Measurements prove high performance of first CB/A axial surface-type steam condenser

Special demands are made on the steam condenser and vacuum deaeration system designed and built by ABB Alstom Power licensee, Evans Deakin Engineering Pty Ltd of Australia, for a 180-MW combined cycle facility near Sydney. In addition to supplying electrical power to the grid, the plant also supplies process steam in large quantities to local industry. A comprehensive test programme has shown that the CB/A axial surface-type steam condenser and the deaeration system easily meet the high performance requirements under the test conditions, while also satisfying environmental needs. Evaluation of the extensive measurements has verified ABB Alstom Power's calculation methods and provided data that will serve as a reliable basis for further development work.

ABB Alstom Power licensee, Evans Deakin Engineering Pty Ltd of Australia, was responsible for designing, building and installing the steam condenser and vacuum deaeration system for the 180-MW combined cycle power station at the Smithfield Energy Facility, 50 km south-west of Sydney. The power station has three gas turbines and one steam turbine for electricity generation, and also supplies up to 50 % of the live-steam mass flow as process steam to a paper factory, making it a significant contributor to the local energy market. Natural gas is used to fire the gas turbines. The steam turbine receives live steam from the gas turbine waste-heat boilers. The steam condenser, a CB/A axial surface-type unit developed by ABB Alstom Power, operates with cooling towers.

Because of the large quantities of process steam involved, the systems installed to condition and, in particular, deaerate the make-up water have to be flexible as well as very efficient.

The CB/A condenser is the result of further development of the proven underfloor CB condensers and is the first axial surface condenser of this type to be built worldwide. The dominating feature of the new design is that the steam flows horizontally in the direction of the turbine axis as it passes from the LP exhaust to the bundle area.

During commissioning ABB Alstom Power teamed up with Evans Deakin, the EPC contractor NEPCO-Transfield Joint Venture Company (NTJV) formed by the engineering companies TRANSFIELD Ltd of Australia and Zurn Nepco of Redmond, USA, and the client and owner of the Smithfield Energy Facility, Sithe Energies Australia Pty Ltd, to investigate the performance of the condenser and vacuum deaeration system. Other goals of the extensive test programme were to obtain detailed data as a basis for further development work and to check ABB Alstom Power's in-house design rules and methods of calculation.

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Steam condenser and vacuum deaeration system

The purpose of the condenser and deaerator system installed at the Smithfield Energy Facility **1** is to condense the working steam leaving the steam turbine and to extract the oxygen from the make-up water and the main condensate.

Steam condenser

Due to its effect on the backpressure of the LP steam turbine, the performance of the condenser has a decisive influence on the efficiency of the entire plant, and therefore on the generator output.

Via the cooling water the condenser is also a link to the environment. Besides fulfilling the requirements of the power plant it therefore also has to satisfy environmental needs. This important requirement is satisfied by ABB Alstom Power condensers in all areas – from the thermal design to the fabrication and operation – and is guaranteed by ISO 14001 certification [1].

The type CB/A surface condenser ('A' stands for 'axial') **2** (*Table 1*) represents

CB/A steam condenser in the 180-MW combined cycle power station of Smithfield Energy Facility, Australia **1**

the most recent result of ongoing development of the CB condenser, which was introduced to the market in 1989. Further development of the CB condensers for axial and lateral turbine exhausts was based on field data from 50 condensers in underfloor arrangement operating worldwide. The thermal load range of this condenser type is 10 to 250 MW [2].

Besides their main function, which is to act as a heat-sink, steam turbine condensers are increasingly gaining recognition as an important part of the vacuum deaeration system in plants in which large quantities of make-up water are used. In the past 2 % of the live-steam was considered to be a characteristic value for the make-up water, which usually had to be added to the system discontinuously via the condenser. Today, make-up water may constitute as much as 50 % of the turbine live-steam mass flow rate and has to be added continuously, as in complex combined cycle systems with large-scale process steam extraction.

Vacuum deaeration system

The vacuum deaeration system used in the Smithfield Energy Facility is reliable under rigorous operating conditions and guarantees a residual oxygen content of less than 7 ppb in the condensate leaving the hotwell even under severe make-up conditions in which the make-up water flow to the condenser constitutes up to 50 % of the turbine live-steam mass flow rate.

