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Modeling of the Process of Drying Potash Fertilizers in Suspended State

Bekkulov Zhahongir Sherboyevich

Karshi Institute of Engineering and Economics, 180100, Republic of Uzbekistan, Kashkadarya region, Karshi, Mustakillik str., 225

Abstract: The work is devoted to mathematical modeling of the drying process of potash fertilizers in fluidized bed apparatuses. The model is based on the material and thermal balance and takes into account the kinetics of the dehydration process of potassium chloride particles. The model is investigated using the tools of the Matlab mathematical computing package. The adequacy of the proposed analytical model to real processes and phenomena has been verified.

Keywords: Mathematical modeling and optimization, potash fertilizers, drying of potassium chloride in asuspended layer, virtual quality analyzer.

There is a significant amount of work devoted to modeling the drying processes of bulk materials, in particular, drying in fluidized bed apparatuses. At the same time, numerous models describing the structure of the fluidized bed reflect only certain aspects of the phenomenon. Due to the complexity of the system and with a large number of internal and external parameters, these models are suitable for use as a basis for reflecting empirical correlations and dependencies [1-2]. The mathematical model is based on the material and energy balance of drying, using simplifications and empirical dependencies defined, for example, in [3]. The material and energy balance of dehydration is determined by the following equations:

$$M(1-U_н)=(M-U)(1-U_к) \quad (1)$$

$$U = R(\frac{q}{q_1}); \quad (2)$$

$$q_1 = (q_{исп} + 2,01t_{сл}) + (m-1)C_{ТВ}t_{сл}; \quad (3)$$

$$m = \frac{(1-U_к)}{(U_к - U_н)}; \quad (4)$$

$$q = (Q + 0,6t_{сл})(1-\frac{t_{сл}}{t_Г}) \quad (5)$$

where $U_к$ – final humidity, (mass fraction); $U_н$ – initial humidity, (mass fraction); U– the amount of evaporated moisture, (*kg/s*); q– the amount of heat, transmitted in a layer by a coolant per one kg of burned fuel, (*J/k*); q_1– the amount of heat per evaporation of one kg of moisture, (*J/kg*); m– consumption of wet material corresponding to one kilogram of evaporated moisture, (*кг/кг* влаги); $C_{тв}$ – heat capacity of the material (potassium chloride-KCl), (*J/(kg·K)*; $t_{сл}$ – fluidized bed temperature, *(°C)*; $t_г$ – coolant temperature, *(°C)*; Q– calorific value of gas, *(Дж/кг)*; $q_{исп}$ – the heat of evaporation of water at 0°C, *(J/kg)*; η– coefficient of heat loss in the furnace and fluidized bed apparatus; M– the

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amount of wet material entering the drying, *(kg/h)*; *R*– total fuel consumption, (*kg/s*).

The gas temperature in the sublattice space , depending on the fuel gas consumption , is calculated by the empirical formula [4]:

$$t_{\Gamma} = 2920 \cdot \beta / \alpha + 0,43. \qquad (6)$$

In this case , the coefficient α is calculated by the formula

$$\alpha = L / (R \cdot 9,4) \qquad (7)$$

where β – coefficient that takes into account heat loss in the furnace; α – excess air ratio; L – hourly secondary air consumption, *(nm^3/s).*

As a result of the transformations we get

$$t_{сл} = \frac{((\frac{U}{R \cdot \eta})(2,01 + (m-1) \cdot C_{TB}) - 0,6 + (\frac{Q}{t_{\Gamma}}))}{(\frac{1,2}{t_{\Gamma}})} + \frac{\sqrt{((\frac{U}{R \cdot \eta})(2,01 + (m-1) \cdot C_{TB}) - 0,6 + (\frac{Q}{t_{\Gamma}}))^2 - 4 \cdot (\frac{0,6}{t_{\Gamma}})((\frac{U}{R \cdot \eta}) q_{ИСП} - Q)}}{(\frac{1,2}{t_{\Gamma}})} \qquad (8)$$

The dependence of the final humidity on the temperature of the layer is expressed by the empirical formula:

$$U = A \cdot e^{(-kt_{сл})} \qquad (9)$$

where the coefficients A and k depend on a variety of process conditions, in particular on the ambient temperature, the granulometric composition of the product, and are determined empirically and take the following values: A=0.02237, wt, ; k=-0,025, $\frac{1}{^0C}$

The model based on the material-thermal balance is implemented using the means of the MATLAB mathematical computing package. The operation of the model was tested on an array of historical data from the automated process control system archive obtained on functioning equipment. At the same time, sampling to determine the moisture content of the product in the laboratory was carried out at intervals of 600 seconds during the working shift. Figure 1 shows graphs of changes in the humidity of potassium chloride particles at the outlet of the fluidized bed dryer. In the graph shown in Fig.1, the series indicated by the dotted line is a sample of the values of the final moisture content of the U_k product in the real process (Fig. 2, a). The series indicated by a solid line represents the result of the analytical model at the values of its parameters indicated above, as well as the values of the crystallizate flow rate at the inlet and the initial humidity indicated in Fig. 2, b. If there is a selective distribution law of random observations (from the experiment) and the distribution law of the general population (determined by the model), then the adequacy of the analytical model can be assessed using the Pearson agreement criterion (χ^2- criteria) [4].

