RESEARCH OF TRANSIENT RESPONSES IN AUTOMATIC MOBILE CONTROL SYSTEMS OF DISTILLATION PROCESS

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Abstract: Improving the control performance of objects with distributed parameters, which include the distillation process, is achievable by using mobile actions. It is known that moving along the column height of the feed point or redistributing a given flow between two contact devices of the apparatus makes it possible to achieve techno-economic indicators of stationary modes unattainable by traditional control. At the same time, transient responses in the column when using mobile actions remained unexplored.

To solve this problem, a mathematical model of the dynamics of the distillation process has been developed, taking into account the mobile control actions, and the features of the dynamic modes of operation of the column when using them have been investigated. The model provides for the possibility of implementing disturbances and control actions of various shapes and intensities through several channels simultaneously or at certain points in time.

It is established that a new stationary mode is achieved by regulating the pressure at the top of the column, the levels in the tanks to collect the bottom fractions and distillate. The use of PID controllers with actions on the refrigerant flow rate into the condenser and separation products is proposed. The dynamic process model is supplemented by a description of these automatic control loops.

Using the developed model, computational experiments are carried out on the example of a column for the separation of a methanol-water mixture. It is proved that transient responses when using mobile control actions on the distillation process are characterized by acceptable quality indicators.

The research results are applicable in the construction of systems for automatic mobile control of distillation processes, adaptive, optimal control systems using predictive models.

Keywords: distillation, column, mobile control, dynamic simulation, transient response, feed tray.

1. Introduction

The distillation process is used to separate liquid mixtures into individual components of high purity. As a control object, the distillation column is characterized by high energy intensity and cost of the products obtained, a large number of parameters, their interconnection, distribution, significant delays and inertia of the control channels [1].

In recent years, systems with distributed parameters have successfully used distributed, mobile [2, 3] control systems. Traditional control actions on the distillation process are intended directly to influence the material and energy balances of the column. While mobile actions suggest changes not in the intensities of the flows, but in the spatial coordinate of their entry into the apparatus. In practice, distributed, mobile control is reduced to the choice of feed trays and selection of side products [4], the redistribution of raw materials during its two-flow feed to the column.

In the direction of mobile control of distillation processes, the problems of developing an adapted static column model and choosing a solution method [5], process optimization [6] are solved. It is proved that the use of mobile control actions provides previously unattainable stationary modes of operation of apparatus, but dynamic modes remain unexplored.

At present, software for modeling chemical-technological processes, such as Aspen Plus [7], Aspen Dynamics [8, 9], ChemCAD [10], and others, are widely used. The use of these tools to study the basics of mobile control is difficult because of the high costs of acquiring and supporting, limited modeling capabilities of automatic control systems and obtaining results that are not provided by the developers.

An urgent task is the development of a mathematical model of the dynamics of the distillation process, taking into account the mobile control actions, as well as the study of transient responses in automatic mobile process control systems.

2. Methods

In modeling, a distillation column is considered as a set of elementary units equivalent to one tray, a reboiler, a condenser, and a reflux receiver for the top of the column. For each link, a system of ordinary differential equations for balance dependencies and nonlinear equations describing hydrodynamics, heat and mass transfer processes is compiled.

The transient response is calculated sequentially, at certain time points, spaced apart by $\Delta\tau$

$$\tau[k+1] = \tau[k] + \Delta\tau = (k+1)\cdot\Delta\tau,$$

where $\tau[0]=0$, k is an integer, $k=0, 1, \ldots, m$.

At the time instant $\tau[k]$, the values of all indicators of the contact device are known. These values are determined using the static model for the initial time instant $\tau[0]$ or directly by modeling transient responses.

The calculation of the column is carried out unidirectionally, from the bottom up, therefore, when switching to the j-th tray, the characteristics of the steam flow leaving the underlying contact device at the time $\tau[k+1]$ are already known. For the liquid flow entering the tray, it is necessary to use its characteristics at the time $\tau[k]$ in the calculations.

The main controlled disturbances to the process are: feed flow rate $F_j(\tau)$, feed composition $\bar{x}_{fj}(\tau)$, feed temperature $t_{fj}(\tau)$ and pressure in the feed pipe $P_{fj}(\tau)$.

