Hydrodynamics and mass transfer deaeration of water on thermal power plants when used natural gas as a desorbing agent

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Abstract. The technology of low-temperature deaeration of water in thermal power plants was developed. It is proposed to use natural gas supplied to the furnace as desorbing agent in the deaerator instead steam or superheated water. Natural gas has low, often - negative temperature after reducing installs. At the same time, it contains virtually no corrosive gases, oxygen and carbon dioxide, thereby successfully may be used as a stripping agent in water deaeration. The calculation of the energy efficiency of the technology for a typical unit of CHP has shown that achieved a significant annual saving of fuel equivalent in the transition from the traditional method of deaeration of water in the low temperature deaeration. Hydrodynamic and mass transfer indicators were determined for the deaerator thermal power plants using as stripping medium natural gas supplied to the boiler burners. Theoretically required amount and the real specific consumption of natural gas were estimated for deaeration of water standard quality. The calculation of the hydrodynamic characteristics was presented for jet-bubbling atmospheric deaerator with undescended perforated plate when operating on natural gas. The calculation shows the possibility of using commercially available atmospheric deaerators for the application of the new low-temperature water deaeration technology.

1. Introduction
Reliable and economical operation of the equipment of thermal power plants depends on the quality of water treatment. For energy companies, water is the main heat carriers and therefore very high requirements are placed on its content. The process of water treatment consists of several stages. The final stage of water treatment at CHP is deaeration - removal of corrosive gases from water.

Deaeration technologies substantially affect the efficiency of CHP. To increase the energy effective power output with the heat consumption due to steam extraction for heating the predeaerated and deaerated water flows, water deaeration must be performed at the minimum possible temperature of these heat carriers [1, 2].

The research laboratory of Heat Power Systems and Plants of Ulyanovsk State Technical University (USTU) developed a series of solutions for decreasing the potential of heat carriers participating in the thermal deaeration that makes it possible to substantially enhance the energy efficiency of domestic CHPs [1–3].

Nevertheless, in the authors' opinion, reserves for enhancing the energy efficiency of CHPs with the make up water deaeration in heating supply systems are not far exhausted. In particular, one of
possibilities to enhance the heat efficiency is connected with the application of new technologies of the low-temperature make up water deaeration. In [4-5], the possibility of a significant increase in the energy efficiency of the thermal power plant turbines at the realization of the technology [6] for low-temperature deaeration of water with the use, as a stripping agent, of natural gas containing no oxygen and carbon dioxide fed to the boilers of the power plant boilers is shown.

2. Materials and research methods

To study the technological feasibility of using the technology [6] for low-temperature deaeration of water, it is necessary to estimate the mass exchange efficiency and hydrodynamic operating conditions of the deaerator when natural gas is used as the stripping medium.

To estimate the mass transfer of this solution the theoretically required consumption of the desorbent—gas should be determined. The procedure for determination of specific natural gas consumption kg/t, required theoretically for removal dissolved oxygen from water is based on solving balance equations of mass and heat transfer at the thermal deaeration under condition that the interphase equilibrium is attained at the deaerator outlet [3]. With the defined assumption, we can accept that the maximum mass transfer and energy efficiency is attained at minimum possible consumptions of the desorbent and the vented steam leaving the deaerator.

The equation for the material balance of the deaeration can be written in the form:

\[ G_{i,w} X_{i,w} + D_{\text{gas}} Y_{\text{gas}} = G_{d,w} X_{d,w} + D_{\text{vent}} Y_{\text{vent}}, \]  

where \( G_{i,w} \) and \( G_{d,w} \) is the consumption of the initial and deaerated waters, kg/h; \( D_{\text{gas}} \) is the consumption of natural gas supplied in the deaerator, kg/h; \( D_{\text{vent}} \) is the discharge of the deaerator vent steam (mixture of corrosive gases liberated from water and natural gas), kg/h; \( X_{i,w} \) and \( X_{d,w} \) are oxygen concentrations in the water at the inlet and outlet of the deaerator; and \( Y_{\text{gas}} \) and \( Y_{\text{vent}} \) are the oxygen contents in the natural gas at the deaerator inlet and in the vented steam at the deaerator outlet.

The calculated flow diagram is given in Figure 1.

![Figure 1. Scheme of deaeration column of countercurrent type: 1 - initial water supply, 2 - desorbing agent supply, 3 - deaerated water drainage, 4 - deaerator vented steam extraction.](image)
According to the Dalton law, the total pressure of the gas and gas–steam mixtures is equal to the sum of partial pressures of gases and steams composing the mixture. From the Henry law, it follows that the concentration of the gas dissolved in water is proportional to the partial pressure of this gas over the water surface.

Oxygen concentration $Y_{\text{gas}}$ in gas at the deaerator input is practically zero. The oxygen concentration in the vented steam leaving the deaerator depends on the flow chart of the water and steam motion in the apparatus. At the countercurrent, mole fraction $Y_{\text{vent}}$ of O_2 in the gas–steam mixture is

$$Y_{\text{vent}} = K_{H}^{O_2} X_{i,w} / p,$$

where $K_{H}^{O_2}$ is the Henry coefficient (phase equilibrium constant for oxygen), Pa; and $p$ is the pressure in the deaerator, Pa.