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To apply the χ^2-criterion, the entire range of variation of a random variable in a sample of volume N is divided into r intervals. The number of intervals when calculating the Pearson consensus criterion is determined by the formula

$$r = 1 + 3{,}322 \cdot \lg(N) \qquad (10)$$

where N is the number of values in the sample, r is the number of intervals.

The number of intervals r (for n = 45) is 6. Based on the maximum and minimum values of the residual humidity index in the sample under consideration and the specified number of intervals, the interval step of 0.02 wt is calculated. %.

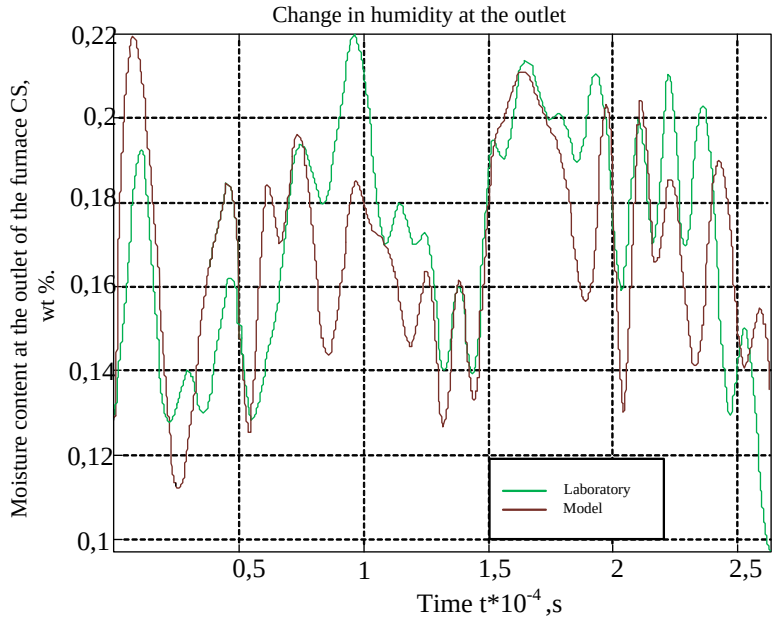
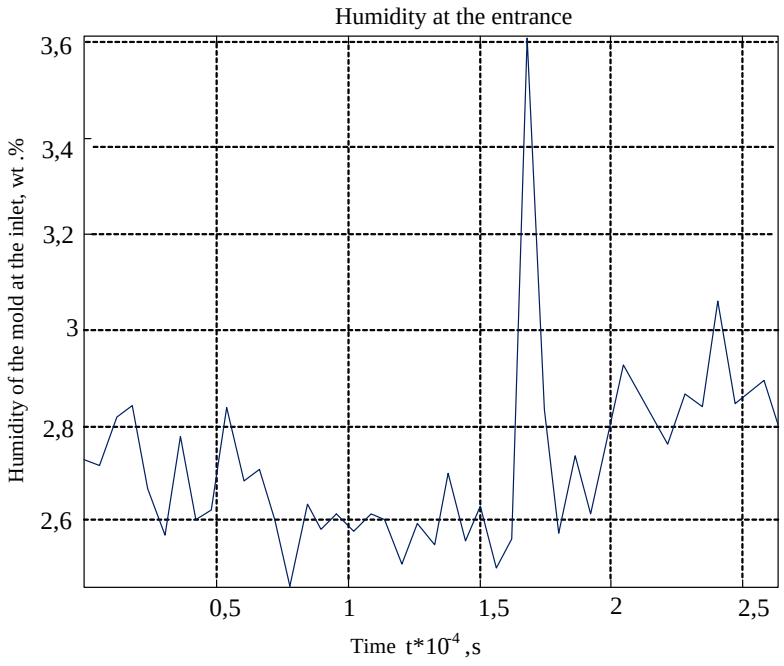


Fig.1. Change in the humidity of potassium chloride (KCl) particles at the outlet of the fluidized bed apparatus



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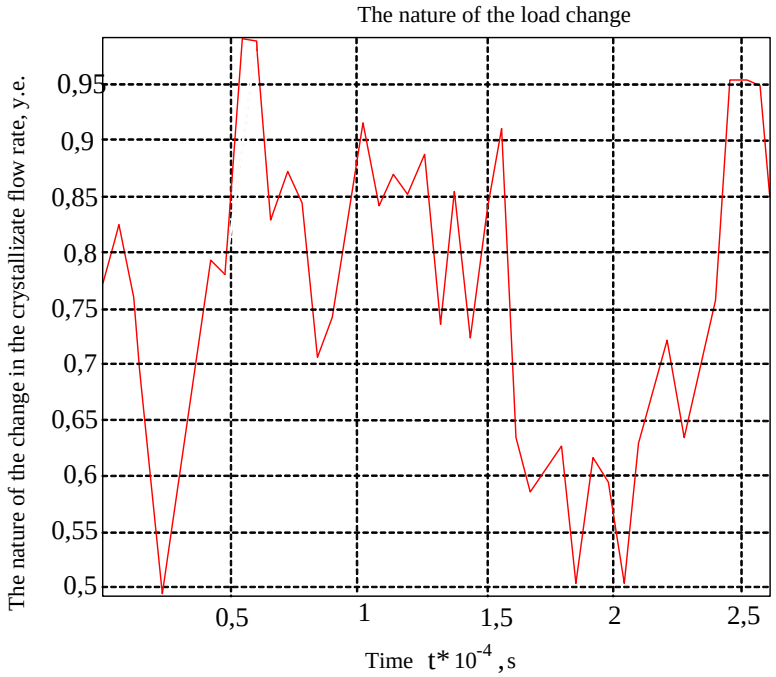

