STRIPPING OF SURFACE WATER FROM PARTICLES IN AN INJECTED BED

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Mechanical water stripping has been observed in an injected bed; measurements have been made on the effects of the water content of the material, the bed depth, particle diameter, and injected gas speed on the stripping rate.

Various methods are commonly used for fluidizing solid particles with gases or liquids; injected beds are of considerable interest [1], their major properties being due to the high speeds of efflux of the gas from the holes in the distributing grid, which has a small working cross section, while the speeds above the bed are comparatively small (they may be below the limit for the onset of fluidization). The large dynamic heads indicated by Bernoulli's equation mean that the gas jets emerging from the holes produce zones of reduced pressure, which draw in particles from the parts between the holes, where the pressure is higher; these are entrained by the gas jets and displaced upwards. The entire body of solid material then moves vigorously, and there are no stagnant solid zones, while the elevated resistance of the gas-distributing grid, which is necessary to realize such a bed, improves the uniformity of the gas distribution.

The inertia of the particles in contact with the fast jets results in a considerable speed difference between the gas and particles (particularly near the grid). This means that certain effects occur at the particle surfaces that are not observed in systems where the relative speeds are lower. For instance, at comparatively low Reynolds numbers ($Re \sim 10$), as calculated from the speed for the complete cross section of the equipment, the mass-transfer coefficients for an injected bed are close to the values characteristic of single fixed particles (they are lower by 1-2 orders of magnitude [2, 3] in ordinary fluidized systems).

We have examined an effect we observed previously, namely, stripping of water from solid particles during drying in an injected bed under conditions designed to remove free water. This mechanical stripping (which differs from ordinary removal by diffusion) means that X_o often appreciably exceeds X_e (the limiting value for mass transfer under conditions of convective diffusion). It is thus possible to remove considerable quantities of water without consuming energy for evaporation; the practical significance of this effect is obvious and is confirmed by the measurements reported here.

The equipment of diameter 180 mm and height 2000 mm was fitted with a perforated grid, with the holes containing Laval nozzles having diameters in the narrow part of 1.0 mm and in the upper part of 1.27 mm; the effective cross section of the distributor (taken over the narrow parts of the nozzles) was 0.25%. The injected gas was air, while the granules were of polycapramide of dimension d from 0.5 to 4.5 mm. We varied the following: U from 0.08 to 0.8 kg per kg of dry material; H_0 from 0.5 to 50 mm; and V from 60 to 180 m^3/h (these correspond to w_n = 150-450 m/sec). The bed temperature in all experiments was 75°C.

At present we have not been able to distinguish entirely the purely mechanical stripping from the surface, so in processing the data we assumed that the convected mass transfer raised the water content of the air to X_e, while the excess $X = X_o - X_e$ was due to the stripping. The relative excess $N = X/X_e$ may be called the stripping number, and it is shown from what follows in relation to the above process parameters.

Figure 1 shows the effects of water content in the material on N_1 for a bed of thickness one particle ($H_0 = d$); zero value for the stripping number corresponds physically to $U_{cr} \simeq 0.07$; if U exceeds U_{cr}, N_1 at first increases rapidly (broken line in the figure), and then linearly (solid lines) up to some limiting value

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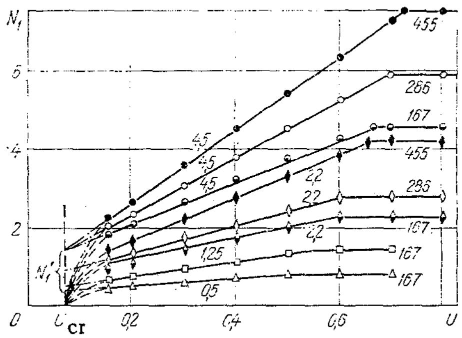

Fig. 1

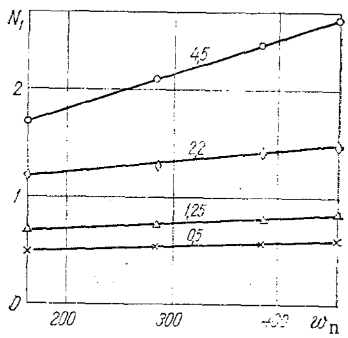

Fig. 2

Fig. 1. Effects of water content U (kg per kg dry matter) on stripping number N_1 for single layers. The numbers on the curves on the right are the air speeds w_n (m/sec) at the nozzle outlet, while the numbers on the curves are the particle sizes d in mm.

Fig. 2. Relation of N_1 to w_n (m/sec) for U = 0.2 kg of dry material. The numbers on the curves are the particle sizes in mm.

