VOL. 16, NO. 20, OCTOBER 2021 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

MATHEMATICAL MODEL OF HEAT TRANSFER PROCESS OF PRODUCTION OF GRANULATED FERTILIZERS IN FLUIDIZED BED

Bogdan Y. Korniyenko[1], Lesya R. Ladieva[2] and Liliya P. Galata[3]
[1]Department of Automation and Control in Technical Systems, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine
[2]Department of Technical and Software Automation Tools, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine
[3]Department of Computerized Information Security Systems, National Aviation University, Kyiv, Ukraine
E-Mail: bogdanko@i.ua

ABSTRACT

A mathematical model of heat exchange of the process of production of granular fertilizers in the fluidized bed was developed. The mathematical models of the fluidization and granulation process in the fluidized bed are analyzed. The main processes affecting the production of granular mineral fertilizers - heat exchange, mass transfer, vaporization, crystallization - are determined. Transient characteristics of air temperature, temperature of granules and moisture content of granules were obtained. The computer experiment confirmed the adequacy of the proposed mathematical model of the process of production of granular mineral fertilizers in the fluidized bed. The main characteristics that affect the production of pellets in a fluidized bed are air temperature and pellet temperature. To obtain a fertilizer of a given quality, it is necessary to control the moisture content of the granules. The proposed mathematical model of heat transfer of the process of production of granular fertilizers in the fluidized bed together with the controller can be used to build an automated process control system.

Keywords: mineral fertilizers, mathematical model, dehydration, granulation, fluidized bed.

INTRODUCTION

Ukraine is one of the largest agricultural countries in Europe. The Ukrainian agricultural sector is a leading industry with a well-developed business structure and high investment prospects. Growing of cereals is a major part of the market and therefore an important issue is to ensure the growth of grain yields. To increase the yield, it is necessary to increase the amount of nutrients in the soil. This is achieved by the introduction of mineral fertilizers.

One of the most common methods of making mineral fertilizers is granulation. Fertilizers in the form of granules have several advantages over conventional fertilizers in the form of powder or liquid, namely, ease of transportation, are well absorbed and less amenable to soil weathering.

To obtain solids from a liquid starting material such as solutions, emulsions or suspensions, processes such as crystallization, granulation, spray drying are used.

Crystallization and granulation are complex dynamic processes involving several phases (liquid and solid), heat and mass transfer between these phases, as well as particle formation processes.

One of the processes commonly used in the pharmaceutical, food, and fertilizer industries is fluidized bed granulation. This allows you to obtain free dusty, free-flowing particles of liquid raw material: the suspension (or solution) is sprayed on the particles in the process chamber and due to drying - the layer is fluidized with hot air - the liquid evaporates. The remaining solid creates a new layer of solid material on the particles.

In addition, spray granulation can be carried out both in batch and continuous mode, the processes of drying and formation of particles can be combined and performed simultaneously in one device. The design of the granulation process apparatus is simple, and due to the high heat transfer and mass transfer rates, it is possible to design compact granulation plants compared to other technologies. On an industrial scale, the granulation process requires a large amount of energy, namely natural gas, which is used to heat the air in the process chamber. Reducing the amount of gas used for the granulation process by at least 10-15% at constant product quality indicators would significantly increase the efficiency of the granulation process and significantly reduce production costs. One important step in solving the problem is to create a mathematical model of the process that should correctly reflect all stages of the granulation process [1-3].

Therefore, the task of developing a mathematical model that will enable the creation of an energy-efficient granulation process control system that will maintain the moisture content of the granules at a given level is an urgent task.

FORMULATION OF THE PROBLEM

To obtain solids from a liquid material such as a solution, emulsion or suspension, there are various processes, such as crystallization, granulation and spray drying. They may be further specialized depending on the characteristic effect used for transformation, such as crystallization cooling or spray granulation [4].

One of the processes commonly used in the pharmaceutical, food, and chemical industries is the fluidized bed granulation.

