On Intensification of Heat Exchange in Steam Condensers Made of Stainless Steel and Brass

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Abstract**:** ***This work highlights continuous increase in capacities of thermal and nuclear power plants (TPP and NPP), as well as current retrofitting of generating facilities, which evidences increased demand for steam condensers. The most popular approaches to increase efficiency of TPP and NPP condensers are described. Experimental condensers were fabricated of brass and stainless steel in as-delivered state, and with functional surface modified by surfactants. The influence of conversion of film condensation to dropwise condensation on heat exchange efficiency in condenser is described evidencing that surfactants on functional surfaces of condensers provide increase in wetting contact angle which in its turn leads to increase in coefficient of heat transfer in condenser and its overall efficiency.***

Index Terms**:** ***thermal power plant, nuclear power plant, steam condenser, intensification of heat exchange, coefficient of heat transfer, hydrophobicity, contact angle, surfactants.***

I. INTRODUCTION OF THE PROBLEM

According to IEA, energy consumption in 2017 increased by 2.1%, which was two times higher than in 2016. Outlook BP forecasts that to 2040 global consumption of electric energy will increase by 40%. Herewith, the portion of heat energy will be 70%, which in its turn will maintain the market of steam condensers [1].

Nowadays total installed capacity of TPPs is about 4,100 GW. The level of 5,320 GW is expected to 2030, and each energy unit includes several steam condensers. In 2015 total scope of global market of condensers was about $2.5 billion, and to 2020 this index will reach $3.3 billion [2].

In 2018 in the Russian Federation 12 new energy units were commissioned with overall capacity higher than 5 GW. In the next two years it is planned to commission another 14 energy units which will increase significantly the market of power generating equipment, including steam condensers.

It is known that efficient operation of TPP and NPP energy units is provided by condensers which together with process water supply comprise the cooling system of power plant. The main function of cooling system is to provide operation of turbogenerators at preset capacity irrespective of variations of their operation modes. Herewith, the following conditions should be met: maximum allowable temperature of cooling water should not exceed 33°C during normal operation of oil coolers; in addition, together with its heating and temperature heat it should comply with allowable steam pressure in the condenser according to factory settings of normal operation of the last stage of turbine low pressure cylinder.

In most cases $p_c^{max} =$ 12 kPa, which corresponds to the temperature of overheated steam $t_s^{max} =$ 49.1°C. It follows that the water temperature at condenser inlet is higher than the specified value (due to its insufficient amount or poor technical state of cooling towers, circulation pumps, water ducts, increased scaling of condenser piping, insufficient capacity of ejectors, weather conditions, etc.) which would increase pressure in the condenser, and at fixed average coefficient of heat transfer this will lead to decrease in steam flow rate across the condenser, that is, capacity restriction of turbogenerator. Due to inefficiency of cooling system, the capacity restriction can reach 20% and higher [3, 4].

Intensification of heat exchange upon steam condensation would lead to decrease in underheating of cooling water to the point of steam saturation, that is, increase in efficiency of heat exchange equipment, increase in vacuum level in condenser, and, hence, to significant increase in overall efficiency of energy unit. In the case of condenser operation at ultimate vacuum level, intensification of heat exchange would permit to decrease significantly energy consumption for own needs: operation of circulation pump of process water supply, additionally increasing efficiency of power plant. Numerous data are available in publications devoted to intensification of heat exchange, such as articles and reports in periodicals: Bergles et al. [5,6], Jensen and Shome [7], Webb [8, 9], Shatto and Peterson [10], and others.

The most known methods of intensification can be subdivided into active, passive, and commanded ones [11]. They include various tube profiling [12], flow pulsation, tube vibration, modification of coarseness [13–17] and surface properties, agitators and others.

One of the most efficient and sufficiently straightforward methods to increase the coefficient of heat transfer is conversion of steam film condensation to dropwise condensation [18–22], for instance, by hydrophobization of external piping surface.

Revised Manuscript Received on May 06, 2019

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Upon film condensation, the heat from steam to wall is transferred via condensate film which is the basic thermal resistance. Upon dropwise condensation, surface becomes unwetted and thermal resistance is absent or decreases significantly, and a portion of steam is in direct contact with heat exchange surface [23]. Peculiar property of wettability is contact angle. There are two cases of surface wetting depending on the value of contact value. Thus, if the contact angle is higher than 90°C, then the surface is hydrophobic, and if the contact angle is lower than 90°C, then the surface is hydrophilic.