Table 1
Main design parameters of the condenser

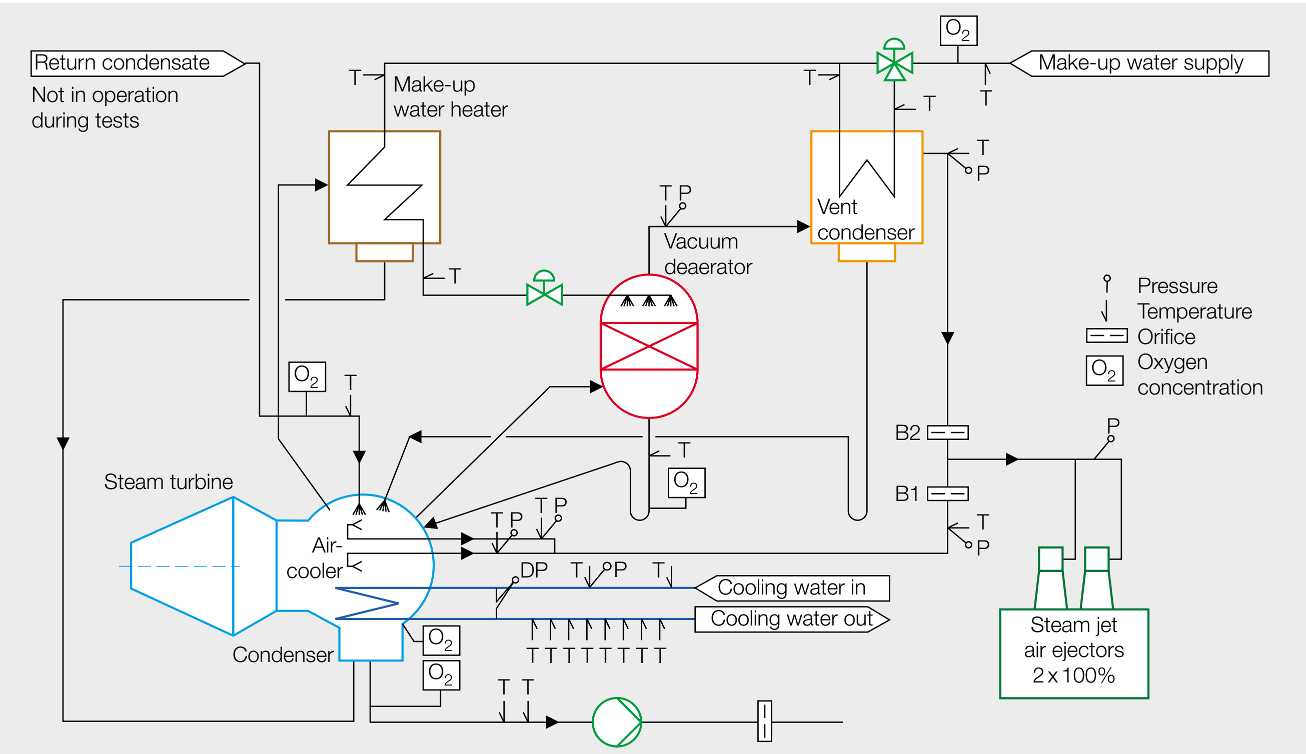
Condenser type	CB/A-108-2x3164/25,4/07
Number of passes	2
Water box type	Non-divided
Tube material	Stainless steel
Tube sheet material	Stainless steel
Tube/tube sheet connection	Expanded
Tube length	10.89 m
Cooling area	5458 m^2
Heat load	92.25 MW
Live-steam mass flow rate	45.0 kg/s
Condenser pressure	0.048 bar
Cooling-water inlet temperature	22 °C
Cooling-water pressure drop	0.543 bar

CB/A condenser for Smithfield Energy Facility being manufactured at Evans Deakin's workshop **2**

As **3** shows, two 100% steam jet air ejectors are provided (one nominally in operation) to vent the condenser and the vacuum deaeration system. Orifices B1 and B2 determine how much of the venting capacity of the ejectors is assigned to the condenser and how much to the deaerator system.

Thorough venting of the vacuum deaerator is ensured by passing some of the make-up water through the vent condenser. The make-up water is subsequently preheated in the make-up water heater almost to saturation temperature at the prevailing condenser pressure, whereby the top section of the packing, where deaeration tends to be ineffective, is minimized. This ensures that the vacuum deaerator operates with the highest efficiency over the full packing height with comparatively small-diameter packing. The section of the condenser shell that receives the make-up water from the vacuum deaerator is designed as a so-called 'fall film' deaerator. In this design, the make-up water is distributed in the form of a film over the full length of the condenser shell's back-wall, thereby providing further intensive contact with fresh turbine exhaust steam for effective final deaeration of the make-up water.

Schematic of measurement system installed for the condensing and vacuum deaeration system in Smithfield **3**



Both the vent condenser and the make-up water heater are designed as ABB Alstom Power shell and tube heat-exchangers.

Determination of characteristic parameters

The condenser performance was determined experimentally using test instrumentation based on ASME PTC 12.2 and the relevant internal guidelines. The scope covered by the tests exceeded the requirements given in ASME PTC 12.2 for such measurements.

The following plant parameters were determined:

Heat load to condenser

This was determined by means of a plant energy balance. Additional relevant data were obtained from the plant's permanent data acquisition system.

Cooling-water flow rate

This was determined via the condenser energy balance with the aid of the determined heat load to the condenser.

Global cooling-water temperature rise

The overall rise in the temperature of the cooling water was measured with medium wetted Pt100 sensors, inserted in special support sleeves. Two measuring points were positioned at the cooling-water inlet, and another eight inserted radially and distributed on the circumference around the cooling-water outlet line.