This process allows to obtain dust-free, free-flowing particles of liquid raw material - a suspension that is sprayed on particles in the process chamber and by drying - the fluidized fluid bed is fluidized - the liquid evaporates. The remaining solid creates a new layer of solid material on the particles.

The main advantage of fluidized bed granulators is that several steps can be performed in the same device, including pre-mixing solid powder, granulation with a suitable liquid solution, followed by drying the granules to a predetermined humidity level. In addition, this technique has several advantages over other methods, such as high speed heat transfer and mass transfer, obtaining particles of a given size. Given the above advantages, the fluidized bed granulation process is widely used in the pharmaceutical, food and chemical industries and has a long history of over 40 years. In the following decades, the fluidized bed granulation process was studied more extensively, leading to the emergence of different mathematical models [5-8].

Product specifications can be very strict, for example, in processes with expensive raw materials or when the product is a life-threatening substance, the product specifications reach a fairly high level. The need to ensure that the product meets the specified specifications motivates the use of process control systems in the processes of particle production. Today, practically implemented control systems mainly focus on regulating the process of heat and mass transfer (humidity and product temperature) and integral values (total mass of the product) or average values (average particle size) of particles. Although management schemes generally satisfy the requirements they are facing, they cannot guarantee that the allocation of properties as a whole meets specifications. This means that, in the light of the increasing rigor of product specifications, production control systems need to be improved.

REVIEW OF MATHEMATICAL MODELS OF PROCESSES OF DEHYDRATION AND GRANULATION IN THE FLUIDIZED BED

Consider the basic approaches to mathematical modeling of fluidized bed transfer processes, classification of models by types of interfacial interaction, taking into account stochastic and chaotic hydrodynamics.

Accordingly [4] we define the purpose of the mathematical model of the apparatus for dehydration and granulation in the fluidized bed:

- assisting in the study of processes occurring in the apparatus (model as a means of cognition and learning);
- data collection and processing (model as calculation method);
- reduction of the number and cost of necessary experiments (model as a means of performing computational experiments).

Consider mathematical models of dehydration and granulation processes in fluidized bed machines, which are necessary to determine the basic process parameters, scale the apparatus, and perform further process control. The studies were performed for a fluidized bed with a rising fluid flow and taking into account the fluidized bed turbulence. Also used are mathematical models for rapid fluidization.

According to the results of the research, the following generalizations are made.

Orcutt model: this model, which allows piston flow in both phases, gives good results of the distribution of concentration profiles due to interfacial mass transfer. Requires specification for specific experimental data [9].

Partridge-Rowe model: The neglect of the two-phase theory has caused a serious problem for this model. The predicted region of the bubble phase exceeds the total area of the layer. Attempts to adjust the gas flows in phases have not completely overcome this problem [10].

Kato-Wen model: This model satisfactorily predicts the concentration distribution profile of the bubble phase, but it cannot predict the concentration in the emulsion phase and cannot predict the concentration drop near the surface of the layer [11].

Kuniy-Lewenshpil model: The best match was found using this model. With this model, the concentration in the dense phase is correct, due to the low velocity of the interphase mass transfer. It is established that the total mass transfer in the Kuniy-Lewenshpil model is limited by the resistance between the cloud and the emulsion and the model is simplified to two phases by combining the phases of the bubble and the cloud [12].

At the same time, the above deterministic mathematical models can be improved by applying a stochastic approach to the processes occurring in the fluidized bed apparatus. In fluidized bed modeling, the stochastic approach allows for fluctuations in local hydrodynamics or interphase exchange. When controlling fluidized bed devices, most of the parameters being measured exhibit random fluctuations with sufficiently high amplitude [13].

