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DEVELOPMENT OF MATHEMATICAL AND IMITATION MODELS OF THE POTASSIUM CHLORIDE DRYING PROCESS IN AN ABSTRACT BOILING LAYER DRYER

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Abstract

In this article, a mathematical model of the drying process of potassium chloride in a fluidized bed dryer was developed. Taking into account the dynamic characteristics of the dryer, a system of differential equations was formulated separately for the bed and gas phases, based on heat balance, moisture balance, and dry matter mass balance. To simplify the model, key assumptions were adopted, such as ideal mixing of particles within the bed and isothermal conditions.

The obtained mathematical model provides the following capabilities: determining the dynamic characteristics of the dryer under nominal and variable operating conditions, calculating the time constants and transfer coefficients, as well as synthesizing optimization and control systems. The results of the study enable a scientifically grounded description and effective control of the potassium chloride drying process in fluidized bed dryers.

Keywords: Potassium chloride, fluidized bed, fluidized bed dryer, mathematical modeling, dynamic model, drying process.

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Introduction

In developing the mathematical description of the potassium chloride drying process in a fluidized bed dryer, the following assumptions are adopted:

- The particles in the bed are ideally mixed.
- The bed is in a fluidized state.

These assumptions make it possible to consider the bed over its entire volume under the condition of isothermal temperature of the solid phase, except for the thin boundary layer [1-4].

The isothermal property of the bed significantly simplifies the development and application of the mathematical model of the drying process, since the bed is considered as an object with lumped heat parameters.

Methods

In describing the drying process, the following assumptions are taken as fundamental conditions:

1.The residence time of the material in the bed significantly exceeds the minimum required duration of the drying process. Therefore, its kinetics cannot be adequately described, even in the simplest case, solely by using balance equations that neglect heat and mass transfer within the bed volume [3-8].

2.The temperature of the gases leaving the bed volume is equal to the bed temperature.

3.The temperature of the material is uniform throughout the entire bed volume, and the temperature measured by the thermocouple installed in the bed is equal to the bed temperature, corresponding to its isothermal behavior with respect to the solid phase.

4.The temperature of the material exiting the bed is equal to the bed temperature.

5.During transient regimes, changes in the bed temperature are negligible, which allows us to consider the heat capacities of the material and the cooler as nearly constant and equal to the actual isobaric heat capacities of the material, corresponding to the temperature of the applied steady-state process.

6.Heat loss through the walls by convection and radiation is proportional to the heat flux.

Using these assumptions, a system of differential equations was formulated:

The heat balance equation (in the drying apparatus, the heat balance includes the heat entering the system [5], the latent heat consumed for moisture evaporation, as

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well as heat losses occurring through the gas flow, the material being dried, and the apparatus walls) is expressed as follows:

$$Q_{heat.input} - Q_{mois.eva} - Q_{heat.los} - Q_{gas.flow} = 0 \qquad (1)$$

- material balance equation:

$$G_{input} - G_v = 0 \qquad (2)$$

The transition from the static model to the dynamic model is carried out under the condition of small perturbations around the steady state.

In this process, the following simplifying assumptions are adopted:

- ➢ The temperature and heat capacity of the incoming (moist) material are constant.
- ➢ In transient regimes, since the expected deviations of item t_{kc} are small, the heat capacities of the material and gas are considered constant and equal to the heat capacities of the material and gas at the temperature of the initial steady-state process.
- ➢ The enthalpy of the gas within the bed volume is small compared to the enthalpy of the material in the bed, and therefore the enthalpy of the gas can be neglected.

The second and third assumptions are quite reasonable:

- ➢ The heat capacity of the dry part of the material is practically constant;
- ➢ The heat capacities of moisture in materials and gases change slightly in the operating temperature range.

