Development of large steam condensers with optimized cost/performance ratio

ABB Power Generation has totally renewed and extended its range of large steam condensers. The primary aim of the development programme was to ensure that customers receive the condenser that meets their requirements most accurately. Besides guaranteeing maximum performance, vendors must nowadays offer very short delivery times, the option of local fabrication and lowest possible costs. This calls for a degree of flexibility in both the technical and commercial areas that can only be achieved with advanced computing tools. In the technical area, two-dimensional design software based on the laws of physics can be relied upon to accurately represent the know-how gained from, eg, 3-D computer simulations. The commercial aspects are optimized, for example, by systematic application of ABB's extensive know-how in the manufacturing and operating areas. A special 'tendering/engineering tool' that includes routines for the calculation of thermal values as well as costs, uses iterative means to find the optimum cost/performance ratio for every condenser.

Suppliers of equipment to power utilities and commercial industrial plants are expected to not only have the requisite technical and professional expertise but also to submit offers that demonstrate an optimum cost/performance ratio. For vendors to meet this requirement, complete transparency in the technical as well as the commercial area is essential. Besides the usual technical constraints that determine the design of equipment or an installation, there are several dominant cost parameters which also have to be taken into account at the tendering stage.

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All the technical and commercial characteristics of a product are defined during its development. The way in which these characteristics pass from the development stage to the sales, tendering and engineering departments is a decisive factor in the success of a product in the marketplace.

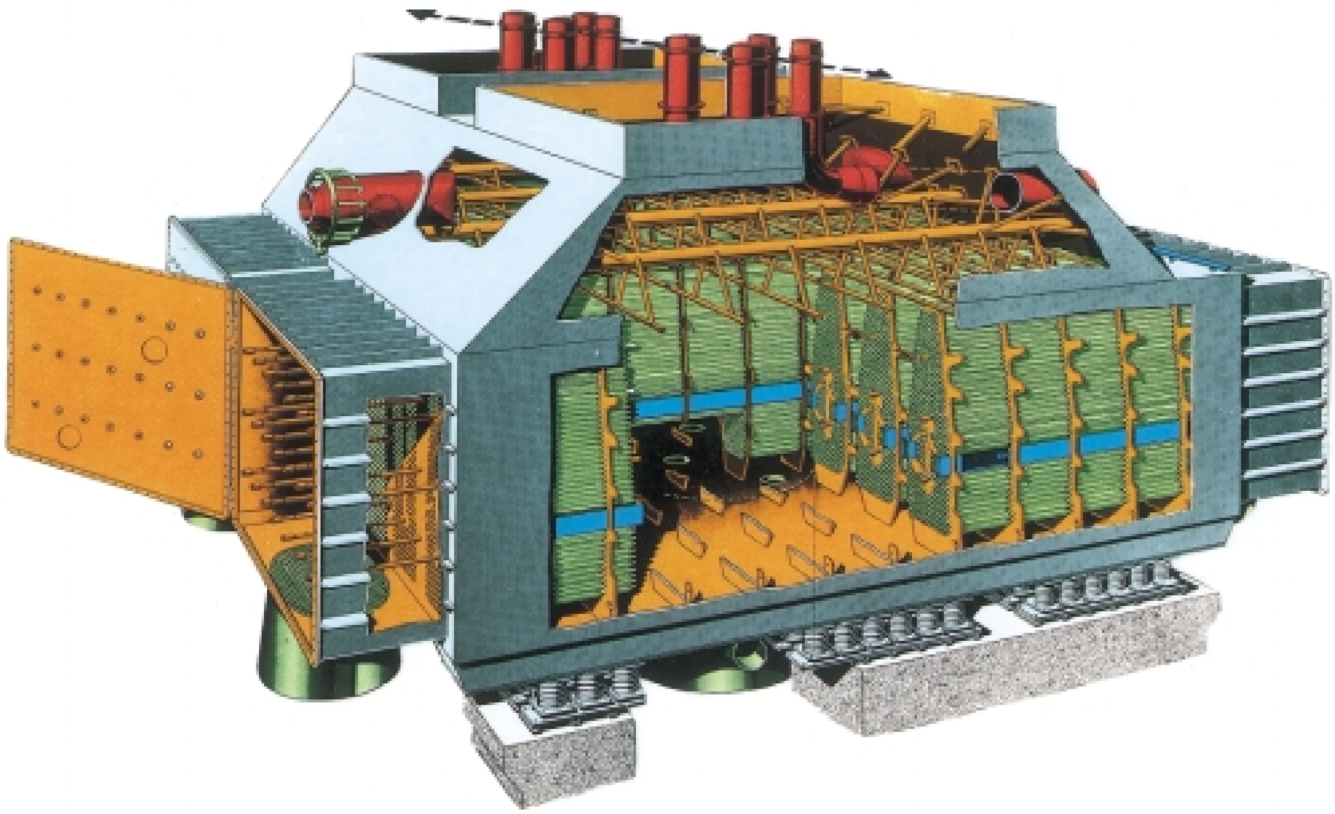
A look at the development of large steam condensers in the 150 MW to 2 GW class shows, by way of an example, the principles and tools needed to ensure that the equipment meets the exact requirements of the customer whilst offering the best possible cost/performance ratio.