Fig. 2. Results of the analytical model of the fluidized bed furnace

Calculation of the frequencies of the results presented in Fig. (2,a), is given in Table.1

Table.1. Results of calculation of the analytical model

Interval number	Interval boundary, wt.%		Values of the frequency of hits in the interval	
	lower	upper	settlement	laboratory
1	0,1	0,12	2	2
2	0,12	0,14	8	10
3	0,14	0,16	11	6
4	0,16	0,18	11	9
5	0,18	0,2	10	13
6	0,2	0,22	3	5

The calculated value of the χ^2-criterion is calculated by the formula

$$\chi_{pac}^{\ 2} = \sum_{i=1}^{r} \frac{(O_i - E_i)^2}{E} \qquad (11)$$

where χ^2_{pac}- calculated value of the criterion χ^2; O_i - hit rate

in the *i*-th interval of calculated values according to the model; E_i – the frequency of hitting the i-th interval of laboratory values; *r* is the number of intervals.

The calculated value of the criterion χ^2_{ras} for the data in Table.1 equals 6,5. According to the table of critical values of χ^2_{ras} , at the significance level $\alpha = 0.05$ and the number of degrees of freedom $\lambda = r - 3 = 6 - 3 = 3$, the value of χ^2_{crete} is equal to 7,8. At the same time, $\chi^2_{ras} < \chi^2_{crete}$, i.e. the calculated value of the criterion turned out to be less than the critical one.Thus, the hypothesis of equality (agreement) of frequencies is not rejected and the model is recognized as adequate.

To assess the quality of the developed model, you can additionally use other indicators, for example:

1. Correlation coefficient. Reflects the tightness of the linear relationship between the calculated values of the model and the experimental ones.

$$R_r = \frac{\sum(y_i - \bar{y}) \cdot \sum(y_i - \bar{y})}{\sqrt{\sum(y_i - \bar{y})^2 \cdot \sum(y_i - \bar{y})^2}} \quad (12)$$

2. Average approximation error

$$delta = \frac{\sum \frac{(y_i - y_i)}{y_i}}{N} \cdot 100 \quad (13)$$

3. Standard approximation Error (RMSE)

$$sko\_delta = \sqrt{\frac{\sum(y_i - y_i)}{N}} \quad (14)$$

4. Maximum approximation error

$$\max\_delta = \max(abc(y_i - y_i) \quad (15)$$

Here: y_i – calculated value according to the model; y_i– experimental value; $\bar{y}$ – estimation of the mathematical expectation of the vector of calculated values; $\bar{y}$ – estimation of the mathematical expectation of the vector of experimental values; N– the number of values in the output vector of the model.

The values of the quality indicators of the analytical model (12)–(15):

correlation coefficient R.....0,673

average relative error..... 0,006

RMS mean square error.....0,023

maximum error.....0,057

Information for assessing the accuracy of the analytical model can also be provided by the errors given regarding the range of values of laboratory analyses in studies and the range of corresponding calculations based on the analytical model. The relative reduced error is calculated by the formula

$$Y = \frac{\Delta}{X_n} \cdot 100\% \quad (16)$$

where Y – relative reduced error of the analytical model; Δ – average absolute measurement error; X_n – the normalizing value of the scale.

The difference between the maximum and minimum values of the laboratory analysis vector, equal to 0.12 wt, % was used as X_n and the difference between the maximum and minimum values of the vector of calculated values, equal to 0.1132 wt.%.

The average absolute error of the analytical model is equal to:

$$\Delta = \frac{\sum_{i=1}^{N} \left| y_i - y_i \right|}{N} \qquad (17)$$

The relative reduced error of the model for the range of values of laboratory analyses (16) is numerically equal to 14.5%. The relative reduced error of the analytical model based on the range of calculations of the model (16) is numerically equal to 15.3%.

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8. СВЕДЕНИЕ ОБ АВТОРАХ:
   - фамилия, имя, отчество: Беккулов Джахонгир Шербоевич
   - место и адрес работы: Каршинский инженерно-экономический институт.
9. Адрес: 180100, Республика Узбекистан, Кашкадарьинская область, г. Карши, ул. Мустакиллик, 225,
   - должность: ассистент
   - рабочий телефон: +99899 081-09-55
   - образование: высшее
   - ученая степень: Независимые исследования в базовой докторской степени (PhD)
   - научное звание:
   - e-mail: *jbekqulov@mail.ru*