However, in the first approximation, it is reasonable to consider the heat capacity of the moist material as a single value, taking into account not only the change in material temperature but also the effect of changes in the moisture content of the material, which is the main factor in the drying process under study[6-8]. Using the above assumptions, the system of equations (1) - (4) is obtained:

$$\begin{aligned}&(1-\beta)\cdot c_m t_{1m}\Delta G_1 + (1-\beta)\cdot c_{1g}(t_{1g})_0\cdot\Delta L_1 + (1-\beta)\cdot(L_1)_0\cdot c_{1g}\Delta t_{1g} + (1-\beta)\cdot 0.01\cdot(\Delta\omega_1)_0\cdot c_v t_{1m}\Delta G_1 +\\&+(1-\beta)\cdot 0.01\cdot(G_1)_0\cdot c_v t_{1m}\Delta\omega_1 - c_{m,kc}(t_{kc})_0\cdot\Delta G_1 + (G_1)_0\cdot c_{m,kc}(t_{kc}) - (L_1)_0\cdot c_{g,kc}(t_{kc}) - c_{g,kc}(t_{kc})_0\cdot\Delta L_1 -\\&-5{,}95\cdot(\omega_1)_0\cdot\Delta G_1 + 5{,}95\cdot(G_1)_0\cdot\Delta\omega_1 - 0{,}047\cdot(\omega_1)_0\cdot(t_{kc})_0\cdot\Delta G_1 - 0{,}047\cdot(G_1)_0\cdot(t_{kc})_0\cdot\Delta\omega_1\cdot(t_{kc})_0\cdot\Delta G_1 -\\&-0{,}047\cdot(G_1)_0(t_{kc})_0\cdot\Delta\omega_1 = dQ_m/d\tau,\end{aligned} \qquad (3)$$

$$[(G_p)_0 - \Delta Gp] - [(G_v)_0 + \Delta G_v] = F, \qquad (4)$$

$$Q_m = M_{ks} c_{m,kc} t_{kc} \qquad (5)$$

For the case of introducing the product at the surface, solving the system of equations leads to operational-form equations with the object's time constants and transfer coefficients:

$$(T_{\alpha} p + 1)\Delta t_{kc} = k_1 \Delta G_1 + k_2 \Delta t_{1g} + k_3 \Delta L_1 + k_4 \Delta \omega_1, \tag{6}$$

$$p\Delta M_{kc} = k_5 \Delta G_p + k_6 \Delta G_{v,} \tag{7}$$

By taking expressions (6)–(7) into account, the dynamics of the dryer under study can be calculated.

To determine the time constants and transfer coefficients of the system, it is necessary to know the parameters of the design operating mode, the auxiliary parameters of the material and gas, and the fluidization regime domain. All these parameters are established during the modeling stage, which allows the calculation of the system's dynamics simultaneously with the design of its structural configuration [7].

The dynamic characteristics of the drying process are described through the following interaction channels:

- «feed rate – bed temperature»;
- «cooling – bed temperature»;
- «cooling medium – bed temperature»;
- « initial moisture content of the material – bed temperature».

The system along these channels is represented by first-order differential equation.

In the "feed rate – material mass in the bed" and "discharge – material mass in the bed" channels, the dryer exhibits a first-order astatic connection.

The main advantage of the proposed model is that it allows the determination of the dryer's dynamic characteristics, as well as its time constants and transfer coefficients, using simple analytical expressions already at the design stage.

The most reliable quality indicator is the product moisture content. Its relationship with the bed temperature is precisely defined only under conditions of stable drying time and constant parameters in the bed, i.e., in the steady-state regime [4-6].

In the dynamic regime, however, this relationship becomes significantly uncertain due to the time-dependent variability of the parameters.

Therefore, due to the insufficient justification of some simplifying assumptions adopted in the model described above, it is necessary to develop a separate mathematical model of the drying process for a single-chamber fluidized bed dryer without directed material movement.

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To obtain the mathematical description of the fluidized bed dryer as a control object, the method of formulating balance equations under nominal operating conditions is applied.

Results

In a combined apparatus, where the gas distribution grid is located below and the bed above, with the finished product being discharged at the grid level, the drying process is carried out in a single-zone cylinder-cone unit, taking into account the dynamic characteristics of the dryer and two cooling streams[6].

At the same time, the method for formulating the model equations and accounting for individual components is also applicable to simpler cases of drying under a gas distribution grid.

To determine six parameters, a system of six equations is formulated.

