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NEW GENERATION 'BLOCK-MODULAR' CONDENSER FOR K-1000-60 / 1500-2 TURBINE UNITS IN ZAPOROZHSKAYA NPP

Проведена модернізація конденсаторів турбоустановки К-1000-60 / 1500-2 ВП «Запорізька АЕС» на енергоблоці № 3, в результаті якої здійснено заміну трубних систем з охолоджуючими трубами з мідно-нікелевого сплаву і зовнішніми дошками з вуглецевої сталі на нові системи з охолоджуючими трубами і зовнішніми дошками з корозійностійкої сталі аустенітного класу. Запропонована «блочно-модульна» конструкція конденсатора нового покоління підвищує надійність, працездатність, безпеку і збільшує термін служби.

Introduction

The condensing devices of steam turbine plants considerably determine the reliable and economical operation of NPP power units. Particularly noticeable is the influence of deterioration in the functioning of condensers on the efficiency of NPP power units, where the steam discharge intensity is much higher than that in TPPs. In some cases, breakdowns in the operation of the condenser result in a forced decrease in the electric capacity of the power unit and a decline in the reliability, as well as in a significant underproduction of electric power.

The Public Joint Stock Corporation (PJSC) 'Turboatom' has modernized the condensers for the K-1000-60/1500-2 turbine unit of the SE 'Zaporozhskaya NPP' power unit No. 3. The proposed 'block-modular' design of the new generation condenser will improve reliability, efficiency, safety and prolong the service life. In the created design of the condenser, author's developments of PJSC 'Turboatom' [1] were used. The design of the 'block-modular' condenser, in particular, of the tube systems, has no analogs in nuclear turbine construction, and it is an invention of PJSC 'Turboatom' [2].

Technological aspects of modernizing NPP condensers

The main reason determining the necessity to modernize the condensers is the damage to the metal in different sections of the cooling tubes, caused by erosion-corrosion under the influence of the turbulent flow of the cooling water saturated with oxygen, as well as presence of solid particles and other contaminants, which results in the breakage of the water density of the tube systems, leakage of copper into the cycle of the turbine unit and, in the long run, in the loss of the turbine electric power, reduction in resource and deterioration of the operational reliability of the auxiliary equipment and steam generators, which, finally, sharply worsens the performance of the NPP.

Leakages are formed at the 'tube-to-external plate' joints due to the leakage from the tubes, as well as due to the development of water drop erosion and ammonia corrosion from the side where the steam passes.

Fig. 1. depicts the defects of tube systems during their operation in NPP condensers.

Exclusion of copper-containing materials from the equipment of the second circuit and achievement of the complete absence of the cooling water leakages into the vapor space of the condenser is the priority and main task for ensuring the reliable and safe operation of the turbine unit equipment and, ultimately, improving the performance of the NPP.

Fig. 1. Defects of tube systems during their operation in NPP condensers

Based on the results of surveying the condensers, it was established that after prolonged use, defects appear in turbine condensers, which results in suctions of cooling water. They become apparent after a certain time, tend to gradually grow and lead to deviations of the water-chemical regime of the turbine unit second circuit both in the concentration of 'chloride ions' in the purging water of the steam generators and in the concentration of 'sodium ions' in the main condensate.

Based on the analysis of the condition of the tube systems of the operating condensers and the factors affecting their damageability, it can be concluded that the most likely causes of appearance of this type of defects are: corrosion cracking of the metal in the places of local mechanical impact; development of pitting-ulcer defect or application of loads in the places of rolling joints; mechanical damage to the tubes. Among the main reasons, leakages in the condenser tubes can also be singled out due to the development of water drop erosion and ammonia corrosion from the side where the steam passes, the development of phosphate slime corrosion as a result of the addition of phosphorus compounds to the steam-water circuit, the disruption of the integrity of the polymer anticorrosion coating in the places of rolling pipes in a tube plate, the development of crevice corrosion in the damaged zone, increased by the creation of a contact electrochemical copper-iron couple, erosion-corrosion washouts in sections having polymeric or other type of coating.

