DETERMINING THE MOISTURE CONTENT AND THE TEMPERATURE OF AIR AND OF A MATERIAL AT THE EXIT FROM A WET FLUIDIZATION BED

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A mathematical model has been developed which describes the processes of heat and mass transfer in a wet fluidization bed during assimilation of the liquid by the solid particles while heat of reaction is released (or absorbed). A correlation between this model and actual processes is established.

In engineering one often deals with processes where liquid evaporates from the surface of a wet granular material in a fluidization bed. The purpose of such processes is either to dissipate the heat of chemical reaction and to provide cooling, also to hydrate the granular material [1, 2], or to saturate the liquid with vapor and to lower the temperature of the gas which passes through the apparatus.

In the technical literature there is hardly any information available on the design of such processes. The only reference known to the authors is the article by J. Cyborowski and A. Selecki [3] where limiting values of volume mass transfer coefficients and their dependence on the mass flow rate of fluidizing air are reported.

In this study we will present an analytical solution from which exact values of both the air and the charge parameters at the exit from a fluidization bed can be calculated.

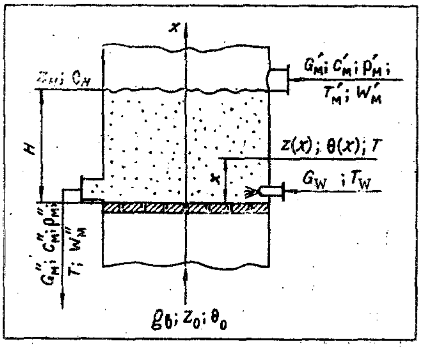

Fig. 1

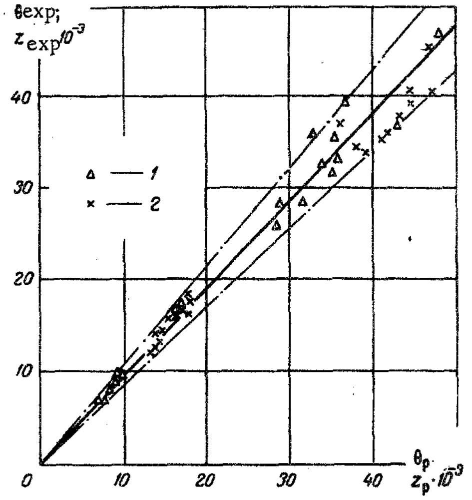

Fig. 2

Fig. 1. Schematic diagram for calculating the process of moisture evaporation from a wet fluidization bed.

Fig. 2. Comparison between measured and calculated values of air humidity (1) and air temperature (2) at the exit from the fluidization apparatus.

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The process is represented schematically with all essential symbols in Fig. 1. We consider the one-dimensional problem along the x-axis in the direction of the air flow. The following assumptions are made here:

1. Solid particles in the fluidization bed mix perfectly and, consequently, are all at the same temperature.

2. In formulating the differential equations it is assumed that both the evaporation process and the heat transfer obey the conventional laws of heat and mass transfer.

3. The process is steady.

The differential equations describing the processes of heat and mass transfer can be written as follows:

$$g_A \frac{dz}{dx} = \beta P_0 F \,[p(T) - p(x)], \tag{1}$$

$$\frac{d\theta}{dx}\,[c_D + z(x)\,c_V] = \frac{\alpha F}{g_A}\,[T - \theta(x)] + \frac{\beta F c_V P_0}{g_A}\,[p(T) - p(x)]\,[T - \theta(x)]. \tag{2}$$

From the material balance and the heat balance follows

$$[\theta_0 z_0 - \theta_H z_H]\,c_V + c_D[\theta_0 - \theta_H] - r\,(z_H - z_0) + Tc_W\,(z_H - z_0)$$
$$+ G'_M c'_M T'_M - Tc''_M G''_M + G_W\,T_W\,c_W + (G_W + z_0 - z_H)\,\mu + Q = 0. \tag{3}$$