The following are taken as the main equations:

- Heat balance – for the material
- Heat balance – for the gas
- Moisture balance – for the material
- Moisture balance – for the gas
- Dry matter mass balance – for the material
- Dry matter mass balance – for the gas

This system of equations is used to obtain the dynamic description of the drying process. After transitioning to small deviations from the steady-state operating mode, the original system of equations takes a linearized form [2-7]:

$$(\Delta Q_{1m} + \Delta Q_{v,1m} - \Delta Q_{2m} - \Delta Q_{v,2m})((1-\beta) + \Delta Q_v - \Delta(Q_{Ii} + Q_{IIi}) = \frac{d}{d\tau}(Q_m + Q_{v,m}) \quad (8)$$

$$(\Delta Q_{1g} + \Delta Q_{p,1g} + \Delta Q'_{1g} + \Delta Q'_{p,1g} - \Delta Q_{2g} - \Delta Q_{p,2g})(1-\beta) - \Delta Q_v + \Delta(\Delta Q_{Ii}\Delta Q_{IIi}) = \frac{d}{d\tau}(Q_g + Q_{p,g}), \quad (9)$$

$$\Delta W_{1m} - \Delta W_{2m} - \Delta(W_{Ii} + \Delta W_{IIi}) = \frac{d}{d\tau}W_m, \quad (10)$$

$$\Delta W_{1g} - \Delta W'_{2m} - \Delta W_{2g}\Delta(W_{Ii} + \Delta W_{IIi}) = \frac{d}{d\tau}W_m \quad (11)$$

$$\Delta G_1 - \Delta G_2 = dM/d\tau, \quad (12)$$

$$\Delta L_1 - \Delta'_2 - \Delta L_2 = dL_{kc}/d\tau, \quad (13)$$

When separating the individual components of the system of equations (8) - (13), it is necessary to transition to the fluidization temperature value, which is particularly important for automating the drying process. Additionally, this transition reduces the number of unknowns to five, allowing the required number of equations to be reduced to five as well [8]. The procedure consists of incorporating all the conditions of the system equations and expressing them in terms of the increments of the input and output variables while taking this reduction into account.

$$L_{75}(\Delta d_1 \frac{d\Delta d_1}{d\tau}, \Delta L'_1, \frac{d\Delta L_1}{d\tau}, \Delta d_1', \frac{d\Delta d'_1}{d\tau}, \Delta L'_1, \frac{d\Delta L'_1}{d\tau}, \Delta t_{1g}, \Delta t'_{1g}, \Delta G_1, \Delta \omega_1) \quad (14)$$

$$L_{76}(\Delta G_2, \frac{d\Delta G_2}{d\tau}, \Delta \omega_2, \frac{d\Delta \omega_2}{d\tau}, \Delta t_{kc}, d_2) = L_{77}(\Delta G_1, \frac{d\Delta G_1}{d\tau}, \Delta \omega_1, \frac{d\Delta \omega_1}{d\tau}, \Delta L_1, \Delta d_1, \Delta t_{1g}, \Delta L_1', \Delta d_1', \Delta t'_{1g}) \quad (15)$$

$$L_{78}(\Delta t_{kc}, \frac{d\Delta t_{kc}}{d\tau}, \Delta d_2, \frac{d\Delta d_2}{d\tau}, \Delta G_1, \Delta \omega_2) = L_{79}(\Delta d_1, \frac{d\Delta d_1}{d\tau}, \Delta L_1, \frac{d\Delta L_1}{d\tau}, \Delta d_1', \frac{d\Delta d'_1}{d\tau}, \Delta L'_1, \frac{d\Delta L_1}{d\tau}, \Delta t_{1g}, \Delta t'_{1g}, \Delta G_1', \Delta \omega_1') \quad (16)$$

$$L_{80}(\Delta G_2, \frac{d\Delta G_2}{d\tau}) = L_{81}(\Delta G_1, \frac{d\Delta G_1}{d\tau}) \quad (17)$$

$$L_{82}(\Delta L_1, \frac{d\Delta t_{kc}}{d\tau}, \frac{d\Delta d_2}{d\tau}) = L_{83}(\Delta L_1, \frac{d\Delta L_1}{d\tau}, \frac{d\Delta d_1}{d\tau}, \Delta L_1', \frac{d\Delta L'_1}{d\tau}, \frac{d\Delta d'_1}{d\tau}) \quad (18)$$

The obtained system (2.14) - (2.18) is a re-linearized mathematical model of fluidized bed drying with two cooling streams and consists of a system of six first-order ordinary linear differential equations with constant coefficients for the output parameters.

The variable operations in the drying model are similar, and this model can be solved using the same methods. When considered collectively with its parameters, the above mathematical model can be used to calculate the dynamics of fluidized bed drying for the objects described by the corresponding equations. By applying the Laplace transform, the necessary transfer functions through the interaction channels can be constructed [5-8].