Local cooling-water temperature rise

The cooling-water temperature rise was measured locally at the first and second pass of selected individual cooling-water tubes. The temperature sensors were positioned across the entire tube area of the first pass cooling-water outlet and the second pass cooling-water inlet and outlet. The cooling-water temperature was measured at a total of 108 points and allowed the temperature rise to be determined along individual tubes. Thermocouples were used as temperature sensors, the cooling-water inlet temperature serving as reference. As a result of these measurements, cooling-water temperature rise profiles were obtained for the entire areas of the tubes. These provided important information about the condensation behaviour of the condenser.

Condenser pressure/temperature

On the steam side, the condenser was fully fitted with so-called combined sensors for simultaneous measurement of pressure and temperature. To ensure correct pressure measurement, all pressure tapping points were equipped with ASME guide plates. The measurement was carried out in two planes in the exhaust flow path from the turbine to the condenser, namely in the cylindrical turbine exhaust nozzle (12 measuring points) and approximately 300 mm before the first tube row in the condenser tube areas (18 measuring points).

The use of combined sensors and the number that were fitted easily exceeds the requirements stipulated for this area in ASME PTC 12.2.

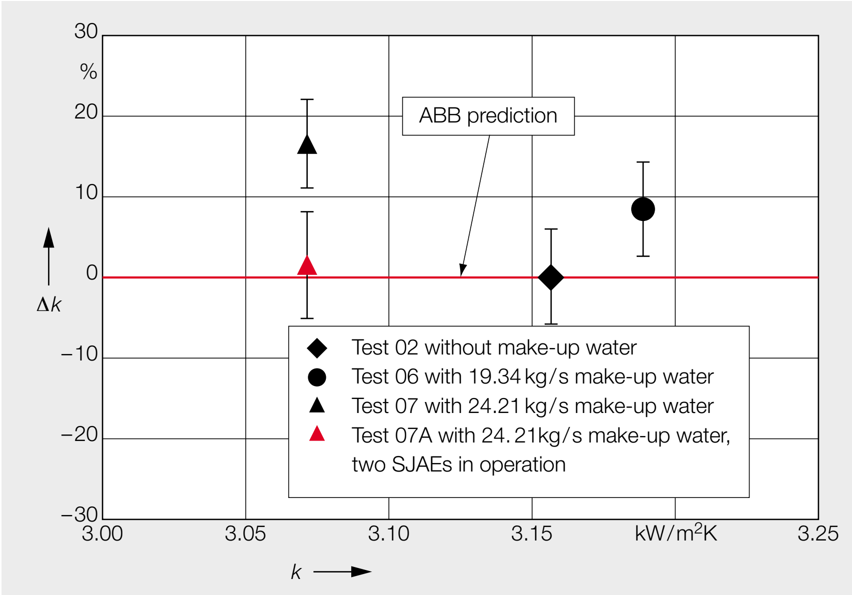
The relatively narrow and complex steam path geometry results in very complex flow and pressure conditions. An extensive installation was therefore necessary to obtain condenser pressure data accurate enough to be used as a basis for further development work.

Vacuum drop test

The steam jet air ejectors were isolated and the pressure rise in the condenser and vacuum deaeration system was recorded with respect to time. This test provided information about the air-tightness of all the evacuated systems, including the vacuum deaeration system, condenser and low-pressure turbine.

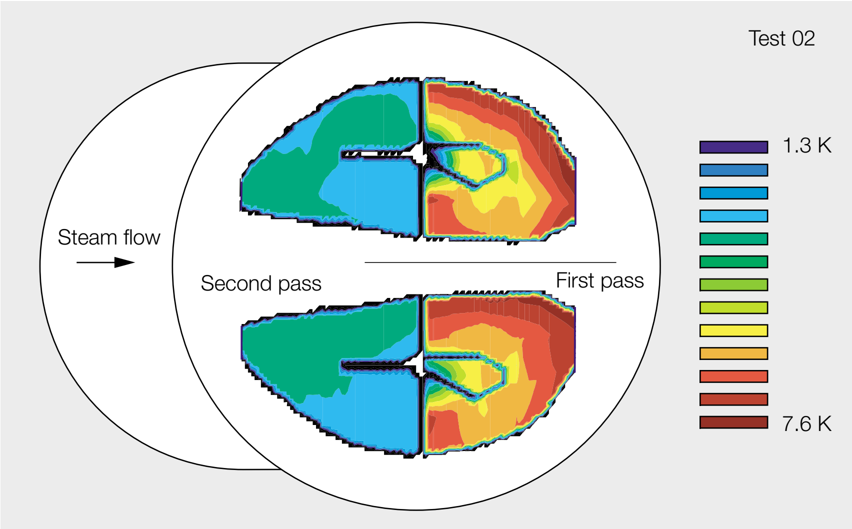
Condensate temperature

Using two Pt100 sensors, the condensate temperature was measured in the condensate extraction pipe downstream of the



Deviation of the measured heat transfer coefficient from values predicted by in-house design calculations **4**

Δk Deviation of heat transfer coefficient, k



Measured cooling-water temperature rise for test 02 (without make-up water) **5**

Thermal load: 112.7 MW; make-up water: 0.0 kg/s

hotwell but upstream of the main condensate extraction pumps.

