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Biography of author

Vladimir Sheyman received his Ph.D. in Mechanical Engineering from Academy of Sciences, Minsk, Belarus. Prior to joining Wayne State University in August 1986, he worked as a Senior Research Scientist and a Scientific Leader of a Special Design Department in the Academy of Sciences and also in industry. His areas of interest include heat and mass transfer and thermal sciences. He has published two research based books, over 100 technical papers, and has received patents for 28 of his inventions.

Thermal Treatment of Solids in the Vibration Fluid-bed Apparatus

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Summary

The thermal treatment of the powdered materials (solids) in fluid-bed apparatus is widely used in various branches of industry. The bed is fluidized by filtration of a gaseous heat carrier through the layer of solids. The height of the layer of solids should be sufficient to secure the evenly distribution of the heat carrier and to prevent it from the outburst in one or several locations and stagnation of the rest of the layer. The extra height of the layer of solids increases the hydraulics resistance and leads to additional energy losses. However, the advantage of such apparatus makes them very attractive.

Unfortunately, such kind of apparatus and processes cannot be used for the thermal treatment of the fine particles due to their adhesiveness. To overcome this hurdle, the vibration motion is applied. The fluidized bed may be obtained by means of vibration with or without filtration heat carrier through the layer of solids.

In this paper, the fluid dynamics equation for the vibration of the bed of the particulates without force air filtration through the layer is solved by numerical method. The results concur with the experimental data that on the whole shows the alternation of pressure and vacuum between the particulates layer and the vibrating plate. This phenomenon has an influence on the quality of the mixing process of particulates.

A set of differential equations describing heat and mass transfer in a batch and continuous modes of operations is presented and solved for variable temperature of the vibrating heating surface.

Our own research of thermal treatment (drying) of salt with average diameter of particles of 0.36 mm is also presented. The parameters of vibration are: the amplitude is changed stepwise from 0.5 mm to 5.0 mm, with increment of 0.5mm; the frequency is from 10 to 50 Hertz. The heat transfer occurs by conduction with constant and variable surface temperatures up to 300 °C. As results of this research, the influence of various parameters on the intensity of the heat and mass transfer were determined. These results have the practical applications.

One of the goals of this paper is to involve student in the scientific research. For this reason, the paper was presented to the students of the Thermodynamics and Fluid Mechanics classes. Students expressed their interest in such research. For example, together with one of the students we prepared application for the patent involving vibration.

Nomenclature

A - Amplitude of Vibration, mm, C_p - Specific Heat, J/kg $^{\circ}$ C, f - Frequency of Vibration, Hz., F- Heating Surface Area, m^2 , G - Mass of solids in the container (eq.17), or mass of air in the volume of height h, (eq.3), kg, g -Acceleration of gravity, m/s^2 , h - Height of air below the layer of particulates, m, or convection heat transfer coefficient, W/m^2 $^{\circ}$ C, k-Coefficient of gas permeability, kg/m sec., m- Mass of particulates, kg., P_a -Absolute pressure of air above the layer, Pa., P_1 -Absolute pressure of air below the layer, Pa., R- Gas constant, J/kg K, r- Latent Heat of Evaporation, J/kg., s- Height of the Dense Layer of Solids in the Container, mm, T- Absolute temperature of air, K, t-Temperature of the Heating Surface, $^{\circ}$ C
X-Moisture Content of Solids, kg of moist/ kg of dry material, v- Specific volume of air at pressure P_a , m^3 /kg, ω -Angular velocity, rad/sec, \bar{v} - Mean Temperature of Solids, $^{\circ}$ C, τ - Time, χ - Relative Coefficient of Drying.

Subscripts

cr Critical Value, ef Effective, eq Equilibrium, f Final, l Liquid, o Initial Value
s Solids

Introduction

Intensive heat transfer process may be achieved by different methods. In particular, the method of fluidization of particulates and fluidized bed apparatus are widely used in the industrial processes for such thermal treatment of materials like heating, cooling, drying, chemical reactions, coatings, and so on. The gaseous heat carrier flows through the bulk in a way that the particulates are partially or totally airborne. The porosity of the layer is significantly increasing. For example, the porosity of layer of particulates having size between 0.66mm and 7.55mm is increasing from initially 40% to 90% when the ratio of actual to incipient fluidization velocity is increased by a factor of seven¹.

