Design And Materials
For Modern Steam Turbines
With Two Cylinder Design Up To 700 MW

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ABSTRACT

Power plant market requirements have changed in recent years. The tendency for highly flexible and efficient power plants with long revision intervals, life times ≥ 200 000h as well as low investment costs have resulted in an increased effort in the improvement of design and materials. One possible way to meet high efficiency requirements is to install sub-critical steam power plants with live steam temperatures of T ≥ 565°C and an optimized steam cycle path. As a result, new challenges have arisen for the design of a two cylinder steam turbine line for a capacity up to 700 MW. In addition, the realization of critical turbine components need improved design and materials, which offer all possibilities for a cost effective and flexible service. At the same time, the combined cycle power plant market demands constantly high performance, reliability and operating flexibility at moderate prices for competitive life cycle costs. For this power range, two cylinder designs are also typically applied for the steam turbine.

This paper outlines the different aspects of a modular design concept. The author's company has been following this concept in recent years with an aim to accurately fulfilling market requirements. It has already been applied to various aspects of the two double-casing configurations for both single and double-flow low pressure turbines. This paper provides examples on how the concept has been realized within various design aspects and features, all with an underlying target to produce steam turbines that meet all named market requirements at competitive prices.

INTRODUCTION

The world's power generation markets have been deregulated to a large extent over the past few years, and this process is still ongoing. In order to remain competitive, power plants need to have features that match with the requirements of the changing market. With the focus on cost efficient production of electricity, the most important requirements of today are low overall life-cycle costs, high reliability, availability and operating flexibility. Additionally, specific customer and local site requirements need to be met by the suppliers of power plants and components. At the same time, the market demands continuously decreasing turbine delivery times and prices. Thus, one of the primary requirements of all steam turbine manufacturers is to standardize their products in order to meet the cost and delivery time targets while – at the same time – providing a high level of flexibility to their customers. This also helps to obtain optimum performance levels and product quality.

For steam turbines, the main design parameters are the power output, the steam conditions, the ambient temperature and the power plant configuration. In combined cycle power plants (CCPP) these are strongly related to the number and type of the installed gas turbines. In single-shaft units a gas turbine and a steam turbine commonly drive a single generator. For start-up and shut-down operations, this configuration requires a switch gear to separate the steam turbine from the shaft train. Multi-shaft configurations use independent gas turbine-generator and steam turbine-generator sets. Commonly, one or two gas turbines power a heat recovery steam generator (HRSG), which drives the steam turbine-generator set.

Within a given CCPP configuration, the steam conditions depend on the power output and temperature level of the applied gas turbine. Hence, as a result of the ongoing gas turbine development, steam temperatures and mass flows are increasing continuously. Typically, the current generation of CCPPs (e.g. [8]) are designed for main steam conditions of 157 bar and 565°C, and reheat temperatures of 565°C. However, due to the numerous gas turbines in the market, steam turbines need to be able to cover a wide power range for CCPP. This range may also be considerably increased if duct-firing is applied.

For sub-critical steam power plants (SPP) the market requires main steam temperatures up to 600°C at main steam pressures of 177 bar. Additionally, steam turbines for SPP need to feature steam extractions as well as an overload injection to support an optimum steam cycle design.

In recent years the steam turbine division of the Siemens Power Generation Group has focused on the development of two-cylinder designs to cover the complete range of applications in CCPP and SPP up to a steam turbine power output of 700MW. The HE series, with a single flow LP, is applied for lower power range and high back pressures, whereas the KN series covers the upper power range and applications with large LP flows. For both product lines, particular effort has been made to fulfill the market requirements with respect to performance, availability, start-up times and delivery times. Due to challenging price levels in the market, this could only be achieved with a modular design concept. The concept allows for high flexibility in the design phase, in order to deliver customer specific designs using standardized modules as a basis.

This paper will provide an overview of the two product lines, and give details on the application of the modular concept within different aspects of steam turbine design.