Cooling-water pressure drop

The pressure drop across the condenser on the cooling-water side was measured by means of a differential pressure sensor. Prior to actual measurement, it was assured via the water box vent lines that the water boxes had been fully vented. The measuring points in the cooling water nozzles were approximately 0.5 m from the respective water boxes.

Oxygen content in condensate

These measurements were carried out with instruments from the company *Orbisphere*. High diffusion tight plastic hoses and high-quality stainless steel lines and fittings were used for the extraction pipes. A variable-speed extraction pump was used to adjust the extraction flow rate to the value specified for the oxygen analyzers.

Cleanliness factor

The condenser was inspected on the steam- as well as on the cooling-water side. The inspections showed it to be technically clean, with the cooling-water side in particular showing no signs of contamination.

A cleanliness factor of 0.85 was therefore used for the evaluation of the results. This value is usual for such a plant without an automatic tube cleaning system, and also corresponds to the design value.

Table 2
Standard qualification of ABB Alstom Power test instrumentation

Instrument type	*Measurement uncertainty*
Resistance thermometers	± 0.03 K
Thermocouples, temperature difference	± 0.02 K
Turbine exhaust pressure transducer	± 0.25 mbar
Difference pressure transducers	± 0.14%
Data acquisition system	± 0.03%

Test instrumentation and additional data

All the measuring points with the temporarily installed high-precision sensors are shown in **3**. (To keep the diagram simple, some of the measuring points used for the condenser assessment are not shown.) All other data required for the energy and mass flow balances were derived from plant instrument readings.

Data recording

The ABB Alstom Power Universal Data Acquisition System, UNIDAS II [4], was used as it permits automatic scanning and recording, and allows even large quantities of data to be evaluated with high accuracy under field test conditions (*Table 2*). The system is specially designed for temporary use in power stations. Highly accurate results are ensured by the transmitters, which are an integral part of the recording and evaluation system and are freshly calibrated each time before use. The system meets the requirements of all the relevant international standards for guarantee tests (ASME, DIN, VGB, BS, ISO, IEEE, IEC, etc).

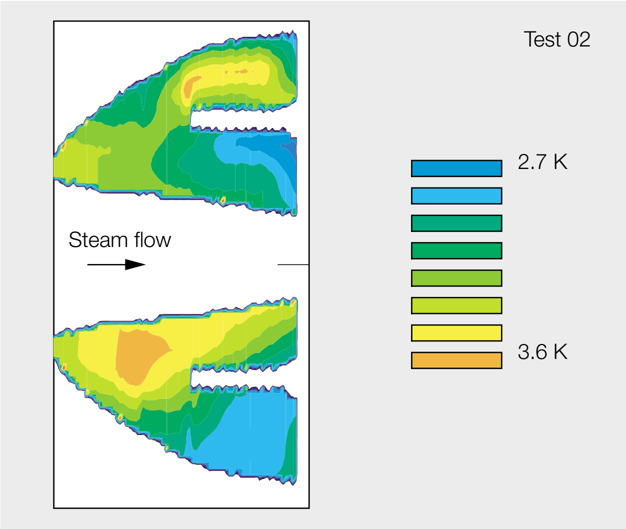
Data evaluation

The calculated 95 % confidence interval for the measured values and error propagation (eg, when determining the global heat transfer coefficient) verifies that UNIDAS II easily satisfies the accuracy requirements of this benchmark test programme.

Test results

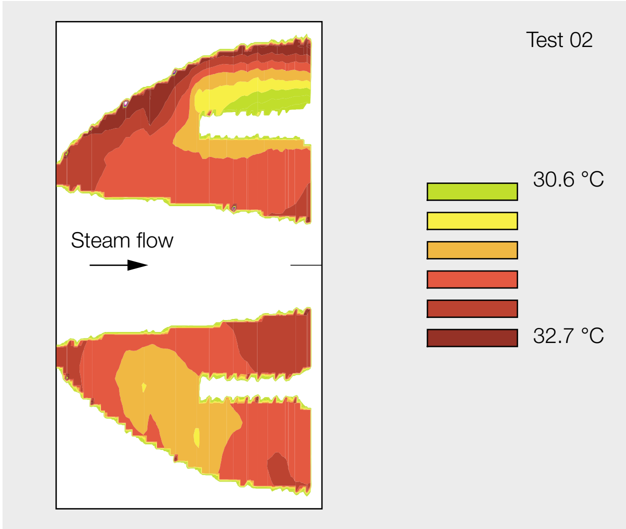
Condenser pressure and heat transfer coefficient

The condenser pressure at the plane immediately before the tube bundles was used to determine the heat transfer coefficient, the so-called *k*-value. This is in agreement with HEI [5] ASME PTC 12.2 and the ABB guidelines.



Cooling-water temperature rise in second pass (test 02), shown with a higher resolution **6**

Thermal load: 112.7 MW; make-up water: 0.0 kg/s



Cooling-water inlet temperature in second pass (test 02) **7**

Thermal load: 112.7 MW; make-up water: 0.0 kg/s

To evaluate the condenser pressure in this plane all the measuring points were used at which the measured pressure did not deviate by more than 0.002 bar from the calculated saturation pressure at the corresponding measured temperature. This was necessary to ensure that only pressure readings that are not falsified by condensate accumulation in the instrument lines are used for the evaluation. The permitted maximum pressure difference, ΔP_{max}, is given by:

$$\Delta P_{max} = P_{exp} - P_{sat}(T_{exp}) \leq \pm\, 0.002 \text{ bar}$$

Where P_{exp} is the experimental pressure and P_{sat} the saturation pressure at the experimental temperature, T_{exp}.

