MOISTURE EVAPORATION IN A FLUIDIZED BED OF INERT PARTICLES

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Results of an experimental study are compared with calculations based on the equations for thermal and material balance.

A method for single-stage dehydration of salt solutions was theoretically developed and introduced to industry in work performed at the All-Union Scientific-Research Institute of Halurgy [1, 2]. Data have been published [3] on a similar application of a fluidized bed for the extraction of radioactive materials from the waste waters of nuclear industry. In both cases, solutions are evaporated in a fluidized bed of solid particles which are heated by hot gases blown through the bed. The basic product in this case is the separated solid phase, which is gradually removed from the apparatus with the unloading of the solid particles or which is collected in the form of dust in cyclones. The water vapor formed escapes from the apparatus along with the outlet gases as a by-product of the process.

The use of this same process was proposed for the desalinization of saltwater in a fluidized [4], or vibratory fluidized [5] bed. In this case, the salt, which crystallizes out on the surface of the inert particles, is pulverized into a fine dust in the fluidized bed and is removed in a cyclone as a by-product of the process. The basic product is pure vapor, which is subsequently condensed during cooling of the outlet gases.

For proper design of the optimum technical mode for desalinization of water in a fluidized bed it is necessary to know to what extent the rate of the process, as a whole, is limited by the kinetics of heat and mass exchange between the solid phase, gas, and solution. Data presently in the literature [6] refer predominantly to the more particular cases of separate heat and mass transfer between the solid particles and the fluidizing gas. The results of these measurements indicate that an active region in which all this transfer is practically completed is located in a fluidized bed at a height of 5-10 granule diameters above the gas-distribution grid. Deviations from the establishment of thermal or concentration equilibrium between gas and particles arise only during significant breakdown of the hydrodynamics of the fluidized bed itself where channelized passage of the gas is observed in a bed that is too low. When the bed is too high, a piston mode of fluidization arises.

Heat and mass transfer are interrelated and superimposed on one another during the evaporation of saltwater in a fluidized bed. In addition, the system becomes three-phase (gas — liquid — solid phases), and the film of solution coating a granule can be heated from both directions through the gas — liquid and liquid — granule interphase surfaces. Solid and sufficiently fine granules may be heated sufficiently deeply in the active region and, because of their high heat capacity, arrive in the upper spray region with a temperature even higher than that of the outlet gas. The existence of such strong temperature oscillations of the granules, which alternately are in a region of heating by the inlet gases and in a region of cooling by the spray of cold solution, is confirmed by thermal breakup of salt particles in nonrecycling processes for dehydration of solutions at the All-Union Scientific-Research Institute of Halurgy.

Heat and mass transfer in three-phase fluidized beds of large, light, hollow spheres have been studied in recent years by foreign [7] and Soviet investigators [8]. A different region of hydrodynamic flow modes (high values of the Reynolds number) and the small relative heat capacity of the thin-walled

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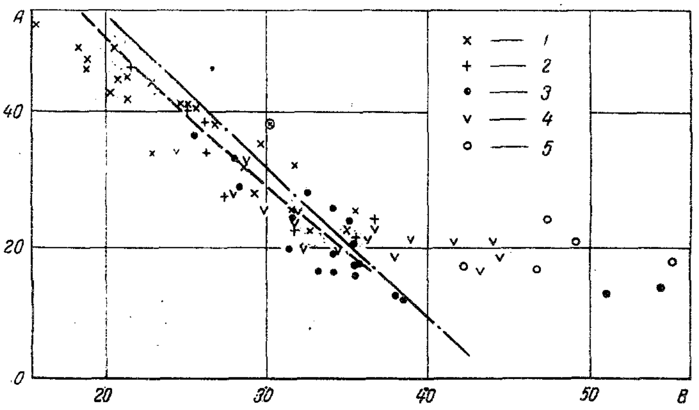

Fig. 1. Effect of evaporated moisture loading on the temperature of outlet gases: 1) particle diameters 1-2 mm; 2) height of fixed bed, 100 mm; 3) height of fixed bed, 200 mm (particle diameters 2-3 mm for 2 and 3); 4) particle diameters 3-5 mm; 5) "flooded" bed; dashed-dot curve is theoretical relation from Eq. (4); dashed curve is theoretical relation from I vs d diagram for $d_i = 0$. $A = t_0/(t_i \cdot 10^{-2})$; $B = d/(t_i \cdot 10^{-2})$ kg/kg·deg.

hollow spheres make it impossible to transfer the correlations obtained in those papers to the systems of interest to us.