Thus, leakages of cooling water in steam turbine condensers is a source of corrosive-aggressive chloride ion and sulfate ion contaminants coming into the cycle of a turbine unit, causing corrosion of the auxiliary equipment of the turbine unit, in particular, steam generators, which is a very serious problem.

The purpose and tasks of modernizing the condenser of the K-1000-60 / 1500-2 turbine unit

The purpose of modernizing the condenser is to develop and install the 'block-modular' condensers on the existing foundation in the engine room, while preserving geometric and layout solutions in the engine room, obtaining the effect of the modernization by deepening the design vapor pressure with the subsequent increase in the turbine unit electrical power across the generator terminals.

The concept of modernizing the condenser design can be formulated as follows:

– ensuring vacuum and water density of the condenser and the requirements associated with the deaeration of the condensate;

– ensuring the calculated value of the pressure of the exhausted turbine steam during the turbine unit operation;

– reliability performance in stationary, variable, and transient operation modes;

– high maneuverability in a wide range of the turbine unit operation modes.

Design features of the new generation condensers

Increased requirements for water density of the condensers for NPP power steam turbines led to the use of cooling tubes made of materials more resistant against erosion and corrosion damage − high-alloyed stainless steels and titanium alloys.

In contrast to the band arrangements of the tube bundles [3] previously used in the condensers of steam turbines, while developing the design, the modular configuration (Fig. 2), having smaller mass and size parameters and a high thermal efficiency, was adopted. The use of such an arrangement allows a design-

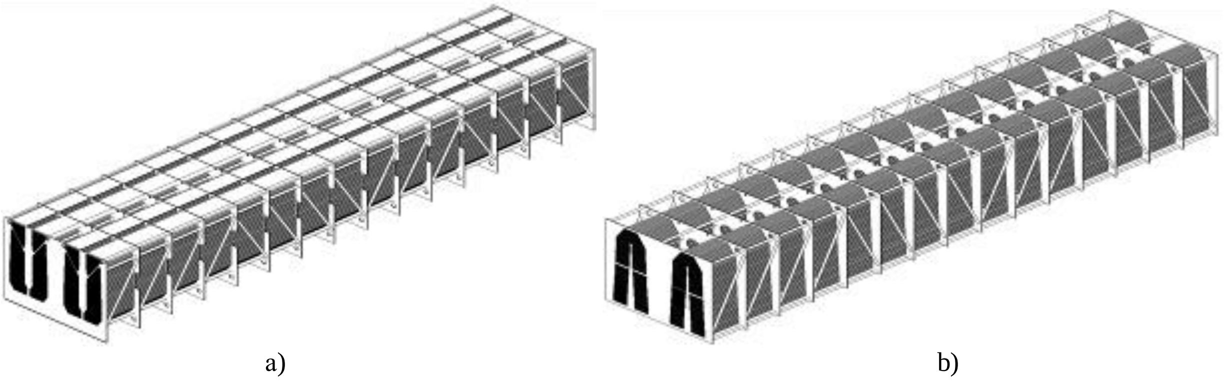

Fig. 2. 'Block-modular' arrangement of the new K-38080 condenser tube bundle:
a) − lower module of the K-38080 condenser housing; b − upper module of the condenser housing

er to create the condenser in blocks and modules, which, in the end, ensures its more convenient transportation and installation during the overhaul period.

The new condenser is a surface-type, two-way and two-flow cooling water condenser structurally made of a shell, water chambers, covers, a transitional branch tube with receiving and discharging devices, condensate collectors, rod-type supports. The condenser housings consist of 6 modules.