If we assume that the motion of particulates in the fluidized bed is reciprocate in the vertical direction, which is closed to the reality, then the average relative velocity between particulates and the gaseous heat carrier is approximately equal to the actual velocity of the heat carrier. The intensive heat transfer process is the result of the following: separation of the particulates that leads to the bounding the latter by the heat carrier, the rather high relative velocity and the turbulence condition. Due to these facts, the majority of the heat transfer between the heat carrier and the particulates occurs approximately within the height of the layer of 15-30mm. However, to avoid the outburst of the heat carrier in one or several locations and stagnation of the rest of the layer, the

actual height of the layer is significantly higher than that necessary for the heat transfer. In many cases it is also required a special design of the gas-distribution grid. This leads to the essential increase of the flow resistance that requires additional energy. Besides this, the fluidization cannot be obtained at all only by filtration of the gas through the layer of the fine particulates due to the strong adhesiveness between them.

The fluidization of fine particulates is easy to obtain by applying a combination of gas filtration through the layer and vibration. The vibrating fluidization is also useful when there is a wide range of particulate sizes; in this case the fluidization is obtained under relatively small filtration velocity of gases to prevent the carrying away the smallest fractions of the particulates from the apparatus.

Feature of the Vibration Fluid-bed

The fluidization may be obtained in different apparatus applying vibration on the friable material by vibrating plates, which in many cases are porous or inclined trays. The trajectory of the vibration motion may be straight, upright or inclined to the horizon, circular or elliptical. The structure of the layer, the intensity and character of the mixing of solids, and the velocity of the directional displacement of the material in the apparatus of continuous operation depend on the amplitude, frequency and the direction of the vibrating motion. It is possible to transfer material in the horizontal plane as well as on the incline surface upward or downward, and therefore to regulate the time of the thermal treatment and the direction of the material motion.

The vibration of the fluidized layer can be created by vibrating actions:

- On the motionless layer of the friable material,
- In combination with the force filtration of the fluid through the layer in upward or downward direction,
- On the layer of the friable material in vacuum.

Therefore it is possible to carry out the thermal treatment of various materials with different fractional composition and requirements of the properties and quality of the final product. It is also significantly decrease the carrying away the smallest fractions of the particulates from the apparatus. The fluidized layer flows like a liquid and follows the laws of the Newtonian fluid. Thus the vibrofluidized bed has the same advantages as the aerodynamics fluidized bed but deprives its drawbacks. For example³, the coal powder of the average particulates size of 4.3 micrometer becomes fluid under the combination of the vibration and filtration of air through the layer having velocity of 0.003m/sec. Practically, at such velocity there is not any carrying away particulates from the apparatus.

The apparatus of the vibrofluidized bed has the following advantages over the aerodynamics fluidized bed: significantly less energy and heat carrier consumption, practically no carrying away the smallest fraction of the particulates from the apparatus, ability to treat the fine particulates, and the possibility to regulate the average residence time of the powder material in the apparatus.

Due to the advantages, many companies manufacture vibration apparatus. For example, Mitsubishi Material Techno Corporation⁴ produces Vibration Flow Dryer with the following features: high vacuum provides low temperature drying, a high stirring and mixing effect. The dryer is using for battery filling agent, resin beads, powdered resin, coffee beans, slurry and other applications. In Lodige's Vibration Dryer⁵ the vibration causes controlled, elliptical movement of the pharmaceutical products around the vessel axis, fluidizing the product. The continuous, radial flow carries the product along the heated wall where the heat transfer by conduction takes place. TGZZ company's Vibration Fluid Bed Dryer /Cooler⁶ intended for drying, cooling or combination of them. It features an extremely high heat transfer coefficient, variable residence drying time, and moisture reduction of 30-40kg/h per 1.0m² of the screen surface area.

Fluid Dynamics of the Vibration Powder Bed

W. Kroll introduced one of the models of dynamics of the vibration powder bed without force filtration through the layer. The author^{7,8} assumed that the cylinder with a layer of particulates is working as a piston and has a central vertical hole. When piston is moving upward, it intakes the outside air and push the air through the layer while it moving in the opposite direction.

The equations are:

$$m \left(\frac{d^2 s}{d\tau^2} + \frac{d^2 h}{d\tau^2} \right) + mg + (P_a - P_i) \cdot F = 0 \quad (1)$$