Chaotic fluid dynamics is also used for mathematical modeling of fluidized bed apparatus [14]. Fluidized bed devices are chaotic systems. Experimental studies have confirmed that local areas of pressure, cavities, and concentrations have disordered fluctuations associated with nonlinear dynamics. Therefore, with the help of chaos, one can describe the dynamics of the fluidized bed and study the processes in the apparatus for different hydrodynamic modes. Determined chaos can occur in the fluidized bed as a result of nonlinear interaction of two bubbles [15]. Thus, one can use the chaotic behavior of the fluidized bed for the classical van Deemter mathematical model [16].

MATHEMATICAL MODEL OF HEAT TRANSFER PROCESS OF PRODUCTION OF GRANULATED FERTILIZERS IN FLUIDIZED BED

The basis for controller design is a dynamic process model. In principle, the more accurate the process description, the more we can say about the result of the process. But the excessive amount of detail can also dramatically complicate the design process of the controller, so assumptions are made at some point that subsequently simplify the controller design without compromising the accuracy of the process result.

The granulation process in the granulator is greatly influenced by such parameters as the temperature of the granules, the fluid temperature of the fluidized bed and the moisture content of the granules. In the mathematical model created, much attention is paid to controlling these parameters so that the control system can ensure efficient use of resources and high quality of products.

The mathematical model must meet the following requirements:

- The temperature range in which the granulator operates must be in the range of 360 K to 480 K;
- the initial conditions for the parameters of the moisture content of the granules, the temperature of the granules, and the air temperature at which the granulator begins to operate must lie within 90 - 92%, 358 - 360 K and 470 - 475 K, respectively;
- boundary conditions for moisture content parameters - the moisture content of the granules at the outlet should be in the range of 15% to 25%, the temperature of the granules - the temperature of the granules should not exceed 360 K - 380 K, the air temperature - should not go beyond the temperature range.

The moisture content of the granules, the air temperature inside the granulator used for the granulation process, and the temperature of the granules are closely related, because if the air temperature exceeds the temperature range, there will be excessive heating of the granules and a critical reduction in the moisture content of the granules. As a result, excess energy will be used to heat the air, which is not energy efficient, and reducing the amount of moisture in the pellets can lead to their fragility, which negatively affects the process of transportation and use of mineral fertilizers, so it is important that mathematically developed the model met the requirements [17-30].

When creating a mathematical model, the following assumptions were made:

- the change of the parameters of the fluidized bed occurs in time, without taking into account the radial component and the change in height;
- heat exchange between air, particles and droplets is convective;
- change in temperature and moisture content along the width of the layer does not significantly affect the formation of granules, so we can neglect it;
- fluidized bed is well mixed, no stagnant zone.

The processes of dehydration and granulation are described by the developed mathematical model in the form of a system of three differential equations. Equation (1) describes the change in air temperature used to heat the layer and pellet formation:

$$\begin{aligned}&\varepsilon\cdot\rho\cdot C\cdot\frac{\partial T_a}{\partial t}+V_a\cdot\varepsilon\cdot\rho\cdot\frac{\partial T_a}{\partial x}=\varepsilon\cdot a\cdot\frac{\partial^2 T_a}{\partial y^2}-\alpha\cdot F\cdot\left(T_a-T_g\right)+\\&+G_p\cdot\left(1-x_p\right)\cdot\left(r+C_a\cdot T_g\right);\end{aligned}\tag{1}$$

where ρ - the density of the granules, kg/m3; C - the heat capacity of the granules J/(kg·K); T_a - temperature of the coolant, K; V_a - velocity of the coolant, m/s; ε - the porosity of the flow of granules; α - the heat transfer coefficient, 1/s; a - the coefficient of horizontal thermal conductivity, m^2/s; F - area of the gas distribution grid, m^2; T_g - temperature of the granules, K; G_p - the consumption of the original solution, m^3/s; x_p - the concentration of the original solution; r - the heat of vaporization, J/kg; C_a - the specific heat of air, J/(kg·K); x - the height of the device, m; y - width of the device, m.