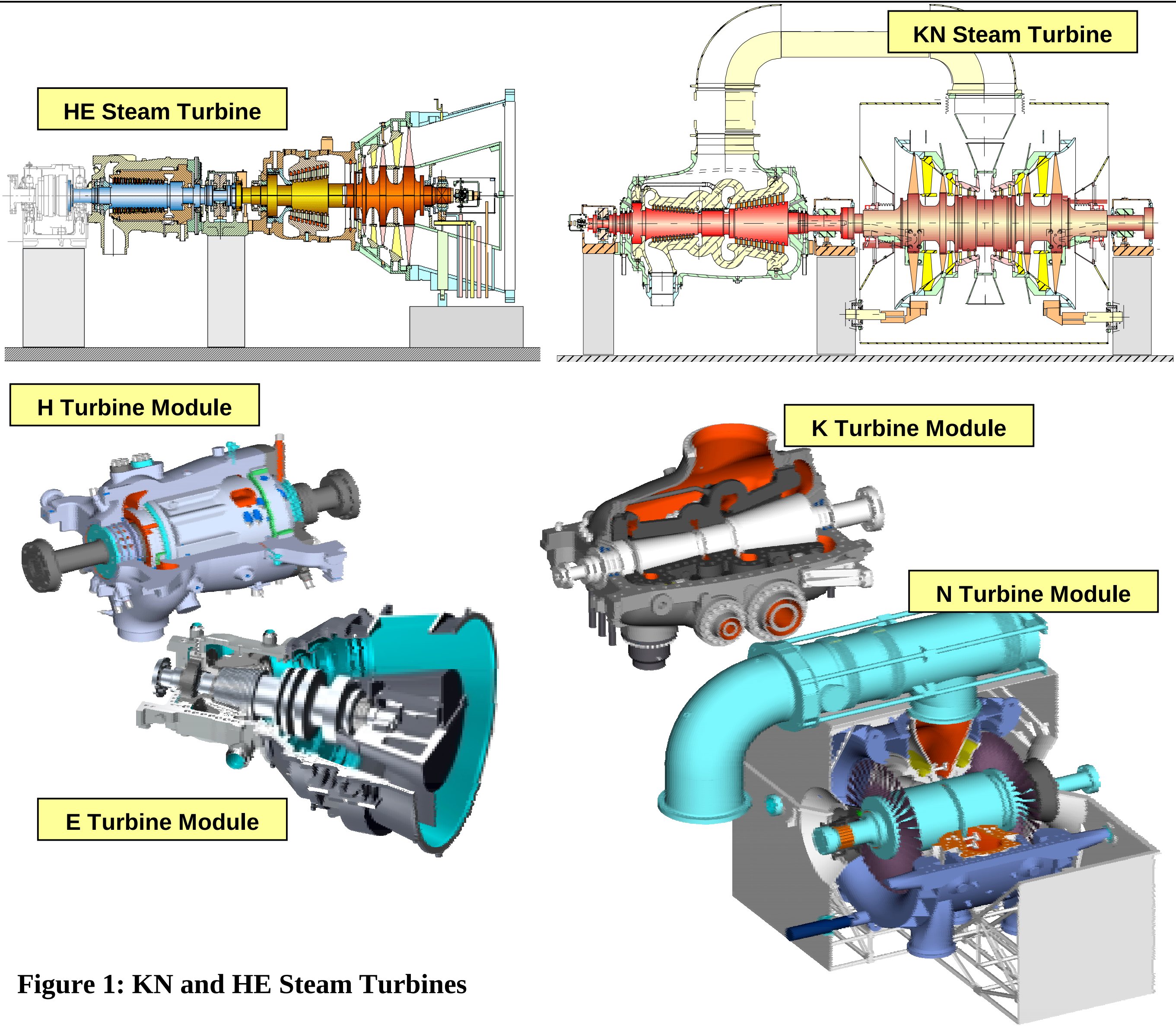

Figure 1: KN and HE Steam Turbines

TWO CYLINDER DESIGNS UP TO 700MW

For the power range from 100MW to 700 MW, Siemens provides two optimized two-cylinder steam turbine designs with single and double flow low pressure sections. (Fig. 1). For applications with lower power output or high back pressures, the HE product line with single flow LP is used. The flat floor mounted HE steam turbine set consists of a high pressure turbine module (H) and a single flow combined intermediate/low pressure module (E) with axial exhaust.

The H-turbine is a single-flow, full-arc admission machine. The steam enters through one combined control and stop valve. The H-turbine casing uses the proven barrel-type design, which does not have horizontal flanges at the outer casing to ensure a homogenous distribution of the forces regarding main steam pressure and thermal load. Additionally, the design improves the symmetrical expansion behavior of the turbine. Thus, small radial clearances between stationary and moving blades are realized.

The new E-turbine design consists of a single flow intermediate pressure (IP) section and a single flow low pressure (LP) section combined in one cylinder. It is designed as a straight flow machine with a double shell casing (inner and outer casing), which can stand temperatures up to 600°C. For SPP applications, steam extractions from both the IP and LP sections can be realized by similar modules.

The KN turbine series consists of a combined HP and IP section (K-turbine) and a double flow LP section (N-turbine). It is typically applied with a power range of 250 MW and 700 MW. Combinations of both modules (K and N) in different sizes are available and may be configured in different arrangements (with down, side and single-side exhaust) to tailor exactly to customer requirements.

The combined HP/IP module, termed K-turbine, is a compact, double shell design with horizontally-split inner and outer casings. The cast inner casing is centered within the cast outer casing via support brackets. This design minimizes the differential expansion between rotor and casing to prevent from any changes in turbine alignment. The main steam is admitted close to the center of the combined HP/IP turbine through a thermal sleeve. After passing the HP blading the steam is routed into the reheater. The steam re-enters the IP-section of the K-turbine again close to the center of the machine and then flows towards the LP turbine. A spring-backed shaft gland seal separates the two single-flow HP and IP expansion sections. Additionally, abradable coatings can be applied to the spring-backed seal segments to improve the sealing efficiency further more.

The double-flow LP turbine section (N-Turbine) consists of a welded inner and outer casing. The horizontally-split inner casing includes the admission section with stationary blade carriers. Again, the design has been optimized to minimize the impact of thermal expansion on the sealing arrangements. The inner casing is provided with the support arms and a thrust rod connection to the outer casing of the K-turbine. These thrust rods cause the LP inner casing to be displaced towards the generator, allowing it to follow thermal expansion of the shaft. The exhaust diffuser of the N-turbine has been carefully optimized by means of extensive fluid analyses in order to improve turbine efficiency.

