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Physical Processes in the Thermal Vacuum System

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Abstract: Physical processes occurring during dehydration of heterogeneous materials in a thermal vacuum system have been analyzed. It has been demonstrated that the thermal-vacuum method provides dehydration and simultaneous wet-stock dispersion due to thermal diffusion, shock-wave and ionization effects, thereby leading to formation of novel-type nanodispersed material at minimum energy input. In recent years the intensification of production processes, as well as the solution of energy- and resource-saving problems have taken on great significance. For the sake of dehydration working-cycle improvement, combination of several process procedures in a single installation is used, resulting in both the intensification of the production process and the reduction in capital expenditures. There are the facilities, where the simultaneous use of mechanical grinding operation and the drying process is practiced. In this case, a preheated air is used as a drying agent, and this considerably increases the energy demands of the technological process. This phenomenon is attributed to the impact action and friction of material particles against grinding surfaces of the mill, to the appearance of new surfaces at crushing, and also, to the dust-gas mixture turbulence in the mill working area. That requires substantial power consumption and prevents from obtaining the product with desirable indicators, in particular, the with dispersion and moisture content, which substantially affect the quality of materials produced from fine-grained products. The analysis of fine grinding methods has shown that the most rational method of material grinding is the combination of impact loads. The impact loads facilitate the structure destruction of wet stock, while the abrasion loads acting in the field of high turbulent flows lead to the material destruction. The aim of the present work has been to define the physical processes in the thermal vacuum system, which can efficiently provide dehydration along with simultaneous dispersion of wet material, yielding a dried and ground feedstock in a short span of time.

Keywords: Intensification, Heat Transfer, Dehydration, Dispersion, Energy Efficiency

1. Introduction

In recent years the intensification of production processes, as well as the solution of energy- and resource-saving problems have taken on great significance. For the sake of dehydration working-cycle improvement, combination of several process procedures in a single installation is used, resulting in both the intensification of the production process and the reduction in capital expenditures. There are the facilities, where the simultaneous use of mechanical grinding operation and the drying process is practiced [1]. In this case, a preheated air is used as a drying agent, and this considerably increases the energy demands of the technological process. It has been demonstrated in refs. [2, 3] that fine grinding of materials in impact mills causes a substantial heat release. This phenomenon is attributed to the impact action and friction of material particles against grinding surfaces of the mill, to the appearance of new surfaces at crushing, and also, to the dust-gas mixture turbulence in the mill working area. That requires substantial power consumption and prevents from obtaining the product with wish-list capabilities, in particular, the dispersivity and moisture content, which substantially affect the quality of materials produced from fine-grained products. The analysis of fine grinding methods has shown that the most rational method of material grinding is the combination of impact loads and abrasion [4, 5]. The impact loads facilitate the structure destruction of wet stock, while the abrasion loads acting in the field of high turbulent flows lead to the material destruction.

The aim of the present work has been to define the physical processes in the thermal vacuum system, which can efficiently provide dehydration along with simultaneous dispersion of wet material, yielding a dried and ground feedstock in a short span of time.

2. The Simultaneous Dehydration and Dispersion System

Based on the performed theoretical and experimental studies, the thermal-vacuum energy-efficient pulse-impact method has been developed for continuous dehydration and dispersion of wet stock. The proposed method rests on the principle of uniting the fast vacuum treatment process with thermal heating at immediate contact of the wet stock with a heated inner surface of a spiral hollow heater, thereby attaining an instantaneous heating of wet material particles in vacuum up to the preset temperature. The wet material contact with the hot wall of the heater initiates the heat transfer from the heater wall to the surface layer of the material, while the reduced pressure inside the heating element makes it possible to dehydrate the material at a temperature substantially lower than the vaporization temperature under atmospheric pressure.