According to numerous research, one of the most promising methods of surface hydrophobization is application of aliphatic amine surfactants, they are sorbed onto surface from water emulsion. As a consequence, polymolecular film is formed on condenser piping surface, the so called Langmuir palisade (Fig. 1) characterized by hydrophobicity and protection against corrosion.

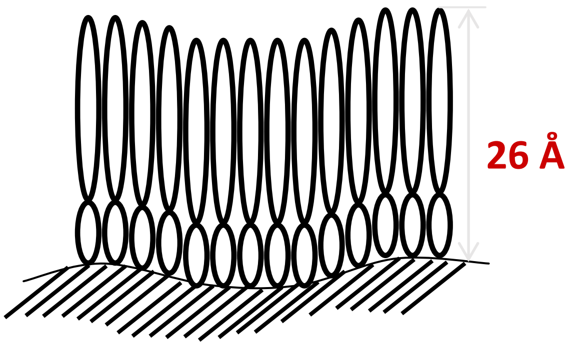

Fig. 1. Langmuir palisade.

II. PROPOSED METHODOLOGY

A. Experimental Studies of The Influence of Surface Hydrophobization of Condensers Made of Brass and Stainless Steel on Coefficient of Heat Transfer

It was decided to perform experimental studies aiming at determination of the influence of hydrophobization of condenser surfaces on coefficient of heat transfer.

The studies were performed with four samples of condenser piping fabricated of the most used materials for TPP and NPP condensers, i.e. brass, grade MNZh5-1, as well as stainless steel, grade AISI-304. Each experimental sample was comprised of six zigzag tubes soldered to flanges on both sides. The tubes were soldered of straight fragments with 45° joints (Fig. 2).

Fig. 2. Samples of condenser piping prepared for soldering (a) and already soldered (b).

Functional surface of two of four samples was modified by surfactants. Surfactant based on aliphatic amines was selected as film forming agent. In order to form surfactant molecular layers, on the surface the finely dispersed multimolecular emulsion was prepared since the used surfactants were insoluble on most liquids. Surfactant emulsion in coolant was prepared according to a proven procedure by ejection. Ejection of surfactant melt at certain temperature is an efficient method to distribute surfactant molecules uniformly across overall coolant and to create conditions for formation of ordered surfactant molecular layers on metal surface, which is achieved by addition of molecules to suction of circulation pump.

In order to form surfactant molecular layers, on external exchange surfaces of condenser a dedicated test rig was used with separate circuit comprised of process reservoir, circulation pump, and ejection unit comprised of surfactant metering tank, shutoff and control valves, joints and ejector.

The rig provides preparation, circulation, heating and temperature maintenance of emulsion or solution during the required time for formation of molecular layer on the reference surfaces.

After modification of samples, the contact and roll-off angles were measured using an OCA 20 tension meter (Germany). This instrument facilitates integrated analysis of material properties. The following properties can be determined using this instrument:

- static and dynamic contact angle on flat, convex and concave surfaces;
- hysteresis of contact angle;
- free energy of solid surface as well as its constituents by nine various methods;
- forecast of complete wettability of considered sample with known liquid;
- surface and interface tension by hanging drop or thin layer method;
- absorption, adhesion;
- free energy of solid surfaces and liquids.

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The following results were obtained after modification of surfaces and subsequent measurements of contact angles:

- the contact angle on the surface of brass condenser modified by surfactant was 110.2°, whereas the initial angle contact was 78.3°;
- the contact angle on the surface of stainless steel condenser modified by surfactant was 103°, whereas the initial contact angle was 74°.

The experimental samples are illustrated in Fig. 3.

a)

b)

Fig. 3. Condenser piping made of brass (a) and stainless steel (b).

The studies were performed on the test rig in order to determine the influence of conversion of film condensation into dropwise condensation on the intensity of heat exchange in condenser with simulation of operation conditions. General view of the test rig is illustrated in Fig. 4. All items, units and their joints, pipelines, fastening of tanks, condensers, pumps and other equipment are fabricated of stainless steel, grade 18Kh18N10T.

