Simulation and Optimization of Transients in Thermal Deaerators

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Abstract—A cellular matrix approach is proposed for calculating transients that occur during thermal deaeration with possible variations in the level of system decomposition due to the available support by empirical data. Matters relating to optimal control of the process are discussed.

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Optimal control of deaeration plants in variable modes of their operation with the minimal loss of steam and energy while keeping the quality of deaerated water at the required level can be implemented in the most efficient way through the use of adequate methods for calculating deaeration plants. Heat and mass transfer processes in deaeration plants were studied in a large number of works, e.g., [1–6]; however, the main focus is placed in them on steady modes of equipment operation. At the same time, since the demand for treated water is nonuniformly distributed over a day, week, and a year, the load of deaeration plants has to be frequently changed, and these plants have to be used in variable modes of operation. All this results in that material and thermal resources are used inefficiently (with overexpenditure) and that process parameters go beyond the permissible range of their values. In the present study, an attempt is made to construct a description of mechanical transients in thermal deaerators by means of cellular models with the use of the mathematical tools available in the theory of Markov circuits [7] and to solve some optimization problems on the basis of this theory.

Matrix cellular models were selected for describing deaeration processes due to the following advantages of these models:

—In cellular models, the working volume is spatially quantified into cells, material flows which can be described using well-known models, primarily through ideal mixing or ideal displacement. By combining these cells, it is possible to simulate flows in the entire structure, including stagnant and circulation zones.

—Existing dimensionless empirical dependences for calculating the coefficients of heat and mass transfer can be used in cellular models. A cellular model can be used to organize automated calculation of complex systems, which, in turn, makes it possible to solve problems connected with optimizing their structure and operating parameters.

—The use of matrix algebra and the corresponding ready-made software for describing a cellular model makes it possible to greatly simplify the technologies of programming and engineering calculations.

Along with constructing a model of steady processes, the use of a cellular approach makes it possible to calculate transient modes of equipment operation.

We will consider the development of a cellular model taking a jet-bubbling deaerator as an example. Its schematic design is shown in Fig. 1. The calculated region of heat and mass transfer is subdivided into elements (cells) the size and number of which are selected taking into account empirical data available for the studied conditions and the required accuracy of calculation. Below, an approach for selecting the number of cells and the structure of their interconnections is analyzed.

The following general algorithm is proposed for constructing a matrix model with the use of the mathematical tools of the theory of Markov circuits: the number of cells and the structure of their connections are selected, after which the state vector is determined and matrix equations for transforming the state of a system for the selected time step are derived.

We introduce a state vector for describing the state of a system, the form of which, constructed from the energies and masses of hot and cold heat agents in the cells and the mass of gas in them (taking the i-th cell as an example), is given by the following expression according to the analysis diagram shown in Fig. 1c:

\[
G = [G_{1i}, G_{2i}, G_{1i}(r_1 + l_1 c_2), G_{2i} c_2, G_{1i} c_1, G_{2i} c_2, G_{2i} c_2, \ldots]
\]  

(1)

where \(G_{1i}\) and \(G_{2i}\) are the masses of heat agents, \(C_{g1}\) and \(C_{g2}\) are the concentrations of gas in heat agents [the first subscript corresponds to heat agent (1 denotes the hot, and 2 denotes the cold one); the second subscript denotes the number of cells, and the subscript “s” points to the saturated state], \(r_1\) is the specific heat of vaporization, \(c\) is the specific heat, and \(l\) is the temperature.

The model is constructed on the basis of energy and mass balances for each cell, the analysis diagrams of
which are shown in Fig. 1c. The possibilities that heat agent will transfer from one cell to another by physical motion for hot ($p_1$) and cold ($p_2$) heat agents are determined by their motion in the apparatus.

A system of six equations is constructed from the six balance relations of mass for steam, mass for water, thermal energy for steam, thermal energy for water, mass of gas in the steam phase, and mass of gas in water that were obtained for one cell. The systems of these six equations are written for all cells of the plant and are brought to the matrix form

$$\mathbf{G}^{i+1} = \mathbf{P}_{GQ}^i + \mathbf{P} \times \mathbf{G}^i + \mathbf{C},$$

where the superscript indicates the number of time step for a process that varies in a discrete manner with the step $\Delta \tau$, and $\mathbf{P}_{GQ}$ is the feed vector that shows all external flows of masses and energies entering into the system considered.

