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# Modernization of Steam Turbine Heat Exchangers Under Operation at Russia Power Plants

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Additional information is available at the end of the chapter

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## 1. Introduction

The authors' experience in the modernization of commercial heat exchangers in steam turbine units is discussed with the individual features of the operation of these heat exchangers at specific thermal power plants taken into account. The variety of conditions under which heat exchangers operate in specific engineering subsystems requires an individualized approach to the model solutions that have been developed for these systems modernizing. New tube systems for commercial heat exchangers have undergone industrial testing and are in successful operation at a wide range of thermal power plants.

## 2. Research problem formulation

Extending the service life and increasing the operational efficiency and reliability of heat exchangers in steam turbine units at thermal power plants are of great current interest. Modernizing heat exchangers, operating at thermal power plants, involves less expense than replacing the entire heat exchanger and is mainly aimed at eliminating structural defects that have been identified. This is done both when worn out components are replaced and in the course of planned major overhauls, so that the efficiency and operational reliability of the heat exchangers and the steam turbine unit, as a whole, can be increased substantially.

The major engineering solutions for improvement of commercial heat exchangers in thermal power plants steam turbine units must, first of all, be directed at enhancing the efficiency and reliability of their tube systems, since they are the most subject to wear during operation. The choice of approaches and modern engineering solutions for heat exchangers improvement must meet a number of specifications including the following [1]:

- taking into consideration the specific operating conditions;
- raising the efficiency of heat exchanger while retaining reliability or increasing reliability while maintaining efficiency;
- improving or sustaining repairability and maintainability;
- meeting the standards and rules of the supervisory agency Rostekhnadzor.

The improvement of heat exchangers is a rather complicated system problem. A large number of factors at different levels which influence the efficiency and reliability of a heat exchanger should be taken into account, along with its relationship to the engineering subsystems of steam turbine unit of a thermal power plant. The choice of a modernization scheme involves solving a specific optimization problem where the target function or criterion determining the choice may be any of various characteristics, such as raising the thermal efficiency or the thermal capacity of heat exchanger, or increasing its operational reliability or repairability.

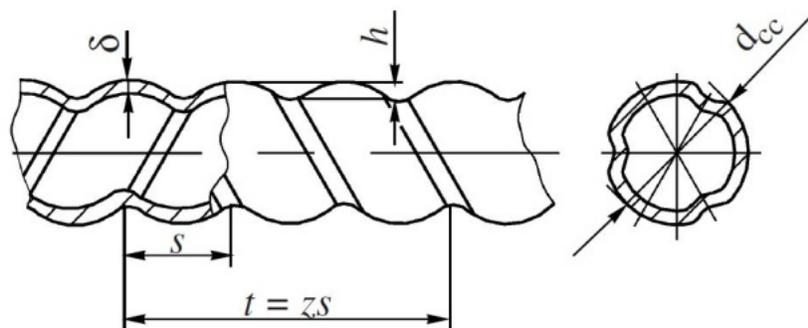
The approach determination for heat exchanger improvement can be divided structurally into three stages: a stage for analyzing the initial data, a stage of computations and accounting for a number of operational and design-engineering factors and a stage of technical and economic analysis and evaluation. One of the most important stages in the analysis is the use of computational methods which take most complete account of the features and behavior of the processes occurring in steam turbine heat exchangers. These methods are used to calculate separately heat transfer coefficients for two heat transfer media, while individual factors affecting the heat transfer are taken into account by introducing corrections to heat transfer coefficients base values. When estimating a choice of improvement method, each specific heat exchanger is considered as a component of a particular engineering subsystem of steam turbine (condensation unit, system for regenerative feed water heating, system of hot water heating, etc.) in which it is employed; here the effect of the proposed modernization scheme on other elements of the subsystem or on the turbine unit as a whole is evaluated.

When improvements are made in heat exchangers at thermal power plants under operating conditions, it is necessary to analyze and take into account a large number of factors and performance indicators, including the specific operating conditions. Most often it is possible to optimize only the basic (thermal and hydraulic) operating characteristics of heat exchanger, leaving the others at levels corresponding to commercial apparatuses.

### **3. Selection and justification of technical solutions for heat exchanger modernization**

Over many years the authors have proposed, tested and brought to realization a series of new, by now commercial, technical solutions for modernizing a large number of different heat exchangers for steam turbine units; these have provided satisfactory solutions of the problems arising during heat exchanger operation, such as [1–3]:

- retaining the external connector dimensions (through pipes and shells) of commercial equipment without change;
- estimation of the choice of material for tube systems and shell components (water chambers);
- use of high efficiency profiled tubes of different materials with optimal profiling parameters (Fig.1);
- optimization of the tube bundles configuration in heat exchangers (in some cases — the increase of heat transfer surface within the shell sizes of commercial heat exchangers);
- optimization of the intermediate partitions arrangement, the rise of tube system vibrational reliability by installing damper belts and clamps;
- employing of a high efficiency method for tubes to tube sheets fixing with the use of annular reliefs made in the tube sheet metal;
- efficient sealing of gaps between the intermediate partitions and the shell (for heat exchangers of “liquid — liquid” type);
- use of special protective coatings.



$\delta$  is the wall thickness,  $h$  is the groove depth,  $s$  is the pitch between neighboring grooves,  $z$  is the number of profiling threads,  $t$  is the thread rolling pitch, and  $d_{cc}$  is the circumferential diameter

**Figure 1.** External view and cross section of profiled twisted tube.

Retrofitting of the oil supply systems of turbine units is intended not only to recover indices characterizing their efficiency and environmental security but also to carry out measures that will improve their characteristics without significant financial and material outlays. These problems may be solved on the basis of technical considerations aimed primarily at oil coolers design.

Our analysis of the efficiency and in-service reliability of over 150 serially produced oil coolers, as well as the data of the Ural All-Russia Thermal Engineering Institute on the vulnerability to damage of oil coolers in service at steam-turbine units, has shown that the elements of these heat-exchangers most susceptible to damage are their tube bundles.

A summary of this data and also the results of tests on a number of apparatuses and experience with their operation under different conditions allowed us to formulate the main lines along which commercially produced oil coolers should be modernized. They are as follows:

- the selection of advanced materials for the elements of the construction;
- the use of heat exchange surfaces that augment heat transfer;
- the creation of optimized layouts for the tube bundles;
- the sealing of gaps in the oil space of the apparatuses;
- the improvement of the reliability of tubes fixing to the tube sheet;
- the protection of the tube sheets against corrosion.

Below, these lines will be considered in more detail.

When selecting the material for the structural elements of an oil cooler, several factors should be taken into account, such as the corrosiveness of the cooling water and the associated corrosion resistance of the heat-transfer tubes; the thermal and hydraulic characteristics of the tubes and their adhesive properties; the compatibility of different materials in one apparatus; the technological features of an assembly of apparatuses with the tubes made of the material selected; and also considerations of cost. The casing of the oil cooler and its parts are usually made of carbon-steel sheets and the tube sheets — of carbon-steel plates or from different types of brass. At most thermal power stations, tubes of brass L68 are installed in the oil coolers; this does not comply with present-day requirements. If a feasibility study is conducted and tubes of corrosion-resistant steels are used in the oil coolers, water chambers and tube sheets made of steels 12Cr18Ni10Ti or Cr23Ni17Mo2Ti can be manufactured. Lately stainless steel tubes are being installed more and more frequently in oil coolers. Considering the higher corrosiveness of the cooling water and the more stringent requirements for environmental safety of thermal power stations, in our opinion, the latter solution is more expedient.