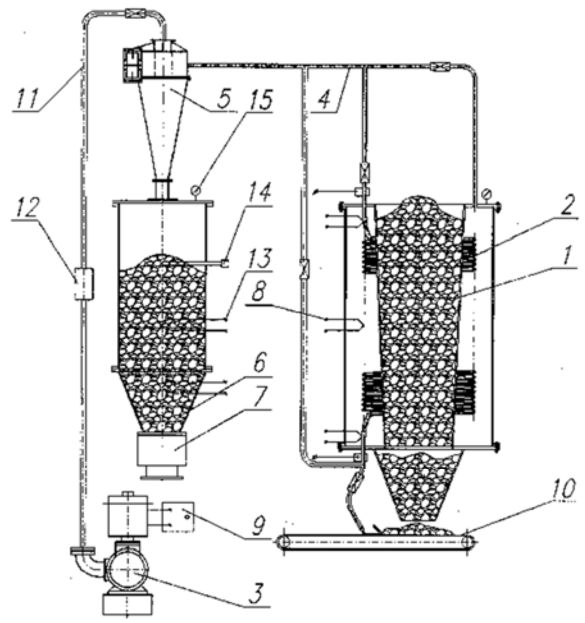

Figure 1. *Scheme of thermal vacuum installation.*

The schematic of the thermal vacuum system of continuous dehydration and dispersion is shown in Figure 1 [6].

The system consists of a feed bin (1), a hollow heater (2), a vacuum pump (3), pipelines (4, 11), a cyclone (5), a dried stock receiver (6), a rotary lock (7). The facility comprises thermocouples (8, 13), the control console (9), a transporter line (10), a filter (12), a dried stock level sensor (14), and a vacuum gage (15).

This facility design provides a high-efficiency uninterrupted dehydration and simultaneous dispersion of the material in thermally insulated environment.

3. Analysis of Heat-mass-exchange Process Regularities in the Thermal Vacuum System

A wet stock, together with air, enters the lower part of the hollow spiral-shaped heating element (2) and stays there for 14 to 20 seconds. The average pressure in the cavity of the spiral heater amounts to 430 mm Hg. When moving in the heater cavity along the spiral channel, the wet stock is subjected to the centrifugal force F

$$F = \frac{m \cdot \upsilon^2}{R}, \quad (1)$$

where m is the mass of the wet stock particle, kg; v is the wet stock particle velocity in the cavity of the spiral heater, m/s; R is the radius of the heater spiral, m.

The centrifugal force presses the wet stock to the heater wall. The wet-stock surface plane comes into contact with the heater wall, thereby making the most use of the heating body, as the instantaneous process of heat transfer from the heater wall to the wet stock takes place [7]. The element of the wet stock surface, dS (m^2), takes in an intense thermal energy flux dQ (J) of temperature T (K), in a short span of time $d\tau$ (s) at the heat-transfer coefficient a ($W/m^2 \cdot K$):

$$dQ = \alpha \cdot T \cdot d\tau \cdot dS \quad (2)$$

The thermal resistance R_c of the surface layer determines the depth of thermal energy penetration into the wet stock:

$$l = R_c \cdot dS \cdot \lambda, \quad (3)$$

where l is the depth of thermal energy penetration into the wet stock, m; R_c is the thermal resistance, K/W; λ is the heat-conductivity coefficient of the stock, W/m·K.

By substituting the dS value from eq. (2) into eq. (3) we obtain the depth of thermal power into the wet stock in a definite period of time dτ:

$$l = \frac{R_C \cdot \lambda \cdot dQ}{\alpha \cdot T \cdot d\tau} = \frac{R_C \cdot \lambda \cdot P}{\alpha \cdot T} \quad (4)$$

where $P = dQ/d\tau$ is the thermal power, W.

At the moment of contacting the heater wall, the temperature (T) inside the surface layer of the wet stock becomes higher than the temperature (T_1) of moisture vaporization ($T >> T_1$). An instantaneous overheating of the fluid occurs. The process of intensive vapor release in the surface layer starts at the ambient pressure (P_1). The pressure (P_1) in the heater cavity is produced by the vacuum pump 3 (see Figure 1). As a result of active vaporization, the saturated vapor pressure (P_2) inside the surface layer becomes considerably higher than the surface pressure ($P_2 >> P_1$). Thus, in the surface layer, at the moment of wet stock contact with the hot wall of the heater, the thermal energy gets concentrated, and, with the restricted space, this gives rise to a local explosion [8] with occurrence of the shock wave, within which the temperature and the pressure increase [9]. As a result, the surface layer of the wet stock breaks down.