The development of thermal power equipment has a long tradition at ABB Power Generation. Large steam condensers of type CM **1** are one of the main products in this segment, and a policy of continuous modification and improvement has ensured their market success over the years. In terms of performance and availability, these condensers are among the leaders **2**. A total of more than 350 units in operation underline their high level of acceptance.

Whereas in the past the main priorities were high efficiency and high availability, today's markets also demand short delivery times, potential for local manufacture and low costs. Current development activity is reflecting this wider range of concerns.

Variations of the original CM condensers have consequently been developed with an optimized cost/performance ratio to satisfy the latest market requirements.

The product has been completely revamped, from the thermohydraulic principles and modelling of the apparatus, through the design and the determination of the material and fabrication costs, to the method used to transfer the results to design programs that can be run on personal computers. This development programme has resulted



Large steam condenser of type CM/H. Condensers of this type cover an output range of 150 to 2,000 MW. **1**

in the following design software now being available for calculations and tendering:

- Advanced routines for thermohydraulic calculations
- Routines for determining the mechanical design, materials and weights
- Routines for calculating costs

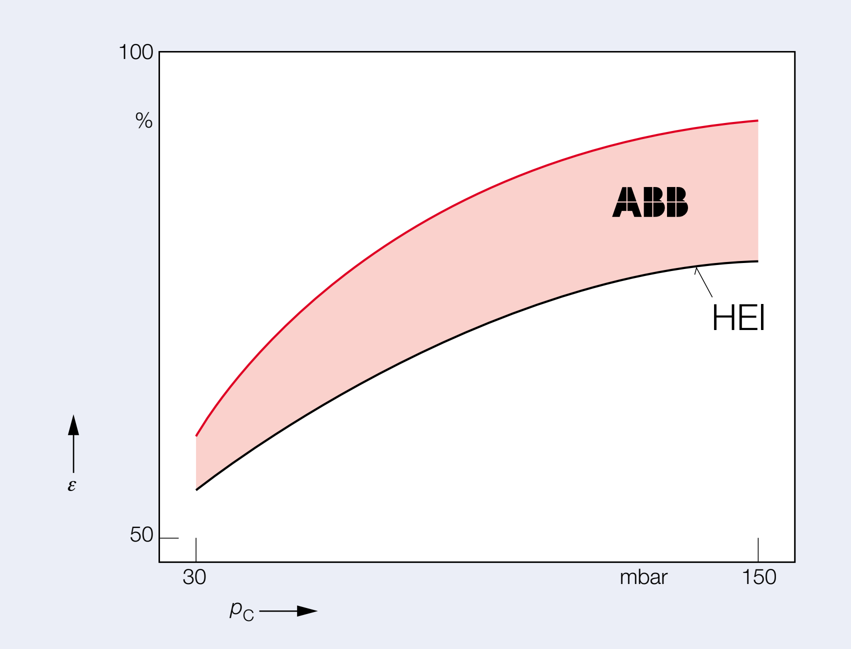
The cost model, which was developed together with the lead center for the fabrication of thermal apparatus, ABB Power Generation Kft of Budapest, allows a chosen design to be immediately analyzed and appraised. Thanks to the new design programs, know-how gained during development and manufacture flows with only minimal losses into the equipment, allowing a product to be offered that is adapted exactly to the requirements of the customer.

Two CM/H condenser modules ready for installation on the site of the 320-MW Avedøre 1 steam power plant in Denmark **2**

Principles of condenser design

Thermohydraulic calculation

The thermohydraulic calculation includes all of the parameters which influence the performance of ABB condensers in nor-



Comparison of condenser effectiveness calculated according to ABB principles and the HEI recommendation **3**

ε *Condenser effectiveness*

p_C *Condenser pressure*

mal operation. The main variable in this calculation, representing the performance of the condenser, is the heat transfer coefficient k:

$$k = \frac{Q_{th}}{A \Delta T_{log}} \qquad (1)$$

The logarithmic mean temperature difference, ΔT_{log}, is given by:

$$\Delta T_{log} = \frac{T_2 - T_1}{ln \frac{T_C - T_1}{T_C - T_2}} \qquad (2)$$

The correct determination of the heat transfer coefficient using eqn (3) provides the physical basis for the condenser design.