Both the HE and KN product lines are applicable to combined cycle and steam power plants in 50Hz and 60Hz regimes respectively. Additionally, in CCPPs both steam turbines have been successfully operated in multi-shaft and single-shaft configurations. In the design of the turbine trains, special emphasis has been placed on an optimized transient operation in order to meet market requirements on short start-up times and operational flexibility. At the same time much care has been taken to maintain the high level of reliability by utilizing well proven components from Siemens technology.

Through-out the development of both two-casing steam turbine product lines, much effort has been made in implementing a modular concept as a basis for the design. Taking into account the independent variables affecting the design, a large number of variants are required even for the major components:

- The power output affects the basic size of each component.
- Different main steam conditions require different materials at the concerned areas.
- The ambient temperature and cooling system affects the size of the low pressure end of the steam turbine.

These are well known effects. But the number of variants resulting from the possible combinations of the independent parameters strongly affects the product costs. Therefore special care has been taken to derive a modular concept which drastically reduces the number of variants in major steam turbine components and hence ensures short lead times, moderate prices and proven reliability over the complete range of applications. In the following, details on the concept will be outlined for the three major parameters power output, temperature and condenser pressure.

MODULAR CONCEPT TO COVER A BROAD POWER RANGE

For given main steam conditions and condenser pressure, power output is directly linked to the mass and volume flow passing the steam turbine. In order to achieve optimum velocities – and hence low losses – within different sections of the machine, a series of modules of different sizes are required for each element of the turbine. The modular concept behind the HE and KN steam turbine product lines focuses directly on matching the afore-mentioned customer requirements: short delivery times and moderate prices without compromising the performance, reliability demands.

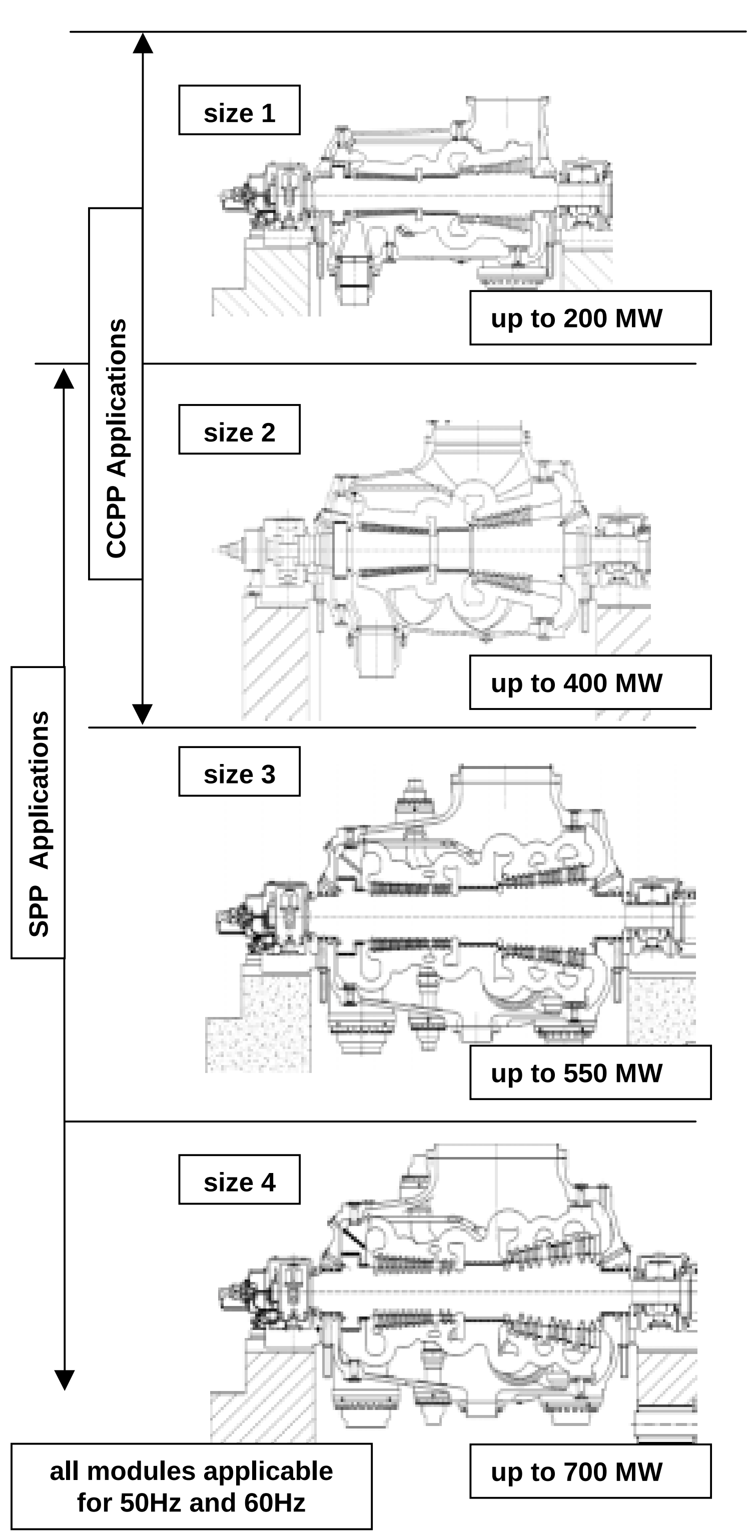

Figure 2: K-Turbine Modules

In the following, examples are given on how this extremely challenging goal is being achieved.