U_{lim}, beyond which N_1 remains constant at the limiting value N_{lim}. The $N_1 = N_1(U)$ curves for the larger particles lie higher up. Figure 1 also shows that N_1 increases with w_n, and the behavior is nearly linear in the working speed range (Fig. 2). Finally, the bed depth also affects the stripping rate (Fig. 3): the points on the extreme left correspond to N_1, and initially N increases with H_0, but beyond certain limiting values H_{cr} the effects of H_0 largely disappear.

The stripping numbers (N_1, N, and N_{lim}) increase with the particle size on account of the increase in the relative speed of the gas with respect to the particles. Also, the thickness of the free water film is proportional to the particle size for a given water content (the amount of water is proportional to the cube of the diameter, and the free water is distributed over the surface, whose area is proportional to the square of the diameter). Obviously, the gas flow strips water more readily from thicker films, i.e., from larger particles. This is also the reason why N_1 increases with the water content.

It is clear that N_{lim} is constant for $U \geq U_{lim}$ because of the limited carrying capacity of the medium in a two-phase flow [4]; also, the transport of water stripped from the particles may be affected by the tendency of the particles to block the gaps. This explains why lower N_{lim} and U_{lim} are obtained for small particles, which have a larger total surface area (Fig. 1).

The increased relative speed of gas and particles is responsible for the rise in N_1, N, and N_{lim} with w_n, in conjunction with the increase in the transport capacity of the flow for the liquid. It is probably the latter increase with w_n that is responsible for the increase in U_{lim}.

The increase in N with bed depth at moderate values of H_0 is due to the increase in the absolute amount of water in the bed, and also to the increased time of contact between the solid particles and the gas flow. Further, N is constant for large H_0 on account of the collecting action of the particles. For this reason, the limiting value H_{cr} increases regularly (see above) with the particle size.

The data processing was based on examining the effects of process parameters on water stripping for a layer thickness of one particle.

Figure 1 shows that the straight lines $N_1 = N_1(U)$ for the various w_n for each particle size (2.2 and 4.5 mm) intersect at a single point whose abscissa is U_{cr} (broken straight lines near U_{cr}). The ordinate N_1' of the point of intersection is dependent on the particle size (this quantity is found as the ordinate of the $N_1 = N_1(U)$ lines at U_{cr} for particles of diameter 1.25 and 0.5 mm). Statistical processing gave the relationship

$$N_1' = 0.11\,\mathrm{Ar}^{1/3}. \quad (1)$$

To describe the variation of N_1 with U we need to specify also the end point on the straight line, whose coordinates are N_{lim} and U_{lim}. Our empirical formulas reflect the effects of particle size and gas speed (Figs. 1 and 2):

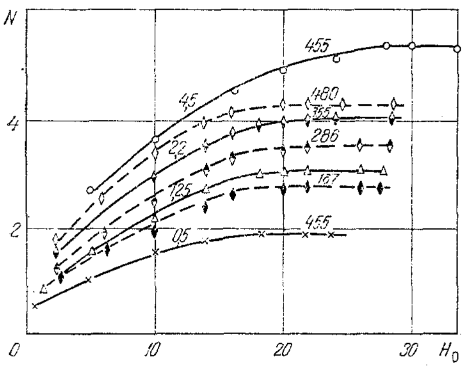

Fig. 3

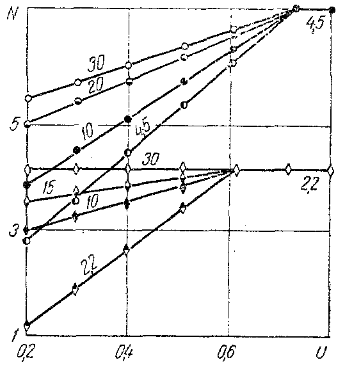

Fig. 4

Fig. 3. Effects of bed depth H_0 (mm) on N for U = 0.2 kg of dry material. The solid lines are for w_n = 455 m/sec; the numbers on the curves on the left are the particle sizes d in mm; the broken lines are for a particle size of 2.2 mm. The numbers on the curves on the right are w_n in m/sec.

Fig. 4. Relation of N to U (kg per kg dry material) for w_n = 455 m/sec for several bed depths H_0 (mm, numbers on curves). The numbers on the curves on the right are the particle sizes in mm.

$$N_{lim} = 0.03\,Ar^{1/6}\,Re^{1/2}, \tag{2}$$

$$U_{lim} = 0.17\,Re_n^{0,13}. \tag{3}$$

Formulas (1)-(3) were derived for the ranges $Ar = 4\cdot10^3 - 3\cdot10^6$ and $Re_n = 4.4\cdot10^3 - 10^5$.