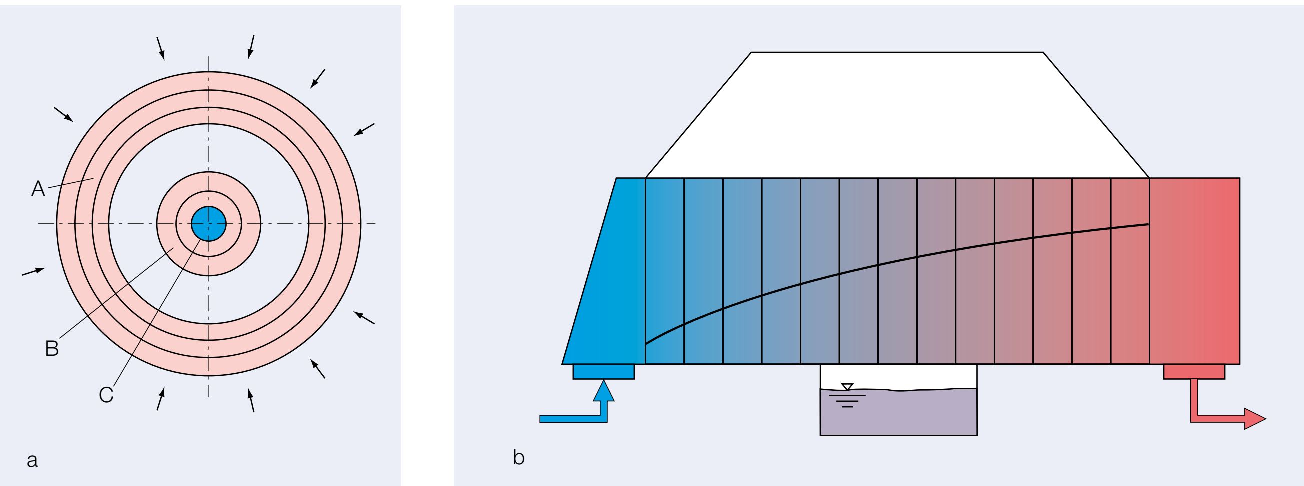
$$k = f(Q_{th}, A, T_1, T_2, T_C, \alpha_w, D, s, h_v, \lambda, \alpha_k, I, \alpha_g, B_A, v_g, \Delta p_C, CS_{cw}, C, ...) \qquad (3)$$

Q_{th}	Rejected heat
A	Total heat transfer surface
T_1	Cooling-water inlet temperature
T_2	Cooling-water outlet temperature
T_C	Condenser temperature
α_w	Heat transfer coefficient, water/tube wall
D	Tube diameter
s	Tube wall thickness
h_v	Thermal resistance due to fouling
λ	Thermal conductivity of tube wall
α_k	Heat transfer coefficient of condensate film
I	Inundation of bulk tubes in tube pattern due to condensate
α_g	Heat transfer coefficient, condensate film/steam
B_A	Air-cooler orifice surface and distribution
v_g	Velocity of steam in steam lanes
Δp_C	Pressure loss on steam side
CS_{CW}	Salt content of cooling water
C	Compactness of tube pattern

Calculation of the local condenser state **4**

a *In radial direction*
b *Along cooling-water path*

A *Tube bank*
B *Air cooler*
C *Venting duct*



CM/H condenser module during fabrication, here ready for mounting of the water box cover **5**

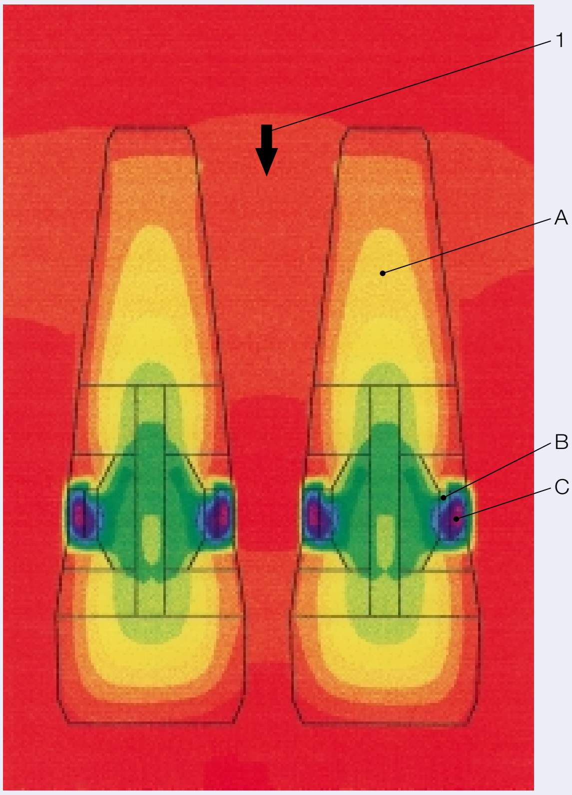
The Heat Exchange Institute (HEI) has issued a recommendation for the design of condensers [1] that is in wide use today. **3** compares the performance of condensers designed to this recommendation with units designed and built by ABB. It shows the effectiveness of the condenser (as a percentage, with an 'ideal' condenser[1]) as reference) versus