The partitioned transfer matrix $\mathbf{P}$ for cells is assembled from block matrices in the following form:

$$\mathbf{P} = \begin{bmatrix}
\mathbf{B}_1 & \mathbf{O} & \ldots & \mathbf{O} & \mathbf{O} \\
\mathbf{P}_{gh} & \mathbf{B}_2 & \ldots & \mathbf{O} & \mathbf{O} \\
\mathbf{O} & \mathbf{P}_{gh} & \ldots & \mathbf{O} & \mathbf{O} \\
\ldots & \ldots & \ldots & \ldots & \ldots \\
\mathbf{O} & \mathbf{O} & \ldots & \mathbf{P}_{gh} & \mathbf{B}_n
\end{bmatrix},$$

Fig. 1. Schematic diagram of flows in a jet-bubbling deaeration plant (a) and its jet stage (b), the analysis circuit for calculating the mass and energy balances of heat agents for a cell (c), and versions of its decomposition (d).
where

\[
\begin{bmatrix}
  p_{1i} & 0 & 0 & 0 & 0 \\
  0 & p_{2i} & 0 & 0 & 0 \\
  0 & 0 & p_{1i} & 0 & 0 \\
  0 & 0 & 0 & p_{2i} & 0 \\
  0 & 0 & 0 & 0 & p_{2i}
\end{bmatrix};
\]

\[
\mathbf{P}_{gh} = \mathbf{B}_i = \begin{bmatrix}
  1 - p_{1i} & 0 & 0 & A/G_{2i} & 0 & 0 \\
  0 & 1 - p_{2i} & 0 & -A/G_{2i} & 0 & 0 \\
  0 & 0 & 1 - p_{1i} & B/G_{2i} & 0 & 0 \\
  0 & 0 & 0 & 1 - p_{1i} - B/G_{2i} & 0 & 0 \\
  0 & 0 & 0 & 0 & 1 - p_{1i} - k_m F/G_{2i} & k_m k_g F/G_{2i} \\
  0 & 0 & 0 & 0 & 0 & 1 - p_{2i} - k_m k_g F/G_{2i}
\end{bmatrix};
\]

\[\mathbf{O} \text{ is a null matrix; } A = \frac{kF \Delta \tau}{r_1 x_1 c_2} \text{; } B = \frac{kF \Delta \tau}{c_2} + \frac{kF_l \Delta \tau}{r_1 x_1} \text{; } F \]
is the heat-transfer area, m$^2$; \( k \) is the heat-transfer coefficient, W/(m$^2$ K); \( k_m \) is the mass transfer coefficient, kg/(s m$^2$); \( k_g \) is the coefficient in Henry’s law; and \( p \) is the probability of transition.

The matrix vector of absolute terms \( \mathbf{C} \) is written as follows:

\[
\mathbf{C} = [-k_1 k_{1i} - k_2 k_{2i} 0 0 0 0 0 0]’,
\]

where \( k_{1i} = \frac{kF t_i \Delta \tau}{r_1 x_1} \), and \( k_{2i} = kF t_i \Delta \tau + \frac{kF_l t_i c_2 \Delta \tau}{r_1 x_1} \).

The matrix \( \mathbf{P}_{gh} \) is written in form (5) when hot and cold heat agents move from one cell to another in the same direction. Otherwise, the probability that a transition of hot heat agent will occur is represented by the matrix \( \mathbf{P}_g \) and that for cold heat agent, \( \mathbf{P}_h \):

\[
\mathbf{P}_g = \begin{bmatrix}
  p_{1i} & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 \\
  0 & 0 & p_{1i} & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & p_{1i}
\end{bmatrix};
\]

\[
\mathbf{P}_h = \begin{bmatrix}
  0 & 0 & 0 & 0 & 0 \\
  0 & p_{2i} & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 \\
  0 & 0 & p_{2i} & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & p_{2i}
\end{bmatrix}.
\]

The obtained model makes it possible to study transients triggered by either a short-term (pulse) or a long-term (stepped) change in the input parameters (disturbance).

The developed model of a deaerator can also be used for calculating direct-contact heat exchangers. The removal of gas from water (degassing) is not taken into account here, and the two last equations in system (2), which describe the deaeration process, are excluded from it. If we simplify system (2) further by excluding the equations describing both deaeration and mass transfer, we can obtain a model of a surface heat exchanger.

The studied deaeration plant can be subdivided into a few characteristic cells, the number of which is determined based on the processes of interest that occur in them. A special numerical experiment was carried out to study how the level of system decomposition influences the shape of transients in a thermal deaerator. The studied schemes for decomposing the jet stage of deaeration (Fig. 1b) are shown in Fig. 1d. If the parameters of heat agents at the inlet remain con-
stant, and also if the overall heat-transfer areas are the same, the characteristics of heat agents at the deaerator outlet obtained in different decomposition versions differ from each other only slightly. An analysis that was carried out has shown that a qualitative assessment of heat-and-mass transfer processes can be obtained by using a scheme containing only one or three cells. Simplicity is the distinguishing feature of calculations carried out according to these schemes. In this case, the transfer matrix has the size equal to $6 \times 6$ or $18 \times 18$ elements, respectively. However, if we wish to calculate the deaeration process more accurately, the scheme comprising nine cells has to be used (see Fig. 1d). In this case, the transfer matrix will have a size of $54 \times 54$ elements. With different cells having essentially different hydrodynamic and thermal characteristics, the use of the model allows the process to be calculated in each cell with the corresponding values of heat-and-mass transfer coefficients.