When using stainless-steel tubes in oil coolers, one should bear in mind that the heating capacity of the apparatuses has decreased, because the thermal conductance of the steel is 6–7 times lower than that of brass.

Lately, the problem of using titanium alloy tubes in the tube bundles of heat exchangers has been widely discussed. Note that, notwithstanding the high corrosion-resistant and adhesive properties of titanium, several problems in its use still exist, such as protection of the “ferrous” metal of the tube sheets against electrochemical corrosion if it contacts the titanium and the insufficient resistance of titanium to friction wear and its corrosion instability in alkaline solutions with a  $\text{pH} > 10$ . Note also that the cost of titanium is higher than that of other materials.

The larger overall dimensions of oil coolers for high-power turbine installations required their developers and manufacturers to revise several basic concepts in the design of apparatuses associated, in particular, with the use of new heat exchange surfaces that augment the process of heat transfer, using variously profiled and finned tubes.

We know oil coolers that have tubes with spiral rolled finning, longitudinal welded finning, spiral wire mesh finning, and other kinds of finning. The comparatively new MP-165 and MP-330 oil coolers (for the K-300-240, K-500-240 and K-800-240 turbines manufactured by LMZ), with stainless steel tubes and cross fins manufactured by LMZ instead of the previously manufactured M-240 and M-540 oil coolers, are very efficient products. However, these new designs have, in our opinion, one shortcoming — comparatively low oil velocity, which is due to the non-optimal tube bundle layout in the apparatus.

#### 4. Special features of optimization calculation techniques for heat exchangers

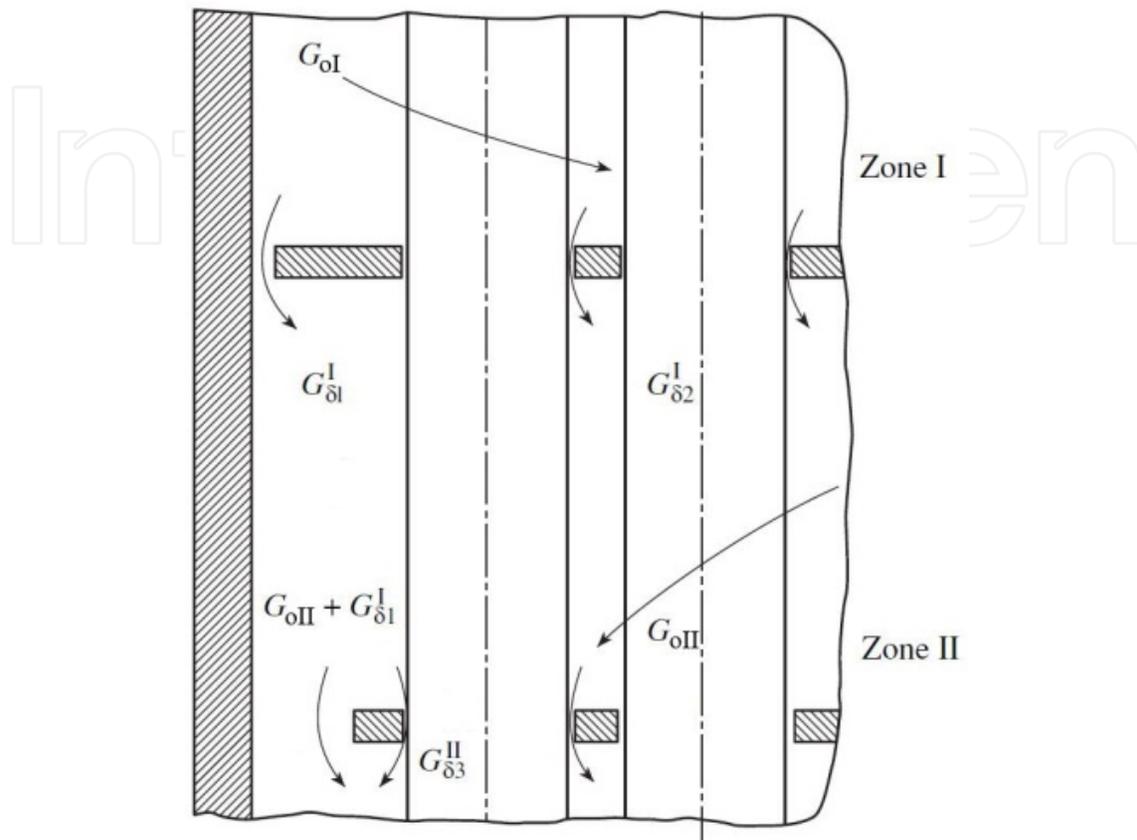
Optimization of the tube bundle layout in heat exchangers, oil coolers included, is one of the most promising ways for improving them. It should be carried out on the basis of a comprehensive calculation of the thermal, hydrodynamic, and reliability characteristics of every given apparatus. The technique for such an optimization calculation has been worked out for oil coolers [4–7] both with plain and with twisted profiled tubes (TPT) that are used in power engineering (see Fig.1). It allows us to account for changes in the parameters of oil in different zones of the apparatus that have been selected downstream of the oil flow. One of the main factors determining the operating efficiency of oil coolers is the leakage of oil through the orifices in the intermediate partition plates and in gaps between the intermediate partition plates and the oil cooler shell. This factor is accounted for in another way.

The permeability of oil through an intermediate partition orifice in the oil cooler was studied at an experimental facility that simulated its geometrical, thermal, and physical performance parameters. The outside diameter of a working tube is 16 mm, the diameter of the orifice in an intermediate partition plate is 16.4 mm, and the thickness of a partition plate is 3 mm. In the experiments we used turbine oil UT30 with a temperature from 35 to 65 °C. The difference in the oil pressures on the partition plate ranged from 850 to 2910 Pa. All the experiments were carried out with the tube centered relative to the orifice in the intermediate partition plate.

Note that the well-known physical laws of liquid flow through an annular slot were confirmed in this study, and the quantitative and qualitative results allowed us to find more exact operating characteristics of oil coolers and to account for them in their designs. The oil flow rate through the annular slot increases as the oil temperature  $t_{oil}$  rises and as the difference in pressure across the slot increases. The throughput capacity for the alternative with twisted profiled tubes (TPT) shown in Fig. 1 is considerably higher than that with an annular gap for a plain tube. In this connection, when designing and calculating oil coolers with TPT bundles and plain tubes, we should allow for a sufficiently high level of idle oil leakages through the annular gaps between the tubes and the orifices in the intermediate partition plates.

In contrast to existing methods, the more exact technique developed by us for calculations of oil coolers employs the zone-by-zone approach and accounts for changes in the oil parameters along the oil flow through the tube bundle (Fig. 2). In this case, the oil space of the oil cooler is divided by the partition plates into a number of zones: the input zone (I), the output zone

(N), and intermediate zones (from I to N) in between. The heights of the zones correspond to the distances between the adjacent partition plates.



