Thermal simulation optimizes design of boiler feed pumps
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Pumps Equipment
The Pumps Equipment division specializes in pumping solutions. Intensive research and development in fluid dynamics, process-oriented products, and special materials as well as reliable service solutions help the company maintain its leading position in its focus market segments.

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The Rotating Equipment Services division provides cutting-edge maintenance and service solutions for rotating equipment dedicated to improving customers’ processes and business performance. When pumps, turbines, compressors, generators, and motors are essential to operations, Sulzer offers technically advanced and innovative solutions.

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The Chemtech division is represented in all important industrial countries and sets standards in the field of mass transfer and static mixing with its leading solutions. The product offering ranges from process components to complete separation process plants. The customer support covers engineering services for separation and reaction technology and tower field services to perform tray and packing installation, tower maintenance, welding, and plant turnaround projects.

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Thermal simulation optimizes design of boiler feed pumps

"Digital solutions support numerous stages of product development. Finite element analysis (FEA) is a computerized method to predict how our products will react to real forces in practice. Sulzer engineers use FEA for all their product development processes. FEA shows whether a product will break, wear out, or work the way it was designed. Our engineers use the results to optimize product design during the development process, thus reducing testing time and increasing reliability significantly. The FEA method works by breaking down a real object into a vast number of finite elements. Mathematical equations help predict the actions of each small element. A computer then adds up all the individual actions of the small elements to predict the behavior of the full object. Sulzer uses FEA to predict the behavior of products affected by many physical effects, such as mechanical stress, vibration, fatigue, motion, heat transfer and fluid flow.

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Abstract
The thermal and mechanical demands on turbomachinery are becoming more challenging from year to year. Flexibility, optimal designs and tight deadlines are typical challenges that confront engineering departments in the order related project business on a daily basis. An obvious approach to meet these challenges and do justice to the required technical innovations is to run computer-aided mechanical-thermal simulations based on the finite element analysis (FEA). The example of a boiler feed pump for a thermal power plant shows how modern and accessible methods of numerical structure simulation (FEA) are being applied to classic designs and design processes and for visualizing problems, even in projects with tight deadlines.

Introduction
The demands on high-performance boiler feed pumps are growing. In the past, the main requirement for typical boiler feed pump applications was reliability during continuous operation. Because of circumstances brought about by new energy policies in several countries that call for an increasing share of power to be generated from renewable sources such as wind and solar energy, pumps in today’s power stations need to operate much more variably. Load fluctuations must be offset with as little dead time as possible. This requires sophisticated configurations of the turbomachinery and of the overall design of power stations and an ability to switch the pumps on and off quickly and in a controlled manner. Cold-start requirements specified by operators have led to new design requirements for the relevant assemblies as well as the integration of sophisticated early warning systems.

Key challenge
Typical main boiler feed-water pumps are multistage centrifugal pumps designed for power ratings of several megawatts in which very high energy densities occur in the components. The temperature range of the superheated feed water is between 160°C and 200°C and is liquid at the prevailing pressures. As in all turbomachines, sufficient clearances are required in centrifugal pumps between the rotor and stator. These running clearances must be as small as possible to optimize efficiency by minimizing volumetric losses due to recirculation of the system fluid, in this case superheated feed water. Fig. 1 shows a typical configuration of a rotating impeller and stationary diffuser or stage casing. The gaps between the impellers and wear rings require the tightest clearances in this field of application.

Fig. 1 Cross-sectional diagram of the rotor of a boiler feed pump with rotating wear rings and shaft (red) and stationary casing with split rings and diffusers (green).
When a centrifugal pump is required to start up from a cold state, this can in extreme cases mean that boiler feed water at a temperature of up to 200°C will flow through the cold pump, the structure of which is still at a typical ambient temperature of around 20°C. The limits of a simple centrifugal pump design can quickly be exceeded, as the thin-walled components will expand more rapidly than the thicker-walled components. In unfavorable cases, this can result in complete closure of the running clearances and cause either blockage of the impeller or increased friction and damage to individual components. Distortions of the impeller pose an additional operational hazard. Depending on the design of the power plant with two to four boiler feed pumps per block, the failure of one centrifugal pump can have a significant impact on the plant’s power output and require further decisive measures to be taken by the operator.

