About the results of experimental study performed on a “decarbonizer – vacuum deaerator” system

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Abstract. The paper discloses the results obtained in experimental study, implemented at an operating water treatment unit of the thermal power plant. The study was carried out via using the method of a complete factorial experiment. As a result of the experiments, the dependencies between objective functions and a number of controlled parameters have been determined. Regression equations have been derived and cross-sections of the response surfaces have been constructed in a natural scale, that adequately describe the processes of corrosive gases desorption within the “decarbonizer - vacuum deaerator” system. The data obtained allows one to assess the minimal technologically acceptable level, when it is possible to lower the temperature of the treated water and, consequently, to reduce the energy costs for its heating, and to specify the conditions when the reduction of the energy costs for supplying air to decarbonizer is possible.

Introduction

The reliability and economic viability of the heat source itself and the heat supply system as a whole depend on the selection of a rational operating mode of water treatment equipment. Decarbonizers and vacuum deaerators serve as the main water treatment equipment for the removal of corrosive gases at most thermal power plants and large boiler houses [1].

To obtain a proper description of the physico-chemical processes, taking place in water treatment units, and to create energy-efficient technologies for water degassing processes control, the experimental studies have been conducted by the authors, jointly with colleagues, at water treatment units of various heat sources [2, 3, 4]. The need to conduct the experimental study is caused by the absence of complex characteristics of the “decarbonizer - vacuum deaerator” system performance, depending on the controlled parameters of the hydraulic, thermal and chemical modes.

Experimental installation

The experimental study was carried out several years ago at an operating water treatment unit of one of the local thermal power plants in Ulyanovsk city [5]. The unit in question includes three parallel-connected packed decarbonizers with a capacity of 550 t/h and two horizontal jet-type vacuum de- aerators of the DV-800 type with a capacity of 800 t/h (Figure 1). Heat and mass transfer devices of this type are most often used for the anticorrosion treatment of makeup water of large heat supply systems. The air is supplied to decarbonizers via centrifugal fans of the C4-76 No.8 type with a nominal capacity of 14000 m³/h and a head pressure of 1.4 kPa.
Figure 1. Schematic diagram of the experimental water treatment unit: 1 – source water heater; 2 – the decarbonizer; 3 – the fan; 4 – decarbonized water tank; 5 – decarbonized water pump; 6 – the vacuum de-aerator; 7 – the ejector; 8 – the heating agent heater; 9 – makeup water storage tank; 10 – the heat supply network feeding pump; 11 – the control damper; 12 – the flow-meter; 13 – source water pipeline; 14 – makeup water pipeline.

The residual concentration of oxygen in de-aerated water was measured using an automatic portable analyzer, the oxygen analyzer “MARK-301T” manufactured by LLV “Vzor” (Nizhny Novgorod). The measurements were made at a sample temperature of 30 ± 5°C. In order to control the oxygen analyzer readings, chemical analyzes of oxygen content in de-aerated water were regularly performed using the “methylene blue” indicator. The pH value of water was determined electrometrically using a standard laboratory pH-meter of the “pH-340” type (Gomel). The content of carbon dioxide was determined by titration with a caustic soda in the presence of phenolphthalein in accordance with operating instructions. Measurements of flow-rates and temperatures were carried out with standard measuring equipment.

Methodology for performing the experiment

The “decarbonizer-vacuum deaerator” system testing was carried out via using the method of a complete factorial experiment of the 2³ type. During this method implementation, the experiment follows a certain strategy, the controlled parameters vary simultaneously, and calculation of statistical estimates is performed in accordance with a strictly formalized procedure, which significantly reduces the number of necessary experiments to be carried out and improves the accuracy of the study [2, 6]. Estimates of the regression coefficients are independent of one another, which allow one to determine the strength and the nature of influence of the parameters and their interaction and to use the obtained model for analysis and optimization of the studied object.