**Figure 2.** Scheme of oil flow in an element of a tube bundle of an oil cooler with partition plates of the "disc-ring" type and with unsealed gaps.  $\delta_1$ ,  $\delta_2$ ,  $\delta_3$  are the gaps between the shell and annular partition plate, in the orifices of the annular and disc partition plates;  $G_o$  is the oil flow rate through the tube bundle

In every zone, the oil is separated into two or three flows:  $G_o$  is the flow through the tube bundle;  $G_{oi} = G_o$  and  $G_{oII}$  are the flow rates in zones I and II respectively;  $G_{\delta 1}^I$  is the flow rate in the gap between the annular partition plate and the shell (see zone I in Figure 2); and  $G_{\delta 2}^I$  and  $G_{\delta 3}^I$  stand for flow rates in the gaps between the tube and the walls of the orifices in the intermediate partition plates, the annular and the disk ones, respectively. Then the weighted mean temperature of the oil in every flow is calculated. Here, the oil flow rates  $G_{oII}$ ,  $G_{\delta 1}^I$ ,  $G_{\delta 2}^I$ , and  $G_{\delta 3}^I$  were determined by an iterative calculation similar. In the course of the calculation, at a certain viscosity, the average oil flow rate through the tube bundle became negative. This meant that the oil did not reach the extreme tube rows; that is, the apparatuses have zones of stagnation. After making changes in the tube bundle layout, in particular, by decreasing the number of rows of tubes along the depth of the bundle, the thermal hydraulic calculation was repeated.

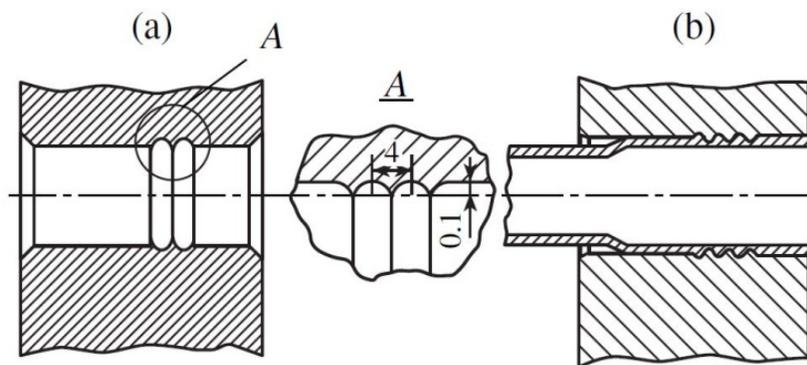
Calculations executed in accordance with the above technique make it possible to optimize the layout of the tube bundles for the oil coolers and to determine such specifics as the number of

rows of tubes that are removed from the center of the tube bundle; the distance between the tubes (the back pitch); the distance between the intermediate partition plates, that is, the number of passes for oil; and others.

## 5. Methods of heat exchanger reliability improvement

It is known that one of the most important elements determining the operating reliability of an oil cooler is the joint attaching the tubes to the tube sheet. Operating experience with shell-and-tube apparatuses shows that mechanical flaring of tubes in the smooth orifices of the tube sheets (the usual way of attaching the tubes) does not ensure a reliable tightness of the joint. It depends on the following factors: the influence of heat cycles in different directions, the inherent and forced vibrations of the tubes in the bundle and in the apparatus as a whole, the corrosive effect of the cooling water, the natural aging of the material of tubes and tube sheets, etc. [1,2].

An improved tightness and reliability of the joint between the tubes and the tube sheets can be obtained by applying a new technology developed by the specialists of the St. Petersburg State Nautical Technical University. It amounts to flaring the tubes using annular reliefs on the metal in the orifices of the tube sheet, which are formed with the aid of a special tool (Fig. 3).



**Figure 3.** Method for attaching tubes to tube plates. (a) An orifice in the tube sheet with annular reliefs; (b) assembly of attachment of the tube to the tube plate after flaring

To find the optimal dimensions, shape, position, and mechanical characteristics of the annular reliefs, computational studies and experiments were conducted that gave the following results:

- in the area of the annular relief, the contact pressure increases considerably (by two to three times);
- the optimal shape of the relief from the standpoint of most complete imbedding into the tube surface is a triangle with a smooth transition from the base to the walls of the orifice (Fig. 3 a);

- the optimal height of the projection on the relief is in the range from 0.07 to 0.15 mm;
- the maximum increase in contact pressure is obtained when the hardness of the surface of the projection is higher by 30 to 35% on average than the hardness of the metal of the tube sheet;
- the annular relief should be located at a distance of at least 5 mm from the boundary of the zone where the tube is attached (flared) in the tube plate.

We checked the efficiency (reliability) of this technology of attachment on one-tube specimens, pilot modules, and a number of commercial apparatuses having tubes of different materials. On the basis of our investigations, we established that the given method provides a higher tightness than other previously known methods used in oil coolers do, and it is actually not inferior to the combined joint with flaring and welding. Nevertheless, note that the labor required by the proposed method is greater than with usual flaring by 25 to 30%. However, this may be justified.

It is known that the tube sheets of oil coolers can be protected against corrosion due to the cooling water in several ways:

- by rational choice of the material;
- by applying metal coatings and coatings based on paints, glass enamels, different resins, etc.

In oil coolers manufacturing, it is expedient to use corrosion-proof materials for the protection of the tube sheets or to apply metal coatings to them. In operation, the surface may be coated with an epoxy resin or minimum.

## 6. Discussion of modernization results for power stations heat exchangers

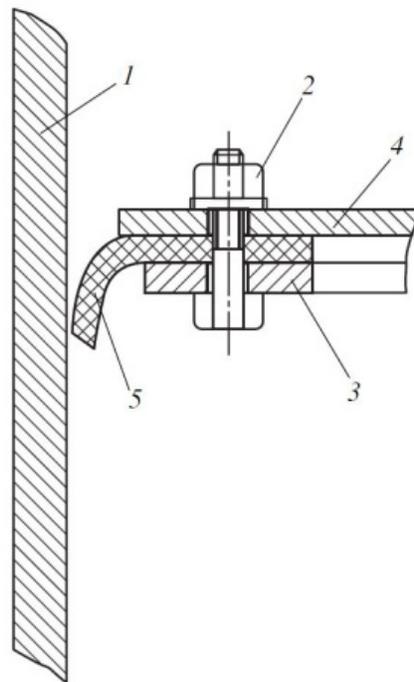
All the above considerations and advanced concepts on improvement of steam-turbine units oil coolers were the basis for modernizing a number of commercially produced oil coolers (MB-63-90; MB-40-60; MP-37; M-21; MOU-12; MO-11; MKh-4), which was done in accordance with our development works. The main measures in retrofitting the oil coolers were taken on the tube bundle, the element most vulnerable to damage in the apparatus. In doing this [1–3]:

- optimization of the layout of the tube bundle is carried out;
- the peripheral annular gap between the intermediate partition plates and the shell of the oil cooler is sealed with an oil-resistant rubber or Teflon plastic (Fig. 4);
- stainless steel twisted profiled tubes (see Fig. 1), whose profile parameters are selected to conform to special apparatuses and conditions of their operation, are employed;
- a new technology for attaching the tubes to the tube plates with annular reliefs is introduced (see above);

- the tube sheets are protected against corrosion.