4. The Mechanism of Vapor Explosion Action on Dehydration of Heterogeneous Material

In the surrounding space of the vapor explosion source, a local impulse of the shock wave is formed, with small particles detached from the great bulk of the wet material. The shock-wave front is characterized by extremely high excess pressure (P_3) values, a high temperature of several thousands K, while the impulse wave velocity may reach 2000 to 8000 m/s [10]. The shock wave duration ranges between 2 and 10 ms [11]. As a consequence, the detached particles, being in the immediate vicinity of the shock wave, are subjected to a powerful impact, which causes their further crushing with the formation of numerous fragments of different shape and masses, thereby increasing the total particle surface. At the same time, particle electrification takes place, with large- and small-size particles acquiring charges of opposite signs [12]. The static electrification voltage may attain the value sufficient to provide electron detachment from atoms. Thus the ionization occurs, and a new crystalline modification of the substance is formed. In this case, the remaining mass of the substance located outside the shock wave is in the metastable state.

The pulsed bunch of gas together with the detached particles is directed towards the wall of the heating element. At the moment of the contact with the heater wall, the pressure and the temperature in the bunch increase still more. In this case, the energy gets concentrated within a small volume (bunch), and this leads to the impact compression of the detached particles. Under the action of the shock wave, the material gets crushed still more. At the instant the incident shock wave begins to reflect from the wall of the heating element, between this wall and the reflected wave [13] the vacuum phase with pressure P_4 (Pa) follows. Since the rate of gas outflow from the reflected wave is higher than the rate of motion of numerous fine particles of the finely divided material, then these particles arrive at the reduced-pressure zone. The effect of the instantaneous pressure drop (about a few MPa) and a high local heating temperature lead to further intensive water evaporation from the wet-stock fine particles.

From the research results it has been established that the dimensional change of the wet raw material l_B (m/s) during its passage inside the spiral heater of the thermal vacuum installation depends in direct proportion to the coefficient of hydrodynamic conditions on the stock surface k (kg/m^{2}s), the shock wave exposure time (τ), the ambient pressure P_1 (Pa), and in inverse proportion to the partial pressure (P_2+P_3+P_4) and the material density ρ (kg/m^3).

$$\frac{l_B}{\tau} = 1{,}5k \cdot \frac{P_1}{(P_2 + P_3 + P_4)\rho} \quad (5)$$

At the instant the partial pressure is (P_2+P_3)=maxi, P_4=0, an intensive material dispersion takes place. When $P_1 \approx (P_2+P_3)$, the material is ground due to heater wall friction and the mutual collision within itself. If the partial shock-wave pressure (P_2+P_3) → min, the phase of vacuum gauge pressure P_4 → maxi arises. At that moment the moisture of the material is intensively evaporating to the surrounding space. For example, the thermal vacuum method enables one to produce nanodispersed graphite of size 10 to 40 nm and moisture content of about 1% (Figures 2, 3).

Figure 2. *Initial graphite.*

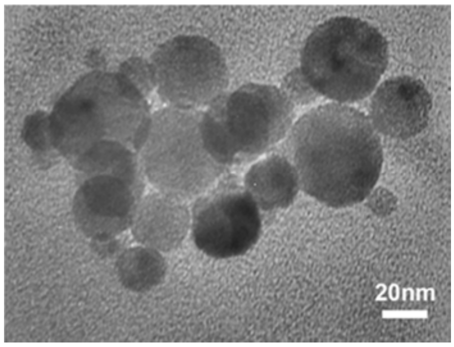

Figure 3. *Graphite treated in the thermal vacuum installation.*

Figure 4a represents the reciprocal lattice of a graphite particle having an ordinary hexagonal lattice with its reflection in the basic crystallographic plane. According to the figure, this particle also includes coherent phase with doubled period a, as evidenced by small points of hexagonal arrangement in close proximity to the center of the electron diffraction pattern. Monoclinic modification of the reciprocal lattice with an angle of 99.5° was also found on the basis of graphite C1 [14]. (Figure 4b).