**Simple design methods and conventional technical solution**

Established physical formulas, such as the thermal expansion of bodies, characterize the relative, linear change in length per degree of temperature change and express the relationship of the values as follows:

### Formula for thermal linear expansion

\[
\Delta l = l_0 \cdot \alpha \cdot \Delta T
\]

- \(\Delta l\) = relative change in length
- \(l_0\) = initial length
- \(\alpha\) = coefficient of linear expansion
- \(\Delta T\) = temperature increase

Applying this formula to an impeller clearance and given a wear ring clearance diameter of 240 mm (initial length) and a sudden temperature difference between the rotating and stationary components of 160°C and a coefficient of thermal expansion of \(\alpha = 10.5 \cdot 10^{-6}/°C\) for 13%-chromium-steel, the estimated relative expansion of the rotating part is 0.4 mm. Taking into account the usual clearances of around 0.5 mm, depending on the design, and suitable safety margins, this example already shows an increased risk of the components scraping against each other.

The aforementioned example is based on a simplified model approach in which it is assumed that the rotating component reaches the temperature of the system fluid relatively quickly owing to its thin wall, while the stationary component is still at the initial temperature. This conservative approach permits very straightforward and fast analysis. It is based on steady-state thermal behavior. However, in reality the process takes place in a state that is far from thermally steady. The thick-walled components also heat up over a reasonably short time, just more slowly. Hence, these components also undergo expansion. This model assumption can therefore quickly lead to costly design measures. Obvious conventional solutions that can potentially reduce the risk of clearances becoming too narrow include:

- allowance of greater clearances (a)
- use of a pump pre-warming system (b)
- choice of materials with suitable coefficients of thermal expansion (c)
- design changes to modify the wall thicknesses (d)
- improvements in the analytical model (e).

Because boiler feed pumps are an essential element of the overall thermal cycle, their efficiency plays a key role. Solution a) inevitably leads to a loss of efficiency resulting from increased internal leakage and volumetric losses. Whereas this approach can certainly be applied in other centrifugal pump applications, it is not a viable option in the field of secondary energy production. One of the governing requirements of a boiler feed pump, as an element in the thermodynamic process of a thermal power plant is to achieve maximum efficiency with minimum internal losses.
Option b), i.e. preheating a boiler feed pump, is common practice and can be compared to a standby system. In this approach, water is actively circulated through the slowly rotating pump. This process keeps the pump at a defined temperature approaching the final operating temperature and permits rapid activation without the risk of component distortions or clearances that result in components scraping against each other. However, such a system requires an additional pre-warming loop system with suitable temperature controls. This must be considered into the boiler feed system from the beginning but increases the investment costs for the power plant designer, operator or both. Moreover, a cold-start function of the main boiler feed pump may still be required as an additional operational safety feature, even if a pre-warming system has been installed.

Option c) is mentioned only for the sake of completeness and is based on the notion of reducing the thermal expansion of the thin-walled rotating components by using a material with as low a coefficient of thermal expansion as possible. Because material requirements are wide-ranging, and structural mechanical strength and compatibility with the system fluid, for example, have the same or even higher priority, such approaches are not applied to boiler feed pumps.

Without detailed analytical models according to e) or after applying the methods described in the following section, option d) is very limited in application or requires elaborate investigations and tests with simplified prototypes to achieve technical qualification. Furthermore, there are limitations to simply increasing the wall thickness of rotating components such as impellers, because multistage boiler feed pumps are generally quite sensitive in terms of their rotordynamic behavior. A change in wall thickness also implies a change in mass. Like all turbomachines, high-speed centrifugal pumps are spring-mass-damper systems that respond sensitively to parameter changes, in this case mass. Moreover, design changes to an impeller always have a direct influence on the installation dimensions of the system as a whole and potentially also on the hydraulic behavior of the pump itself.

Option e) serves as an introduction to the following section, as a detailed analytical model of the reduction in impeller clearances due to a cold start must take into account non-steady-state heat transfer and heat conduction. Today, the finite element analysis method (FEA) provides fast access to useful and practical models that are able to deliver optimal solutions quickly and inexpensively.