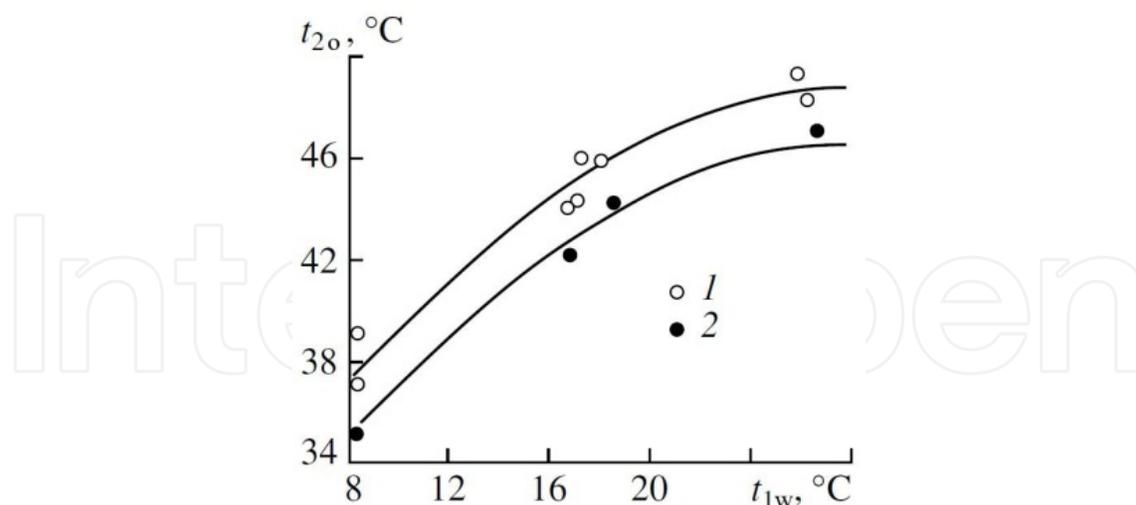
As an example, in Fig. 5 we find the approximated results of comparative tests of an MP-37 oil cooler for a K-100-90 turbine in the Verkhnetagil district power station before and after retrofitting. From the figure we see that the oil outlet temperature of the retrofitted oil cooler is 0.5 to 2.5°C lower than that of a commercially produced oil cooler. Moreover, note that the operating efficiency of the commercially produced plain-tube apparatus conformed to the designed one. Similar results were obtained for other retrofitted oil coolers, as well.

Up to 10 years of operating experience with modernized oil coolers showed that they ensure the reliable service of the apparatuses without any reduction in their thermal efficiency. No remarks about them were received from the operating personnel.



**Figure 4.** The seal between an annular partition plate and the shell of the oil cooler. (1) shell; (2) bolt with a nut; (3) clamping ring; (4) annular partition plate; (5) oil-resistant rubber (plasticized rubber)

By early 2000, the commercially produced oil coolers used in the lubrication systems of all LMZ K-800-240 turbines operating in the Russian Federation had worked out their service life and the question of replacing them arose. Although commercially produced M-540 oil coolers with wire-loop finning were available, replacement of the old oil coolers with these new ones turned to be inexpedient because the design of M-540 oil coolers had considerable shortcomings. The authors of this paper have developed a highly efficient and environmentally safe MB-270-330 shell-and-tube oil cooler with disk-ring partitions and propose for it to be used to replace commercially produced apparatuses. One specific feature relating to the operation of such heat exchangers with single-phase coolants is that the gaps in the structural members of the inter-tube space have an effect on the coefficients of heat transfer on the oil side.



**Figure 5.** Curves of the oil outlet temperature of the MP-37 oil cooler as a function of the water inlet temperature at the Verkhnetagil district power station. (1) commercially produced oil cooler; (2) modernized oil cooler

Experience gained from modernization of oil coolers for 800-MW turbines has shown that stainless tubes should be used in oil coolers for bringing these apparatuses into compliance with the modern requirements for environmental safety of thermal power stations. In this case, in order to compensate for a lower heat conductivity coefficient of tubes (as compared with that in case of using tubes made of nonferrous alloys), it is recommended that smooth tubes be replaced by twisted profiled tubes (TPTs), which can be made of smooth ones by rolling a helical groove on their external surface. The corresponding protrusions will in this case appear on the inner surface of these tubes (see Fig. 1). The use of TPTs in oil coolers with disk-ring partitions is quite efficient, because it results not only in a smaller pressure drop on the oil side of the apparatus (as compared with its smooth-tube version), but also in a lower temperature of oil at the outlet.

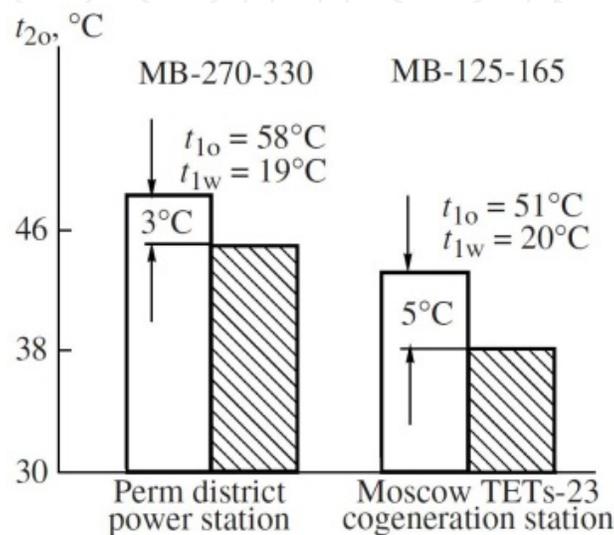
The designs of modernized oil coolers must comply with often contradictory requirements that arise during operation of a thermal power station. This produces a need to carry out calculations of different design versions of oil coolers, which can be performed using zone-to-zone methods. Calculations according to these methods have shown that the number of passes on the oil side has the greatest influence on the thermal- hydraulic characteristics of an oil cooler.

The analysis also shows that there is no sense in sealing the gap in the intermediate partition in oil coolers of “disk-ring” partitions type. The gap between the shell and annular partition, however, should be sealed, because this measure helps improve the efficiency of an oil cooler and obtain lower temperature of oil at the apparatus outlet.

The results of calculations have also shown that the effect of tube material on the oil cooler characteristics is insignificant and that tubes made of Grade 08Cr18Ni10Ti stainless steel are more reliable under specific operating conditions. Changing the diameter of tubes (from 16 to 19 mm) results in that the heat- transfer area becomes 15–18% smaller, and it is hardly

advisable. The transverse pitch between the tubes in the bundle is taken equal to 21 mm in the modernized version, which allowed us to obtain the required level of hydraulic resistance on the oil side.

Fig. 6 shows the results obtained from tests of the pilot MB- 270-330 oil coolers at the Perm district power station. It can be seen from the picture that the new oil cooler has better indicators compared with those of the commercially produced M-540 apparatus, which is manifested in a deeper cooling of oil (by 3°C).