The residual content of carbon dioxide in decarbonized water (objective function $Y_1$, mg/dm³) and the pH value of decarbonized water ($Y_2$) were taken as the parameters of decarbonizers efficiency (objective functions) to be determined. When evaluating the performance of vacuum de-aerators, the residual content of oxygen dissolved in de-aerated water ($Y_3$, μg/dm³) and the pH value of deaerated water ($Y_4$) were used as objective functions.

During study of the efficiency of desorption of the corrosive gases $O_2$ and $CO_2$ dissolved in makeup water, the influence of the three controlled regime factors, namely, the flow rate of source water $G_w$, source water temperature $t_w$, and flow-rate of air supplied to decarbonizer $D_a$, was estimated quantitatively. The values of the controlled parameters are given in Table 1 below.
The intervals of the maximum change in the controlled parameters were as follows: the flow rate of source water was 240–520 t/h; water temperature was 8–18°C; the flow rate of air was 50–100% of the nominal capacity of the decarbonizer by air. The initial content of oxygen in source tap water corresponded to the equilibrium one, the concentration of carbon dioxide was 12.76–13.20 mg/dm³ with the source water alkalinity of 2.1–2.2 mg-eq/dm³. The water heating magnitude in the vacuum deaerator was kept fixed at 15 ± 2°C.

The experimental study results
The key feature of the studies was the fact that for the first time it became possible to assess the impact of the flow rate of air supplied to decarbonizer on carbon dioxide desorption. The change in flow rate of air was implemented by means of a control damper 11, installed in the air duct before the fan 3 (Figure 1). It was assumed that when the damper is fully opened, the nominal fan capacity is $D_a = 100\% \ (X_j = +1)$. The flow rate of air supplied to decarbonizer was measured using a preliminary calibrated hand-held anemometer. Several decarbonization modes were examined at different degrees of opening of the damper, installed on the suction pipe of the fan. As a result, it was managed to specify not only the impact of the flow rate of air on the efficiency of CO₂ desorption, but also to obtain analytical dependencies that allow determining the actual flow rate of air used for decarbonization depending on the flow rate of water under treatment [4].

Based on the results of testing the “decarbonizer – vacuum deaerator” system, the following regression equations, that adequately describe the system operation, were obtained:

$$Y_1 = 3.6 + 0.17 X_1 - 0.5 X_2 - 0.33 X_3 - 0.14 X_2 X_3, \quad (1)$$
$$Y_2 = 7.98 - 0.02 X_1 + 0.06 X_2 + 0.04 X_3, \quad (2)$$
$$Y_3 = 164 + 51 X_1 - 61 X_2, \quad (3)$$
$$Y_4 = 8.25 - 0.06 X_1 + 0.10 X_2 + 0.03 X_3 - 0.04 X_1 X_2. \quad (4)$$

The regime factors $X_i$ are included into the regression equations in the normalized form and, with their substitution in (1) – (4), can take values from -1 to +1. For the practical use of equations, including construction of graphs - diagrams of the modes of operation for decarbonizers and deaerators, it is necessary to convert the values of factors from the normalized form to a natural scale, which, to a certain degree, complicates the calculations and is not always convenient in engineering practice. It is much more convenient to use the graphical interpretation of regression equations and mathematical models, constructed in a natural scale

$$Y_1 = 4.33657 + 0.00121 x_1 - 0.016 x_2 + 0.00136 x_3 - 0.00112 x_2 x_3; \quad (5)$$
$$Y_2 = 7.75829 - 0.00014 x_1 + 0.012 x_2 + 0.0016 x_3; \quad (6)$$
$$Y_3 = 184.17121 + 0.36414 x_1 - 12.2 x_2; \quad (7)$$
$$Y_4 = 7.78057 - 0.00031 x_1 + 0.04171 x_2 + 0.0012 x_3 - 0.00006 x_1 x_2. \quad (8)$$

In equations (5) – (8), $x_1, x_2, x_3$ are the values of the corresponding controlled parameters in their natural form.
In order to visualize the results of the experiment using the regression equations (1) – (4), calculations for the array of the values of objective functions for various combinations of regime factors were made and the cross-sections of the response surfaces in two-dimensional space were obtained (Figures 2 – 5).