To check the adequacy of the proposed model, we carried out studies (using the method of active experiment) for a DSA-300 jet-bubbling atmospheric-pressure deaerator, which was equipped with special devices for taking samples of water and steam. The following parameters were measured: the flowrates and temperatures of heat agents at the inlet to the deaeration plant and at the outlet from it, as well as the concentrations of oxygen dissolved in water. The flowrate of blow-off steam was determined from the flowrate of its condensate. Modern high-precision instruments for measuring thermal engineering parameters, which had been checked against reference measurement facilities prior to beginning the studies, were used during the experiments.

An analysis diagram of the DSA-300 deaerator was constructed and its mathematical model was developed using matrix (2). Figure 2 shows the analysis diagram of the deaerator, in which the following elements are indicated:

(i) the zone of the deaeration column under a jet-generating plate (nine cells);

(ii) the zone of the deaerator tank above the free water surface, using which it is possible to simulate the admission of main steam (one cell); and

(iii) the deaerator tank's zone in which bubbling is performed (one cell).

The cells lying along the flow of hot heat agent differ from each other in heat-transfer area. This is due to the selected pattern in which the holes in the jet-generating plate are distributed along the radius, the cylindrical shape of the deaerator column, and identical widths of the cells.

Figure 3 shows the change with time in the concentration of gases in water at the deaerator outlet in response to a stepped change in steam flowrate for bubbling.
response to a stepped change of steam flowrate for bubbling. The time step found in the course of identification is equal to 9 s. A comparison between the calculated and experimental dependences points to the fact that the model adequately describes the real process.

The developed model was also used to study how the design parameters influence the pattern of transients in a jet-bubbling deaerator. Dependences characterizing the change in the parameters of a transient for different profiles of channels for heat agents were obtained [8]. An analysis of these dependences show that the profile of a channel for a cold heat agent has an essential effect on the duration and amplitude of transients. The suitable profile of the channel for passing a hot heat agent can be arranged by placing additional profiles and guiding inserts in the calculated region of heat and mass transfer along the direction in which the cold heat agent moves. In this case, inserts will not affect the motion parameters of cold heat agent, and the profile of the channel for a hot heat agent can be shaped by changing their placement density. The profile of the channel for a cold heat agent is adjusted by changing either the diameter of holes or their number in the plates of the deaeration column.

An approach for setting up optimal control of transients was proposed on the basis of the developed mathematical model. A need of shifting to a new load or output of the deaeration plant frequently occurs in practice. The output must be changed without technological infringements of operating conditions. The concentration of oxygen in deaerated water is taken as a monitored parameter. To ensure that the concentration remains within the permissible limits when the flowrate of the cold heat agent into the deaerator increases, the flowrate of supplied steam must be increased accordingly. The time dependences of the controlled flowrates of water and steam are the sought optimized functions. The loss of steam with the blowoff steam flowrate $G_i$ can be considered as an objective function characterizing the optimal control of operating conditions. The mathematical formulation of the problem is written as follows:

$$F_{obj} = G_1 \{ G_{10}(t), G_{20}(t), u(C_{g2}) \} = \min_{G_{10}(t), G_{20}(t)} F_{obj}$$

where $u(C_{g2})$ is the constraint on the concentration of gas in deaerated water, and $G_{10}(t)$ and $G_{20}(t)$ are the sought time dependences (for control of steam and water supply) that must be fulfilled when the steam output of the plant is changed.

The solution of the problem carried out using the enumeration method is shown in Fig. 4 in the form of found dependences for control of steam flowrate when changes occur in the plant load and the corresponding responses of outlet parameters. The change in water flowrate is represented by a single dependence that was not varied in the course of analysis. The saving of steam obtained in case of different control versions is shown in the figure by shaded regions between the corresponding control cases. The minimal loss of steam is observed in case of control version 4; however, the constraint on the concentration of gas in deaerated water ($C_{g2}^* \leq 20 \mu g/kg$) is violated in the case of using this version of control. Thus, control version 3 is the optimal one in performing control of transients, which does not result in violation of the requirements for the concentration of gas.

A conclusion can be drawn from an analysis of the obtained dependences that the profile of the channel for passing the cold heat agent has a considerable effect on the duration and amplitude of the transient. The larger the channel’s cross section, the faster the transient runs.

The optimal control system has been put into operation in the line of the chemical water treatment system used at the thermal power department of a metallurgical enterprise. The use of this system made it possible to reduce heat losses by 54000 GJ/year and expenditure of steam for water treatment, by 1500 t/year.

REFERENCES

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