The condenser pressure now being known, an experimental heat transfer coefficient was determined and compared with the ABB Alstom Power design calculations.

Table 3 shows the thermal load and amount of make-up water for four representative tests, designated 02, 06, 07 and 07A. In **4**, which shows how the measured data deviate from the calculated values, good agreement can be seen for the test without make-up water (02). Also worth noting is the difference in the deviation for tests 06 and 07, ie for operation with large quantities of make-up water and one steam jet air ejector (SJAE) in operation. As soon as the second SJAE is put into operation, the condenser pressure improves considerably (test 07A).

These results indicate that the higher than expected air in-leakage prevailing during the test programme (approximately three times the design air in-leakage rate) did to some extent impair the heat transfer in the tests with large quantities of make-up water, and particularly during test 07. However, in spite of this higher air in-leakage the tube bundle venting remained effective and the oxygen readings for the condensate leaving the hotwell were still better than the guaranteed value of 7 ppb. This was true even for test 07 with the largest quantity of make-up water.

Local cooling-water temperature rise in individual cooling water tubes

Operation without make-up water

5 shows the cooling-water temperature rise along the first and second pass for test 02 (without make-up water). Also clearly

Table 3
Thermal load and make-up water for four representative tests

Test	Thermal load [MW]	Make-up water [kg/s]	Make-up water [% of main steam flow]	No of SJAEs in operation
02	112.7	0.0	0.0	one
06	100.2	19.34	29.5	one
07	92.9	24.21	37.3	one
07A	92.9	24.21	37.3	two

seen is the steam penetration in the first pass of the tube bundle and the local influence of the condensate flow in the bundle on condenser performance.

In the top and bottom bundles of the first pass the steam and condensate flows are in the same direction at the upper periphery. The result is a typical 'onion shell' pattern describing the condensation performance along the steam flow path.

In the lower bundle halves the steam and condensate flow in opposite directions. It can be clearly seen where the condensation capacity is reduced due to cascading condensate or increased to nearly full condensation capacity due to the shielding effect of the air-cooler plates. The air-cooler tubes also show a very high condensation capacity, demonstrating the perfect venting of the bundle. The nearly identical behaviour of the upper and lower bundles of the first pass can be explained by the condensate baffle plate between the bundles.

In the second pass the profile of the cooling-water temperature rise tends to be homogeneous, the maximum difference in temperature rise being 0.9 K. A condensate baffle between the bundles is not necessary here because of the relatively small quantity of condensate.

A more detailed look at the second pass

A closer look at the second pass of test 02, using a higher resolution for the cooling-water temperature rise, is shown in 6. The flat pattern is due to the combination of three effects:

- Flooding of bundle areas due to cascading condensate
- Cooling-water temperature profile at inlet to second pass
- Different steam admission conditions
  – steam/condensate in parallel flow
  – steam/condensate in counter flow

It can be assumed that all the cooling-water tubes in all bundle areas operate with the same quantity of cooling water.

A common characteristic of both the upper and lower bundle of the second pass is that the cooling-water temperature rise is smallest in the right-hand, lower bundle section. This is caused on the one hand by a relatively high cooling-water inlet temperature 7 and on the other by flooding of this bundle area, which increases gradually due to condensate cascading downwards. Furthermore, the steam entering the bundle flows in a counter direction to the condensate flowing down to the bottom.

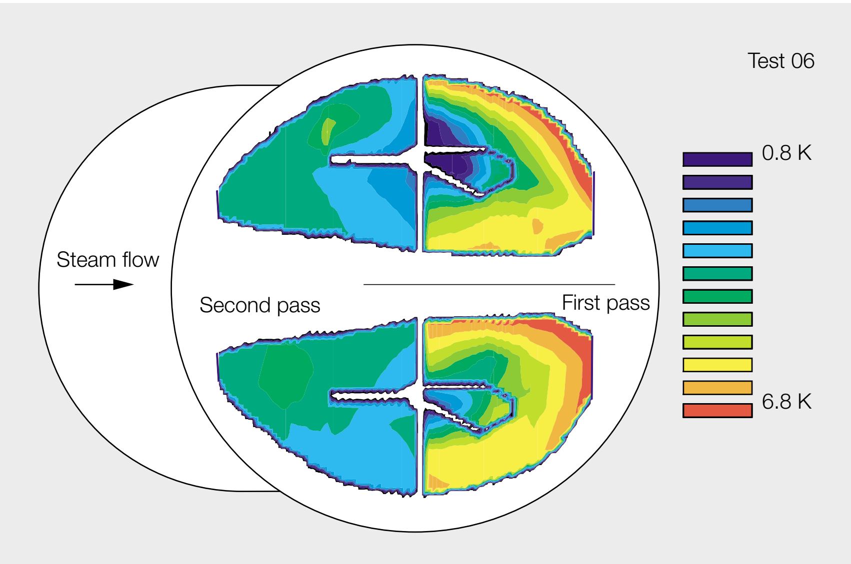
6 also shows stratification of the cooling-water temperature rise and an isolated maximum in the lower bundle. This would not normally be expected with such a shape. The stratification can also be explained by the flooding of the bundle by condensate cascading from above. The fact that the maximum temperature rise in the lower bundle represents an 'island' can be explained by the distribution of the cooling-water inlet temperature 7. As warm water approaches the upper periphery of the lower bundle, the rise in the cooling-water temperature there is smaller than it is inside the bundle. Although the cooling-water inlet temperature in the middle section of the lower bundle is lower than at the upper periphery, it rises much less than at the upper periphery. This can also be explained by greater bundle flooding and poorer steam admission at the lower bundle periphery due to cascading condensate.