Integrating Eqs. (1) and (2), we find

$$\frac{\beta F P_0}{g_A}\,H\,[1 - p(T)] = z_0 - z_H - \frac{K}{1 - p(T)}\ln\frac{z(T) - z_H}{z(T) - z_0}, \tag{4}$$

and

$$\frac{\theta_H - T}{\theta_0 - T} = \left[\frac{c_D + z_0 c_V}{c_D + z_H c_V}\right]^{\frac{1}{A}\frac{[Kc_V - c_D][1 + Ap(T)] + c_D A}{P_0[1 - p(T)][z(T)c_V + c_D]}} \left[\frac{z(T) - z_H}{z(T) - z_0}\right]^{\frac{Kc_V}{P_0^2 A\,[1 - p(T)]^2\,[z(T)c_V + c_D]}}. \tag{5}$$

The system of Eqs. (3), (4), (5) relates the process output parameters with the input quantities, which makes it feasible to derive several important practical formulas.

The validity of this mathematical model was verified by comparing the output parameters according to the proposed model with respective test data. The calculations were made on a computer.

We used the test data by J. Cyborowski and A. Selecki [3] pertaining to the case of maximum moisture content in a fluidization bed and our test data for a glass model 30 mm in diameter and 300 mm high. As the solid material we used electrical-grade corundum grains 0.25, 0.80, and 1.5 mm in diameter. The air velocity per total apparatus section was varied from 0.83 to 3.99 m/sec, the air temperature at the exit was varied from 11 to 18°C and its humidity from 6 to 12 g/kg. The height of the dense bed was varied from 25 to 100 mm. Water was supplied to the apparatus in an amount sufficient to compensate for evaporated moisture and to cover all particles with a water film.

The quantities needed for these calculations were determined as follows.

The surface of particles F per unit bed height and per unit gas distributor area was calculated according to the expression

$$F = \frac{6(1 - \varepsilon)}{d_e}. \tag{6}$$

The bed porosity ε was calculated according to the O. M. Todes formula [4].

Inasmuch as the surfaces of particles in the fluidization bed were covered with a water film, the values of the mass transfer coefficient were taken from the data in [5] (L. D. Berman). The heat transfer coefficient α was determined from the known ratio $\alpha/\beta = 0.33\text{–}0.35$ kcal · atm/kg · °C valid for evaporation from the surface of a water film.

For our tests we estimated the amount of heat leaking in from the ambient medium. It was ascertained that this heat could not contribute more than 0.06°C to the temperature rise at the apparatus exit – well within the accuracy limits of the measurements. For this reason, the effect of heat leakage was henceforth disregarded.

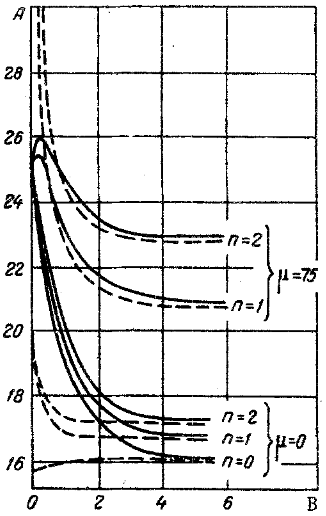

Fig. 3

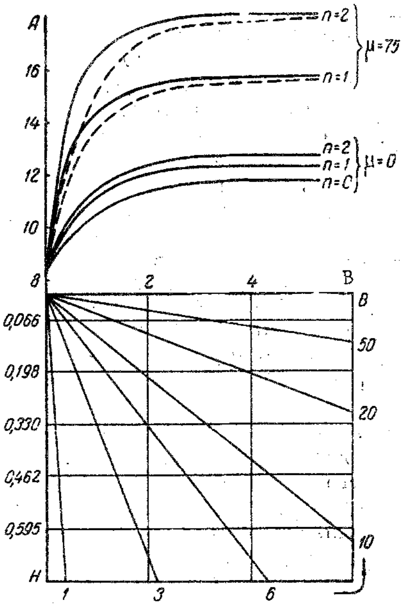

Fig. 4

Fig. 3. Temperature (A-axis) as a function of the complex HB (B-axis): solid lines represent air temperatures (°C), dashed lines represent charge temperatures (°C); apparatus loading n, heat released μ (kcal/kg).

Fig. 4. Air humidity (g/kg, A-axis) as a function of the complex HB (B-axis): solid lines represent humidity at the exit from a bed of height H, dashed lines represent humidity at a height h inside the bed with a fixed total height H corresponding to HB = 5.5.