The determined quantities are the rates and characteristics of the flows leaving the simulated traces – flow rate $L_j[k+1]$, $V_j[k+1]$, compositions $\bar{x}_j[k+1]$, $\bar{y}_j[k+1]$, enthalpies $h_j[k+1]$, $H_j[k+1]$ of the liquid and vapor phases, as well as the temperature $t_j[k+1]$ and the amount of liquid $G_j[k+1]$ on it at a subsequent point in time $\tau[k+1]$.

The system of equations describing a single tray of the column:

$$\frac{\mathrm{d}G_j}{\mathrm{d}\tau} = L_{j+1} + V_{j-1} + F_j - L_j - V_j;$$

$$G_j \cdot \frac{\mathrm{d}x_{j,i}}{\mathrm{d}\tau} = L_{j+1} \cdot \left(x_{j+1,i} - x_{j,i}\right) + V_{j-1} \cdot \left(y_{j-1,i} - x_{j,i}\right) + \\ + V_j \cdot \left(x_{j,i} - y_{j,i}\right) + F_j \cdot \left(x_{f,j,i} - x_{j,i}\right);$$

$$G_j \cdot \frac{\mathrm{d}h_j}{\mathrm{d}\tau} = L_{j+1} \cdot \left(h_{j+1} - h_j\right) + V_{j-1} \cdot \left(H_{j-1} - h_j\right) + \\ + V_j \cdot \left(h_j - H_j\right) + F_j \cdot \left(h_{f,j} - h_j\right);$$

$$G = \frac{\pi \cdot d^2 \cdot U \cdot \rho}{4 \cdot \mu};$$

$$\rho_i = \rho_{i,1} \cdot t + \rho_{i,2};$$

$$\rho=\frac{1}{\sum_{i=1}^{n}\left(\frac{x_i}{\rho_i}\right)}=\frac{1}{\sum_{i=1}^{n}\left(\frac{x_i}{\rho_{i,1}\cdot t+\rho_{i,2}}\right)};$$

$$\mu=\sum_{i=1}^{n}\left(\mu_i\cdot x_i\right);$$

$$m_j=\frac{\partial y_j^*(\bar{x})}{\partial x_j};$$

$$K_{y,j}=\frac{S}{\frac{1}{\beta_{y,j}}+\frac{m_j}{\beta_{x,j}}};$$

$$\eta_j=1-e^{-\frac{K_{y,j}}{V_{j-1}}};$$

$$y_{j,i}=y_{j-1,i}+\left(y_{j,i}^*-y_{j-1,i}\right)\cdot\eta_{j,i};$$

$$\bar{y}_j^*=f\left(\bar{x}_j,P_j\right);$$

$$t_j=f\left(\bar{x}_j,P_j\right);$$

$$h_j=f\left(\bar{x}_j,P_j\right);$$

$$H_j=f\left(\bar{y}_j,P_j\right);$$

$$h_{f,j}=f\left(\bar{x}_{f,j},P_{f,j},t_{f,j}\right),$$

where d is the diameter, m; K is the mass transfer coefficient for binary mixtures; m is the tangent of the angle of inclination of the tangent to the vapor-liquid equilibrium line; n is the number of components in the mixture; N_f is the number of the feed tray; q is the redistribution feed coefficient, kmol/kmol; S is the effective tray area, m^2; U is the level, m; β is the mass transfer coefficient calculated per unit of effective tray area, kmol/(m^2·h); η is the Murphree tray efficiency; μ is the molar mass, kmol; ρ is the density, kg/m^3. Subscripts: f is feed parameter; i is the parameter of the considered component of the mixture; j is the parameter of the considered contact device of the column; x is the parameter of the liquid phase; y is the vapor phase parameter. Superscript: * is the equilibrium parameter.

In order to take into account the mobile control actions on the process in the developed mathematical model, each contact device is considered as a potential feed tray

$$\begin{cases} F_j=q\cdot F, & j=N_{f,1}, \\ F_j=\left(1-q\right)\cdot F, & j=N_{f,2}, \\ F_j=0, & j\neq N_{f,1},\neq N_{f,2}. \end{cases}$$

Stationary modes of operation of the column are provided by effects on the material and energy flows of the apparatus. Thus, when controlling the process of distillation together with mobile, traditional control actions, consisting in changes of heat consumption in the reboiler and reflux flow rate, are also required. The calculation of the optimal values of these actions is implemented using a predictive nonlinear mathematical model of statics by the method of optimization of the distillation process [6].