The same difficulties were observed in the work of Tsiborovskii [9] and Volkov [10] on the evaporation of water in fluidized beds of small solid granules as those in most of the work on the kinetics of heat and mass transfer in two-phase fluidized beds. Deviations of the state of the outlet gases from equilibrium with the solid phase are not so great as to yield accurate values and correlations for the heat- and mass-transfer coefficients based on them. As follows from what has been said, this problem is even more complicated for a three-phase fluidized bed because of the existence of a temperature gradient along the bed itself.

Based on the above, we found it necessary to perform a special experimental study of the evaporation of water in a fluidized bed of particles fluidized by hot gases. In our opinion, with good organization of the hydrodynamics of the bed itself, as in a two-phase fluidized bed, the kinetics of heat and mass transfer ought not limit the process as a whole. If this assumpion is valid, the temperature of the outlet gases should be calculated entirely from the equations for thermal and material balance. As the spray intensity increases, this temperature should fall until the outlet gas becomes saturated with water vapor. Going beyond the equilibrium state leads to "flooding" of the bed.

In a first approximation (without considering heating of the water and the temperature variation of the latent heat of vaporization), the temperature of the outlet gases can be determined from

$$G_g(t_i - t_o)\,c_p = rG_w, \tag{1}$$

$$G_w = G_g\Delta d. \tag{2}$$

Assuming $c_p \approx 240$ cal/kg·deg, $r \approx 540$ cal/g, we obtain

$$t_o = t_i - \frac{r}{c_p}\Delta d \approx t_i - 2.25\,\Delta d. \tag{3}$$

Or, dividing both sides of Eq. (3) by t_i, we obtain the relation in general form as

$$\frac{t_o}{t_i} = 1 - 2.25\frac{\Delta d}{t_i}. \tag{4}$$

Solving Eqs. (1) and (2) with respect to Δd, we obtain

$$\Delta d = \frac{c_p}{r}\Delta t \approx 0.444\,\Delta t. \tag{5}$$

More precise values of the numerical coefficients in Eqs. (3) and (5) and a direct representation of the relation by a curve can be obtained from I vs d diagrams for combustion products or for the humidity of

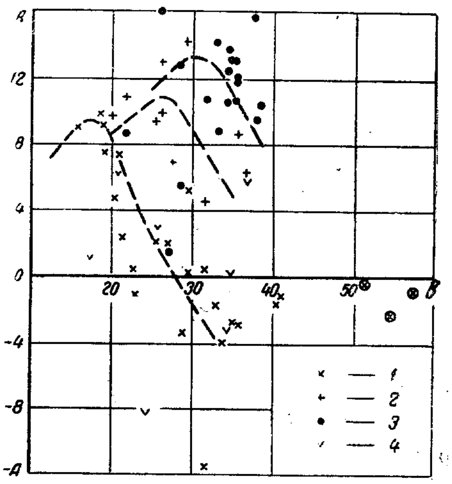

Fig. 2. Dependence of evaporated-moisture loading of the difference between measured bed temperature and outlet gas temperature: 1-4) correspond to 1-4 in Fig. 1; A = $(t_b - t_o)/(t_i \cdot 10^{-2})$; B = $\Delta d/(t_i \cdot 10^{-2})$ kg/kg·deg.

air. Heat- and mass-balance relations can be represented in the following form:

$$G_gI_i + G_wI_w = G_gI_o + G_w(t'' - t_w)c_w + Q_l, \tag{6}$$

$$G_gd_i + G_w = G_gd_o. \tag{7}$$

Normalizing to 1 kg of dry gas, we obtain

$$I_i + \Delta dI_w = I_o + \Delta d(t'' - t_w)c_w + Q'_l, \tag{8}$$

$$d_i + \Delta d = d_o. \tag{9}$$

The maximum temperature of water heated by the contact method can be equal to the temperature t_{wb} of the wet-bulb thermometer. This is the temperature at which unsaturated outlet gases, adiabatically cooled because of the evaporation of water, become saturated. The quantity t_{wb} depends on the thermodynamic state of the gas supplied to the bed — its temperature and moisture content.