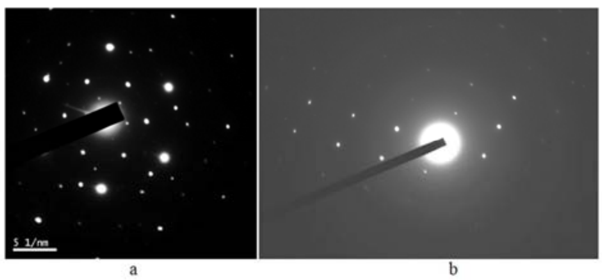

Figure 4. *Electron diffraction patterns of hexagonal (a) and monoclinic (b) reciprocal lattices in graphite C1 after thermal vacuum treatment.*

Studies on dehydration and dispersion of brown hydrogenous coal in the thermal vacuum installation have been also performed. The lower minimum size of dried particles was measured to be 40 nm. At the same time, the amount of thermal energy expended for obtaining the fine brown coal with a moisture content of 1% from raw materials with an initial moisture content of 40% and the initial particle size 6 mm at the heating element temperature T=525K made up 600 MJ/ton. With a rise in the heater temperature up to T=573K the brown lignite takes fire in spite of a low pressure inside the heater (Figure 5).

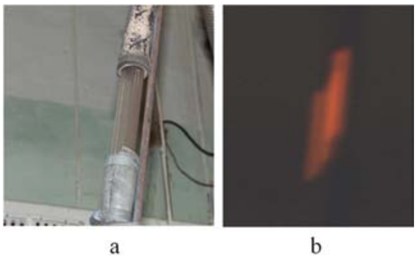

Figure 5. *Brown lignite ignition in the heater: a – pipeline general view; b – lignite burning in the pipeline.*

The reason of brown lignite ignition in the heating element is the thermal electrization, which leads under certain external conditions to the discharge occurrence. The development of electrical breakdown is substantially influenced by the electron avalanche, which sets up an increased concentration of charge carriers in the temperature range between 533K and 573K, sufficient for direct initiation of glow discharge with its further transformation into a streamer. After streamer propagation over the whole interelectrode gap at the heater temperature T ≥ 573K, powerful electric discharges take place, and this accounts for self-ignition of the lignite. At a gap of length 1 cm, the breakdown duration varies between 10^{-7} s and 10^{-8} s [15].

So, by analyzing the mechanisms of action on the subject under study, it is possible to develop a high-performance safe technological process of dehydration and dispersion. To this end, there is a need to elucidate the relationship between the dehydration dynamics of the material under study and the technical capabilities of the thermo production equipment. It is also essential that the ionization value and the threshold spark- energy value should be determined experimentally to exclude the ignition of the specific material.

The quantity of moisture m_m (kg/s) removed from the stock to be dried in the thermal vacuum installation depends in direct proportion to the heater power P_H (W), the heating temperature of the dryable material (T), the heat exchange rate between the heater and the dryable material (a), the evaporation area (S). At the same time, the m_m value is in inverse proportion to the ambient pressure P_o (Pa), the kinetic vapor viscosity v (m^2/s), the impact toughness W_1 (J/m^2) and the volume V (m^3) of the dryable material. So, we have

$$m_m = \frac{2(m - m_c)P_H \cdot T \cdot a \cdot S}{P_o \cdot v \cdot W_1 \cdot V} \tag{6}$$

where m_c is the material mass at the moment of dehydration, kg.

In expression (6), we consider how the S/V ratio changes. We shall call this ratio as the geometric factor of the sample and denote it as $G=S/V$. The finer the particles are ground, the greater is the total surface of the particles, from which the moisture is evaporated to the surrounding medium. The calculations show that with particle size reduction the geometric factor G increases. Let us assume that the dispersed stock particles are spherical in shape. The full-sphere area is $S=4\pi \cdot R^2$, the volume V is given by $V=4/3\ \pi \cdot R^3$, then we have

$$G = \frac{12\,\pi \cdot R^2}{4\pi \cdot R^3} = 3R^{-1}, \tag{7}$$

where R is the radius of the sphere, m.

The comparison of the calculated data leads to the conclusion that if the radius of the worked stock sphere is equal to 10^{-3}m, then the geometric factor G equals $3 \cdot 10^3$, and if R is equal to 10^{-6}m, then $G=3 \cdot 10^6$. Similar calculations can be carried out for the particles of other shapes, and they will give the similar results.

Thus, in the thermal vacuum facility, with reduction in the particle size the total evaporation surface increases, and in this connection the rate of moisture removal from the fine-dispersed material considerably increases, too, reaching a few milliseconds.