**Figure 6.** Results obtained from comparative tests of oil coolers. (□) Serially produced oil cooler and (▨) modernized oil cooler;  $t_{1o}$  and  $t_{2o}$  are the temperatures of oil at the inlet to the oil cooler and at the outlet from it, and  $t_{1w}$  is the temperature of water at the oil cooler inlet

Thirteen of the fifteen K-800-240 LMZ turbine units that are installed at Russian thermal power stations now are furnished with MB-270-330 oil coolers. Experience gained from long-term (up to 10 year) operation of the modernized oil coolers has confirmed the advisability of the design and engineering solutions used in these apparatuses that ensure their reliable and efficient operation.

Fig. 6 also shows the results obtained from tests of the MB-125-165 oil cooler that was developed by the authors of this paper and is installed in T-250/300-240 turbines of Ural Turbine Works production instead of the M-240 oil coolers with wire-loop finning that have worked out their service life. The main design and engineering solutions implemented in the MB-270-330 apparatus were used in the course of developing the MB-125-165 oil cooler. It follows from Figure 6 that the oil outlet temperature of the MB-125-165 cooler is 5°C lower than that in the commercially produced M-240 oil cooler. Fifteen MB-125-165 oil coolers have now been manufactured and installed at Russian thermal power stations.

In the following we discuss new designs for other heat exchangers that have been developed and carried out using the above proposed approaches and are well to be recommended for

prolonged operation in thermal power plants. The scientific justification for these developments employs a set of theoretical and test stand (physical) studies.

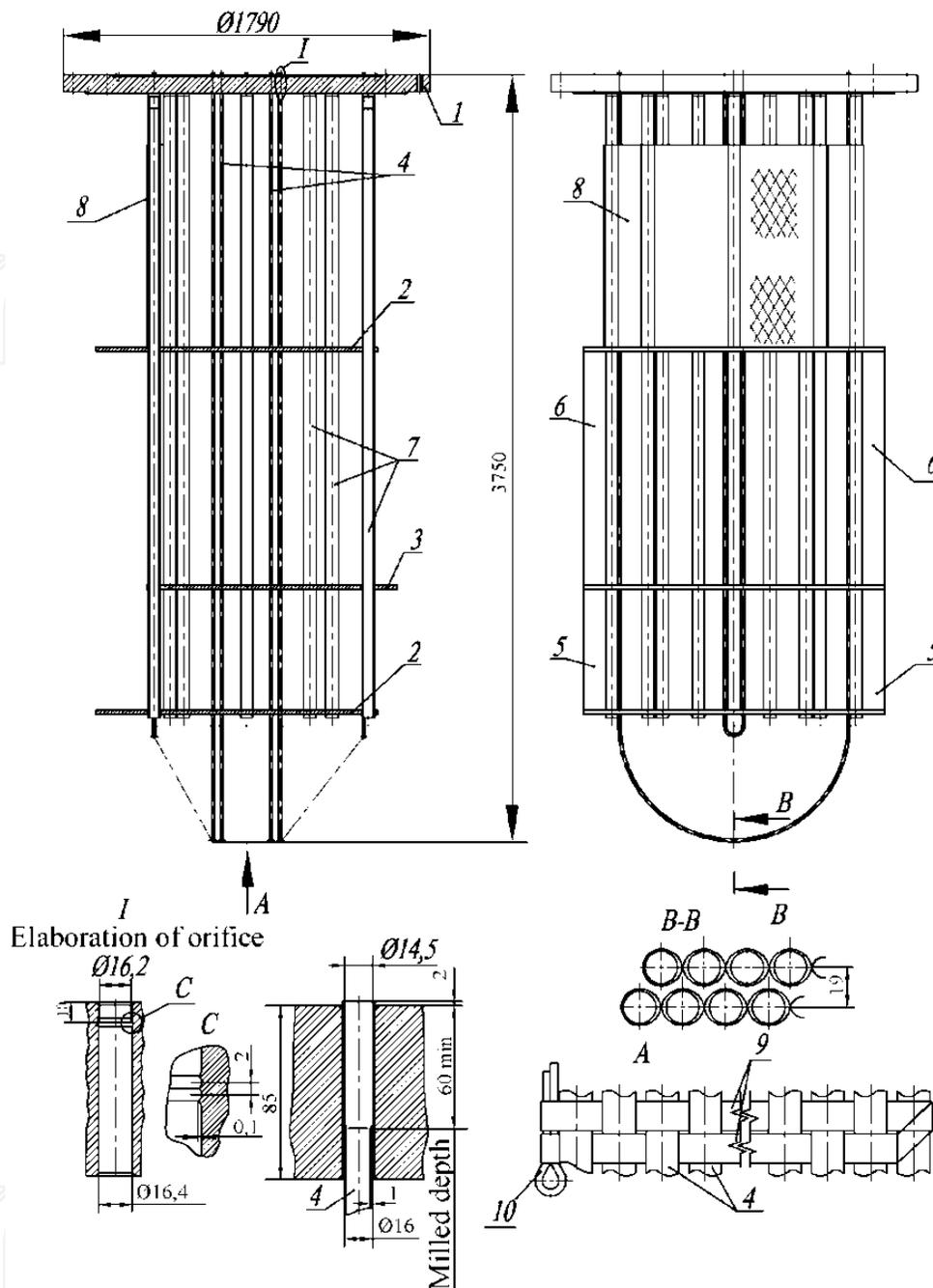
The major problem in modernizing the PSV-315-14-23 hot water heater of KhTZ production K-300-240 turbine at the district heating system of the Reftinskaya State regional electric power plant (GRES) was to develop a design for the preheater which would compensate for the large thermal stresses which develop during startup and shutdown of the preheater while retaining the thermal capacity of the system. Here it was necessary to take into account the fact that during operation under the conditions at the Reftinskaya GRES the main water preheaters essentially operate without being contaminated and they are not cleaned.

This problem is solved by choosing a tube system for the heater (Fig. 7) made of 16/14 mm U-shaped tubes (material CuNi5Fe). The positions of the intermediate partitions are optimized and the bends in the pipes are wound with damping belts in order to reduce the danger of vibrational damage to the tube system. The design of the steam guard shield is changed; this increased the operational reliability of the peripheral sequences of tubes. The casing of the tube system of the heater has vertical and intermediate horizontal baffles whose design facilitates a reduction in the steam return flows alongside the tube bundle, thereby raising its thermal efficiency. The heat exchange surface of the preheater is increased to 335 m<sup>2</sup>. A special method is used to fix the tubes to a tube sheet with orifices flared in advance (see Fig. 7).

The major problem in modernizing a VVT-100 heat exchanger intended for distillate cooling in the water cooling system for the generators of the LMZ K-800-240 turbines at the Perm GRES (Fig.8) was to increase the reparability of the heat exchanger while retaining its reliability and thermal capacity. The problem is stated this way because, after disassembly, repair, and reassembly, the gland seal in the VVT-100 heat exchanger is often not leakproof and, with time, the seals on the annular tube partitions are destroyed.