It is mainly in the area where flooding with condensate has only a small influence that the condensation capacity is determined by the local cooling-water inlet temperature. This is confirmed by the results of measurements carried out on the upper bundle of the second pass.

7 shows two interesting phenomena: first, a minimum cooling-water inlet temperature prevails in the top section of the upper bundle above the inner bundle steam lane; second, the cooling water in the reversing chamber is stratified such that there is a significant maximum cooling-water inlet temperature at the upper bundle periphery. Although this upper bundle periphery is well-charged with steam, no significant flooding by foreign condensate is evident. In spite of the parallel steam and condensate flows, the rise in cooling-water temperature 6 is smaller than in the bun-

Measured cooling-water temperature rise for test 06 (with make-up water) 8

Thermal load: 100.2 MW; make-up water: 19.34 kg/s



dle area with a lower cooling-water inlet temperature.

ABB Alstom Power design calculations for condensers are based on physical models which take account of the effects described above. This explains the close agreement between the calculated and measured values in tests 02 and 07A.

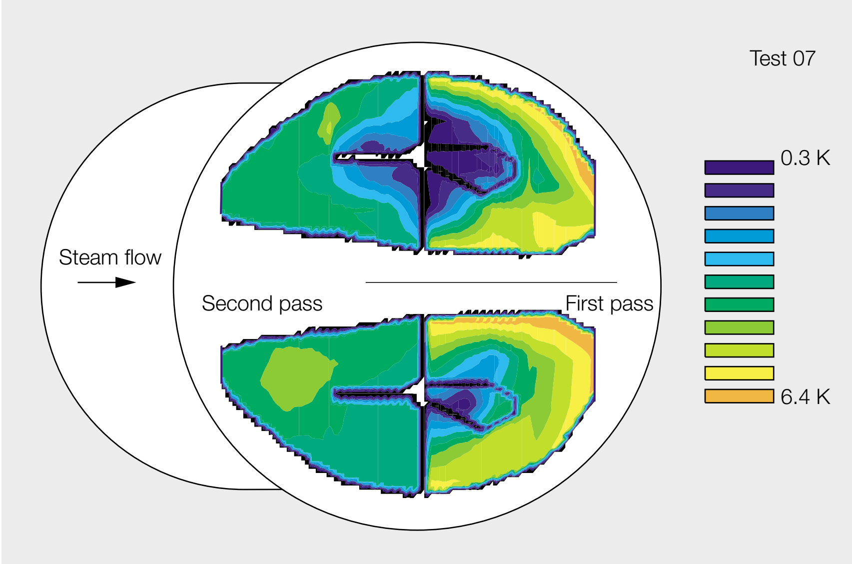
Operation with make-up water

8 shows the distribution of the cooling-water temperature rise for test 06, in which 29.5 % of the main steam flow rate is make-up water. The deterioration in the cooling-water temperature rise profile, indicating impairment of the condenser heat transfer capacity in the air-cooler area, is clearly visible.

A further increase in the quantity of make-up water results in the conditions shown in **9** for test 07. Here, nearly 40 % of the quantity of live steam is supplied as make-up water. Comparison of test 07 and test 06 shows clearly the impaired condensation capacity due to air blanketing in the air-cooler area, with an obvious center in this area, indicating that the total non-condensable load exceeded the extraction capacity of one steam jet air ejector unit under the test conditions.

Hence, increasing the venting capacity or limiting the air in-leakage to the condenser to the design value should result in a significant improvement in condenser performance. This is supported by the fact that the area with the lowest cooling-water temperature rise is located, and also remains, in the air-cooler section. Next to this area a cooling-water profile forms which is always directed towards the air cooler. This is consistent with a pressure profile on the steam side, which ensures that the venting flow is always directed towards the air cooler. The formation of isolated zones with no cooling-water temperature rise outside the air-cooler area is prevented by the ABB Alstom Power tube bundle design. A higher venting capacity or the limitation of air in-leakage will therefore always result in an improvement in the condenser performance under high non-condensable load conditions, as evident in test 06 and test 07. This has been clearly demonstrated by changing from operation with one to operation with two steam jet air ejectors (tests 07 and 07A).