Calculated and measured values of the parameters at the apparatus exit are compared in Fig. 2. The discrepancy between them does not exceed 10%, neither on the air humidity scale z nor on the air temperature scale θ. The comparison here pertains to the case where the parameter values at the exit differ appreciably from those at the entrance, with the Cyborowski–Selecki test results also accounted for. The air temperature increased from 11 to 51°C at the exit, as it was raised from 15 to 162°C at the entrance, and the air humidity increased from 0.0035 to 0.0127 kg/kg.

The agreement between calculated and measured data for process variants with widely different entrance and exit parameter values indicates a high degree of correlation between the mathematical model and an actual process.

In order to demonstrate the feasibility of using this mathematical model in an analysis of processes which occur in a fluidization bed, we will calculate a specific process for illustration. The initial values are assumed close to those in the process of hydrating sodium sulfate in a fluidization bed prior to molding – a process which has been designed by the authors for the production of sodium sulfide. The calculation will be based here on a specific loading equal to n = 0.8 kg of charge material per 1 kg of dry air, with n subsequently taken equal to 0, 1, and 2.

The amount of released hydration heat μ is assumed equal to 75 kcal per 1 kg of hydration water. The amount of water supplied to the apparatus is such as to raise the moisture content in the charge to 9%.

The temperature of air entering is assumed 25°C. We also consider a hydration process without release of heat ($\mu = 0$) and a process without replenishment of material (n = 0). The results are shown in Figs. 3 and 4. Along the axis of abscissas has been plotted the product of the complex $B = \beta F P_0 / g_D$ and the total bed height above the gas distributor inside h. In the lower part of Fig. 4 are given the values of HB and hB as functions of B and of H or h respectively. Let us examine these graphs closer.

The air temperature at the exit from a fluidization bed of height H and the charge temperature are shown in Fig. 3 for various levels of specific loading n with or without heat release during hydration.

Most noteworthy is that for HB > 3.5 the air temperature θ at the exit and the charge temperature T are almost the same. These temperatures can be determined from the heat balance. Under conditions close to those the Na_2SO_4 hydration process $B = 7.5\ m^{-1}$, corresponding to an active bed height $H \approx 470$ mm.

The curves for $\mu = 0$ indicate a rising level of the process temperature during an increase of the specific loading. This is characteristic only for the given conditions here, with the initial temperature of the supplied material 20°C being higher than the process temperature for $n = 0$. The calculations for the process variant with heat release ($\mu = 75$ kcal/kg) reveal an appreciable rise of both the charge temperature and the gas temperature at the exit. In this case an increase of the specific loading results in much higher air and charge temperatures at the exit, which has to do with the much larger amount of heat released in the bed.

We will now consider the temperatures of both air and charge within the active zone of the fluidization bed.

An active zone exists at HB < 3.5 (the height of an active zone is less than 3.5/B). Within this zone the temperatures of the air and the charge are quite different, and the respective curves indicate rather divergent trends of both.

At $n = 0$ the charge temperature rises somewhat with increasing bed height H. At HB = 0 this is the wet-bulb temperature. Some rise in the charge temperature due to an increase in the value of HB has to do with the heat which the charge receives from the fluidizing air as the latter cools down. During the process with $\mu = 0$ and $n = 1$, 2 the temperature difference $\theta - T$ is due to the difference between the temperatures of air and charge at the apparatus entrance. As HB approaches the value 3.5, this difference decreases gradually.

The temperatures of both air and charge vary in a much more complex manner when heat of hydration is released. At very small values of HB the temperature of the charge in the bed is much higher than the temperature of fresh material (T'_M). At slightly larger values of HB the air temperature also rises appreciably. In still higher beds (in our case HB = 0.25, H > 35 mm) the charge temperature and the air temperature both begin to drop. These curves intersect at θ_0, i.e., at 25°C. All this can be explained as follows.