Equation (2) describes the change in temperature obtained in the granulation process of granules:

$$\begin{aligned}&\left(1-\varepsilon\right)\cdot\rho\cdot C\cdot\frac{\partial T_g}{\partial t}-V_g\cdot\left(1-\varepsilon\right)\cdot\rho\cdot\frac{\partial T_g}{\partial x}=\alpha\cdot F\cdot\left(T_a-T_g\right)-\\&-G_p\cdot\left(1-x_p\right)\cdot\left(r+C_a\cdot T_g\right)+G_p\cdot x_p\cdot q;\end{aligned}\tag{2}$$

where V_g - the speed of the spray solution, m/s; q - the heat released during the crystallization of the solution, J/kg.

Equation (3) describes the change in the moisture content of the granules:

$$\begin{aligned}&\varepsilon\cdot\rho\cdot\frac{\partial W_g}{\partial t}+V_a\cdot\varepsilon\cdot\rho\cdot\frac{\partial W_g}{\partial x}=D\cdot\varepsilon\cdot\frac{\partial^2 W_g}{\partial y^2}+\\&+\beta\cdot F\cdot(\varsigma_1\cdot T_a-\varsigma_2\cdot T_g);\end{aligned}\tag{3}$$

where W_g - the moisture content of the granules; D - the diffusion coefficient, m^2/s; β - the mass transfer coefficient, kg/m^2; ς_1, ς_2 are the weights.

The mathematical model developed in the form of equations (1) - (3) takes into account the fluid dynamics of the fluidized bed, as well as the kinetics of the granulation and dehydration processes.

EXPERIMENT

The solution of the system of differential equations of the mathematical model was carried out using the fourth-order Runge-Kutta method.

To obtain the results of the developed mathematical model of the system, a program is implemented that calculates and displays graphs of air temperature, temperature of granules and moisture content in the Python programming language PyCharm. The xlsxwriter library was used to add the results to the table and to plot the graphs. After executing the program, this library generates a .xslx result file and graph that can be opened with Microsoft Exel.

The simulation of the granulation and dehydration process was based on the data in Table-1.

The adequacy of the mathematical model developed was performed with an integration step of 0.01 and with an iteration amount of 60 000. The graphs show the values of air temperature, temperature of the granules and moisture content of the granules at a height x = 0.5 m in the fluidized bed granulator.

Transient characteristic of air temperature change in the granulator is shown in Figure-1.

The air temperature in the granulator from the initial value of 473 K falls to the value of 415 K - 410 K. Since the process of granule formation and their subsequent drying requires a large amount of heat, we observe a decrease in air temperature. The transient characteristic of the temperature of the granules is shown in Figure-2. The transient characteristic of the moisture content of the granules is shown in Figure-3.

During the drying process, the temperature of the granules should increase and the amount of moisture should decrease, which we can observe from the transient characteristics (Figures 2-3). As can be seen from the graphs obtained, the nature of the air temperature behavior in the granulator remains unchanged, ie it remains in the range 410 K - 415 K, but the longer the process, the more the granules will heat up, the more moisture and energy consumption will evaporate from them. There will be more to accomplish this process. The specified moisture content of the granules should be in the range of 15% to 25%. Continued drying can lead to the loss of quality characteristics of the granules and increase their fragility.

Table-1. Basic parameters of the fluidized bed granulation process.

Parameter name	Conventions	Value	Dimension
The heat transfer coefficient	a	5.56	$W/m^2 \cdot K$
The consumption of the original solution	G_p	0,0068	kg/s
Air capacity	C_a	1970	J/kg·K
The concentration of the solution	X_p	0,4	
Specific heat of vaporization	r	129000	J/kg
The heat released during the crystallization of the solution	q	82300	J/kg
Coefficient of heat transfer	α	800	W/m^2K
Mass transfer coefficient	β	0.054	kg/m^2s
Diffusion coefficient	D	0.000245	m^2/s
Initial air temperature	T_{a0}	473	K
Initial temperature of the granules	T_{g0}	360	K
Initial moisture content of granules	W_{g0}	90	%