The criteria for selecting the number of modules in the condenser housings are: geometric dimensions of the end surface of the tube plates; total heat transfer surface area; number of tubes; configuration of the tube bundle, taking into account the multiplicity of cooling; design speeds in the flow sections in the tube bundle; places for air removal and their addition; places of discharge of high-potential steam streams; stability conditions; places of installation on the road-type supports of the foundation. All this determined the optimal choice of the number of modules in the condenser housings as a whole, both for the basement and lateral location in the engine room.

The advantage of the 'block-modular' type tube bundle consists in a significant decrease of the coefficient of filling the tube plates to optimal values ($ή = 0.25 − 0.26$), which improves the steam admission to the cooling tubes and intensifies the heat exchange process. This makes it possible to fully implement the calculated thermal characteristics of the condenser in all the operation modes.

The design of the condenser with the arrangement of the 'block-modular' tube bundle in combination with a tapered tube makes it possible to evenly distribute the loads on the foundation rod-type supports as well as install de-aeration devices, which ensures the de-aerating capacity for the condenser and reduces the oxygen component in the condensate. The shell of the 'block and modular' condenser consists of 6 modules supplied in the form of longitudinal 'block-modules' with the cooling tubes assembled, flared and welded to the external plates by the manufacturer and meant to be later connected to each other during installation by welding. The design of the tube systems (modules No. 1 − 6) provides for the elimination of thermal stress in the tubes at welding points in the external plates when a relative movement of the shell and tubes occurs.

Modernization of the condensers of 1,000 MW NPP turbine plants is aimed at replacement of the existing tube systems (cooling tubes made of MNZh 5-1 copper-nickel alloy, external plates made of grade ST.3SP5 carbon steel, intermediate plates made of grade ST.3SP5 carbon steel) with new pipe systems (cooling tubes made of grade TP 316L austenitic corrosion-resistant steel, with resistance to pitting corrosion, with a coefficient of pitting corrosion of PRE = 27 units, external plates made of grade 316L or 08X18H10T austenitic corrosion-resistant steel, intermediate plates made of grade 09G2S silicon-manganese steel, other parts and assemblies made of grade 20 carbon steel).

The tube bundle consists of tubes welded of austenitic corrosion-resistant steel and is made up of Ø23×0.5×14,060 mm and Ø23×1.0×14,060 mm cooling tubes, respectively.

The arrangement of the 'modular' type tube bundle is developed on certain design principles [4, 5] of steam exhausts from law pressure cylinders (LPC), taking into account the aerodynamics of the steam flow in the exhaust part of the LPC, and has its own design features associated with the direction of the steam flow relative to the tube bundle and the mutual arrangement of the steam turbine LPCs and condensers:

– with minimal losses at the entrance to the tube bundle, which are determined by the aerodynamic flow of steam at the exhaust part of the turbine LPC ;

– at low values of steam velocities at the entrance to the tube bundle, which are achieved due to tube discharge in the first rows of the bundle along the steam path, which leads to a significant decrease in the resistance of the steam flow.

The tube bundle of the 'modular' type is so designed that it makes it possible to reduce the circumferential unevenness of the pressure behind the LPC last stage blades and creates more favorable conditions for restoring pressure from the LPC last stage to the condenser, which allows ensuring their dynamic reliability.

The condenser tube bundle is supported by intermediate plates which are located at equal distances from each other, taking into account the optimization of the distance. In the intermediate plates, in the places between the individual zones for the holes intended for the cooling tubes, there are cutouts for equalizing the pressure in the condenser shell, as well as cutouts in the lower parts for the condensate flow towards the condensate collectors. The vapor-air mixture from the air cooler zone is withdrawn by means of boxes located in each compartment of the condenser, passes through the rear water chamber, where it is accumulated in the single collector and sucked off by the steam jet ejector. Cooling water is supplied to the lower part of the front water chamber of each half of the condenser. Cooling water is then discharged from the upper part of the front chamber of each half of the condenser.