At small values of HB the amount of evaporated moisture is insignificant and, consequently, the heat of hydration released here raises the bed temperature above the temperature of fresh charge ($T > T'_M$) as well as above the initial air temperature. As HB increases, so does the amount of moisture evaporating from the surface of particles, while the charge temperature drops. Within the range of small HB values, when the charge temperature T is higher than the air temperature at the entrance (θ_0), the air temperature at the exit (θ_H) rises above θ_0. As the value of HB increases, the charge temperature drops below the temperature of air supplied to the fluidization bed and, therefore, the air temperature at the exit (θ_H) drops below θ_0. In this way, the curves of T and θ can intersect only at the point corresponding to the temperature of air entering the fluidization bed (θ_0).

The curves in Fig. 4 represent the humidity of air leaving the apparatus, as a function of HB. According to expectations, the air becomes saturated when $HB \approx 3.5$, i.e., at values of HB corresponding to the height of the active zone. An increase in the maximum level of air humidity for $n > 0$ when hydration heat is released ($\mu > 0$) is related to higher charge and air temperatures (Fig. 3).

From Eq. (4) one can either determine the exit parameters of the air when the total height of the fluidization bed (H) in the apparatus changes, or with a given bed height one can determine the parameters of the air inside the bed at a height h. For illustration, the curves in Fig. 4 represent the variation of air humidity along the bed height h when HB = 5.5, corresponding to a total bed height H = 735 mm. The curves $z_h = f(h)$ and $z_H = f_1(H)$ almost overlap for $\mu = 0$. When heat of hydration is released, then the $z_h = f(h)$ curves depart from the $z_H = f_1(H)$ curves appreciably. Their relative trend is determined by changes in the T-curves which in turn depend on HB.

Let temperature T_0 correspond to the value H_0B. If T decreases with increasing HB, then for fluidization beds with HB equal to $hB < H_0B$ temperature T is higher than T_0 and, therefore, $z_H > z_h$ with the z_H curve above the z_h curve. This is the case when $\mu = 75$ and $n = 1$ or 2.

Temperature T drops particularly low at small values of HB. For this reason, the maximum departures of z_h and z_H occur also at small values of HB. Then, when temperature T varies only slightly with HB, the z_h values almost do not differ from the z_H values – as shown in Fig. 4 for $\mu = 0$.

With the aid of Figs. 3 and 4 it is possible to analyze the effect of specific loading and of the released heat μ on the charge temperature T and on the air temperature θ. With these curves one can determine the minimum height of a fluidization bed necessary for an efficient apparatus performance; one can also determine how the performance changes as the bed height is further reduced.

We have considered here only one example.

The proposed mathematical model is also suitable for the design of similar processes in a fluidization bed as, for example, granular precipitation from solutions, when liquid or solid substances in the bed react chemically, or when liquid is supplied to the bed.

NOTATION

c'_M, c''_M	is the specific heat of charge material at the apparatus entrance and exit respectively;
ρ'_M/ρ''_M	is the density of charge material at the apparatus entrance and exit respectively;
T'_M, T''_M	is the temperature of charge material at the apparatus entrance and exit respectively;
W'_M, W''_M	is the moisture content in charge material at the apparatus entrance and exit respectively;
G_W, T_W	are the weight of water supplied, per unit apparatus area, and its temperature;
H	is the total height of fluidization bed;
h	is the height above gas distributor in a bed of height H;
z_0, z_H	are the air humidity at the apparatus entrance and exit respectively;
θ_0, θ_H	are the air temperature at the apparatus entrance and exit respectively;
$z(x)$, $\theta(x)$	are the air humidity and temperature at distance x from the distributor grid;
z_h, θ_h	are the air humidity and temperature at height h;
c_D	is the specific heat of dry air;
c_V	is the specific heat of water vapor;
c_W	is the specific heat of water;
g_A	is the mass flow rate of air;
F	is the surface of particles in the bed, per unit grid area and per unit height;
α	is the heat transfer coefficient;
β	is the mass transfer coefficient;
$z(T)$	is the equilibrium humidity of air at temperature T;
$p(T)$	is the partial pressure of water vapor at temperature T;
μ	is the heat of hydration;
Q	is the heat received from ambient medium;
T	is the temperature of particles in the fluidization bed;
$A = \beta c_H/\alpha P_0$	is the complex;
$B = \beta F P_0/g_D$	is the complex.

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