All components of the tube system of the modernized VVT-100M heat exchanger (profiled 16/14.4-mm-diam tubes, tube sheets, special casings) were made of corrosion resistant 08Cr18Ni10Ti (12Cr18Ni10Ti) alloy. The positions of the "disk-and-ring" partitions were determined taking the vibration characteristics of the tubes into account. Special casings which provided additional paths for the cooled distillate in the space between the tubes of the heat exchanger were installed in the upper and lower parts of the tube system to increase the heat transfer efficiency and segmented seals made of teflon tape were installed in the annular partitions to eliminate leakages alongside the tube bundle. A special method with pre-flaring of the orifices was used to fix the tubes in the tube sheets. The upper tube sheet has specially developed gland seals which make it possible to maintain a pressure of up to 2.5 MPa (25 kgf/cm<sup>2</sup>) in tube space. This joint ensures leakproofing of the tube space of the heat exchanger when it is repeatedly assembled and disassembled (see Fig. 8.)

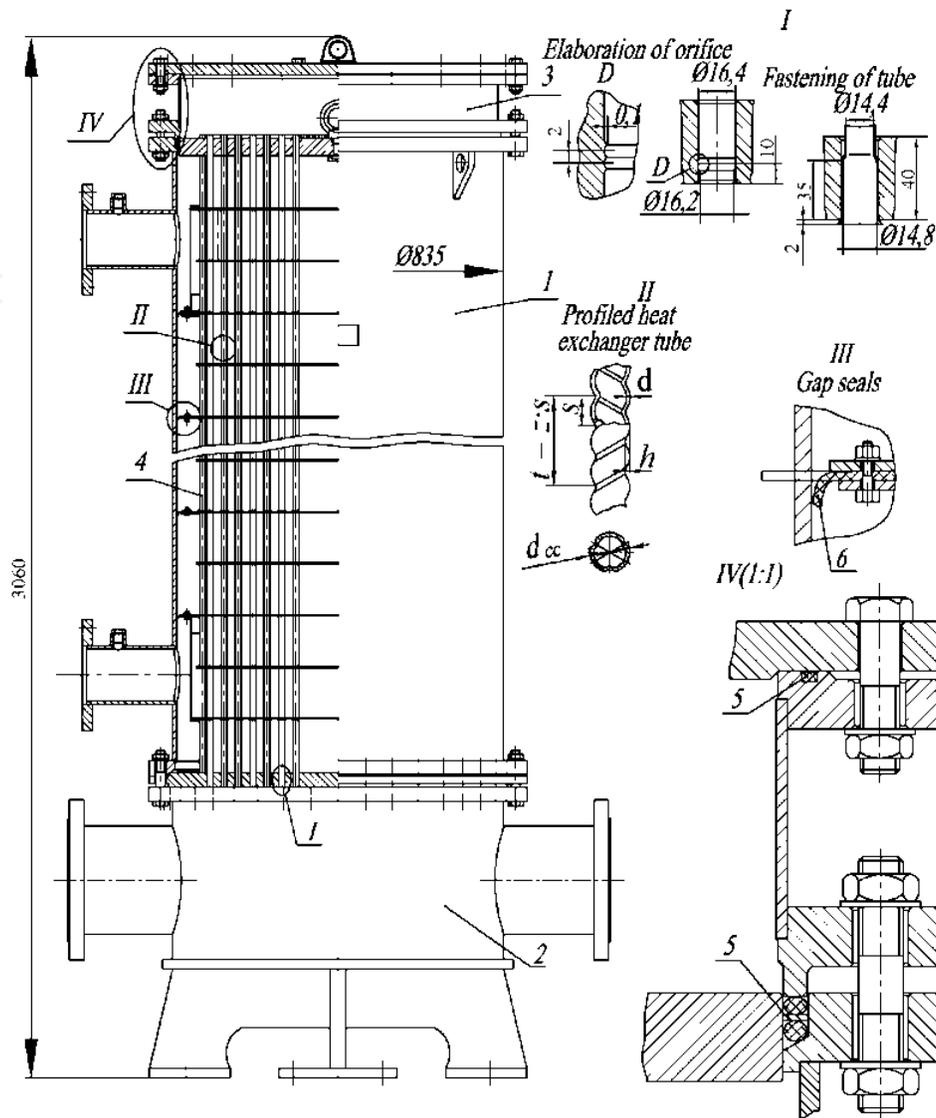
The upper water chamber of the heat exchanger has a removable lid for inspection and cleaning of the tubes without breaking the leaktightness of the tube space. For protection from corrosion the inner surfaces of the water chambers are coated with a special enamel.



**Figure 7.** Modernized tube system for a type PSV-315M-14-23 hot water heater: 1 — tube sheet; 2, 3 — disk partitions; 4 — U-shaped heat exchanger tubes; 5, 6 — vertical baffles; 7 — frame tubes; 8 — steam guard shield; 9 — damping belt; 10 — cotter pin

The main task in modernizing the MB-190-250 oil cooler for the lubrication system of the KhTZ K-500-240 turbine at the Reftinskaya GRES (replacing a worn out unit) was to increase its reparability and reliability while retaining its thermal capacity.

The overall and connector sizes for the MB-190M-250 oil cooler (Fig. 9) are the same as those for the commercially manufactured MB-190-250 oil coolers. In the modernized oil cooler the



**Figure 8.** Modernized VVT-100M heat exchanger: 1 — shell; 2 — lower water chamber; 3 — upper water chamber; 4 — tube system; 5 — silicone ring; 6 — teflon seal

major components of the water chambers, tube sheets and 16/14.4-mm-diam heat exchanger tubes are made of corrosion resistant 08Cr18Ni10Ti (12Cr18Ni10Ti) alloy. A special method was used for fixing the tubes to the tube sheets (see Fig. 9.) The system for arranging the “disk-and-ring” partitions and the configuration of the tube bundles were optimized taking the task of modernizing the oil cooler into account. (Plain tubes are installed in the oil cooler, since profiled tubes would lead to an unacceptable increase in the hydraulic resistance on the water side and to a limitation on the flow rate of cooling water in the unit.) In addition, special casings are installed in the upper and lower parts of the tube system to provide additional paths for the cooled oil in the tube space, while segmented seals made of teflon tape are mounted in the annular partitions in order to eliminate leakage along the tube bundle. The oil cooler was made more repairable by changing the design configuration for compensating the temperature

expansion of the tube system relative to the shell. For this, the upper tube sheet has an elastic diaphragm (membrane) junction with the shell, while the upper water chamber has a removable cover for inspection and cleaning of the oil cooler tubes without breaking the leaktightness of the oil space. The surfaces of the covers and bottoms that are in contact with the cooling water are coated with a special anticorrosion coating.

Reconstruction of the main ÈP-3-25/75 ejectors coolers of the KhTZ K-300-240 turbine and the ÈP-3-50/150 ejectors coolers of the KhTZ K-500-240 turbine at the Reftinskaya GRES was carried out in connection with the end of the coolers' service lives and was related to a need to replace tubes made of CuNi5Fe alloy with tubes made of 08Cr18Ni10Ti stainless steel. The arrangement system for the tube partitions in the steam space of the cooler was optimized taking the change in the tube rigidity into account and the heat exchanger surface was increased as well. When the tubes were flared in the tube sheets a special method was used with the orifices pre-flaring. Profiled heat exchanger tubes were installed in the cooler.