At the countercurrent of water and natural gas in the deaerator, the minimum consumption of natural gas is

$$D_{\text{gas}}^{\text{min}} = G_{i,w} \frac{p}{K_{H}^{O_2}} \frac{X_{i,w} - X_{d,w}}{X_{i,w}},$$

and its specific value is

$$d_{\text{gas}}^{\text{min}} = \frac{D_{\text{gas}}^{\text{min}}}{G_{i,w}}.$$

The results of calculating the theoretically required natural gas consumption to ensure the normative residual oxygen content in the deaerated water are shown in Figure 2.

![Figure 2](image)

**Figure 2.** Theoretically required desorbent (natural gas) consumption at the countercurrent of water and gas as a function of the deaerator load. Quantities of $X_{i,w}$, mg/dm³: (1) 8, (2) 10, and (3) 12.

In the actual operating conditions of the deaerator, the required specific gas consumption for deaerating should be taken as 3-5 times as much as theoretically necessary (by analogy with thermal deaerators operating on a steam). Ensuring the necessary consumption of natural gas for deaeration of water in thermal power plants does not present any difficulties. With deaeration of 800 t/h of make up water, the required gas flow will be 2400-4000 m³/h, while a steam boiler with a steam capacity
of 500 t/h requires about 40000 m$^3$/h of gas, i.e. deaeration will require no more than one tenth of the gas flow to the boiler.

Calculation of the hydrodynamic characteristics of low-temperature deaeration of water using natural gas as a stripping medium is made for a jet-bubbling atmospheric deaerator DA-25 with an unsubmerged perforated bubble-plate installed in the lower part of the deaeration column. The choice of this deaerator as an example for the calculation is due to the fact that this deaerator has a rather perfect design allowing to provide a very high quality of deaeration when using water steam as a working agent. Our tests of this deaerator have shown that it is possible to achieve extremely low residual concentration of dissolved oxygen in deaerated water - up to 2-3 mg/ dm$^3$.

Hydrodynamic operating conditions of the deaerator for effective deaeration:
1. Maintaining the desired gas velocities in the holes of the bubble-plate.
2. The presence of a gas cushion under the bubbling sheet, due to which the sheet is not immersed in water.
3. Absence of entrainment of droplets from the deaerator column.

The use of an unsubmerged principle of bubbling, according to which water on a perforated sheet is continuously and repeatedly treated with gas supplied under the sheet and passing through the holes in it, is most effective when operating bubbling deaerators.

Under the sheet a gas layer ("cushion") is formed, which prevents dropping of liquid through the holes of the sheet. The hydrodynamic stability of unsubmerged bubble sheet is determined by the rate of gas flow through the holes.

The minimum required speed may be determined by the empirical form [8 – 10]

$$w_{\text{min}} = \frac{20.6}{\sqrt{\rho_{\text{gas}}}},$$

(5)

where $\rho_{\text{gas}}$ – the gas density under the sheet, kg/m$^3$.

The height of the gas cushion under the sheet is

$$h = 2 \cdot \frac{\sigma^2}{\left(g\rho_w - g\rho_{\text{gas}}\right)^2 d} + \frac{\zeta w^2 \rho_{\text{gas}}}{2g\left(\rho_w - \rho_{\text{gas}}\right)},$$

(6)

where $\sigma$ – coefficient of surface tension of water-gas system, kg/m; $\rho_w$ – the density of water, kg/m$^3$; $d$ – the diameter of the holes in the perforated sheet, m; $w$ – the rate of passage through the holes of the sheet, m/s; $\zeta = 1.9...2.0$ – the coefficient of hydraulic resistance of the perforated sheet.

To assess the presence or absence of entrainment of drops from the deaerator is necessary to determine the gas velocity in the column deaerator (Figure 3) [10, 11]. Sustainable mode downward flow exists at gas velocities of about 15-30 m/s, above which the entrainment of droplets [12].

In traditional thermal deaerators, used as the working medium is water steam, which condenses in the process of deaeration, flow rate of steam in the jet of the column is small and the danger of entrainment of droplets is practically absent. In deaerator using natural gas as a stripping agent the gas velocity and the risk of entrainment of drops from the column of deaeration to the gas pipeline before boiler is slightly higher, since natural gas by deaeration is not condenses.

The gas velocity in the column deaerator is

$$w_{\text{col}} = \frac{G_{\text{gas}}}{S},$$

(7)

where $G_{\text{gas}}$ – gas consumption, m$^3$/h; $S$ – section area, m$^2$. 
3. Conclusions

As a result of calculation according to formulas (5) - (7) with a specific gas consumption of 3-5 m³/t, i.e. 3-5 times more than theoretically necessary, the following hydrodynamic characteristics of the deaerator DA-25 were determined:

1. The estimated gas velocity in the holes of the bubble sheet $w_{min} = 57.58$ m/s.
2. The height of the gas cushion under the bubble sheet $h = 0.025$ m.
3. The gas velocity in the column of deaerator $w_{col} = 0.13$ m/s. Consequently, the entrainment of droplets is impossible, as in deaerator using steam as the stripping agent.

Thus, the operation of the deaerator jet-bubbling atmospheric deaerator on natural gas provided the required hydrodynamic conditions of operation of jet and bubbling steps of deaerating column.

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