The design of the condenser with a 'modular' arrangement of the tube bundle prevents the condensate from being overcooled and saturated with non-condensable gases. It is airtight and eliminates air suction, as well as the ingress of cooling water into the vapor space. The maximum value of the possible suction of cooling water in the vapor space of the condenser is not more than 0.00001 % of the steam flow rate to the condenser during the latter’s service life. When the condenser is operating and the suction of cooling water is possible, the electroconductivity of the main condensate does not exceed 0.2 μS/cm.

In the design of the lower modules, additional elements (de-aeration shields and de-aeration devices) are provided, making it possible to reduce the oxygen component in the condensate and ensure the reliable and safe operation of the condensate pumps of the main condensate system of the turbine unit (Fig. 3). This is a new technical development that was not previously used in the existing designs of the condensers developed by PJSC 'Turboatom', operating at NPPs and TPPs in Ukraine, as well as in condensers of foreign designs.

This design has the advantage that the condensate formed inside the condenser, after passing the elements of the de-aeration system in the modules (de-aeration shields installed under the tube bundle and deaerating devices located above the de-aeration shields), makes it possible to significantly reduce the mass content of oxygen in the main condensate (before the high-speed desalting unit is reached) to the low values of 10 − 5 mcg/kg, which are lower than the standard ones (25 mcg/kg) for the power unit.

The design of the shell (modules Nos. 1 − 6) provides for the elimination of thermal stress in the tubes at welding points in the external plates when a relative movement of the shell and tubes occurs.The thermal stresses in the tube-to-external plate junction points are taken into account in the evaluation of the strength of the condenser design elements both when calculating the peak-to-peak values of reduced stresses (σ) RV determined by the sums of the membrane, flexural, temperature and compensating stress components, and the amplitude of reduced stresses (σaF)V determined by the sums of the membrane, flexural, temperature and compensating stress components, taking into account the stress concentration. Reduction in temperature and compensating stresses in the design elements of the condenser to the level of requirements in [6] is achieved by the optimum ratio between the stiffness characteristics of the mating elements of the structure when the axis of the cooling tubes is installed in a bow-like manner. The peak-to-peak values of reduced stresses (σ) RV and the amplitude of reduced stresses (σaF)V in the structural elements satisfy the requirements in [6] when estimating the static and cyclic strength, respectively.

The thermal stresses in the tube-to-external plate junction points are taken into account in the evaluation of the strength of the condenser design elements both when calculating the peak-to-peak values of reduced stresses (σ)RV determined by the sums of the membrane, flexural, temperature and compensating stress components, and the amplitude of reduced stresses (σaF)V determined by the sums of the membrane, flexural, temperature and compensating stress components, taking into account the stress concentration. Reduction in temperature and compensating stresses in the design elements of the condenser to the level of requirements in [6] is achieved by the optimum ratio between the stiffness characteristics of the mating elements of the structure when the axis of the cooling tubes is installed in a bow-like manner. The peak-to-peak values of reduced stresses (σ)RV and the amplitude of reduced stresses (σaF)V in the structural elements satisfy the requirements in [6] when estimating the static and cyclic strength, respectively.

The new 'block-modular' design of the condenser tube systems was developed in accordance with real structural features of the foundation and a possibility for the new tube systems to be installed on the existing systems of flexible rod-type supports, which were determined on the basis of the strength and stability conditions of the condenser design and distribution of loads on the lower part of the foundation (Fig. 4).

Providing the vibration strength of the cooling tubes (the assortment of tubes being Ø23x0.5x14,060 mm and Ø23x1.0x14,060 mm) and the stability of the entire condenser design led to the technical need to change the number of plates in each module of the shell from 10 (20 mm thick) pieces to 16 (16 mm thick) pieces, which allowed to choose and calculate the optimal distances between the intermediate plates, ensuring the vibration strength of the cooling tubes, taking into account the stability of the entire structure during normal operation. When installing tubes in a bow-like manner, the distances between the intermediate plates are optimized equaling to 781.5 − 781.0 mm. The inner surfaces of the front and rear water chambers have an anti-corrosion coating to prevent corrosion damage. In the tube bundles of the condenser modules, zones for the withdrawal of uncondensed vapor-air mixture are provided.