With a further advance of the initial wet stock in the spiral heater cavity, accompanied by intensive heating, the moisture inside the stock boils up, giving rise to the instantaneous pressure gradient with the result that with time the material disintegrates into small particles. The rate of destruction, in turn, depends on the temperature of heating temperature of the wet body at the moment of contact with the heated surface and the internal state of the material under study.

The effectiveness of dehydration and dispersion in the thermal vacuum installation depends on the external action and physicochemical properties of the wet material, namely, the heat supply efficiency, the ambient pressure, the rate of moisture removal from the wet stock surface, the material structure, the intensity of moisture motion in the material being dried, the bond forms of moisture in the material, the thermal resistance of the material surface layer that specifies the depth of heat penetration into the body in a short span of time, collisional ionization.

The fine-dispersed parts of the wet stock, which move in the cavity of the heating element of the thermal vacuum installation, are also affected by the flow of thermal radiation from the surface of the shock wave front and from the wall of the heating element:

$$H = \sigma\,(T_f^{\,4} + T_c^{\,4}), \tag{8}$$

where σ is the Stefan-Boltzmann constant, $W/m^2 \cdot K^{-4}$; T_f is the shock-wave front temperature, K; T_c is the heater wall temperature, K.

If the finely dispersed particles are beyond the shock front, they are acted upon only by the heat emission flux T_c coming from the heater wall.

According to the Wien law, the heat emission wavelength λ is given by

$$\lambda = \frac{2{,}89 \cdot 10^{-3}}{T_c} \quad (9)$$

Hence it follows that as the body heating temperature changes, the spectral density distribution of the body-emitted radiation also changes. In the ultraviolet-rays range (400 … 180) nm, the rays are easily absorbed by water, and this contributes to the moisture evaporation at minimum energy consumption [16]. A part of the absorbed energy turns into heat. The ultraviolet photon energy is very high; therefore at photon absorption the water molecule gets ionized and breaks down. In the shock wave, the irreversible processes proceed so quickly, that the rate of polymorphic transformations varies within very wide limits, depending on both the mechanism of lattice rearrangement and the shock wave strength. If the new crystal modification is attained through the ordered atomic displacement due to volume/shear deformation of the initial lattice, then the transformation goes very quickly, in a time of about 10^{-8} s. The pulsed shock waves in the thermal vacuum installation give rise to new crystalline modifications.

For example, if in the installation under discussion, the local pulsed shock wave operates on zirconium hydroxide of original size 6 mm and 80% moisture content, then the formation of nanodispersed zirconium dioxide with the moisture content of about 1% is observed. In this case, the energy consumption is reduced by a factor of >3 in comparison with the existing industrial drying installations.

Thus, the motion of wet stock in the spiral heater cavity of the thermal vacuum facility leads to its dehydration and dispersion with the result that the initial material turns into a dried nanodispersed powder within 15 to 20 s. The processes of dehydration and dispersion will continue for as long as $dm/d\tau$=0.

The air, entering the heater cavity together with the wet stock, also warms up rapidly, circulates between the heated fine-dispersed particles, and takes up a part of their moisture content for itself. The ground product comes from the spiral heater 2 to cyclone 5, where the moisture gets detached from the dried material. The steam, evaporated together with air through filter 12, enters the vacuum pump 3, while the dried product goes away to the storage hopper 6 (Figure 1). The overall time of wet-stock dehydration and dispersion in the thermal vacuum installation makes a few seconds due to the maximum surface of evaporation, quick heating, reduced ambient pressure. The effective movement of the wet stock in the thermal vacuum installation requires such an air flow that would provide its continuous advance inside the spiral heating element.

5. Recommendations

Development and implementation of new energy-saving thermal-technology installations is important scientific and technical problem, which is being solved within the framework of scientific direction - industrial heat power engineering. Therefore, methodological aspects associated with the use of systematic approach to solving energy saving problems in thermal-technology systems and complexes are of great importance, taking into account their diversity, purpose, design architecture and operating parameters.

The promising areas of research to reduce energy consumption in the area of technical thermal physics and industrial heat power engineering are:

1. development and implementation of innovative technical solutions in the design of thermal-technological lines;
2. development and implementation of the state-of-the-art and prospective energy saving approaches;
3. improvement of technological processes;
4. creation of fundamentally new thermal-technological installations.

