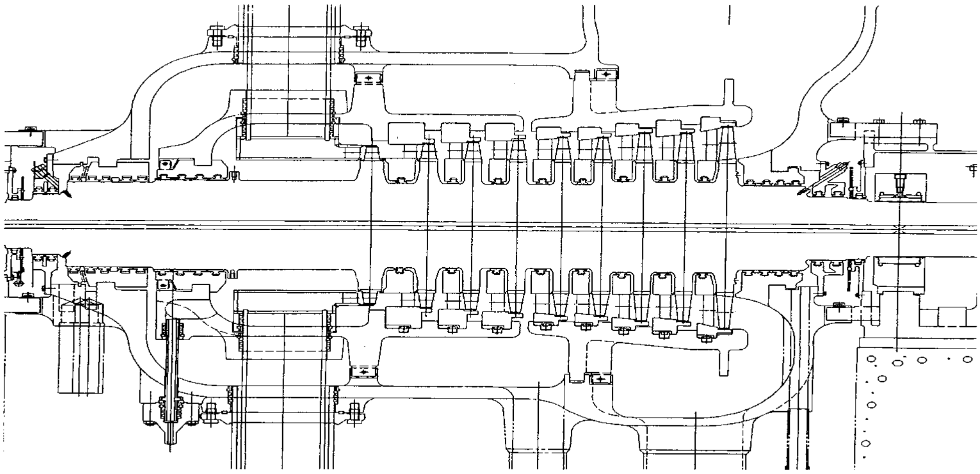
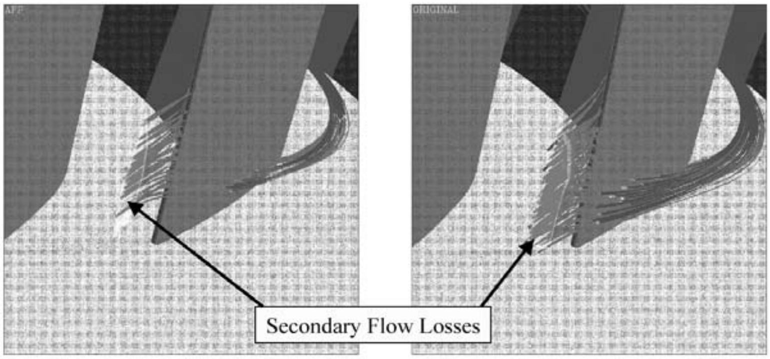


Figure 3-4 IPT Cross Section

We also adopted recently developed aerodynamic technology. Advanced flow pattern nozzles and blades (Figure 3-5) are employed to reduce aerodynamic loss by suppressing the secondary flow on the steam path end-walls. A 3D-flow analysis showed this reduction (Figure 3-6).

Figure 3-5 Advanced Flow Pattern Cascade

Blades are covered with a snubber to reduce the leakage flow through the tip clearance of the blades and to decrease vibration stress. The last stage blade height, the configuration of the low-pressure turbine inlet and the exhaust diffuser were also optimized to reduce aerodynamic loss.



Advanced Flow Pattern **Conventional**

Figure 3-6 3D Flow Analysis

The reheat valve is another important component. We designed the reheat valve using a conventional design scheme, as it seemed difficult to use cooling technology to reduce the valve body temperature. Consequently, we chose Ni-based super alloy for the body material. Figure 3-7 shows an analysis model of the body. The wall thickness of the body is thin enough that thermal stress during plant start up and shut down is kept to an acceptable level.

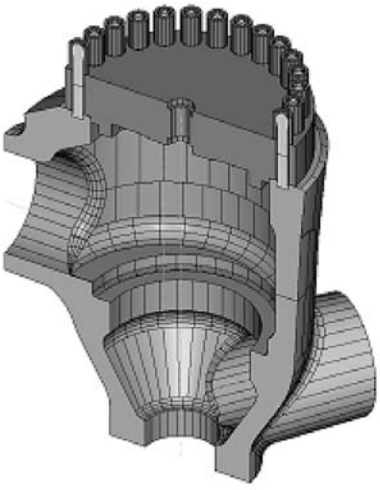


Figure 3-7 Analysis Model of Reheat Valve

Iwasaki[9] studied the feasibility of a boiler with a 700-deg C reheat temperature and had promising results.