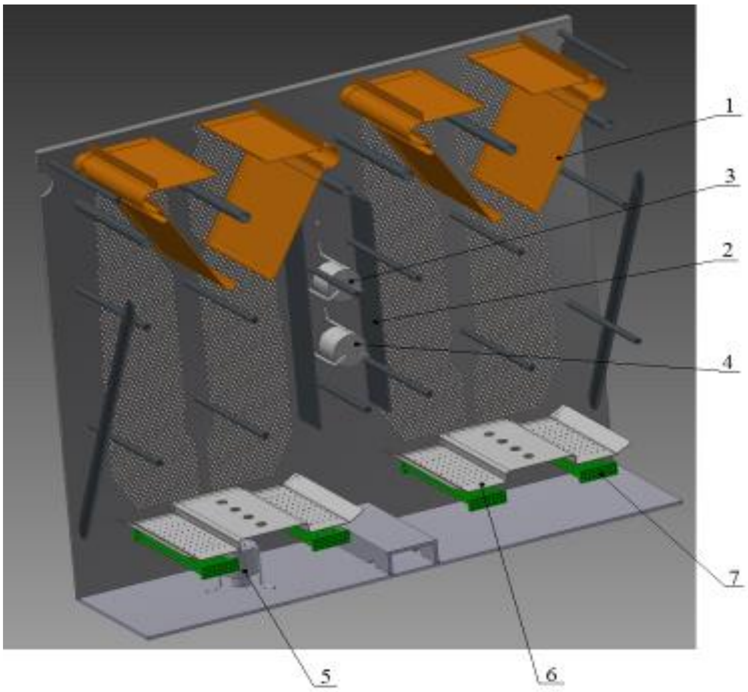

Fig. 3 Elements of the module construction:
1 – steam shield; 2 – protection plate;
3, 4 – branch pipes (for reception of discharges of high-potential drains);
5 – branch pipe (for reception of discharges of low-potential drains);
6 – de-aeration shield; 7 – de-aeration device

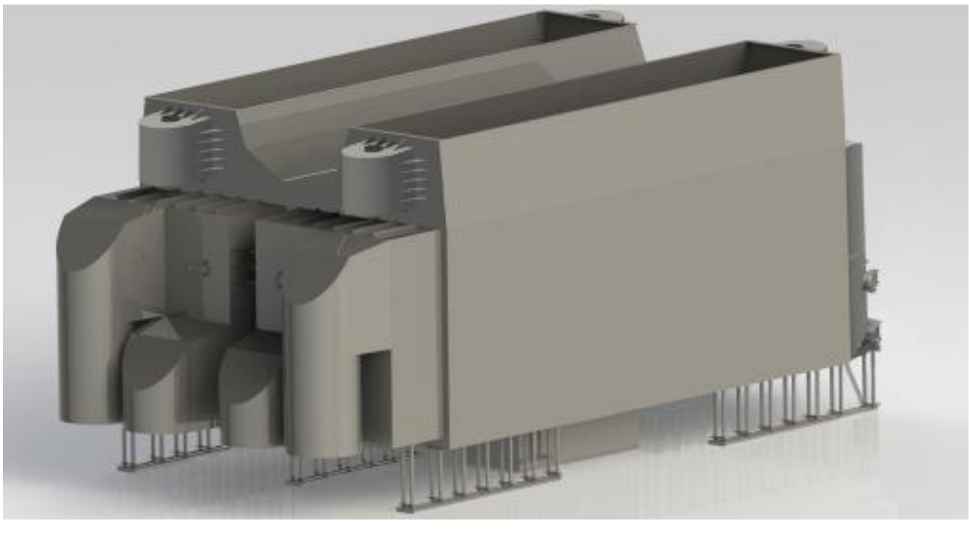

Fig. 4 Three-dimensional model of the 'block-modular' K-38080 condenser on rod-type supports

For the uniform distribution of the loads acting on the existing rod-type supports in case of an increase in the number of the intermediate plates, 'rigid elements' are installed on the bottoms of the modules, from the side of the steam space, between the intermediate plates. These elements are beams of the required rigidity, which serve to equalize the possible deformations and, as a consequence, the support reactions where the condenser is installed on the supports. This makes it possible to install the new condenser tube systems on the existing foundation rod-type supports without changing their design and layout solutions.