[1]) The term 'ideal' condenser refers to a so-called single-tube condenser in which the tube pattern and the possible deterioration in performance resulting from it play no role.

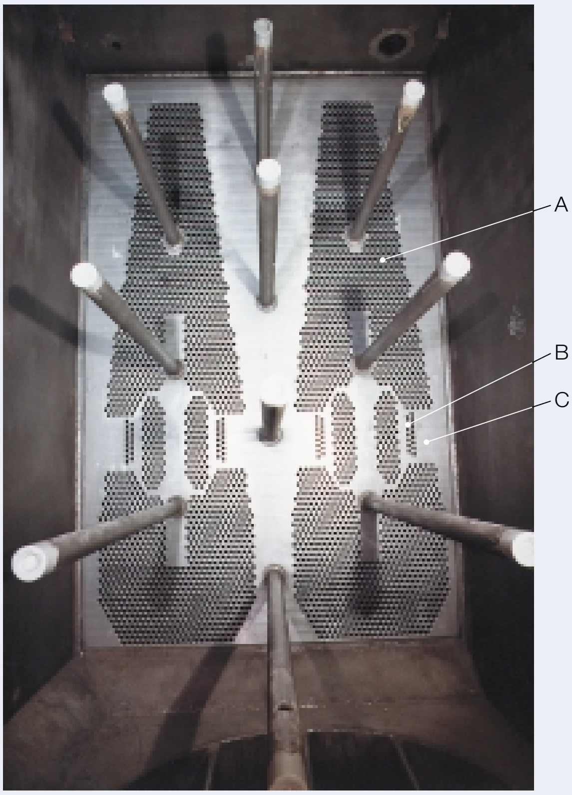
Performance-optimized CM/H condenser **6**

a *Computer image of shell-side pressure field*
b *Fully assembled CM/H condenser module – view inside the water box*