Turbine Modules

For the K-Turbine, the full application range from 100-700 MW (for 60Hz) is covered with four module sizes (Fig. 2). All modules are based on the same design philosophy in order to apply similar proven design features to all turbines. The latest design incorporates the K-turbine experience of the past 30 years from both Siemens and Westinghouse.

The scaling factor between the different turbine modules have been carefully chosen, primarily with regard to turbine efficiency. As a result, the K-turbine family covers the complete application range with a constantly high performance.

Additionally, the modular design yields further cost and delivery-time benefits to the customer. Firstly, developmental efforts for new K-turbine types is considerably reduced and contract specific design work is minimized, while at the same time the high level of reliability is maintained. Secondly, the long lead time items are standardized for 50Hz and 60 Hz applications in order to reduce the delivery times. As an example, identical casing patterns can be used for 50Hz and 60Hz as well as for CCPP and SPP applications. Due to the design of the patterns, required extractions and overload admission can be added by means of separate parts.

Sub-Modules

The turbine modules are furthermore divided into sub-modules of different sizes, which may be combined as required. This approach has been especially favorable for the E-turbine, since size of the IP part is mainly linked to the main steam flow, whereas the size of the LP part also strongly depends on the ambient temperature. Therefore the modular concept consists of a standardized axial separation plane between the IP and LP casings and of a welded rotor module. The five main components of the E turbine are shown in Fig. 3.

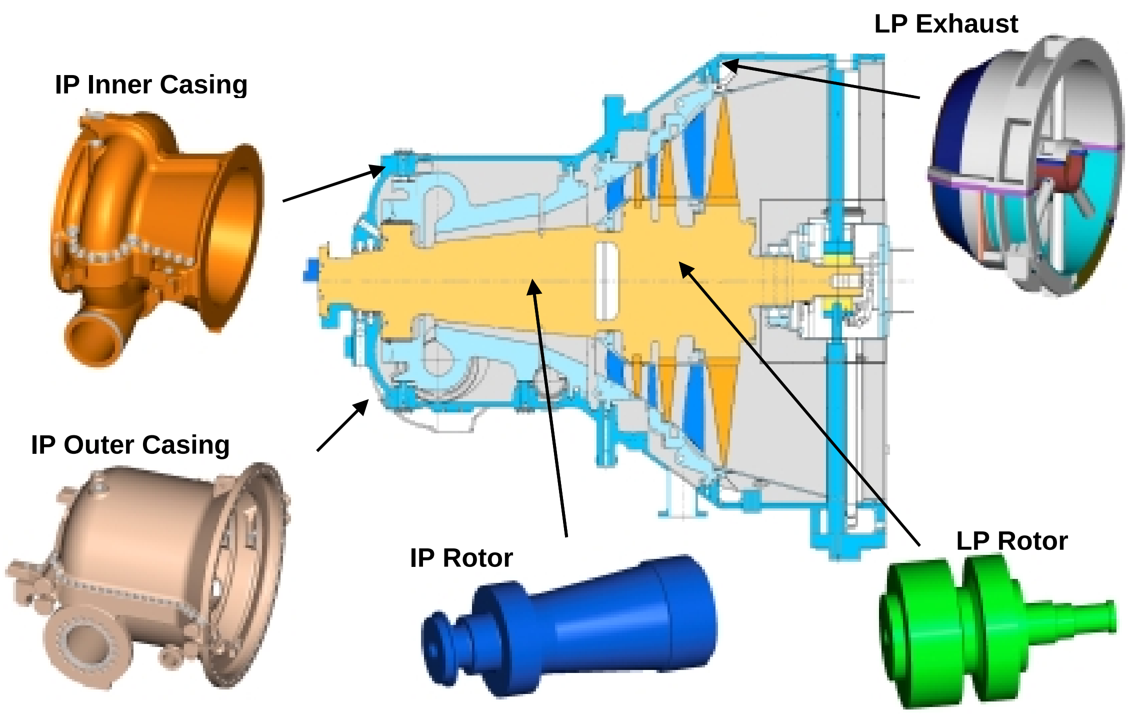

Figure 3: Modular Concept of the new E-Turbine for CCPP Application

The modular concept yields an optimum number of required components to cover a wide range of applications for both CCPP and SPP. For the latter, an additional set of casing components is available with steam extractions. Again, the main benefits from the modular concept are reduced prices and delivery times due to the standardized long lead time items – while at the same time a very high performance level is maintained.

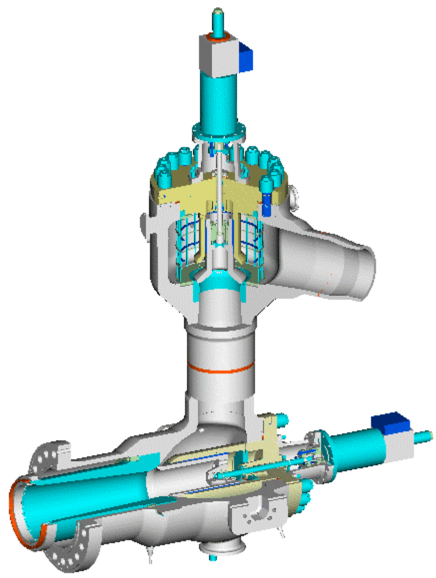

Figure 4: Stop and Control Valve

Valves

The HP, IP and LP admission valves comprise stop and control valves arranged at right angles to each other and combined in a single casing (Fig. 4). For both the E and the K turbines, the valve assembly is provided with a flange connection at the bottom of the outer casing of the turbine.

