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АНАЛІЗ СПОСОБІВ ІНТЕНСИФІКАЦІЇ ТЕПЛОМАСООБМІНУ В ПРОЦЕСІ СУШІННЯ ТА ОСОБЛИВОСТІ ЗНЕВОДНЕННЯ ТЕРМОЛАБІЛЬНИХ ОРГАНІЧНИХ МАТЕРІАЛІВ

В статті представлений аналіз традиційних способів інтенсифікації процесів тепломасообміну при сушінні матеріалів. Експериментально доведено перспективність застосування способу сумісних процесів сушіння та диспергування в одній камері за допомогою механічного ротора при інтенсифікації процесу сушки високовологих термолабільних матеріалів.

Ключові слова: *сушка, інтенсифікація, термолабільний матеріал, камера, сумісний процес, механічний ротор.*

1. Introduction

As is known, drying is a complex process that depends on many factors, knowledge of which is essential to the process analysis and calculation.

The drying rate is determined by the drying process speed that decreases and usually tends to zero as equilibrium is approached. Drying rate depends on several factors that indicate the complexity of real drying process, especially in the working environment and complexity of obtaining an adequate mathematical description. The drying process is most influenced by the factors that define the material as an object of drying. They characterize the material's resistance to moisture transfer inside and on its surface into the environment, the force of moisture binding with the material, the material's ability to absorb heat supplied to it. These factors include the internal structure of the material, its thermophysical properties and the size, shape and condition of the outer surface, the range of changes in the moisture content of the material in the drying process [1]. In practice, it is important to find methods of speeding up the heat and mass transfer processes during drying of materials.

2. Analys of literature and formulation problems

Traditional intensification methods of the dewatering process in the workspace of equipment are:

- intensifying the heat and mass transfer at the contact interface of phases;
- developing the contact surface of phase;
- increasing the relative velocity of the coolant;
- reducing the characteristic linear dimension of the material;
- increasing the temperature difference value.

Also, conditions that create artificial turbulization of the flow are used. When drying materials, the effect of artificial turbulization can be obtained by giving rational roughness or waviness to the surface of products if technically permissible, thus increasing the heat transfer coefficient by 50–100 % [2, 3] and the heat transfer surface.

There are methods of flow turbulization by means of vibrations. Studies show that this can intensify the heat transfer process for certain types of drying units. Under vibration of the heat transfer surface in fluids, heat transfer coefficient increases by 1,5–2 times, in the air — by 1,5–4 times.

The vibration of the material dried, especially with small dimensions is of great practical interest. The implementation of such vibration is possible by mechanical means during drying of the disperse material in the layer of moving fibers, etc. It is possible to implement vibration of particles (that have received an electrostatic charge during dispersion or otherwise) in the coolant flow by applying pulsating electric fields is possible.

Moisture transfer intensification inside the material during drying, which is an interconnected set of breaking processes of moisture binding with the material, moisture diffusion through the material elements, its movement through capillaries, transport of the gas and vapor phases, formation and rupture of polymolecular films, electrostatic moisture bonds with the material, and other processes is also important. Obviously, the internal transfer processes occur the more intensively, the smaller the size of the material dried. Moisture transfer in the material is significantly affected by the existence of concentration fields, the direction of heat flows and temperature fields. The main driving force of moisture transfer in the material is a concentration gradient. Transfer can be facilitated or hindered by thermal diffusion. Heat supply towards moisture movement carried out by the contact method, current conduction through the material or elements that carry it, as well as induction and high-frequency heating are promising in this regard. Studies of many authors [4–6] have shown that drying is markedly accelerated at the material temperature change from 50 to 95 °C. They attribute this to changes in the moisture viscosity and rupture of polymolecular films in the material.

In the literature [7–9] there are data on the effect of acoustic oscillations of coolant flows on the moisture transfer in the material, caused by the pressure pulsations in the surface of the material that contribute to moisture extraction from it.

Partly mentioned above intensification methods are implemented in the chambers of combined processes. Combined process means complex aerodynamic, thermal, mechanical impact on the material, which causes the reduction of internal and external resistance to the transfer of momentum, energy and mass, dramatically increasing the integral characteristics of the process — value of volumetric heat and moisture stress.