A *Tube bank*
B *Air cooler*
C *Venting duct*
1 *Steam inlet flow*



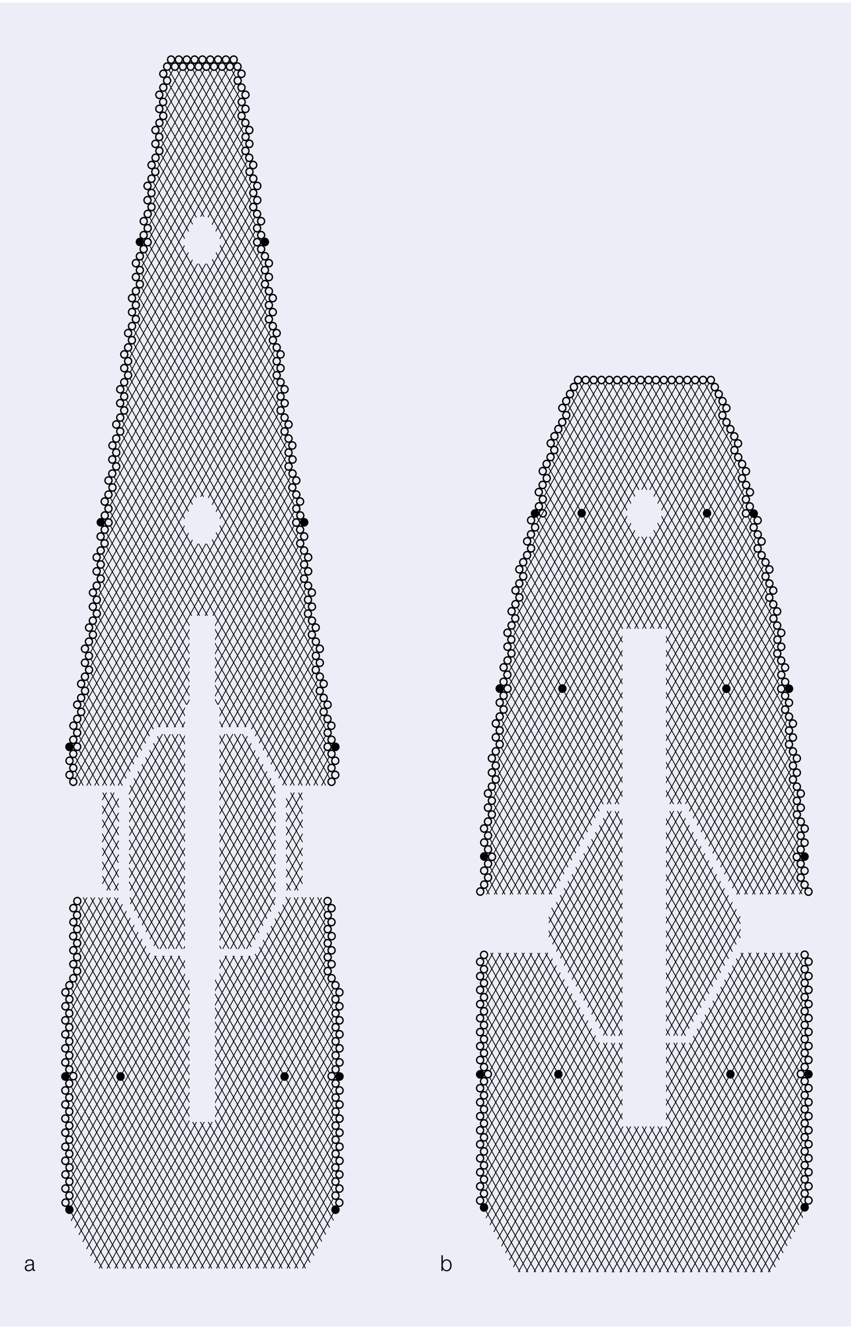
a



b

the condenser pressure in mbar. As is seen, the effectiveness of condensers built to the ABB design can be 20 percent higher than that of units with the same condensing surface but based on the HEI recommendation. This illustrates clearly how the company's good understanding of the physical principles involved enables condensers to be offered which satisfy a wide range of customer requirements. It is this know-how, plus precise knowledge of the cost structure, that allows ABB to submit tenders that meet the exact requirements of the customers, ie for condensers offering an optimum cost/performance ratio. Depending on the priority the customer gives to improving the total plant efficiency through high condenser effectiveness, a condenser can be chosen which lies at either the upper or the lower end of the performance scale.

Comparison of the tube pattern of type CM/H (a) and type CM/C (b) condensers, in each case with the same total number of tubes. The surface area of the CM/C condenser is 10 to 15 percent smaller. **7**



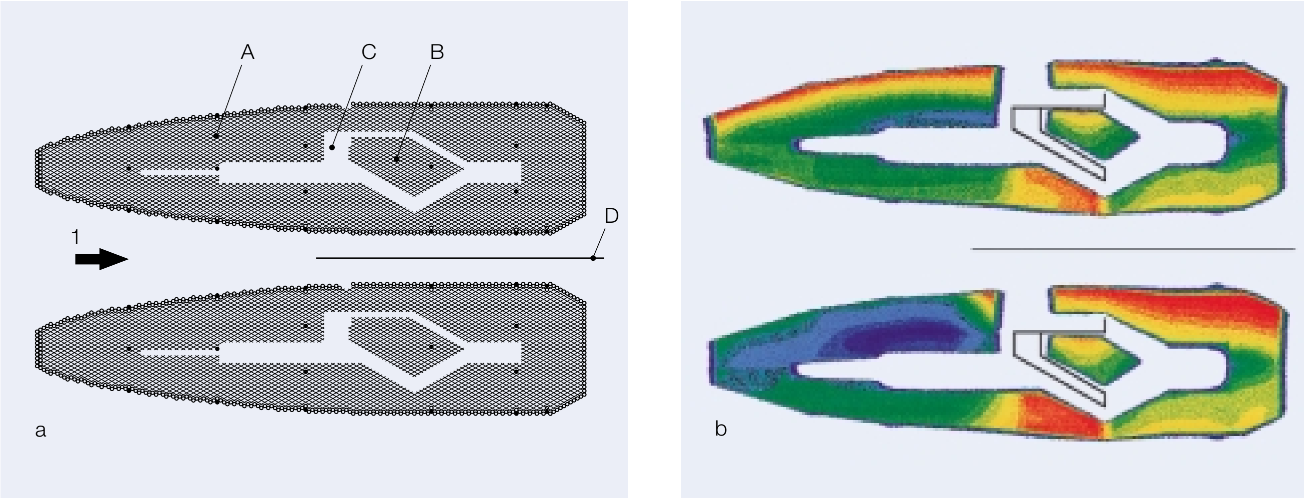
Geometric modelling

The local thermohydraulic processes taking place in large power plant condensers can vary strongly. For example, the load caused by the steam is much greater at the cooling-water inlet than at the outlet. In parallel with this, there is a significant difference in steam pressure loss along the cooling-water paths as well as a wide variation in venting capacity. This situation is taken into account by using a quasi-2D method to calculate the performance of the condenser: the condition of the condenser is computed locally along the flow path of the steam through the tube bank **4a** and along the path travelled by the cooling water **4b** by iterative means until the conditions for a global energy balance are fulfilled.