Fig. 4. Experimental test rig.

The elements were joined by argon arc welding which provided the required tightness, strength, and rigidity of overall test rig designed for operation in the pressure range of 2–100 kPa. External surfaces of the test rig were thermally insulated, thus, heat loss to environment was eliminated, i.e. the influence on the obtained results was minimized.

The test rig is based on two identical independent circuits with natural circulation, sealed with respect to steam–water. Steam generator of each circuit supplies steam to the system by means of tube electric heaters. Then, wet saturated steam is supplied to separator via steam conduit where moisture is separated and drained to collecting pipe back to steam generator. After separation steam is supplied to the considered condenser. After condensation on pipe bundle water is collected into inclined condensate receiver and drained to descending pipe with metering chamber. The adjusting unit of condensate level comprised of fast electromagnetic valve and constraining rings provides the required level of steam overheating by dynamic variation of condensate flow rate. The vacuum pump is connected with each circuit by separate lines and provides the required initial level of rarefication. The water-cooling system of condensers is comprised of circulation water cooling (chiller) and circulation pump and provides the required variables (temperature, flow rate) in this circuit. In order to provide the required vacuum in a circuit, the test rig was equipped with vacuum pump capable to decrease the pressure in condenser to 5 kPa. However, in order to maintain the required vacuum during long time of the rig operation, it is required to activate periodically the vacuum pump, which leads to condensation of excessive moisture during removal of steam and air mix from the condensate receiver. Thus, the test rig was connected to additional water circuit comprised of water tank, circulation pump, and water-to-water ejector connected to expansion tank in the test rig. The circulation water cooling system is a chilling machine. The aim of this equipment is to chill the coolant which is supplied to fan coils via pipelines. In our case the chiller performs several functions:

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– chilling coolant during operation of cooling water circuit in order to maintain constant temperature at the required level;

– chilling coolant upon deactivated circuit of cooling water aiming at obtaining high water amount (at least 1 m3) of constant temperature.

The chiller composition can be subdivided into two circuits:

– hydraulic unit;
– chilling unit.

The hydraulic unit is an auxiliary element of the chiller intended for conveyance of coolant from the chiller to the fan coils and back. The chiller is based on accumulating tank and circulation pump. The operation principle and hydraulic layout of the chilling unit are similar to those of any vapor compression refrigerating machine. Cooling water from buffer reservoir is supplied by pump to evaporator input. In the evaporator water is chilled by coolant which, in its turn, is cooled in air cooling condenser and then returned to the buffer reservoir, thus, it is possible to compensate heat input from consumer and to maintain the temperature in buffer reservoir at preset level. Then the chiller is deactivated, only hydraulic unit is active, its pump supplies cooled water with the required variables (flow rate) to condenser piping.

Data from all sensors and primary converters of the test rig are shown in real time on display of operator station of the test rig and, partially, on instruments of automation cabinet.

III. RESULTS

The influence of cooling water at condenser input on the intensity of heat transfer was experimentally studied upon steam condensation on surface of piping fabricated of as-delivered brass and modified by surfactant. The coefficient of heat transfer K as a function of cooling water temperature at condenser input t_w was determined (Fig. 5).

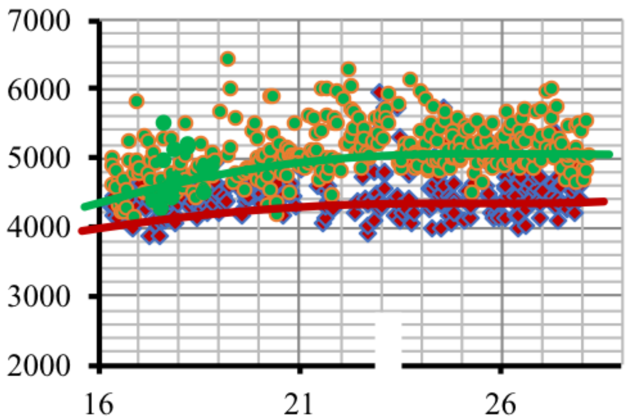

Fig. 5. Coefficient of heat transfer K as a function of cooling water temperature t_w at condenser inlet.

