INTENSIFICATION OF HEAT EXCHANGE PROCESSES IN CONDENSERS OF STEAM TURBINES OF THERMAL AND NUCLEAR POWER STATIONS

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ABSTRACT

This article reviews intensification of heat exchange in condensers of steam turbines. The importance of cooling system of thermal power station and its influence on operation efficiency of steam turbine assembly are described. Numerous existing procedures of heat exchange intensification in steam condensers are highlighted. The most promising methods are evaluated, importance of development of new designs is stressed. A method to achieve hydrophobicity effect on brass surfaces by means of surfactants is presented. A new approach is described related with formation of multilevel relief on surface of condenser tubes using laser radiation. Market of steam condensers of thermal power stations is analyzed including trends of its development up to the year 2020.

Key words: thermal power station, nuclear power station, heat exchange intensification, hydrophobicity, surfactants, laser textured surface.


INTRODUCTION

In the recent decade global energy consumption increased by 3.6%, this growth still continues due to industrialization, urbanization and population increase. In foreseeable future thermal energy will remain the main source of electricity production which, in its turn, will support the future global market of condensers.

Nowadays total installed capacity of thermal power stations is about 4000 GW. It is expected that this value will achieve 5320 GW to 2030, herewith, each power generation unit includes from one to three steam condensers. In 2015 total size of condenser market was about US$ 2.5 billion and in 2020 it will reach US$ 3.3 billion [1].
In the nearest future (to 2022) in Russian Federation it is required to decommission up to 190 GW of generating facilities due to moral and physical depreciation, therefore, wide scale construction of new power generation units is planned which would increase significantly the market of power generating equipment, including condensers.

2. STATE OF THE ART

Operation efficiency of steam turbine assemblies depends significantly on cooling systems of thermal power stations. Thus, for instance, pressure increase in condenser by 1 kPa decreases power of turbine assemblies in condensing mode by 0.8-1.5%, and that of turbine assemblies of low and medium pressure by 1.5-2%. Dependence of available power of generating station on operation efficiency of cooling system is reduced to determination of capabilities of water supply system and hydrocoolers to transfer and release heat into environment. In this regard there are certain constraints of installed power of generating unit due to temperature increase of cooling water in summer season (as a consequence of insufficient amount of cooling towers, insufficient capacity of circulation pumps and so on). Thus, maximum allowable temperature of cooling water after treatment in cooling towers upon normal operation conditions of oil and gas coolers should not exceed 33°C. Maximum allowable temperature of cooled water in combination with heating and temperature head should correspond to maximum allowable steam pressure in condenser according to normal operation conditions of final stage of low pressure cylinder predefined by manufacturer (as a rule, 0.12 kgf/cm², which corresponds to saturated steam temperature t = 49.1°C). In Mosenergo at the installed power of all stations higher than 9000 MW the power constraint due to inefficient operation of cooling system exceeds 1600 MW (18% of the installed power) [2, 3].

Therefore, intensification of heat exchange upon condensation would lead to decrease in under heating of cooling water to the steam saturation temperature, that is, to increase in operation efficiency of heat exchangers, vacuum increase in condenser, hence, to significant increase in operation efficiency of overall generating unit. In the case of operation of condensers at ultimate vacuum the intensification of heat exchange would permit to reduce significantly electricity consumption for own needs – operation of circulation pumps for water supply, thus increasing efficiency of power station.

3. METHODS OF HEAT EXCHANGE INTENSIFICATION

More than 10,000 articles and reports on intensification of heat exchange are available in periodical editions and numerous bibliographic reviews.

The most popular methods of heat exchange intensification can be subdivided into several groups (Table 1) [4]:

A simple method is known for intensification of heat exchange by increase in flow rate of operation fluids in apparatus channels. However, in this case hydraulic pressure rapidly increases, as well as power consumption for pump drives which results in inefficiency of such heat exchange intensification [5]. Two-fold increase in flow rate increases heat exchange by 1.75 times and hydraulic resistance by 3.4 times. Therefore, it is impossible to consider heat exchange intensification separately from power consumption. A determining criterion is the efficiency of heat exchange at preset (equal to the compared variants) level of power consumption for pumping of working fluids via apparatus.
Table 1 Classification of heat exchange intensification procedures

<table>
<thead>
<tr>
<th>Intensification procedures</th>
<th>Description</th>
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<tr>
<td>Active</td>
<td>Mechanical</td>
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<td></td>
<td>Surface vibration</td>
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<td></td>
<td>flow pulsation</td>
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<td>Electrostatic fields</td>
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<td>Injection</td>
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<td>Suction of boundary layer</td>
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<td>Jet apparatuses</td>
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<td>Passive</td>
<td>Processed surfaces</td>
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<td></td>
<td>Rough surfaces</td>
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<td>Developed surfaces</td>
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<td>Agitators</td>
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<td>Flow swirling devices</td>
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<td></td>
<td>Coils</td>
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<td>Surface tension devices</td>
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<td></td>
<td>Additives to liquids</td>
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<tr>
<td></td>
<td>Additives to gases</td>
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<tr>
<td>Combined</td>
<td>Two or more passive and/or active methods simultaneously</td>
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According to [6] heat exchange intensification is efficient if increase in heat exchange is in advance of increase in hydraulic resistance. That is, if $\frac{Q_{mod}}{Q_{ini}} > \frac{\Delta P_{mod}}{\Delta P_{ini}}$ is valid, then the mentioned heat exchange intensification is promising. Figure 1 illustrates the relationship:

$$\frac{Q_{mod}}{Q_{ini}} = f\left(\frac{\Delta P_{mod}}{\Delta P_{ini}}\right),$$

where $Q_{ini}$, $\Delta P_{ini}$ are the heat flow and the hydraulic resistance of initial heat exchanger, respectively; and $Q_{mod}$, $\Delta P_{mod}$ are the heat flow and the hydraulic resistance of modified heat exchanger, respectively.

One of conventional methods of heat exchange intensification is production of rough surface [7]. In such heat exchangers surface shapes are modified, thus creating turbulence in heat carrier flows. Geometrical properties of these surfaces cover wide range of roughness: from granular (sandy) to discrete 3D surface cavities and/or extrusions. Depending on geometrical parameters of the used rough surface the coefficients of heat exchange upon condensation increase from 30% to 5 times.

Figure 1 Heat flow as a function of hydraulic resistance after modification of heat exchanger.
Another well-known and efficient method is based on developed (ribbed) surfaces [8]. Such surfaces provide increase in active surface area of heat exchange. Recently designed shapes of ribbed surfaces in addition to extension of the surface itself also influence on the flow, disturb it and intensify additionally the heat exchange.

Small diameter tubes made of highly heat conductive materials become more and more popular in shell and tube heat exchangers. Aiming at intensification, the surfaces of such tubes are equipped with spiral, herringbone, ring, 3D and other extrusions and cavities (Fig. 2).

*Figure 2.* Shaped tubes with spiral or circular rolling or spherical grooves, HRS Group (*a*) and Energy Transfer MDE (USA) (*b*), MPG Mendener Präzisionsrohr (*c*) and Turbotec Products, Inc (*d*).

Swirlers in channels promote generation and development of secondary circulation in the flow. Such devices can be made in the form of spiral bands, screws or helical tubes.

For instance, a US company, Spirelf System, manufactures spiral wire insertions for heat exchange intensification in shell and tube heat exchangers. Spiral intensifiers manufactured by Brown Fintube are also known. The main advantage of swirlers is the ease of their mounting and dismounting from heat exchange channels.

Shell and tube heat exchangers with helical tubes are widely applied in power engineering. Application of helical tubes makes it possible to eliminate partitions of heat exchange matrix since each tube is supported by two adjacent tubes. This system, in addition to heat exchange intensification is characterized by such positive feature as elimination of vibration which is one of major issues upon operation of heat exchangers. Another issue is increase in hydraulic resistance.

Another efficient method of intensification is application of tubes rolled into certain profile, that is, coils. Application of such tubes promotes decrease in sizes of heat exchangers. Flow swirling in coil channel leads to occurrence of secondary flows or the Dean flows, which increase coefficients of heat exchange.
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Coils of low bend radius are used in heat exchangers. Advantages of apparatuses with heat exchange surface made of coils are as follows:

- Intensity of heat exchange at high turbulence of mediums;
- Combination in modules makes it possible to use smaller tubes and optimizes sizes;
- Countercurrent of medium flow;
- Self-compensation of temperature expansions.

Passive (structured surfaces, additives to fluids and gases), active and complex methods should be also mentioned.

The method is known of heat exchange intensification in condenser on the steam side due to transition from film to dropwise condensation. The dropwise condensation is steam condensation on surface in the form of individual droplets, this providing direct steam contact with tube metal surface. Such approach increase the coefficient of heat exchange by an order of magnitude [9-12].

One of numerous methods of transition from film to dropwise condensation was developed in 1950-s. Experimental evidences are available that hydrodynamic mode and high steam velocity makes it possible to destroy laminar condensate film and to spray condensate, thus decreasing thermal resistance of heat exchange by tenfold. Thus, the experiments by Salikov [13] suppressing steam by thin jets at high velocities demonstrated decrease in thermal resistance of heat exchange upon condensation of water steam by tenfold, thus confirming that it is possible to provide conditions for occurrence and progress of artificial dropwise condensation (ADC).

ADC mechanism in heat exchangers is sufficiently simple: rapidly moving steam jet impinges on condensate film, destroys it and disintegrates. It is obvious that the maximum effect is observed on the tube front surface, however, condensate is collected on the back surface with the thickness exceeding significantly that of condensate film. Herewith, surface tension forces, forming the condensate film, terminate their action. Condensate flow on the back side becomes turbulent accompanied by sharp drop of thermal resistance.

The Lotus heat exchangers are known [14], where ADC is based on engineering decisions. In such heat exchangers rapid spiral motion of steam is arranged in shell side which promotes blowout of the condensate on surface of heat exchange tubes and pushing it to internal surface of heat exchanger shell by the action of centrifugal force together with increase in hydraulic resistance. Then, the condensate flow continues its spiral motion at the velocity of 2.0…2.5 m/s, filling all cross section between partitions.