This type of condenser calculation enables the cost/performance ratio to be optimized and the knowledge resulting from the CFD calculations [2] to be transferred with only minimal losses to the design tools. At the same time, certain proven properties are retained, for example:

- Optimum air-cooling and venting
- Oxygen content of condensate minimized
- No risk of droplet impact erosion of cooling tubes
- No risk of cooling tubes vibrating
- No condensate subcooling
- Maximum compactness for condenser
- Optimum introduction of make-up water

Thus, the customer is guaranteed a product that satisfies the highest availability, lifetime and performance require-



Pair of tube patterns for floor-mounted condensers of type CM/A+S (a) and the local condensate load for this type of condenser (b) **8**

A *Tube bank*
B *Air cooler*
C *Venting duct*
D *Condensate baffle plate*
1 *Steam inlet flow*

ments. At the same time, a contribution is made to minimizing the cost of equipment situated outside of the condenser system; for example, the low-pressure preheaters can be made smaller on account of the negative condenser subcooling. The smaller preheaters and the more compact condenser together allow a saving in the cost of the machine room. Finally, providing the O_2 content of the condensate allows it, separate vacuum deaeration will not be needed even for larger quantities of make-up water, helping to reduce the cost of the overall system by a significant amount.

Tube pattern modelling for CM condensers

A typical feature of the type CM condenser is the arrangement of the cooling tubes in groups with identical tube patterns **5**. **6a** shows a pair for the type CM/H with the computed pressure pattern, and **6b** a pair for the type CM/H during fabrication. The CM/H tube pattern has been designed for optimum performance and is an industry leader in this respect, the condenser performance being largely determined by the cooling-tube arrangement that is used. One of the parameters having a direct influence on this is the surface area of the tube pattern through which the steam is able to penetrate. An equivalent measure of this surface area is the compactness C of the tube pattern, being defined as:

$$C = \frac{\textit{Total number of tubes per tube pattern}}{\textit{Number of peripheral tubes per pattern}} \qquad (4)$$

Therefore, to design a condenser with an optimized cost/performance ratio the compactness of the tube pattern has to be included in the equation.

7 compares the CM-COMPACT tube pattern (CM/C), which was developed on the basis of the above considerations, with a CM/H pattern, the total number of tubes being the same in each case. The resulting saving in overall height is 20 to 25 percent. Although the tube nest is somewhat wider, this can be partially compensated for by optimizing the distance between the bundles with the help of the quasi-2D condenser model. The condensers built using CM/C and CM/H tube patterns cover the performance band shown in **3**.

Besides the direct influence CM/C condensers have on the cost of the apparatus, it is seen once again that their use allows a significant saving in the cost of the machine room.

Another pair of tube patterns designed to meet the cost-optimization requirements of a specific project is shown in **8**. The CM/A+S condenser that was built is designed for floor mounting and is the same in terms of its availability, lifetime and optimized cost/performance ratio as the other ABB condensers referred to.

New design features

Besides the above-mentioned measures for optimizing cost and performance, there are also many new design features which have been introduced. These have been specially chosen to reduce costs without exerting a negative influence on the effectiveness of the condenser. The main ones are:

A typical 'generator output correction curve' for the condenser pressure at full load **9**

ΔP *Change in output* p_C *Condenser pressure*

- Newly designed air coolers
- An optimum strengthening concept
- Optimum employment of materials
- Optimized design of the water box

Optimization of the cost/performance ratio

Principles of cost calculation

The interrelationships between the discussed possibilities for designing a CM condenser with an optimized cost/performance ratio are complex by nature, and it is not always clear whether and to what extent a cost reduction that is achieved for a particular component will reduce the overall costs. For example, increasing the distances between the condenser supports saves on material and fabrication hours (M&F), but makes it necessary for the walls of the supported parts to be thicker, which increases the M&F expenditure at these locations. To find out if there is a net reduction in costs, a cost calculation based on the M&F has to be carried out in close cooperation with the fabrication center. Four CM condensers were consequently subjected to a detailed analysis of their M&F costs in the course of the callaboration with ABB Power Generation Kft.