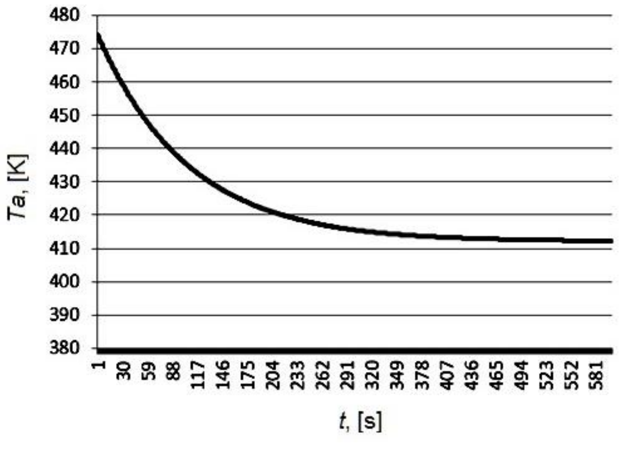

Figure-1. Transient characteristic of air temperature in fluidized bed granulator.

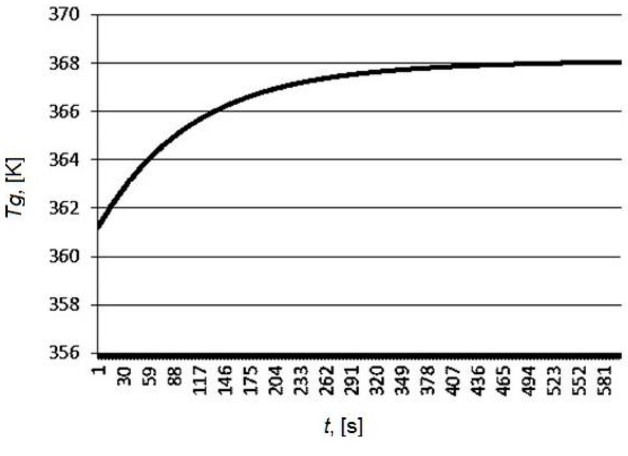

Figure-2. Transient characteristic of the temperature of the granules in fluidized bed granulator.

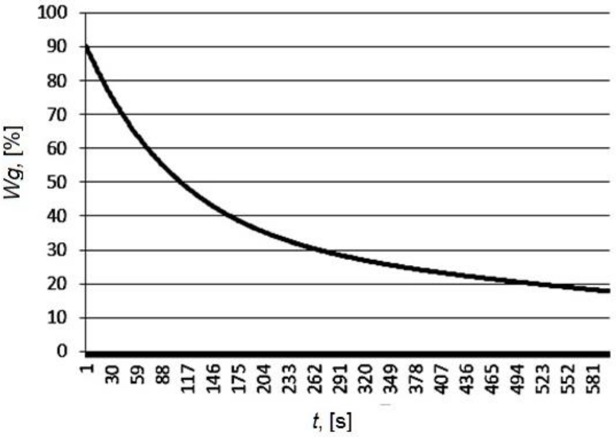

Figure-3. Transient characteristic of the moisture content of the granules in fluidized bed granulator.

CONCLUSIONS

A mathematical model of heat exchange of the process of production of granular fertilizers in the fluidized bed was developed. The mathematical models of the fluidization and granulation process in the fluidized bed are analyzed. The main processes affecting the production of granular mineral fertilizers - heat exchange, mass transfer, vaporization, crystallization - are determined. Transient characteristics of air temperature, temperature of granules and moisture content of granules were obtained. The computer experiment confirmed the adequacy of the proposed mathematical model of the process of production of granular mineral fertilizers in the fluidized bed. The main characteristics that affect the production of pellets in a fluidized bed are air temperature and pellet temperature. To obtain a fertilizer of a given quality, it is necessary to control the moisture content of the granules. The proposed mathematical model of heat transfer of the process of production of granular fertilizers in the fluidized bed together with the controller can be used to build an automated process control system.

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