The modular valve concept consists of a standardized connection to the turbine casings for different sizes. Thus different valve sizes can be assembled to a single turbine size, and a single valve fits to different turbine types. Hence an optimum valve arrangement with respect to flow velocities can always be applied to achieve maximum element efficiency.

Bearings

The HE and the KN steam turbine arrangements both consist of three bearings. All three bearing pedestals are separated from the turbine casings and are supported directly on the foundation. Only one bearing is located between the turbine sections to minimize the effect of foundation deformation on loads to bearings and shaft journals. Axial thermal expansion of the entire rotor train starts at the combined journal and thrust bearing as the fixed point. If required, the bearing pedestal can

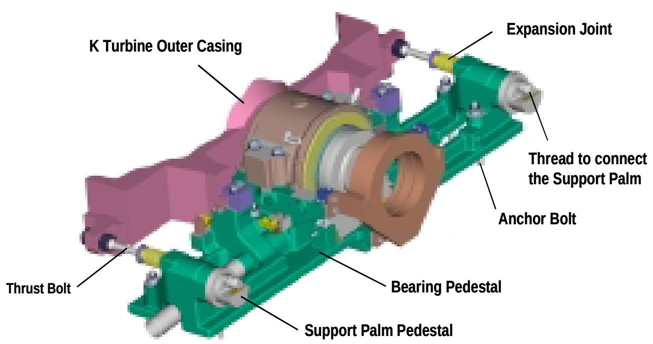

Figure 5: Standard Bearing

support the thrust rod arrangement allowing the LP-inner casing to follow thermal expansion of the shafts (Fig. 5). A shaft turning gear (mainly comprising a hydraulic motor and an overrunning clutch) is used for intermittent rotation of the shafts.

HP/IP Blading

The HP/IP blading as well as the initial stages of the LP section are designed as reaction type stages, but with a variable degree of reaction (3DV™, [3]). The design of these integrally shrouded blades (Fig. 6) results in an elastically pre-stressed blade ring after assembly that is characterized by an excellent damping behavior during operation. This robust and proven blade construction with more than 40 years of experience now incorporates the company's latest highly efficient three-dimensional airfoil designs. Within the blade path section interlocking labyrinth seals are applied.

Since the overall efficiency of steam turbine power plants is very strongly related to the turbine blading performance, it is necessary to design each turbine bladepath individually – but within today's tight design lead times – in order to match the desired efficiency and performance levels in each particular application.

Therefore, considerable effort has been spent during the past decade within the steam turbine blading development group of Siemens Power Generation (PG). As a result, a highly standardised but flexible blading technology has emerged. This is essentially based upon the latest generation of highly efficient fully three-dimensional blading with compound lean (3DS™, [1,2]) and variable stage reaction (3DV™, [3]). However, since not only the technology but also the quality and speed of the design process decide whether the overall performance and lead time requirements are met, the entire bladepath design process has been automated within a very powerful design system [4]. Design automation enables more design cycles in a given time and hence leads to a much more efficient design process reaching a better optimum in a shorter period of time [5]. Thus, from this automation significant cost and time savings due to accelerated and robust processes can be achieved, while at the same time a contract specific bladepath

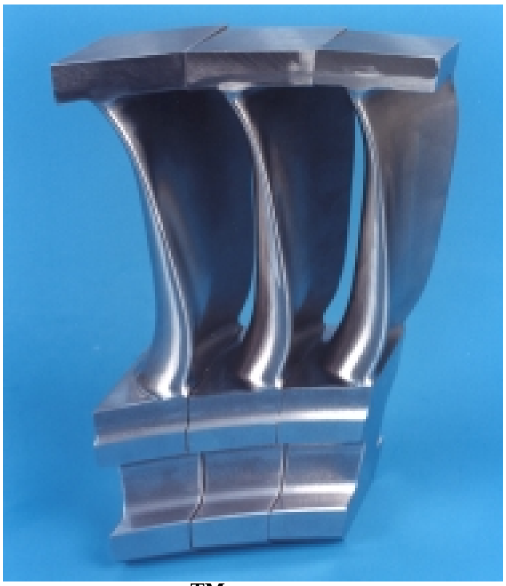

Figure 6 3DV™ Blading

design with optimum efficiencies is delivered to the customer.