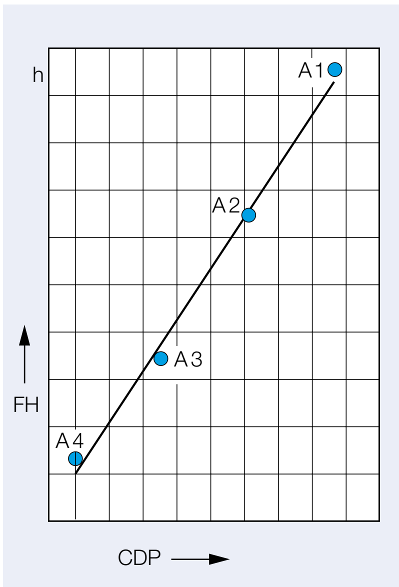
In order to calculate the fabrication hours for the condensers, each one was broken down into its main parts. Afterwards, production drawings and work schedules were used to determine, item by item, the fabrication hours for each individual component. These were then referred to the different cost centers in the factory.

Using the above method, a matrix was created with which the fabrication hours could be calculated for the CM condensers. *Table 1* shows this matrix, which is made up of 22 condenser components and 10 cost centers per condenser. The net cost of the materials for the analyzed condensers was determined on the basis of the parts lists, and the gross material costs (material plus waste) on the basis of the materials ordering list.

Providing the specific cost parameters are known for each cost center and for the materials, and assuming the overheads are taken into account, the total costs can therefore be determined.

A study involving CM condensers in the 150-MW and 350-MW classes has shown that designing for an optimized cost/performance ratio (CM-COMPACT) results in considerably lower costs than when designing for optimized performance only (CM-H). The benefit of such a cost/performance optimization will obviously depend on how the customer rates the output of his condenser vis-à-vis the total efficiency. A good starting point is the 'generator output correction curve' for the condenser pressure. **9** shows a typical curve for a 300-MW unit [3]. It can be seen from this that at the design point the total output changes by approximately 0.2 MW for each mbar of condenser pressure. This potential change in the overall output can be considered against the optimized condenser investment costs for different points on

Fabrication hours (FH) as a function of the dominant cost parameter (CDP) for the four investigated condensers A1, A2, A3 and A4. Providing the fabrication process is represented correctly by the CDP, it is possible to establish a definite relationship between it and the fabrication hours. **10**



the curve. Thus, the customer can be offered an optimum design, tailored to his exact requirements.

Fabrication

The cost reduction achieved up to this point in the discussion, which has dealt with the general optimization of the cost/performance ratio, is based exclusively on technical innovation. A further reduction is obtained in the fabrication area through improvements to the employed processes and methods.

The analyzed condensers are also used as the basis for these further reductions. To this end, each point in the matrix in *Table 1* is investigated with respect to the fabrication hours, material costs and dominant cost parameters. Once the correct dominant cost parameter (CDP) involved in the processing of a component at a cost center has been found, a definite relationship between the fabrication hours (FH) and the CDP can be established **10**.

The potential for a cost reduction now lies in the extent to which the sequence of fabrication processes and methods can be controlled or improved, based on the determined dominant cost parameters.

Tendering/engineering tool

Another important task is to make the verified potential for optimizing the cost/performance ratio available to the engineers who prepare the tenders, and thereby pass it on to the customers. This is done with the help of a cost calculation program that forms part of the so-called ‘tendering/engineering tool’. Such programs have to designed to the highest standards to ensure that cost reductions confirmed for individual condensers flow into the entire product range with no more than minimal losses.

The ‘tendering/engineering tool’, by allowing an iterative approach, makes it possible to find an optimum balance between the technical design and the cost calculation.