Assuming in the preliminary calculations that $Q_l = 0$, $c_w = 1$ cal/g·deg, $t'' = t_{wb}$, we obtain

$$I_o = I_i - \Delta d(t_{wb} - 2t_w). \tag{10}$$

Supplying water to the bed with $t_w = t_{wb}$ and assuming that in the limit t_o cannot be less than t_{wb}, i.e., $t_o \approx t_{wb}$, the maximum specific output of evaporated moisture, normalized to 1 kg of dry gas, takes the form

$$\Delta d^* = \frac{I_i - I_o}{595 - 0.54\,t_{wb}}. \tag{11}$$

It is clear from Eq. (11) that the maximum value Δd^* is unambigously determined by the initial thermodynamic state of the gas and does not depend on other parameters of the fluidizing agent or bed, since $t_{wb} = f(I_i)$. It then follows that it is desirable to use a fluidizing agent with an acceptably high temperature in order to obtain the greatest output of the device in terms of evaporated moisture when supplying the bed with water at $t_w = t_{wb}$.

Flow greater than the maximum value produces condensation of water vapor and leads to "flooding" of the bed. The type of behavior of the bed in this state will depend on the bed parameters and the particle size. For small particles, an increase of t_o in comparison with t_{wb} is possible because of clumping of the particles and bursting through of gas bubbles without sufficient heat transfer. Particles of larger sizes have greater stability with respect to preservation of the hydrodynamics of the bed even in the "flooded" state, which makes it possible to expect roughly constant values $t_o \approx t_{wb}$ in this state.

It is pointed out [9] that the temperature of outlet gases falls with an increase in the spray intensity in accordance with the I vs d diagram for moist air; however, failure of device operation is always observed upon reaching the 100%-saturation line. In our opinion, an I vs d diagram can be used successfully for the calculation of heat- and mass-transfer processes in the evaporation of saline water in fluidized-bed equipment including equipment with relatively low beds (of the order of the height of the active region or slightly more). The initial point of the process on the I vs d diagram is determined from the known t_i and d_i of the fluidizing agent. The process line follows the line of the wet-bulb thermometer [$t_{wb} = f(I_i)$]. Its intersection with the 100%-saturation line gives the value of the maximum increment of moisture content per 1 kg of dry gas.

The experimental study was carried out on two pilot models with grid diameters of 100 and 200 mm. Particles of sea sand in the size ranges 1-2, 2-3, and 3-5 mm were used to create the bed. The ratio between the height of the fixed bed and the diameter of the apparatus was 0.5-1.0. A basic technologic scheme was used with the salt deposited from the inlet water being abraded from the surface of the particles in the fluidized bed. Fine salt particles carried away were trapped in a cyclone. The vapor produced was condensed, and the salt content of the condensate determined. In the experiments, the thermal head varied from 100 to 575°C. The difference between the gas temperature below the grid and that at the outlet of the apparatus, $\Delta t = t_i - t_o$, was used as the design temperature head for the process. The resultant values of the specific moisture removal varied from 400 to 3550 kg/m^2·h, and the increment of

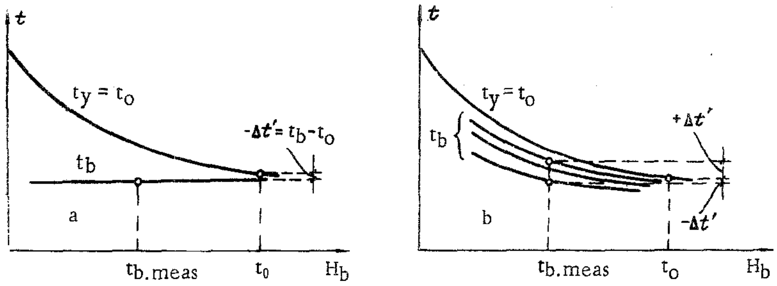

Fig. 3. Variation of temperature (°C) of gases and bed with height of fluidized bed: a) based on ideal mixing with respect to the solid phase and ideal displacement with respect to gas; b) assumed dependence.

moisture content of dry gases varied from 32 to 257 g/kg. The salt content of the final condensate was from 80 to 400 mg/liter for an initial water salinity of 5000 to 35,000 mg/liter.

