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FLUIDIZED-BED (FB) DEHYDRATION ON AN INDUSTRIAL SCALE

Yu.Ya. Kaganovich,
LenNIIGyprochim, Russia

INTRODUCTION

Fluidized-bed drying, under an adequate process organization ensures, as compared to the known methods, the maximum productivity with the minimum fuel consumption, a significant reduction in equipment and working area, and a resultant high quality product due to uniform drying. However, despite the many advantages of this technology and numerous publications, up to now, the conditions of scaling, optimization of the regime, the choice of a rational design and some other essential problems have not yet been clearly defined.

The objective of this paper is an attempt to answer these questions on the basis of analyzing the results attained in the course of development and commercial operation of the intense dehydration method in FB. A detailed discourse on this subject is given in the monograph by the author ("Fluidized-Bed Dehydration on an Industrial Scale". L.Chemistry.1990).

SCALING UNIFICATION

The difficulties encountered while passing from testing the process on pilot plants to designing of the commercial apparatus, are primarily associated with the lack of theoretical grounds for a scale transition. For the first time, the solution of this problem was proposed by Todes* on the basis of a principally new interpretation of the physical nature of the FB as a system, in which, along with a random motion of particles, the processes of self-organization take place in the form of directed contour of particle circulation from the grid to the upper boundary of the bed The motion of particles from the grid to the upper boundary of the bed gives way to subsidence under the influence of gravitational forces. Visually observed FB pulsation reflects the elastic state of the system which allowed Todes to use it for describing the pattern of a simple pendulum. As is known, the oscillatory frequency and period of a pendulum are a function of its scale (length). Todes showed that the most important property of the FB is its mixing intensity, expressed by the mixing coefficient $D_{mix.}^*$, depends on the scale of Z system, as

$$D_{mix.}^* \cong \frac{1}{60} \sqrt{Z^3} \qquad (1)$$

In the conclusions by Todes on the problem, parameter of scaling i.e. the grid diameter or the bed height, is the decisive one, and at what scale the transition is optimal, remains open.

When we developed the FB dehydration method, the conditions of scaling were considered by us on the basis of assessment of attainment of stationarity in case of a continuous regime of the process. It has been practically established that there exists the minimum bed height, i.e. the determining parameter of the scale, at which the process proceeds at a constant temperature within the range of the bed, moisture of the product when unloaded and its granulometric composition, thus, in case of a stationary regime. The minimum height depends on the load after evaporated moisture, as:

*Todes, O.M., Khim. Prom. 1987, N° 8, pp. 48-53

Load after evaporated moisture, kg/m^2/hour	Height of the bed (immobile) mm
200-300	250-300
300-1000	450-500
1000-1500	550-600
1500 and above	750-700

The necessary condition for stationarity is the ratio of the apparatus diameter D to the bed height H, irrespective of the grid area, equal to $\frac{D}{H} \geqslant 1$.

Correlating our data with the conclusions drawn by Todes, one can assess, to what extent the minimum height of the bed ensures the stationarity conditions expressed by the homochromeity degree of the heat-and-mass content fields, i.e. Fourier number

$$F_O = \frac{D_{mix} . T}{Z^2} \qquad (2)$$

T = time of complete mixing

It is presumed that the system attains stationarity at F_O = 0.1; therefore, the time of complete mixing is

$$T \approx 0.1 \frac{Z^{1/2}}{Z^{3/2}} \approx \sqrt{Z} \qquad (3)$$

In case of the minimum bed height of 350 mm, D_{mix} according to Todes, is 100 $\frac{cm^2}{s}$:s ;

thus, the time of the complete mixing is $T \approx 0.1$ s, which is much less than the mean particle residence in a bed time. Therefore, at the minimum bed height of 350 mm, the conditions of homochromeity are ensured; the diameter of the apparatus should be not less than 350 mm (0.1 m^2), and the load after evaporated moisture, 1000 kg/m^2/hour; at higher loads the height and diameter of the trial apparatus should be increased, observing $\frac{D}{H}^{-1}$ conditions.

It has been practically confirmed that the bed height in commercial apparatus should remain constant under changing productivity and, respectively, the grid area (scale transition) of 100 times, from 0.1 to 10 m^2.