The condenser pressure characteristic for the cases with one and two SJAEs in operation is shown in **10**. Similarly, the local cooling-water temperature rise is different for these two cases. The situation shown in **9**, which reflects the local cooling-water temperature rise with one SJAE in operation, is used as the starting point. The mode with two SJAEs in operation passes through a transient phase (9:47 to



Measured cooling-water temperature rise for test 07 (with make-up water) **9**

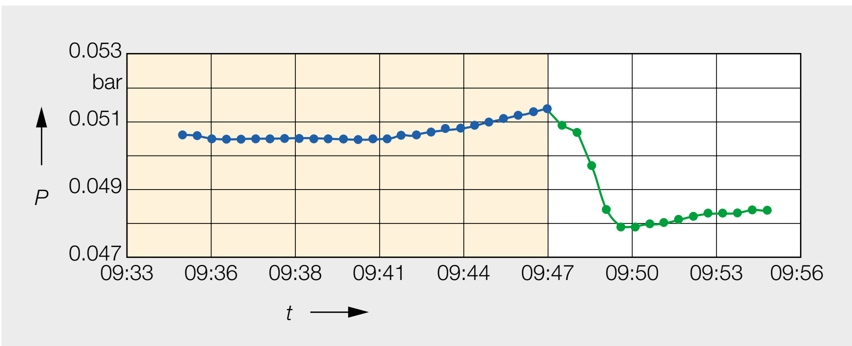
Thermal load: 92.9 MW; make-up water: 24.21 kg/s

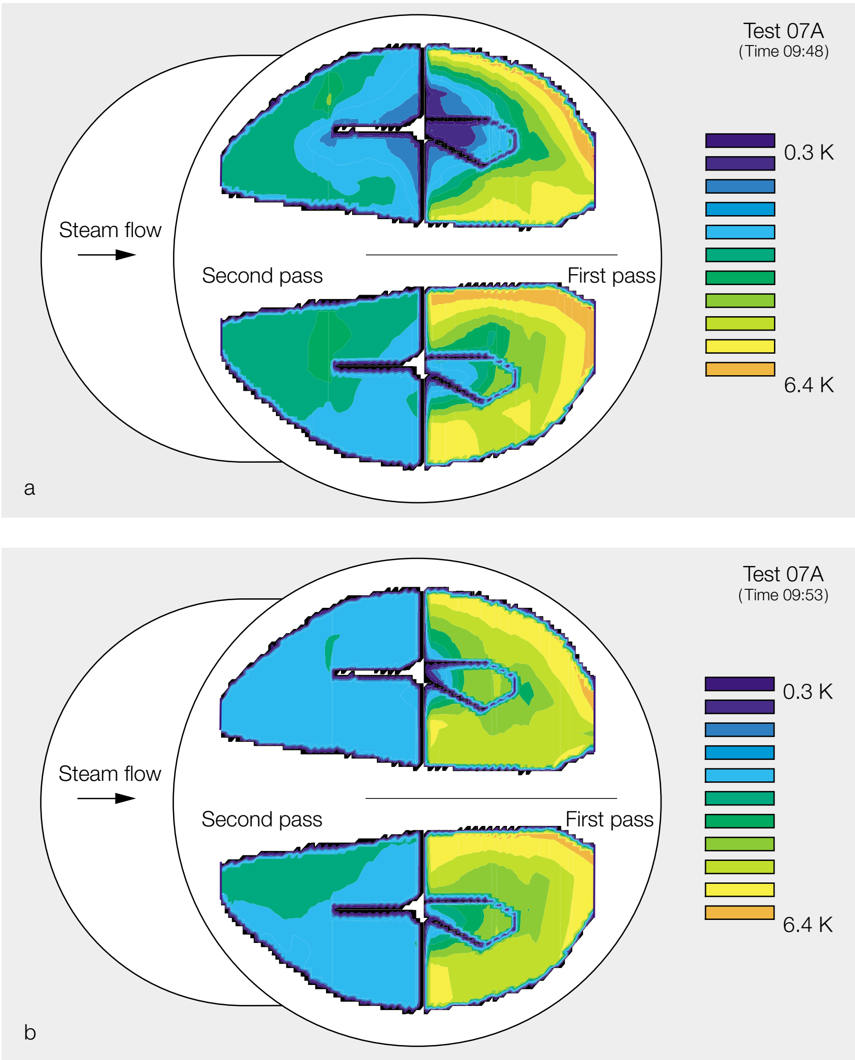
Condenser pressure readings during test with one and two steam jet air ejectors in operation **10**

Test 07; 1 SJAE in operation
Test 07A; 2 SJAEs in operation

P Pressure
t Time

Make-up water: 24.21 kg/s





Cooling-water temperature rise for two SJAEs in operation (test 07A), measured during the transient phase (a) and steady-state phase (b) **11**

Thermal load: 92.9 MW; make-up water: 24.21 kg/s

9:49) 11a, followed by steady-state conditions 11b. The trend is clearly towards a perfectly functioning condenser, the reason for the significant improvement in performance being in this case the increased venting capacity, which effects the rapid elimination of the air blanketing in the air-cooler area.