The concept of the 700-deg C reheat temperature can be applied to the up-rating of existing plants. It is possible to up-rate old pulverized coal power plants by replacing components related to the reheat system.

There are many plants that have a single casing type HPT and IPT. In such cases, both the main and reheat steam temperatures should be increased. Figure 3-8 shows an example of a single casing type HPT and IPT that are up-rated from a 538/566-deg steam condition to a 630/700-deg C steam condition. These up-rated turbines are fitted into the old foundation. In this case, the amount of remodeling necessary for the boiler is small.[9]

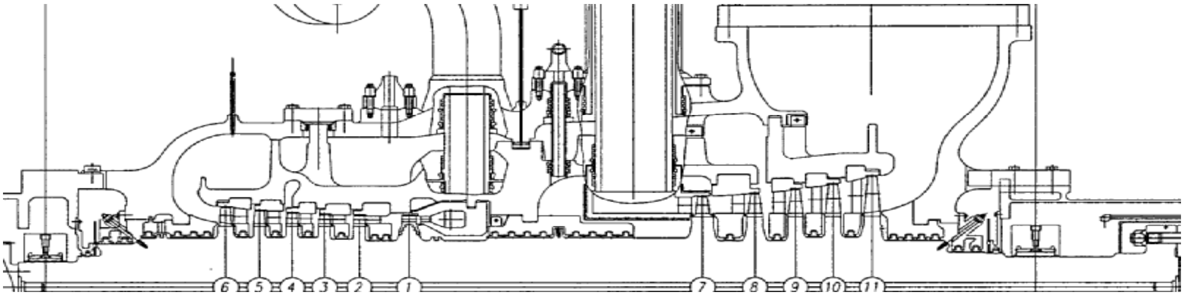


Figure 3-8 Single Casing Type HPT and IPT

As shown above, we studied the 700-deg C reheat turbine system and found high technological and economical potential for the market in the near future.

3-3 Material issues for the high temperature steam turbine system

In order to develop the 700°C reheat turbine system, some technical issues must be resolved. The first major technical issue is the development of material technology for the reheat valve. The large-sized valve body must be manufactured using Ni-based super alloy with the correct material properties. Ni-based super alloy is generally applied to small-sized parts. Large-sized parts manufactured with Ni-based super alloy tend to contain chemical segregation because many active chemical elements are added to the Ni-based super alloy. Also mechanical properties tend to decrease and vary widely in large-sized parts made with Ni-based super alloy. In order to prevent such problems, suitable material selection and the application of appropriate manufacturing methods are necessary.

The second issue is the welding technology using Ni-based super alloy. Steam pipes are joined to the reheat valve body generally by welding and repair welding may be required if the valve body contains material defects. Suitable welding materials and welding methods are required for obtaining a welding joint with good mechanical properties.

The last issue is the bolting material. The temperatures for most parts of the IPT are maintained below 630°C through steam cooling in the 700°C reheat turbine system. Therefore, the proven bolting materials such as Alloy 718 or Refractalloy 26 can be used for the casing bolts. However, there are bolted portions which are directly exposed to the 700°C steam, such as the reheat valve cover and the steam inlet pipe flange. Ni-based super alloy with not only superior resistance to the relaxation but also good machinability will be required for the bolts applied to the high temperature portions.

In order to establish the material technology for the 700°C reheat turbine system, we are planning verification programs such as long term material testing and the trial manufacturing of important parts.

4.Conclusion

Using coal efficiently and cleanly to reduce CO2 and other emissions is a key technological issue to keep sustainable progress of our society. The pulverized coal power generation with super critical steam condition is expected to be the most promising technological option for the issue.

We have been developing high temperature materials, such as 12% Cr steels, to realize more efficient steam turbine systems with the super critical steam condition. We also studied the 700-deg C reheat turbine system and found the high technological and economical potential for the market in the near future.

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