If the end points of the straight lines $N_1 = N_1(U)$ are available, one can readily construct a general relationship for the entire linear part in terms of the reduced stripping number N* and water content U*:

$$N^* = U^* \quad \text{or} \quad \frac{N_1 - N_1'}{N_{cr} - N_1'} = \frac{U - U_{cr}}{U_{cr} - U_{cr}}. \tag{4}$$

From (4) one can determine N_1 for a given U in the range from $2U_{cr}$ to U_{lim}.

As regards calculation of stripping number for a bed of arbitrary H_0, we would emphasize that the limiting point (i.e., the numerical values of N_{lim} and U_{lim}) are independent of H_0 (Fig. 4); the data (Fig. 3) are clearly best represented in coordinates N/N_1 and H_0/d, and in that approach the observed points for the various gas speeds, particle sizes, and bed depths fit with acceptable accuracy to a common curve described by the simple relation

$$N/N_1 = (H_0/d)^{0.5}. \tag{5}$$

Equation (5) has been derived for the range H_0/d = 1-36; of course, this relationship does not fit the measurements outside the critical bed depth H_{cr}, for in the case $H_0 \geq H_{cr}$ the stripping rate remains unaltered and is the maximum possible for particles of a given size for the given gas speed. To find H_{cr}, above which $N = N_1 = N_{lim}$ = const, we have the empirical formula

$$H_{cr}/d = 4.4\cdot10^2\,Ar^{-0.3}. \tag{6}$$

NOTATION

X_o, water content of outgoing air, kg/kg air; X_e, equilibrium water content, kg/kg; H_0, bed depth, mm; V, gas flow rate, nm^3/h; w_n, gas velocity at nozzle exit, m/sec; U_{cr}, U, and U_{lim}, critical, initial, and limiting water contents, kg/kg; N_1', N_1, and N_{lim}, fictious, instantaneous, and limiting stripping rates; $Ar = (gd^3/\nu^2)[(\gamma_s - \gamma)/\gamma]$, Archimedes number; g, acceleration due to gravity, m/sec^2; d, equivalent particle diameter, mm; ν, kinematic viscosity, m^2/sec; γ_s and γ, densities of solid particles and gas, N/m^3; $Re = wd/\nu$, Reynolds number; w, gas speed in apparatus, m/sec; $Re_n = w_n d/\nu$, Reynolds number derived from w_n; $N^* = (N_1 - N_1)/(N_{lim} - N_1')$, reduced stripping rate; $U^* = (U - U_{cr})/(U_{lim} - U_{cr})$, reduced relative water content.

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NUMERICAL SOLUTION OF THE PROBLEM OF HEAT AND MASS TRANSFER IN A MOIST POROUS BODY

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A system of controlling equations is derived. The method of finite differences is used to obtain numerical solutions for the temperature distributions, the moisture content, and the pressure of the air — vapor mixture in a porous body during contact heating.

Heat and mass transfer in a two-dimensional moist porous body during contact heating and molding are discussed. The nonstationary heating of a porous body from a molding surface at constant temperature T_{ms} leads to the vaporization of the moisture in the skeleton and to the formation of an air — vapor mixture in the pores which moves toward the free (permeable) surfaces of the body. The molding process is considered complete when the porous body reaches a given temperature and moisture content.

The motion of the air — vapor mixture in a porous two-dimensional body is described by Darcy's filtration law [1] in the form

$$\Pi \rho u = -k_x \frac{\partial p}{\partial x} \text{ and } \Pi \rho v = -k_y \frac{\partial p}{\partial y}, \tag{1}$$

where Π is the volume and surface porosity of the body.

According to the accepted mathematical model of an elementary volume of a porous body shown in Fig. 1, the equation for the transport of the air — vapor mixture can be written in the form

$$\Pi \left(\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} \right) = \beta (p_{sv} - p_v), \tag{2}$$

in which

$$p_v = \rho_v R T, \tag{3}$$

where

$$R = R_v \frac{\rho_v}{\rho} + R_a \left(1 - \frac{\rho_v}{\rho} \right) = R_v \frac{p_v}{p} + R_a \left(1 - \frac{p_v}{p} \right). \tag{4}$$

It is assumed that vaporization and condensation of moisture occur at the pore surfaces and that the moisture in the system of capillary channels of the skeleton is in the liquid state at the skeleton temperature T_{sk}. It is assumed that the mass transfer rate in the bulk of the body is proportional to the difference between the saturated vapor pressure at the temperature T_{sk} and the partial pressure of the vapor p_v.

The moisture content in the skeleton is characterized by W, and its local time rate of change is described by the moisture content equation

$$(1 - \Pi) \frac{\partial W}{\partial t} = \beta (p_v - p_{sv}). \tag{5}$$

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