The established stationarity conditions enable to unify the FB apparatus for processing of different materials in the form of solutions, suspensions, moist loose and paste-like precipitates, etc.; the initial moisture content is practically unlimited.

Depending on the properties of the material, only the method of loading into bed changes.

HEAT AND MASS TRANSFER: OPTIMIZATION OF THE PROCESS REGIME

In general, from the experience of operation, it shows that the productivity does not depend on the drying kinetics (residence time of the material in the bed, of the initial moisture content, etc.) and is, as a rule, determined by the heat balance introduced into the bed. Therefore, the intensification of the process is based on increasing consumption and temperature of the heat-transfer agent.

Investigations have shown that the structure of the near-grid zone changes with changing gas rate. It increases markedly at a definite rate of particle circulation efficiency on the grid, which enables to use the heat-transfer agent at a temperature close or equal to the temperature of lumping, melting or decomposition of the material without overheating of particles and sealing of the grid by melting. Gas rate, corresponding to transition of the bed structure, is described by the criterial dependence as:

$$Re_{trans.} = \varphi\sqrt{Ar} \quad (4)$$

where φ is the coefficient depending on the shape and structure of particle in most cases, φ = 0.24. Fluidization number at a transitional rate appeared to be much higher than the known recommendations. At a working temperature of gases close to melting or lumping temperature (for salts, - 700-750°C) and high fluidization numbers the moisture removal is correspondingly increased to 1000-2500 kg/m^2/hour, which is much higher than the characteristics of plants of the number of firms of the USA and Germany.

In case of a high specific productivity, it was necessary to use special techniques of loading into the bed of moist material to avoid lumping at the feeding site. For this purpose, the method of dispersed loading was developed with the use of mechanical spreaders or injectors (a.c. 163534 USSR).

It has been experimentally established that the most important property of the process consists in the constancy of the final moisture content at the outlet of the apparatus, when not only the air-dried, but also the physico-chemically bound moisture is removed, irrespective of the material residence time in the bed and its initial moisture content. The final moisture content varies uniformly with the changing bed temperature at t $\geqslant$ 100°C and approaches the equilibrium one. During dehydration of crystalline hydrates the removal of crystallization water corresponds to the phase transition temperatures of crystalline hydrate forms. Generalization of experimental data enabled to express this dependence as

$$U = Ae^{-kt} \quad (5)$$

where U is the relative moisture content, kg/kg;

t, bed temperature, °C;

A and K, constants, depending on the physicochemical nature of the material.

The specific character of FB dehydration, therefore, disproves the widespread notion about an inevitable irregularity of drying in one stage as a consequence of a broad spectrum of changing residence time in the bed of separate particles under conditions of ideal mixing. This presumption serves as a basis for the recommendations on the use of multichannel apparatus, which are supposed to be necessary for a deep and uniform drying, which has not been justified in practice.

Presumably, the real characteristics of drying in a single-chamber apparatus confirm the dominant influence on the properties of the process in its ability to self-organize. Descending into the near-grid zone, the particles cool the gas to bed temperature T, being overheated by ΔT'; during the ascent of particles into the upper zone of moist material loading, the particles are cooled by Δ T'' in the course of moisture evaporation at the expense of the heat accumulated by particles. A continuous and multiple succession of the cycles of heating-cooling, drying-moistening takes place under efficient mixing conditions, which ensures the levelling of heat- and mass-content fields; for attaining the stationary state the bed height is required, which corresponds to a definite ration of the mass of dry, heated particles and moist, cool particles fed into the bed.

Therefore, the optimum dehydration regime in a single-chamber apparatus corresponds to:

- the maximum specific productivity for the given product and the minimum specific fueld consumption. It is attained by means of performing the process at a high gas working rate and the initial temperature close to lumping or melting temperature of the material (700-800°C).

- uniform drying to the required final moisture content, attained by the choice of the corresponding bed temperature.