Chambers of combined processes are highly specialized devices, and their choice is dictated by the structural and physical-mechanical characteristics of the materials processed.

There are the following ways to implement the chambers of combined processes: mechanical dewatering and drying, drying and grinding, drying and granulation (of solutions, suspensions, melts, thermogranulation of powders), drying and encapsulation, drying and heat treatment, drying and trapping, as well as with simultaneous chemical reactions.

An example of a multifunctional device with controlled fluid flow may be a device with counter-swirling flows, designed for drying with the simultaneous dust collection, drying and heat treatment, dewatering and granulation, as well as for other chemical processes (absorption, conditioning, desorption) [10–15].

As is known, the drying process begins when the pressure difference over the body surface and in the environment and the temperature difference, which provides heat supply to change the physical state of moisture are formed. Upon heat supply, the wet body is warmed, the partial pressure of the vapor over its surface increases and moisture evaporates. Herewith, the body temperature rises to a certain value (wet-bulb temperature), which depends primarily on the temperature and partial vapor pressure in the environment. This temperature remains virtually unchanged while evaporation occurs from the body surface and is not limited by the rate of moisture supply from deep layers. The rate of moisture removal from the body is determined only by the conditions of the heat supply thereto and moisture vapor removal from its surface. Conditions of moisture supply from deep layers to the material surface in this period do not affect the process, drying speed is determined by the heat supply rate and is constant at a stable mode. The drying period with constant moisture removal rate and the material temperature is called the first period. In most cases, any heat supply intensification in it is appropriate and secure since this increases the process speed while maintaining safe, in terms of quality, temperature of the material that can be implemented in the chambers of the combined processes using the mechanical rotor during drying of thermolabile high-moisture materials.

As the moisture near the surface layers of the material is removed, the drying process begins to be limited by the rate of moisture supply to the surface of evaporation from deep layers. At first, evaporation takes place from the material surface at constant deceleration and a gradual increase in the material temperature. Further, as the moisture movement rate decreases, evaporation zone begins to move from the surface into the depth of the material and a sharp increase in its surface temperature occurs. This period is called the second period of drying. From this point on, the temperature of the material surface layers increases more intensively, moisture removal is significantly reduced, and, most importantly, surface layers of the material overdried, which have an increased temperature appear.

The speed of this drying period is determined by disturbances in moisture binding with the material and its transfer. Thus, to speed up drying, these processes need to be intensified.

There are several ways to intensify the second drying period to overcome diffusion and heat resistance of materials. These include high-frequency current drying [16], discharge pressure drying, oscillating drying regime [17].

Structural analysis of combined process plants has shown that in order to implement active hydrodynamic regime in the chamber when processing high-moisture thermolabile materials such as chicken manure, sludge after fermentation process and so on, using a mechanical rotor, rotating along the chamber axis is the most advisable. This leads to the formation of a weighted layer of the material, separation of large pieces, gas flow swirling, reduction of adhesion to working surfaces of the chamber, constant renewal of the heat transfer surface.

3. Object, purpose and task of the investigation

Analysis of methods to increase the materials drying rate, mentioned above has shown that along with the intensification of thermal effect on thermolabile material, it must be dispersed into small-size elements, which is appropriate in the same chamber. This will allow to artificially maintain the material surface temperature close to the wet-bulb temperature, thereby reducing finding the material in the second period to a minimum.

The object of study is heat-mass transfer processes in the chamber of units of combined processes of drying and grinding.

The purpose of work is studying the method of selection of intense heat and mass transfer processes in the chamber of combined drying and grinding by mechanical rotor dehydration of high-heat-sensitive organic materials.

The main objectives of the study:

1. Literature review with analysis and synthesis of information on the intensification of heat and mass transfer in drying processes and the use of the process of drying and grinding in one chamber by dewatering heat-sensitive materials.
2. The study of heat and mass transfer processes in the chamber of combined drying and grinding processes with marking the main thermal and thermodynamic parameters.
3. The development of energy-saving technology of organo-mineral fertilizers on the basis of a waste of poultry (chicken manure).