Equation of the State for air

$$P_i h F = G R T \quad (2)$$

The Hagen - Poiseuille equation for the air filtration through the layer of particulates is

$$\frac{dG}{d\tau} = k \frac{P_a - P_i}{P_a} \quad (3)$$

The harmonic fluctuation of the cylinder is described by the following expression

$$s = A \sin \omega \tau \quad (4)$$

and

$$\frac{d^2 s}{d\tau^2} = -A \omega^2 \sin \omega \tau \quad (5)$$

Introducing the following variables

$$q = \frac{(P_a - P_i) \cdot F}{P_a} \quad (6) \quad \alpha = \frac{P_a}{m} \quad (7) \quad v = \frac{G}{hF} = \frac{RT}{P_a} \quad (8)$$

one has instead of equations (1), (2), and (3)

$$\frac{d^2h}{d\tau^2} + \alpha q = -\frac{d^2s}{d\tau^2} - g \quad (9)$$

$$(1 - q) \cdot h = vG \quad (10)$$

$$\frac{dG}{d\tau} = kq \quad (11)$$

It is assumed that $F = 1.0\text{m}^2$ and therefore it is omitted in eqs. (9)-(11).
The initial conditions are:

$$h(0)=0, q(0)=0, G(0)=0 \quad (12).$$

To solve the equation, W. Kroll assumed $q = 0$ in eq. (10) keeping it in eq. (11). This simplification is not acceptable, since $(P_a - P_i)$ is never equal to zero with the exception when time $\tau = 0$. The difference $(P_a - P_i)$ is variable and it is alternated as negative-positive-negative during one cycle due to the pumping effect of the vibration layer of the particulates and filtration of the air through the layer. The difference $(P_a - P_i)$ depends upon number of parameters such as frequency and amplitude of vibration, height of the layer, size of the particulates and so on.

According to the experimental data, in some cases $-1.600 < (P_a - P_i) < + 2000$ mm of the water column. Taking this into account, we keep q in equations (10) and (11).

From equations (3), (4), (9), (10), and (11) one has:

$$\frac{d^2h}{d\tau^2} = -\frac{\alpha}{k} \frac{dG}{d\tau} - A\omega^2 \text{Sin}\omega\tau - g \quad (13)$$

$$\frac{dG}{d\tau} = k \left(1 - v \frac{G}{h} \right) \quad (14)$$

Integration of equation (13) in the limits from 0 to τ results:

$$\frac{dh}{d\tau} = -\frac{\alpha}{k} G - A\omega(\text{Cos}\omega\tau - 1) - g\tau \quad (15)$$

The system of equations (14) and (15) is solved by the numerical method with the following assumption of the initial condition:

$$h(\tau)_{\tau=0} = 10^{-5} \text{ m}.$$

This gives an error of less than 1%. With this assumption, from equation (10) one has:

$$G(0) = \frac{h(0)}{v} = \frac{10^{-3}}{8.25 \cdot 10^5} = 1.21 \cdot 10^{-5} \text{ kg / m}^2,$$

where the specific volume v is calculated for air at $t = 20^{\circ}\text{C}$. The results of both our solution and experimental data^{7,8} of W. Kroll are shown on Figure 1. They are obtained for the following data: $f = 23.3 \text{ Hz}$, $A = 3,72 \text{ mm}$, material is sea sand $d = 0.29 \text{ mm}$, specific weight $\gamma = 1450 \text{ kg/m}^3$, $k = 1.95 \cdot 10^{-3} \text{ kg/cm.sec}$. and $h = 70 \text{ mm}$.

The curves obtained by calculation using our solution and that by experiments^{7,8} have the same shape (Fig. 1). However, the calculated data of Kroll (curve 3) concur with the experimental data only for a limited height of the layer of particulates that is called critical. For the height above 70mm, (the critical height) the actual pressure starts sharply lowering instead of increasing as it was predicted by Kroll calculations (curve 3).

Heat and Mass Transfer

One of the main advantages of the vibration apparatus is that the impulse of vibration motion disintegrates the particulates in the layer and intensifies the mixture of them, which continually ensure the renovation of the heat transfer surface. Research shows that the vibration significantly influences on the intensity of the heat and mass transfer process⁹. This is true especially for the fine particulates having size of a fraction of a millimeter. Usually, such material may be thermal treated only in the apparatus of low effectiveness such as a stove or a screw conveyer with conduction heat transfer. Contrary to this, the conduction, convection, thermal radiation or combination of them may be applied to the vibration fluidized bed. Our own experiments of drying fine salt particulates in the vibration apparatus witnesses of significant intensification of the heat and mass transfer process. The main influence of the intensity of the process has amplitude of vibration.

In number of cases it is useful to supply heat to the vibrofluidized bed by conduction from the heated surface, especially when the direct contact of the material with the gaseous heat carrier is not acceptable. This method of the heat supply leads to a significant reduction of the amount of the filtrating gaseous heat carrier, which is important for the thermal treatment of the very fine particulates. As an example of heat and mass transfer process, the drying of powdery material with the conduction heat supply is considered.