It is also known that the heat exchange intensity also depends on rational arrangement of tube bundle in condenser. In laboratory studies the coefficients of heat exchange on steam side even without intensifiers of heat exchange reaches 15-20 kW/(m²·K), whereas in a commercial heat exchanger the coefficient of heat exchange is only 6-7 kW/(m²·K). Such low values can be attributed to poor ventilation of certain segments of tube bundle, accumulation of non-condensing gases in the tubes and, as a consequence, significantly non-uniform distribution of heat flow density over heat exchange surface.

Various methods of conversion of steam film condensation into dropwise condensation by hydrophobization of external tube surfaces are the most efficient and promising methods of heat exchange intensification.
Upon conversion of conventional film condensation into dropwise condensation of steam released from output of turbine low pressure cylinder the coefficient of heat exchange on steam side significantly increases which is attributed mainly with decrease in thermal resistance of liquid film (on the tube surface, instead of film with the thickness of hundreds of microns and even several millimeters separate drops are formed which intensively drop from cylindrical surface into shell space, thus exposing tube metal surface). In addition, as a consequence of supplemental dispergation of liquid phase in steam and drop flow in shell space the interphase heat exchange is intensified due to increase in phase contact surface area, which leads to reduced overcooling of condensate, that is, to increased operation efficiency.

Evacuation intensity of liquid phase from heat exchange surface depends directly on the rate of its hydrophobicity or contact angle. The higher is the angle, the more intensive is rolling of drops from tube surface, therefore, the coefficient of heat exchange of the condenser increases.

Recently numerous publications were devoted to the study of interaction between droplets and hydrophobic surfaces. Superhydrophobicity with very high contact angle (more than 150°) and low inclination angle (lower than 10°) attracts great attention due to its practical importance. It was noted that lotus leaves are covered with multilevel micro/nano-structures, this fact encourages researchers to develop artificial superhydrophobic surface similar to lotus leave [15, 16].

One of the methods to achieve hydrophobicity on tube surface is the use of surfactants, for instance octadecylamine. Upon modification of condenser tubes using octadecylamine its molecules are adsorbed on tube surfaces, thus hydrophobicity is achieved, herewith, the coefficient of heat exchange in condenser can increase to 50% [17].

The predefined target, that is, superhydrophobicity, can be achieved not for all surfaces after processing by hydrophobic agent. It was demonstrated that the contact angle depends not only on surface chemical structure but also on its local curvature [18], which allows to adjust wetting selecting curvature and shape of texture elements.

In order to achieve superhydrophobicity first of all, multimodal surface roughness is required: surface relief should be characterized by dimensions of various spatial scales (microns, hundreds of nanometers, nanometers).

Numerous methods are available in literature used in laboratories in order to achieve multimodal roughness [19-22]. Most works devoted to achievement of superhydrophobic brass surfaces were performed in China, Singapore, Russia and some others.

Laser ablation is one of efficient methods for achievement of hydrophobicity on brass surface [23]. Microspikes are formed on brass substrates under the impact of laser beam moving along quadrilateral mesh. Brass specimen is initially heated due to absorption of laser energy accompanied by surface melting and evaporation. Total mass of removed metal depends on energy density of laser radiation and number of pulses. Surface area of materials removed by laser ablation depends on the size of focused laser spot. A step of quadrilateral mesh is set to laser spot size pf focused beam by ~40 µm. Therefore, it is possible to achieve dense distribution of spike shape of microstructural sets with the height of ~20 µm.

After laser treatment the contact angle of texturized brass surface is ~110°. However, the studies demonstrated that the contact angle of texturized brass surfaces increases upon exposure in air. After two weeks the contact angle on a specimen reaches its maximum and
surface becomes superhydrophobic with the contact angle of $\sim 161^\circ$ as illustrated in Fig. 3 (a). As a comparison, the contact angle of flat brass substrate is $\sim 110^\circ$, see Fig. 3 (b).

Figure 3 Microimages of water drops on (a) laser textured surface after two-week exposure in air and (b) on initial brass surface prior to laser processing.

While varying laser capacities and frequencies upon modification of surfaces and further conditions of exposure in air it is possible to achieve various angles of contact and inclination. Thus, in [24] the method for obtaining of contact angle of $141.6^\circ$ at inclination angle of $8.4^\circ$ on brass surface.

The main drawbacks of this method is impossibility to apply it on already active equipment as well as high cost of production of surface microroughness.

4. CONCLUSIONS
We assume that the scheduled wide-scale replacement of thermal power units in Russia will be based on conventional assemblies of Russian production. In this regard, the issues of efficiency of cooling systems in general and condensers in particular are highly important. Analysis of existing approaches to efficiency improvement of condensers, on the one hand, reveals unavailability of inexpensive and feasible relatively simple method, and on the other hand, development of new engineering materials, related in particular with variation of surface properties caused both by steam and by water.

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