4. Materials and methods of research studying the effect of particle size of the material by the amount of heat and mass transfer coefficients and the energy performance of the drying process

Experimental research, conducted by the author during processing of such materials (green mass, organic sludge, poultry waste) confirms that the simultaneous dispersion of the material into sizes from 1 to 3 mm with its drying allow to reduce the residence time of the material in the second period.

5. The results of studying the effect of particle size of the material by the amount of heat and mass transfer coefficients

The effect of the spherical shape of the boundary layer on its thickness and «equivalent» thermal conductivity will be the greater, the smaller the streamlined diameter of the spherical part. During the heat emission of the spherical part of thermal conductivity into the infinite environment, dimensionless heat transfer coefficient *Nu* has the minimum possible value, equal to a constant 2.

In the flow around of these parts, the *Nu* criterion is determined from the expression [2]. The results are shown in Fig. 1.

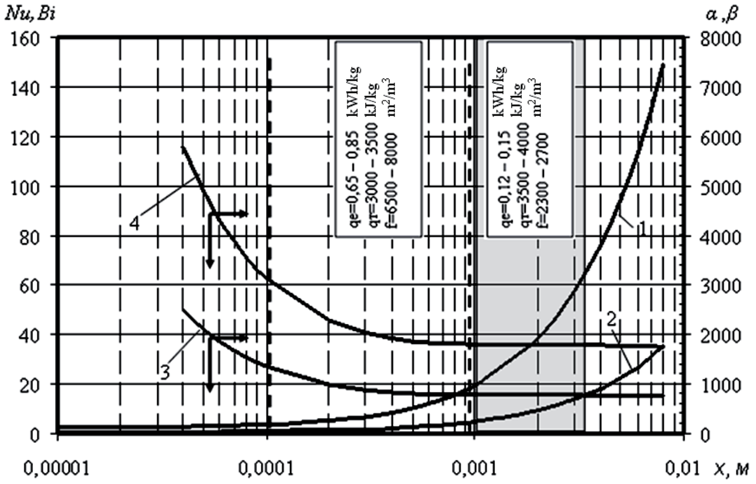

Fig. 1. A change of the criteria from the characteristic dimension of the material particle: 1 — Nusselt criterion; 2 — Bio criterion; 3 — heat transfer coefficient α, W/($m^2 \cdot$°C); 4 — mass transfer coefficient β, kg/($m^2 \cdot$hr·atm).

6. Discussion of the results of the effect of particle size of the material by the amount of heat and mass transfer coefficients

As characteristic linear dimension of particles decreases, differences in the values of thermal resistance, resulting from the existence of molar and molecular transfers (in the boundary layer and integral, caused by convection exchange) are reduced, external energy and mass transfer rate is equally dependent on the reduction of the characteristic linear dimension of the particle, which reduces the influence of the molar transfer on the total rate of external energy and mass transfer (*Nu*, *Sc*).

Integral heat transfer characteristics — coefficients α and β — are equally dependent on both the rate of molecular transport in the boundary layer, and the active aerodynamic environment in the chamber — the speed difference of the coolant and part of the material. Thus, the speed difference reduction is compensated by the curvature and thickness decrease of the boundary layer around the part, leading to the constancy of the coefficients α and β (Fig. 1).

At the same time, the reduction of the characteristic linear dimension of the material particles favorably influences the internal transfer rate, which is proportionally dependent on the dimension of the particle (*Bi*) — the internal resistance of heat- and moisture conductivity decreases.

The size range of the parts, which is of interest for research (an area highlighted in Fig. 1) is characterized by high specific values of the contact surface *f*, low specific heat energy consumption (q_T) per 1 kg of moisture evaporated and, most importantly, low specific electric energy consumption (q_e) for the organization of such an active aerodynamic environment. In addition, operation in this size range of parts is of interest in terms of controlling the amount of removal of the parts from the working volume of the chamber.

The author has experimentally proved the possibility to obtain the following orders of magnitude:

— the heat transfer coefficient within 900–1200 W/($m^2 \cdot$deg);
— the initial coolant temperature within 600–800 °C;
— the average heat amount for moisture evaporation within 3500–4000 kJ/kg of evaporated moisture;
— the average stress on the chamber by moisture evaporated 350–400 kg/($m^3 \cdot$h).