**Non-steady-state thermal transient FEA simulation as a design tool**

FEA is an established method for the numerical simulation of multiphysical phenomena to solve a differential equations system, as for example deformation and stress fields of the structural mechanics. In this method – depending on the characteristics and requirements of the structure being analyzed – a 2D or 3D geometry produced by CAD (computer-aided design) is subdivided into a finite number of small elements (see Fig. 2), each of which is assigned appropriate mechanical properties in the FEA program. Each of the small cubes visible in Fig. 3 is a FEA calculation element.
Whereas mechanical FEA models are based on the relationship between stress, strain and the elastic modulus (elasticity theory), thermal models use physical effects and relationships arising from thermal conductivity, for example, mass, specific heat capacity and heat conduction. To investigate the application field of boiler feed pumps more closely, it is first necessary to define the task at hand. Besides visualizing temperature changes over time in the relevant components, which the hot system fluid heats up abruptly from a cold initial temperature, the deformation behavior is also of considerable interest. Because the time factor must be considered in addition to the geometric characteristics and, indeed, is a crucial factor, this process is known as a non-steady-state or also a transient process. The aim is to investigate which areas of the pump reach what temperatures at given times and to determine when a homogeneous equilibrium state is reached. This would make it possible to visualize the thermal expansion of all the relevant components – both rotating and stationary – as a function of time. In this way it is possible to show the desired clearance changes over time. If specified design parameters and safety factors are exceeded, design changes can be virtually simulated in an iterative process in order to achieve an optimal design that ensures the desired cold-start function with adequate operational safety.

"The finite element analysis (FEA) method delivers practical solutions to help us design improved processes faster and at less expense than real tests would. It is an integral part of the development process at trend-setting companies."

Torsten Johne, Head Mechanical Integrity Pumps Equipment Winterthur, Switzerland

Because a multistage boiler feed pump is a nearly rotationally symmetric design, a 2D axisymmetric FEA model of the initial design was set up. In the FEA model, the physical properties of the structure as well as peripheral conditions such as the initial temperature and heat-flow conditions (heat-transfer behavior) were defined. Areas of the fluid that have a significant impact on the thermal behavior of the system must also be assigned relevant properties. Important physical properties in this context are the thermal conductivity and the specific heat capacity.

**Results**

In the following example, the customer specified a cold-start (or thermal shock) function. Fig. 4 shows the immediate temperature rise of the system fluid together with the corresponding rotational speeds and flow rates over time. The specification was that when in the “cold” (ambient temperature) state, the pump must be able to pump hot boiler feed water at a temperature of around 190°C immediately and ramp up to operational speed within a few seconds.

**Fig. 4** Time-dependent cold-start condition (thermal shock).
The pump has a nominal power rating of 13.4 MW at the operating point. It features a six-stage design for operation in a thermal power plant and is driven by a steam turbine. At the nominal operating point, it pumps over 380 liters per second and generates a pressure of approximately 300 bars.

The hot pumped feed water is the source of the heat flow and produces a heat gradient in the pump. Inside the pump, the wet surfaces take on the temperature of the feed water through heat transfer and increasingly heat up. The thin-walled components (mainly the impeller parts) heat up after a few seconds, whereas the casing, for example, does not reach operating temperature for around two minutes. The time-lapse video shows the calculated temperature distribution inside the pump from 0 to 3500 seconds.

This interval represents the critical phase in terms of impeller clearances. As another important design characteristic, it was determined that the shaft is not heated through until several minutes after the impellers (see difference between Figs. 5 and 6). This is another important analytic design characteristic, where the required shrink fit between the shaft and impellers and between the shaft and balance drum must be ensured at all times.
It has been found that the impeller clearances reach a steady state after about two and a half minutes and that, once design adaptations have been applied, they meet the cold-start requirements with the required margin of safety. Fig. 7 shows an example of the analysis of the running clearance between the stationary split rings of each pump stage and the rotating impeller. The running clearance reaches its minimum after around 5–10 seconds, shortly after which it increases again.

The stationary rings first expand due to their thinner wall structure compared to the casing, exerting radial forces that are only later relieved by the expanding casing. In addition to analyzing all non-steady-state elastic deformations, it was also possible to determine and assess secondary thermal stresses in the components. Based on the stresses determined in this way, we were able to demonstrate the mechanical integrity and fatigue strength of the components.

Optimization possibilities

The analyses led to design changes to the wear rings and casings that made it possible to design the pump line so as to meet cold-start (thermal-shock) requirements.

Design improvement processes are characterized by iterative steps, whereby FEA provides practical solutions relatively quickly and inexpensively compared to real tests. However, this requires close cooperation between various engineering disciplines, including hydraulic, dynamic, design and mechanical thermal fields.

The optimized, already patented design is successfully implemented in a main boiler feed pump for a thermal power plant in Germany. Thus, if specified by the end user, it is possible to achieve a high level of operation flexibility required in the power industry.

"Thanks to FEA, we have been able to develop a robust design. It is also able to handle critical transient conditions like cold startups without opening running clearances or the requiring prewarming. This ability simplifies the control and operation of the pump and keeps the efficiency high.

Thomas Welschinger, Head Product Development Winterthur, Switzerland"