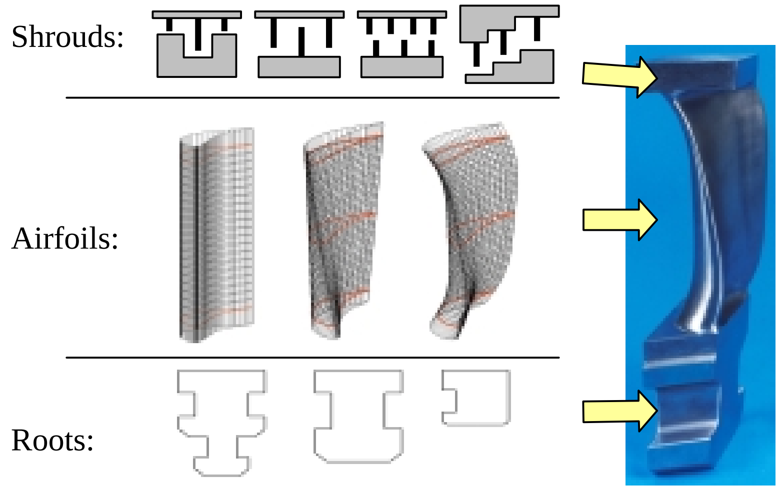

Figure 7: Modular Concept of Blade Construction

Different to the other elements of the steam turbine, the primary goal of standardization with regard to HP/IP blading has been to standardize the "way to the product" instead of the product itself. The basis is a strictly modular concept of bladepath construction from standard and proven elements (e.g. airfoils, roots, grooves, shrouds, extractions, locking devices). As an example (Fig. 7), the composition of a single blade from root, shroud and airfoil is demonstrated. For each element, different types exist for the various applications, each type having its own advantages and disadvantages with respect to performance, mechanics and costs. Within the modular concept all these different types may be combined freely to give an optimum blade for the specific design boundary conditions such as aerodynamics, forces, materials and temperatures. Hence, cylindrical, twisted or bowed airfoils can be assembled with any of the roots or shrouds. Details on the concept applied for HP/IP blading are given in [6].

MODULAR CONCEPT TO FULFILL TEMPERATURE AND PRESSURE REQUIREMENTS

Besides the main steam flow, the second major design parameters are the main steam conditions. Main steam temperatures are continuously increasing to optimize the overall performance of SPPs, and as in gas turbine development, also for CCPPs. At the same time high temperatures require expensive material to withstand the associated optimum pressure levels. In order to keep price increase moderate for such advanced steam cycles, one focus of the modular concept is to reduce the amount of required high-temperature material to a minimum. The basic design elements of the concept are:

- to apply identical designs for the main components at different temperature levels (e.g. 565°C and 600°C) and thereby only to change material.
- to weld main components in order to minimize the amount of high-temperature material.
- to shield components against the hot steam.

- to cool affected areas.

The application of the concept to HE and KN product lines will be outlined below.

K-Turbine Material Concept for Temperatures up to 600°C

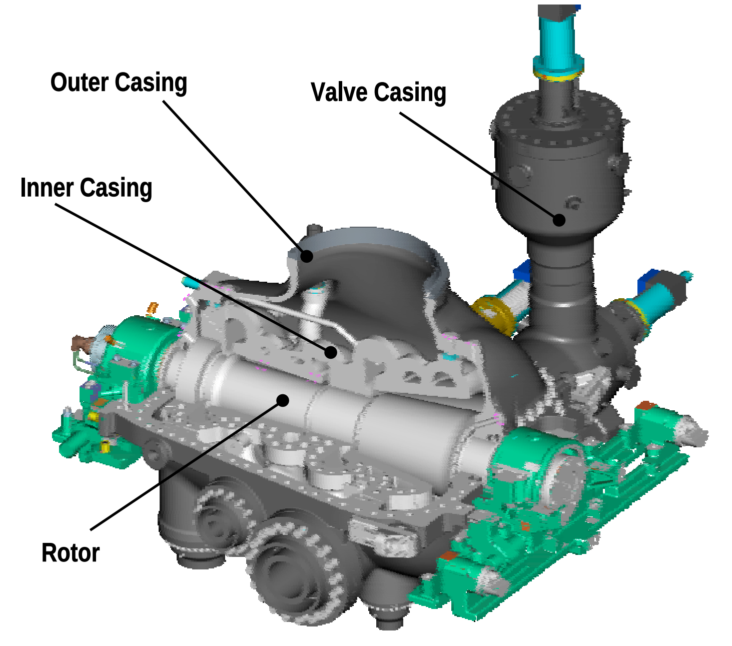

Figure 8: Modular Design of the K-Turbine

The combined HP/IP turbine (K-Turbine, Fig. 8) consists of a top and a bottom half of inner and outer casings with horizontal flanges. The thermal load due to the high main steam and reheat steam temperatures and pressures is completely carried by the inner casing. For this reason, the material of the inner casing is selected according to the specific application temperatures. Similarly, the rotor material is chosen depending on the size of the K-turbine, the application temperature and the rotational speed (50 or 60 Hz).

Steam Temperature Main / Reheat Steam	Variant 1 540°C / 540°C	Variant 2 566°C / 566°C	Variant 3 600°C / 600°C	Future 600°C / 620°C
Rotor (50Hz or 60Hz)	low alloyed	low alloyed or high alloyed	high alloyed	high alloyed
Inner Casing	low alloyed	low alloyed	high alloyed	high alloyed
Outer Casing	globular cast iron	globular cast iron	globular cast iron	globular cast iron
Valve Casings	low alloyed or high alloyed	low alloyed or high alloyed	high alloyed	high alloyed

Table 2: K-Turbine and Valve Materials

The design consists of special features which shield the outer casing from the hot main steam and reheat steam temperatures. The valve is connected to the inner casing via a flexible L-ring and a thermo sleeve that guides the hot steam directly into the inner casing and the HP or IP blading respectively. As a result, the outer casing only needs to withstand the IP-exhaust pressure and temperature. Therefore the outer casing material for all applications is globular cast iron, which yields considerable cost reductions.