Figure 2. Dependences between the residual content of CO$_2$ in decarbonized water and the temperature of the treated water and the flow rate of air supplied to decarbonizer at the flow rate of source water $G_w = 240$ t/h; constructed for representative values: 1 - $C_{CO2} = 2.5$ mg/dm$^3$; 2 - $C_{CO2} = 3.0$ mg/dm$^3$; 3 - $C_{CO2} = 3.5$ mg/dm$^3$.

Figure 3. Dependences between the residual content of O$_2$ and the pH value of deaerated water and the flow rate and temperature of the treated water at $D_a = 100\%D_a^{nom}$, constructed for representative values: 1 - $CO_2^{act} = 50$ μg/dm$^3$; 2 - $CO_2^{act} = 100$ μg/dm$^3$; 3 - $CO_2^{act} = 150$ μg/dm$^3$; 4 - pH = 8.5; 5 - pH = 8.33; 6 - pH = 8.2.
Figure 4. Dependences between the residual content of CO₂ in decarbonized water and the flow rates of treated water and air at \( t_w = 18^\circ \text{C} \), constructed for representative values: 1 - \( C_{CO2} = 2.5 \text{ mg/dm}^3 \); 2 - \( C_{CO2} = 3.0 \text{ mg/dm}^3 \); 3 - \( C_{CO2} = 3.5 \text{ mg/dm}^3 \).

Figure 5. Dependences between the pH value of deaerated water and the flow rate and temperature of treated water at the flow rate of source water \( G_w = 240 \text{ t/h} \), constructed for representative values: 1 - pH = 8.5; 2 - pH = 8.33; 3 - pH = 8.2

Graphical dependencies (Figures 2 – 5) are based on calculation, but they are constructed on the basis of the experimentally obtained models of operation for decarbonizers and vacuum deaerators \((1) – (4)\). The accuracy of predicting the values of the objective function using the diagrams is the same as when using the experimentally obtained regression equations. This accuracy is determined by the values of the variances of reproducibility and adequacy.
It can be seen from the diagrams that despite the low temperature level of makeup water treatment processes, the required efficiency of carbon dioxide desorption in decarbonizers \((Y_1 = 3 \text{ mg/dm}^3)\) and vacuum de-aerators \((Y_4 = 8.33)\) is achieved within a wide range of studied modes. This can be explained by a sufficiently high bicarbonate alkalinity of the treated water.

The required efficiency of dissolved oxygen desorption \((Y_3 = 50 \mu\text{g/dm}^3)\) is achieved only at the lower level of the unit's capacity and at the upper level of the temperature of the treated water, within the range of the studied intervals of the parameters change \([4]\).

When setting up, maintaining and analyzing the operation of decarbonizers and vacuum deaerators, one can use both the regression equations and the polynomial dependencies and their graphical interpretation in the form of two-dimensional cross-sections of the response surfaces.

**Conclusion**

- The study of the “decarbonizer - vacuum deaerator” system, which is a part of the water treatment unit of one of the urban thermal power plants, was carried out via using the method of a complete factorial experiment.
- Based on the experimental data, multifactor regression equations were derived and cross sections of the response surfaces of objective functions in two-dimensional space were constructed, that adequately describe the processes of water degassing in a water treatment unit at low coolant temperatures.
- The mathematical models and diagrams obtained, characterizing the operation of the treatment unit for preparing makeup water of the heat supply network, allow one to assess the minimal technologically acceptable level, when it is possible to lower the temperature of the treated water and, consequently, to reduce the energy costs for its heating.
- The equations and graphical dependencies, describing the efficiency of carbon dioxide desorption from makeup water allow one, as well, to specify the minimal technologically acceptable level and the conditions when the reduction of the energy costs for supplying air to decarbonizer is possible.

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