It is well known that the drying process consists of two periods, namely the first period or period of constant drying rate and the second period of the fallen drying rate^{10,11}. The temperature of the drying material in the first period is constant and easy to determine. The second period starts when the moisture content of solids reached the critical value, and the temperature of the solids are increasing. The temperature of the solids in this period is of a greater interest.

The kinetics of the drying process in the second period is described by the equation suggested in¹¹.

$$-\frac{dX}{d\tau} = \chi N(X - X_{cr}) \quad (16)$$

where the experimental coefficient N (drying rate) depends on the drying parameters, and the relative drying factor χ depends on the properties of the material and on its initial moisture content.

There are two principal modes of operation, whether continuous or batch wise. The equation of the heat balance for the batch wise mode of operation may be written in the form:

$$h_{ef} F(t - \nu) d\tau = GC_{ps} \left(1 + \frac{C_{pl}}{C_{ps}} X\right) d\nu - rGdX \quad (17)$$

The similar balancing equation

$$h_{ef} F_{sp}(t - \nu) dx = G^* C_{ps} \left(1 + \frac{C_{pl}}{C_{ps}} X\right) d\nu - rG^* dX \quad (18)$$

also describes the thermal treatment process for the continuous mode of operation with the following differences: there are a path differential $dx = \nu d\tau$ instead of the time differential $d\tau$, the specific heating surface area F_{sp} – the heating surface area per unit of the displacement path of the bulk material – instead of the heating surface area F , and also the mass of the bulk of material in the container G is substituted by the mass of the flow rate G^* in terms of the dry material. Equations (17) and (18) are adapted from reference¹² with modification for the case under consideration.

If gases are used for the surface heating, the following expression is true¹³:

$$t = t_f + (t_0 - t_f) \cdot \exp(-m\tau) \quad (19)$$

where m is the empirical coefficient determined by the experiments.

Integration of the expression (16) in the limits from 0 to τ and from X_{cr} to X gives

$$X = X_{eq} + (X_{cr} - X_{eq}) \exp(-\chi N\tau) \quad (20)$$

The solution of eq. (17) to determine the temperature of the drying material together with conditions (19) and (20) is

$$\nu = \nu_1 \left(\frac{y}{y_1}\right)^a - \frac{A^* t_f}{\chi Na} \left[\left(\frac{y}{y_1}\right)^a - 1 \right] - \frac{A^* (t_0 - t_f) - B}{\chi N(a-1)} \left(\frac{y^a}{y_1^{a-1}} - 1 \right) \quad (21)$$

The following notations are accepted in equation (21):

$$A^* = \frac{h_{ef} F}{GC_{ps}}, \quad B = \frac{r\chi N(X_{cr} - X_{eq})}{C_{ps}}, \quad a = \frac{A}{\chi N \left(\frac{C_{ps} + C_{pl} X_{eq}}{C_{ps}} \right)},$$

$$y = \exp(-\chi N \tau), \quad \text{and} \quad y_1 = \exp(-\chi N \tau_1)$$

where τ_1 is the time at the end of the first drying period. The eq. (21) expresses the relationship between the temperature of the solids and time.

The experimental research was carried out in apparatus with the following parameters of vibration: the amplitude is within the limits $A^* = 1-5$ mm, and the frequency is $f = 10-50$ Hz. The temperature of the heating surface is $150-300$ °C., the height of the dense layer of the particulates is $h_0 = 20-90$ mm. The rectangular container has a cross section of 55 mm x 240 mm, its height is 350 mm. The material, crystal sodium chloride, having initial moisture content is loaded into the vibrating container, and it is dried to a constant weight.

It was established that the drying process is intensified with increase of the amplitude of vibration. Another parameter of vibration (frequency) influences on the drying rate to a lesser extent. For example, the decrease of amplitude from $A = 4.5$ mm. to $A = 1.5$ mm at a constant frequency of $f = 21.4$ Hz results in the decrease of the drying rate from $N = 7.4 \cdot 10^{-3}$ kg/kg./min. to $N = 5.1 \cdot 10^{-3}$ kg/kg/min. in the first period, i.e. approximately in 1.5 times. When the amplitude was constant at $A = 2.5$ mm and the frequency is decreased from $f = 40$ Hz to $f = 14.7$ Hz, the drying rate varies from $N = 7.6 \cdot 10^{-3}$ to $6.7 \cdot 10^{-3}$ kg/kg/min., that is, only 1.1 times. These experiments were carried out at an average temperature of the heating surface of $t = 165$ °C, with the height of solids having initial layer of $h_0 = 44$ mm and $X_0 = 5.5 \cdot 10^{-3}$ kg/kg.