The experimental data for the increment of moisture content of dry gases corresponded to the theoretical values in a completely satisfactory manner. Plotting of the desalinization process on an I vs d diagram demonstrated acceptable matching of its line with the line for the wet-bulb thermometer of the fluidizing agent.

The variation of the temperature of the outlet gases as a function of the evaporated-moisture loading in the apparatus is shown in Fig. 1. The values are normalized to $t_i \cdot 10^{-2}$ to eliminate the effect of initial temperatures of the gases. Also plotted are lines for the relations given theoretically by Eq. (4) and by the I vs d diagram for an initial moisture content $d_i = 0$. It is typical that differences in particle size and in height of the fixed fluidized bed have no effect on the nature of the dependence. Deviations from the line for the relation were obtained in experiments in which the bed was in a "flooded" state or close to it.

Results of an analysis of experimental data on the reduction of a fluidized bed to the "flooded" state confirmed our hypothesis about the decisive effect of particle size on the kind of behavior of a bed in this state. Even for a bed with particles in the size range 3-5 mm, a fluidized "sand + water" bed was created during "flooding" for which constant temperature of the outlet gases was typical. The spray intensity at which breakdown of the hydrodynamics of the bed arises is determined by the size of the bed particles in the final analysis. The degree of approximation of the bed temperature to the wet-bulb temperature of the gas in the space below the grid is of great importance. For particles in the 1-2-mm fraction, an unstable mode begins for a difference $t_b - t_{wb}$ of the order of +10°C with typical equalization of t_b and t_o. A difference of +10°C only corresponds to the beginning of a transition period for particles in the 3-5-mm fraction. A fluidized bed in such a state still allows considerable increase in the flow of sprayed water without changing the quality of the condensate produced.

In most experiments, the temperature of the outlet gases was 20-40°C above the measured temperature of the bed. The difference between these temperatures decreased as the moisture loading increased (Fig. 2). If one explains the difference noted only by additional cooling because of the arrangement of sprays above the bed, it is reasonable to expect values of the difference to be independent of the particle sizes in a fluidized bed and of the height of a bed for particles with sizes limited to a given range. The experimental data do not confirm this hypothesis.

Numerous measurements of heat transfer between gas and a fluidized bed and mass transfer from a gas to a fluidized bed showed that in these cases the apparatus can be considered an ideal mixture with respect to the solid phase and an ideal displacement with respect to a gas (Fig. 3a). However, we have a more complex case with the evaporation of saltwater from the surface of a fluidized bed together with simultaneous dampening of it. Work at the All-Union Scientific-Research Institute of Halurgy showed that during dehydration salt particles (granules) cracked because of thermal stresses. This means that there is a temperature gradient with height in the solid phase in the bed. All this is complicated to a considerable degree by the fact that evaporation may proceed mainly because of heat storage in the solid phase. In some locations in a fluidized bed, vapor is even condensed on cold particles.

We assume that the temperature of a bed measured by a thermocouple varies approximately exponentially over the height of a fluidized bed (Fig. 3b). Reduction of the temperature of the bed at the point of measurement (ordinarily at the center of the bed) with an increase in moisture loading leads to a reduction in the difference between the temperature mentioned and to their equalization at a given time or even to t_o exceeding t_b, along with bursting of gas bubbles through the bed because of agglomeration of the particles in the bed. Moistened particles descending into the active region of heat and mass transfer near the grid are not sufficiently heated and return to the upper portion of the bed cooler, which is recorded by the thermocouple as a reduction in the temperature of the bed. Thus, transfer of heat from particles is eliminated from the overall process of heat transfer for certain moisture loadings. This has an effect on the reduction in the intensity of heat- and mass-transfer processes and leads, in the final analysis, to "flooding" of the bed.

NOTATION

G_g, G_w	are the weight flow rate of dry gases and water, respectively, kg/h;
t_i, t_o	are the gas temperature at the inlet and outlet of the apparatus, °C;
Δd	is the increment of gas moisture content, kg/kg;
d_i, d_o	are the initial content moisture and outlet, kg/kg;
I_i, I_o	are the heat content of inlet and outlet gases, kcal/kg;
t_w	is the temperature of water supplied to the bed, °C;
Q_l, Q'_l	are the heat losses, kcal;
r	is the vaporization heat, kcal/kg;
c_p	is the specific heat at constant pressure, kcal/kg·deg.

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