It can be seen that with the increase in cooling water temperature at condenser input, the coefficient of heat transfer also increases, and when the cooling water temperature reaches 22°C, the coefficient of heat transfer becomes stable. This can be attributed to stabilization of underheating in the condenser due to restriction of ejector flow rate and increased pressure in the condenser. It can be seen that the coefficient of heat transfer of the condenser with the surface modified by surfactant is significantly higher than the initial one. It can be concluded that increase of the contact angle of brass condenser from 78.3° to 110.2° leads to increase in the coefficient of heat transfer in average by 17%.

Similar studies were performed with the condenser piping fabricated of as-delivered stainless steel and modified by surfactant. The obtained results are illustrated in Fig. 6.

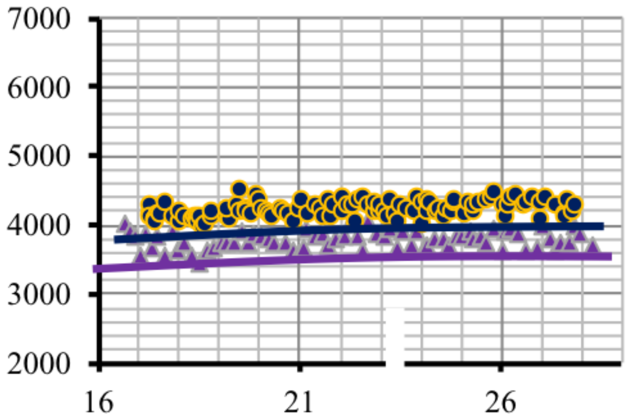

Fig. 6. Coefficient of heat transfer K as a function of cooling water temperature t_w at condenser inlet.

It can be seen that the coefficient of heat transfer of condenser with the surface modified by surfactant is significantly higher than the initial one. It can be concluded that increase of the contact angle of stainless steel condenser from 74° to 103° leads to increase in the coefficient of heat transfer in average by 11%.

It can be seen in Fig. 7 that the coefficient of heat transfer of the condenser with surface modified by surfactant made of brass is significantly higher than that of condenser made of stainless steel. It should be mentioned that the coefficients of heat transfer in as-delivered state are also significantly different.

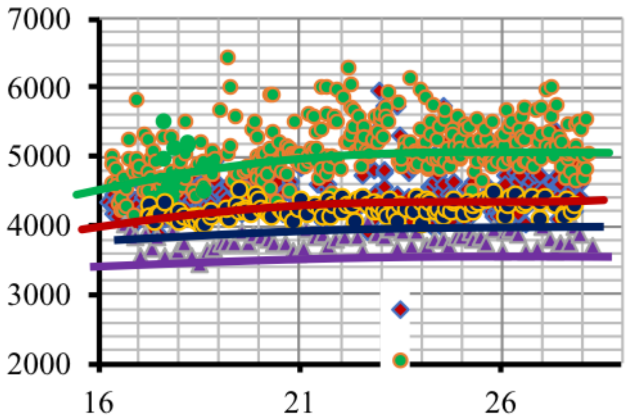

Fig. 7. Coefficient of heat transfer K as a function of cooling water temperature t_w at condenser inlet.

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IV. CONCLUSION

Continuous growth of global energy consumption is accompanied by increase in capacities of TPP and NPP, and, finally, leads to increased demand for steam condensers. Therefore, the increase in efficiency of condenser operation remains an urgent issue. This work analyzed operation of experimental condensers made of brass, grade MNZh5-1, and stainless steel, grade AISI-304, as well as with surfaces modified by surfactants. On the basis of the performed experimental studies, the coefficients of heat transfer in condenser as a function of cooling water temperature at inlet were determined. Analysis of the functions demonstrated that upon modification of brass condenser surface by surfactant, the contact angle increased from 78.3° to 110.2°, resulting in increase in coefficient of heat transfer by 17%. After modification of stainless steel condenser, the contact angle increased from 74° to 103°, resulting in average increase in coefficient of heat transfer by 11%. Therefore, formation of surfactant molecular layers increases operation efficiency of condensers made both of brass and stainless steel, thus offering wide scale opportunities to apply this method for TPP and NPP condensers.

ACKNOWLEDGMENTS

This work was supported by Russian Science Foundation (Project No. 17-79-10413).

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