Oxygen content in the vacuum deaeration and main condensate system

The guaranteed value of the oxygen content in the condensate from the hotwell is 7 ppb. All the tests verified, and 12 shows, that the oxygen content in the condensate line upstream of the main condensate pumps remains well below this value. Even with the largest quantities of make-up water (test 07), the oxygen content in the condensate remains below 3.5 ppb, being clearly due to the significant contribution made by the fall-film deaerator.

Condensate subcooling

Condensate subcooling, T_{cs}, is defined as the difference between the condenser temperature (saturation temperature at condenser pressure), T_c, and the condensate temperature in the main condensate line, T_{ch}:

$$T_{cs} = T_c - T_{ch}$$

As 13 shows, condensate subcooling is always negative, regardless of the operating conditions. This fact, which has also been verified by other tests, confirms the excellent regenerative properties of this condenser concept and underlines the considerable contribution ABB Alstom Power condensers make to minimizing the exergetic losses of the overall plant.

Vacuum decay

By measuring the condenser vacuum decay rate it is possible to determine the air in-leakage into all parts of the system at below-atmospheric pressures.

A vacuum decay rate of 6 mbar/min was measured, indicating that the air in-leakage into the system during the tests was approximately three times the design air in-leakage rate. As verified by tests 06 and 07, the excessive air in-leakage had

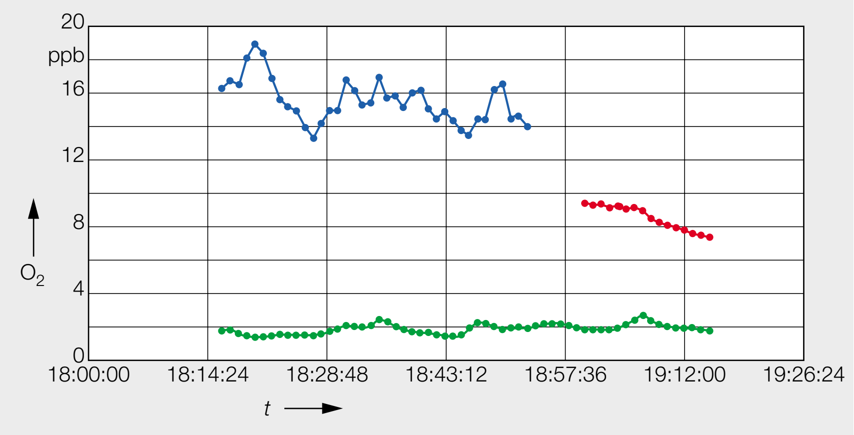
Table 4
Cooling-water pressure loss, Δp

Test no	Thermal load [MW]	Make-up water [kg/s]	Δp_e experiment [bar]	Δp_c calculated [bar]	$\frac{\Delta p_e - \Delta p_c}{\Delta p_e}$ [%]
Test 02	112.69	0.000	0.531	0.510	4.100
Test 06	100.21	19.340	0.534	0.554	–3.600
Test 07	92.9	24.210	0.540	0.535	0.900

an adverse effect on the heat transfer at the condenser tubes, especially with high make-up water flow rates and only one SJAE in operation.

Pressure loss on the cooling-water side

Table 4 shows the good agreement of the test results with ABB Alstom Power's design calculations. The accuracy of the measurements of the pressure loss on the cooling-water side also made it possible to verify the rate of flow of the cooling water supplied by the cooling-water pumps.



Oxygen content in condensate (test 06) **12**

Thermal load: 100.2 MW; make-up water: 19.34 kg/s

Condensate pipe
After falling film deaerator
After deaerator

O_2 *Oxygen content*
t *Time*

Summary of test results

The measurements show that the performance of the condenser and vacuum deaeration system easily meets the customer's requirements under the test conditions. It can also be clearly seen that the outstanding regenerative characteristic and the deaerating capability of the ABB Alstom Power tube bundle is in no way impaired by higher than expected air in-leakage rates, even with high make-up water mass flows. As the evaluation shows, the experimental findings reflect the reliability of the in-house calculation methods for CB steam condensers in axial arrangement.

The success of the comprehensive measurement programme and its completion within a tight time schedule can be attributed to a large extent to the excellent co-operation between all parties involved.

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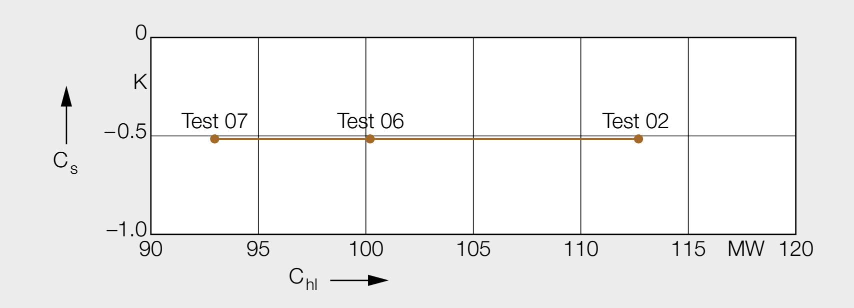

Condensate subcooling (tests 02, 06, 07) **13**

C_s *Condensate subcooling*

C_{hl} *Condenser heat load*

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