Similarly, the valve casing materials are cost optimized for different design pressure and temperature regimes.

As an example of the modular material concept, an overview of the K-turbine material combinations applied for different main steam and reheat steam temperatures is given in table 2.

Welded Rotor Design

A welded design has been applied to the rotor of the new E-turbine (Fig. 9). The required material properties for the hot IP section with smaller blades and the cold LP section with large centrifugal forces are completely different. Therefore, only a welded rotor design enables the use of optimal materials for both the hot IP section and the cold LP section. The combination of two materials for the rotor yields an optimum of mechanical properties over a wide reheat temperature range: up to 565°C 2%-Cr-steel is utilized for the IP rotor block and the inner casing. Up to 600°C, the rotor and inner casing material is substituted by a 10%-Cr-steel. The LP rotor block consists of a 3.5%-Ni-steel. The rotor welding seam is positioned behind the LP front stages. This offers the advantage to implement a cost effective welding seam at the low diameter of the IP drum.

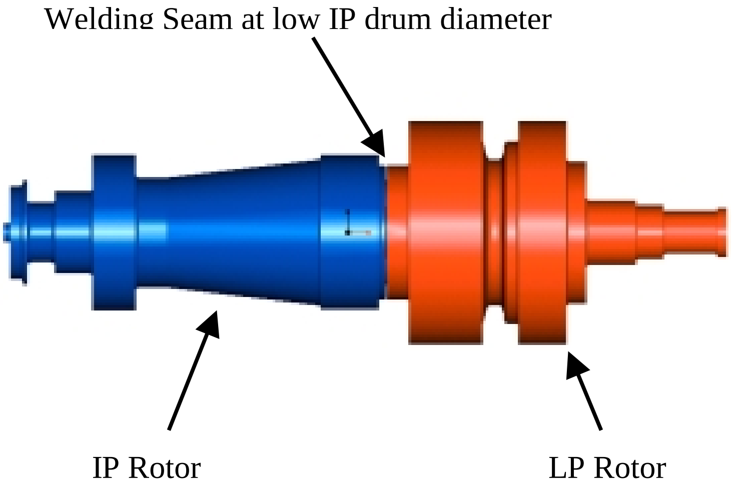

Figure 9: Welded Rotor Design from New E-Turbine

Cooling of Dummy Piston

To achieve maximum thermodynamic efficiencies, a straight-flow design was chosen for the new E-turbine. In contrast to a reverse-flow concept, the chosen straight-flow design requires a large IP piston diameter for sufficient axial thrust compensation. Due to the mechanical impact of this large piston diameter at reheat temperatures, a forced rotor cooling has been developed for the IP piston to ensure high life cycles.

Cooling steam (350°C) from the cold reheat is blown into a special mixing space in front of the IP piston and mixed with hot reheat steam (between 565°C and 600°C) from the IP inlet to achieve an optimum temperature of 450°C. At this temperature, two advantages for both the IP rotor and the IP piston are combined: optimum rotor life cycles and minimum clearances at the IP piston seal. Thereby 2%-Cr-steel can be used for the IP rotor up to temperatures of 565°. Thus, performance and reliability remain at a high level without increasing material costs. The cooling system has successfully been tested in E-turbines with high temperature capability in the US-market.

Modular Concept For Optimum LP Ends for a Wide Range of Condenser Pressures

The third major design parameter with respect to modularity is the volume flow through the LP end stages, which is directly connected to the mass flow and the condenser pressure. The performance of the last stages and the exhaust diffuser is strongly related to the mean axial velocity in this area. A number of different LP sizes are therefore required to cover the range of condenser pressures without compromising the performance of the LP section. In this case, the focus of the modular concept is to achieve an optimum balance between maximum LP performance and moderate costs. Therefore, the main targets where set

- to define an optimum set of LP standard stages to cover the required range of volume flows.
- to enable cost effective connections of all required combinations of LP and IP components
- and thereby to maintain optimum performance.

Thereby, a large condenser pressure range of 20 to 200mbar is being considered.

Figure 10: Free Standing LP End Blades

LP Blading

Since the axial velocity after the last blade is primarily related to the exit area (and not to length of the last blade), a homogenous distribution of exit areas has been chosen for the Siemens family of LP standard stages (see table XX). For each of the given exit areas, a set of three standard stages has been designed, which is not being modified during contract design work.

50Hz		60Hz	
Notation [m²]	Length [inch]	Notation [m²]	Length [inch]
5.0	27.5	3.5	22.9
6.3	31.4	4.4	26.2
8.0	36.3	5.6	30.2
10.0	38.5	6.9	32
12.5	45.1	8.7	37.6
		10.3	42
16.0[1)]	56	11.1[1)]	47

[1)] under development

Table 2: Overview of LP Exit Areas and End Blades

In general, the last two rows of LP moving blades are designed as free-standing blades with curved fir-tree roots for a homogenous stress distribution. The highly-efficient three-dimensional airfoil design consists of super-sonic tip section for the large end blades (Fig. 10). The inlet edge is flame or laser hardened, respectively, to prevent from droplet erosion.

Additional erosion protection measures are applicable to the last stationary blades. They are designed as hollow blades that either consist of drainage slots (Fig. 11) to remove moisture from the blade surface or can be heated with steam. An advanced three-dimensional airfoil design is applied in order to increase stage reaction at the blade hub and hence improve performance at low load (Fig. 11).