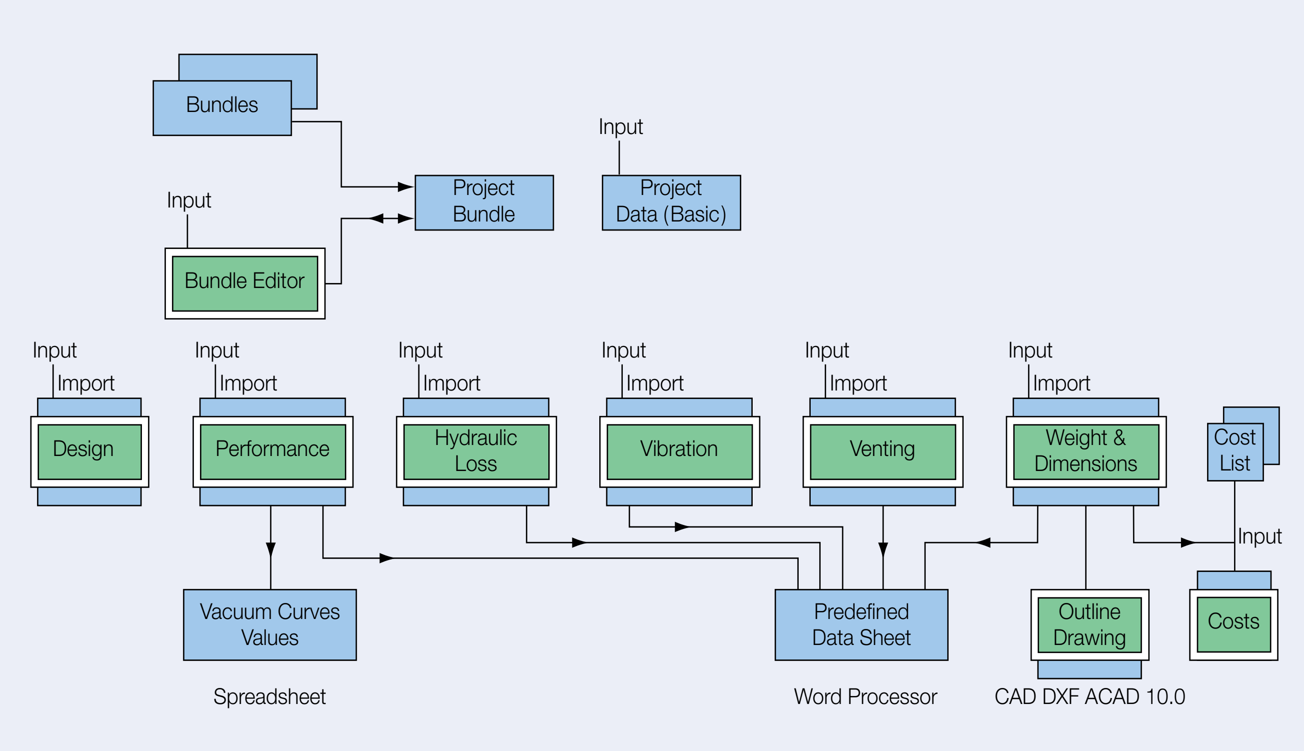
Together with a weight calculation, and given the fabrication hours, specific cost parameters (hourly rates, material costs) and various overheads, the tool allows a detailed break-down of the total fabrication costs in a very short time.

The cost calculation program was developed in collaboration with ABB Power Generation Kft, Budapest, and is designed for use in all the ABB Group fabrication centers. Account has also been taken of the fact that any optimization of the cost/performance ratio has to meet different requirements in different countries. With this tool, a solution to suit the exact requirements of the customer can be found in every case.

11 depicts a flow chart that shows

Table 1:
Matrix for calculating the fabrication hours and mateial costs for CM condensers

Components	*Time in hours for*									
	Surface preparation	Burnout & cutting	Rolling & bending	Machining (small m/cs)	Machining (big m/cs)	Locksmith & welding	UP welding	Cleaning & corrosion protection	Tubing/ drilling	Total
Shell										
Support plates										
Air cooler										
Beam										
Hotwell										
Water box outlet										
Water box inlet										
Tube sheet										
Coatings										
Neck/turbine conn.										
Flashbox										
Inlets										
Extraction pipes										
Compensators										
Transport part										
Tubing										
Transport preparation										
Shop assembly										
Pressure test										
Cleaning/painting										
Supports										
Total										



Organization of the 'tendering/engineering tool' for type CM condensers. A cost calculation can be prepared in a very short time for a pre-calculated thermal design. **11**

Green *Program* Blue *File*

how the 'tendering/engineering tool' is set up. Without going into the many different possibilities offered by the tool, it is seen that all the modules – those for the technical as well as for the cost calculations – are linked to one another via 'IMPORT' and 'INPUT' functions. Thus, it is possible to perform a weight calculation for any chosen technical solution and then carry out a reliable cost calculation. 'Reliable' in this context means that the fabrication costs determined with the program are binding both for the ABB company submitting the tender as well as the ABB fabrication center.

Commercial and technical transparency – the platform for success

From a commercial standpoint, it is imperative when entering into binding contracts that the cost structures are fully transparent since they are the common basis for fabrication, engineering and sales. It is the task of the development department, as the link between all parties, to find a common platform and to guide the business process. Thanks to the efforts of all the participants, the described CM condenser project was successful in achieving the defined goals.

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[1] HEI (Heat Exchange Institute): Standards for steam surface condensers, 1995. Ninth Edition, Cleveland, Ohio

[2] **J. Palm, M. Arnal:** CFD condenser design tool. Technical Report HTGE-ST-0387, 11. 9. 96.

[3] **S. Beer:** Ueberwachung und Optimierung des Betriebes von Kondensatoranlagen in thermischen Kraftwerken. VGB Kraftwerkstechnik 76 (1996) 9, 739–745.

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