CHANGES OF PARTICLE SIZE: GRANULATION

The most important feature of FB salt materials dehydration is the coarsening of particles from agglomeration during drying of moist precipitates to the expressed granulation in the course of solutions dehydration. Processing of solutions with granulation enables to created a new technology, which replaced multistage processes of evaporation, crystallization, filtration, and drying for a direction production of the dry, granulated product*. The control and optimization of dehydration with granulation are based on the developed physical and mathematical model of the process, which presumes that in the stationary regime the balance of granulation is sustained in the bed in accordance with the kinetic growth function and the generation in the bed of new particles, function of sources, compensating the loss of particles at the expense of continuous unloading. In the majority of the developed processes the stationarity, i.e. constancy of the granulometric composition during unloading, is ensured without introduction from outside of the recycling of minor particles; self-similarity points to the generation of an inner recycle in the bed. Experimental studies on the character of dependence of granulation of the regime of the process enable an assumption that inner recycling is due to thermal crushing of the bed granules in the course of a periodical temperature variation on the surface of a particle, i.e. abrupt cooling in the solution feeding zone and a subsequent heating within the bed and the near-grid zone, that is in accordance with the model of the gravitional-oscillatory structure of the bed.

Minor particles during temperature changes are heated entirely; large particles are heated to the heat wave depth with significant heat stresses being generated in them; and splitting into two inequal parts takes place: of the heat-wave scale and a larger residue, which can acount for the bimodality of the granulometric characteristics of this group of processes. The elaboration of a mathematical model of granulation with inner recycling made it possible to create the system of differential equations for computer-based calculations of granulometric composition; however, in each case, it is necessary to experimentally determine the coefficient of the growth rate and crushing of granules; therefore, for obtaining data for designing of new processes, it is necessary to conduct tests of a pilot plant under conditions corresponding to the requirements of scaling. Along with thermal crushing, the appearance of new particles ~~in the bed is possible during mechanical destruction~~ of non-strong agglomerates, local dissolution observed during dehydration of non-saturated solutions, generation of new particles without fixing on the surface of granules, and several other mechanisms.

Regulation of dehydration with granulation is based on the studies of the influence of the process regime on the granulometric composition. It has been ascertained that in all the cases, temperature increase in the bed stimulates the shift towards minor classes, since heat crushing, mechanical destruction, etc. are intensified; the increase of material residence time in the bed during increase of the bed height or reduction of productivity and solution concentration also result in the growth of the minor fractions content due to increasing duration of the action of factors, which favour the destruction of granules.

*O.M. Todes, Yu.Ya Kaganovich, S.P. Nalimov et al. Dehydration of solutions in the fluidized bed. M.Metallurgy. 1973

Along with common influence of the process regime on the changes in the granulometric characteristics, the absolute dimensions (as well as the shape) of particles obtained in the course of dehydration of different solutions are markedly different, starting with a practically non-granulated sodium chloride solution to a clearly expressed granulation of solutions of sodium, zinc, manganese sulphates, non-stationary growth of granules during dehydration of the magnesium chloride solution etc.

It was possible to establish a close analogy between the ability of different salt solutions to granulation and the strength of compositions obtained on the basis of electrolytes*. In both cases, the size and strength of the formation increases with the force of the cation field and the anion polarizability. On the basis of this analogy, a qualitative classification of the ability of salt solutions to granulation has been elaborated in the form of a series:

a) for cations: $NaCl < KCl < CaCl_2 < MgCl_2$;

$ZnS0_4 < MnS0_4 < CuS0_4$

b) for anions: $NaCl < Na_2S0_4 < Na_2C0_3 < NaH_2P0_4$

The qualitative classification enables to predict the trend of the new processes, including the processing of mixed solutions, as well as to stimulate granulation by introducing the solution additives with a high force of the cation field or anion polarizability, or to suppress a non-stationary granule growth by additions of surface active substances reducing the degree of adhesive action.

UNIFIED SERIES OF FB APPARATUS: VERSIONS OF FLOW CHARTS OF THE PLANTS

The studies of the scaling conditions and generalization of long-term experience of commercial operation enabled to develop at LenNIIgiprokhim a unified series of FB apparatus intended for processing of the materials in the form of solutions, suspensions, crystalline hydrates, moist plastic and loose precipitates during productivity variation from hundreds of kilograms to 100-130 t/hour and grid area from 0.1 to 10 m^2. The bed height is constant; the height of the separation zone increases with the growth of working gas rate and the grid area.

Apparatus of a round and rectangular sectional area are envisaged and the use of flat grids of several modifications.