In order to allow for larger axial movement due to thermal expansion, non-interlocking labyrinth seals are applied within the LP section of the turbine. The seal design provides an optimum sealing efficiency within a relatively short seal length.

LP Exhaust Casing for Single Flow E-Turbine

The modular concept of the E-turbine provides only three different LP exhaust casings to cover the complete exit area range specified in table 1. The six related sets of standard LP stages are installed by means of standardized interfaces. Also, the axial joint between the LP exhaust casing and the IP outer casing is a standard interface that allows any combination

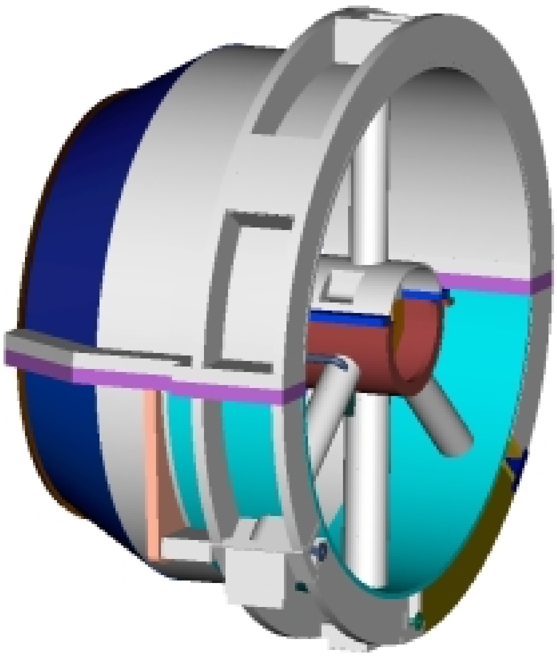

Figure 12: E-Turbine LP Exhaust Casing Module

Figure 11: Advanced 3-Dimensional Design for Hollow LP Stationary Blades

of sizes of the two casings. Fig. 12 shows the LP exhaust casing module for the 12.5m^2 exhaust section.

Exhaust Geometry Optimization

Detailed computational fluid analyses are performed in the design phase, in order to optimize the geometry of the LP turbine exhaust as well as the transition region to the condenser. In conjunction with measurements on models and on turbines in the field, effort is focused on increasing exhaust pressure recovery and hence improving the overall steam turbine performance.

As an example, Fig. 13 shows the results of an exhaust analysis with flow lines for a classic turbine deck arrangement with the condensers mounted below the turbine. The steam flow downstream of the last turbine stage passing into the exhaust hood shows considerable vortices, which were also observed in the flow in the exhaust casing itself. As vortices cause energy loss in the flow, guide vanes have been installed to improve flow and thereby reduce pressure losses.

SUMMARY

For a power range from 100MW up to 700MW Siemens provides the HE and KN steam turbine product lines for both CCPP and SPP. Both turbo sets consist of a two casing design. The HE is applied where a single flow LP section is sufficient to take the steam flow at optimum velocities. For large power output and low condenser pressures the KN product line with a double flow LP turbine is applied.

Both designs are based on a modular design concept. Details have been given in the paper on how the concept is applied to compensate for the effects of the major design parameters power output, temperature and condenser pressure. Thereby, the main targets are to reduce the number of variants of major components and to minimize the material cost impact of high temperatures.

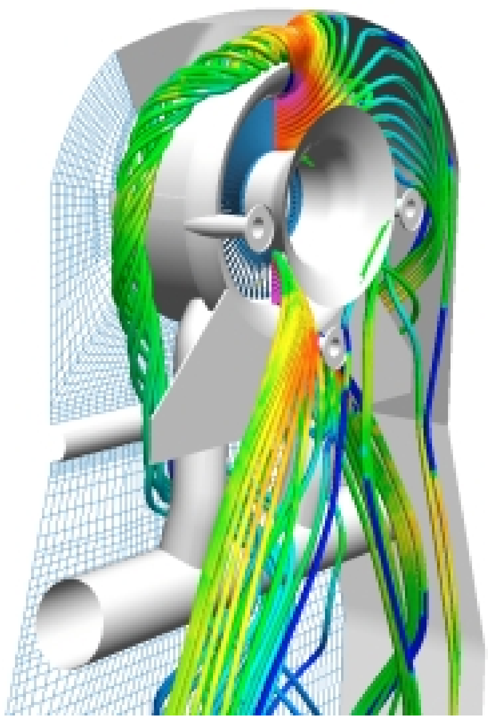

Figure 13: LP Exhaust Flow Visualization

The concept has successfully been applied within the HE and KN product lines and is seen a fundamental basis to fulfill the challenging requirements in today's steam turbine market. The reduced number of major components ensures short delivery times and low costs. At the same time the concept stands for reliability due to the application of proven Siemens technology and similar designs through-out each set of module sizes. Special design features such as the welded E-turbine rotor contribute to short start-up times and operational flexibility. All configurations consist of Siemens latest LP standard stage designs. In the HP and IP sections a high-performance fully three-dimensional reaction blading is applied, which is designed on a contract specific basis to provide maximum blade path efficiency.

Hence, Siemens' two casing designs have been optimized to fulfill the market's most important requirements of low overall life cycle costs, high reliability, availability and operating flexibility in order to support the customer focus on cost efficient production of electricity.

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