Discussion

The model based on material and heat balances was implemented using the MATLAB mathematical computation package. The model's performance was verified using data obtained from the technological information archive of the automatic process control system [2]. In this verification, samples of the wet concentrate were taken every 12 minutes during the work shift to determine moisture content in the laboratory. The simulation scheme, built in MATLAB to

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adjust the drying agent temperature by controlling the thermal regime of the drum dryer, is shown in Figure 1.

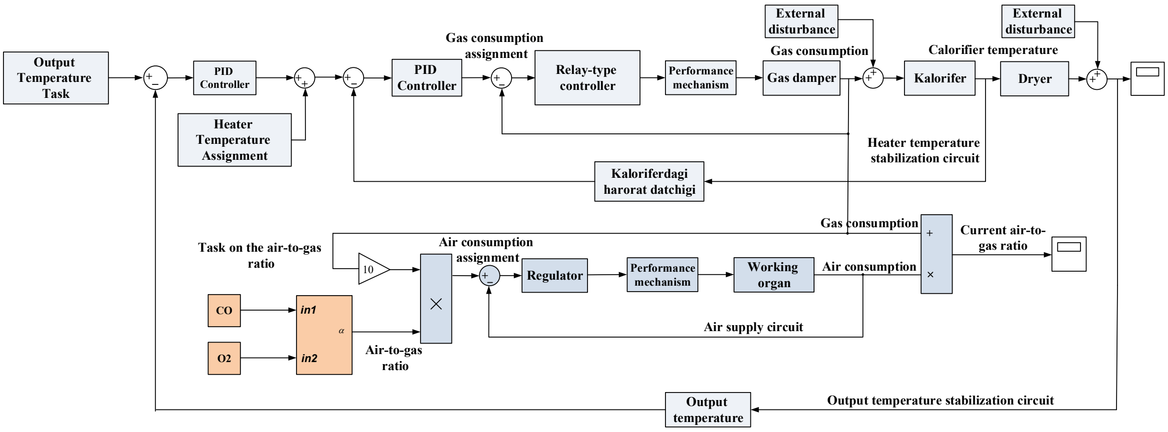

Figure 1. MATLAB simulation scheme for adjusting the drying agent temperature.

Figures 2 and 3 show the graphs of the variations in the final values of the drying agent temperature and the product moisture content.

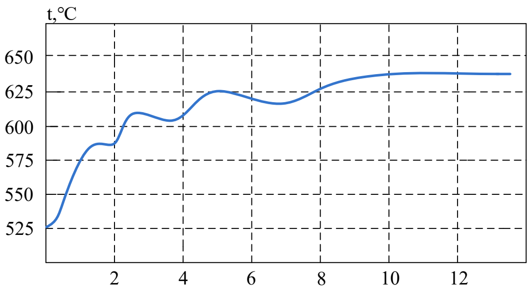

Figure 2. Graph of temperature variation.

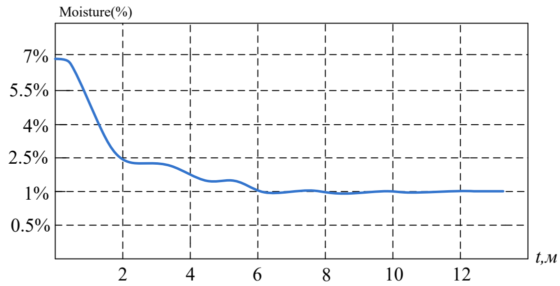

Figure 3. Graph of moisture content variation.

Conclusion

In this work, a mathematical model of the potassium chloride drying process in a fluidized bed dryer was developed. Considering the dynamic characteristics of the dryer, the study provides the following key conclusions:

➢ Assumptions such as ideal mixing of particles in the bed and the isothermal nature of the bed significantly simplified the model. At the same time, except for thin boundary layers, parameters were considered homogeneous throughout the bed.

➢ To describe the drying process, a system of six differential equations was formulated separately for heat, moisture, and dry matter mass for both the material and the gas. This system allows simulation of dynamic processes and evaluation under various operating conditions.

- The model is linearized under nominal operation and small deviations, simplifying the calculation of time constants, transfer coefficients, and steady-state moisture parameters.
- The developed mathematical model can be used at the dryer design stage, serving as a convenient tool for optimization, control system synthesis, and forecasting operational parameters.

Overall, the model enables a scientifically grounded description and effective control of the potassium chloride drying process in fluidized bed dryers.

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