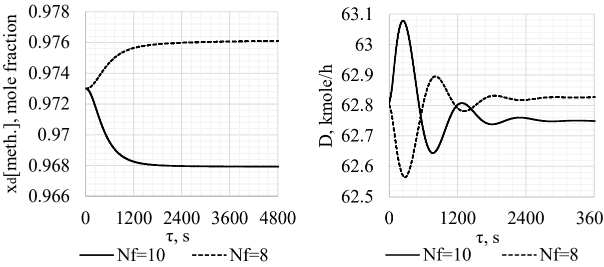
In order to maintain the material balance of the bottom of the column, it is necessary to stabilize the level in the bottom receiver by changing the flow rate of the bottom fractions. It also controls the level in the reflux receiver by draining the required amount of distillate and regulating the pressure at the top of the column by changing the flow rate of the refrigerant to the condenser. The use of PID controllers is proposed, the optimal settings of which are determined taking into account the necessary oscillability index.

3. Results

A column for the separation of a binary methanol-water mixture containing 18 contact devices, an external reboiler, and a condenser is studied. The concentration of methanol in the feed is 0.273 molar fractions. Indicators that determine the normal mode of the column: N_f=9, heat flow Q_w=6.4 GJ/h, distillate flow D=62.8 kmol/h, F=229.3 kmol/h, P_f=$P_{j=0}$=$P_{j=18}$=1 atm, β_x=3060.5 kmol/(m^2·h), β_y=142.82 kmol/(m^2·h), feed, reflux and distillate are at boiling temperature. The target component is methanol, and the product is distillate.

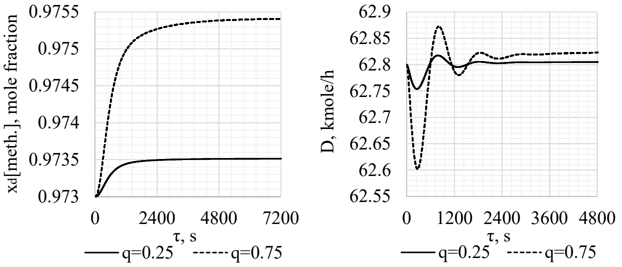
The calculations were performed with a step $\Delta\tau$ equal to 0.05 s. The following values of the tuning coefficients of the model were used: level in bottom receiver and reflux receiver U_w=U_d=0.3 m; the level on the contact devices is U_j=0.04 m. The distance between trays is h_y=0.2 m.

Transient responses are calculated using discrete mobile control actions, which consist in changing the feed point into the column (**Fig. 1**), and continuous, consisting in the redistribution of the feed flow between two contact devices (**Fig. 2**).



a *b*

Fig. 1. Transient responses when changing the number of the feed tray by the channels: *a* – "number of the feed tray – concentration of methanol in the distillate"; *b* – "number of the feed tray – flow rate of distillate"



a *b*

Fig. 2. Transient responses when changing the ratio of the feed flows rates by the channels: *a* – "feed redistribution degree – methanol concentration in the distillate"; *b* – "feed redistribution degree – flow rate of distillate"

Transient responses by the $N_f - x_d$ channel are monotonous aperiodic in nature. Changes in concentrations on other contact devices may be characterized by overshooting.

Since mobile actions do not change the total material and energy load of the column, dynamic errors during stabilization of levels are insignificant. The settling time is comparable with the duration of transient responses with basic disturbances to the process.

4. Discussion and conclusions

Using the developed model of the dynamics of the distillation process, a high calculation speed of non-stationary modes is achieved. It is possible to simulate disturbances and control actions of various shapes and intensities on the process through several channels simultaneously or at certain points in time. The structure of the model provides for the possibility of taking into account transport delays of the vapor and liquid phases in the column, non-stationary processes of mass and heat transfer.

The model allows to carry out calculations of multicomponent and complex distillation processes; it can be used to calculate the startups of the columns. The results of the research are applicable in the construction of systems for automatic mobile control of distillation processes, adaptive, optimal control systems using predictive models.

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