The aim in reconstructing the tube bundles for the fire resistant liquid coolers in the regulatory system for LMZ K-300-240 turbines (Sredneural'sk GRES, Konakovo GRES — horizontal tube bundles) and LMZ K-800-240 turbines (Surgut GRES-2, Nizhnevartovsk GRES, Berezhovskii GRES — vertical tube bundles) was to replace tube bundles that had gone past their service lifetimes, as well as to increase their thermal capacity and reliability.

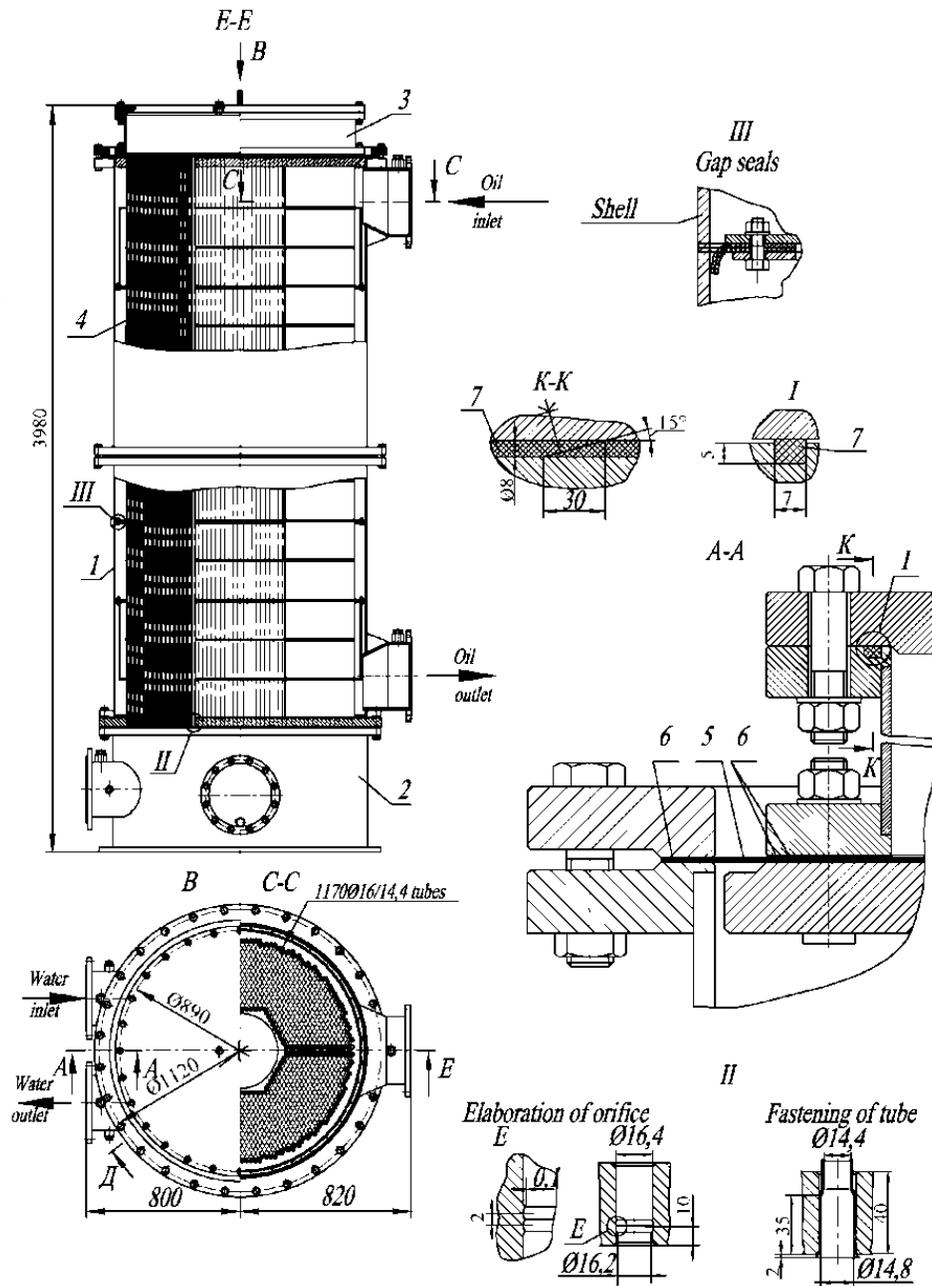
The basic components of the cooler (profiled 16/14.4- mm-diam tubes, tube sheets, special casing) were made of corrosion resistant 08Cr18Ni10Ti (12Cr18Ni10Ti) steel. The configuration of the tube bundle is optimized on the basis of a set of thermal-hydraulic calculations. The thermal capacity of the cooler was raised by increasing its heat exchange surface beyond that of the commercial units. The tubes were flared in the tube sheets using special fixing method with the pre-flared orifices in the tube sheet.

Leakage of the fire resistant liquid off the tube bundle was eliminated by installing a special casing at the annular partitions which ensured that it was joined in a leakproof seal to the annular partitions to prevent the "idle" oil leakage.

Modernization was also carried out for water-to-water heat exchangers of OB-700-1 type deployed in a technological subsystem of Perm state district power station. Heat exchangers of OB-700-1 type are vertical shell-and-tube apparatuses of integral design and this considerably reduces the opportunities of diagnostics, maintenance and repair to be performed by operational personnel of state district power station.

Heat exchanger OB-700-1 is installed at Perm state district power station in the closed system of oil ( or fire resistant liquid) cooling for K-800-240 turbines, so for the river Kama protection against oil pollution there is accomplished two-loop system of oil cooling. On passing through the oil coolers the cooling water is directed to two OB-700-1 heat exchangers where it is cooled by circulation water flowing inside the tubes.

The analysis of operation regimes of said heat exchangers showed that during 20 years they were operated with smaller than recommended (nominal) rates of water flow. Because of strong pollution of outside tube surface and significant number of gagged tubes (up to 50%)



**Figure 9.** Modernized MB-190M-250 oil cooler: 1 — shell; 2 — lower water chamber; 3 — upper water chamber; 4 — tube system; 5 — diaphragm (membrane); 6 — oil resistant gasket; 7 — silicone ring

the apparatuses have high intertube and inner tube hydraulic resistance. Besides significant corrosion deterioration is observed on tube plates.

According to technical project of Perm state district power station it was necessary when performing OB-700-1 modernization to meet the following basic requirements:

- to reduce surface pollution and lower its affect on thermal efficiency of heat exchangers;
- tube bundle should be disassembling to make it possible to disunite it from the shell provided that all the external connecting dimensions are left without changes;
- to raise the heat exchangers reliability and reduce corrosive affect of the cooling mediums;
- to provide an opportunity of hydraulic test of tube system to be carried out without removing it from the shell;
- to optimize heat exchangers thermal and hydraulic characteristics in order to minimize circulating water consumption.

To meet these challenges during modernization lots of optimizing calculations were carried out with reference to heat exchangers operating conditions at Perm state district power station.