Some experimental drying curves and the temperature variation of the material are plotted in Fig.2. The parameters are as follows: $A = 2.5$ mm, $h_0 = 44$ mm, $t_0 = 300$ °C, ($1-f = 31.7$ Hz, $2-28.3$ Hz, and $3-25$ Hz). The significant portion of the drying process takes place at a constant drying rate, i.e. in the first period. Within this period, the main quantity of moisture is removed at all drying conditions. The remaining moisture is removed in the second period. However, the drying time is approximately equal in both periods. The dash lines are the temperature curves calculated according to the equation (21). The deviations from the experimental data do not exceed 10%.

Conclusions

In this paper, it is shown the advantage of using the vibration for thermal treatment of particulates, especially for the fine powder materials. The equations describing the fluid dynamics of the vibration bed of the powder materials were solved numerically. The results of variation of air pressure below the layer of the particulates are in a concord with the experimental data. The differential equations of the heat and mass transfer for the conduction heat transfer from the surface to the particulates are formulated and solved. These solutions established the relationship between temperature of the solids to be dried and time of the process that in turn allows

control the quality of the final product. The comparison of the experimental data of the temperature of the solids with that calculated using the theoretical equation shows very good results with maximum deviation not to exceed 10%. The proposed equations may be used for different materials and to some extent for various thermal treatment processes. This investigation is also serves as a basic for student's research that is already in the progress.

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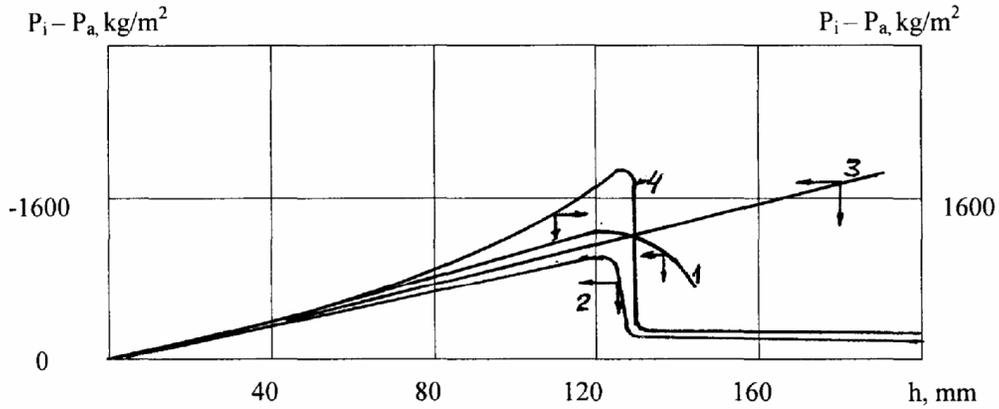


Fig.1. The influence of the height of layer on the maximum vacuum and pressure. 1 – amplitude vacuum (W.Kroll's experiments), 2 – the same – our calculations, 3 – the same – W.Kroll's calculations, 4 – amplitude pressure – our calculations.

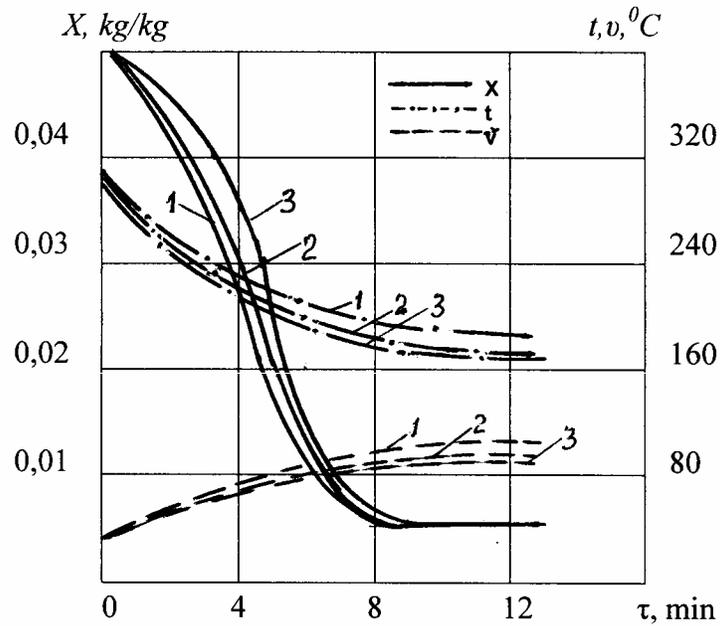


Fig.2 Curves of drying and temperature