The characteristics of the condenser before and after modernization are presented in Table 1, and the efficiency of the modernization is presented in Table 2.

Table 1. Condenser design characteristics before and after modernization

Name	Condenser:	
	before modernization	after modernization
Constructive characteristics:		
type	surface , К-33160	surface , К-38080
cooling surface, m^2	33160	38080
tube type	solid tube	welded tube
tube assortment, mm	Ø28x1x8970 Ø28x2x8970	Ø23x0,5x14060 Ø23x1,0x14060
number of tubes	26940	37644
fastening of tubes in external plates	rolling	rolling and welding
number of passes/flows	2 / 2	2 / 2
Calculation characteristics per one condenser:		
steam flow rate in the condenser, ton/h	1114,22	1114,22
steam pressure in condenser, kPa	3,825	3,570
cooling water flow rate in the condenser tubes, ton/h	56600	56000
calculated temperature of cooling water, °C	15	15
speed of water in tubes, m/s	2,1	2,0
Materials:		
tube cooling	copper-nickel alloy	steel grades TP 316L
external plate	steel grade 20	steel grades 08Х18Н10Т
intermediate plate	steel grade Ст.3 сп5	steel grade 09Г2С
Mass characteristics:		
Condenser without supports, kg	621000	523000

Table 2. Condenser operating characteristics before and after modernization

Estimated temperature of the cooling water at the entrance to the condenser, °C	Average value of the steam pressure of the existing condenser, kPa	Average value of the steam pressure of the modernized condenser, kPa	Increase in the turbine plant electrical power across the generator terminals after the condenser modernization, MW
15	3,825	3,570	0,90
20	4,923	4,668	2,10
25	6,414	6,100	3,10
30	8,345	7,963	4,10
35	10,846	10,356	5,20

Conclusion

Thus, the new design of the condenser provides:

– installation of the shells on the existing foundation supports without changing the foundation design and its calculation;

– density of fastening the cooling tubes in the external tubes due to rolling and welding according to the technology of the manufacturer;

– deepening the design vapor pressure in the condenser (vacuum) with a corresponding increase in the electrical power of the turbine unit across the generator terminals;

– installation of hatches at the entrance, exit, and intermediate chambers, providing access to the cooling tubes to determine the possible tube defects and control the tightness of the connection between the cooling tubes and the external plates;

– coating the internal surfaces of the water chambers, covers, and anchor connections with anti-corrosion material;

– withdrawal of the uncondensed vapor-air mixture from the tube bundle;

– complete condensation of the vapor coming from of the turbine LPCs;

– operability when forcing the reactor plant's thermal power to 3210 MW (107 %).

The reliable and economical operation of the condenser is achieved by using:

– materials for tube systems, which are resistant to erosive and corrosive effects from the cooling water;

– ensuring the reliability and tightness of the cooling tubes in the external plates (rolling and welding of the cooling tubes in the external boards);

– prevention of parking corrosion (installation of the tubes in a bow-like manner);

– correct choice of the distance between the external and intermediate plates in order to reduce vibration and the use of an efficient arrangement of the tube bundle as well as ensuring the optimal speed of the steam flow;

– application of the modular arrangement of the tube bundle;

– arrangement of receiving steam-water streams into the condenser in order to eliminate erosion of the cooling pipes;

– supply of module-blocks with the cooling tubes full of factory readiness, with the required control and quality ensured.

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