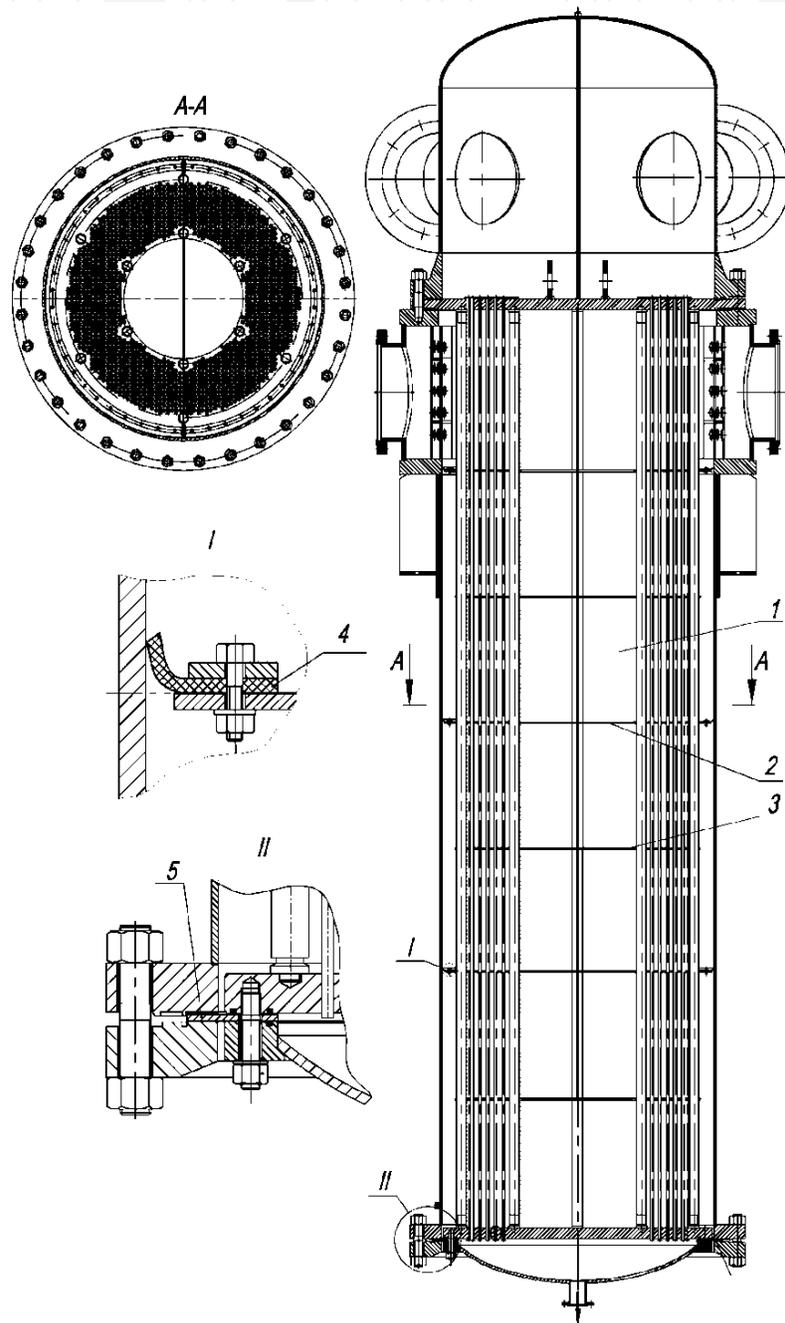
At the concept phase of modernization project the calculations were performed of thermal, hydraulic and reliability characteristics for OB-700-1 heat exchangers. For all the apparatus elements operating under pressure 0.5 MPa durability and reliability characteristics were calculated according to actual normative and technical documentation. On the basis of thermal and hydraulic characteristics optimizing calculations and in order to reduce surface pollution an effective cross section of intertube space was increased due to tube bundle configuration change and to employing of intermediate partitions of «disk-and-ring» type. Also heat transfer surface was reduced from 896 m<sup>2</sup> to 480 m<sup>2</sup>, demanded operational characteristics being unchanged. Tube system vibration characteristics calculation permitted to choose a number of its constructive parameters such as thickness of intermediate tube partitions, technological annular clearance between tube and tube sheet orifice, distance between intermediate tube sheets.

According to the design project developed by authors the tube system of modernized heat exchangers OB-700M (Fig. 10) employs intermediate tube partitions of «disk-and-ring» type, welded to frame tubes of tube bundle. Absence of leakage between intermediate tube partitions and cylindrical shell is provided by means of special sealing (Fig. 10).

During modernization of OB-700-1 type heat exchangers for Perm state district power station the following technical conceptions have also been accomplished:

- connecting and overall dimensions of the new (modernized) tube system make possible its installation into the existing cooler shell;
- tubes are made of copper-nickel alloy CuNi5Fe possessing high corrosion resistance. The anticorrosive covering is rendered on tube sheets and on internal surfaces of water chambers to increase their corrosion stability;
- for increasing of tube and tube sheet jointing tightness a special way is used employing reliefs rolled on a tube plate aperture surface;
- inward flange (item 5 in Fig. 10) is used which allows after bottom water chamber removal to carry out hydraulic test without tube system lifting out of the shell;

- for bottom water chamber as well as for inward flange sealing a silicon cord is employed enabling repeated disassembly of the chamber without replacement of sealing material;
- hatches of 500 mm in diameter are made in the top water chamber for tube sheets survey and cleaning.



**Figure 10.** Heat exchanger OB-700M. 1 — tube system assembly, 2 — intermediate tube partition of «ring» type, 3 — intermediate tube partition of «disk» type, 4 — special sealing, 5 — inward flange

According to the described concept in 2005 modernization and advanced development were performed of two samples of OB-700M type heat exchangers. After the modernization some starting-up and adjustment tests on OB-700M heat exchangers were carried out at Perm state district power station. For this purpose the heat exchanger was equipped with measuring devices permitting complete thermal balance definition. During the tests the temperatures and flow rates were measured for cooling and cooled water as well. The maximal divergence of heat flow values did not exceed 9.2%.

Test results showed that modernized heat exchangers are capable to function effectively, i.e. to cool the water to temperature demanded by technological process.

The measured values of heat exchanging mediums temperatures are close to designed ones. Thus, for example, the difference between designed and measured water temperature does not exceed 0.6°C.

## 7. Conclusion

The article presents the results of selection and justification of a number of technical solutions for power station heat exchanger modernization. The calculation technique is laid down for oil coolers with TPTs. The results are shown of preproduction tests for the new heat exchangers as well as a number of advanced and refined designs of oil coolers and water heaters.

The heat exchangers of steam turbines modernized according to described concepts have undergone industrial tests and are in successful use at various thermal electric power plants of Russia. Prolonged (up to 20 years) operating experience for more than 500 developed and manufactured apparatuses has confirmed the validity of the technical solutions, as well as high efficiency and operational reliability of these heat exchangers.

## Nomenclature

TPT — twisted profile tube

$\delta$  — wall thickness

h — depth

s — pitch between the neighboring grooves

z — number of profiling threads

t — thread rolling pitch

$d_{cc}$  — circumferential diameter

$\delta_1, \delta_2, \delta_3$  — the gaps between the shell and annular partition plate, in the orifices of the annular and disc partition plates correspondingly

$G_o$  — oil flow rate through the tube bundle

$t_{1o}$  and  $t_{2o}$  — oil temperatures at the inlet and outlet of the oil cooler

$t_{1w}$  — temperature of water at the oil cooler inlet

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