Charging devices are located on the lateral wall of the apparatus above the bed front. Depending on the physicochemical properties of the moist product, different designs of spreaders are used; the nozzle entrance (coarse spraying, mechanical and pneumomechanical) is placed into the discharged upper zone of the bed. The characteristic of the unified series is given in Table I.

A comparison of the fluidized bed unified series against drum driers and FB apparatus of foreign design is shown in Table 2.

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*M.M.Sychev. Inorganic glues. L.Chemistry, 1973. pp. 28-35

Table 1

Unified series of FB apparatus of LenNIIgiprokhim

	Grid area	Apparatus height	Approximate mass		Air consumption (maximum)	Fuel consumption (maximum)	
			metal	lining		natural gas	Fuel oil
	m^2	m	t	t		m^3/hour	kg/hour
1	1.0	7.0	3.6	10.6	10000	300	270
2	2.0	9.0	6.45	17.5	20000	600	540
3	4.0	11.0	12.3	28.9	40000	1200	1080
4	6.0	13.0	17.3	41.1	60000	1800	1620
5	8.0	15.0	21.6	50.2	80000*	2400	2160
6	10.0	16.0	25.4	61.3	100000**	3000	2700

* Maximum fuel consumption corresponds to temperature under grid of 700°C.

** Apparatus with the grid area of 8 and 10 m^2 were brought to a commercial level under air consumption of 40-45000 m^3/h in accordance with the granulometric composition of the processed product.

Table 2

Comparison of the economic efficiency of FB apparatus of a unified series, drum driers and FB apparatus of foreign firms

Property	Drying in FB apparatus		Drum drier (USSR)
	Product of USSR	Product of foreign firms	
Productivity of a single apparatus after evaporating moisture, t/hour	8-11*	6**	5-6***
Grid area, m^2	8-10	25	Diameter of apparatus, 3.5 m; length, 22 m
Metal mass, t	Carbon steel, 21.6-24.5 Steel 12X18HIOT and 15X25T - 0.5-0.9	No data	220
Fuel consumption (fuel oil), kg/h	1100-1200	1400	1200
Specific fuel consumption kg/t moisture	120-150	220-230	200-240
Air consumption, m^3/hour	$(44-45).10^3$	100.10^3	37500
Specific air consumption, m^3/t moisture	4500-5500	16600	6200-7500

* Initial moisture content to 30% (during dehydration of crystalline hydrates).
** Initial moisture content for salts not more than 5% (mass).
*** Initial moisture content not more than 10-12% (mass).

Automatic regulation is based on stabilization of two parameters, i.e. temperature and bed height, perfomed by the action, after the bed temperature on the productivity of the feeder at loading and productivity of unloading devices in accordance with the bed resistance. At constant temperature and height (resistance) of the bed the overall air consumption is stabilized. Temperature of gases under the grid and discharging in the upper part of the apparatus have a remote control.

Several versions of flow charts of the plants have been developed with a view to:

a) Removing dust (complete or partial) from the ready products, which is attained under a definite hydrodynamic regime, dust recycling after drying cleaning to the loading of wet material. In the course of dehydration of high moisture, plastic precipitates, they are mixed in a special mixer with cyclone dust and are further directed to the spreader; dust-like material is injected into the bed above the grid or fed into the feed line in the course of dehydration of suspensions or solutions.

b) Using the physical heat of the dry product for its cooling and drying of a part of moist material. The new method solves two problems: cool hot dry materials and drying a part of moist material without consuming fuel. Commonly, cooling is performed by cool air in drum coolers or FP apparatus. In the given case, cooling is accomplished at the expense of moisture evaporation during mixing of hot dry material with a moist precipitate with a necessary removal of the water vapour generated. The possibility of cooling salt from ~ 130° C to 50-60°C has been established experimentally; the moisture of the product after processing is ~ 0.2-0.5% (mass) with the ratio of the moist and dry equalling ~ 0.2-0.35 t/t; saturation degree of the air removed from the apparatus should be not more than 0.65. Realization of the new cooling technique requires a strict regulation of the ratio of flows.

c) Dehydration of fine-dispersed material on the bed of inert particles, for instance, corundum, with a complete removal of the product to the dry cleaning unit. Such a modification of the process ensures a specific moisture removal of about 2000-2500 $kg/m^2/h$ during reworking of the particles with the grain size less than 100-120 microns. one should specially emphasize the efficiency of using FB apparatus with inert for dehydration of solutions and suspensions. As compared to spray driers, the specific productivity is increased practically, by an order; the specific metal content and heat losses are reduced correspondingly. For dehydration on the surface of inert particle, it is not necessary to use complicated devices for fine dispersion of liquid; the process proceeds in a stable mode in the course of coarse spraying through nozzles above the bed front.