7. Conclusions

The analysis of traditional intensification ways of heat and mass transfer processes during drying of thermolabile materials was given.

The author has experimentally proved that the dispersion into small-size elements, which is organized in the same chamber will allow to artificially maintain the material surface temperature close to the wet-bulb temperature, thereby reducing finding of material in the second period to a minimum.

The resulting approximate thermodynamic parameters indicate the promising nature of using simultaneous drying and dispersion chambers in the processing of thermolabile materials.

The results of the author's work can be used in the design of energy-efficient drying equipment for production lines to process thermolabile organic materials.

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АНАЛИЗ СПОСОБОВ ИНТЕНСИФИКАЦИИ ТЕПЛОМАСООБМЕНА В ПРОЦЕССЕ СУШКИ И ОСОБЕННОСТИ ОБЕЗВОЖИВАНИЯ ТЕРМОЛАБИЛЬНЫХ ОРГАНИЧНЫХ МАТЕРИАЛОВ

В статье представлен анализ традиционных способов интенсификации процессов тепломасообмена при сушке материалов. Экспериментально доведена перспективность использования способа совмещенных процессов сушки и диспергирования с помощью механического ротора при интенсификации процесса сушки высоковлажных термолабильных материалов.

Ключевые слова: сушка, интенсификация, термолабильный материал, камера, совмещенный процесс, механический ротор.

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ОПТИМІЗАЦІЯ ГРАНУЛОМЕТРИЧНОГО СКЛАДУ ПЕРИКЛАЗОВОГО БЕТОНУ

З використанням симлекс-гратчастого методу планування експерименту досліджено вплив гранулометричного складу бетонних сумішей, які містять в якості заповнювача вторинну сировину — подрібнений брак периклазових виробів і спечений периклаз, на показники властивостей периклазового бетону після термічної обробки. Оптимізовано гранулометричний склад периклазового бетону на гідравлічному в'яжучому — суміші периклазового і кальцій-алюмінатного цементу, який забезпечує досягнення комплексу заданих показників властивостей бетону.

Ключові слова: *гранулометричний склад, периклазовий бетон, заповнювач, гідравлічне в'яжуче, показники властивостей.*

1. Вступ

Сучасна концепція розвитку вогнетривкої галузі спрямована на комплексне вирішення задач щодо раціонального використання сировинних матеріалів, зниження паливно-енергетичних і трудових витрат за умов забезпечення підвищеного експлуатаційного ресурсу вогнетривів у футеровках агрегатів різного функціонального призначення. Ефективним напрямком реалізації означених задач є впровадження технологій виготовлення неформованих матеріалів, зокрема вогнетривких бетонів, які застосовуються для виготовлення монолітних футеровок, блоків, панелей і виробів складної геометричної конфігурації. Серед широкого спектру вогнетривких бетонів найбільш високою вогнетривкістю та стійкістю до хімічної взаємодії з агресивними компонентами середовища (розплавами металів і шлаків, газів) характеризуються магнезіальні бетони,до яких відносяться периклазові бетони, що містять понад 85 % MgO і менше 6 % CaO [1–3]. Висока зносостійкість периклазових бетонів до комплексної дії руйнуючих факторів обумовила їх використання у футеровках теплових агрегатів чорної та кольорової металургії, хімічної та цементної промисловості, а саме, печей з високим вмістом сірчаних газів у пічному просторі, пристроїв призначених для транспортування розплавів металу, форм для лиття титанвміщуючих металів у вакуумі, високотемпературних фільтрів тощо [1, 2, 4, 5].

Для виготовлення периклазових бетонів використовують заповнювачі (спечений периклаз, брак виробів і лом магнезіальних вогнетривів) і в'яжуче, яке містить периклазовий цемент і хімічні зв'язки та за хіміко-мінеральним складом поділяється на гідратаційні, сульфатно-хлоридні, силікатні, фосфатні та органічні [1–3]. Проблематика застосування бетонів на гідравлічних в'яжучих (дисперсійна система «периклазових цемент — вода») пов'язана з утворенням гідроксиду магнію (бруситу), що супроводжується розпушенням структури композиційного матеріалу та погіршенням механічної міцності бетону в процесі твердіння і в умовах термічного