This requires integrated approach to solving a number of interrelated problems of energy saving and thermal-effectiveness for the production processes.

At present, all over the world, the activity is underway to create efficient, energy-saving thermal-technological installations. Methods of intensifying technological processes are being improved in order to increase the efficiency of heating equipment. Among the thermal-technological installations there are ones that are used in various branches of industrial production to obtain new materials and remove moisture from heterogeneous media. Existing thermal-technological installations in most cases are expensive, bulky, metal-intensive, consume a lot of energy. The processes of dehydration and dispersion of heterogeneous materials occur at high temperatures and atmospheric pressure, which often leads to undesirable structural, chemical, and biological changes in the processed materials. Most thermal-technological installations operate on liquid fuel, and the mixture of flue gases with air is used as the dehydration agent. This mixture may contain products of incomplete combustion of fuel and harmful substances.

Creation of new and modernization of existing thermal-technological installations is the complex scientific and engineering task. The new energy-efficient thermal-vacuum method for simultaneous dehydration and dispersion of heterogeneous materials has been developed for the first time on the basis of the conducted scientific and engineering research. Obtained increased efficiency of the process of dehydration and dispersion of heterogeneous materials and obtaining high-quality products are mainly associated with the introduction of new modern environmentally friendly installations and energy-saving technologies into production, which can successfully solve the assigned tasks.

The efficiency of thermal units' operation is determined by the degree of perfection of thermal technology applied, by the innovative approach to the development of thermal-technological equipment and by the choice of heat-physics processes. This allows solving many problems of heat and mass transfer in heterogeneous environments, and manufacturing of modern energy-saving, highly efficient thermal-technological plants for various purposes.

Solution of vital problems in the field of dehydration and dispersion should be based on scientific foundations. It is also necessary to study the properties of the processed material. Based on innovative methods and modes of dehydration and dispersion processes, it is possible to create rational designs of thermal-technological installations with improved operational, technical and economic performances: intensified heat exchange processes; effective heat supply to the processed material; accelerated process of heat and mass transfer; reduced time of technological process. It is the vital scientific and engineering problem, and its solution will result in decrease of material consumption and improvement of heat exchange processes for the thermal equipment.

Performed analysis of scientific literature, analytical and experimental research methods showed that the most effective way of dehydration and dispersion is the thermal vacuum technology, which emphasizes the relevance of this topic, the prospects for further use. The thermal vacuum technology shall: reduce energy consumption per unit of dried products; increase productivity; reduce temperature of the technological process; reduce cost of the resulting products; improve their quality; improve environmental and operational conditions for service personnel; preserve biological value of dried agricultural products; generate alternative types of energy from waste of agricultural products and forestry industry.

It is common knowledge, that thermal vacuum installations can differ significantly from each other both in their design and in their intended purpose. However, similar working processes, such as heating temperature, ambient pressure, heat and mass transfer in the processed material make it possible to apply common approach in order to select promising directions for energy efficiency. That emphasizes the essential importance of this topic and determines further direction of scientific research in the field of heat and mass transfer processes depending on the heating temperature, ambient pressure, time and structure of the processed material.

6. Conclusions

1. It has been established that the wet stock in the thermal vacuum system is successively subjected to thermal/deformation/ionizing effects, which substantially contribute to acceleration of the process of moisture removal from a capillary-porous material, and thereby, to production of nanodispersed materials with new physico-chemical and mechanical characteristics in a short span of time. Each physical process in the thermal vacuum installation has its space-time continuum, and account must be taken only of those parameters, which correspond to a particular interaction.
2. Whereas the existing methods of forming a new crystal lattice call for complex atomic rearrangements, heavy expenditure of energy and much time to overcome great activation barriers (ranging from a few eV to tens of eV), in the thermal vacuum system crystal modifications of materials with new properties arise within a few milliseconds due to thermo diffusion and pulsed shock wave at minimum energy input.
3. The thermal vacuum technique is an advanced method of dispersed material dehydration, which enables one to improve the thermal processing equipment efficiency owing to energy input reduction, with simultaneous improvement of product quality and cutting of production costs.

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