APPLICATION FIELD

FB apparatus of the unified series are widely used for drying different salts, sand, dehydration of suspensions and solutions. The overall volume of the processed products amounts to millions tons per year. The development of the method was started in the middle of the 60's. During these years, for the first time worldwide drying in FB was brought to commercial level at potash works in the Ukraine, Urals, and Byelorussia, on large-tonnage plants for obtaining different types of potash salts. The experience of bringing to commercial level served as the basis for a subsequent unification of the apparatus and confirmed the rightfulness of the developed scaling conditions and optimization of the process. The technique of dispersed loading made it possible to feed into the bed the material practically unlimited by the initial moisture content as exemplified by the dehydration of crystalline hydrates. In the course of dissolution and crystallization processing of polymineral potassium ores, schoenite is produced ($K_2S0_4.MgS0_4.6H0$); in the course of flotation, a mixture of minerals with a significant clay content; the moisture content of these products before drying is from 25 to 32%. Along with drying of different types of potash salts, these enterprises also perform drying of common salt.

Dehydration of solutions in FB started with bringing to the commercial level the process of producing zinc sulphate at non-ferrous metallurgical plants. Subsequently, the new technology was used for processing discharged solutions of sodium sulphate, sodium chloride, and other salts. The method of dehydration with rendering harmless the slimes and production of a new type of phosphate-potash fertilizers has been developed and is being used in phosphorus production. Successfully used are apparatus with inert bed for dehydration of supensions and thermolabile solutions.

EFFICIENCY OF ECONOMIC USE

The advantages of the method and of the unified apparatus are due to:

a) reduction of fuel consumption;
b) intensification of the process, which made it possible to create apparatus of high unit power, reduce the specific metal content and the area taken by production;
c) replacement of multistage processes of processing of the solutions by evaporation, crystallization and drying with a single-stage dehydration;
d) attainment of a high quality of the product due to the uniform and deep drying

Saving of fuel, as compared to drum driers, is due to reduction of heat losses on the apparatus walls from 25-30% to 3-5%; additional fuel saving is attained due to a high initial and a relatively low final temperature of flue gases. A specific physical nature of drying in FB, as was shown above, ensures drying to the equilibrium moisture content at the temperature of waste gases equal to or ~ 20-30 lower than the temperature of the product, whereas in the course of drying in drum driers the temperature of waste gases should be 50-100° higher.

Intensification based on the specific character of the hydrodynamics of the process (in case of a high-temperature heat-transfer agent) enabled to reduce 8-10 times the specific metal content of large-tonnage plants and 2-3 times the production area covered.

A significant reduction of the operational costs and capital outlay is ensured in the case of a single-stage dehydration of solutions and replacement of driers on the apparatus with a inert bed.

Summing up, it should be said that the proved possibility of unification of FB apparatus and optimization of the regime determines the justification of further extension of the application of this method. Among the most promising trends, one can mention the solution of ecological problems by means of liquidation of sludge liquors. No less urgent is the task of processing and preparation for storage of vegetables, crops, and products of their processing.

Lennilgyprochim has long experience of designing and operating unified plants of dehydration in fluidized bed of solutions, suspensions, crystal hydrates, salts, plastics and freeflowing products.

. Fluidized-bed apparatus capacity is in the range from hundreds kilograms to 120-150 t/h
  Initial moisture isn't limited; thorough drying is guaranteed
. Fuel consumption is reduced by 30-40%
. Production area and metal consumption are reduced several times

Different variants are offered:

. single-stage solution dehydration and granulation
. combination of drying, dust removal and sizing of product
. drying of finely-dispersed products, solutions and suspension in inert layer
. utilization of dry product physical heat